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Cubesat constellation in LEO for air navigation monitoring

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Abstract

This project's aim is to design a Matlab simulator capable of representing satellite constellations in Low Earth Orbits with the mission of monitoring air navigation trajectories. The objective is to create a tool capable of visually simulate the distribution of satellites in space along with the communication links between satellites, ground stations and aircraft.

The aerospace industry is one of the most technologically and economically powerful in the world. This sector has evolved and grown exponentially in recent years thanks to the many applications it offers. In addition, the arrival of the New Space initiative has brought a new paradigm to the aerospace market, which has promoted the use of cubesats in LEO for telecommunication purposes. Furthermore, air transportation is one of the means of mobility that moves more passengers worldwide. Therefore, it is crucial to have the necessary elements to ensure constant and global coverage of air traffic, with the aim of improving the efficiency and safety of aircraft tracking.

For the construction of the constellations, an analysis of the Walker pattern has been carried out. This methodology distributes the satellites symmetrically around a celestial body, providing global coverage. In addition, the effect of the different orbital parameters on the operation of the constellation has been studied. Finally, the structure of the ground segment required for the optimal performance of the mission has also been defined.

The simulator designed in this thesis allows the user to create customized satellite configurations and visually represent the connections between the different objects in the defined scenario. The obtained result is able to perform a 3D representation of the orbits of the satellites, the ground stations network and the aircraft's flight trajectory. Moreover, visibility intervals and communication links between satellites and antennas, and between satellites and aircraft are calculated. In addition, the simulator illustrates the efficiency of the constellation defined by the user taking into account the visibility with the aircraft through the entire flight route.

Keywords:

Walker constellation, Flight trajectories, Communication links, Ground stations

Resumen

El objetivo de este proyecto es diseñar un simulador de Matlab capaz de representar constelaciones satelitales en órbitas terrestres bajas (LEO) con la misión de monitorear trayectorias de navegación aérea. El objetivo es crear una herramienta capaz de simular visualmente la distribución de satélites en el espacio junto con los enlaces de comunicación entre satélites, estaciones terrestres y aeronaves.

La industria aeroespacial es una de las más potentes tecnológica y económicamente del mundo. Este sector ha evolucionado y crecido exponencialmente en los últimos años gracias a las numerosas aplicaciones que ofrece. Además, la llegada de la iniciativa New Space ha traído un nuevo paradigma al mercado aeroespacial, el cual ha promovido el uso de *cubesats* en LEO con fines de telecomunicación. Además, el transporte aéreo es uno de los medios de movilidad que desplaza a más pasajeros en todo el mundo. Por lo tanto, es crucial contar con los elementos necesarios para garantizar una cobertura constante y global del tráfico aéreo, con el objetivo de mejorar la eficiencia y la seguridad en el seguimiento de las aeronaves.

Para la construcción de las constelaciones se ha realizado un análisis del patrón Walker. Esta metodología distribuye los satélites simétricamente alrededor de un cuerpo celeste, proporcionando cobertura global. Además, se ha estudiado el efecto de los diferentes parámetros orbitales en el funcionamiento de la constelación. Por último, también se ha definido la estructura del segmento terrestre necesario para el funcionamiento óptimo de la misión.

El simulador diseñado en esta tesis permite al usuario crear configuraciones satelitales personalizadas y representar visualmente las conexiones entre los diferentes objetos en el escenario definido. El resultado obtenido es capaz de realizar una representación 3D de las órbitas de los satélites, la red de estaciones terrestres y la trayectoria de vuelo de las aeronaves. Además, se calculan los intervalos de visibilidad y las conexiones de comunicación entre satélites y antenas, así como entre satélites y aeronaves. Asimismo, el simulador ilustra la eficiencia de la constelación definida por parte del usuario teniendo en cuenta la visibilidad con la aeronave a lo largo de toda la ruta de vuelo.

Palabras clave:

Constelación Walker, Trayectorias aéreas, Conexiones de comunicación, Estaciones terrestres

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,
- all references have been clearly cited.

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Albert Servitje Roca 21st June 2023

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List of abbreviations / Glossary

- AAIB: Air Accidents Investigation Branch
- ABEP: Atmosphere-Breathing Electric Propulsion
- ADS-B: Automatic Dependent Surveillance–Broadcast
- ALTAIR: Air Launch space Transportation using an Automated aircraft and an Innovative Rocket
- CRS: Celestial Reference System
- ECEF: Earth-Centered Earth-Fixed
- ECI: Earth Centered Inertial
- ESA: European Space Agency
- FAA: Federal Aviation Administration
- GEO: Geostationary Orbit
- GPS: Global Positioning System
- GS: Ground Station
- GSaaS: Ground Station as a Service
- HEO: High Earth Orbit
- ISLs: Inter-Satellite Links
- LEO: Low Earth Orbit
- MEO: Medium Earth Orbit
- NAS: National Airspace System
- NASA: National Aeronautics and Space Administration
- RAAN: Right Ascension of the Ascending Node
- VLEO: Very Low Earth Orbit

Chapter 1

Introduction

1.1 Object

The aim of this thesis is to design a simulator of cubesat constellations in Low Earth Orbits for air navigation monitoring purposes. The objective of the simulated satellite constellations consists in covering different dark radar areas around the globe in order to ensure an optimum tracking and communication with aircraft. Therefore, the results obtained with the simulator will illustrate the efficiency of the defined constellation taking into account the visibility with the aircraft throughout the entire flight path.

The constellations are defined and simulated with a Matlab code, which is capable of visually represent both the satellites and aircraft location, as well as the communication link between them. The tool developed is able to simulate user-customized constellation designs, including a number of adjustable parameters related to orbit configuration and communication properties. Furthermore, an analysis of the required ground segment for the space mission will be performed. Finally, an analysis from the mission design point of view will be included, taking into account the influence of orbital parameters on other aspects of the mission, such as the launch program and the operating costs.

1.2 Scope

The project will include:

- The design of a cubesat constellation simulator for air navigation monitoring.
- A study of the most suitable flight trajectories to fulfill the mission's objective.
- A visual representation of the aircraft flight trajectory.
- A visual representation of the inter-satellite links.
- A visual representation of the communication links between the aircraft and the constellation.
- A visual representation of the communication links between ground antennas and satellites.

- The visualization of the location of the ground stations required for the mission.
- The characterization of the satellites orbits.
- An analysis of possible business collaborations and alliances with international companies for the mission development regarding the ground segment.
- A study of satellite constellation creation methodologies.
- An analysis of the influence of the orbital parameters on the mission's hypothetical cost and launch.

The project will not include:

- A 3D representation of the cubesats used for the mission.
- A complete and detailed characterization of the satellites design, it will not include specific parameters such as mass, dimensions or shape.
- A detailed study of the manufacturing costs of the cubesats.
- An estimation of the overall mission operational costs.
- The definition of the entire cubesat subsystems and payload.
- An atmospheric drag model for the simulation.
- A detailed analysis of the perturbations caused by atmospheric drag to the satellites.
- An analysis of the power requirements for the cubesats of the mission.

1.3 Requirements

- The project's code will be developed in Matlab.
- The final code must plot the visual representation of the aircraft's trajectory.
- The chosen flight paths to monitor with the project's constellation must suit the objectives of the mission.
- The simulator must be capable of visually represent the communication links between satellites and aircraft, as well as between satellites and ground stations.
- The project will include the location of the ground stations required for the mission.
- The constellation simulation must not take into account atmospheric drag perturbations.
- The simulator must determine the aircraft tracking efficiency of the constellation created.

1.4 Justification

The main objective of the simulated constellations is to cover some specific flight routes that cross dark radar zones. In other words, the satellites distribution will allow to continuously track the aircraft in long distance flight paths that pass through areas with poor GPS communication with the nearest ground stations. A study of which global flight paths are more affected by these conditions have been made.

Air transportation is one of the most commonly used means of transport worldwide. Thousand of flights are constantly being monitored all around the globe at the same time. This is why it is crucial for the safety of the passengers to develop an effective system that provides constant global coverage in order to track and communicate efficiently with aircraft. Moreover, this would not only increase the security of passengers but also the performance of air traffic control. Dark radar areas are a real life issue that may cause extremely negative outcomes in case an aircraft can not establish communications with the nearest ground station. The creation of this simulator is to avoid these situations, improve the communication methodology in these type of areas around the world and increase the safety of air navigation operations.

Another aspect to take into account as a motivation to develop this project, is the exponential growth of the aerospace industry with the introduction of the New Space initiative. This concept has involved a great revolution in technology and democratization of the economy of the space market. The New Space program is based on the simplification of access to space, that is, the construction of smaller, compact and economical satellites is promoted. This reduces production costs and enables a more accessible market for the involvement of private companies willing to invest in advanced technology with great growth potential. New Space missions generally use nano-satellite constellations in LEO orbits to conduct telecommunication and Earth observation operations. Then, the creation of this simulator is the perfect tool in order to design a product with potential in the future space market. Professional companies could use this project to rapidly simulate different constellation configurations and moreover, the purpose of these constellations is suitable with the needs of the industry.

Chapter 2

State of the art

For the development of this thesis some other research projects on the design of constellation simulators have been studied. This is the case of the final degree projects of Xavier Pozo and Sergio Prieto, both former students of the Universitat Politècnica de Catalunya. First, Pozo's thesis focuses primarily on analyzing the attenuation and loss of messages in the communication links between cubesats in LEO and Earth [1]. Apart from that, his research includes a Matlab code capable of representing satellite scenarios, which the user can define by introducing manually the orbital elements, TLE data or constellation parameters. On the other hand, Prieto's work consisted of extending some of the capabilities of the simulator designed by X. Pozo with the aim of studying the communication between satellites and airplanes, performing a theoretical analysis on parameters such as transmission power, gain and noise [2]. Taking into account all this previous research, some aspects concerning the design of the Matlab simulator have been taken into account in the creation of this project.

In addition, for the technical development of the simulator regarding the constellation creation, further analysis has been done focusing on the influence of orbital parameters on tracking efficiency. To do this, other research papers specialized on this field have been studied. Furthermore, currently operational constellations such as GPS or OneWeb have been taken as example for the development of the simulator. The properties of these satellite constellations are explained later in section 6.5.

Chapter 3

Methodology

The development of this thesis has required a period of study prior to the realization of the simulator. First of all, the idea of this project was born from the desire to bring a concrete objective to the simulator created by Xavier Pozo [1]. Therefore, the first steps consisted of analyzing the possible applications of the simulator within the space market. After some time of analysis, it was decided that the tracking of air navigation trajectories is a purpose that fits the capabilities of the simulator.

Then, a deep study of Pozo's work was performed in order to comprehend the functionality of the simulator along with the different Matlab variables and functions described in the code. In this way, it was possible to decide which sections of his code were suitable with this project. Finally, some of the functions designed by Xavier have been adapted, such as the calculation of the ISLs and their definition in the simulation scenario. Subsequently, the rest of the code concerning the construction of the constellation, the representation of the flight paths, the communication between the objects in the scenario, the parameters for the visualization of the simulation and the interaction with the user were designed. To perform the necessary calculations in order to determine the geographic coordinates of the aircraft throughout its trajectory, part of the work done by Sergio Prieto in his final thesis was used [2], which details the mathematical solution for the calculation of spherical coordinates.

On the other hand, an analysis of the influence of the orbital design parameters on the constellation performance and the impact they have on other elements such as the launch program design or the mission cost has been carried out.

Finally, a theoretical study has also been carried out regarding the different elements of knowledge essential for the development of the project. Some of these fields of research have been for instance the functioning of different reference systems, basic fundamentals of orbital mechanics, types of orbits and the creation of satellite constellations.

Chapter 4

Air navigation monitoring

4.1 Primary tracking method

Air traffic control is performed by radar tracking, which detects and measures the approximate position of aircraft using reflected radio signals. This tracking methodology permits air traffic control to determine the aircraft position whether or not the subject wants to be tracked. Although this technology works well when aircraft are flying over land areas, when they are crossing long distances over water, rainforests or deserts, radar technology has certain limitations [3]. In addition, radars do not allow aircraft to be monitored below a certain altitude due to the curvature of the Earth. These days, only some of the most modern aircraft are able to uplink GPS data to satellite tracking services. Moreover, such systems are only used in remote areas with no radar coverage because handling large volumes of flight data is expensive [4].

Airplanes have several elements that form the primary tracking method during the flight. The first of them is the transponder, which emits radio signals with information about the aircraft such as identification, air speed and altitude. Before departure, pilots receive a specific four-digit number to enter into their transponder, which is known as the squawk code, identifying that aircraft to air traffic control. The transponder receives an interrogation or request signal from an air traffic control station, which can demand certain pieces of information [5]. Then, it sends back a coded signal containing the demanded information. This way, radar stations can determine the aircraft speed and direction by monitoring successive transmissions.

On the other hand, aircraft also carry a GPS. However, this device is not used to share the location of the airplane with traffic control, instead, it is used to track the position of the aircraft itself. For this reason, the location of airplanes is only known through radar tracking from the ground and as a consequence, when they move away from the radar range of view, their position cannot be detected.

In order to improve the communication system of airplanes, some new technologies have been installed during the last few years. This is the case of the ADS-B system (Automatic Dependent Surveillance–Broadcast), a new method of satellite-based tracking in which the aircraft transmits its position to other aircraft and ground-based receivers [3]. This technology has opened up coverage in areas where it was previously limited, for instance in remote areas or regions where the installation of a radar antenna is not feasible, and therefore, it allows a more efficient aircraft routing and spacing. As a result, air traffic control can track the aircraft's position even when they are flying over the ocean. Furthermore, it has allowed aircraft to fly safely with the most optimum and fuel-efficient flight profile [5]. The implementation of the ADS-B system in the aviation sector has allowed airlines to have access to real time data such as flight routes, position, speed, height, direction and the model of the aircraft. In fact, flight tracking websites use this information to broadcast the real time flights worldwide [6].

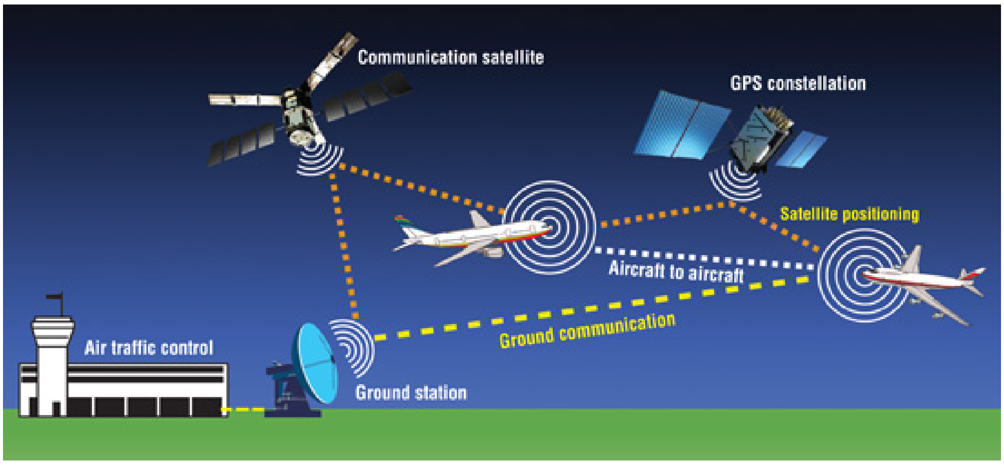

Figure 4.1: ADS-B air traffic control system.

Source: ADSBHub [7]

4.2 Aircraft disappearances

Due to the limitations of tracking technology in the aviation sector, there have been several cases of missing aircraft throughout history. Some of the most recent and well-known are explained bellow.

Air France Flight 447

The 1st of June of 2009 an Air France Airbus A330 disappeared from air traffic control in the middle of the South Atlantic ocean. The plane was carrying 228 people, with 216 passengers and 12 crew members [8]. The flight route was from Rio de Janeiro to Paris, however, the aircraft went missing after four hours of departure and ended crashing into the ocean causing the accident with the largest number of fatal victims in history.

After flying over northeastern Brazil, where the last point of communication was established, the aircraft flew over the Atlantic Ocean in an area without radar coverage. According to the on-board data system, the cabin crew then decided to enter an area of turbulent clouds, instead of surrounding them as usual. As a result, the aircraft's Pitot tubes, elements responsible for measuring its speed, began to freeze [9]. Then, the aircraft began to perform erroneous speed measurements, causing the autopilot system to deactivate. One of the pilots took manual control but, because of the strong sidewinds he made a mistake in trying to stabilize the plane. He increased the angle of attack of the plane causing it to lose speed as they ascended.

As a result, the aerodynamic drag of the aircraft increased until they went into stall and began to fall. The pilots were not in time to recover lift and ended up crashing into the water at great speed.

Figure 4.2: Airbus A330 aircraft model involved in the accident.

Source: Pedro Carvalho [9]

Malaysia Airlines Flight MH370

On March 8 of 2014, a Boeing 777 from Malaysia Airlines suddenly disappeared flying between Kuala Lumpur and Beijing with 227 passengers and 12 crew members. The aircraft disappeared because the cockpit crew did not switched the radio frequency to the one instructed for the approach to the Vietnamese air traffic control [5]. The aircraft transponder was switched off. After more than two weeks of search, the Air Accidents Investigation Branch (AAIB) concluded that the flight crashed in a remote part of the Indian Ocean. The first piece of debris was found on July 29, 2015 in Reunion Island. Afterwards, other components appeared all over the east coast of Africa.

Since the day of the disappearance many theories have been proposed, including the possibility of the pilot's suicide or some form of hijacking [10]. Nowadays, the crash site of the accident and the real reason that caused the aircraft to crash are still unknown. However, a mechanical malfunction was deemed extremely unlikely, therefore, the change of the flight path was assumed to be performed with manual inputs.

These two tragic aircraft accidents remark the importance of developing efficient tracking systems in order to ensure constant and global coverage from air traffic control stations. Either by mechanical failure or by cabin crew error, these accidents could have been avoided by the use of a satellite monitoring system that allows absolute control of the flight conditions of the aircraft without the need to depend on the actions of the pilot or the on-board communication instruments.

4.3 Satellite air navigation

Satellite navigation is being widely used by aviators throughout the world to overcome many of the deficiencies in today's air traffic infrastructure. In contrast to current ground-based equipment, this technology provides continuous, all-weather and four dimensional coverage, which permits accurate aircraft position determination anywhere on or near the surface of the Earth [11]. The implementation of satellite navigation provides significant benefits to the aviation sector. For instance [11]:

- Enhanced safety of flight.
- A service based on common avionics.
- More efficient, optimized, flexible, and user-preferred route structures.
- Reduced separation minimums. resulting in increased capacity and capabilities.
- Precision approach capability.
- Increased landing capacity.
- Reduced fuel consumption.
- Reduced operational costs.

Although aviation is the safest form of transportation, the Federal Aviation Administration (FAA) has a strategic plan to provide the safest, most efficient aviation system in the world for the U.S. National Airspace System (NAS). The FAA initiative is called NextGen, which promotes the use of geospatial technology to enable precision time-management for controlling air traffic. The objective is to increase the safety, efficiency, capacity, predictability and resiliency of aviation [12]. The NextGen system is based on using ADS-B technology to monitor real time data of the status of the aircraft. The system consists on digitally coordinate airplanes in the same area in order to safely reroute air traffic as necessary. Moreover, it can also calculate geospatially the point at which a plane has to begin its descent based upon its altitude, weight, glide slope and distance to the airport [13].

Chapter 5

Coordinate systems

5.1 Earth Centered Inertial System (ECI)

The ECI system, also known as Celestial Reference System (CRS), has its origin in the Earth's center of mass or Geocenter. Its fundamental plane is the mean Equator plane and the X-axis is pointing to the mean Vernal equinox of epoch J2000.0 (Julian Date of the 1st January 2000 at 12:00 h). The Z-axis is aligned with the rotation axis of the Earth or equivalently, to the celestial North Pole at J2000.0. The Y-axis is orthogonal to both X and Z-axis. This system is fixed with respect to the stars because the equinox and plane of the equator move very slightly over time. Therefore, it is an inertial reference frame which is mainly used for the description of satellite's and other celestial bodies' motion.

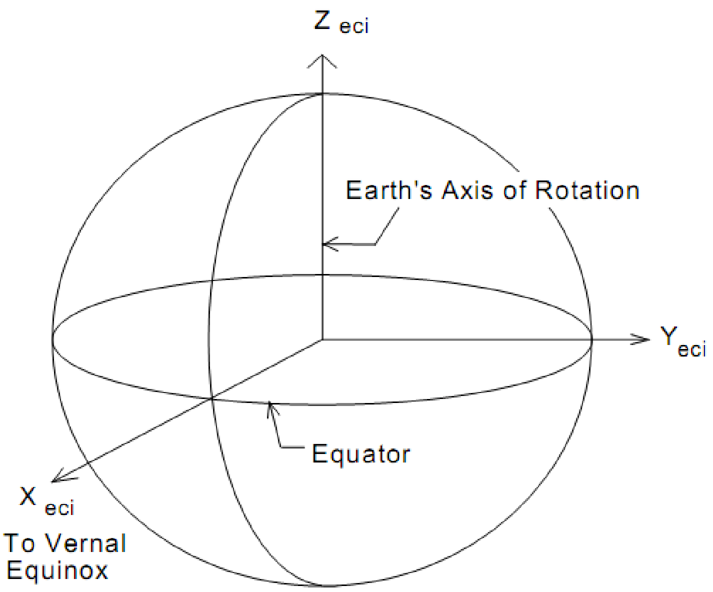

Figure 5.1: Earth Centered Inertial (ECI) Coordinate System.

