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Project to extend the MATLAB simulator for communications links between LEO, GEO, Aircraft and Earth satellites

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Abstract

In the present thesis, a MatLab simulator originally designed to calculate connections between satellites and ground stations has been expanded to include airplane routes and their respective connections. The goal is to provide an accurate and efficient ground-air-space simulation tool for monitoring air connections, which will allow for improved air traffic efficiency and safety.

Air transportation is one of the most widely used modes of transportation worldwide, and its efficiency and safety are of vital importance. Using satellites for monitoring airplanes is of utmost importance due to several reasons, including the ability to provide continuous global coverage, real-time data on aircraft parameters, improved air traffic management, and enhanced safety.

The designed tool allows for the simulation of multiple aeroplanes and satellites, and automatically calculates the connections between aircraft and satellites and between satellites and ground stations. In addition, a module has been added to simulate and calculate connections between aircraft and ground stations.

This project is part of the PLATHON project of the Polytechnic University of Catalonia, which aims to develop a simulator to study the communications between constellations of cubes and the Earth. The simulator developed in this thesis will be used as a basis for the study of the communication between cubes, airplanes and ground in the PLATHON project.

Testing and validation of the simulator have been conducted, and it has been demonstrated to be an effective tool for simulating and monitoring air connections.

In conclusion, this project represents a significant advance within the PLATHON project in the monitoring of air connections, and has proven to be a very useful and necessary tool for monitoring aircraft routes across the globe.

Keywords:

Aircraft routes, Satellites, Radio communications, Link budget

Resumen

En la presente tesis, se ha expandido un simulador de MatLab diseñado originalmente para calcular conexiones entre satélites y estaciones terrestres, para incluir rutas de aviones y sus respectivas conexiones. El objetivo es proporcionar una herramienta de simulación precisa y eficiente para el monitoreo de conexiones aire-tierra-espacio, lo que permitirá mejorar la eficiencia y la seguridad del tráfico aéreo.
El transporte aéreo es uno de los modos de transporte más utilizados en todo el mundo, y su eficiencia y seguridad son de vital importancia. El uso de satélites para monitorear aviones es de suma importancia debido a varias razones, incluyendo la capacidad de proporcionar cobertura global continua, datos en tiempo real sobre parámetros de aeronaves, mejora en la gestión del tráfico aéreo y seguridad mejorada.
La herramienta diseñada permite la simulación de múltiples aviones y satélites, y calcula automáticamente las conexiones entre aviones y satélites, y entre satélites y estaciones terrestres. Además, se ha agregado un módulo para simular y calcular las conexiones entre aviones y estaciones terrestres.
Este proyecto forma parte del proyecto PLATHON de la Universidad Politécnica de Cataluña, que tiene como objetivo desarrollar un simulador para estudiar las comunicaciones entre constelaciones de cubesats y la Tierra. El simulador desarrollado en esta tesis se utilizará como base para el estudio de la comunicación entre cubesats, aviones y tierra en el proyecto PLATHON.
Se han llevado a cabo pruebas y validación del simulador, y se ha demostrado que es una herramienta eficaz para simular y monitorear conexiones aéreas.
En conclusión, este proyecto representa un avance significativo dentro del proyecto PLATHON en el monitoreo de conexiones aéreas, y ha demostrado ser una herramienta útil para el monitoreo de rutas de aeronaves a nivel global.

Palabras clave

Rutas de aviones, Satélites, Comunicaciones por radio, Balance de enlace

Declaration of Honour

I declare that:

- all the work in this Degree Thesis is completely my own work,
- no part of this Degree Thesis is taken from other people's work without giving them credit,
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Sergio Prieto Hernández 1st may 2023

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List of Abbreviations

ADS-B	Automatic Dependent Surveillance-Broadcast
ATC	Air Traffic Control
ASK	Amplitude Shift Keying
BER	Bit Error Rate
BSS	Broadcasting satellite service
CPFSK	Continuous Phase Shift Keying
CS	Control Segment
DME	Distance Measuring Equipments
DPSK	Differential Phase Shift Keying
ECI	Earth Centered Inertial
ECEF	Earth-Centered Earth-Fixed
FSS	Fixed satellite service
GEO	Geosynchronous Equatorial Orbit
GNSS	Global Navigation Satellite System
GPS	Global Position System
ILS	Instrument Landing System
INS	Inertial Navigation System
LEO	Low-Earth Orbit
LFR	Low Frequency Radio-Range
MEO	Medium Earth Orbit

MSK Shift Keying

NED North-East-Down

OQPSK Offset Quadrature Shift Keying

PSK Phase Shift Keying

QAM Quadrature Amplitude Modulation

RADAR Radio Detection and Ranging

SNR Signal to Noise Ratio

VHF Very High Frequency

VOR VHF Omnidirectional Radio Range

Chapter 1

Introduction

1.1 Aim

The aim of this project is to expand a MatLab simulator originally designed to calculate connections between satellites and ground stations to include airplane routes and their respective connections. The goal is to provide an accurate and efficient ground-air-space simulation tool for monitoring air connections, which will allow for improved air traffic efficiency and safety.

1.2 Scope

The project will include the following work packages and deliveries:

- Brief study of the current state of air traffic control and the use of satellites for this purpose.
- Description of the initial simulator and its capabilities and limitations.
- Development of the extension of the simulator to add aircraft routes.
- Development of the simulator extension to add connections between aircraft routes and satellites.
- Development of the simulator extension to add basic connections between aircraft routes and ground stations.
- Study of the need to include satellites in aircraft monitoring.

The project will not include:

- The development of a visualisation tool for the added functions.

- The in-depth study of satellite-to-satellite connections and their optimisation for tracking aircraft routes.
- The in-depth development of connections between aircraft and ground stations

1.3 Requirements

- The software used will be MATLAB R2022a
- The simulations will be carried out with the simulator developed by the UPC in the PLATHON project.
- The constellation in the study case will be designed with LEO satellites.
- The satellites used in the simulation will be CubeSats.

1.4 Justification

The monitoring of airplanes is a crucial task to ensure the safety of passengers and crew, as well as to maintain air traffic control and prevent collisions. Although modern airplanes are equipped with a variety of communication and tracking systems, there are situations where these systems are not sufficient to provide accurate and up-to-date information about the location and status of the airplane. For this reason, satellites are used to monitor airplanes in real-time.

Satellites are an important tool for monitoring airplanes because they can provide global coverage, which means that airplanes can be tracked anywhere in the world, including remote areas and over the ocean. Additionally, satellites can provide accurate and real-time information about the airplane's location, speed, altitude, and heading, as well as data on weather and atmospheric conditions in the area.

Satellite monitoring systems can also be useful in emergency situations, such as in the case of an accident or airplane disappearance. In these situations, satellites can help quickly locate the airplane's position and provide valuable information to rescue and recovery teams.

Another important benefit of using satellites to monitor airplanes is that they can provide increased safety and efficiency in air traffic control. Satellites can help reduce the risk of airplane collisions, as they can provide real-time information about the location and heading of airplanes in the air, allowing air traffic controllers to make more informed and accurate decisions.

Therefore, if we want to study the monitoring and connections between aircraft and ground stations, it is necessary to develop the communications and connections of the different links in the ground-aircraft-satellite system. This will provide a significant advance to our simulator, as it will not only allow us to use the tool for the simulation of cases in which information is only transmitted between ground stations and satellites, but it will also open up a new spectrum of possibilities in the study and monitoring of aircraft routes and will extend the usefulness of the simulator.

Chapter 2

Air Navigation Systems

Air navigation is the process of guiding an aircraft from an initial position to a final position, flying along a defined route and meeting certain safety and efficiency requirements. Each aircraft performs navigation independently using a variety of external information sources and appropriate on-board equipment[1].

Of course, as mentioned above, the main objective of air navigation is to ensure a safe and efficient flight to its destination. In particular, the following objectives can be defined: [1]

- Maintain orientation at all times and avoid getting lost.
- Detect other aircraft and obstacles in order to avoid a collision.
- Minimise the influence of adverse meteorological conditions on the flight in terms of safety, efficiency and flight orientation.

Air navigation is a fundamental aspect of modern aviation and is crucial to ensure safe and efficient flight. Air Navigation systems and aeronautical communications allow pilots and air traffic controllers to determine the position and movement of aircraft, as well as to communicate with each other throughout the flight. Advances in these systems have transformed the way flights are planned and operated around the world, and continue to evolve to meet the demands of an ever-growing industry.

2.1 Historical Development

In the early days of air navigation, rudimentary methods were used during daytime flights, consisting of observing the terrain and determining the position of the aircraft by means of maps and tools such as compasses. However, in order to carry out night flights and/or flights in adverse weather conditions, the need arose to develop technical means that would allow flights to be carried out safely and efficiently. This is how the different means and methods of Air Navigation began to be designed, which have led us from the use of maps and chronometers to the current navigation systems based on inertial platforms and satellites [2].

2.1.1 Autonomous Navigation

The first of the air navigation methods introduced was the so-called dead reckoning. This method estimates the future position of an aircraft based on its current location, speed and heading. Pilots are equipped with anemometers to calculate the airspeed of the aircraft and clocks to measure time. Flights are composed of points (usually landmarks on the ground) and the pilot must follow a given trajectory [1].

Obviously this method produced large errors in terms of Air Navigation. These errors were based on the instruments used (compass, chronometer and anemometer), wind effects and pilot errors. Moreover, this method had a serious drawback: the point chosen as a reference must be visible to the pilot in all cases. Of course, these points can be difficult to determine in bad weather conditions or at night during night flights. In addition, it is difficult to get references to monotonous landscapes such as the ocean [1].

Therefore, methods were developed to avoid these problems. For this purpose, astronomical tools such as the astrolabe and the sextant were used to determine the position of the aircraft and reduce errors. The use of these tools combined with dead reckoning enabled a significant advance in aerial navigation that led to major aeronautical milestones such as the first transoceanic flight in 1919 (Alcock and Brown) aboard the Vickers Vimy heavy bomber[1].

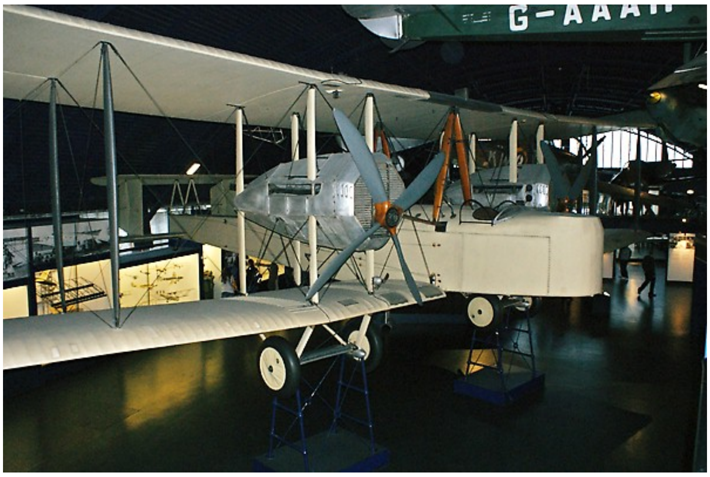


Figure 2.1: Alcock and Brown's Vickers Vimy in the Science Museum, London.

Source: Hugh Llewelyn , 2008 [3]

The methods described above are the so-called autonomous navigation methods, because no supporting infrastructure is required and it is the crew that performs the measurements and controls the positioning at all times. The fact that these methods required complicated on-board calculations meant that they were not really useful and that it was necessary to develop more advanced methods that would allow the aircraft to be controlled from the ground.

2.1.2 Assisted navigation

Due to the limitations described above, the need arose to develop new methods that would allow better tracking of aircraft and greater control over them. As early as 1918, the so-called airway beacon, a rotating ground light that allowed aircraft to fly at night, came into use. But the real breakthrough came with the advent of radio communications in air navigation in 1919. Transmitters were first used in cockpits for communication, and later radio angle sensors (radio-goniometers) began to be used. These sensors were installed on board and navigation was carried out by determining the aircraft's orientation in relation to two ground stations whose position was known[1].

From the 1930s onwards, numerous methods based on radio communications began to be developed and used. Some of the most commonly used technologies from the 1930s to the 1970s are listed below:

- The Low Frequency Radio-Range (LFR), which was the main navigation system used for instrumental flight in the 1930s.
- The VHF Omnidirectional Radio Range (VOR), which arrived in the late 1940s and was used in route navigation and in instrumental approaches.
- The Distance Measuring Equipments (DME), which began to be used in the late 60s-early 70s.

- The fully automated ILS approach system, that appeared in the late 60s.

From the 1970s onwards, new technologies began to be developed that drastically improved air navigation. It was at this time that the so-called inertial navigation systems began to be used, which used instruments such as accelerometers, gyroscopes and a computer to calculate orientation, speed and dead reckoning position[4]. Although these systems were used in civil aviation, more powerful satellite-based navigation systems were developed for military use as early as the 1960s. However, it was not until 1983 that the US government was forced to release this technology due to the incident involving Korean Air Lines Flight 007, which was shot down by a Soviet Sukhoi Su-15 interceptor[5].

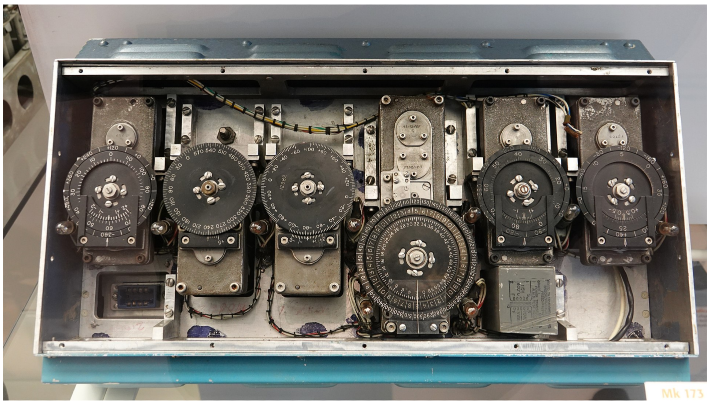


Figure 2.2: A 1950s inertial navigation control developed at MIT.

Source: Sanjay Acharya , 2017 [6]

Thus, air navigation has developed numerous systems and technologies throughout history. As is to be expected, many of them have fallen into disuse, and a large number of them are used today to ensure the safety and efficiency of aircraft. All air navigation systems are important in different situations and contexts and it is usually the combination of several of them that enables modern air navigation and ensures adequate safety and efficiency.

It is not the purpose of this thesis to delve into each of the systems that are used today for air navigation and aeronautical communications, however, in order to contextualise the project, it is useful to know some of them and more specifically those that base their technology on the use of satellites. The following section presents the most widely used technologies that meet these characteristics.

2.2 Air Navigation Technologies

This section presents some of the most commonly used technologies enabling aircraft communications, control and navigation. As previously mentioned, the objective of this section is to contextualise the development of the project and therefore, the technologies that the author has considered most suitable for this purpose will be briefly described. Specifically, the following technologies will be presented:

- ADS-B (Automatic Dependent Surveillance-Broadcast): a surveillance system used to provide better identification, position and speed of aircrafts.
- Global Navigation Satellite Systems (GNSS): the most widely used navigation systems worldwide due to its accuracy and global availability. Some examples of GNSS are the American GPS, The European Galileo or the Russian GNSS [7].

2.2.1 Automatic Dependent Surveillance-Broadcast

Automatic Dependent Surveillance-Broadcast (ADS-B) is a satellite-based surveillance system used in aviation to improve the efficiency and safety of air traffic. It uses transponder and GPS technology to transmit information about an aircraft's position, speed and direction of flight to other aircraft and air traffic controllers in real time. This allows air traffic controllers to have a more accurate and complete picture of the situation in the airspace, enabling them to make more informed decisions and reduce the risk of collisions[1].

