NATIONAL AND KAPODISTRIAN UNIVERSITY OF ATHENS

SCHOOL OF SCIENCE

DEPARTMENT OF INFORMATICS AND TELECOMMUNICATIONS

POSTGRADUATE PROGRAM

"SPACE TECHNOLOGIES, APPLICATIONS AND SERVICES"

THESIS STATEMENT

Design, Modelling and Analysis of Satcoms for UAV operations

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ATHENS

DECEMBER 2022

ΕΘΝΙΚΟ ΚΑΙ ΚΑΠΟΔΙΣΤΡΙΑΚΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΑΘΗΝΩΝ

ΣΧΟΛΗ ΘΕΤΙΚΩΝ ΕΠΙΣΤΗΜΩΝ

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Σχεδιασμός, Μοντελοποίηση, και Ανάλυση των Δορυφορικών επικοινωνιών για UAV αποστολές

Παναγιώτης Γ. Καρδαράς

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ΑΘΗΝΑ

ΔΕΚΕΜΒΡΙΟΣ 2022

MASTER THESIS

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ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

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ABSTRACT

The need for immediate contribution, response, and accuracy of results has led to the entry of drones and especially Unmanned Aerial Vehicles (UAVs) as new technological vehicles. However, the integration of such a colossal technological acquisition is by no means an easy task. Many requirements appear in various areas such as telecommunications, payload problems that the UAV must carry, and operations plans, requirements that must be met to avoid safety issues, collision avoidance, unstable connections, and so more.

The purpose of this thesis is to study as best as possible and most effectively the contribution of satellite communications to achieve reliable and durable Unmanned Aerial Vehicles (UAVs) operations. A three-level analysis will be presented which will concern the Design, Modeling, and Analysis of satellite communications in combination with UAV operations in a way where efficiency of the link will be maximum. After all, an experiment will take place that results and parameters used will be discussed in order to compute the efficiency of the link budget.

It is important to know that cellular communications have so far played the most important and accurate role in both terrestrial and air communications. This is about to change as satellites promise features that cannot compete with terrestrial networks, resulting in the integration of UAVs with satellite communications. However, things are unclear, and the risks posed either from the point of view of personal data or from safety and health can act as an obstacle in developing and upgrading communications.

SUBJECT AREA:	Terrestrial communication, Satellite communication, UAVs, Architecture of UAVs
KEYWORDS	Reliability, UAV, satellites, link budget analysis, safety needs, satellite and UAV providers

ΠΕΡΙΛΗΨΗ

Η ανάγκη για άμεση συνεισφορά, απόκριση και ακρίβεια των αποτελεσμάτων οδήγησε στην είσοδο των drones και ιδιαίτερα των μη επανδρωμένων εναέριων οχημάτων (UAV) ως νέα τεχνολογικά οχήματα. Ωστόσο, η ενσωμάτωση ενός τόσο κολοσσιαίου τεχνολογικού αποκτήματος δεν είναι καθόλου εύκολη υπόθεση. Πολλές απαιτήσεις εμφανίζονται σε διάφορους τομείς όπως τηλεπικοινωνίες, προβλήματα ωφέλιμου φορτίου που πρέπει να φέρει το UAV και σχέδια λειτουργίας, απαιτήσεις που πρέπει να πληρούνται για την αποφυγή προβλημάτων ασφάλειας, αποφυγή σύγκρουσης, ασταθείς συνδέσεις και άλλα.

Σκοπός της παρούσας διπλωματικής εργασίας είναι να μελετήσει όσο το δυνατόν καλύτερα και αποτελεσματικότερα τη συμβολή των δορυφορικών επικοινωνιών στην επίτευξη αξιόπιστων και ανθεκτικών επιχειρήσεων Μη Επανδρωμένων Αεροσκαφών (UAV). Θα παρουσιαστεί μια ανάλυση τριών επιπέδων που θα αφορά τον Σχεδιασμό, τη Μοντελοποίηση και την Ανάλυση δορυφορικών επικοινωνιών σε συνδυασμό με λειτουργίες UAV με τρόπο που η αποτελεσματικότητα της ζεύξης θα είναι μέγιστη εφικτή. Σε τελική ανάλυση, θα πραγματοποιηθεί ένα πείραμα που θα συζητηθούν τα αποτελέσματα και οι παράμετροι που χρησιμοποιούνται προκειμένου να υπολογιστεί η αποτελεσματικότητα του προϋπολογισμού των ζεύξεων.