Source: Gabriel Popescu [14]

5.2 Earth-Centered Earth-Fixed System (ECEF)

The ECEF system is a right-handed Cartesian coordinate system with the origin at the center of the Earth, which rotates with it around its spin axis. The X-axis passes through the Equator and Prime Meridian intersection. The Z-axis is directed along the rotation axis and passes through the North Pole. Then, the Y-axis is orthogonal to the X-axis and Z-axis.

Since the entire ECEF reference frame rotates with the Earth, this coordinate system is useful for positioning geostationary objects such as satellites. In fact, the Global Positioning System (GPS) uses ECEF as it's primary coordinate system [15].

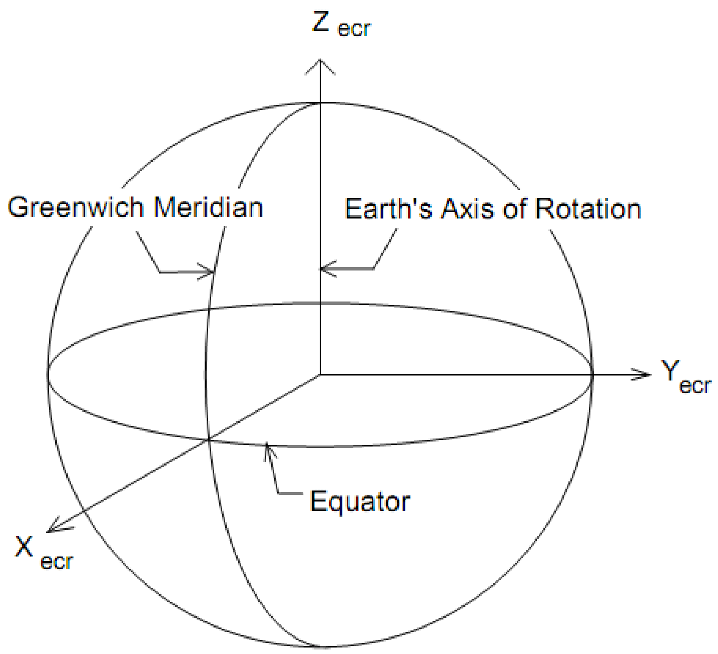

Figure 5.2: Earth-Centered-Earth-Fixed (ECEF) Coordinate System.

Source: Gabriel Popescu [16]

5.3 Geographic Coordinate System

The Geographic Coordinate System is a system that uses a three-dimensional spherical surface to determine locations on the Earth. Latitude and longitude are the units that represent this system and every single point on the surface of Earth can be specified with these coordinates. Both latitude and longitude are measured in degrees, which can also be expressed as a combination of minutes and seconds.

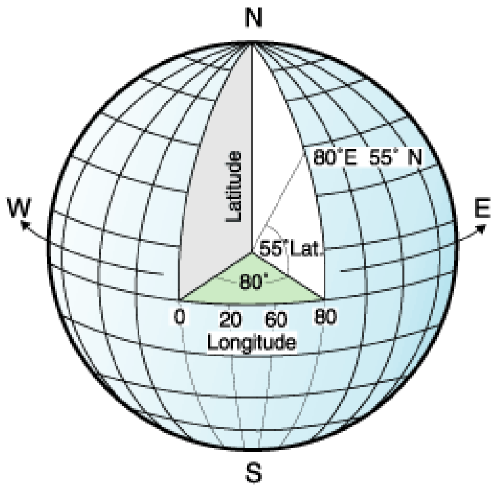

Figure 5.3: Geographic coordinate system.

Source: IBM [17]

Latitude

The latitude is a coordinate that specifies the north-south position of a point on Earth's surface. It is measured from the equatorial reference plane, which passes through the center of the Earth and is represented as lines that run east and west. These latitude lines, called parallels, have a constant latitude value and they are equidistant and parallel to one another. Then, the latitude angle is the one measured between two connecting lines: the line connecting the parallel and the center of the Earth and the line connecting the equator with the center of the Earth. This coordinate is represented with the symbol ϕ and it's range goes from 0° at the equator, to 90° at the North and South poles. Therefore, latitude degrees are usually defined with the letter N at the North hemisphere (positive latitudes) and with an S, at the South hemisphere (negative latitudes), as shown in the next figure:

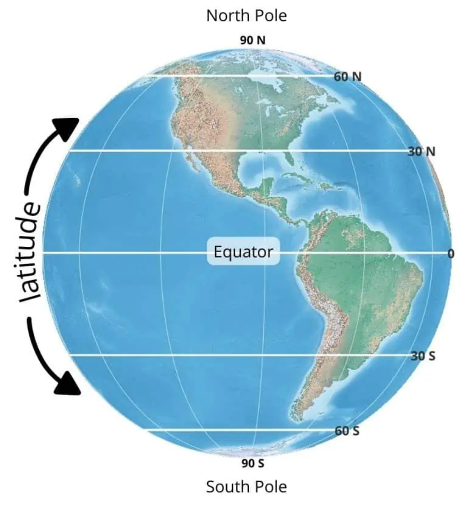

Figure 5.4: Lines of latitude, parallels.

Source: Geography Realm [18]

Longitude

The longitude is a coordinate that specifies the east-west position of a point on Earth's surface and it is represented as half-circle lines that run from the North Pole to the South Pole. These lines are called meridians and they are perpendicular to the equator and every latitude. Longitude is measured from a reference line called the prime meridian, which passes through Greenwich, England, and it has a longitude of 0°. Then, the longitude coordinate is the angle between a meridian and the meridian of Greenwich and it is represented with the symbol λ. Longitudes are measured by up to 180° both east and west of the prime meridian, and are usually defined with the letter E at the eastern hemisphere (positive longitudes) and with the letter W at the western hemisphere (negative longitudes).

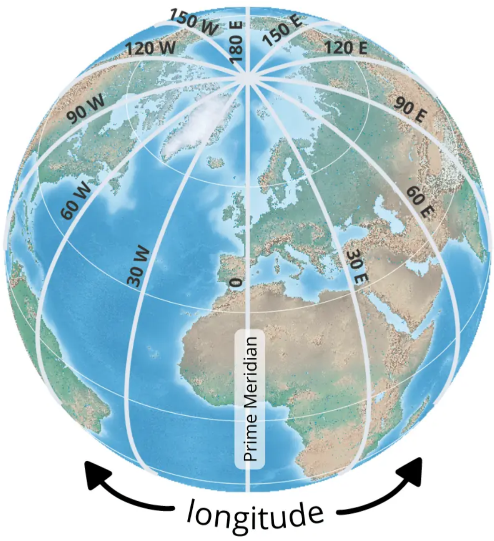

Figure 5.5: Lines of longitude, meridians.

Source: Geography Realm [18]

Chapter 6

Orbital Mechanics

6.1 Kepler's Laws of Planetary Motion

Johannes Kepler, a German mathematician and astrologer born in 1571, determined three laws to describe how planetary bodies orbit the Sun. The scientist had the opportunity to work with the astronomer Tycho Brahe, which gave Kepler the task of understanding the orbit of Mars. After years of research, he eventually realized that the orbits of the planets, based on the Copernican model of the solar system known as heliocentric, were not circles, but ellipses [19].

Kepler's First Law

All planets orbit the Sun in elliptical orbits with the center of the Sun at one focus. Some of the main properties of ellipses are the following:

- The sum of the distances to the foci from any point on the ellipse is always a constant.
- The amount of flattening of the ellipse is called the eccentricity (e) and it goes from 0 to 1, being e = 0 a circular orbit and e = 1 a parabolic orbit.
- The longest axis of the ellipse is called the major axis, while the shortest axis is called the minor axis. Half of the major axis is called the semi-major axis (a) [19].
- The nearest point of the planet's orbit to the Sun is named perihelion.
- The point of greatest separation from the Sun is the aphelion.

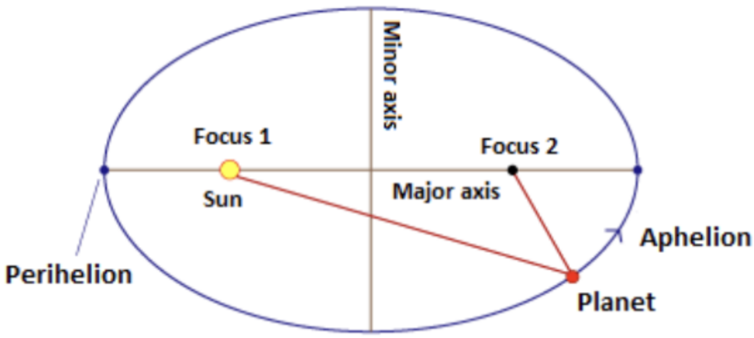

Figure 6.1: Elliptical orbit scheme of a planet.

Source: MyRank [20]

Kepler's Second Law

The imaginary line joining a planet and the Sun sweeps equal areas of space during equal time intervals as the planet orbits [19]. In other words, planets don't move with constant speed along their orbits. The maximum velocity is achieved when the planet passes through the perihelion and on the contrary, the slowest point is at the aphelion.

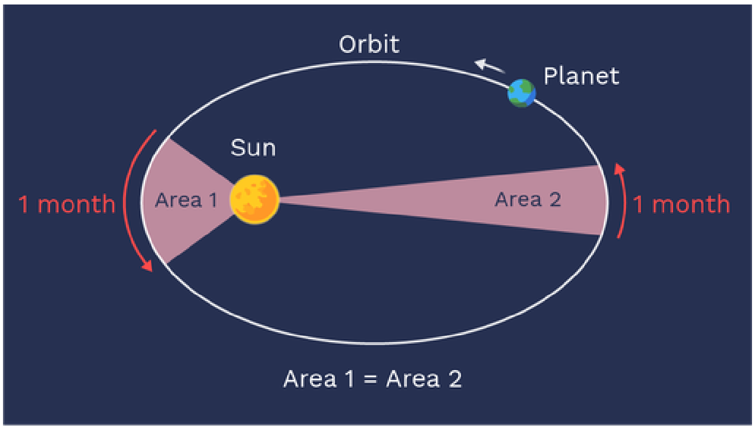

Figure 6.2: Kepler's second law.

Source: Labster Theory [21]

Kepler's Third Law

The square of the orbital period of a planet is directly proportional to the cube of the semi-major axis of its orbit. This law implies that the period for a planet to orbit the Sun increases rapidly with the radius of its orbit. Therefore, the planets closer to the Sun have shorter periods than those located at greater distances. This theorem can be expressed with the next formula:

$$T^2 = \frac{4\pi^2}{GM}a^3$$

Where T is the planet's orbital period, a the semi-major axis of the orbital ellipse, M the planet's mass and G the universal gravitational constant, that has the value of $G = 6.6742 \cdot 10^{-11}\ m^3/(kg \cdot s^2)$.

6.2 Keplerian orbital elements

Kepler's Laws of planetary motion also apply to any celestial body orbiting an object with an elliptical orbit. Since satellites follow elliptical orbits around the Earth, a number of parameters are needed to characterize their orbits uniquely. These are called the Keplerian elements or traditional orbital elements, which are derived from Kepler's Laws. There are six orbital elements that allow to define the shape of the elliptical orbit, orient it around its central body and define the position of the satellite around the orbit.

Semi-major axis (a)

The semi-major axis determines the size of the orbit. It measures half the distance of the major axis of the ellipse. For a circle, it is the radius, while for an ellipse, it describes the width of the ellipse. It can be also defined as the sum of the periapsis and apoapsis distances divided by two.

Eccentricity (e)

The eccentricity describes the shape of an orbit and measures the deviation of the trajectory from a circle. When e = 0 the orbit is circular, for values of $0 < e < 1$ the orbit is elliptical. When e = 1 the trajectory is parabolic and for $e > 0$ the trajectory is hyperbolic [22]. It can be determined as the ratio of the distance between the two foci (c) and the length of the major axis (a).

$$e = \frac{c}{a}$$

Inclination (i)

The inclination describes the tilt of an orbit. It is the angle between the angular momentum vector ($\vec{h}$) and the unit vector in the Z-direction ($\vec{K}$). It is measured in degrees within the range from $0 < i < 180$.

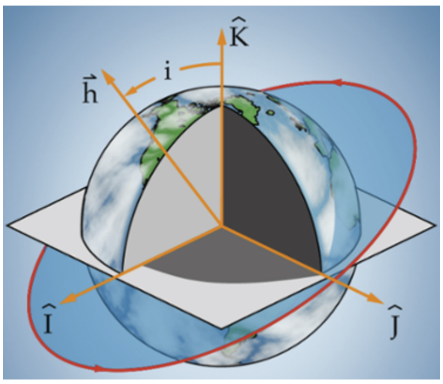

Figure 6.3: Orbital inclination.

Source: Pressbooks [23]

The next figure defines different types of orbits depending on the inclination value.

Inclination	Orbital Type	Diagram
0° or 180°	Equatorial	 prograde orbit shown
90°	Polar	
0° ≤ i < 90°	Direct or prograde (moves in the direction of Earth's rotation)	
90° < i ≤ 180°	Indirect or retrograde (moves against the direction of Earth's rotation)	

Figure 6.4: Types of orbits regarding inclination values.

Source: Pressbooks [23]

Right Ascension of the Ascending Node or RAAN (Ω)

The RAAN indicates the orientation of an orbit. It is the angle measured between the X-axis and the ascending node vector, which is the vector pointing to the location where the satellite passes from the southern to northern hemisphere. The intersection between the orbit's plane and the reference plane of the coordinate system (equatorial plane) is called node line [22]. Then, the ascending node is the point when the spacecraft goes from below to above the reference plane. The RAAN can range from 0° to 360°.

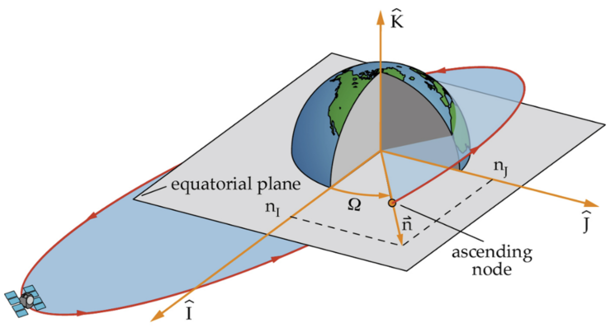

Figure 6.5: Right ascension of the ascending node.

Source: Pressbooks [23]

Argument of periapsis (ω)

The argument of perigee indicates the orientation of the orbit and defines where its perigee is located. It is the angle measured between the ascending node vector $\overrightarrow{n}$ and the location of perigee.

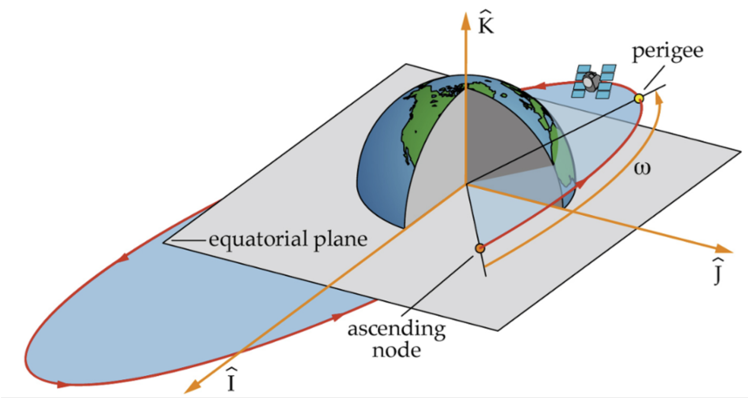

Figure 6.6: Argument of periapsis.

Source: Pressbooks [23]

True anomaly (ν)

The true anomaly indicates the location of the satellite in the orbit. It is the angle measured between the direction of the periapsis and the current position vector to the satellite.

The following figure illustrates all the different orbital elements:

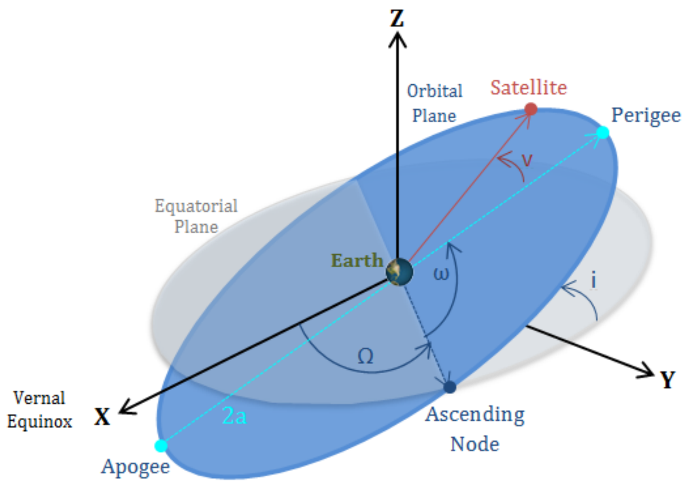

Figure 6.7: Orbital elements.

Source: EUSPA [24]

6.3 Types of orbits

There exist infinite types of orbits depending on the characterization of the Keplerian elements seen in the previous section. Different Earth orbits give satellites varied perspectives, each valuable for different reasons. This is why orbits are usually classified regarding their altitude. Satellites' orbital periods are directly influenced by their altitude. As they orbit closer to Earth, the pull of gravity gets stronger, and satellites move faster [25]. As a consequence, the orbital speed of satellites also increases as the orbital altitude decreases. The most commonly used orbits in satellite communication constellations are listed below:

- **Low Earth Orbit (LEO):** these orbits are relatively close to the Earth's surface, designed with altitudes between 160 km and 1000 km. Satellites in LEO orbits do not need to follow a specific path around Earth, these orbits can be tilted and therefore, there are an infinite number of possible configurations and routes for satellites. For this reason, LEO orbits are very commonly used these days [26], specially for scientific and Earth observation missions. These kind of orbits are mostly controlled by Earth's gravity, that is why satellites have short orbital periods, which usually last between 90 and 120 minutes.

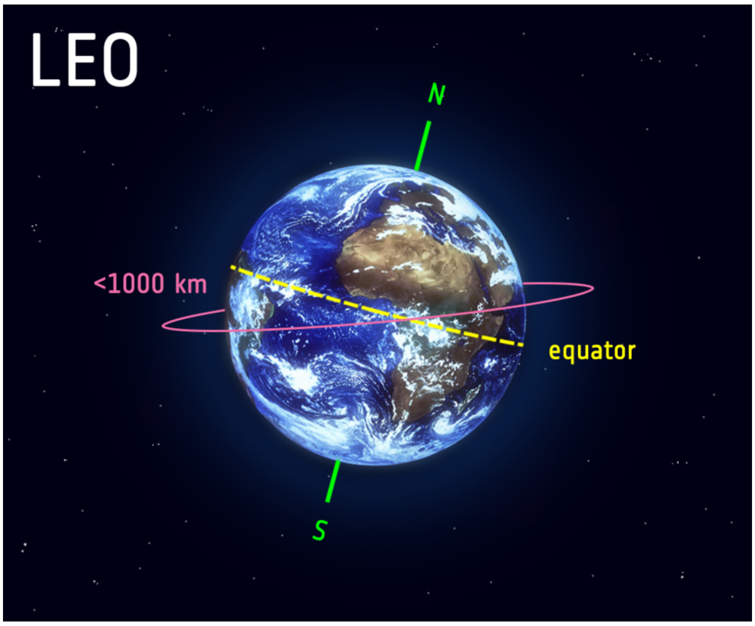

Figure 6.8: LEO orbit.

Source: ESA [26]

- **Medium Earth Orbit (MEO):** MEO orbits are comprised in a range of altitudes between LEO and GEO. Similarly to LEO, satellites do not have to follow specific paths and the orbital planes are also defined with inclination. In this case, the orbital periods are usually set to 12 hours, but they can be defined between 2 and 24 hours. MEO orbits are commonly used for navigation purposes such as the European Galileo system [26].

- **Geostationary Orbit (GEO):** satellites in GEO circle Earth above the equator from west to east following Earth's rotation. The objective of these orbits is to match Earth's rotation in order to be able to place satellites that need to stay constantly above one particular place over Earth, such as telecommunication satellites. To accomplish this, the speed of GEO satellites should be about 3 km per second at an altitude of 35786 km. Moreover, the orbit described must have both eccentricity and inclination equal to zero in order to orbit just above the equator. As a result, the orbital period of satellites is a sidereal day, taking 23 hours 56 minutes and 4 seconds to complete one orbit. This way, since satellites in GEO appear to be 'stationary' over a fixed position, an antenna on Earth can always stay pointed towards that satellite without moving. Therefore, these orbits are used by weather monitoring satellites, because they can continuously observe specific areas to see how weather tends to emerge there. Due to the large distance from Earth's surface of GEO orbits, satellites can cover big areas of territory at once and in fact, only three equally-spaced satellites can provide near global coverage [26].