The ADS-B system works by transmitting radio signals from an ADS-B equipped aircraft to other aircraft and to air traffic controllers on the ground. The aircraft uses an ADS-B transponder to send information about its position, speed and direction of flight via radio signals to other aircraft and ground stations. The information is transmitted in real time and displayed on air traffic controllers' screens. This system consists of two transponders, the "ADS-B Out" and the "ADS-B In".

The ADS-B "Out" functions as a transmitter. It broadcasts information such as the aircraft's position, speed , direction or identification code of flight to other aircraft and to air traffic controllers on the ground.

The ADS-B "In" functions as a receiver. It receives ADS-B information from other aircraft and displays it on a screen in the aircraft cockpit.

Various frequencies are used for data transmission by ADS-B, the most frequent being the 1090 MHz and the 978 MHz. Generally, in order to relieve congestion on the 1090 MHz frequency, the 978 MHz frequency band is used for aircrafts flying exclusively below 18000 feet [8]. Although these frequencies are the most commonly used, the choice of frequency depends on the region in which the system is used. A schematic of ADS-B operation is shown below:

Figure 2.3: ADS-B sketch.

Source: Soler, Manuel, 2014 [1]

It is a very modern technology that was developed with the aim of becoming the main surveillance system and of replacing the previous system in use. Previously the leading system was the primary radar-secondary radar system. Radar systems can be limited by line-of-sight (L.O.S.) and radio wave propagation, which can make it difficult to detect aircraft at high altitude or in areas with uneven terrain. This is why the need to develop a new system arose. Compared to this system, the ADS-B system is an improvement in the following aspects: [1]

- Greater accuracy in the identification and positioning of aircraft.
- Improved air safety by reducing the possibility of collisions.
- Increased airspace capacity and air traffic efficiency.
- Reduced waiting times on the ground and in the air.
- Improved route planning capability and reduced airline operating costs.

As described above, this system represents a major advance in aeronautical surveillance and, despite some drawbacks such as its high implementation cost, it is the most suitable system for the aeronautical industry today.

2.2.2 Global Navigation Satellite Systems

The GNSS (Global Navigation Satellite System) is a system formed by a constellation of satellites , ground stations and receivers that allows to obtain location information in real time and at a global level of a target. The most famous GNSS systems are the American GPS, the European Galileo, the Russian GNSS or the Chinese BeiDou[7].

GNSS and more specifically GPS are currently the most widely used systems to provide en-route guidance and for other phases of flight such as approach. The fact that it can provide global, real-time coverage makes it ideal for navigation surveillance and air traffic control systems. This is why, as we have seen above, systems such as ADS or ADS-B rely on this technology to build their technology. Specifically, the GPS system makes it possible to obtain information on the position and speed of an aircraft in real time and this uses the ADS-B system to transmit the information to the different aircraft and to the ATC services [9].

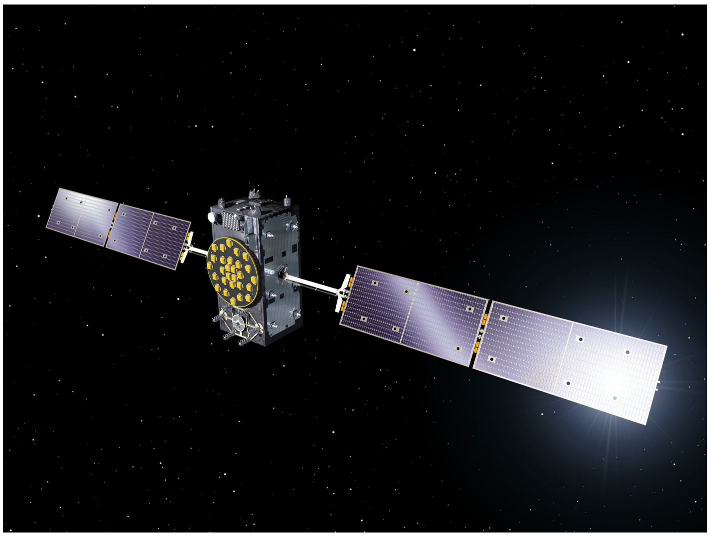


Figure 2.4: A Galileo Full Operational Capability (FOC) satellite.

Source: European Space Agency, 2013 [10]

The GPS system consists of 3 distinct parts, each of which performs one or more functions:[9]

The first of these is the so-called space component, which basically consists of the satellite constellation. The function of this component is to provide the ranging signals and data messages to the user equipment. Specifically, the satellites transmit a coded signal from which the measurements are extracted. This makes the system a passive system for the user as the user simply receives the signals that are constantly being emitted by the satellites and allows an unlimited number of users to use the system simultaneously.

The second part is the Control Segment (CS). This is responsible for monitoring, controlling and maintaining the health of the satellites and thus the constellation. The objective of this system is to ensure the correct functioning of the GPS space component at all times. Specifically, this system performs tasks such as monitoring the batteries, solar panels and propellant levels of the satellites, activates spare satellites or updates data such as the satellite clock on a daily basis. The terrestrial infrastructure of this system consists of 3 parts: the main control station (MCS), the monitoring stations and the terrestrial antennas.

The last of the systems is the user system. It acts as a receiver of the signals emitted by the satellites and from these signals it determines data such as user identification.

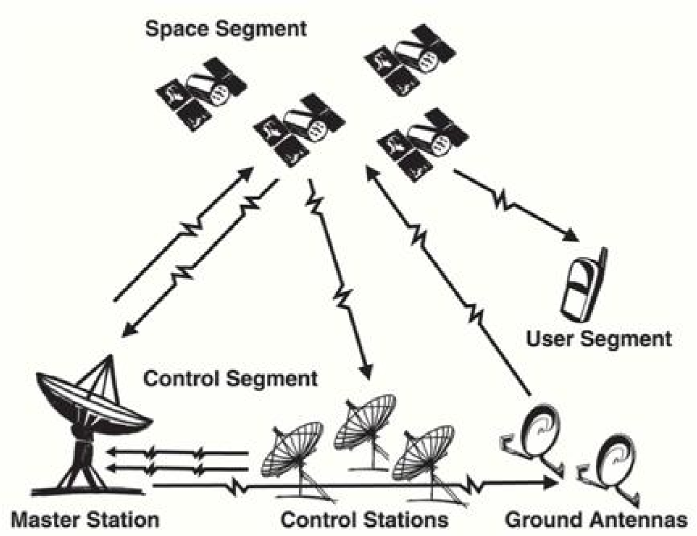


Figure 2.5: Segments of GPS.

Source: R.Selvapriya, 2014 [11]

Chapter 3

Satellite Communications

Satellite communications refers to the set of techniques that use artificial satellites to establish communications with points on the Earth's surface. It mainly consists of two main segments: the space segment, formed by the satellites themselves and/or the constellations they constitute, and the terrestrial segment, which consists of a point on the terrestrial sphere with which the satellites communicate [12].

Satellite communications have played a fundamental role in the technological development of mankind and have enabled great advances. In the aeronautical industry, as described in the previous chapter, they have played a fundamental role in air navigation and air traffic control and have ensured excellent standards of safety, control and efficiency in the aeronautical industry.

For the development of this project, it is crucial to understand how satellite communications work. This is due to the fact that both the simulator on which our project is based and the further development that we intend to carry out require technical knowledge in this area of telecommunications.

This chapter aims to study satellite communications from the point of view of their operation, segments and development. This is done with the aim of establishing a theoretical basis that will allow us to understand the development of the simulator to date and to be able to carry out the task of extending it with security and guarantees.

3.1 Satellite Systems

As we have seen, the use of satellites is of vital importance for modern telecommunications and offers great advantages over other systems. In this section, the systems formed by these elements are studied and their structure and operation are described. This is of utmost importance, as it is the theoretical basis on which the simulator is based.

3.1.1 Satellite Orbits

Because human-made satellites are artificial bodies that orbit the Earth for the most part, they follow the same universal laws as all celestial bodies. The first to derive the laws describing the motions of the two-body problem was Johannes Keppler. In order to describe and define orbits, it is therefore important to know the laws that the German scientist enunciated.

Kepler´s Laws

There are three of Kepler's famous laws, and they state:

- **Kepler´s first law :** the path followed by a satellite around the primary will be and ellipse, and the primary is at one focus [13].

  Therefore, in the two-body problem, the secondary will follow an elliptical motion around the primary. We can describe this trajectory with the equation of an ellipse. The characteristic parameters of an ellipse are shown below:

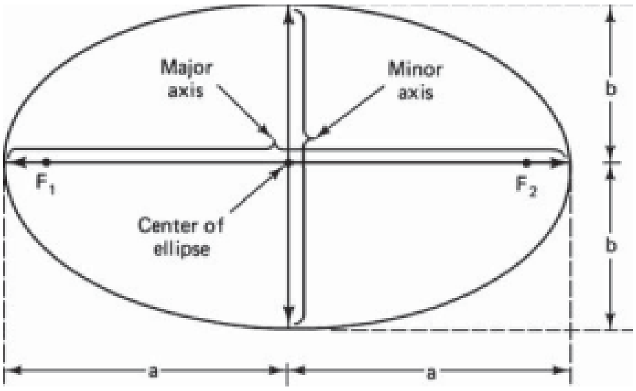


Figure 3.1: Ellipse parameters sketch.

Source: Roddy, 2006 [13]

- **Kepler´s second law :** for equal time intervals, a satellite will sweep out equal areas in its orbital plane, focused at the barycenter [13].

  This is a very important result that can be used, for example, to maximise the visibility time of a satellite, since the speed of the satellite is lower if the body is far away from the primary focus. Kepler's second law is shown graphically in the figure 3.2.

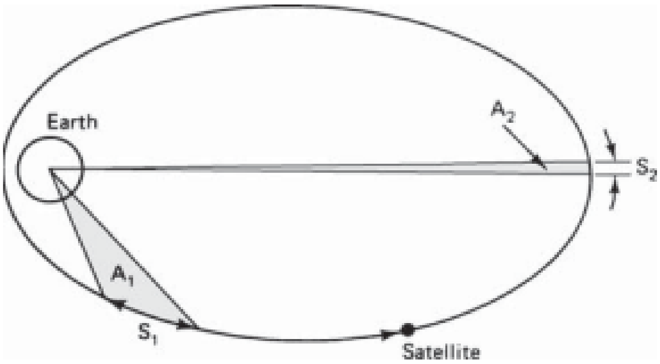


Figure 3.2: Kepler´s second law.

Source: Roddy, 2006 [13]

- **Kepler´s third law :** the square of the periodic time of orbit is proportional to the cube of the mean distance between the two bodies[13].

  For satellites orbiting around Earth, this law can be written as:

  $$a^3 = \frac{\mu}{n^2} \tag{3.1}$$

  Where a is the semi-major axis, $\mu = 3.986005 \cdot 10^{14} \frac{m^3}{s^2}$ is the earth's geocentric gravitational constant and n is the mean motion in rad/s.

Orbits definition

We can define satellites orbiting the earth with the following 6 elements:[13]

- **Semimajor axis (a):** Is the distance of the major axis of an ellipse divided by two, as defined in figure 3.1.
- **Excentricity (e):** Defines the shape of the ellipse.. For an elliptical orbit, $0 < e < 1$.
- **True Anomaly (M_0):** gives the position of the satellite in its orbit at a reference time known as the epoch.
- **Argument of the perigee (ω):** gives the rotation of the orbit's perigee point relative to the orbit's line of nodes in the earth's equatorial plane.
- **inclination (i):** Is the angle between the orbital plane and the earth's equatorial plane.
- **Right ascension of the ascending node(Ω):** is the angle measured eastward, in the equatorial plane, from the line to the ascending node.

A common way of defining orbital elements is to encode them in what are known as two-line elements. Figure 3.3 shows how to interpret the NASA two-line elements.

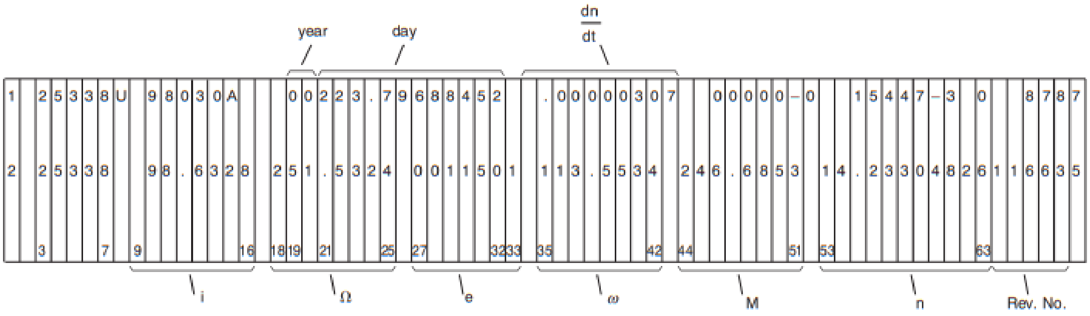


Figure 3.3: TLE for NOAA-15.

Source: Roddy, 2006 [13]

Coordinates systems

Various coordinate systems are available to define the movement of satellites. It is of vital importance for the development of this thesis to define a good coordinate system which in turn allows us to define the motion of the satellites. The coordinate systems that have been chosen as options to define the satellite motion around the Earth are shown below.

- **Earth Centered Inertial system (ECI):** Also known as the Conventional Celestial Reference System. Its origin is defined as the Earth's centre of mass, its fundamental plane as the mean equatorial plane of epoch J2000.0, and the principal x-axis points to the mean vernal equinox of epoch J2000.0[14].The following figure shows a scketch of such a system:

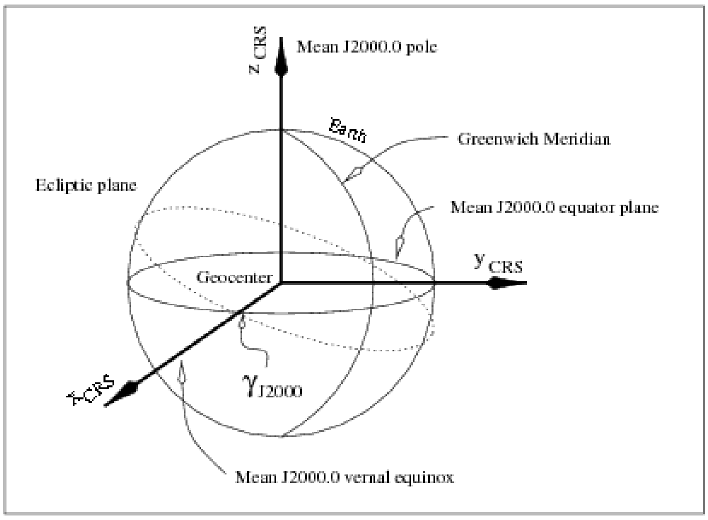


Figure 3.4: Earth Centered Inertial system.

Source: ESA, 2011 [15]

- **Earth-Centered Earth-Fixed system (ECEF):** Also known as the Conventional Terrestrial Reference System. This system rotates with the Earth in its diurnal rotation. Its origin is defined as the Earth's centre of mass, its fundamental plane is perpendicular to the Earth's Conventional Terrestrial Pole (CTP) and contains the origin, and the principal X-axis is defined as the intersection of the orthogonal plane to Z-axis (fundamental plane) and Greenwich mean meridian[16].The following figure shows a sketch of such a system:

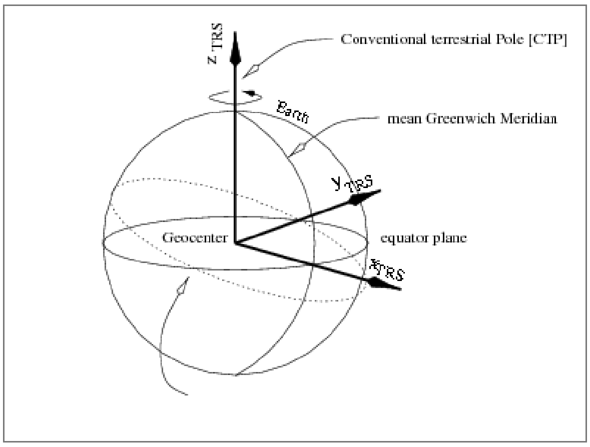


Figure 3.5: Earth Centered Inertial system.