Είναι σημαντικό να γνωρίζουμε ότι οι κυψελοειδείς επικοινωνίες έχουν παίξει μέχρι στιγμής τον πιο σημαντικό και ακριβή ρόλο τόσο στις επίγειες όσο και στις αεροπορικές επικοινωνίες. Αυτό πρόκειται να αλλάξει καθώς οι δορυφόροι υπόσχονται χαρακτηριστικά που δεν μπορούν να ανταγωνιστούν τα επίγεια δίκτυα, με αποτέλεσμα την ενοποίηση των UAV με τις δορυφορικές επικοινωνίες. Ωστόσο, τα πράγματα είναι ασαφή και οι κίνδυνοι που ενέχουν είτε από την άποψη των προσωπικών δεδομένων είτε από την ασφάλεια και την υγεία μπορούν να λειτουργήσουν ως εμπόδιο στην ανάπτυξη και την αναβάθμιση των επικοινωνιών.

ΘΕΜΑΤΙΚΗ ΠΕΡΙΟΧΗ	Επίγειες επικοινωνίες, Δορυφορικές επικοινωνίες, Μη Επανδρωμένα Εναέρια Οχήματα, Αρχιτεκτονική Μη Επανδρωμένων Εναέριων Οχημάτων
ΛΕΞΕΙΣ ΚΛΕΙΔΙΑ	Αξιοπιστία, Μη επανδρωμένα εναέρια οχήματα, δορυφόροι, ανάλυση προϋπολογισμού των ζεύξεων, ανάγκες ασφάλειας, πάροχοι δορυφόρων και Μη επανδρωμένων εναέριων οχημάτων

To my father, mother and sister

ACKNOWLEDGMENTS

Words cannot express my gratitude to my professor and the chair of my committee for their invaluable patience and feedback. Prof. Vaios Lappas was available throughout the whole thesis and always willing to help even when his time was short. I also could not have undertaken this journey without my KIOS work partners, who generously provided knowledge and expertise.

Lastly, I would be remiss in not mentioning my family, especially my parents and my girlfriend. Their belief in me has kept my spirits and motivation high during this process even when there was a lack of time. I would also like to thank my gym buddies for all the entertainment and emotional relief/support.

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PREFACE

THESIS STRUCTURE

This Thesis is structured in five (5) chapters. The first Chapter is an introduction to the fundamentals of UAV systems. Some basic questions are answered here such as what a UAV is, what are the network and protocol restrictions, what are the operations that a UAV can handle and many more.

In the second Chapter an analysis of terrestrial communications is achieved. The categories of terrestrial networks, protocols with some advantages and disadvantages are discussed in order to understand how this architecture is implemented in everyday life.

In the third Chapter satellite communications are considered. Features, advantages and disadvantages are also included. All the available satellite orbits with a very basic link budget analysis and some effects such as doppler or atmospheric is also given in this part.

Then, the fourth Chapter follows with information about the Analysis and the Design of Satcoms. In this Chapter hardware and software architecture solutions are given to improve the performance of the system, while satellite and UAV providers are mentioned too. Furthermore, as there are many satellite services in real world, some safety measures and needs are necessary to achieve a reliable and robust system.

Finally, the fifth Chapter presents the Modelling of a satellite link. All the equations with its parameters are calculated. Two experiments took place through MATLAB Simulink which are for two (2) Ground Stations and two (2) satellites and the other experiment refers to one (1) Ground Station, one (1) UAV and one (1) satellite acting a relay link.

1 INTRODUCTION

More and more UAV missions and operations often require high resources so that they can be as efficient as possible. Typically, drones fall into one of the following six functional categories: Target and decoy, Reconnaissance, Combat, Logistics, Research and Development, and Civil and Commercial. [1] Performance for such systems is defined as flexibility, easy access, low cost, fast response, real-time data transmission, reduction of human life risks, component damage reduction, and, largely reliable and secure communication without interference and packet loss.

For these applications to perform at their best and to meet all the conditions, it is necessary to study the integration of satellite communications over terrestrial for such missions where the delay and the transfer of information from one point to another are necessary. Satellite communications promise transmission rates, and latency times where terrestrial networks alone could not succeed given the circumstances. Payload size and weight are critical factors for small Unmanned Aerial Vehicles (UAVs) thus, it is necessary to optimize the design of these.

As satellite communications are an interesting and at the same time difficult part of communications, it is necessary to study the design and modeling of satellite communications before getting to a conclusion. That means that there are risks in various areas that should be considered before any decisions on the contribution of satellites in achieving well oriented communication is taken.

However, it is impossible to present only the Satcoms (Satellite communications) as a communication method for UAV operations because it is almost impossible to have communication in this way, meaning in real time and for high speed mobile terminals with big data rates and reliable links, so Satcom shall not be addressed as a "stand-alone topic" but as a component of a communication system. To have a global perspective of an air-communication system we must examine the pros and cons of terrestrial communication with UAV and compare the given results. Then, a reference point to Satcoms and the impact the satellite offers on a link budget, also optimization techniques, safety factors, and advantages and disadvantages of both terrestrial and air communications will be mentioned.