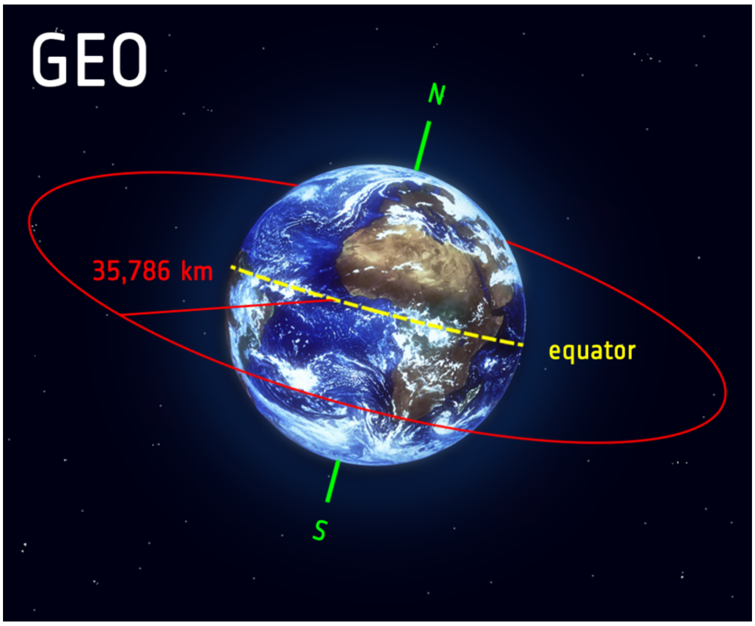

Figure 6.9: GEO orbit.

Source: ESA [26]

- **High Earth Orbit (HEO):** in HEO orbits, satellites are placed in altitudes greater than 35786 km. Consequently, orbital periods last longer than 24 hours. These types of orbits are often used for solar activity monitoring missions. In fact, beyond HEO orbits there are the Lagrange points, where the pull of gravity from the Earth cancels out the pull of gravity from the Sun. This means that anything placed at these points will feel equally pulled toward the Earth and the Sun and will orbit with the Earth around the Sun. These points are really interesting in order to place satellites in stable locations, where they can perform solar monitoring or space exploration operations [25].

The following table summarizes the key characteristics of the orbits explained above, classifying these orbits by altitude.

Table 6.1: Orbit types classified by altitude.

Orbit type	Altitude	Period
LEO	160-2000 km	90 - 120 min
MEO	2000-35786 km	Usually 12 h (2 h $<$ T $<$ 24 h)
GEO	35786 km	1 sidereal day (23 h 56 min 4 s)
HEO	$>$ 35786 km	$>$ 24 h

At first instance, it may seem that the most recommended orbit type for telecommunication missions is MEO, since LEO satellites orbit at high velocities and this prevents them from being able to maintain a prolonged tracking of an object on Earth, besides being difficult to monitor from GS. However, communications satellites in LEO often work as part of a large combination or constellation of multiple satellites to give constant coverage at any point and any time on Earth. In order to increase coverage, constellations made of several of the same or similar satellites are launched together to create a network around the globe that operate simultaneously for the same objective. For this reason, this thesis simulator is designed in order to study constellations that are defined with LEO orbits.

The following section lists some of the main advantages and disadvantages of LEO orbits.

Advantages of LEO orbits

There are several advantages to designing a communication constellation in LEO. Some of them are related to orbital mechanics and others to mission cost and design. However, one of the most important factors is the relevance of the New Space strategy. Currently the international aerospace market is growing rapidly around the concept of the New Space, an initiative that promotes and enhances the integration of private companies and investors into the market with the objective of creating space technology that is simpler, more compact, smaller and therefore more affordable to send missions to space. For this reason, the development of micro-satellite technology has led to the exploitation of the LEO orbit zone, especially for Earth observation and telecommunications purposes.

- LEO satellites operate at high levels of efficiency since they work at low latencies and can perform fast scanning as they are closer to the ground [27].
- Moreover, as the orbit altitudes are low, satellites have low transmission and communication losses. This increases the efficiency of the communications subsystem and ensures fast and secure transfer of data.
- A network of not many LEO satellites can provide global coverage thanks to the symmetrical Walker Pattern configuration, explained later in section 6.4, allowing users to monitor multiple air trajectories at the same time. This way, several airlines would be interested in acquiring the services of the simulator.

- Thanks to its proximity to the Earth's surface, it is cheaper to launch satellites into space, since the rocket requires less fuel consumption to reach the final orbit.
- In addition, the fact of creating a constellation with lightweight cubesats (micro-satellites) makes the payload to be lifted by the rocket even smaller and the mission costs lower.
- As the New Space strategy is quite a new concept, the LEO orbiting area is rather unexplored compared to the GEO region. Therefore, the density of satellites is lower and the risk of collision is reduced.
- Finally, since satellites are close to the surface, when their lifetime is over, a re-entry maneuver is performed towards the Earth. This reduces the accumulation of space debris and the risk of collision.

Disadvantages of LEO orbits

However, there also exist some disadvantages when orbiting at LEO.

- The main drawback of LEO altitudes is that the atmosphere is still quite dense. Therefore, there are a large number of gas particles in those layers of the atmosphere. This leads to several harmful effects for the satellites and the mission.
- The high density of the atmosphere increases the aerodynamic drag on the satellite against its motion. Consequently, satellites are slowed down by this resistance and eventually their orbit loses altitude. On the one hand, this means that the duration of missions in LEO is reduced and on the other hand, to counteract the drag effect and maintain the orbit, propulsive and attitude control systems must be installed, making the mission more expensive [28].
- Moreover, there are some space environment considerations to take into account at LEO. These are atomic oxygen and radiation. Low atmosphere layers have an elevated presence of atomic oxygen, which is a very reactive element that can easily cause erosion and degradation of structural parts and electronic components. In addition, the ionization of gas particles in this area of the atmosphere is also a phenomenon to consider, since radiation particles are generated and they can damage the satellite's electronic elements. Therefore, the payload and the satellite structure must be well covered and protected to avoid damaging the systems and to increase the duration and efficiency of the mission.

6.4 Walker satellite constellations

Satellite constellations consist in a group of satellites operating in unison as a single system to achieve the mission's objective. In this case, the simulator designed for this thesis is developed for communication purposes. For this reason, the simulated constellations must provide global coverage in order to ensure that at any time and at any point on the Earth, there is at least one visible satellite that the aircraft can communicate with.

Walker configurations have been widely used in navigation systems due to its symmetrical distribution and favourable global coverage. This is why this methodology has been selected for this thesis.

There are several methodologies to design a satellite constellation depending on the mission's requirements and objectives. In order to characterize the orbit of the satellites, the Keplerian elements described in section 6.2 are used. In this thesis, the Walker Pattern constellation will be used. This method consists of either a plane or multiple planes, each containing several satellites spaced at different locations [29]. Then, a Walker Pattern constellation is described by three key integers with the following notation [30]:

$$i : T/P/F$$

where

- i: inclination of the orbit
- T: total number of satellites
- P: number of equally spaced planes
- F: relative spacing between satellites in adjacent planes

There are a few considerations in order to design a Walker Pattern constellation correctly:

- The total number of satellites (T) are equally distributed in the defined number of planes (P). Therefore, the value of T must be a multiple of P. Then, the number of satellites per plane is given as:

$$S = T/P$$

- Moreover, the satellites in each orbital plane are distributed in intervals of 360°/S.
- The value of F describes the relative angular spacing between satellites in adjacent planes, such that the change in true anomaly (in degrees) for equivalent satellites in neighbouring planes is equal to [30]:

$$\Delta\nu = \frac{F \cdot 360}{T}$$

- The phasing parameter F can take integer values from 0 to P-1.
- All satellites in the different planes orbit at the same height and with the same values of semi-major axis and eccentricity. In fact, Walker constellations are usually described as circular, with e = 0.
- There are two different types of Walker constellations depending on the range of RAAN defined for the orbit planes. These are the Walker Delta and Walker Star constellations, which are explained below.

Walker Delta

Walker Delta constellations have orbit planes evenly distributed over the full 360° range of RAAN. These kind of constellations are defined with inclined orbits, generally with prograde or retrograde orbits. Therefore, the orbital planes are uniformly distributed around the Earth in intervals of 360°/P.

Walker Star

Walker Star constellations have orbit planes evenly distributed over 180° range of RAAN. In this case, orbits are nearly polar (i = 90°), because otherwise the satellites trajectories would overlap. Then, orbital planes are uniformly distributed in intervals of 180°/P.

Figure 6.10 illustrates the scheme of a Walker Star, Walker Delta and mixed satellite constellation configuration:

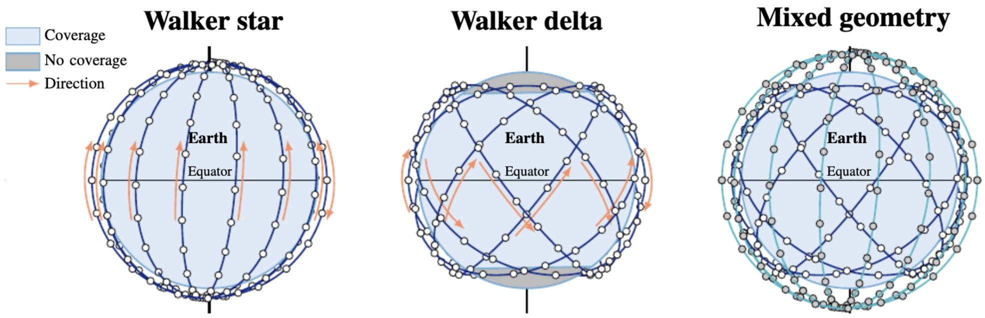

Figure 6.10: Walker Star, Walker Delta and mixed configuration of satellite constellations.

Source: I. Leyva-Mayorga, B. Soret, B. Matthiesen, M. Röper, D. Wübben, A. Dekorsy and P. Popovski [31]

There is another relevant factor related to Walker Star configurations which is the phasing method. This parameter influences the variation of true anomaly of the equivalent satellites in the adjacent planes. The phasing method can be defined in two different ways:

- **Standard phasing method:** this is the regular configuration where the change in true anomaly for equivalent satellites in neighbouring planes increases as $\Delta\nu = F * 360/T$.
- **Alternative phasing method:** this other case consists in changing the true anomaly as a factor of $\Delta\nu = F * 360/T$ every two planes.

In order to understand better how this parameter works let's see an example. Firstly, imagine that a constellation has been defined with the following parameters:

- P = 4
- F = 2
- T = 36
- $\Delta\nu = \dfrac{F \cdot 360}{T} = 20^\circ$

On the one hand, if the constellation has been defined with the standard phasing method, the offset in true anomaly would increase by a factor of 20° for each equivalent satellite in adjacent planes. This means that in plane number 1 the satellite would have 0° of true anomaly, in the second plane 20°, in the third plane 40° and in the last one 60°. On the other hand, if the phasing method was the alternative, the true anomaly offset would be applied alternatively every two planes. In other words, planes number 1 and 3 would have 0° of true anomaly and planes 2 and 4, 20°.

Table 6.2: True anomaly offset for equivalent satellites with the standard and alternative phasing methods.

Plane number	True anomaly in standard (°)	True anomaly in alternative (°)
1	0	0
2	20	20
3	40	0
4	60	20

The following figures illustrate the satellite configuration for both cases:

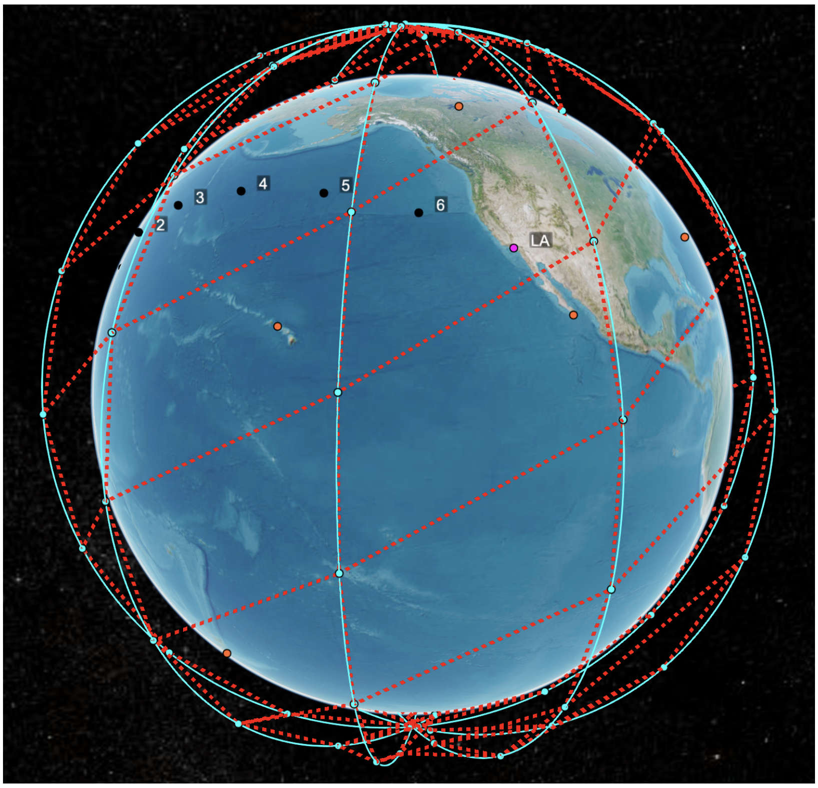

Figure 6.11: Simulation of a Walker Star constellation with the standard phasing method.

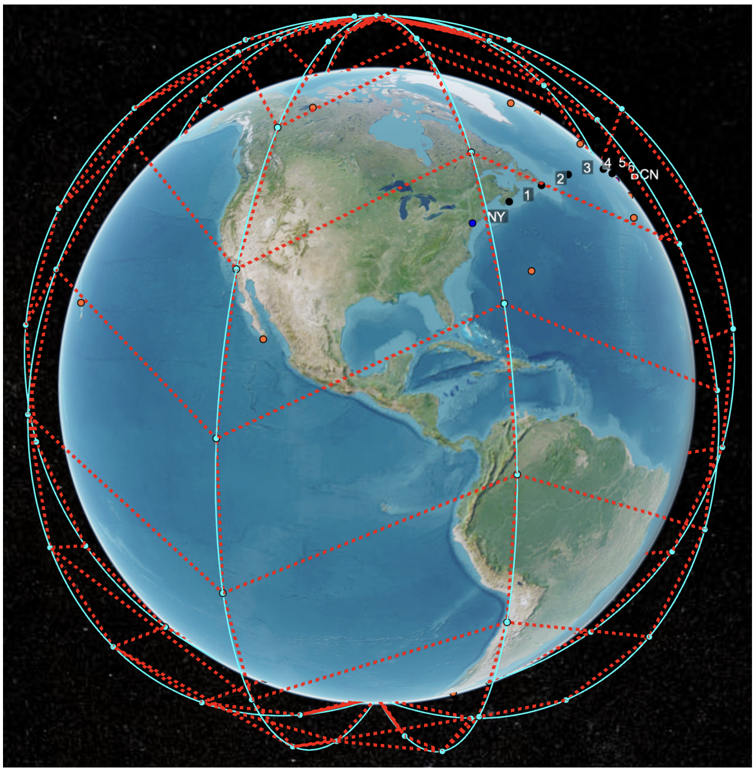

Figure 6.12: Simulation of a Walker Star constellation with the alternative phasing method.

Optimum relative factor (F) calculation

In order to create the most optimized satellite configuration with a Walker Pattern, there is another factor to take into account. As mentioned before, the phasing parameter F determines the relative phasing between satellites in different orbital planes and thereby affects the relative position of the satellites in a constellation [32]. It can only take values within the range from 0 to P-1. However, there is a value of F within the accepted range that makes the constellation more safe and optimized.

Since F modifies the relative position between satellites, the distances between them are affected along with this parameter. In particular, it is important to control the value of the minimum distance between all the satellites of the constellation during the simulation time. Collision between satellites can be avoided if the minimum distance between them is large [33]. In other words, the objective is to determine the constellation with the largest possible minimum distance between cubesats. Therefore, the optimal value of F will be the one that allows to create the constellation with the maximum minimum distance between satellites during the mission [32]. In this way, the constellation reduces to the maximum the risk of collision between satellites for the desired orbital parameters and creates the most optimized and safe satellite configuration.

To determine which is the value of the optimum relative phasing factor, the code developed in this thesis has a function that calculates all the minimum distances between satellites for each possible value of F between 0 and P-1 and then, the simulator defines the final constellation with the factor F that creates the satellite configuration with the maximum value of the minimum distances.

6.5 Operational Walker constellations

Global Positioning System

The GPS constellation is a well-known example of a Walker Delta constellation. It consists of 24 satellites flying in a MEO with six orbital planes, which are spaced 60° longitude apart, and four satellites per plane. This distribution allows the constellation to provide global coverage of the Earth, ensuring the visibility of at least four satellites from any point on Earth [34].

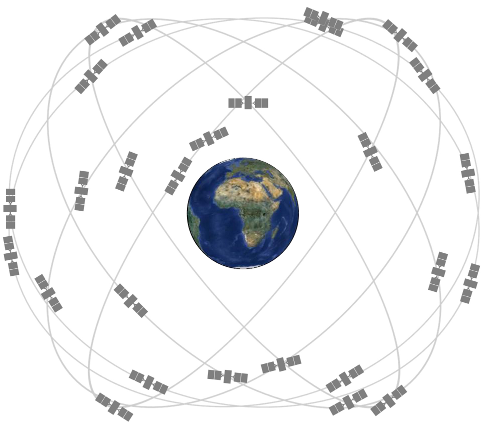

Figure 6.13: GPS satellites distributed with the Walker Delta pattern.

Source: GPS [34]

OneWeb

OneWeb is a LEO constellation designed with 648 satellites distributed in 12 polar orbits with a Walker Star pattern. It provides low latency 5G signal connectivity for costumers worldwide, covering different types of operations such as maritime, aviation and land mobility or government and military actions [35].

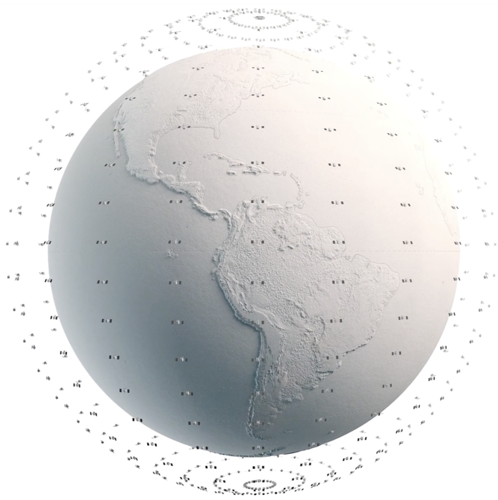

Figure 6.14: OneWeb satellites distributed with the Walker Star pattern.

Source: OneWeb [35]

Chapter 7

Constellation development

7.1 Calculation hypothesis

In this thesis, some computational hypothesis have been defined to develop the satellite constellation and flight trajectories. These are listed below:

- The flight altitude and flight speed of the aircraft have been considered constants with a value of 11000 m ($\approx$ 36000 ft) and 850 km/h (236,111 m/s).
- The flight path of the aircraft is considered to be the shortest one. The origin and destiny points of the trajectory are united by the minimum distance between them. In other words, the real flight trajectories of the determined routes are not considered.
- No drag model has been considered during the simulator development in order to simplify calculations.

7.2 Orbital data

Orbit characterization

- **Orbit type:** the simulator lets the user choose between a Walker Delta or Walker Star constellation configuration. The difference between these two satellite distributions is explained in section 6.4.
- **Orbit height (h):** as justified in section 6.3, the most suitable orbit height for this type of satellite communications mission is LEO. However, the simulator will create the desired scenario with any height value.
- **Total number of satellites (T):** the user must define the number of satellites of the constellation.
- **Number of planes (P):** then, the number of planes must be set. It is important to remark that T must be divisible by P.
- **Orbit inclination (i):** the inclination of the orbits can be defined as a number between 0° and 90°.

- **Phasing method:** in case of selecting a Walker Star configuration, the phasing method between satellites can be defined as *standard* or *alternative*. The properties of both methodologies are explained in section 6.4.

Orbit Propagator

The simulator uses a model of an orbit propagator in order to describe the motion of the satellites and determine their position and velocity in every instant of time. An orbit propagator is a solver that calculates the position and velocity of an object whose motion is predominantly influenced by gravity from celestial bodies [36]. The Matlab function that creates the satellites during the simulation can accept three types of propagator models when satellites are described with Keplerian elements. The following orbit propagation definitions extracted from [36] are accepted by the simulator:

- **Two-Body-Keplerian:** This propagator is based on the relative two-body model that assumes a spherical gravity field for the Earth and neglects third body effects and other environmental perturbations.
- **Simplified General Perturbations-4 (SGP4):** The SGP4 orbit propagator accounts for secular and periodic orbital perturbations caused by Earth's geometry and atmospheric drag, and is applicable to near-Earth satellites whose orbital period is less than 225 minutes.
- **Simplified Deep-Space Perturbations-4 (SDP4):** The SDP4 orbit propagator builds upon SGP4 by accounting for solar and lunar gravity, and is applicable to satellites whose orbital period is greater than or equal to 225 minutes.