Source: ESA, 2011 [17]

- **Local North-East-Down system (NED):** Also known as a navigation or ground coordinate system. It is fixed to the earth's surface. Its origin is is arbitrarily fixed to a point on the earth's surface, its X-axis points toward the ellipsoid north (geodetic north), its Y-axis points toward the ellipsoid east (geodetic east)and the Z-axis points downward along the ellipsoid normal[18].The following figure shows a sketch of such a system:

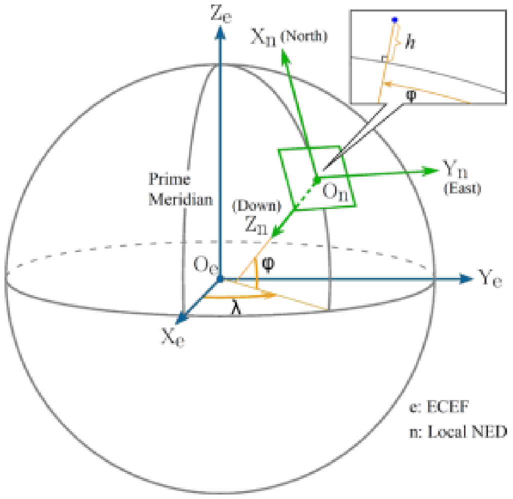


Figure 3.6: Geodetic, ECEF, and local NED coordinate systems.

Source: Unmanned Rotorcraft Systems , 2011 [18]

Types of orbits

There are a multitude of orbit types and classifications. We have seen above that by using the orbital elements we can define any type of orbit. Here are some of them which are especially used for satellite communications:

- **Geostationary orbit (GEO):**The main characteristic of this orbit is that its period is equal to the earth's rotation period. This gives it certain advantages in telecommunications, since the satellite is over a fixed point from the perspective of the earth's surface. This type of orbit is located at about 35 786 km above the earth's surface. Its characteristics make it the most widely used in telecommunications and, specifically, it is used for television, telephony, data transmission and satellite navigation services[19].

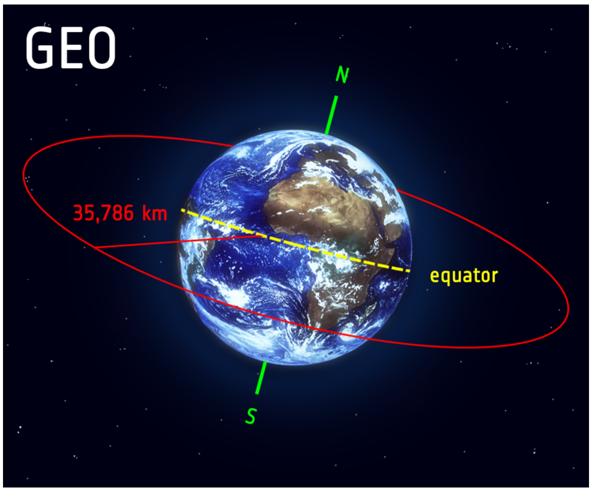


Figure 3.7: Geostationary orbit.

Source: ESA , 2020 [20]

- **Low Earth orbit (LEO):**As the name suggests, these orbits are at a very low altitude, i.e. close to the Earth's surface. Specifically, an orbit is defined as LEO if it is less than 1000 km above the Earth's surface. This type of orbit is used for many applications, but in communications it is often used to create constellations of mini-satellites[19]. That is why for this work we will focus on this type of orbits, since the PLATHON project of which this thesis is part, is designed to work with cubesats.
- **Medium Earth orbit (MEO):**This type of orbit groups satellites between LEO and GEO orbits, i.e. between 1000 and 36000 km approx. It is a type of orbit widely used for GNSS such as the European Galileo[19].

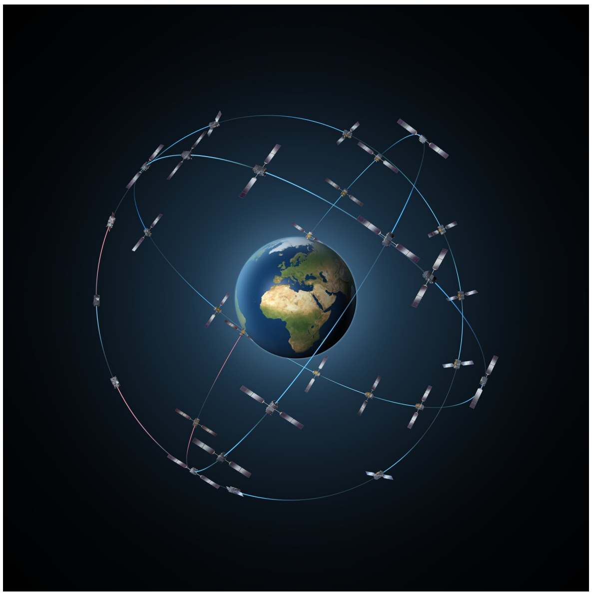


Figure 3.8: Galileo constellation.

Source: ESA , 2014 [10]

3.1.2 Satellite Constellations

As discussed above, LEO satellites are normally grouped into constellations, i.e. systems of satellites acting together. This allows global coverage and the development of systems such as GNSS. In the development of this project we focus on a very famous type of constellations, the so-called Walker constellations.There are two types of Walker constellations, and both have in common a circular geometry in the orbits of their satellites[21].

- **Walker Star :** This type of constellation is characterised by satellites with nearly-polar orbits, i.e. with an inclination $i \approx 90°$ and evenly spaced at 180°. An example of this type of constellation is the Iridium constellation[21].
- **Walker Delta :** This type of constellation is characterised by satellites with orbits with an inclination $i < 60°$ and evenly spaced at 360°. This type of constellation has the disadvantage of very high or very low latitudes, such as the polar areas[21].

Obviously each type of constellation has its advantages and disadvantages and that is why companies like SpaceX sometimes combine to form mixed constellations[21].

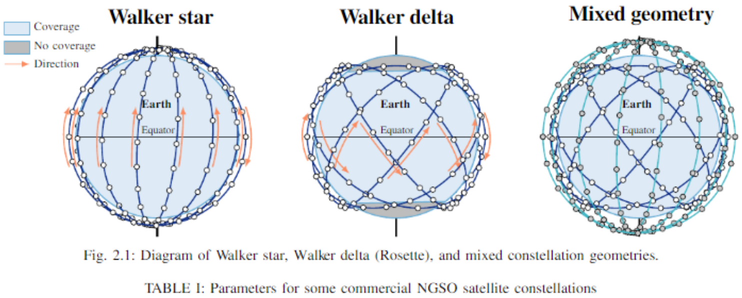


Figure 3.9: Walker constellation types.

Source: Leyva-Mayorga et al. , 2022 [21]

3.2 Comunication Links

As mentioned above, satellite communication systems consist of two distinct parts. The first of these parts, the space segment, as discussed in the previous section, consists of satellites or satellite systems that act as a link between elements of the earth's sphere. The second part is the set of ground stations or targets to be connected to. The mechanisms used by aircraft to connect to satellites have been described earlier in the chapter on Air Navigation systems.

In this section, we will study the basic principles governing communication between the different elements of a satellite communication network. The development of this section will be approached from the point of view of communication between a satellite and a ground station. However, in this thesis, aircraft routes are added to the equation. As will be seen later, this does not affect the principles that will be studied in this section, simply that each part will act in a particular way depending on which element of the system it is connected to. For example, when developing communications between an aircraft and a satellite, the aircraft will be treated as a ground station that moves over time. When the aircraft connects to a ground station, it will be treated as the upper part of the link, i.e. as the satellite was treated in the first case. The structure of the system can be seen in the figure below.

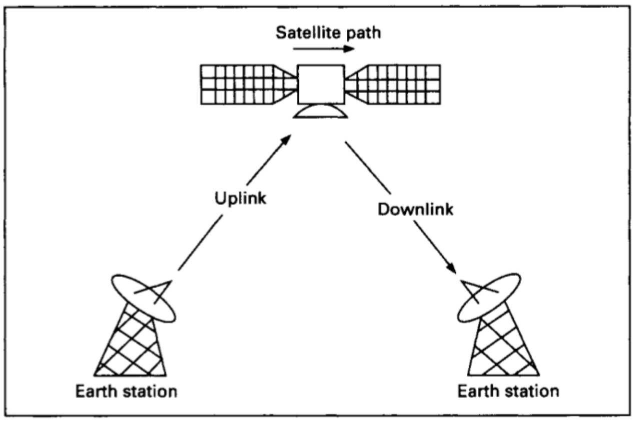


Figure 3.10: Satellite communication link.

Source: Richharia, 1995 [22]

3.2.1 Antenna Fundamentals

A basic element of satellite communications is the antenna. This is why it is necessary to study its principles of operation. An antenna is an element that has the ability to both transmit and receive signals. It is a reciprocal element. This means that its receiving and transmitting and receiving properties are identical at a given frequency [22]. The most important characteristics that define the performance of an antenna are [22]:

- **Radiation pattern:** Is the graphical representation of the radiation properties of the antenna as a function of different directions in space at a fixed distance. Actually, the radiation pattern of an antenna is a three-dimensional plot, since antennas can emit in all spatial directions. However, for its representation is common to use two planar patterns known as called the principal plane patterns[22]. In figure 3.11 a radiation diagram in polar conditions together with its parts it's represented. The main lobe represents the direction in which you want to transmit, while the sidelobes represent the signal transmitted to unwanted directions. The side lobes are minimised when designing antennas, as they cause interference and undesired effects[22].

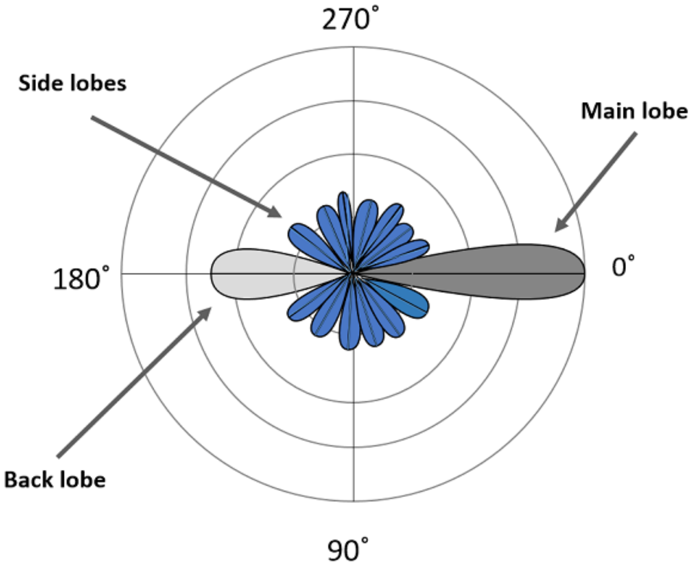


Figure 3.11: Radiation pattern.

Source: Truckle, Timothy, 2008 [23]

- **Beamwidth:** It is usually represented as half-power beamwidth or the 3-dB beamwidth and it represents a measure of the angle over which maximum gain occurs.
- **Radiation intensity** $P(\theta, \phi)$**:** is defined as the power radiated from an antenna per unit solid angle in a specific direction (θ, ϕ).
- **Directivity** $D(\theta, \phi)$**:** It measures the focusing property of an antenna. It can be written as follows:

$$D(\theta, \phi) = \frac{P(\theta, \phi)}{P_{av}} \tag{3.2}$$

  Where $P_{av} = \frac{P_r}{4\pi}$ is the average radiation intensity, and P_r is total radiated power from an antenna.
  An efficiency factor η is added to this definition, since directivity is defined as a function of the energy transmitted into space and losses obviously occur.

- **Gain:** the gain is the increase in strength achieved by concentrating the energy of the radio waves. It is defined as the maximum value of the gain function. Gain is usually defined in relation to an isotopic antenna, which is one that emits uniformly in all directions in dBi. However, the definition of gain takes into account the efficiency of the antenna. We can say in general terms that:

$$G(\theta, \phi) = \eta \cdot D(\theta, \phi) \tag{3.3}$$

And we can relate the gain of the antenna to its physical dimensions as follows:

$$G = \eta \frac{4\pi A}{\lambda^2} \tag{3.4}$$

Where :

- A is the apperture area of the antenna.
- λ is the wavelength of the working frequency.

Numerous types of antennas have been developed throughout history, but the most commonly used types for satellite systems are linear dipole, the horn antenna, the parabolic reflector, and the array antenna [24].

- **Linear dipole :** This is an isotropic, i.e. omnidirectional, type of antenna. They are very used in tracking, telemetry, and command links, in launch operations and for LEO systems.
- **Horn antenna :** They are used when relatively wide beams are required that's the case of global coverage from a GSO satellite.
- **Parabolic reflector antenna :** This are the most used antennas for satellite systems.
- **Array antennas :** is a system in which multiple antennas are connected together and function as a single element.

Figure 3.12: Parabolic reflector antenna.

Source: Bartz, Richard, 2008 [25]

3.2.2 Transmission Basics

The transmission equation plays a fundamental role in antenna transmissions. It relates the received power to the emitted power and the distance between the two elements. In order to develop and extend our simulator, it is of vital importance to know its principles and elements.

For an isotropic radiator, the received power per unit of area at a distance R from the emission source can be expressed as[22]:

$$P_{FD} = \frac{P_s}{4\pi R^2} W/m^2 \tag{3.5}$$

Where P_s is the transmitted power from the isotropic source.

If we add some gain to the isotopic antenna the equation can be written as:

$$P_{FD} = \frac{P_s \cdot G_s}{4\pi R^2} W/m^2 \tag{3.6}$$

The value of the numerator of the equation is usually expressed in logarithmic scale due to the wide range of values. Thus, we can express the above expression as follows:

$$P_{FD} = 10 \cdot log(Ps) + 10 \cdot log(Gs) - 10 \cdot log(4\pi R^2) dBW/m^2 \tag{3.7}$$

The received power at an antenna of area A_d, taking losses into account, can be expressed as a function of the power flux Density as follows:

$$P_r = A_d \cdot P_{FD} \cdot \eta \tag{3.8}$$

Taking into account the equation 3.4 we can express the received power as a function of the commonly used parameters of the antenna:

$$P_r = P_s \cdot G_s \cdot G_d(\frac{\lambda}{4\pi R})^2 \tag{3.9}$$

Again, is a good practice to express the equation in logarithmic terms as follows:

$$P_r = P_s(dB) + G_s(dB) + G_d(dB) - 20log(\frac{4\pi R}{\lambda}) \tag{3.10}$$

Equations 3.9 and 3.10 are known as the transmission equations[22].

3.2.3 System Noise

Noise plays a major role in telecommunications as it limits the capabilities of systems. In the case of satellite communications it is especially necessary to take it into account, as the received power is usually quite low. When developing a telecommunications system using satellites, it is therefore essential to know the characteristics of these undesired signals in order to minimise them and to guarantee adequate signal reception.