The present work studies the possibility of using satellite communication for UAV operations, while the requirements of every operation needed to be done from a UAV change concerning the mission. In Chapter 2 discussion is achieved about UAVs and drones in a general way, so it would be clear and understandable the different types of missions, communication networks, and drones. After that, terrestrial and satellite networks are described in Chapter 3 and Chapter 4 respectively. Chapter 5 mentions different types of drones, satellite communication providers and some strategic plans for UAV operations, and also some dangers behind the scenes that must be solved but more emphasis is given on both the satellite and drone providers and the missions that are able to be held on this category. Chapter 6 is for the experiment and the explanation behind the formulas of how a link budget analysis is achieved, given with the code used and a few plots to provide the given results. After all, conclusions about the utility of Satcoms to

UAV operations will be taken. Design, modeling, and analysis are the three stages extracted to achieve the above communication methods.

2 FUNDAMENTALS OF UAV SYSTEMS

In 1849 the Australians used unmanned balloons filled with explosives to attack Venice. In 1915, the British military used unmanned balloons for photographic-based surveillance in the Battle of Nueva Chapelle. One year later, the US designed and develop the first unmanned aircraft that was able to fly $1000\ yards$. During the 2000 Afghan war, it was a Predator drone that located Osama bin Laden in Afghanistan. In 2014, Amazon initially suggested using UAVs for delivery purposes. [2]

It is now known and accepted that Unmanned Aerial Vehicles (UAVs) will relay as a second communication network in anticipation of terrestrial. It will probably surpass the terrestrial means as well. Having this in mind, while watching the UAV market and industries implement new prototypes to maximize performance, UAVs are shown as the beginning of a new area called aerial communications concerning the needs of every mission. In anticipation of the wide implementation of 5G technologies, the scarcity of spectrum resources for unmanned aerial vehicles (UAVs) communication remains one of the major challenges in arranging safe drone operations. Two mechanisms exist in this study i.e., the delivery of command, control, and communication (C3) messages, and the heartbeat message for the periodic monitoring purpose. [3] Before starting to analyze the communication architecture of these systems, it is important to understand what a UAV is, what are the different types and what is their contribution to operations.

2.1 What is a UAV, a drone, and what is a UAS?

An unmanned Aerial Vehicle (UAV) is a vehicle working autonomously and carrying payloads like cameras, sensors, and antennas so it would be possible to operate remotely way and complete a task or a mission. There is not a person or a pilot on this vehicle, but a specialized person is required to remote control the UAV or to supervise that everything goes well and that the onboard computer is working based on what has been assigned to do. The traditional technologies cannot handle heterogeneous data types generated by the sensors and other new technology like big data, which are being used in the sophisticated onboard computer that computes the computing applications and involve artificial Intelligence for target identification, detection, and recognition of the tasks.

However, there is a difference between UAVs and drones. A drone is called a robot which same as a UAV can be autonomously or remotely controlled by software in association with its on board computer (OBC). The drone definition is false relative to an unmanned aerial vehicle. A drone can be every unmanned vehicle, either an unmanned submarine or a space rover, or a UAV. Thus, a UAV is a drone, but a drone maybe is not a UAV. For example, an unmanned submarine is a drone and not a UAV, but an aerial vehicle like a Quadro copter is both a UAV and a drone. The correct nomenclature will be followed, but it probably could be referred to a as drone while the definition allows it.

On the other hand, there is an Unmanned Aircraft System (UAS) that needs to be defined. A UAS consists of a UAV connected via a data link to a pilot on the ground. The pilot guides the UAV and may communicate with the air traffic control (ATC). [4] By data link, is called the connection link between the pilot and UAV, where the pilot may have direct access to the aircraft or indirect access through a network of data links such as cellular or satellite communications. The pilot may be in communication with the ATC to have real-time situation awareness using a terrestrial link. Image 1, which is based on [4], depicts both UAS and UAV entities.