For this thesis, the selected orbit propagator is the SGP4 model. This is because it is the one that suits better with the simulator orbital properties. By comparing the three models, since the two-body-Keplerian only considers the influence of Earth's gravity it is clearly the least accurate. Then, regarding the orbital parameters of the satellite constellations of this project, which are defined in LEO altitudes, the cubesats have an orbital period less than 225 minutes. Moreover, these orbits are relatively close to the Earth's surface, in an area where the atmospheric layer is quite dense. Therefore, it is interesting to take into account the impact of the aerodynamic drag generated by the atmospheric gases on the satellite. Since it has been decided not to add any drag model in the rest of the calculations of the project, this orbit propagator model will bring some more reality to the simulation. In addition, the SDP4 model takes into account the effect of the gravity of third celestial bodies such as the Moon, which is not a very influential parameter in LEO. Therefore, the most suitable propagator for this simulator is the SGP4.

7.3 Satellite to Ground Station link

The ground segment of a space mission is as important as the space segment (including the onboard segment and the launch vehicle). Therefore, it is essential for the success of the mission to have a network of ground stations to ensure the optimum functioning and tracking of the satellites. From the ground segment, mission control, command and information transfer, data post-processing and satellite status monitoring operations are performed.

For this thesis, a study of the space market has been carried out with the objective of finding the ground segment company that best suits the mission's operations. In this way, it has been possible to evaluate the performance of the simulated constellations with a global network of ground stations in real operation. Finally, the company selected to perform the ground communication tasks for this project is Leaf Space.

7.3.1 Ground Segment - Leaf Space

Leaf Space is an Italian aerospace company dedicated to the construction and management of ground stations for monitoring space missions. The company was established at the Polytechnic University of Milan in 2014 with the aim of creating a network of ground stations at global level oriented to the control and monitoring of small satellite operations. Its technology is oriented to collaborate with missions of the New Space initiative [37]. New Space missions are performed with nano-satellites in the LEO region of the atmosphere, which fits the operational conditions of this project.

Leaf Space has designed its antenna network in such a way as to achieve the greatest efficiency and safety during its operations. To accomplish this, they analyzed the types of orbits and satellites to be supported and determined that the most efficient network was to distribute the antennas in different locations around the world, instead of working from high latitudes at the poles. In this way they can support a larger number of satellites, in more different orbits and with fewer ground stations. Consequently, Leaf Space's operational cost is reduced and the price of the service for customers is reduced as well. In addition, this antenna network configuration creates a redundancy system where multiple connection points to the satellites are available in case an antenna fails. Furthermore, it reduces interference in communications and increases the flexibility of the system to redistribute the connection points [38]. All these factors increase the number of missions that Leaf Space can support.

The company currently supports more than 80 satellites and has participated in 6 launch programs performing vehicle control operations. Some of its main customers and partners include Kleos, D-Orbit, ESA, Astrocast, Pixxel, Kubos, Nano Avionics, among many other international aerospace companies [37].

Leaf Space offers to their customers the use of an international network of ground stations for tracking and monitoring space operations, known as GSaaS (Ground Station as a Service). One of the company's product offerings, called Leaf Line [39], is a multi-mission GSaaS system for customers with need for high flexibility, fast service delivery, daily mission contacts, low latency and better pricing.

In order to define the best service from Leaf Space, Mireia Colina, Vice President Of Commercial Sales at Leaf Space, has been contacted. After some meetings where the idea and the objectives of this project were presented to her, Mireia assured that the company's operations are in line with those of this thesis and that Leaf Line's service is perfect to perform the mission control tasks for the project. In addition, she provided the necessary data of the antenna network that the company will have by the end of 2023, information that is not yet on the company's website. Leaf Line will have a network of 21 ground stations around the world.

The distribution of these antennas is shown in the figure bellow:

Figure 7.1: Leaf Space international ground station antennas network plan for 2023.

Source: Mireia Colina from Leaf Space

Then, the geographical coordinates and altitude of these antennas has been introduced in the simulator in order to provide global monitoring of the constellation. Figure 7.2 shows the ground stations map created with the simulator.

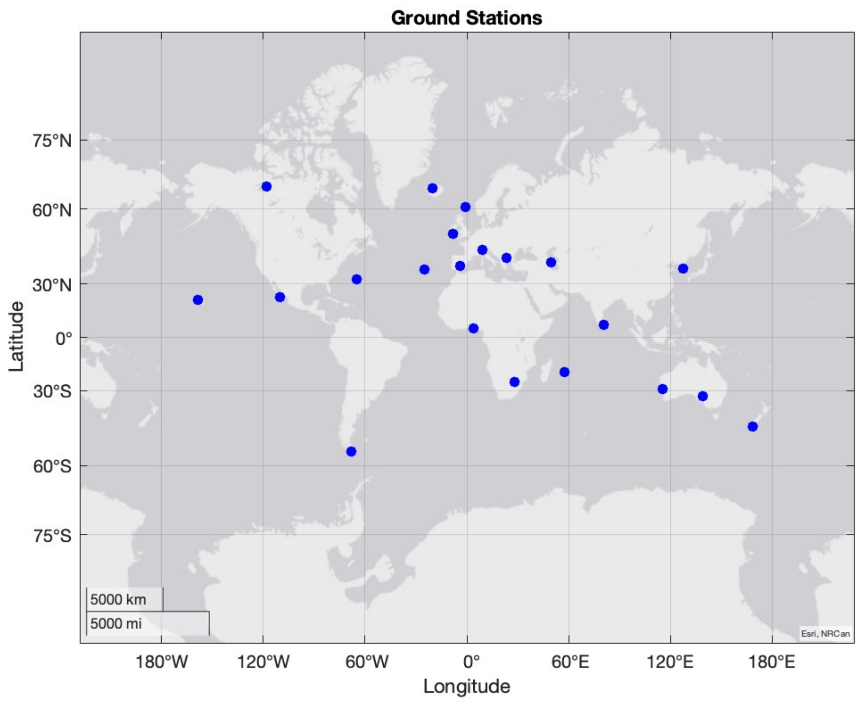

Figure 7.2: Map with the geographic coordinates of the Leaf Space ground stations introduced in the simulator.

7.3.2 Minimum elevation angle

The definition of the communication links between satellites and ground stations depends on the geometry of the constellation while the simulation is moving forward. Ground antennas can only establish communication with satellites when they are seen above the ground station's horizon plane, which is considered tangent to the Earth's surface at the location of the observer antenna.

In order to determine the position of satellites, the azimuth and elevation angles are used. These parameters are the two coordinates that define the position of a celestial body (sun, moon or satellite) in the sky as viewed from a particular location at a particular time [40]. On the one hand, the azimuth (Az) is the angle between a celestial body and the North, measured clockwise around the observer's horizon. It determines the direction of the celestial body. On the other hand, the elevation angle (El) is measured as the vertical angular distance between a celestial body and the observer's local horizon, which is also called the observer's local plane [40]. Then, the azimuth and elevation angles range from 0° to 360° and from 0° to 90°, respectively.

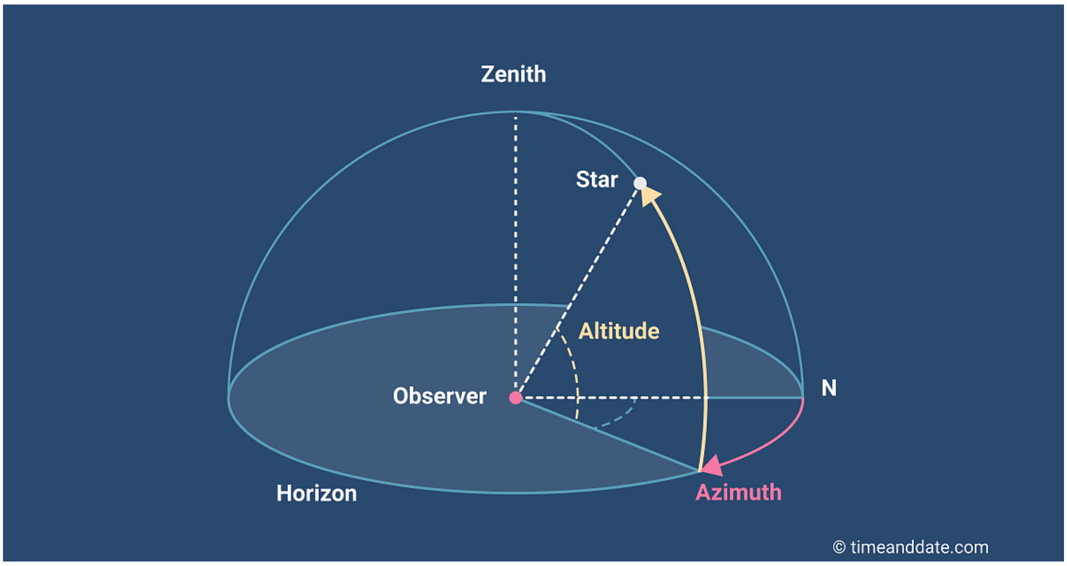

Figure 7.3: Horizon plane, azimuth and elevation angles representation.

Source: Konstantin Bikos [41]

When the satellite is located exactly at the horizon plane, the value of $El = 0°$. Therefore, the objective is to determine the satellite's elevation angle with respect to the antennas in order to determine the visibility of both objects. Antennas will only communicate with satellites when they are moving through the visibility region described for the mission. The ideal horizon plane for ground antennas would be in fact the visibility region under 0° of elevation angle. However, due to the presence of natural barriers or too high buildings in urban areas, the practical horizon plane differs from the ideal one. This is why ground segment antennas are usually placed in remote and lowland areas, far from big buildings and other natural interferences.

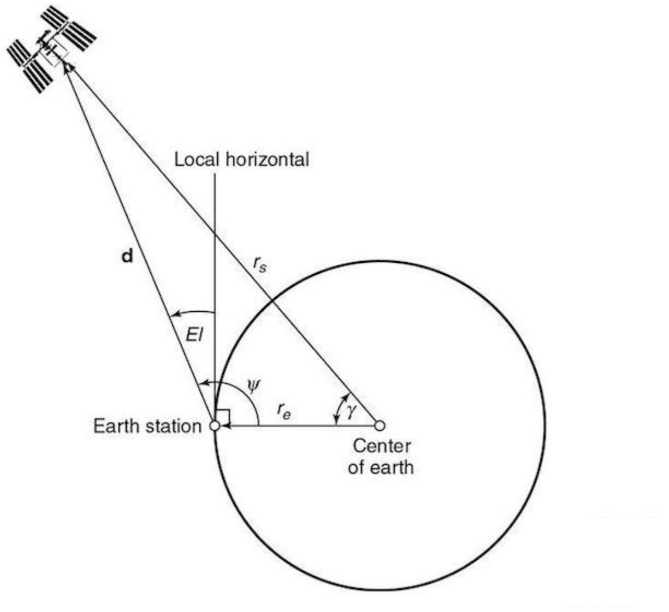

Figure 7.4: Ground station's elevation angle geometry.

Source: ISSOT [42]

Furthermore, the duration of the visibility periods and so the communication duration varies for each satellite pass at the ground station [43], since LEO satellites move too fast over the Earth and the distance between the antenna and all the satellites in the constellation will be different, depending on the orbital plane where they are located.

The antennas used by Leaf Space are defined with a minimum elevation angle, which delimits the acceptable visibility region for each GS. According to Mireia Colina, the optimal minimum elevation angle is 10°. In this way it is possible to define an adequate communication region to avoid interference with other objects on the Earth's surface. It is important to mention that the value of the minimum elevation angle has no influence on the power requirements for the antennas or other factors such as noise in data transmission.

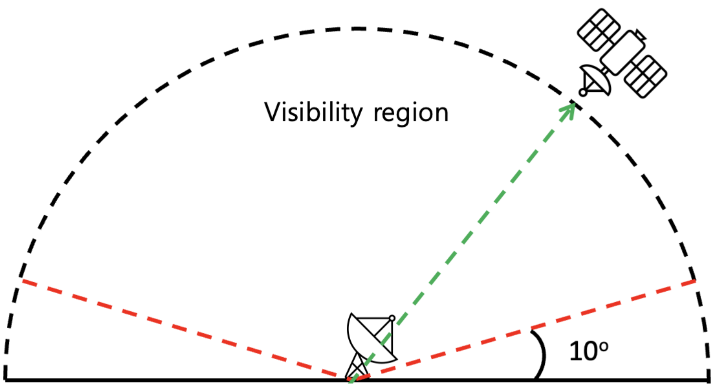

Figure 7.5: Visibility region for Leaf Space's antennas.

Finally, once all the ground stations are uploaded to the simulator with the value of the minimum elevation angle defined, the communication links between satellites and GS can be determined. The following figure shows the visual representation of the communication links between satellites and a series of Leaf Space ground stations, which are defined in green.

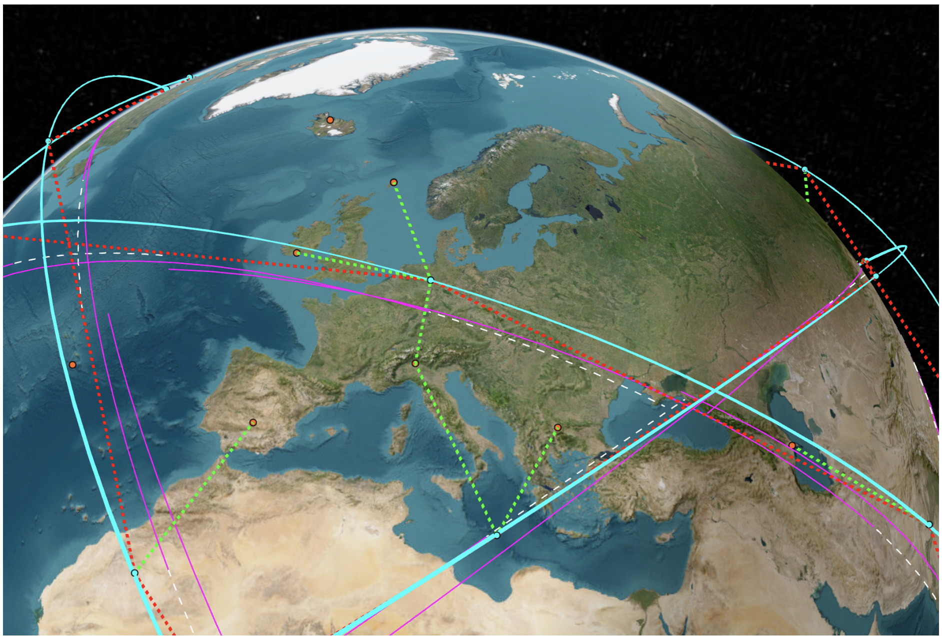

Figure 7.6: Simulation of the satellite to GS communication links.

7.4 Inter-satellite links

The design of the satellite's configuration is a critical factor for the construction of a mega-constellation system in LEO. Two essential aspects to take into account for the cubesat's distribution is collision avoidance and global coverage. Therefore, in order to maximize the minimum distance between satellites, the simulator calculates the optimum relative phasing factor, as explained at the end of section 6.4. Moreover, the number of satellites in the constellation must ensure global coverage at any time and any point on Earth's surface. The more uniformly the satellites are scattered across the celestial sphere, the better for rapid coverage over large areas [44]. In contrast to communication between satellites and GS, not all satellites in the constellation can communicate with each other. In order to determine the visibility between two satellites of the constellation, a geometrical model has been used. In this thesis, two different methodologies have been defined to establish the communication links between cubesats, which are detailed below. The definition of these linking methodologies in the simulator is extracted from X. Pozo's thesis [1].

7.4.1 Visibility calculation

As a consequence of constructing the constellation in LEO, the relative position between satellites changes rapidly. Therefore, the communication periods of ISLs between cubesats in different orbital planes are usually of short duration. As a result, frequent link switching occurs. This increases the complexity of the inter-satellite communication network, which must be well defined to ensure efficient operation. In addition, the fast speed of the satellites makes guidance and tracking operations more complex.

Figure 7.7 shows the geometry problem of the ISLs visibility:

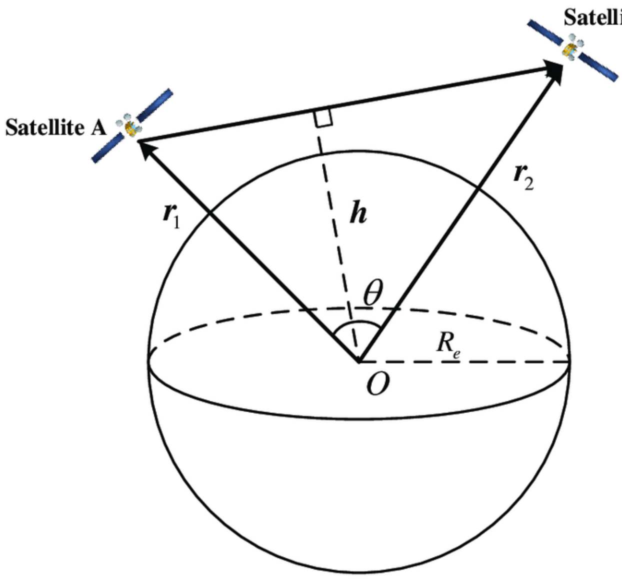

Figure 7.7: Inter-satellite visibility geometry.

Source: Lu Jia, Yasheng Zhang, Jinlong Yu and Xuan Wang [44]

The position of satellites A and B is defined by vectors $\vec{r}_1$ and $\vec{r}_2$, respectively. The objective is to determine the distance between both satellites, which will be defined as δ, and the distance h, which is perpendicular to the line that connects both satellites and passes through the center of the Earth (O). In order to establish an ISL between satellites A and B, the value of h must be greater than R_e, which is the Earth's radius. The value of h can be defined as follows [44]:

$$h = \frac{|r_1| \cdot |r_2| \cdot sin\theta}{\|r_1 - r_2\|}$$

The definition of the visibility status between two satellites is based on the calculation of the distance between a point and a line. The following figure represents an scheme of the geometry of the problem.

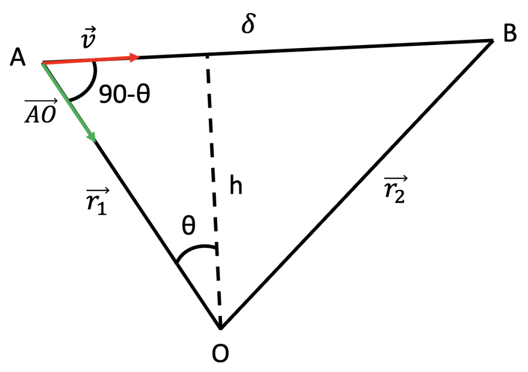

Figure 7.8: Visibility calculation scheme.

The next calculations are performed considering an ECI coordinate system. Taking the points A and B, which are the instant positions of satellites A ($\vec{r}_1$) and B ($\vec{r}_2$) at the moment of the calculation, respectively, the director vector of the line that joins them can be defined as $\vec{v} = \vec{r}_2 - \vec{r}_1$, where $\vec{r_1} = (x_A, y_A, z_A)$ and $\vec{r_2} = (x_B, y_B, z_B)$.

Then, defining the vector $\vec{AO}$ that joins the satellite A with the center of the Earth, the following vector product can be obtained:

$$\|\vec{v} \times \vec{AO}\| = |\vec{v}| \cdot |\vec{AO}| \cdot sin(90 - \theta) \tag{7.1}$$

$$sin(90 - \theta) = \frac{\|\vec{v} \times \vec{AO}\|}{|\vec{v}| \cdot |\vec{AO}|} \tag{7.2}$$

Where $90 - \theta$ is the angle between the line δ and the vector $\vec{AO}$.

Then, applying the trigonometric rule of the sinus for a rectangular triangle:

$$sin(90 - \theta) = \frac{h}{|\vec{AO}|} \tag{7.3}$$

Substituting Equation 7.3 in Equation 7.2, distance h can be obtained:

$$h = \frac{\|\vec{v} \times \vec{AO}\|}{|\vec{v}|} \tag{7.4}$$

Finally, as the satellites' positions are known, the vector $\vec{AO}$ can be defined as $\vec{r_1 O}$ and the distance h is determined as:

$$h = \frac{\|\vec{v} \times \vec{r_1 O}\|}{|\vec{r_2} - \vec{r_1}|} \tag{7.5}$$

If $h < R_e$ there is no visibility between the two satellites and on the other hand, if $h > R_e$, an ISL is created.

7.4.2 Cross linking method

Firstly, the cross link method is one of the most widely used in the satellite telecommunication sector. It consists of establishing four links for each satellite, two intra-plane and two inter-plane ISLs [45]. This way, satellites are able to communicate with the satellites orbiting in front and behind in the same orbital plane, and also with the satellites located to the left and right in the nearest planes.

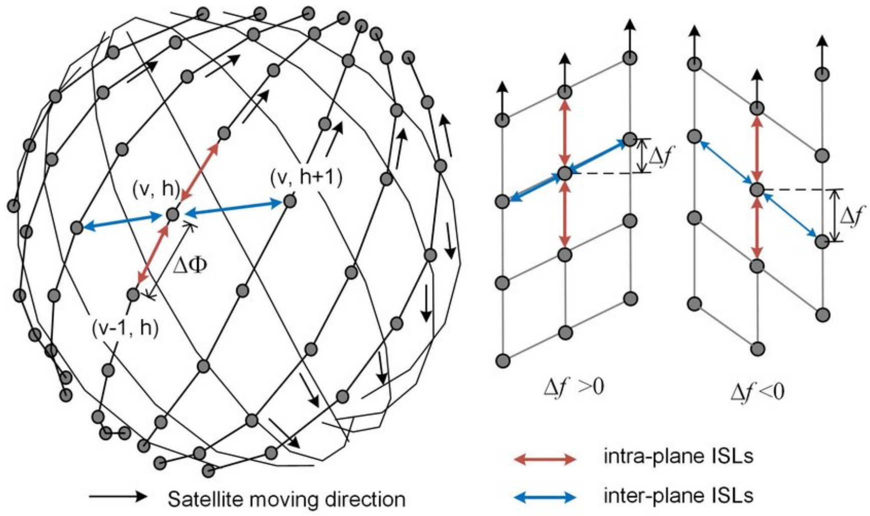

Figure 7.9: Constellation ISLs for the cross method.