Noise is defined as unwanted power or signals introduced when transmitting a signal. There are several types of noise, but of all of them, the most important to consider at radio frequencies is thermal noise.This is caused by the movement of electrons in the receiving devices and is calculated by introducing the so-called noise temperature. This temperature is is defined as the temperature of a passive resistor producing a noise power per unit bandwidth that is equal to that produced by the device[24].In the following table, typical equivalent noise temperatures of the front-end elements of receiving systems of satellite communication systems are shown:

Element	**Noise temperature [K]**
Low noise receiver (C, Ku, ka band)	100 to 500
1 dB line loss	60
3 dB line loss	133
Cooled parametric amplifier (paramp)	15 - 30

Table 3.1: Typical equivalent noise temperatures of the front-end elements of receiving systems of satellite communication systems.

Source: Louis J. Ippolito, Jr., 2008 [24]

We can define **noise power** using the Nyquist formula, which can be written as follows: [24]

$$N = k \cdot T \cdot B \qquad [W] \tag{3.11}$$

Where:

- k is the Boltzmann's constant $k = 1.39 \cdot 10^{-23} J/K$
- T is the equivalent noise temperature of the noise source, in K.
- B is the noise bandwidth, in Hz.

Another important definition to consider is the **signal-to-noise ratio** (SNR or S/N), which is defined as the ratio of the received power to the noise at the receiver[22]. It is a very important ratio when designing a satellite telecommunications system as it will allow us to calculate the errors in the modulation or what is known as the bit error rate or BER. We can write:

$$SNR = \frac{P_r}{N} \tag{3.12}$$

3.2.4 Modulation

Modulation is the process of transmitting information on a carrier wave (usually sinusoidal) by altering its characteristics to improve the efficiency of information transmission and to increase resistance to noise and interference. There are several ways of altering the carrier wave[22]:

- **Amplitude modulation:** Also known as Amplitude Shift Keying (ASK). Where amplitude A of the sinusoidal wave is varied.
- **Phase modulation:** Also known as Phase Shift Keying (PSK).Where the phase θ of the sinusoidal wave is varied.

- **Frequency modulation:** Also known as Frequency Shift Keying (FSK).Where the frequency f of the sinusoidal wave is varied.

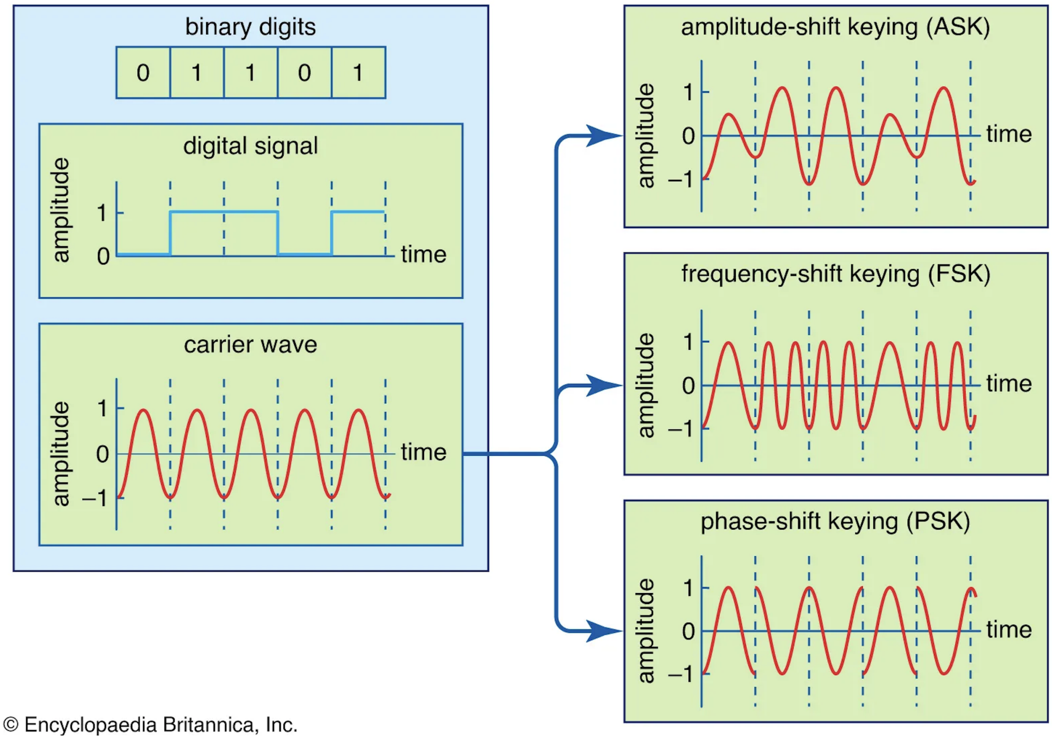


Figure 3.13: Digital signal modulation.

Source: Encyclopædia Britannica,2023 [26]

From these basic modulation schemes, more advanced forms of modulation can be obtained. In this simulator, as will be seen later in the text, it is possible to choose between different types of modulation such as MSK, OQPSK, DPSK, CPFSK or QAM which, as will be seen later in the text, is the modulation of choice to develop the MATLAB simulator extension.

The opposite process to modulation is called demodulation. This process produces errors when measuring the information, which are measured with the so-called Bit Error Rate (BER). This is defined as the number of erroneous bits per unit of time. A factor that interferes with the accuracy of the information during demodulation is the signal-to-noise ratio. However, modulation efficiency is usually expressed as the ratio of the ratio between the spectral energy and noise density (Eb/N0) of the required bits. Which is related with SNR by the following equation[22]:

$$SNR = \frac{E_b}{N_0}[dB] + 10 \cdot log\frac{R_b}{B}[dB] \tag{3.13}$$

Where:

- R_b is the bit rate [bit/s]
- B is the noise bandwidth, in Hz.

BER as a function of SNR or (Eb/N0) is usually expressed in graphics sich as 3.14

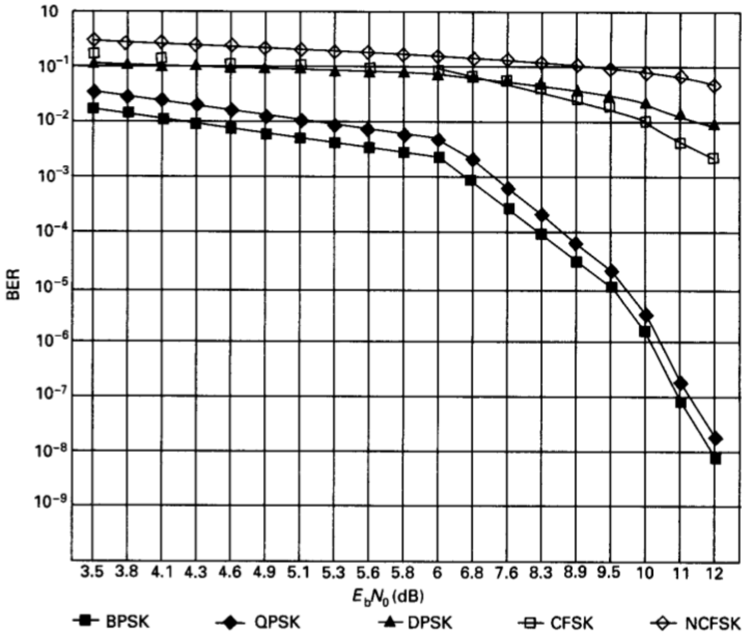


Figure 3.14: (Eb/N0) vs bit error rate (BER) for various modulation schemes.

Source: M. Richharia, 1995 [22]

3.2.5 Frequency Allocations

The allocation of frequencies to the different satellite telecommunication services is the responsibility of the International Telecommunication Union (ITU). In order to carry out this arduous task, the organisation divides the world into three major regions and within these regions each satellite service is assigned a different frequency. Specifically, these regions correspond to [13]:

- Region 1: Europe, Africa, what was formerly the Soviet Union, and Mongolia
- Region 2: North and South America and Greenland
- Region 3: Asia (excluding region 1 areas), Australia, and the southwest Pacific

Figure 3.15 shows the commonly used frequency band designations for the satellite services.

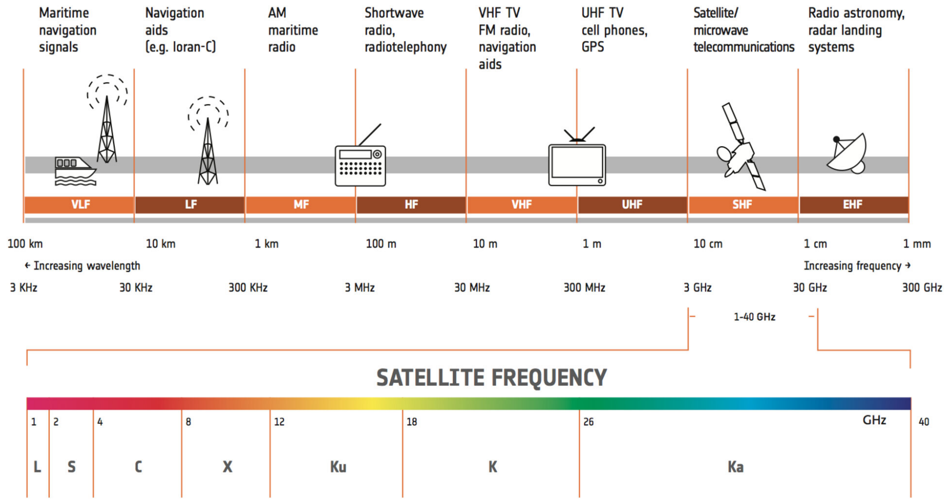


Figure 3.15: Satellite frequency bands.

Source: ESA, 2013 [27]

Below are some of the services that the satellites offer and to which various frequencies are assigned [13]:

- Fixed satellite service (FSS), that provides links for telephone networks and for the transmission of signal to cable television.
- Broadcasting satellite service (BSS)
- Mobile satellite services
- Navigational satellite services
- Meteorological satellite services

Chapter 4

MatLab Simulator

As described earlier in the text, the aim of this project is to extend a MatLab simulator originally designed to calculate connections between satellites and ground stations to include aircraft routes and their respective connections. Specifically, this simulator was designed by Xavier Pozo Diaz, a former student of the Aerospace Vehicle Engineering degree in his final degree thesis *Study of attenuation and loss of messages in radiofrequency communication links between Cubesats and Earth* [28] in 2022.

This chapter will describe the operation and capabilities of this simulator in order to lay the groundwork for the further development of the extension. If the reader wishes to obtain more precise information on how this simulator was developed, it is recommended to consult the work of Xavier Pozo at [28].

4.1 Simulator capabilities

The Matlab simulator designed by Xavier Pozo allows the following tasks to be carried out:

Satellite Systems Introduction

The simulator allows the user to enter individual satellites or constellations of satellites. In particular, the user can choose between the following options:

- Enter data for one or more satellites using the orbital elements of each satellite.
- Enter data from one or more satellites using TLEs.
- Modelling a Walker constellation by introducing its characteristic parameters .

Once the data has been entered, a Satellite object is created for each of the satellites entered using the Aerospace Toolbox library from Matlab.

In addition, the simulator allows the user to enter one or more Ground Stations based on their geographical coordinates i.e. latitude, longitude and altitude above sea level.

The user can choose between several models of orbit propagators to determine the position and velocity of a satellite at any instance of time given its initial state. Specifically, the user can choose between the 3 following models that are described in [28] :

- Two-Body-Keplerian
- Simplified General Perturbations-4 (SGP4)
- Simplified Deep-Space Perturbations-4 (SDP4)

The user must also enter the temporary data of the simulation such as the start date, the duration of the simulation, or the sample time. This can be done in a number of ways:

- With the epoch time of the TLE.
- User defines the start date specifying year, month, day, hour, minute and second in UTC.
- With the date at the time the simulator is being used.

The duration of the simulation can be defined in minutes or in orbital periods.

When all the data has been entered, the simulator calculates the position and velocity of the satellites. This can be obtained using the ECI reference systems ECEF and NED (See section 3.1.1).

Visibility periods calculation

Once the previous data has been entered, the MatLab simulator calculates the periods of visibility between the satellites and the ground stations and between the different satellites (if a constellation or more than 1 satellite has been defined).

This is done through the process described in [28] which can be summarised as follows:

- For the links between ground stations and satellites, the elevation angle is calculated using the Matlab aer function and if this is greater than a minimum angle defined by the user, its considered that there is visibility.
- In the case of satellites, a geometric method is used in which the perpendicular distance is calculated that originates from the center of the Earth and ends with the line that joins the satellites to be studied. It is considered that if this distance is equal or greater than the radius of the earth plus the height of the satellite above the earth's surface, there is visibility.These distances are graphically represented in 4.2 In summary:

$$\text{If } d_{perp} \geq H + R_e \Rightarrow \text{there is visibility}$$

With

- d_{perp} = Perpendicular distance.
- H = Height of the satellite above the earth's surface.
- R_e = Earth radius.

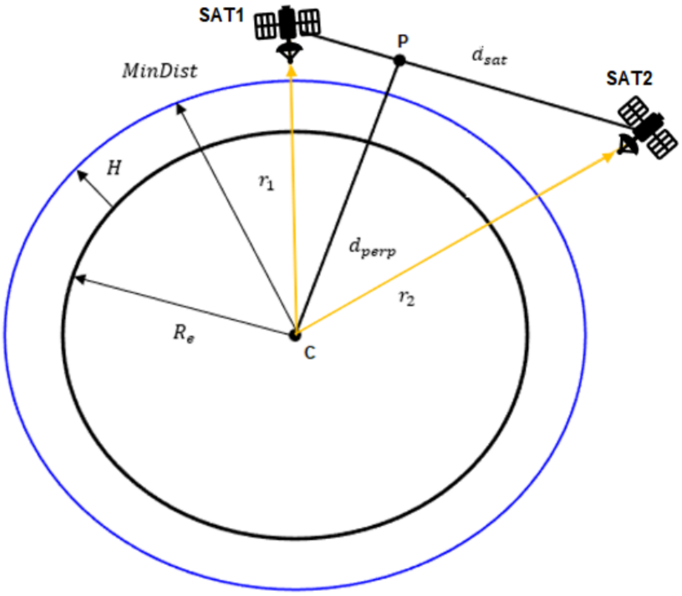


Figure 4.1: Satellite sketch used for the visivility calculation.

Source: P. Xavier, 2022 [28]

In this way, the periods of visibility between satellite-satellite and ground station-satellite are obtained for each time step and for each element of the simulation.

Received Power and Noise calculations

The received power is calculated for each link using the equation 3.10. In the case of connections between satellites and ground stations, the possibility of adding atmospheric losses and other losses to the equation is added. The new equation used can be written as follows:

$$P_r = P_s(dB) + G_s(dB) + G_d(dB) - 20log(\frac{4\pi R}{\lambda}) - L_a - OtherLosses \tag{4.1}$$

Where:

- The atmospheric losses are calculated with the Matab function *GaseousAttenuationITU10*.
- The term *OtherLosses* must be entered by the user.

Once the received power has been calculated, the noise is calculated from equation 3.11 and from this the signal-to-noise ratio is obtained through equation 3.13 .

Communication quality evaluation

Once the required power is obtained, the code allows to evaluate the quality of the communication through 3 different methods that are described in [28] and will be seen later in the development of the simulator extension. As summary, the methods used are:

- Transceiver method
- Berspec method
- SNRmin method

From the results obtained, depending on the method used, the minimum required power necessary for the connection to be established is obtained.