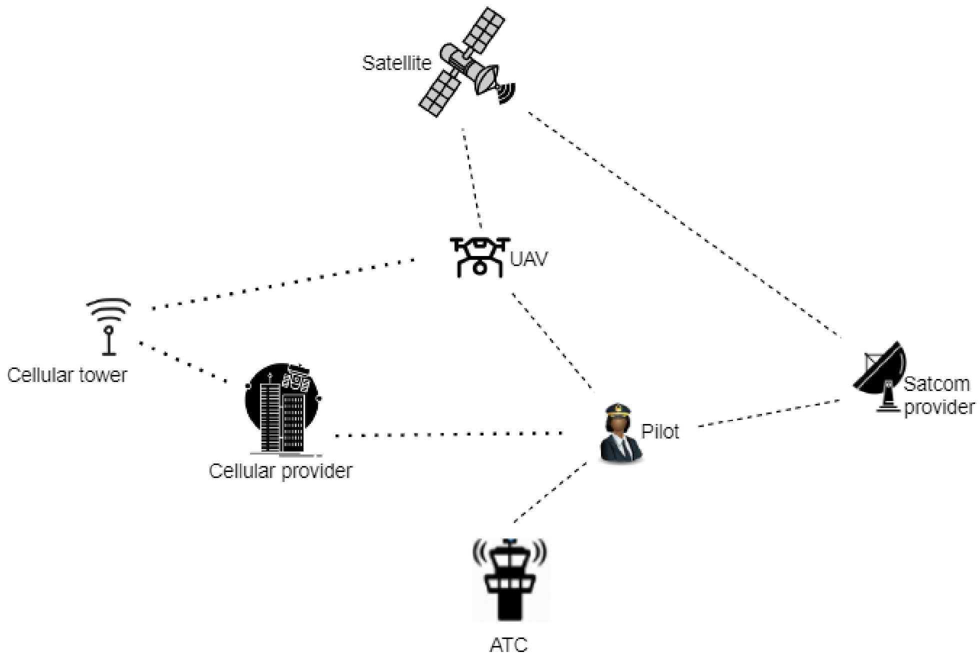

Image 1: UAS system

In the beginning, this technology was developed only for military purposes. The main reason for this technology being so popular is because there is not a pilot on board and because UAVs facilitate smooth operation. Such characteristics help to minimize human impact and life risks while drones navigate easily and cheaper in areas that are harmful in different ways both to humans and environment, nevertheless these are some of the reasons why they stand out in the market and have a high demand. By the end of 2036, it has been anticipated that the total revenue of UAVs would add up to $\$30\ billion$ supporting $300{,}000$ American jobs by 2035. [2], [5]. In Figure 1, someone can study the market of UAS, based on the details are mentioned before.

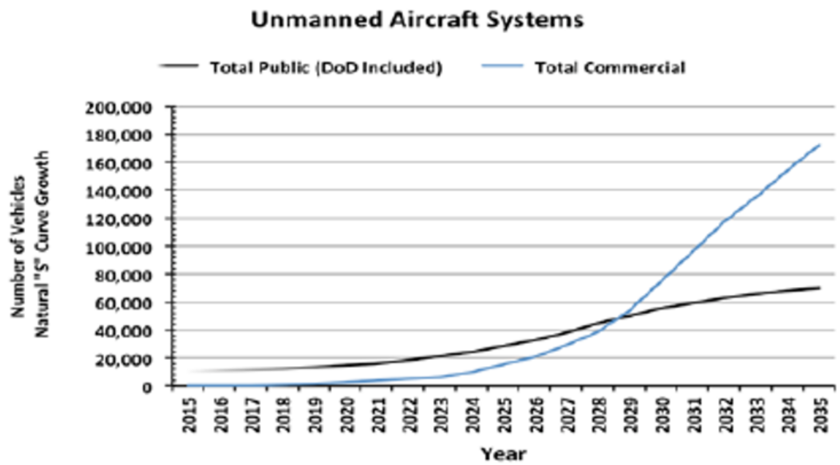

Figure 1: Market of UAS *[2]*

2.2 What are the types, categories and what the restrictions of UAVs?

While it's now understood what a UAV is, it could be a great idea to study about types of UAVs and some restrictions that commonly face. Based on their flying mechanics, UAVs can be separated into these categories: [6]

- **Rotary wing:** same concept as helicopters. These UAVs can vertically take off and land. They can fly around obstacles and be easily flexible due to their hovering capability.
- **Fixed wing:** same concept as aero planes. These UAVs are energy efficient because they don't need the power to stabilize in the air, but only to horizontally lift or depart. Also, they can handle and carry heavy cargo and payload.
- **Hybrid wing:** a combination of the two types before. They travel fast and can-do hover by using their rotary wings.

Except for the types of UAVs, some categories implement the areas and how close to people a drone can fly. These categories are: [7] [8]

- **Open A1 and A3:** standard category, low flying risk. This is the starting point and the first certificate. It allows you to fly over and far from people but not above crowded areas.
- **Open A2:** more risk than A1 and A3. This allows you to fly close to people.
- **Specific:** moderate risk-flying. To operate in this category, you must be a drone operator, which means you have permission to supervise a person, and you need operational authorization from the National Aviation Authority they are registered.
- **Certified:** high risk and complex flying. Future drone flights with passengers on board such as the air taxi, for example, will fall into this category. The approach used to ensure the safety of these flights will be very similar to the one used for manned aviation.