Source: Quan Chen, Giovanni Giambene, Lei Yang and Chengguang Fan [45]

The following figures 7.10 and 7.11 illustrate the cross link simulation for a Walker Delta and Walker Star configuration, respectively.

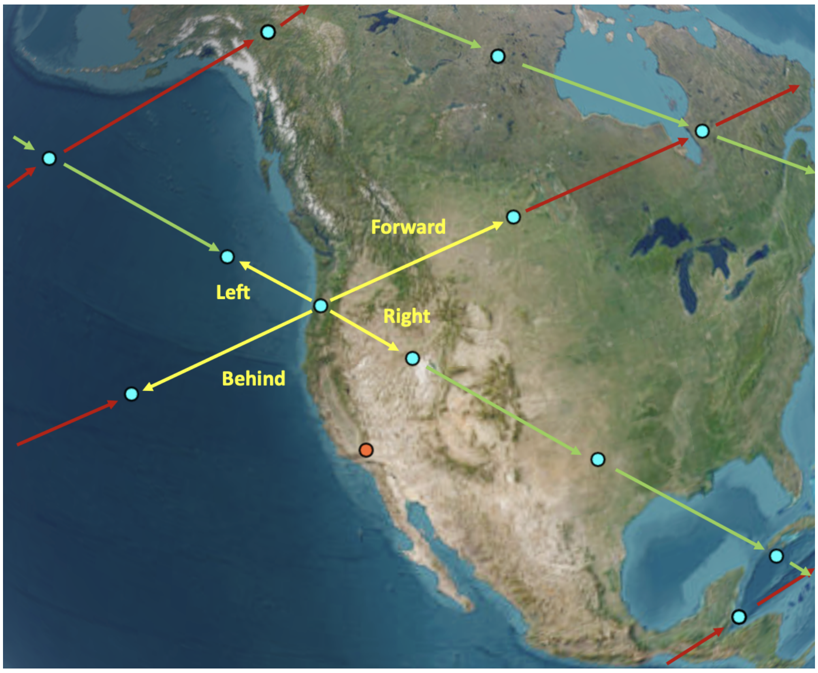

Figure 7.10: Cross inter-satellite linking method for a Walker Delta constellation.

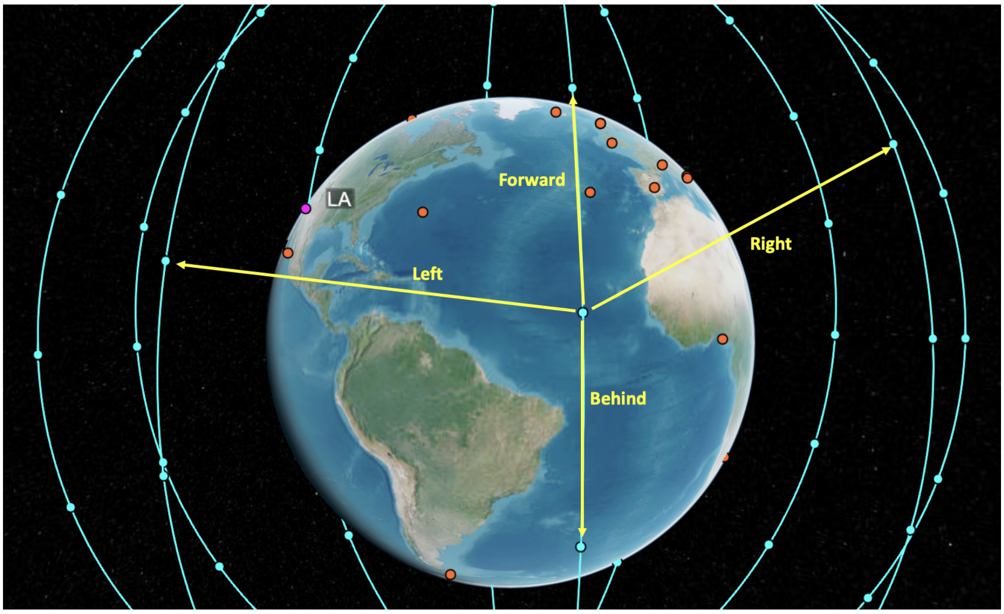

Figure 7.11: Cross inter-satellite linking method for a Walker Star constellation.

7.4.3 Forward-behind linking method

In second hand, the forward-behind linking method has also been defined in the simulator. This method consists of only establishing a communication link with the satellites moving forward and behind in the same orbital plane. In this way, the developed communication matrix for the constellation is simpler and in case of designing a network with a large number of nodes, this method can be sufficiently efficient, achieving global coverage in the same way as with the previous method. This linking configuration also implies a lower cost in power requirements and operational complexity.

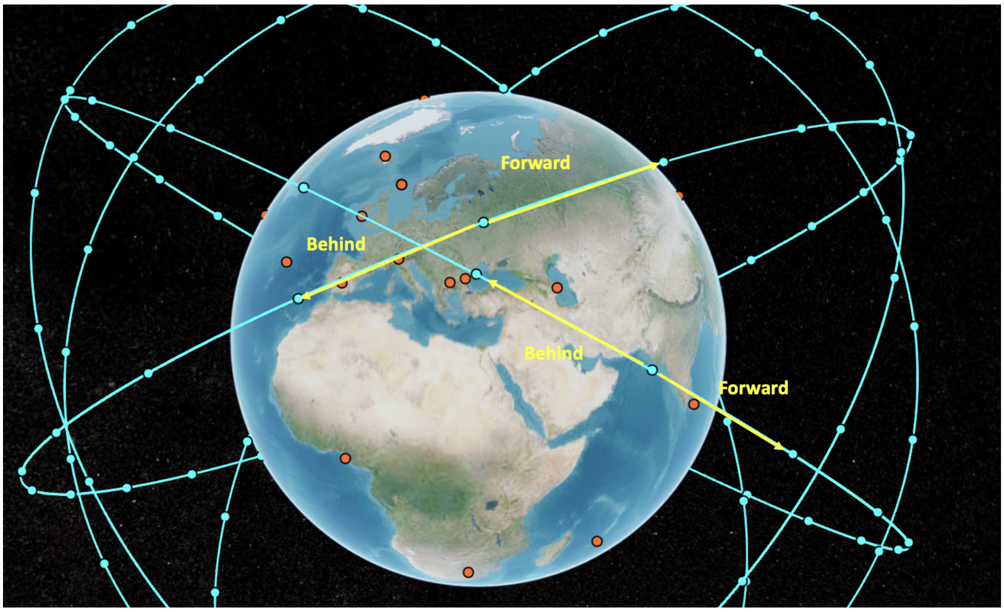

Figure 7.12: Forward-behind inter-satellite linking method for a Walker Delta constellation.

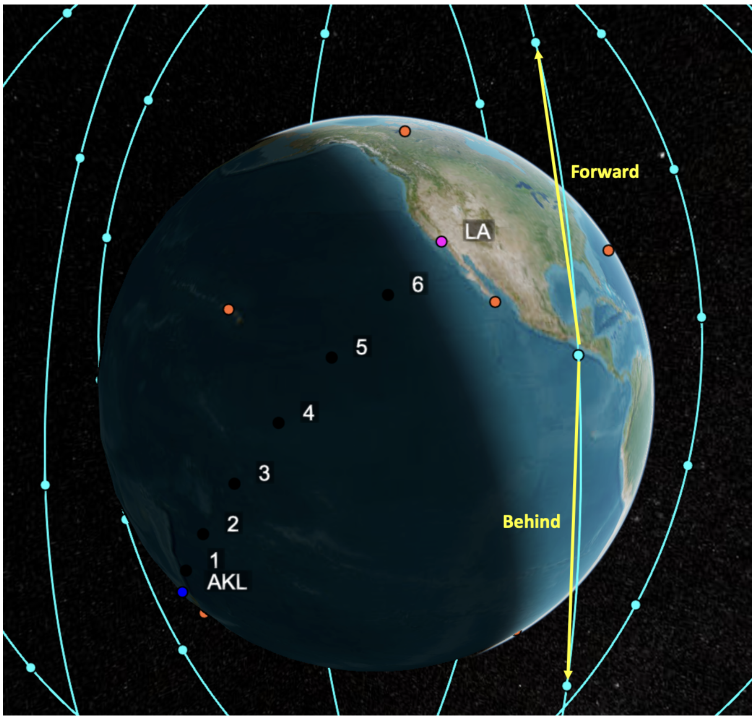

Figure 7.13: Forward-behind inter-satellite linking method for a Walker Star constellation.

7.5 Satellite to aircraft link

The main objective of this thesis is to create a simulator capable of visually representing air navigation routes and the communication links between the aircraft and the satellites of the constellation. However, the Matlab Toolbox that have been used for the development of the simulator only allows the user to generate satellite and ground station objects to the simulation scenario. Therefore, the visual representation of the trajectory described by the aircraft have been defined as a group of ground station objects that together replicate the flight path. Then, the trajectory appears as a discretized domain divided with as many points as the user has defined.

The communication links between the satellites in the constellation and the hypothetical aircraft represented with the series of GS is defined in the simulator in the same way as explained in section 7.3 with the ground segment antennas. The same value of the minimum elevation angle for the trajectory points has been set, being 10°.

The discretization of the flight route has been calculated assuming that the distance between the origin and destiny points is the shortest. This distance is defined as the orthodromic angle or great-circle distance between two points on the surface of a sphere [46]. As mentioned in section 7.1, the aircraft is supposed to maintain the same speed and flight altitude during all the trajectory. Then, the coordinates of the aircraft at any point of the trajectory can be obtained using the theorem of the central angle between two points in a sphere. This calculation methodology uses the geographical coordinates (latitude and longitude) of the origin and destiny points to determine the aircraft coordinates at any time of the simulation. This spherical distance can be mathematically obtained as follows [47]:

Lets define the geographical latitude (λ) and longitude (ϕ) of the origin and destiny points of the trajectory as λ_1, ϕ_1 and λ_2, ϕ_2, respectively. Moreover, the absolute differences between both coordinates can be described as $\Delta\lambda$, $\Delta\phi$. Then, the central angle distance $\Delta\sigma$ between the two points is given by the spherical law of cosines:

$$\Delta\sigma = arccos(sin(\phi_1)sin(\phi_2) + cos(\phi_1)cos(\phi_2)cos(\Delta\lambda)) \quad (7.6)$$

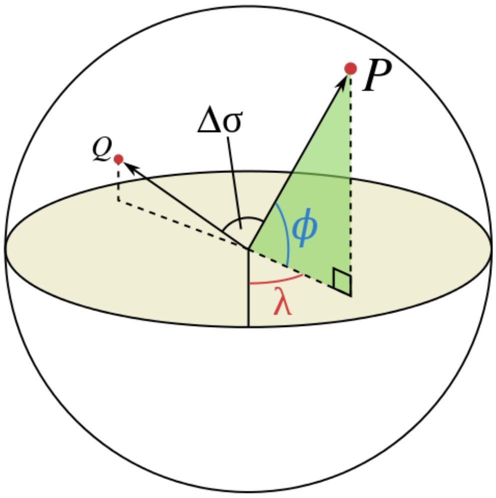

Figure 7.14: Central angle representation.

Source: Wikimedia Commons [47]

Furthermore, the geometrical problem that needs to be solved in order to calculate the coordinates of the aircraft at any point is a spherical triangle. Figure 7.15 illustrates the trigonometry problem. The basic formulas to solve spherical triangles are known as Bessel formulas [48]. To solve the trigonometric problem, the first rule of spherical cosines will be required [49]:

$$cosa = cosb \cdot cosc + sinb \cdot sinc \cdot cosA \quad (7.7)$$

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

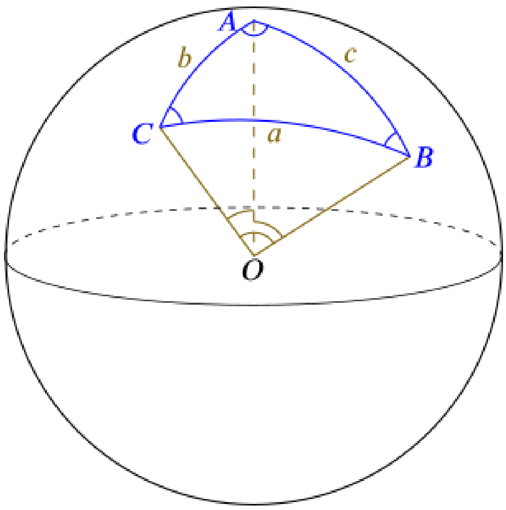

Figure 7.15: Spherical triangle illustration.

Source: Underground Mathematics [49]

Once defined the necessary mathematical rules to solve the geometrical problem, the next calculation process is used to determine the aircraft coordinates at any time in the trajectory.

Lets first define the variables of the problem. Figure 7.16 illustrates the spherical triangle dimensions and angles nomenclature that will be used.

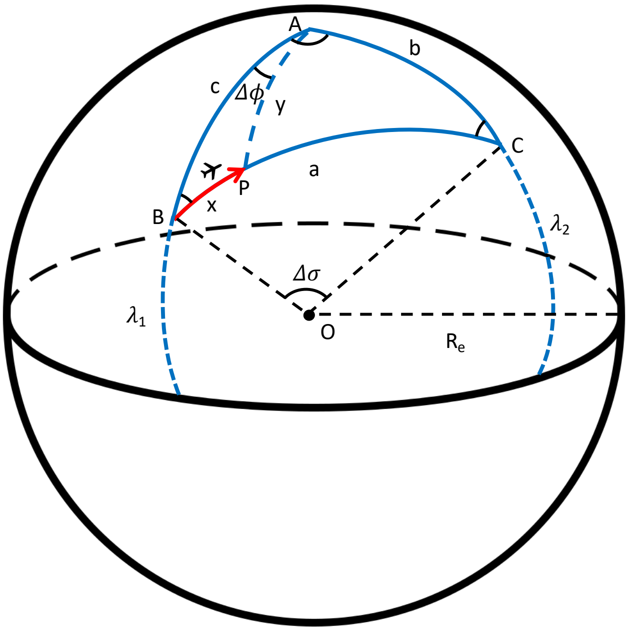

Figure 7.16: Spherical triangle illustration.

Where point A represents the Earth's north pole, points B and C the origin and destiny points of the flight route respectively, point O is the Earth's center and point P the instant coordinates of the aircraft at the time of the calculation.

First of all, distance a can be easily determined using the center angle equation 7.6. Then, both sides b and c of the triangle can be obtained as the differences between the latitude of point A and the latitudes of points B and C.

$$a = \Delta\sigma$$

$$c = 90 - \lambda_1$$

$$b = 90 - \lambda_2$$

Afterwards, the angle A can be determined rearranging Equation 7.7 as:

$$A = arcos[(cosb - cosc \cdot cosa)/(sinc \cdot sina)]$$

Once all the parameters of the triangle ABC are known, the objective is to determine dimensions x and y from triangle ABP in order to find the aircraft location at that time step. Firstly, the angular velocity of the airplane is calculated using its linear velocity (V) and the flight altitude (H).

$$\omega = \frac{V}{R_e + H} \tag{7.8}$$

Then, distance x is obtained in radians according to the angular velocity definition as:

$$x = \omega \cdot \Delta t$$

Where Δt is the time interval from the start of the simulation to the time when the aircraft reaches point P. Next, distance y is determined with Equation 7.7:

$$y = arcos[cosc \cdot cosx + sinc \cdot sinx \cdot cosA]$$

The latitude of the aircraft at point P is obtained as:

$$\lambda_P = 90 - y$$

Then, the longitude increment from the origin to point P $\Delta\phi$ is calculated:

$$\Delta\phi = arcos[(cosx - cosc \cdot cosy)/(sinc \cdot siny)]$$

Finally, the longitude of the aircraft at P is determined differing two cases:

- If $\phi_1 \geq \phi_2$, then $\phi_P = \phi_1 - \Delta\phi$
- If $\phi_1 < \phi_2$, then $\phi_P = \phi_1 + \Delta\phi$

The final representation of the aircraft trajectory in the simulator is illustrated in the figure below, where a number of six discretization points, apart from the origin and destiny, have been set.

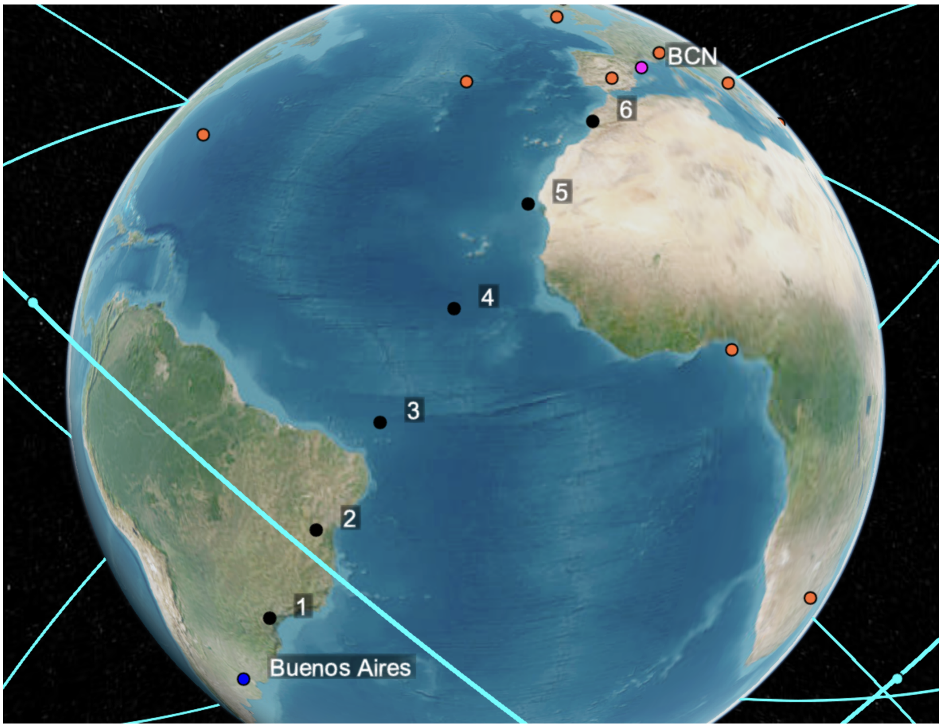

Figure 7.17: Simulation of a Buenos Aires - Barcelona flight route.

Chapter 8

Code development

The purpose of this thesis is to develop a cubesat constellation simulator for air navigation monitoring with the representation of the communication links between the satellites and the tracked aircraft. In order to create a visual representation of the performance of the constellation, a Matlab code has been developed. This simulator is an interactive program that includes several customizable options by the user that are explained in section 8.1. All the necessary code scripts and secondary functions are attached in the annexes of this thesis.

In order to use the simulator, some Matlab Toolboxes must be installed. The following toolboxes are required:

- **Aerospace Toolbox:** it allows the user to create satellite scenarios to model and visualize satellites and constellations, and to perform mission analysis such as line-of-sight calculations with GS.
- **Satellite Communications Toolbox:** it offers tools to analyze links between satellites and includes a link budget analysis app, useful for checking results. It also offers a 3D visualization of the Earth and satellites, where the line-of-sight can be seen.
- **Communications Toolbox:** it includes some useful functions for calculations related to communication systems, such as the calculation of BER (Bit Error Rate) as a function of modulation.
- **Antenna Toolbox:** it offers functions and apps to design, analyze and visualize antennas. It has an extensive antenna catalog and is very useful to obtain important parameters such as beamwidth, gain or radiation patterns.
- **Phased Array System Toolbox:** it allows to design and simulate phased array and beamforming systems in wireless communication, radar, sonar, and acoustic applications.
- **DSP System Toolbox:** this package provides algorithms, apps, and scopes for designing, simulating, and analyzing signal processing systems. It permits to model real-time DSP systems for communications, radar, audio, medical devices, IoT, and other applications.
- **Signal Processing Toolbox:** provides functions and apps to manage, analyze, pre-process, and

extract features from uniformly and non-uniformly sampled signals.

All these Matlab Toolboxes include a series of unique and specialized functions in order to create satellite scenarios, which are explained in detail in the Appendix A of the Attachments document of this project. Moreover, Appendix B includes a list of the necessary Matlab scripts in order to use the simulator, as well as a brief explanation of their purpose. Finally, all the simulator's Matlab scripts are attached in Appendix C.

8.1 Code functionality

In this section, the code's functionality since the user starts the simulation is explained. The simulator asks the user for a several input options in order to create the desired satellite scenario and visualization parameters. The user must respond by entering the corresponding number that is assigned to the desired response. If the introduced number is outside the range permitted for the question, the simulator will redraw the question until the answer input is correctly introduced.