Visualisation

Finally, the simulator offers the possibility of visualising the content of the simulation through the Matlab Scenario Viewer. Below is an example of how this visualization is, presented by Xavier Pozo in [28]

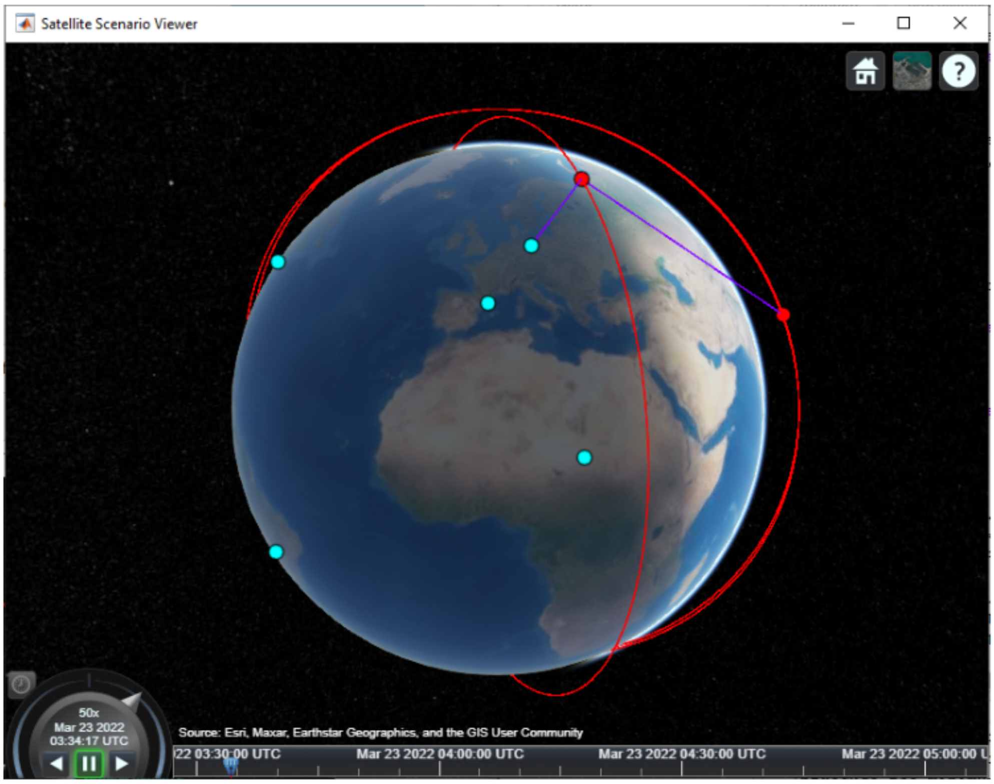


Figure 4.2: Scenario Viewer.

Source: P. Xavier, 2022 [28]

4.2 Simulator operation

It is not the aim of this thesis to describe exactly how to use the simulator developed in [28]. However, it is necessary to know what parameters are requested from the user and how the user interface looks like.

The simulator has two ways of entering data. The first way is to enter the data manually. At the beginning of the code, a series of parameters are defined that the user can modify at will. Specifically, the parameters that the user can modify are the following:

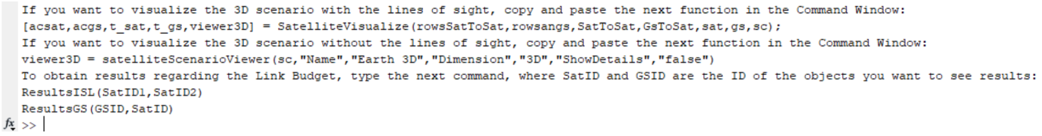
- Orbital Mechanics Parameters
  - Minimum elevation angle
  - Minimum altitude above Earth's surface for a link between two satellites.
  - The orbit propagator.
  - The pointing method of the ground station antenna.

  - The method used for the relative spacing between adjacent planes in Walker star.
- Link Budget Parameters
  - Antenna noise temperature (interlink,uplink and downlink).
  - Noise figure of the receiver.
  - Reference temperature (K) for the noise figure.
  - Receiver sensitivity.
  - Frequency (interlink,uplink and downlink).
  - Transmission power (satellites and Ground Stations).
  - Bandwidth.
  - Bit rate.

The other method is to enter data through the Matlab Command window. When running the code, the user is prompted to enter various data manually. This data includes:

- Satellite data (as described in 4.1).
- Ground stations data (as described in 4.1).
- Simulator time data (as described in 4.1).
- Link Budget.

At the end of the simulation, the simulator gives the results as shown in the following figure:



```
If you want to visualize the 3D scenario with the lines of sight, copy and paste the next function in the Command Window:
[acsat,acgs,t_sat,t_gs,viewer3D] = SatelliteVisualize(rowsSatToSat,rowsangs,SatToSat,GsToSat,sat,gs,sc);
If you want to visualize the 3D scenario without the lines of sight, copy and paste the next function in the Command Window:
viewer3D = satelliteScenarioViewer(sc,"Name","Earth 3D","Dimension","3D","ShowDetails","false")
To obtain results regarding the Link Budget, type the next command, where SatID and GSID are the ID of the objects you want to see results:
ResultsISL(SatID1,SatID2)
ResultsGS(GSID,SatID)
>> |
```

Figure 4.3: Results Interface.

Source: P. Xavier, 2022 [28]

Chapter 5

Matlab Extension

This section aims to explain what new functions and capabilities have been developed for the simulator and how they have been developed. As described earlier in the text, the aim of this project is to extend the simulator presented in the previous chapter to include aircraft routes and their connections to both satellites and ground stations. The purpose of this development is to provide an accurate and efficient ground-air-space simulation tool for monitoring aircraft connections.

The development of the new simulator extension has been based on three main points, which are presented below:

- Development of the extension of the simulator to add aircraft routes.
- Development of the simulator extension to add connections between aircraft routes and satellites.
- Development of the simulator extension to add basic connections between aircraft routes and ground stations.

5.1 Aircraft Routes

The first step in developing a ground-air-space simulation tool is to be able to enter data pertaining to the aircraft routes to be studied. Therefore, the thing that needs to be done is to define how these aircraft routes are to be entered. The solution that has been proposed is that the user can define the route by means of a series of characteristic parameters.

From the characteristic parameters belonging to each route and other parameters that the simulator obtains from previous stages, a data matrix is generated that allows all the calculations belonging to the subsequent stages of the simulation development to be carried out.

Specifically, the parameters required to define the route are:

- The aircraft velocity.
- The aircraft altitude.
- The geographical coordinates (latitude and longitude) of the starting point of the route.
- The geographical coordinates (latitude and longitude) of the final point of the route.
- The sample time of the simulation.

From these characteristic parameters the geographical coordinates of the aircraft can be obtained for each time step.

For this purpose, the aircraft has been assumed to follow the shortest route between the defined start and end points. This distance is known as the orthodromic or great-circle distance. And mathematically represents the shortest distance between two points in the surface of a sphere.

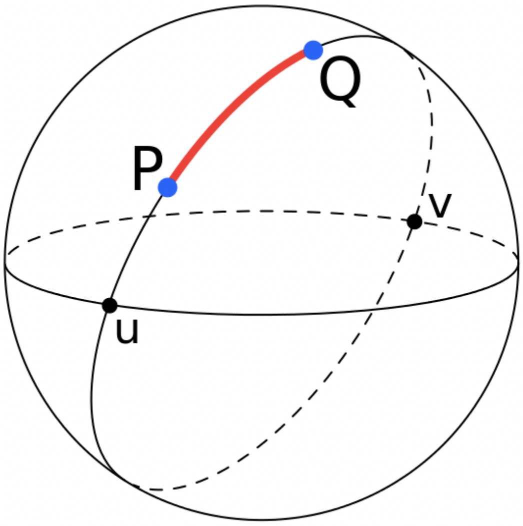


Figure 5.1: Great-circle distance.

Source: CheChe DaWaff, 2016 [29].

To simplify the calculations we will assume that the aircraft maintains the same altitude throughout the flight. Therefore, for our calculations we must consider a sphere of radius:

$$R = R_e + H$$

.

Where:

- R_e is the earth radius
- H is the flight altitude of the aircraft above the sea level.

To calculate the coordinates of a plane travelling over the orthodromic at the next time step from an initial point, we will use the definition of the central angle between two points on a spherical surface. This is defined mathematically as follows[30]:

Let λ_1, ϕ_1 and λ_2, ϕ_2 be the geographical longitude and latitude of two points 1 and 2 and $\Delta\lambda, \Delta\phi$ their absolute differences. Then the central angle $\Delta\sigma$ between them, is given by the spherical law of cosines if one of the poles is used as an auxiliary third point on the sphere:

$$\Delta\sigma = arccos(sin(\phi_1)sin(\phi_2) + cos(\phi_1)cos(\phi_2)cos(\Delta\lambda)) \tag{5.1}$$

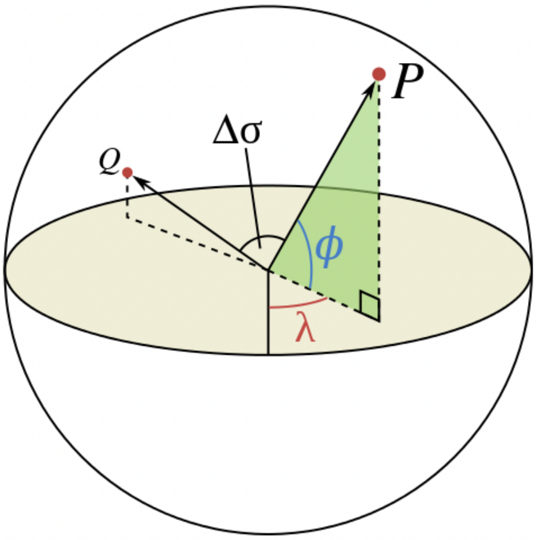


Figure 5.2: Central angle illustration.

Source: CheChe DaWaff, 2016 [31].

The following process uses spherical triangles to calculate the coordinates of the aircraft at each time step. The basic formulas for solving spherical triangles are known as the Bessel formulas and state that in every spherical triangle ABC the following relations are true[32]:

- Cosine Theorem: 1st Bessel's Formula can be written as follows:

$$cos(a) = cos(b)cos(c) + sen(b)sen(c)cos(A) \tag{5.2}$$

- Sine Theorem: 2nd Bessel's Formula can be written as follows:

$$\frac{sin(A)}{sin(a)} = \frac{sin(B)}{sin(b)} = \frac{sin(C)}{sin(c)} \tag{5.3}$$

- Bessel Analogies: 3rd Bessel Formula can be written as follows:

$$sen(a)cos(B) = cos(b)sen(c) - sen(b)cos(c)cos(A) \tag{5.4}$$

Where the upper case letters represent the angles at the respective vertices and the lower case letters represent the opposite sides of these angles.

To reinforce the explanation we will use the figure 5.3.

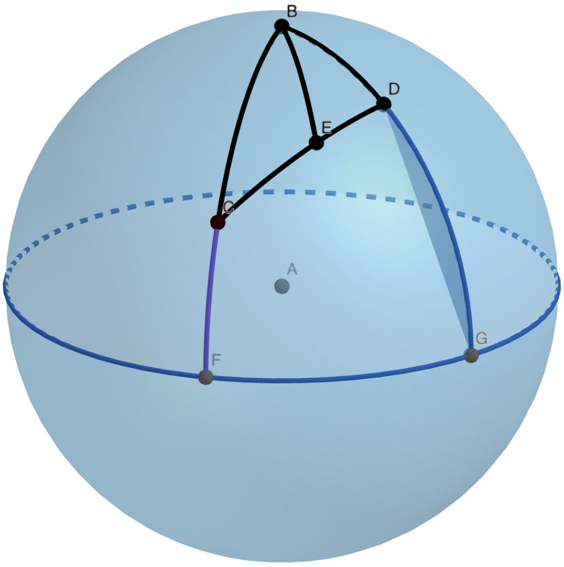


Figure 5.3: Spherical triangles.

Source: Own work, 2023.

Let us assume that the start and end coordinates of our route are respectively points C and D in the figure and the point E is a point for which we wish to obtain the coordinates. It is easy to obtain the sides of the spherical triangle CBD. We can write that:

- CD can be obtained from 5.1
- CB = 90 -λ_1
- DB = 90- λ_2

Using 5.2 the angle C can be obtained.

The CE centre angle can be easily obtained from the aircraft speed as follows:

First the linear velocity is converted to angular velocity as follows:

$$\omega = \frac{v}{R_e + H} \tag{5.5}$$

- R_e is the earth radius
- H is the flight altitude of the aircraft above the sea level.

The angle can be expressed according to the definition of angular velocity as follows:

$$CE = \omega \cdot \Delta t$$

Now it's easy to obtain EB using the equation 5.2.

The latitude of the point E will be $\lambda_E = 90 - EB$.

The length can be obtained in a similar way by solving the small triangle CEB using Bessel's first formula. The angle formed by this triangle at point B corresponds to the longitude increment $\Delta\phi$. However, in order to determine the length of the new point we must differentiate between 2 cases:

- If $\phi_1 \geq \phi_2 \Rightarrow \phi_E = \phi_1 - \Delta\phi$
- If $\phi_1 < \phi_2 \Rightarrow \phi_E = \phi_1 + \Delta\phi$

Thus, from the parameters described above, the geometric coordinates of an aircraft following a given route past a given Δt can be obtained.

The simulator extension calculates a matrix with as many rows as time steps in the simulation and with three columns corresponding to the altitude, latitude and longitude of the aircraft at each time step of the simulation.

5.2 Aircraft - Satellites link

The next step in the development of the simulator extension is to determine the connections between the defined aircraft and the satellites along their route. For this purpose, it has been decided to treat the aircraft for code purposes as a ground station object that moves over time. This facilitates calculations, as Matlab functions can be used to determine the connections.

Thus, the code creates a matrix where the columns correspond to the different routes the user wants to enter and the rows correspond to Ground Station objects at each time step of the simulation. For each time step, the row corresponding to this time instant contains Ground Station objects with the positions of each aircraft at that moment of the simulation, which have been calculated as described in the previous section. Once this is defined, visibility, power and noise calculations are performed for each aircraft at each instant in time.

Firstly, the code for calculating the visibility between aircraft and the satellites has been extended. The critical parameter defining visibility is the angle of elevation. This is defined as the angle between the horizontal plane and the line pointing to the satellite[33].

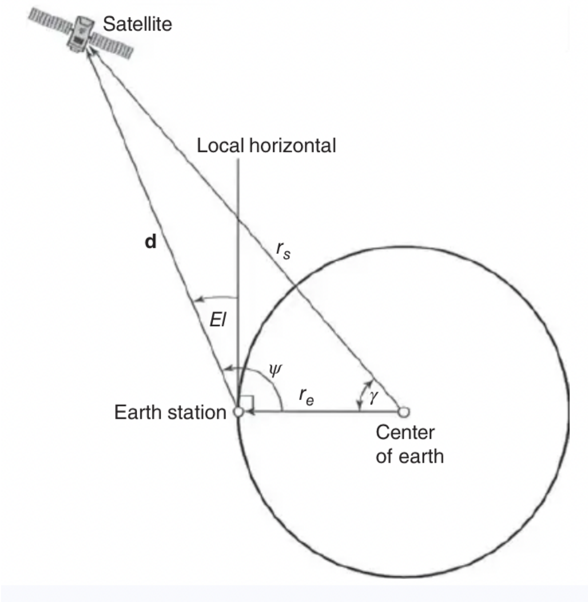


Figure 5.4: Elevation angle (El) geometry.

Source: Timothy Pratt et al., 2020 [33].

This parameter can be determined geometrically using the relationships described in the figure 5.4. However, as previously mentioned, the fact of having created Ground Station objects within the Satellite Scenario environment allows us to calculate this value using the *aer* function indicating the Ground Station and the target satellite.

Thus, a minimum elevation angle is defined from which the visibility for each satellite-ground station link is determined at each instant of time.

The next thing that is calculated is the link budget. The received power is determined from the transmission equation 4.1. Where:

- The transmitted power is defined by the user.
- The gains depend on the type of antenna chosen. In[28] an antenna was developed for the ground station and another one for the satellites. In the extension of the code, the same type of antennas are considered for the calculations.