Flight restrictions are also mentioned based on the weight of the UAV and the flight category that someone must be to be able to fly a UAV: [8]

- **0.25kg or lighter:** There is no minimum age, no training required, nor a certificate unless the vehicle has a camera. No flight above people. Belongs to A1 and A3 class certifications.
- **0.5kg or lighter:** The person must be at least 16 years old and must have a certificate of A1 or A3 category. No flight above people. Belongs to A1 and A3 class certifications.
- **2kg or lighter:** The person must be at least 16 years old and must have a certificate of A2 category. Lower flight height must not exceed $50\,m$. Belongs to the A2 classification.
- **25kg or lighter:** Same as $0.5\,kg$ vehicle but you can fly $150\,m$ above people and the certificate belongs only to the A3 subcategory.
- **above 25kg:** cannot exceed this limit, but if you do, you need to ask permission from the civil aviation authority or be licensed as a drone pilot under p.102 to fly your drone.

If it is necessary to study the drones in depth in a general way, it should also be mentioned the way of operation over long distances. UAV control can be classified into the below types:

- **Full autonomous:** this vehicle does not need any human interaction to apply the tasks and missions. If a human is needed will rely on the start/load of the mission specifications.
- **Remote controlled:** this vehicle is unmanned and does every command from the onboard computer, but it is necessary to have a ground pilot to check and verify control and command messages.
- **Remote supervised controlled:** basically, it is autonomous, but a human interaction may be used if changes appear on a task/mission or if it’s a critical decision making.

Finally, a classification based on the height of the flight is presented below with some examples. [6]

- **Tier:** contains small UAVs like Netra.
- **Tier 1:** contains UAVs in low altitude and long endurance such as RQ-2, and IAI Searcher.
- **Tier 2**: contains UAVs in medium altitude and long endurance such as MQ/1 Predator.
- **Tier 2+:** contains UAVs in high altitude and long endurance such as Global Hawk.
- **Tier 3:** contains UAVs in high altitude, long endurance, and the ability for low observations such as RQ-170-Sentinel.

2.3 What are the types of missions that UAS can be involved?

Having already explained the basic features of UAVs and UAS, it would be helpful to find out the missions in that a drone can and should be involved. The different types of missions and their purposes are mentioned below: [2]

- **Payload delivery:** it includes cargo and payload transport like amazon or military equipment.
- **Environmental:** measure and monitoring of temperature, humidity, wind velocity, and CO_2 emissions.
- **Search and rescue:** finding and retrieving people and objects, while data are transmitted to the control center. They are currently used in firefights and earthquakes.
- **Intelligence, surveillance, and reconnaissance:** these missions vary from big data transmission to real-time and low latency operations.
- **Relay:** used to relay communication when terrestrial units fail to do.
- **Robotics:** like a space rover. It should be used to manipulate or activate an object remotely.
- **Training:** not only on the UAS pilots but in the way, someone is elaborating on the mission. The goal is to control the aspects of the mission than the UAS.
- **Pilot augmentation:** missions that must be tested first on manned vehicles and after that, if the results are good enough, the crew shall be decreased and get replaced by automated systems, without safety factors getting involved concerning minimization of the cost.
- **Recreation:** new era missions which implement more powerful, cheaper, and lighter UAS.
- **Unique specialized missions:** missions that are not well fitted on the above missions.

Figure 2 and **Error! Reference source not found.**Figure 3 as shown below, represents some percentages of different types of civil and commercial applications. Especially, the latter Figure provides the analysis behind some missions and the goals or the extracting factors that need to be calculated to have the desired results.