- **Trajectory selection:** First of all, the code asks the user which air navigation trajectory wants to simulate. The final version of the simulator includes a variety of 15 different trajectories to select.
- **Start time definition:** Secondly, the satellite scenario will be created by defining the date of the simulation. For the start date, the user has the following options:
  - The user defines the start date by entering the desired date.
  - The current computer time is used.
- **Simulation duration definition:** Then, the duration of the simulation is determined. The flight time of the aircraft depends on its velocity. Then, according to the hypothesis defined in section 7.1, the flight time of any trajectory can be determined as follows:

$$t_{flight} = \frac{Distance\ between\ origin\ and\ destiny\ in\ m}{Flight\ speed}$$

- **Constellation type selection:** The next step consists of creating the cubesat constellation. For this, the simulator can create two different types of constellations according to the orbital parameters defined at the beginning of the code, a Walker Delta and a Walker Star constellation. The user is asked to choose one of them.
- **Ground track visualization:** Then, the user is asked if he wants to visualize the ground track of the satellites or not.
- **Trajectory map visualization:** Afterwards, analogously to the previous question, the code asks the user if he wants to plot a map of the chosen trajectory or not.
- **Linking method type selection:** After this, the simulator asks to define the type of linking method between satellites. There are two different available options:

  - Cross: each satellite can establish a communication link with four satellites, located in front and behind in the same orbital plane, and the ones to the right and left in the closest adjacent planes.
  - Forward and behind: satellites can only communicate with the satellites in front and behind in the same orbital plane.
- **Type of visualization selection:** Finally, the simulator asks the user which communication links wants to calculate and visualize. The available options are:
  - All of them: all links between satellites, the aircraft and ground station are represented in the simulation scenario.
  - Satellite to satellite: just links between satellites are visualized.
  - Satellite to airplane: just links between satellites and the aircraft are visualized.
  - Satellite to airplane and satellite to satellite: both links between satellites in the constellation and with the aircraft are represented.
  - Satellite to ground stations: just links between satellites and the ground stations are visualized.
  - Satellite to ground stations and satellite to satellite: both links between satellites in the constellation and with the ground stations are represented.

8.2 User adjustable parameters

The Matlab simulator also has some adjustable parameters which are defined in the *USER CRITICAL ENTRY DATA* section at the top of the code. These critical parameters are the following:

- **Flight velocity (V) and flight altitude (H) of the aircraft.**
- **Number of communication points of the airplane's trajectory (n):** this value defines the number of communication points of the simulation through the aircraft trajectory.
- **Minimum elevation angle (MinEleAngle):** it defines the ground station's minimum elevation angle.
- **Phasing method (Phasingmethod):** the user can choose between *standard* or *alternative.*
- **Number of satellites (T) and number of equally spaced geometry planes (P).**
- **Orbit inclination (I) and orbit height in km (hkm).**
- **Constellation name (ConstName).**
- **Visualization colors:** the user can select the visualization colors of the links between satellites and ground stations, as well as the ground track trail lines. This parameters can be defined inside the visualization secondary functions in the case of the link colors, and in the *GROUND TRACK* section of the main script. The available colors for the simulation are the following: red, green, blue, cyan, magenta, yellow, black, and white.

- **Ground stations file:** the ground stations of the simulator are loaded from an Excel file containing the names and the coordinates of the antennas from Leaf Space. The user could modify this document or even upload a different one if it is of interest from the function *GroundStations.m*.

8.3 Simulation results

The simulator includes different results in addition to the visual representation of the satellite scenario created by the user. Once all the steps explained in section 8.1 are completed, the code returns a series of tables and figures as supplementary results. One of the main objectives of this project is to determine the efficiency of aircraft tracking. To do this, in order to generate the 3D visualization, the code creates the communication links between the different objects chosen by the user. Next, the different communication intervals that are carried out throughout the simulation are registered in a table. Depending on the option selected, different tables are created to save the ISLs, links between satellites and the airplane, and the communication between satellites and GS. In addition, these results are automatically saved on the user's computer. It is important to mention that the monitoring efficiency will only be determined for the visualization cases that include the aircraft, since in the other cases such links are not generated. The following table illustrates an example of the information that is recorded in these tables:

Table 8.1: Communication links table example.

Source	Satellite 5
Target	Spain
Interval Number	2
Start Time	14-Jun-2023 20:58:22
End Time	14-Jun-2023 21:02:22
Duration	240
Start Orbit	3
End Orbit	3

This example represents a communication link that has been established between the satellite number 5 of the constellation and the GS antenna in Spain. In this case, it is the second communication interval that these two objects are performing. Moreover, the table indicates the start and end time of the connection, as well as its duration in seconds. Finally, it is also registered the number of the orbit where the communication begins and ends.

Afterwards, from this information the simulator determines which are the satellites that establish connection with each point of the discretized flight path. The trajectory is divided into n user-defined discretization points. Therefore, the simulation time is also divided into n intervals that define the time ranges associated with each point of communication of the trajectory, which are defined as GS objects as explained in section 7.5. To do this, the simulator analyses all the connections registered in the tables mentioned before between the satellites and the aircraft and selects the ones that are performed within the ranges associated with each point in the path. The following figure illustrates an example of the communication links performed during the simulation:

	1	2	3	4	5	6	7	8
1	1	1	1	1	1	0	0	0
2	1	1	0	1	0	0	0	0
3	0	0	1	1	1	1	0	0
4	0	0	1	1	1	1	0	0
5	0	0	0	0	1	1	1	1
6	0	0	0	0	1	1	1	1
7	0	1	0	0	0	0	1	0
8	1	0	0	0	0	0	1	1
9	0	0	1	0	0	0	0	1
10	0	0	1	0	0	0	0	1

Figure 8.1: Communication links between satellites and GS for each trajectory point.

In this case, a constellation with 10 satellites and 8 discretization points (n=6 plus origin and destiny points) have been defined. Columns represent the GS associated with each point on the path and the rows represent the satellite number. Boxes with a 1 indicate combinations of objects that establish communication within the required interval. This table is named as *visits_true* in the simulator.

Moreover, the simulator saves in the user's computer another table with a summary of the configuration parameters defined in the scenario and the results of the tracking efficiency of the simulation, which is called *constellation_data.mat*. It also contains the value of the optimum phasing factor (F) calculated for the constellation. An example can be seen in table 8.2:

Table 8.2: Summary table with the constellation parameters and efficiency results.

Const. Name	**Traj.**	**Const. Type**	**Link Method**
Walker Delta	8	1	1
T	**P**	**I**	**F**
25	5	50°	4
hkm	**n**	**Min. El**	**Start Date**
500 km	6	10°	14-Jun-2023 21:55:06
Stop Date	**Flight Time**	**Time monitored**	**Efficiency**
15-Jun-2023 11:44:52	829.769 min	345 min	41.516 %

Finally, through all this information, the simulator creates two graphs. The first one represents the time periods where the aircraft is being monitored by the constellation over the flight time, specifying the intervals corresponding to each discretization point. The second chart depicts the visibility windows of each of the satellites individually over the simulation time. In this way, with these two figures it can be analyzed how the aircraft is tracked in every time step. The representation of these graphs will be shown later in the results section 9.

Chapter 9

Results

The objective of this project is to design a simulator capable of determining the tracking efficiency of flight routes of any user-customized constellation configuration. Then, the aim of this section is to illustrate the different capabilities that the simulator has, as well as a comparison of the influence of the different orbital configuration parameters on monitoring efficiency. To do that, seven different scenarios have been simulated.

To begin with, lets define which parameters are of interest in order to study the different ways to increase the tracking efficiency of satellites. First, since the simulator has several different patterns for distributing the satellites in the constellation, three simulations with the same orbital parameters and a different pattern of construction will be simulated. On the other hand, the effect of modifying the minimum elevation angle, the number of satellites, the number of planes and the height of the orbits will be analyzed. Then, the following constellations will be represented:

- **S1:** Walker Star constellation with the standard phasing method.
- **S2:** Walker Star constellation with the alternative phasing method.
- **D1:** Walker Delta constellation with the same parameters as S1 and S2.
- **D2:** Walker Delta constellation with the minimum elevation angle reduced.
- **D3:** Walker Delta constellation with the number of satellites increased.
- **D4:** Walker Delta constellation with greater number of planes.
- **D5:** Walker Delta constellation with higher orbital altitude.

However, in order to analyze the true effect of modifying certain constellation parameters on the tracking performance, it is necessary to establish certain common conditions for all scenarios. Therefore, the same flight route and start date have been set for all simulations. In addition, the height and speed of the aircraft and the number of discretization points of the trajectory will also remain constant. Finally, it has been decided that the inclination of the orbits will be a fixed parameter, since the effect of modifying this variable really depends on the flight path selected. Depending on the geographic coordinates of the origin and destination points, the airplane sometimes flies over latitudes near the poles and others more equatorial. The proper inclination for the constellation depends on the range of latitudes to be covered. The following table summarizes the common parameters for all the simulations:

Table 9.1: Common parameters between all the simulation examples.

Parameter	**Value**
Flight altitude (H)	11000 m
Flight speed (V)	850 km/h
n	6
Inclination (I)	50°
Trajectory	Barcelona - New York
Start Date	11th July 2023 18:30:00
Flight Time	434.83 min

First, the S1 constellation has been simulated with a standard phasing method and with the orbital elements specified in table 9.2. This first example serves also to show some of the capabilities of the simulator, such as the visualization of the ground track of the satellites or the 2D representation the geographical coordinates of the discretization points of the trajectory.

In the figure bellow the ground track of the satellites can be seen, where the magenta lines represent the projection of the satellite's current position on the Earth's surface and the dashed white line is a leading guide that represents the satellite's future path.

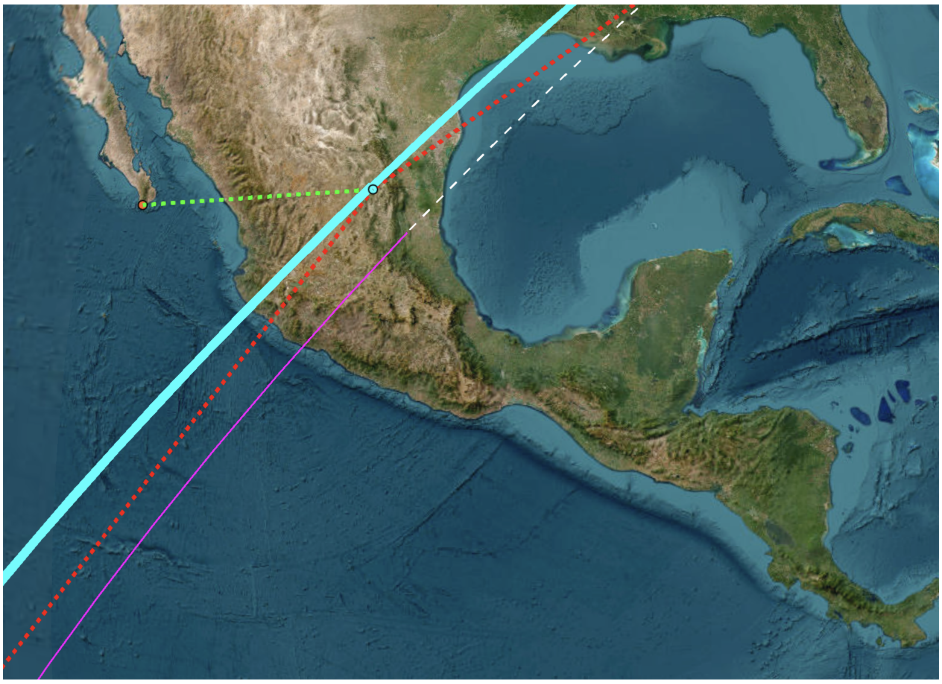

Figure 9.1: Simulation of the ground track of the satellites.

In addition, figure 9.2 represents the different discretization points of the trajectory, locating them on a geographical coordinate system.

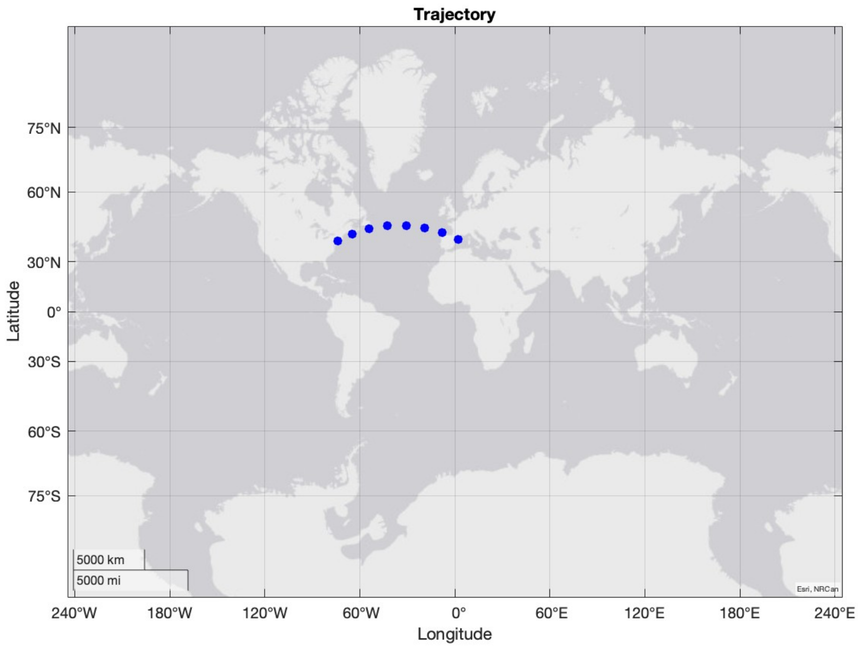

Figure 9.2: Trajectory map for the Barcelona - New York flight route.

Furthermore, for this simulation the first visualization option has been selected, which allows to visualize all the communication links simultaneously.

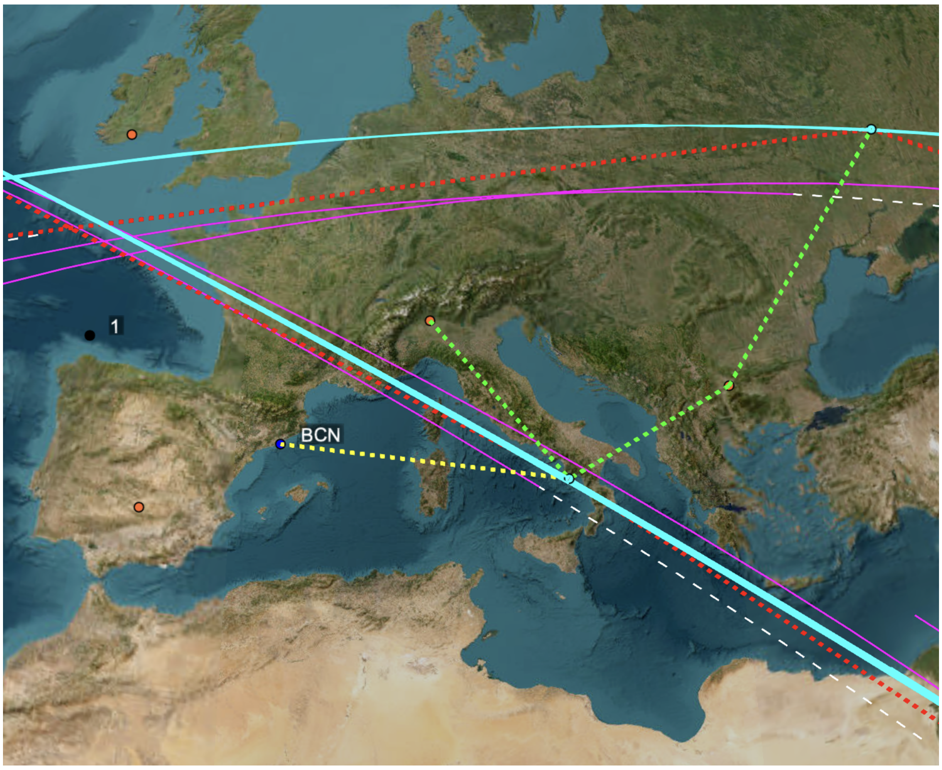

Figure 9.3: Communication links visualization.

Figure 9.3 shows a satellite establishing the following communication links:

- Satellite-Aircraft: connection with the aircraft at the trajectory's origin, Barcelona, shown in yellow.
- Satellite-Satellite: two ISLs with the satellites located forward and behind in the same orbital plane, represented in red.
- Satellite-GS: at the time step captured, that satellite is communicating with two antennas, which are located in Italy and Bulgaria. These links are shown in green.

All the scenarios detailed at the beginning of this section have been simulated and the results obtained have been gathered in table 9.2, which shows the orbital configuration parameters defined for each scenario, as well as the tracking efficiency results of the simulation.

Table 9.2: Comparison between the configuration parameters and efficiency results of the different simulations.

Const.	**T**	**P**	**hkm**	**El (°)**	**t_monitor**	**Eff.**
S1 (stand.)	32	4	600	10	323 min	74.08%
S2 (altern.)	32	4	600	10	280 min	64.22%
D1	32	4	600	10	271 min	62.16%
D2	32	4	600	5	342 min	78.44%
D3	48	4	600	10	431 min	98.85%
D4	48	8	600	10	400 min	91.74%
D5	48	8	1000	10	432 min	99.08%

Where T is the number of satellites, P the number of planes, hkm the orbital altitude in kilometers, El the minimum elevation angle in degrees, *t_monitor* is the time that the aircraft has been monitored during the flight and Eff. stands for the tracking efficiency.

To begin with, the first three results will be analyzed focusing on the effect of the constellation construction pattern on tracking performance.

Firstly, by comparing the results of the two Walker Star constellations, it can be observed that the monitoring time efficiency increases with the standard phasing method. This can be justified because the alternative method organizes the equivalent satellites in neighboring planes so that they have similar latitudes at the same time. On the contrary, in the standard case, the equivalent satellites in adjacent planes are more out-phased and as a result, they manage to cover a greater area of vision. Secondly, it can be seen that Delta constellation D1 offers lower performance for the same orbital conditions as S1 and S2. This happens because the Delta pattern distributes orbital planes every 360°/P, while the Star pattern does it every 180°/P. This way, orbital planes in Star constellations are closer and a as a result, better coverage is achieved for this trajectory.

On the other hand, the effect of modifying orbital parameters will be analyzed in order to increase coverage efficiency. By comparing simulations D1 and D2, it can be clearly observed that the fact of decreasing the minimum elevation angle significantly increases efficiency. As explained in section 7.3.2, the elevation angle determines the range of vision of an object and therefore, by changing this value to 5° the coverage increases. In space operations, communications are carried out over long distances, which is why a slight decrease in the minimum elevation angle causes the satellites to be able to connect with the aircraft much earlier.

Secondly, in simulation D3 the number of satellites has been increased, allowing a major number of communication possibilities. As a result, tracking efficiency increases greatly. Afterwards, scenario D4 has increased the number of orbital planes and the result has been a decrease in performance. This is because by increasing P and maintaining T, there are fewer satellites in each plane than in the previous case and in this way, these are more separated. Consequently, fewer connections are established. Finally, orbital height has been increased to 1000 km. This way, the area of vision of the satellites is greater and as a result, almost total coverage of the airplane along the trajectory has been obtained.

Some conclusions can be drawn by analyzing all the results. First, it is important to properly choose the constellation creation pattern as it can directly influence its performance. The optimum distribution may depend on the performance that is of interest to achieve but, generally Walker Star constellations offer a greater area of coverage. Secondly, clearly by increasing T and the orbital height the efficiency increases. However, it can be observed that placing satellites farther from the surface does not make a very significant difference. Clearly the most influential parameter is the number of total satellites. Even so, it is necessary to perform several simulations with different configurations to analyze which is the best combination.

Finally, as mentioned in the end of section 8.3, the simulator also plots two different graphics in order to visualize the monitoring performance of the constellation. The first figure consists of representing the global monitoring time periods that are performed by all the satellites in the constellation as a group. Therefore, the visibility periods throughout the flight trajectory are represented. On the other hand, the second graph represents the communication periods performed for each satellite individually. This way, it can be observed which satellites establish a communication link with the aircraft at every discretization interval. Furthermore, the time intervals associated to each of the discretization points of the trajectory are also represented in both figures.