- The user can choose if he wants to include atmospheric loss. In case the user decides to include atmospheric losses, the matlab function *GaseousAttenuationITU10* is used.
- The user can choose if he wants to include other losses.

Finally, the quality of communication is evaluated. The user can choose between several methods:

- **Transceiver :** The user enters the sensitivity of the transreceiver.
- **Berspec :** The user specifies a modulation type and a BER. From these data, the minimum SNR that must be met is obtained. The simulator offers the possibility to choose between the following modulations:
  - Phase shift keying (PSK)
  - Offset quadrature phase shift keying (OQPSK)
  - Differential phase shift keying (DPSK)
  - Quadrature amplitude modulation (QAM)
  - Frequency shift keying (FSK)
  - Minimum shift keying (MSK)
  - Continuous-phase frequency shift keying (CPFSK)
- **SNRmin:** The user enters a minimum SNR value and it is compared to the SNR value calculated from the equation 3.13

The minimum transmitted power is calculated depending on the chosen method.

- **Transceiver :** It's the sensitive power of the transmitter.
- **Berspec and SNRmin:** It can be calculated as follows:

$$PR_{min} = SNR_{min} + 10log(N) \tag{5.6}$$

Where N is the noise power.

5.3 Aircraft - Ground stations link

The last extension that has been developed for the simulator is the one that calculates the connections between the ground stations and the aircraft. For the development of this extension, the calculations described below have been carried out according to the formulas described in the theoretical section of this thesis. Objects from the aerospace toolbox such as ground stations objects have not been used because satellite scenario is designed for calculations with satellites and in this extension the calculations for connections between aircraft and ground stations are performed. Specifically, the following is calculated:

Received Power and Vision Status

First of all, the distance between each ground station and each aircraft is calculated for all the time steps of the simulation. This is done as follows:

- First the minimum distance on the earth's surface taking only into account latitude and longitude of each element is calculated using the formula 5.1. And taking into account that the distance d can be calculated as $d = \Delta\sigma R_e$.
- The altitude difference between ground stations and aircraft is calculated.
- The distance d and the altitude form a right triangle whose hypotenuse is the distance between the aircraft and the ground station we are looking for. Thus, this distance can be easily obtained using the Pythagorean theorem. In summary:

$$R = \sqrt{(\Delta\sigma R_e)^2 + (\Delta h)^2} \tag{5.7}$$

Where Δh is the altitude difference between ground stations and aircraft.

The received power on the link is calculated from the equation 3.10. For this extension, losses that may be caused by atmospheric effects or other effects have not been taken into account. The user must define in advance both the ground station antenna gain and the aircraft antenna gain.

For the visibility calculation, a minimum power is taken into account that must be defined by the user when writing the data that he wishes to use for the simulation. From this minimum power, it is considered that there is visibility if the received power is greater than the threshold.

Noise

Using equation 3.11 the noise power is calculated for both the uplink and the downlink. Once this is done, the signal-to-noise ratio is calculated using the formula 3.13.

Finally, the user has to define a minimum Bit error rate and from this it is calculated whether the link meets the minimum BER requirements.

The modulation chosen for these calculations is QAM (Quadrature Amplitude Modulation) . This type of modulation combines amplitude and phase modulations to obtain more information. There are several types of QAM modulations. Four cases are calculated in the code:

- 4-QAM Modulation
- 16-QAM Modulation
- 32-QAM Modulation
- 64-QAM Modulation

There are graphs relating SNR to BER for each QAM modulation type (). The code requires the user to manually enter the minimum SNR obtained for a specific BER. From this data it is calculated whether the link criteria are adequate or whether there will nevertheless be a larger error than desired.

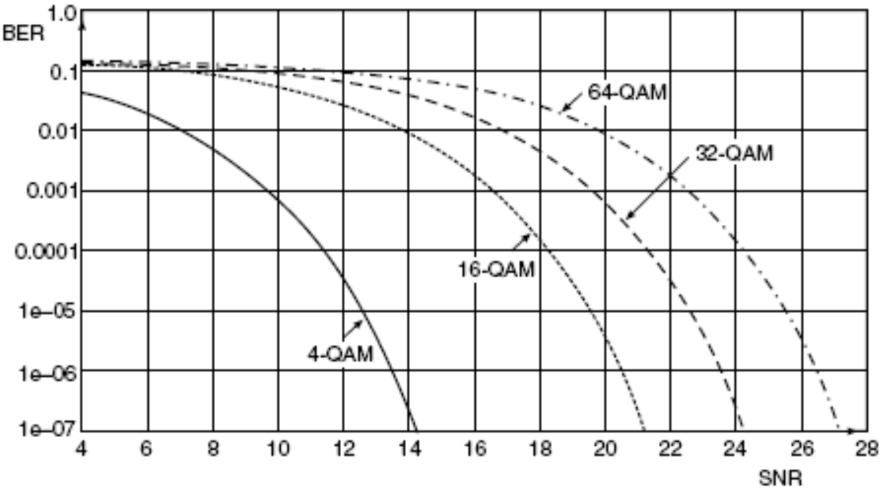


Figure 5.5: SNR to BER for each QAM modulation .

Source: obtained from professor Javier Gago Barrio.

5.4 Simulator extensions guide

In order to be able to use the extensions that have been developed the following aspects must be taken into account:

- The version of Matlab to be used is Matlab R2022a. Correct operation with other versions of Matlab is not assured.
- The following Libraries must be installed: Aerospace Toolbox, Satellite Communications Toolbox, Phased Array System Toolbox, Communications Toolbox, Antenna Toolbox, DSP System Toolbox and Signal Processing Toolbox
- The Matlab files required to run the simulator are:
  - main_aircraft.m

  - computeAngleBetween2Vector.m
  - CrossLinkCalculation.m
  - DefaultGS.m
  - DigitalModulation.m
  - Distance__points.m
  - EbNo_To_SNR.m
  - gammaFITU120.m
  - GaseousAttenuationITU10.m
  - GroundStations.m
  - point_to_line.m
  - ResultsGS.m
  - ResultsISL.m
  - SatelliteVisualize.m
  - xiCalculationITU10.m
  - GainPatternGs.mat
  - GainPatternSat.mat
  - route.m

Before starting the simulator, the parameters described in section 4.2 must be adjusted. In addition to the parameters described in that section, the following values must be added:

- **P_TR.Pr:** Transmission power in watts of the aircrafts.
- **limSNRqam.four:** The minimum SNR for the required BER in the tracking calculations for 4-QAM (obtained from 5.5)
- **limSNRqam.sixteen:** The minimum SNR for the required BER in the tracking calculations for 16-QAM (obtained from 5.5)
- **limSNRqam.threetwo:** The minimum SNR for the required BER in the tracking calculations for 32-QAM (obtained from 5.5)
- **limSNRqam.sixfour:** The minimum SNR for the required BER in the tracking calculations for 64-QAM (obtained from 5.5)

- **AntgainPRtoGS:** The antenna gain of the aircrafts used in the link ground station-aircraft.
- **AntgainGStoPr:** The antenna gain of the Ground Stations used in the link ground station-aircraft.
- **PT_track.up:** The antenna transmission power of the Ground Stations used in the link ground station-aircraft.
- **PT_track.down:** The antenna transmission power of the aircrafts used in the link ground station-aircraft.

Once the code is run. You will be prompted to enter information about the satellite systems, as described in section 4.2 and in [28].

Next, the data of the Ground Stations is requested, as described in 4.2 and [28].

Next, the data of the Time schedule is requested, as described in 4.2 and [28].

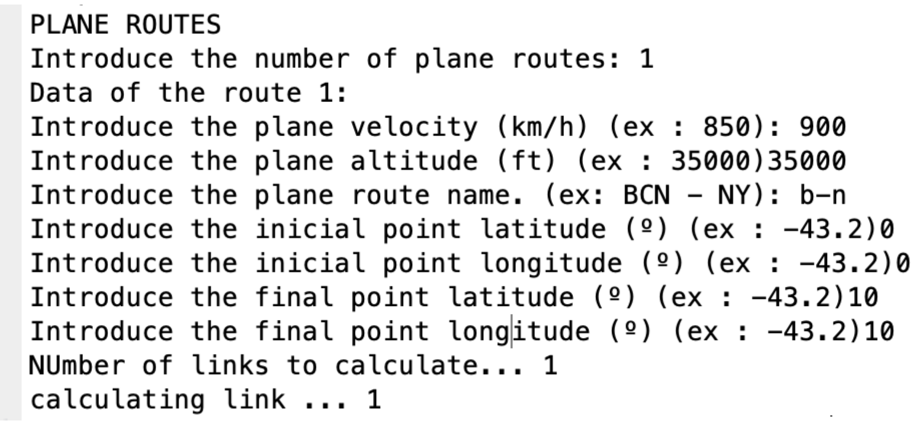
In the next step, the code asks the user to enter basic information about the aircraft routes they wish to incorporate. Specifically it asks for:

- The number of routes

  And for each route:

- The plane velocity in km/h.
- The plane altitude in ft.
- The plane route name.
- The initial point latitude in degrees.
- The final point latitude in degrees.
- The initial point longitude in degrees.
- The final point longitude in degrees.

And it starts to calculate the links between plane routes and satellites. This may take some time, especially if many satellites and/or many time steps are defined. This is why the progress of the calculation is shown on the display. The process of entering aircraft routes is shown in the figure below:



```
PLANE ROUTES
Introduce the number of plane routes: 1
Data of the route 1:
Introduce the plane velocity (km/h) (ex : 850): 900
Introduce the plane altitude (ft) (ex : 35000)35000
Introduce the plane route name. (ex: BCN - NY): b-n
Introduce the inicial point latitude (º) (ex : -43.2)0
Introduce the inicial point longitude (º) (ex : -43.2)0
Introduce the final point latitude (º) (ex : -43.2)10
Introduce the final point longitude (º) (ex : -43.2)10
NUmber of links to calculate... 1
calculating link ... 1
```

Figure 5.6: Entering aircraft routes .

Source: Own work

After this, the simulator asks whether you want to add atmospheric losses or other types of losses. And later, about the type of method for the Link Budget as described in [28] and 4.1.

After some calculations the simulator asks if the user wants to access to the visualisation. This is only possible if no plane routes are added to the simulation, since no visualization tool has been developed for the extensions.

Finally, the simulator does some final calculations of the last extension and the results are ready.

The results pertaining to the ground stations can be obtained as described in the section 4.2.The results pertaining to the new extensions are stored in various variables. The way in which the results are saved is described in appendix A.

Chapter 6

Simulation Results

In this chapter, a series of simulations are carried out to test the importance of using satellite constellations for en-route aircraft communications. Specifically, the following scenarios will be simulated:

- Simulation 1 : Madrid-Berlin Route only with ground stations.
- Simulation 2 : Amazon-Berlin Route only with ground stations.
- Simulation 3 : Amazon-Berlin Route + Simpira.
- Simulation 3 : Amazon-Berlin Route + Satellite constellation.

6.1 Simulation 1

A Madrid-Berlin Route has been simulated and Ground Stations have been placed in Terrassa, Berlin, Beijing, Washington, Chad, Brasilia, Madrid, Paris and Stuttgart.

The geographical coordinates of these ground stations can be seen in the following table:

Ground Station	**latitude (deg)**	**longitude (deg)**	**altitude (m)**
Terrassa	41.5631	2.0230	290
Berlin	52.5243	13.4105	34
Pekin	39.9075	116.3972	44
Washington	38.8951	-77.0363	125
Brasilia	-15.7797	-47.9297	1172
Chad	15.4541	18.7322	298
Madrid	40.4129	-3.6989	657
Paris	48.8564	2.3516	35
Stuttgart	48.7761	9.1812	245

Table 6.1: Geographical coordinates of the ground stations

The time schedule of the simulation is presented bellow:

- **Start date of the simulation:** Computer data time at Sunday April 30th 2023 12:00.
- **Duration:** 150 min
- **Sample time:** 10 s

The plane route parameters of the simulation are presented in the following table:

Velocity	900 km/h
Altitude	35000 ft
Inicial Point	Madrid
Final Point	Berlin

Table 6.2: Madrid-Berlin Route Parameters

Neither atmospheric losses nor other losses have been considered in the simulation. The link budget method used in the simulation was transceiver method. The link budget parameters are sumarized in the following table:

Transmitted ground station power	5 W
Transmitted aircraft power	1 W
Ground Station antenna gain	10 dB
Aircraft antenna gain	10 dB
Antenna temperature (Uplink)	290 K
Antenna temperature (Downlink)	290 K
Frequency	2.2 GHz
Transceiver sensitivity	-134 dBW
Bandwidth	750 kHz

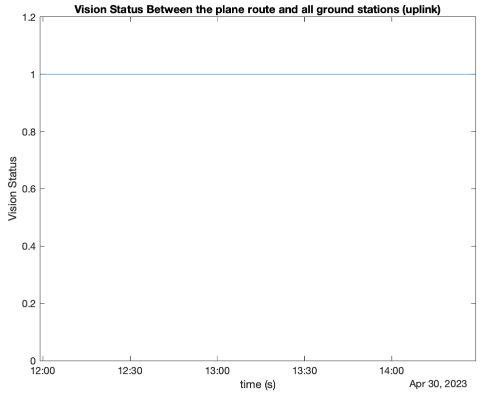
Table 6.3: Madrid-Berlin Link Budget Parameters

The limit BER to work with will be 10^{-6}. From figure 5.5 We can obtain the minimum SNR requirements for each modulation:

Modulation	**Minimum SNR**
4-QAM	13.5
16-QAM	20.5
32-QAM	23.5
64-QAM	26.5

Table 6.4: Minimum SNR requirements for each modulation

In the following graphs a 1 is shown if there is at least one Ground Station with visibility to the aircraft and a 0 if no Ground Station has visibility.



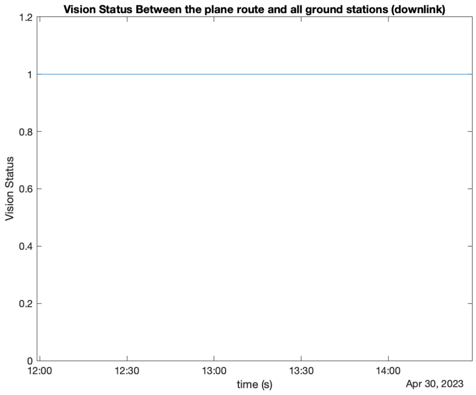


Figure 6.1: Vision Status between the plane route and all ground stations (uplink) .

Source: Own work

Figure 6.2: Vision Status between the plane route and all ground stations (downlink) .

Source: Own work

We can therefore see that for the entire simulation there is visibility with at least one Ground Station.