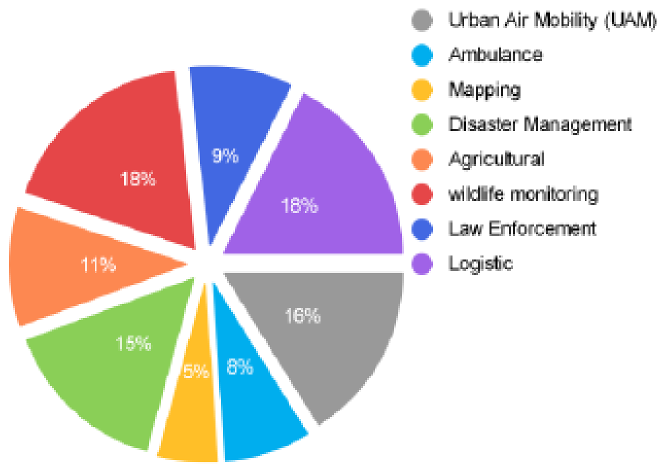

Figure 2: Civil and commercial applications *[1]*

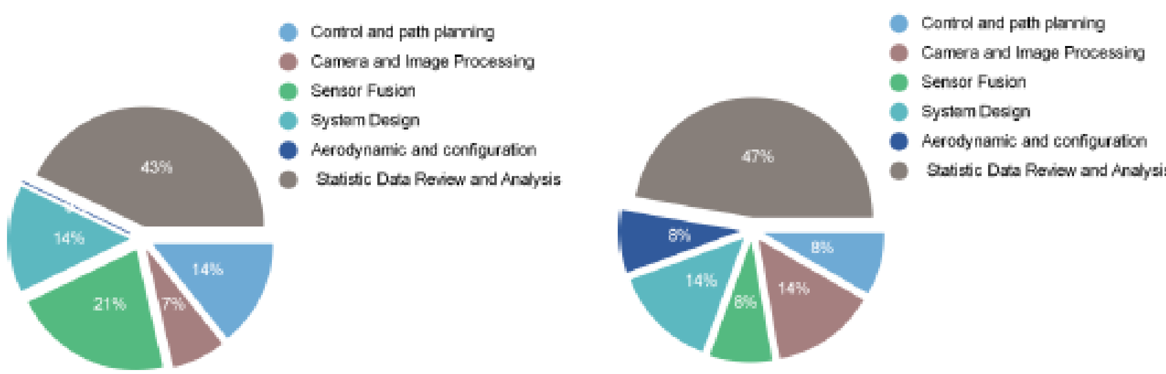

Figure 3: Example of different mission goals *[1]*

It is acceptable that many missions not only need to achieve a unique goal but plenty. For example, below is considered a border security mission to show how challenging these systems are, especially their communications systems which will be mentioned later. Aspects of the missions are: [9]

1. Long-range communications and data handling.
2. Operate both day and night.
3. Be able to adapt to low or high flight profiles.
4. Possibility of cross-border.
5. Face up with dense electromagnetic environments.
6. Immediately respond between ground and satellite relays.
7. Frequently handovers.
8. Successful information dissemination.

One of the most important factors of UAS is the communication link which relies on data and controls messages. It is necessary to optimize these parameters to achieve maximum performance as it going to be seen later on the next Chapters.

2.4 What are the network types available for UAVs?

For ease of use, it is considered that there are two types of networks, terrestrial and aerial. Explanation of these types will be accomplished at a basic level for the suitable information that it's needed. Sources and papers for these networks are many, so there is no reason to analyze them in-depth while this is not the purpose of this thesis.

Terrestrial networks are:

- Cellular: mobile network communications.
- Wireless local area networks (WLAN): Wi-Fi protocols, WiMax, etc.

In these networks, there are communication links between ground station (eNB) and User Equipment (UE), Device-to-Device (D2D), Vehicle-to-Everything (V2X) communications, etc. In the next chapter, some characteristics of these systems will be mentioned.

Aerial networks rely on:

- UAV to ground communication: the link between a drone and a ground station.
- UAV to UAV communication: when there is a connecting link between two UAVs.
- UAV to satellite communication: the link between a UAV and a satellite in a specific orbit.

These two networks, meaning terrestrial and aerial, are easy to be combined but it is hard to optimize such communication channel. Image 2, Image 3, Image 4 and Image 5 show the different ways that a UAV or a swarm of UAVs can communicate with a base station.