The following images represent the monitoring efficiency and the satellites visibility of constellations D1 and D5:

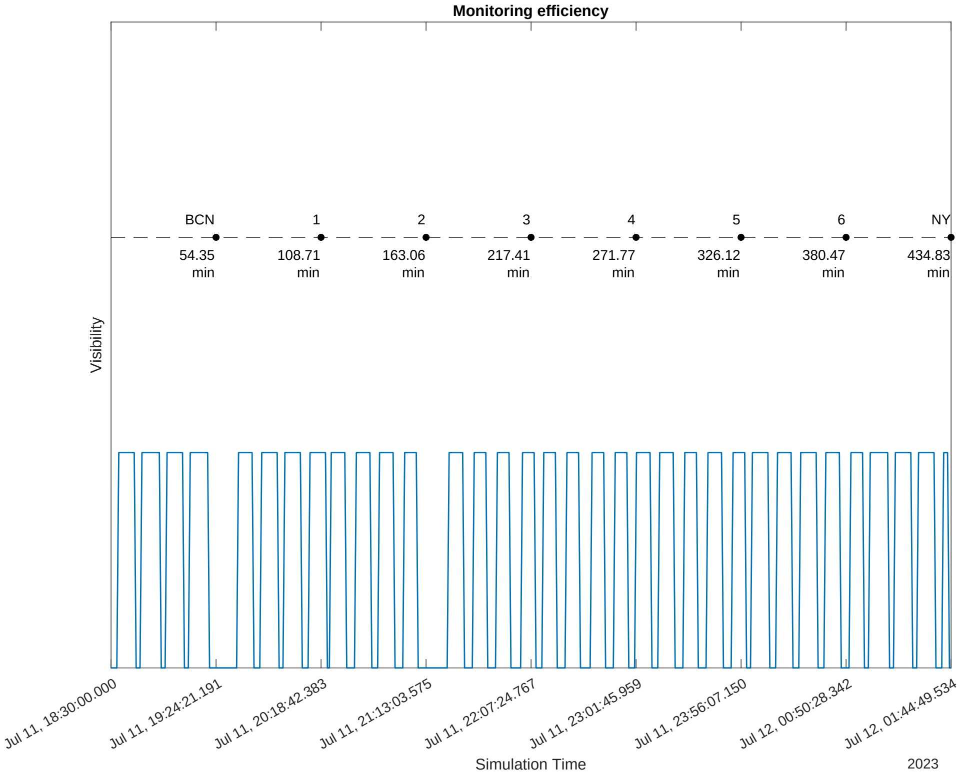

Figure 9.4: Monitoring efficiency of constellation D1.

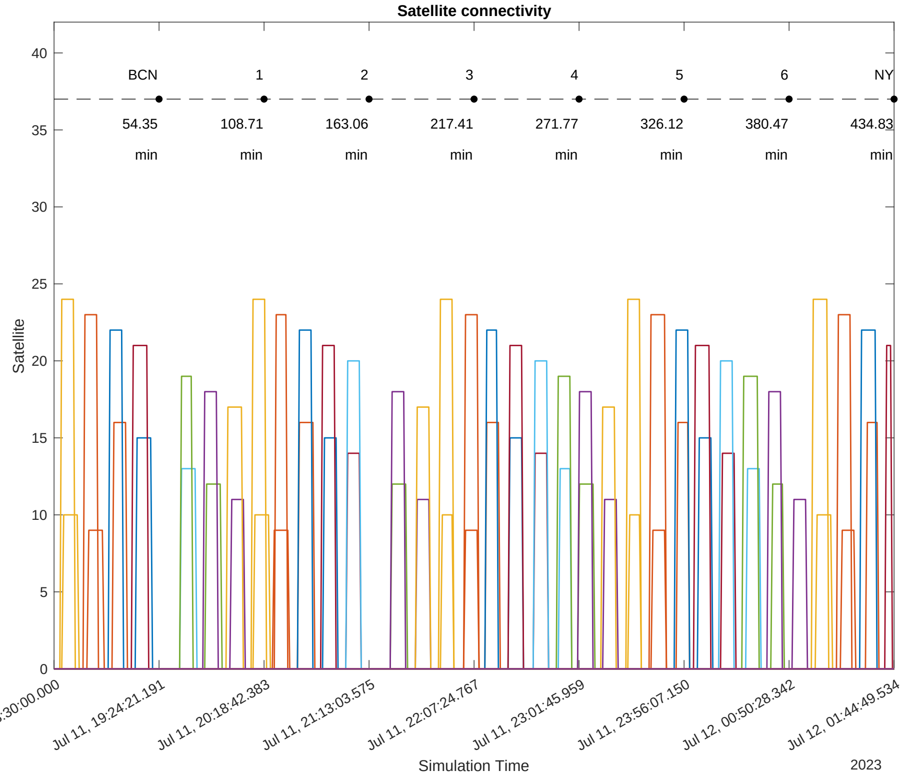

Figure 9.5: Satellite visibility of constellation D1.

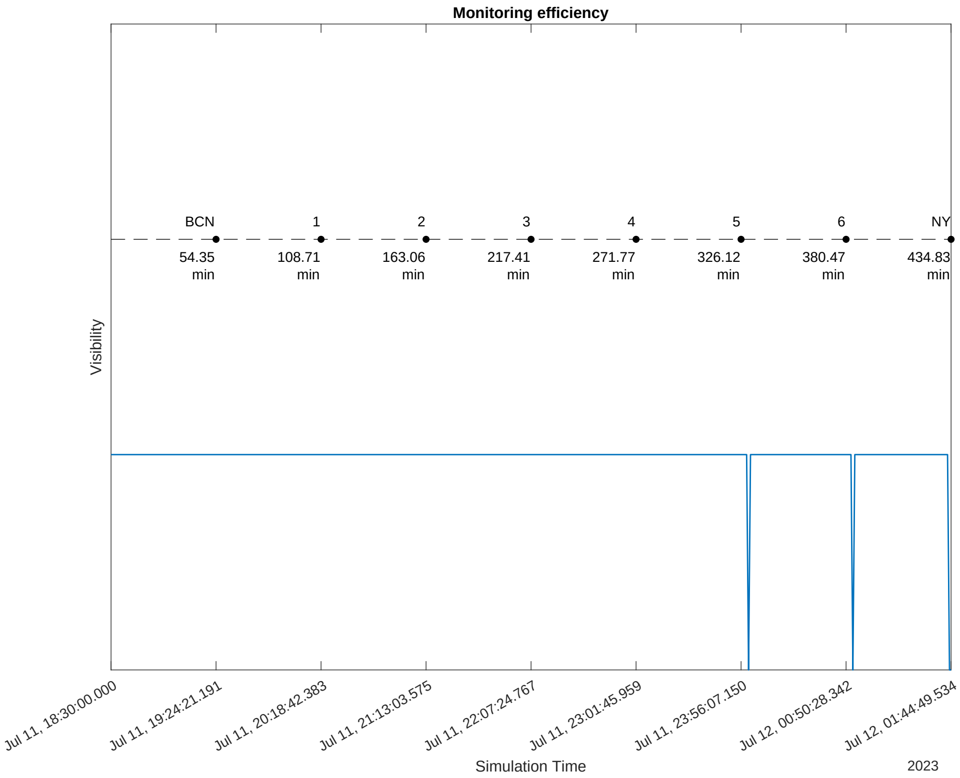

Figure 9.6: Monitoring efficiency of constellation D5.

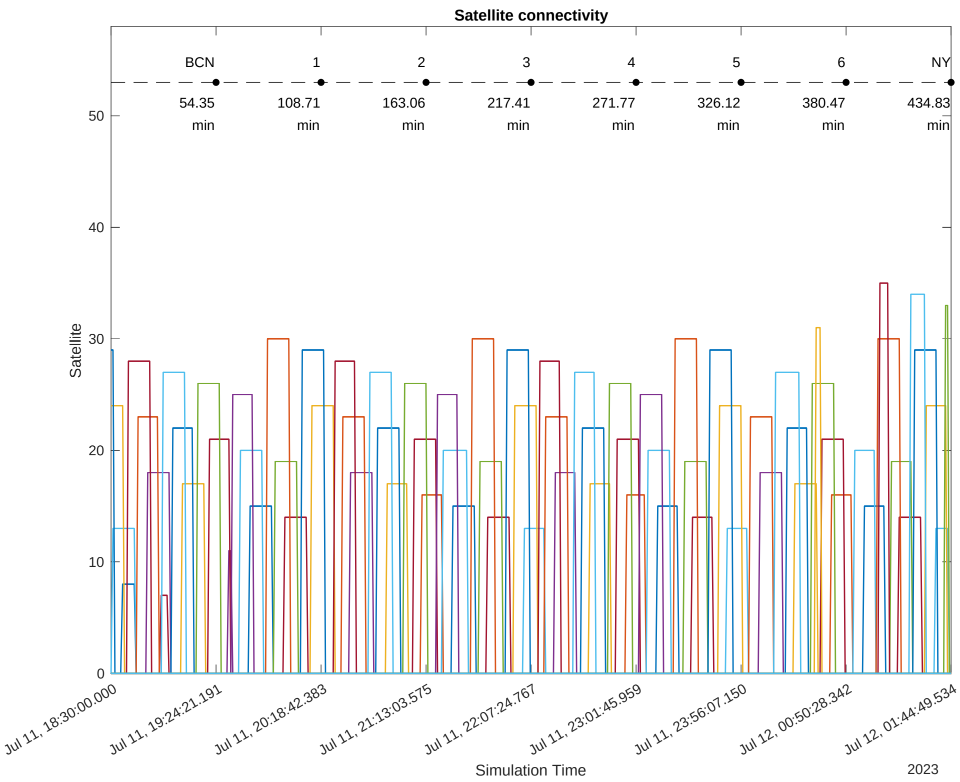

Figure 9.7: Satellite visibility of constellation D5.

Chapter 10

Mission cost analysis

After analyzing the influence of orbital parameters on the constellation's tracking performance, a brief study of the impact of these orbital elements on the hypothetical cost of the space mission will be carried out. The objective of this section is to complement the theoretical development of the simulator's constellations with an analysis from the mission design point of view, regarding factors such as the operation costs and economic viability. A brief explanation will therefore be made of how the value of the constellation's orbital elements can impact the cost of the mission, either in relation to the required manufacturing processes of the satellites or to the mission's launch program.

Number of satellites (T)

First of all, after analysing the results obtained in section 9, it can be observed that the number of satellites is a very influential parameter regarding tracking efficiency. The higher the number of satellites in space the greater area of coverage is achieved and therefore, the performance in aircraft monitoring also increases. Therefore, it is of interest to have a relatively high number of satellites, which allows to obtain global coverage for any selected flight path. However, this implies a great increase in the mission's cost, as well as in its complexity. Requiring a high number of satellites implies a higher cost in technology manufacturing. However, with the growth of New Space, satellite production processes have been greatly simplified, as simpler and more accessible technology is used. In addition, the manufacturing designs of cubesats are also simpler, smaller and lighter. All these factors have made the creation of constellations with large numbers of satellites more accessible and economical.

Even so, it is important to define this parameter in a way that global coverage can be achieved with the least number of satellites possible, taking into account a margin of redundancy in case one of them fails.

Furthermore, the number of satellites required for the mission also have a great influence on the launch process. The higher the number of cubesats that are need to be sent into space, the greater will be the payload capabilities required for the rocket. Since the number of space operations has increased a lot after the emergence of New Space, small satellite launches are becoming more and more frequent. Therefore, it is very common for launch vehicles to load technology from several missions at once, which are sent to similar orbits. This reduces the costs of the mission, although on the other hand, companies must adapt to the launch dates of the main mission launched in the rocket. The number of satellites in the constellation will also define the required payload to be lifted by the launch vehicle, and as the payload mass increases, both the fuel consumption and launch cost increase too.

Number of equally spaced planes (P)

As noted in the results section, by increasing the number of equally spaced planes in the constellation, fewer satellites are distributed per each plane and the efficiency decreases. The value of P also influences the design of the mission launch and its cost. The smaller P is, the separation angle between planes increases. It is important to mention that every launch site has a restricted range of allowed azimuth directions, since some of them might involve overflying urban territories. Therefore, rockets are launched generally over the ocean in order to reduce the damage caused in case of failure. So depending on the required number of planes, satellites may be launched from different sites. Consequently, a higher mission cost would be required.

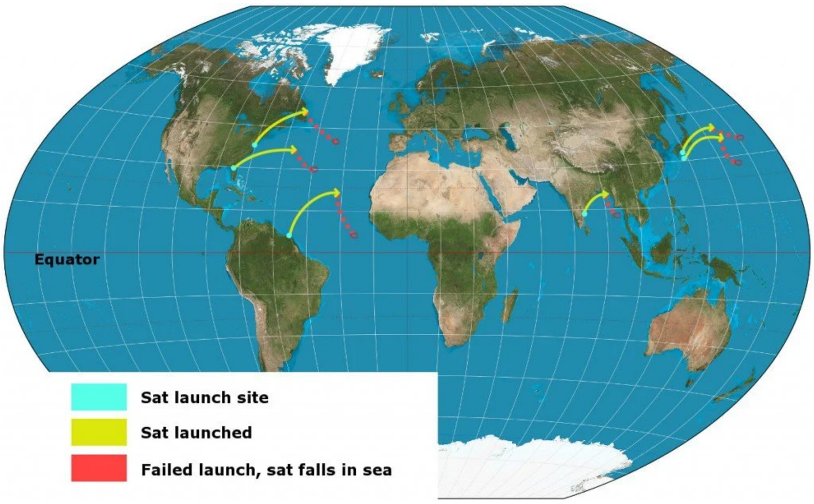

Figure 10.1: Launch directions.

Source: Ashish [50]

Orbit altitude (hkm)

The altitude of the orbits clearly influences the cost of the mission. The farther from the surface are the satellites, the rocket needs higher fuel expenditure to achieve the required jettison point and therefore the mission's cost increases. However, after observing the results of table 9.2, it can be seen that it is not necessary to send the satellites farther to achieve greater efficiency, there are other parameters such as the number of satellites that have a greater influence.

However, one of the biggest drawbacks of creating a constellation in low orbits is the high density of the atmosphere. Atmospheric gases generate a lot of aerodynamic resistance and as a result, satellites lose speed and end up re-entering into Earth. This significantly reduces the useful lifespan of satellites, which is why they are built with simpler and more economical technology. Therefore, it is necessary to find a balance between the height of the satellites and the rest of the orbital parameters since if they are very close to the surface, it will be necessary to replace them within a few years of starting the mission.

Orbit inclination (I)

Orbital inclination is a design parameter that has not been analyzed in the results section, since the same trajectory has always been simulated. However, the inclination of the orbits has a direct impact on the area of visibility of the constellation. If the inclination is increased, the satellites will have the capacity to monitor elevated latitude zones, while if the inclination is small, the coverage range decreases. Generally, Walker Star constellations tend to be organized with polar orbits (I = 90°) and as a result, the performance is higher than in Walker Delta constellations. In addition, the results of section 9 show that the tracking efficiency is greater in the Walker Star simulation than in the Walker Delta for the same design properties.

After this analysis, it seems that the best option is to design a constellation with polar orbits, however, this entails a greater complexity for the launch of the satellites. As the inclination of the desired orbit increases, the fuel consumption required during launch also increases. This is because equatorial orbits (or low-inclination orbits) take advantage of Earth's rotation to place satellites at the desired point. That is why they are launched from launch sites located close to the equator. Instead, polar orbits (or orbits with high inclination) require higher fuel consumption to achieve the necessary speed to perform the orbital transfer to the final orbit. In order to minimize this fuel consumption, satellites in polar orbits are launched from high latitudes, where the effect of Earth's rotation is less and easier to counteract. Therefore, Walker Star constellations tend to be more expensive than Walker Delta constellations.

Once analyzed the influence of the orbital elements of a constellation on the mission's cost, the next section presents a brief study of the current market of launch vehicles and the main systems of access to space for low orbits.

10.1 Access to space

There are many factors that influence the design of a satellite constellation. It is essential to define the constellation design parameters taking into account the effect of orbital elements on the performance of the space operations and the optimal fulfilment of the mission's objectives. However, it is also crucial to analyze the impact on economic requirements for the mission. One of the main requirements in the design of a space mission is the reduction of manufacturing and operating costs, where the reduction of weight and fuel consumption are the main protagonists.

The space market is an essential part of the economy of many countries since it is a sector with great technological development. With the growth of New Space, private sector involvement in the development of space technology has been enhanced. One of the main discoveries of this New Space market is the exploitation of the LEO area for Earth observation and telecommunication operations. The LEO region, and even the VLEO below 450 km in height, offer important benefits thanks to its proximity to the Earth's surface. The main advantages are the improvement in imaging resolution and the reduction of latency in communication systems [51]. This leads to a reduction in the power requirements of satellites and as a result, a reduction in mass and cost is achieved. However, the operation of spacecraft in LEO is challenging due to the increased atmospheric density at these altitudes, which increases drag perturbations. Therefore, this leads to the necessity of improved propulsive and attitude control systems for satellites. There have been some technological advancements such as the use of materials to facilitate drag-reduction and aerodynamic control, or the atmosphere-breathing electric propulsion system (ABEP), which uses atmospheric gasses to create little impulses [28].

Due to the large increase in New Space LEO operations, there has been a significant growth in small satellites launches over the past years, where commercial satellite operations are receiving a lot of attention from the private market, especially in the communications sector [52]. This is the reason why one of the main areas of technological development in the space sector nowadays is the creation of new and advanced space access systems. Space exploitation by private technology companies is the future of the space market. For this reason, large government space agencies such as NASA or ESA are promoting and supporting new start-ups that offer technological designs with great potential.

As mentioned earlier in this section, it is very common to launch multiple missions on the same rocket, as costs are shared. Even so, finding a suitable match is a complicated task because secondary launch satellites must meet dimensional and weight requirements in order to have a place in the rocket's payload piggyback. Moreover, they also need to adapt to both launch date and destiny orbit, which are set by the primary payload [53]. For this reason, the creation of microlaunchers capable of launching small satellites directly into low orbits has been boosted. The main competitor in this regard is SpaceX's Falcon 9, which has been responsible for sending all the satellites of the Starlink constellation to LEO orbits. The Falcon 9 has marked a major change in the space industry due to the reusability capability of the first stage propellants [54]. The creation of reusable launch vehicles is one of the main objectives of the European space industry as it allows to reduce production and launch operation costs. For this reason, other agencies such as ESA, Airbus or Arianespace have been forced to accelerate the creation of the new generation of rockets [52]. ESA has developed Vega-E, a microlauncher with improved payload mass and volume capabilities compared to its old version, the Vega-C. It is designed with additive manufacturing which allows to reduce the operating costs in relation to the cost per kilo of the current market [55]. Furthermore, the European company has also launched the Themis program, which will become the first launch vehicle with reusability capabilities in Europe.

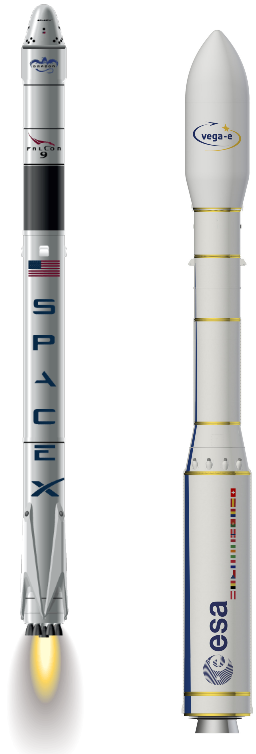

Figure 10.2: SpaceX's Falcon 9 and ESA's Vega-E small satellites launchers.

Sources: SpaceX [54] and ESA [55]

However, it is also crucial to take into account other ways of accessing space apart from reusable rockets. Some innovative designs and with great potential are for instance the initiatives proposed by the H2020 ALTAIR project, which have designed a cost-effective launch system for small satellites based on a semi-reusable air-launch system, the Rocket-Balloon Hybrid Launch System created by Zero 2 Infinity, or the SpaceLiner DLR, which is a concept for a hypersonic and suborbital winged transport vehicle [52].

Figure 10.3: Air-Launch system designed by Altair.

Source: Arquimea [56]

Figure 10.4: Rocket-Balloon Hybrid Launch System created by Zero 2 Infinity.

Source: Zero 2 Infinity [57]

In conclusion, it is not only important to design a satellite constellation to meet the established performance requirements, but it is also essential to develop the project to minimize the operational costs. As analyzed in this section, the design parameters of a constellation directly influence the design of the mission's launch operations and the overall costs. Thanks to the growth of the aerospace industry, new and advanced technological solutions are being developed to access space. An essential part of the design of a space project is to find a suitable, effective and economical launch program to send the satellites to the desired point in space.

Chapter 11

Budget

The development of this thesis has been purely theoretical thus it doesn't include any physical manufacturing or material expenses. Therefore, only the costs associated with the technical design of the simulator have been considered, taking into account expenditures such as professional fees, cost of the required equipment (Matlab license and computer) and office rent. The detailed break down of the project cost is explained in the Budget document of this thesis. However, the following table summarizes the budget for the development of the project:

Type of cost	**Cost (€)**
Professional fees	5250
Equipment	2422
Office rent	900
Total	**8572**

Table 11.1: Project development costs.

Chapter 12

Environmental and social implications

The development of the simulator of this thesis has not implied a direct impact on the environment, since it has consisted merely of theoretical analysis and the creation of the simulator at a computational level. However, the real mission posed in the project does have relevant implications for the environment, sustainability and other social factors.

First, it is obvious that the space sector has a great impact on the environment as large quantities of fuel are consumed during launches. In addition, the market of technological components manufacturing for the aerospace sector is growing on a large scale and this generates a significant increase in energy consumption and CO_2 emissions.

On the one hand, in reference to the air navigation industry, airlines currently have great technological advances to improve sustainability. One of the most influential aspects of aircraft fuel consumption is the flight path described. For this reason, one of the greatest technological developments in the aviation sector is the implementation of digital meteorological monitoring systems in real time, with the aim of tracing the most efficient flight routes, avoiding turbulent zones and in this way, using the minimum necessary fuel. As a result, flight trajectories reduce CO_2 emissions and they are more sustainable.