Below is the uplink and downlink SNR for all ground stations together with the SNR limits for each modulation type:

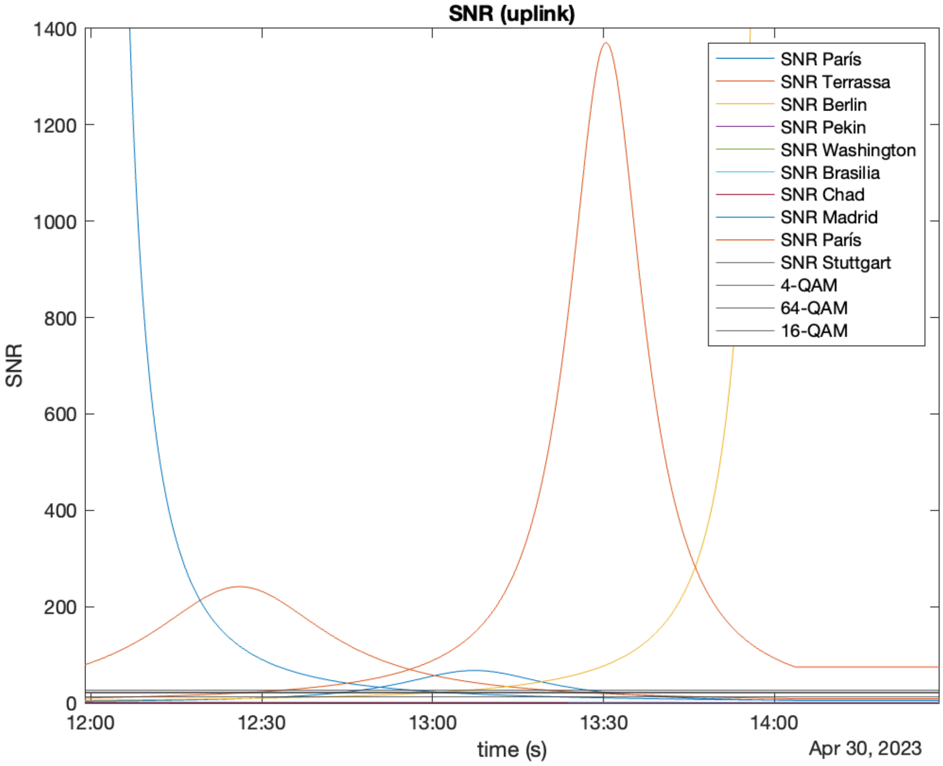


Figure 6.3: SNR for all ground stations (uplink).

Source: Own work.

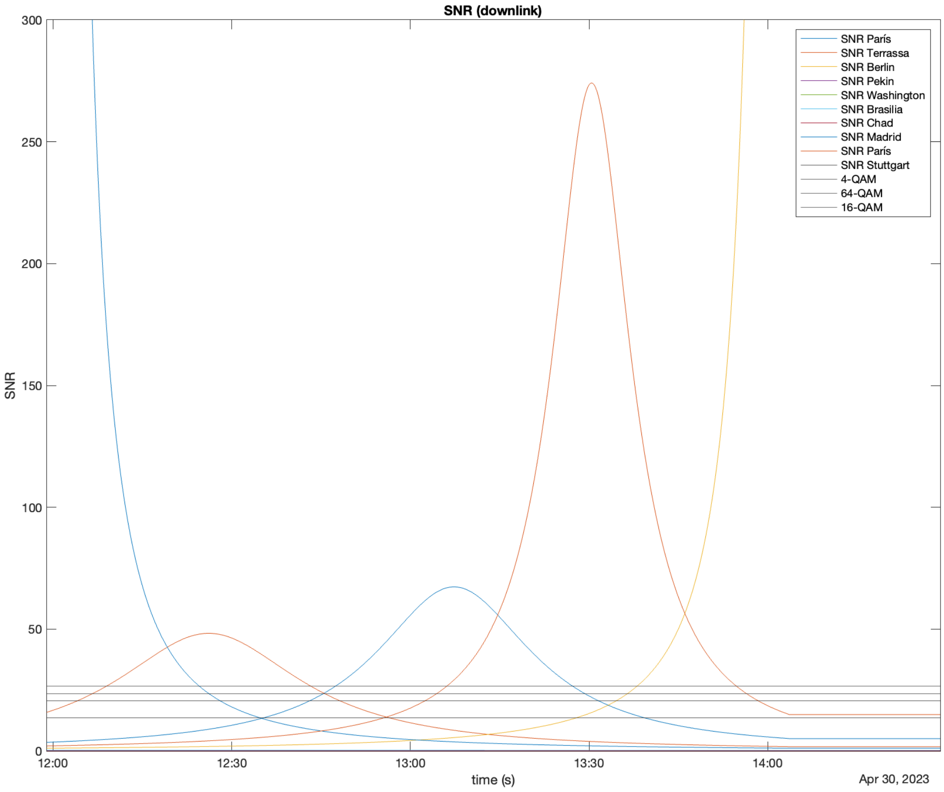


Figure 6.4: SNR for all ground stations (downlink).

Source: Own work.

As can be seen, for the uplink at any time there is one station with an SNR greater than the limit, and this happens for all modulations. However, in the downlink, for the downlink, in the 64-QAM modulation there is a gap between 12:30 and 13:00. Therefore The BER requirements for this modulation will not be met.

Even so, as can be seen, for an aircraft flying over land, if we distribute a set of ground stations evenly spaced along the surface it flies over, it is not necessary to use satellites to establish communications between the ground stations and the aircraft. Let us now consider the case where the aircraft flies over the ocean, where evenly spaced ground stations are not feasible.

6.2 Simulation 2

A route from a point in the Amazon to Berlin will now be simulated. The ground stations will be placed in the same way as in the previous simulation, but now an extra ground station will be placed at the departure point in the Amazon. The geographical coordinates of the chosen point in the Amazon are:

Ground Station	**latitude (deg)**	**longitude (deg)**	**altitude (m)**
Amazon	-2.8169	-63.4372	92

Table 6.5: Geographical coordinates of the Amazon chosen point

The time schedule of the simulation is presented bellow:

- **Start date of the simulation:** Computer data time at Sunday April 30th 2023 21:28.
- **Duration:** 650 min
- **Sample time:** 30 s

The plane route parameters of the simulation are presented in the following table:

Velocity	900 km/h
Altitude	35000 ft
Inicial Point	Amazon
Final Point	Berlin

Table 6.6: Amazon-Berlin Route Parameters

Neither atmospheric losses nor other losses have been considered in the simulation. The link budget method used in the simulation was transceiver method. The link budget parameters are same used in table 6.3.

The BER limit to work will be 10^{-6}, whose limit SNR values can be observed in the table 6.4 .

In the following graphs a 1 is shown if there is at least one Ground Station with visibility to the aircraft and a 0 if no Ground Station has visibility.

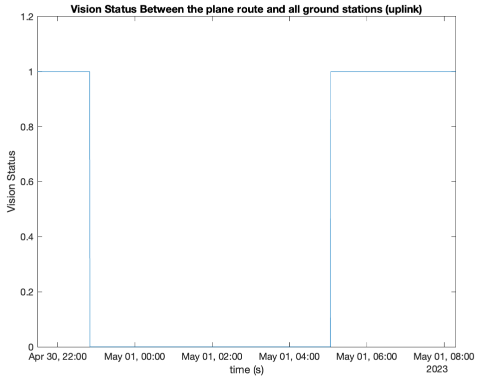


Figure 6.5: Vision Status between the plane route and all ground stations (uplink) .

Source: Own work

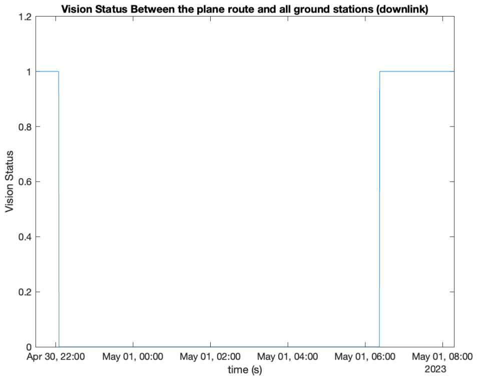


Figure 6.6: Vision Status between the plane route and all ground stations (downlink) .

Source: Own work

As can be seen, both for the uplink and the downlink, in the first moments of the simulation there is visibility with at least one ground station (Amazon). However, then a large gap is created in which there is no visibility for any ground station until the aircraft reaches European land, where it is able to have visibility again.

Below is the uplink and downlink SNR for all ground stations together with the SNR limits for each modulation type:

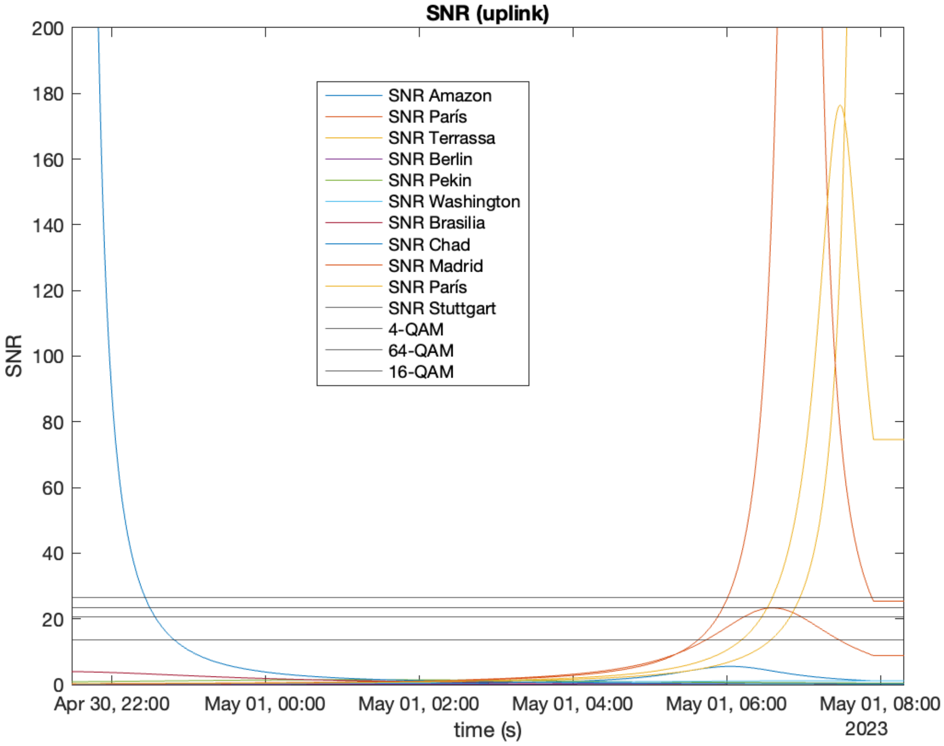


Figure 6.7: SNR for all ground stations (uplink).

Source: Own work.

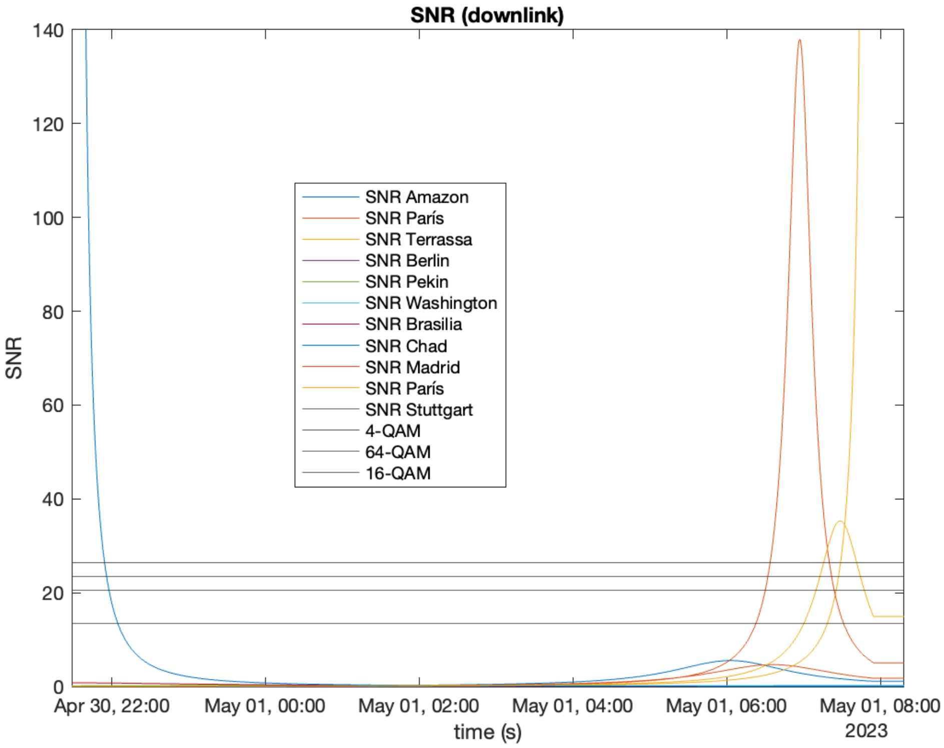


Figure 6.8: SNR for all ground stations (downlink).

Source: Own work.

As can be seen, the SNR plots act in the same way as the visibility plots. A connection will be established meeting the minimum BER requirements both at the beginning of the simulation and at the end of the simulation, however in the middle a large gap is created.

This gap is logically due to the fact that no ground stations are placed over the ocean surface and shows that it is necessary to extend the ground station system if an aircraft is wnated to be monitored at all times during the simulation.

6.3 Simulation 3

This simulation takes exactly the same route with the same ground station scheme as in the previous section, but now adds a satellite whose orbit passes over the chosen aeronautical route.

A satellite that was developed in [28] has been chosen for the simulation. This satellite was chosen because it was designed to have an orbit that would pass both over the Amazon and the Terrassa ground station. Its orbit characteristic parameters can be summarised in the following table:

Name	Simpira
Eccentricity	0
Semiajor axis (km)	500
Argument of periapsis (deg)	0
Right ascension of ascending node (deg)	105
Inclination (deg)	45
True Anomaly (deg)	320

Table 6.7: Simpira's parameters.

Source: P. Díaz, Xavier [28]

If the periods of visibility between the satellite and the aircraft are plotted, the following graphs are obtained:

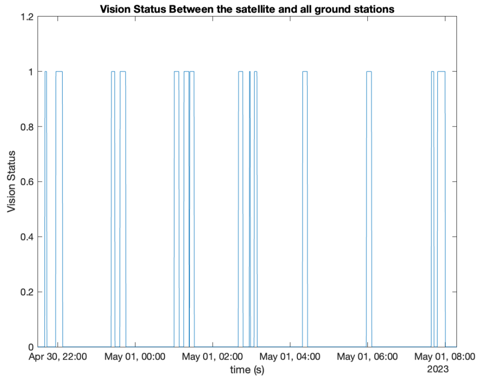


Figure 6.9: Vision Status between the satellite and all ground stations.

Source: Own work

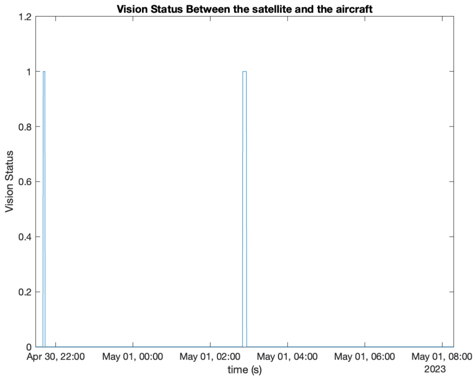


Figure 6.10: Vision Status between the aircraft and the satellite.

Source: Own work

It can be seen that the satellite is periodically connecting to at least one ground station. On the other hand, in the graph on the right, we can see that it only connects with the aircraft at two specific moments in the simulation, which is not sufficient to monitor the aircraft using this satellite.

In the next plot a 1 represents whether there is visibility between the aircraft and at least one Ground Station, between the satellite and the aircraft or between the satellite and at least one Ground Station.