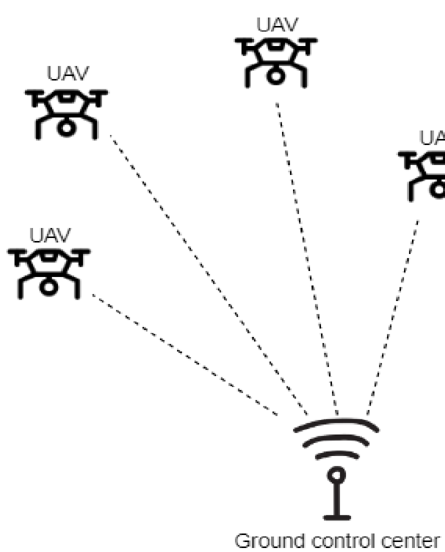

Image 2: Star topology

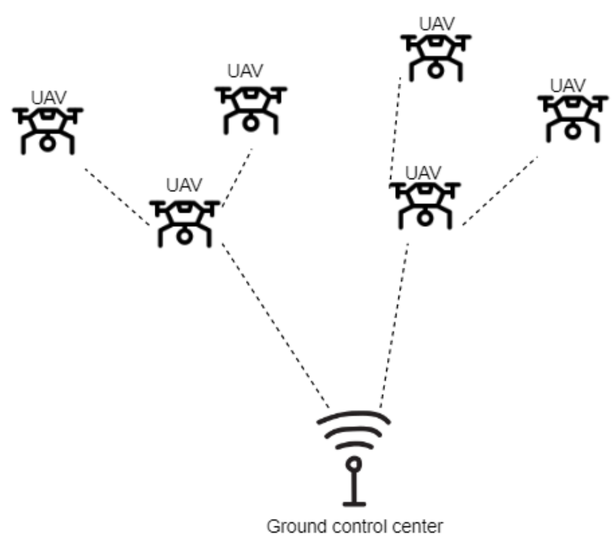

Image 3: Multi star topology

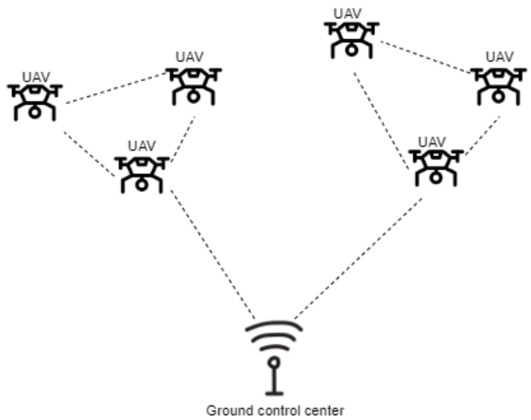

Image 4: Mesh topology

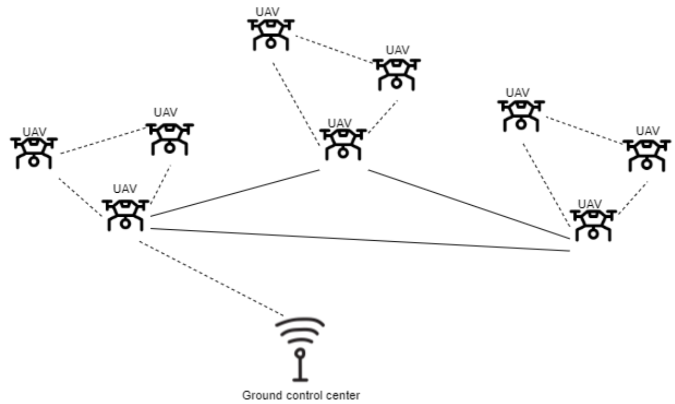

Image 5: Hierarchical mesh topology

In general conclusion, mesh networks are more flexible, and reliable and offer better performance characteristics than star networks. Due to their direct communication and interconnection, a packet can pass through intermediate nodes and find its way from any source to any destination in multiple hops. On the other hand, in applications requiring fast UAV mobility, there is a higher likelihood of disruptions. Delays in transmitting data could be because of poor link quality. Star configurations suffer from high latency as the downlink length is longer than inter-UAV communication, thus the end-to-end link is only created through the ground control center. Also, if the ground center fails there is no inter-UAV communication. So, the choice of network topology, the weight of the payload, the height of the fly, and the communication protocol are all based on the operation that the UAV is called to accomplish. This study doesn’t negotiate the way that the network is set-upped at such a low level. For example, techniques and examples for the type and the topology of the network are referred to but at a basic level, just to provide the necessary assumptions and optimizations.

However, it is worth mentioning that a UAV can be used in multiple ways, for instance, as a relay on/for uplink or downlink. Except for two users that the Figures below simulate, someone could use two ground stations, or a ground station, and a user or whatever simulates better its needs. Image 6 shows that the UAV operates as the middle node between two endpoints. This may happen due to no Line of Sight (NLoS) communication, so a UAV link must be created.