On the other hand, in the space market currently dominates the development of missions for the New Space initiative, where operations of Earth observation and telecommunications in low orbits are carried out. As a result of the growth of this industrial sector, large-scale production of satellite technology has increased greatly. However, the positive side is that the creation of nano-satellites of little weight and size is promoted and therefore, the production processes are simpler and more economical. In addition, the design of low-weight space technology missions allows satellites from different missions to be sent to space together on a single launch. The fairing of new generation rockets has the ability to connect numerous satellites at the same time and in this way, it is possible to launch multiple missions in the same vehicle, reducing fuel consumption. In addition, since New Space operations are mostly performed in LEO, the fuel consumption to reach the desired height for the mission is much lower.

Another key factor that needs to be taken into account for the development of space missions is the management of space debris. In 2020, the Artemis Accords were implemented, a document with the objective of emphasizing the importance of the Outer Space Treaty of 1967, where a series of agreements and regulations are issued with the aim of promoting peaceful and collaborative space exploration [58]. In addition, these treaties also involve a commitment to the implementation of plans for the safe recovery of space debris after the completion of a space mission, as well as the intention to generate the least possible harmful debris in space. The fact of designing this project for LEO orbits contributes to the reduction of the space debris generated, since when satellites reach the end of their useful life they can be easily recovered with a re-entry maneuver thanks to the proximity with the terrestrial surface. New Space missions promote technological recovery and, in addition, the fact of carrying out short-lived missions due to the loss of orbital height as a consequence of the effect of atmospheric drag, facilitates the re-entry of the satellites.

Unfortunately, as a consequence of the rapid growth of the space industry, the design of numerous new missions and the short duration of satellites in LEO orbits, the number of annual launches has grown significantly. This leads to an increase in fuel expenditure. However, with the aim of improving the efficiency of launch vehicles and reducing manufacturing costs, the most pioneering rocket companies in the market are dedicated to the development of reusable rockets.

Finally, the design of this project also has some social implications. The most relevant one is that the product created with this simulator allows constant tracking of aircraft in long distance trajectories, which pass through dark radar zones and in this way, the safety of air navigation operations and its passengers is increased.

Chapter 13

Conclusions

The main objectives of this thesis where to design a simulator capable of creating user-customized satellite constellations at Low Earth Orbit for air navigation monitoring purposes. The final simulator that has been developed is considered to meet the initial objectives of the project. Thanks to the tool designed, different methodologies for the construction of constellations have been studied, as well as the influence of orbital parameters on satellite distribution. This way, the simulator includes a series of adjustable elements that allow the user to create many different satellite configurations and analyze the results obtained for each one of them.

Furthermore, it has been possible to visually represent the 3D scenario defined by the user, where it can be observed the inter-satellite links, the communication connections between the satellites and the aircraft, and also the links between satellites and ground stations. Moreover, the visual representation of the aircraft flight trajectory has been also included in the simulation. In addition, it has been possible to include the international antenna network of the space communications company Leaf Space, which has been considered the most suitable collaborator to perform the mission control tasks of the ground segment for the project.

Finally, the results obtained with the simulator illustrate the monitoring efficiency of the defined constellation taking into account the visibility with the aircraft throughout the entire flight path. This way, the simulator determines which are the visibility periods all over the flight time and represents graphically the communication intervals between the aircraft and the constellation, illustrating which satellites establish connection with the aircraft at each point of the trajectory. The tool developed permits to study the performance of satellite communications at LEO in order to develop a satellite network with global coverage capable of monitoring aircraft at any point on Earth.

Chapter 14

Future work

The simulator obtained at the end of this thesis is able to create any satellite scenario customized by the user with the objective of creating a LEO cubesat constellation to monitor air navigation trajectories. Furthermore, the simulator calculates the tracking efficiency of the constellation defined. Therefore, the future work to be done would consist of designing the most optimal satellite constellation capable of monitoring all the aircraft routes included in the simulator. This would require an in-depth analysis of the orbital parameters and their influence on the constellation performance. The most optimal, efficient and also economical constellation configuration should be able to provide global coverage and track all the desired aircraft simultaneously with the minimum number of satellites required. The most suitable orbital parameters, such as constellation type, number of satellites and planes, orbit altitude, orbit inclination and phasing method, should then be justified.

Moreover, further tasks could be performed:

- All these orbital properties should be defined in relation to cubesat communication capabilities and power requirements. Thus, a study of the required payload instruments and power and communication subsystem would also be necessary. The on-board segment of the satellites would then be partially defined.
- In addition, the final constellation parameters must also be influenced by an economical factor. The financial investment required is a key factor in carrying out a space mission. In other words, the objective is to minimize both the manufacturing and operational costs of the mission. There are several factors that have an essential impact on the project's budget, where some of the most critical elements are directly related to the orbital design of the constellation. Consequently, a study of the optimal launch considerations for the mission should be performed in relation to parameters such as launch site and vehicle. This would provide an approximation of the required payload, fuel and operating costs for the launch program.
- Finally, once the optimal constellation configuration and launch considerations have been defined, an approximation of the budget necessary for the mission could be made, taking into account the launch cost and part of the satellite's payload and subsystems costs. Once this result is obtained, a study

could be made of possible companies and private investors interested in financing and collaborating with the project in terms of mission control, launch, satellite manufacturing and component suppliers.

In conclusion, the future work of this thesis will consist of three main objectives: define the more efficient constellation configuration to monitor air navigation trajectories, obtain an estimation of the mission's budget regarding some components of the payload, subsystems and launch program of the satellites and finally, determine some companies and investors suitable with the mission's goals in order to find economical investment and operational collaboration. Furthermore, there are other elements that could be also studied in second place and implemented to the project, such as a drag model, the solar cells definition and even a 3D model of the cubesat.

Bibliography

1. POZO DÍAZ, Xavier. *Study of attenuation and loss of messages in radiofrequency communication links between Cubesats and Earth*. 2022. Available also from: https://upcommons.upc.edu/handle/2117/373518. Accessed: June 6 2023.
2. PRIETO, Sergio. *Project to extend the MATLAB simulator for communications links between LEO, GEO, Aircraft and Earth satellites*. 2023.
3. CALAMUR, Krishnadev. *Is There A Better Way To Track Aircraft During Flight?* 2014. Available also from: https://www.npr.org/sections/thetwo-way/2014/03/11/289091812/how-to-better-track-aircraft-during-flight. Accessed: June 9 2023.
4. NEWS, BBC. *How do you track a plane?* 2014. Available also from: https://www.bbc.com/news/world-asia-pacific-26544554. Accessed: June 9 2023.
5. PAGE, Charlie. *How are planes tracked when they fly around the world?* 2023. Available also from: https://thepointsguy.com/guide/aircraft-tracking-methods/. Accessed: June 9 2023.
6. HAYWARD, Justin. *How Do Flight Tracking Websites Work?* 2022. Available also from: https://simpleflying.com/how-do-flight-tracking-websites-work/. Accessed: June 9 2023.
7. ADSBHUB. *Real time aircraft tracking by FlightRadar24*. 2023. Available also from: https://www.adsbhub.org/docs/real-time-aircraft-tracking-by-flightradar24/. Accessed: June 9 2023.
8. VIANA, Israel. *El misterio de los aviones que desaparecieron sin dejar rastro*. 2014. Available also from: https://www.elcorreo.com/vizcaya/20140312/mas-actualidad/sociedad/misterio-aviones-desaparecieron-dejar-201403112138.html. Accessed: June 9 2023.
9. CARVALHO, Pedro. *Pesadilla sobre el Atlántico: qué sucedió en el vuelo 447 de Air France*. 2022. Available also from: https://www.elconfidencial.com/alma-corazon-vida/2022-01-22/pesadilla-sobre-el-atlantico-vuelo-447-de-air-france_3362346/. Accessed: June 9 2023.
10. GREGERSEN, Erik. *Malaysia Airlines flight 370 disappearance*. 2023. Available also from: https://www.britannica.com/event/Malaysia-Airlines-flight-370-disappearance. Accessed: June 9 2023.
11. ADMINISTRATION, Federal Aviation. *Satellite Navigation - GPS - User Segment - Aviation*. 2023. Available also from: https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/gps/usersegments/aviation. Accessed: June 9 2023.
12. ADMINISTRATION, Federal Aviation. *Next Generation Air Transportation System (NextGen)*. 2023. Available also from: https://www.faa.gov/nextgen. Accessed: June 9 2023.

13. WILLIAM TEWELOW, GISP. *A new era begins with geospatially based aviation.* 2020. Available also from: `https://www.gpsworld.com/a-new-era-begins-with-geospatially-based-aviation/`. Accessed: June 9 2023.

14. POPESCU, Gabriel. *Earth Centered Inertial (ECI) Coordinate System.* 2023. Available also from: `https://www.researchgate.net/figure/Earth-Centered-Inertial-ECI-Coordinate-System_fig2_311807426`. Accessed: May 7 2023.

15. *Coordinate Systems.* 2023. Available also from: `http://dirsig.cis.rit.edu/docs/new/coordinates.html`. Accessed: May 7 2023.

16. POPESCU, Gabriel. *Earth-Centered-Earth-Fixed (ECEF) Coordinate System.* 2023. Available also from: `https://www.researchgate.net/figure/Earth-Centered-Earth-Fixed-ECEF-Coordinate-System_fig3_311807426`. Accessed: May 7 2023.

17. IBM. *Geographic coordinate system.* 2023. Available also from: `https://www.ibm.com/docs/en/informix-servers/12.10?topic=data-geographic-coordinate-system`. Accessed: May 7 2023.

18. GEOGRAPHYREALM. *Latitude and Longitude.* 2023. Available also from: `https://www.geographyrealm.com/latitude-longitude/`. Accessed: May 7 2023.

19. NASA. *Orbits and Kepler's Laws.* 2023. Available also from: `https://solarsystem.nasa.gov/resources/310/orbits-and-keplers-laws/#:~:text=Kepler's%20Laws%20of%20Planetary%20Motion&text=They%20describe%20how%20(1)%20planets,its%20semi%2Dmajor%20axis).`. Accessed: May 7 2023.

20. MYRANK. *Kepler's Laws of Planetary Motion.* 2023. Available also from: `https://blog.myrank.co.in/keplers-laws-of-planetary-motion/`. Accessed: May 7 2023.

21. THEORY, Labster. *Kepler's Second Law.* 2023. Available also from: `https://theory.labster.com/keplers_second_law/`. Accessed: May 7 2023.

22. MECHANICS, Orbital. *Classical Orbital Elements.* 2023. Available also from: `https://orbital-mechanics.space/classical-orbital-elements/classical-orbital-elements.html`. Accessed: May 7 2023.

23. PRESSBOOKS. *The Classical Orbital Elements (COEs).* 2023. Available also from: `https://oer.pressbooks.pub/lynnanegeorge/chapter/chapter-3-the-classical-orbital-elements-coes/`. Accessed: May 7 2023.

24. EUSPA. *Orbital and Technical Parameters.* 2023. Available also from: `https://www.gsc-europa.eu/system-service-status/orbital-and-technical-parameters`. Accessed: May 7 2023.

25. OBSERVATORY, NASA Earth. *Catalog of Earth Satellite Orbits.* 2023. Available also from: `https://earthobservatory.nasa.gov/features/OrbitsCatalog#:~:text=There%20are%20essentially%20three%20types,orbit%2C%20and%20low%20Earth%20orbit.`. Accessed: May 14 2023.

26. ESA. *Types of orbits.* 2023. Available also from: `https://www.esa.int/Enabling_Support/Space_Transportation/Types_of_orbits#MEO`. Accessed: May 14 2023.

27. JIANG, Yifei; HE, Wanxia; LIU, Wenzheng; WU, Shufan; WEI, Xiao; MO, Qiankun. *A B5G Non-Terrestrial-Network (NTN) and Hybird Constellation Based Data Collection System (DCS).* 2023. Available also from: `https://www.mdpi.com/2226-4310/10/4/366`. Accessed: May 19 2023.

28. CRISP, Nicholas H.; MCGRATH, Ciara N.; ROBERTS, Peter C.E.; EDMONDSON, Steve; HAIGH, Sarah J.; HOLMES, Brandon E.A.; ROJAS, Alejandro Macario; OIKO, Vitor T.A.; SINPETRU, Luciana A.; SMITH, Katharine L.; ARCOS, Antonio; JENSEN, Thomas Kauffman; HANESSIAN, Virginia; HERDRICH, Georg H.; SKALDEN, Jonathan; FASOULAS, Stefanos; TRAUB, Constantin; PAPVRAMIDIS, Konstantinos; GARCIA-ALMIÑANA, Daniel; RODRIGUEZ-DONAIRE, Silvia; SUREDA, Miquel; KATARIA, Dhiren; BELKOUCHI, Badia; CONTE, Alexis; SEMINARI, Simon; VILLAIN, Rachel. *Very Low Earth Orbit Constellations for Earth Observation*. 2023. Available also from: `https://pure.manchester.ac.uk/ws/portalfiles/portal/226465339/IAC_22_D1_2_11_x71519.pdf`. Accessed: June 17 2023.
29. COURSES, Ansys Innovation. *Walker Constellation*. 2023. Available also from: `https://courses.ansys.com/index.php/courses/intro-to-orbit-types/lessons/walker-constellation-lesson-9/`. Accessed: May 8 2023.
30. PLANNER, Savoir Multisatellite Swath. *Walker constellation*. 2023. Available also from: `http://1.help.taitussoftware.com/SaVoir/ReleaseNotes/Content/6.Advanced/Constellations/Walker/Walker.htm`. Accessed: May 8 2023.
31. LEYVA-MAYORGA, Israel; SORET, Beatriz; MATTHIESEN, Bho; RÖPER, Maik; WÜBBEN, Dirk; DEKORSY, Armin; POPOVSKI, Petar. *NGSO Constellation Design for Global Connectivity*. 2022. Available also from: `https://www.researchgate.net/publication/359647076_NGSO_Constellation_Design_for_Global_Connectivity`. Accessed: May 8 2023.
32. LIANG, Jintao; CHAUDHRY, Aizaz U.; YANIKOMEROGLU, Halim. *Phasing Parameter Analysis for Satellite Collision Avoidance in Starlink and Kuiper Constellations*. 2021. Available also from: `https://arxiv.org/pdf/2109.13994.pdf#:~:text=The%20Walker%20constellations%20use%20a,satellites%20in%20different%20orbital%20planes.`. Accessed: May 8 2023.
33. ZHU, Qinyu; TAO, Haicheng; CAO, Yanhua; LI, Xinhong. *Laser Inter-Satellite Link Visibility and Topology Optimization for Mega Constellation*. 2022. Available also from: `https://www.mdpi.com/2079-9292/11/14/2232`. Accessed: May 31 2023.
34. GPS. *Space Segment*. 2023. Available also from: `https://www.gps.gov/systems/gps/space/`. Accessed: June 10 2023.
35. ONEWEB. *The world is changing with connectivity at its core*. 2023. Available also from: `https://oneweb.net/`. Accessed: June 10 2023.
36. MATHWORKS. *satellite*. 2023. Available also from: `https://es.mathworks.com/help/aerotbx/ug/satellitescenario.satellite.html`. Accessed: May 5 2023.
37. LEAFSPACE. *About Us*. 2023. Available also from: `https://leaf.space/about-us/`. Accessed: June 3 2023.
38. LEAFSPACE. *Technology*. 2023. Available also from: `https://leaf.space/technology/`. Accessed: June 3 2023.
39. LEAFSPACE. *Leaf-Line*. 2023. Available also from: `https://leaf.space/leaf-line/`. Accessed: June 3 2023.

40. PONS, Rafael. *Understanding Azimuth and Elevation*. 2023. Available also from: https://www.photopills.com/articles/understanding-azimuth-and-elevation. Accessed: June 3 2023.
41. BIKOS, Konstantin. *Pyephem compute elevation angle*. 2023. Available also from: Altitude%20&%20Azimuth:%20The%20Horizontal%20Coordinate%20System. Accessed: June 3 2023.
42. ISSOT. *International Space Station Orbit Tracker*. 2023. Available also from: https://ieiuniumlux.github.io/ISSOT/. Accessed: June 3 2023.
43. CAKAJ, Shkelzen; KAMO, Bexhet; KOLIÇI, Vladi; SHURDI, Olimpjon. *The Range and Horizon Plane Simulation for Ground Stations of Low Earth Orbiting (LEO) Satellites*. 2011. Available also from: https://www.scirp.org/journal/paperinformation.aspx?paperid=7225. Accessed: June 3 2023.
44. JIA, Lu; ZHANG, Yasheng; YU, Jinlong; WANG, Xuan. *Design of Mega-Constellations for Global Uniform Coverage with Inter-Satellite Links*. 2022. Available also from: https://www.researchgate.net/publication/360176696_Design_of_Mega-Constellations_for_Global_Uniform_Coverage_with_Inter-Satellite_Links. Accessed: May 31 2023.
45. CHEN, Quan; GIAMBENE, Giovanni; YANG, Lei; FAN, Chengguang. *Analysis of Inter-Satellite Link Paths for LEOMega-Constellation Networks*. 2021. Available also from: https://www.researchgate.net/publication/349182493_Analysis_of_Inter-Satellite_Link_Paths_for_LEO_Mega-Constellation_Networks. Accessed: May 31 2023.
46. TRANSPORT SYSTEMS, The Geography of. *The Great Circle Distance*. 2023. Available also from: https://transportgeography.org/contents/chapter1/transportation-and-space/great-circle-distance/. Accessed: June 1 2023.
47. KELLS, Lyman M.; KERN, Willis F.; BLAND, James R. *Plane And Spherical Trigonometry*. 2023. Available also from: https://www.dbraulibrary.org.in/RareBooks/Mathematics_1951_54967_Plane%20and%20spherical%20trigonometry.pdf. Accessed: June 1 2023.
48. DOMÍNGUEZ, Manuel Berrocoso; RAMÍREZ, María Eva; ENRÍQUEZ-SALAMANCA, José Manuel; PEÑA, Alejandro Pérez. *Notas y apuntes de trigonometría esférica y astronomía de posición*. 2003. Available also from: https://core.ac.uk/display/161353191?utm_source=pdf&utm_medium=banner&utm_. Accessed: May 12 2023.
49. MATHEMATICS, Underground. *The great circle distance*. 2023. Available also from: https://undergroundmathematics.org/trigonometry-compound-angles/the-great-circle-distance. Accessed: June 1 2023.
50. ASHISH. *Why Are Rockets Launched From Areas Near The Equator?* 2022. Available also from: https://www.scienceabc.com/eyeopeners/why-are-rockets-launched-from-areas-near-the-equator.html. Accessed: June 17 2023.
51. CRISP, N.H.; ROBERTS, P.C.E.; LIVADIOTTI, S.; OIKO, V.T.A.; EDMONDSON, S.; HAIGH, S.J.; HUYTON, C.; SINPETRU, L.; SMITH, K.L.; WORRALL, S.D.; BECEDAS, J.; DOMÍNGUEZ, R.M.; GONZÁLEZ, D.; HANESSIAN, V.; MØLGAARD, A.; NIELSEN, J.; BISGAARD, M.; CHAN, Y.-A.; FASOULAS, S.; HERDRICH, G.H.; ROMANO, F.; TRAUB, C.; GARCÍA-ALMIÑANA, D.; RODRÍGUEZ-DONAIRE, S.; SUREDA, M.; KATARIA, D.; OUTLAW, R.; BELKOUCHI, B.; CONTE, A.; PEREZ, J.S.; VILLAIN, R.; HEISSERER, B.; SCHWALBER, A. *The Benefits of Very Low Earth*

Orbit for Earth Observation Missions. 2020. Available also from: https://arxiv.org/pdf/2007.07699.pdf. Accessed: June 17 2023.

52. RODRIGUEZ-DONAIRE, Silvia; GIL, Paulino; GARCIA-ALMIÑANA, Daniel; CRISP, Nicholas H.; HERDRICH, Georg H.; ROBERTS, Peter C. E.; KATARIA, Dhiren; HANESSIAN, Virginia; BECEDAS, Jonathan; SEMINARI, Simon. *Business roadmap for the European Union in the NewSpace ecosystem: a case study for access to space*. 2022. Available also from: https://link.springer.com/article/10.1007/s12567-022-00450-3. Accessed: June 17 2023.
53. ESA. *ESA explores microlaunchers for small satellites*. 2018. Available also from: https://www.esa.int/Enabling_Support/Space_Transportation/ESA_explores_microlaunchers_for_small_satellites. Accessed: June 17 2023.
54. SPACEX. *Falcon 9*. 2020. Available also from: https://www.spacex.com/vehicles/falcon-9/. Accessed: June 17 2023.
55. ESA. *Vega-E*. 2023. Available also from: https://www.esa.int/Enabling_Support/Space_Transportation/Launch_vehicles/Vega-E. Accessed: June 17 2023.
56. ARQUIMEA. *New space launch system for the access to LEO of small satellites*. 2023. Available also from: https://www.arquimea.com/case-studies/hdrm-h2020-altair/. Accessed: June 17 2023.
57. ESA. *Bloostar microlauncher*. 2018. Available also from: https://www.esa.int/ESA_Multimedia/Images/2018/02/Bloostar_microlauncher. Accessed: June 17 2023.
58. LEA, Robert. *What are the Artemis Accords?* 2023. Available also from: https://www.space.com/artemis-accords-explained. Accessed: June 6 2023.