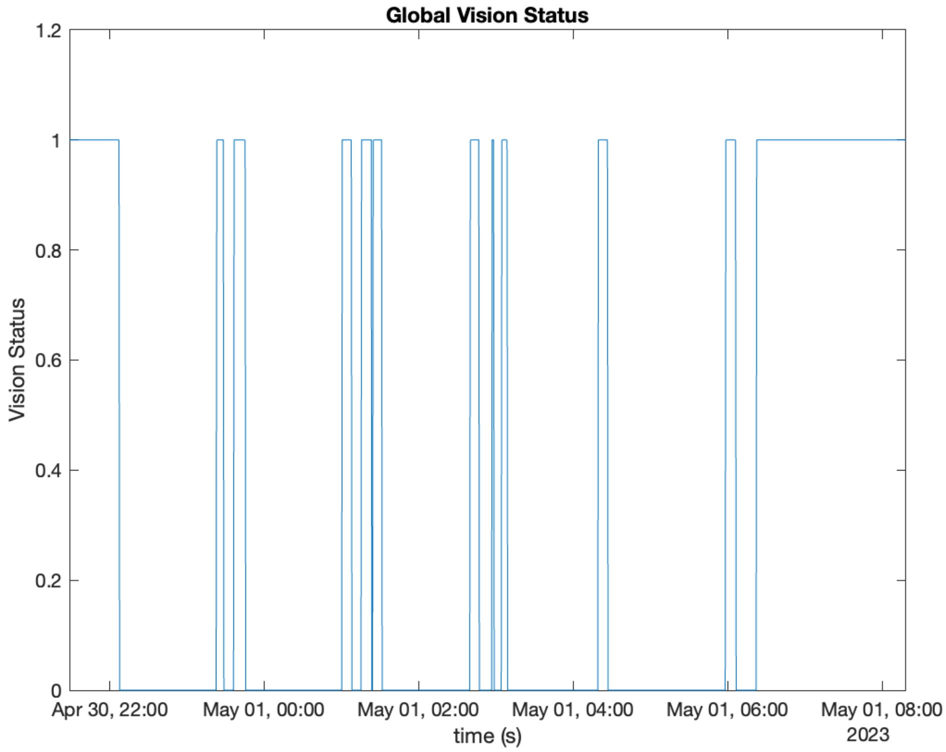


Figure 6.11: Global Vision Status.

Source: Own work.

As can be seen, using a single satellite to monitor an aircraft route does not give good results even if the orbit is passed over the trajectory of the aircraft. This is why it is considered appropriate to analyse the situation if a constellation of satellites is used.

6.4 Simulation 4

In this section, a simulation is performed with the same ground station scheme and the same route as in cases 2 and 3. However, a Walker constellation of satellites will now be included in the simulation, instead of a single satellite. The Walker constellation used has the following parameters:

Name	Atlas
Constellation type	Star
Inclination (deg)	98
Orbital planes	12
Total satellites	360
Satellites per plane	30
Altitude (km)	650
Relative phase parameter	0
Linking method	cross

Table 6.8: Atlas constellation parameters.

Source: Own work

The time schedule of the simulation is presented bellow:

- **Start date of the simulation:** Computer data time at Sunday April 30th 2023 01:36.
- **Duration:** 650 min
- **Sample time:** 30 s

The link budget parameters will be the same as in simulations 2 and 3 and the chosen method is the transceiver method. No atmospheric losses or other types of losses have been considered.

Let's take a look at the visibility status:

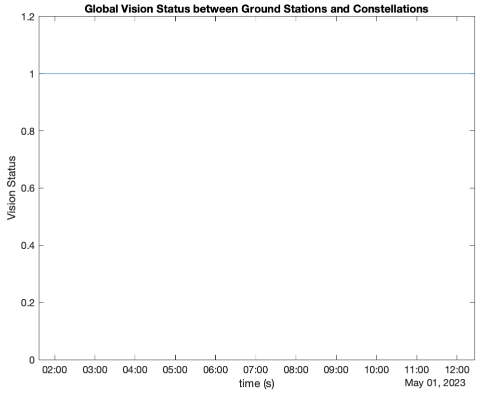


Figure 6.12: Vision Status between the satellite constellation and all ground stations.

Source: Own work

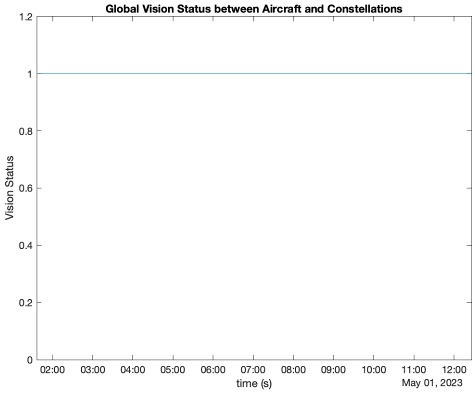


Figure 6.13: Vision Status between the aircraft and the satellite constellation.

Source: Own work

Figures 6.12 and 6.13 show that for all the simulation, the aircraft is connected to the constellation of satellites and this, in turn, is connected at all times to at least one ground station. This means that in terms of visibility there is the possibility of creating an Aircraft - Ground Station - Constellation connection scheme with which the three elements have link. Let's see if the requirements are met for this connections to take place.

Ground Stations - Satellite connections:

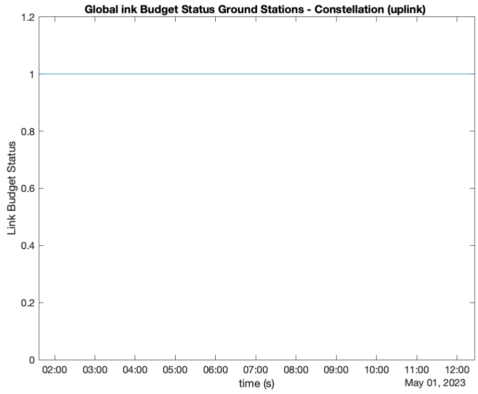


Figure 6.14: Link Budget status between the satellite constellation and all ground stations(uplink).

Source: Own work

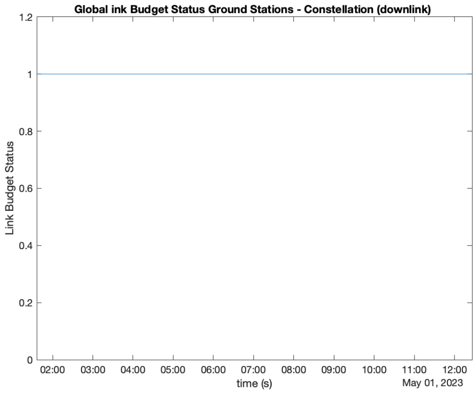


Figure 6.15: Link Budget status between the satellite constellation and all ground stations (downlink).

Source: Own work

And for the aircraft satellite connection:

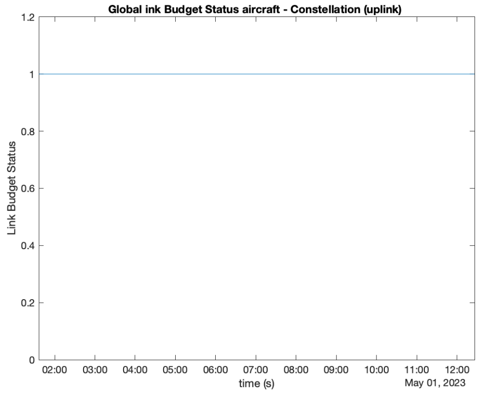


Figure 6.16: Link Budget status between the satellite constellation and the aircraft (uplink).

Source: Own work

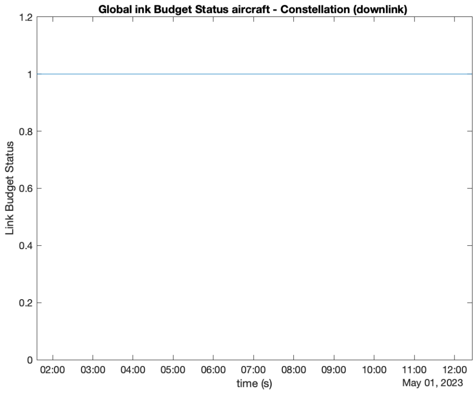


Figure 6.17: Link Budget status between the satellite constellation and the aircraft (downlink).

Source: Own work

As we can see, the minimum power requirements are met for the connections between the ground stations and the satellite constellation at all times for at least one ground station (both uplink and downlink). In the case of connections between the aircraft and the satellite constellation, this is also true for both of the links at all times.

This shows that using a constellation of satellites, it is possible to obtain a connection at a global level between an aircraft route and the ground stations located on the earth's surface. This offers a plane - ground station - satellite connection scheme that allows to monitor and establish a connection with an aircraft route globally.

Chapter 7

Budget

This chapter summarises the final cost of the speculated budget for this project. As this is a purely theoretical project and does not require any physical development, the costs to be taken into account are only those associated with the technical cost of drafting the project, i.e.: professional fees, cost of the material and software used and cost of the energy consumption used.

Only the summary of the final cost is included in this chapter, as the breakdown of how these numbers have been obtained can be found in the Budget document.

The budget is summarised in the table below:

Type of Cost	**Cost (Euros)**
Professional fees	6000
Equipment costs	2860
Energy costs	56.69
Total costs	**8916.69**

Table 7.1: Costs of the project development

Chapter 8

Environmental impact

This chapter analyses the impact that the development of the project has had at the environmental level. Again, as it is a purely theoretical project, it will be considered that the environmental impact generated is due solely to the light consumption, the energy consumption of the computer used to carry out the project and to the trips made to carry out the project. For the calculation of energy consumption, it will be taken into account that approximately 400 hours have been used to do the project.

Computer emissions

The computer used to do the project is a MacBook Pro (16-inch, 2021). According to the specifications of the brand [34], this computer has an average consumption per hour of 100 W. If we estimate an emission factor of 0.3 $KgCO_2/kWh$ [35] we can estimate the CO_2 emissions related to the computer energy consumption:

$$CO_2computer = 0.1KW \cdot 400h \cdot 0.3KgCO_2/kWh = 12KgCO_2 \tag{8.1}$$

Electricity emissions

If we consider that the consumption of light in the room where this work has been carried out is that of 3 LED bulbs (1 bulb consumes 10 W [36]), we can calculate the CO2 emissions relative to light consumption.

$$CO_2light = 3 \cdot 0.01KW \cdot 400h \cdot 0.3KgCO_2/kWh = 3.6KgCO_2 \tag{8.2}$$

Transport emissions

It will be considered that 10 trips have been made to the university, which is located 30 km from the student's residence. The average consumption of CO_2 of the car used is 139.1g/km. Therefore the total emissions are:

$$CO_2car = 10 \cdot 30km \cdot 0.1391KgCO_2/Km = 41.73KgCO_2 \tag{8.3}$$

The breakdown of consumption and the total consumption are shown in the following table:

Emissions source	**Emissions of CO2 (kg)**
Computer	12
Light	3.6
Car	41.73
Total	**57.33**

Table 8.1: CO2 Emissions

Chapter 9

Conclusions

The objective of this project was to extend the Matlab simulator described in [28] to include aircraft routes, the connections between aircraft and ground stations, and the connections between aircraft and satellites. The initial objectives are considered to be met, since these extensions have been able to be developed and a ground-air-space simulation tool for monitoring aircraft connections has been created.

An extension to add aircraft routes has been developed. The code has been extended to calculate the visibility and the connections between aircraft and satellites, and an extension to compute the connections between aircraft and ground stations has been programmed. Finally, it has been verified that this tool provides good results, since it allows to create a network of connections between the aircrafts and the ground stations through the constellations of satellites, and offers global coverage.

In summary, the proposed extensions have been successfully developed, and it has been shown that they allow to establish connections with aircraft routes at all times and globally. Therefore, the project results are considered satisfactory and meet the initial objectives. However, the developed code has certain limitations that may be the subject of future work or studies. To continue advancing in this field, new functions can be included to improve the possibilities and efficiency of the developed tool and the program can be used to study various topics of interest.

Chapter 10

Future Work

In this chapter, a series of ideas are expressed about the possible future work that can be done once the project has been developed. There are numerous options to expand the project and develop new avenues of research that are related to it. The most interesting possibilities have to do with including new features and improving the current features of the simulator or with the use of the simulator to study various topics. Some of the most interesting ideas are collected below:

- Develop a visualisation tool for satellite-to-aircraft and aircraft-to-ground station connections.
- Include other possible modulation types in the connections between aircraft and ground stations in addition to the 4 QAM options presented, and include various methods such as Berspec or SNRmin.
- Include atmospheric losses or other losses in aircraft - ground station connections.
- Work on the efficiency of the code to make it faster and easier to work with larger simulation scenarios.
- Improve the user interface to make it simpler and more accessible to everyone.
- Use the simulator to study different topics of interest.
- Develop connections between different aircraft.
- Expand the simulator to create a system that allows detecting from an aircraft other nearby aircraft and prevent collisions.

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Appendix A

Appendix A: Results storage

For the aircraft routes definition :

- **proutes(i,j,k):** (i,j) is a matrix with as many rows as time steps in the simulation and with three columns corresponding to the altitude, latitude and longitude and the index k corresponds to the plane route number.

For the aircraft-satellites link :

- **elegs_p(i,j):** Elevation angle for the route i in the time step j.
- **visiStatusPr(i,j):** Vision Status. If the value is 1 there is visibility.
- **P_RE.Up_p(i,j):** Received Power (dB) in the uplink in the timestep j and for the link i.
- **P_RE.Down_p(i,j):** Received Power (dB) in the downlink in the timestep j and for the link i.
- **P_TRreq_p.UpDown (i,j):** Required Transmission Power (W) in the timestep j and for the link i.
- **SNRdB_p.Up(i,j):** The SNR in dB in the uplink in the timestep j and for the link i.
- **SNRdB_p.Down(i,j):** The SNR in dB in the downlink in the timestep j and for the link i.
- **SNRlin_p.Up(i,j):** The SNR in W in the uplink in the timestep j and for the link i.
- **SNRlin_p.Down(i,j):** The SNR in W in the downlink in the timestep j and for the link i.
- **LinkBudget_p.Up.Status(i,j):** The Link Budget Status in the uplink in the timestep j and for the link i. If the value is 1 there is link.
- **LinkBudget_p.Down.Status(i,j):** The Link Budget Status in the downlink in the timestep j and for the link i. If the value is 1 there is link.

For the aircraft-ground stations link :

- **PR.up_track(i,j,k):** Received Power (dB) in the uplink in the timestep j and for the ground station i and the route k.
- **PR.down_track(i,j,k):** Received Power (dB) in the downlink in the timestep j and for the ground station i and the route k.
- **vistatus_track.up(i,j,k):** Vision Status in the uplink in the timestep j and for the ground station i and the route k. If the value is 1 there is visibility.
- **vistatus_track.down(i,j,k):** Vision Status in the downlink in the timestep j and for the ground station i and the route k. If the value is 1 there is visibility.
- **SNR_track.up(i,j,k):** SNR in the uplink in the timestep j and for the ground station i and the route k.
- **SNR_track.down(i,j,k):** SNR in the downlink in the timestep j and for the ground station i and the route k.
- **statusBER.four_up(i,j,k):** BER Status in the uplink in the timestep j and for the ground station i and the route k. If the value is 1 the BER requirements for 4-QAM are met .
- **statusBER.four_down(i,j,k):** Vision Status in the downlink in the timestep j and for the ground station i and the route k. If the value is 1 the BER requirements for 4-QAM are met .
- **statusBER.sixteen_up(i,j,k):** BER Status in the uplink in the timestep j and for the ground station i and the route k. If the value is 1 the BER requirements for 16-QAM are met .
- **statusBER.sixteen_down(i,j,k):** Vision Status in the downlink in the timestep j and for the ground station i and the route k. If the value is 1 the BER requirements for 16-QAM are met .
- **statusBER.sixfour_up(i,j,k):** BER Status in the uplink in the timestep j and for the ground station i and the route k. If the value is 1 the BER requirements for 64-QAM are met .
- **statusBER.sixfour_down(i,j,k):** Vision Status in the downlink in the timestep j and for the ground station i and the route k. If the value is 1 the BER requirements for 64-QAM are met .
- **statusBER.threetwo_up(i,j,k):** BER Status in the uplink in the timestep j and for the ground station i and the route k. If the value is 1 the BER requirements for 32-QAM are met .
- **statusBER.threetwo_down(i,j,k):** Vision Status in the downlink in the timestep j and for the ground station i and the route k. If the value is 1 the BER requirements for 32-QAM are met .