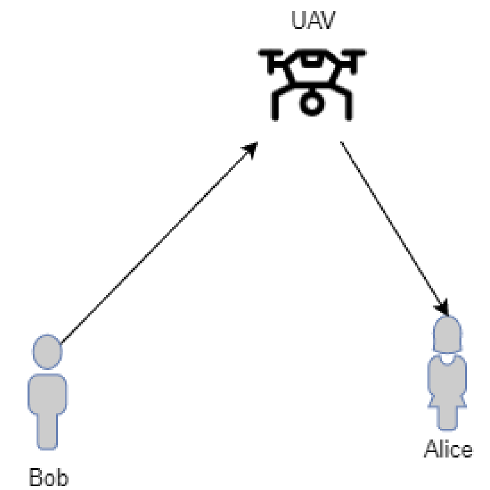

Image 6: UAV operates as rely on node

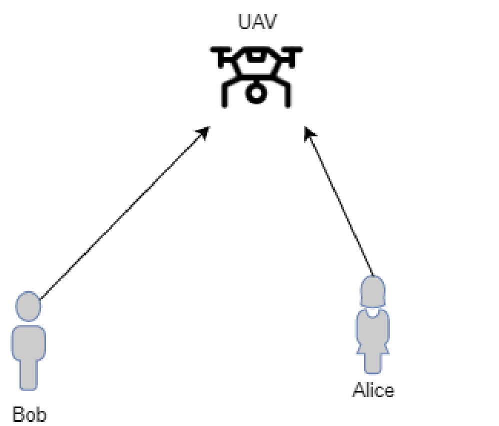

Image 7: UAV only used for uplink

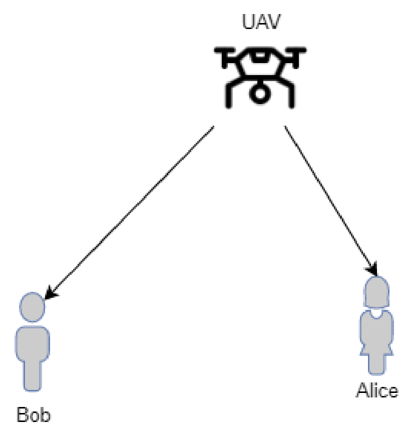

Image 8: UAV only used for downlink

Both Image 7 and Image 8 show the one-way communication between a terrestrial entity and an aerial vehicle. The first one supposes that UAVs are only used to receive data that are stored locally, while the latter one only transmits data to specific entities. The difference between Image 8 and Image 9 is that the last one multicast the message to everyone in the coverage area and not to specific users, thus if a 3^{rd} person was in the coverage area, could normally receive the UAV data.

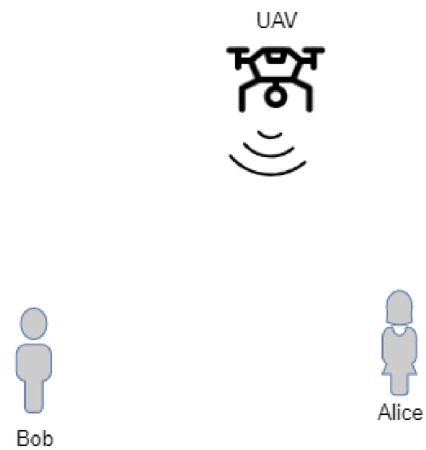

Image 9: UAV operates as a multicasting node

2.5 What are the communications requirements?

The need of exchanging control or heartbeat messages from a UAV in a secure way with other parties, such as remote pilots, nearby aerial vehicles, and air traffic controllers, is very high so it should be possible to ensure a safe, reliable, and efficient flight operation. This is commonly known as control and non-payload communication (CNPC). [10] On the other hand, UAVs may need to transmit and/or receive mission-related data, such as aerial images, high-speed video, sensor metrics, and data packets, to/from various ground entities, such as UAV operators, end users, or ground gateways. This is known as payload communication. CNPC is usually of low data rate, say, in the order of kilobits per second (kb/s) but has a rather stringent requirement on high reliability and low latency, in addition to payload data which is built on extremely high rates. Thus, a non-payload communication link is dedicated to secure and reliable communications between the remote pilot, ground control station and the aircraft to ensure safe and effective UAV flight operation. This link can be either a line of sight (LoS), either air-ground (AG) link between the two entities, or a beyond-line-of-sight (BLoS) link using another platform such as a satellite to establish the end-to-end terminal communication. Different channel links and protocols mean different channel conditions and frequencies of operation, with different metrics such as jitter, latency, and range to be calculated.

2.5.1 Examples of requirements for UAV missions

To justify the above variables and show how they change every time, it's because they depend on the operation of every UAV. Some examples of UAVs operations and their requirements are provided below: [10]

- **Delivery goods:** height coverage at least $100\ m$, payload traffic latency below $500\ ms$ while data rate should be around $300\ kbps$.
- **Recording areas:** height coverage at least $100\ m$, payload traffic latency below than $500\ ms$ while data rate should be $30\ Mbps$.

- **Surveillance or inspection**: height coverage at least $100\,m$, payload traffic latency below $3000\,ms$ with a data rate of approximately $10\,Mbps$.
- **Search and rescue:** height coverage at least $100\,m$, payload latency max $500\,ms$ with data rate about $6\,Mbps$.

2.5.2 Examples of radio and mmWave frequencies for UAV operations

Given the above information and some different types of traffic routing, it is now easy to separate a little bit of the whole situation and how this work in real-life scenarios and not only in theory. Below are given some radio frequencies (RF) and microWave frequencies (mmWave) and their usage.

- **900 MHz:** this band can penetrate obstacles more than the other high-frequency bands. It has low data rates and it’s a narrow band.
- **2.4 – 3 GHz:** it can penetrate obstacles in lower rate than $900\,MHz$. However, it achieves better data rates.
- **4 GHz:** most known, with maximum penetration of 2 walls and data rates of about $10 - 50\,Mbps$. A disadvantage of this band is the number of people using the channels.
- **8 GHz:** it is based on beyond/above 5G, due to the high frequency, the coverage rate is low but the data rates are high enough.
- **Satellite frequency bands:** could be 5 or $8\,GHz$, but commonly they belong in a range of $10 - 60\,GHz$. Extremely high data rates but almost no penetration. Like the room in an X-ray office. Beyond the wall, no exposure to radiation.

Many times, some of these radio bands have common uses based on what they are capable of regarding range and penetration there are differences. The lower the frequency the greater penetration into obstacles between the operator and the UAV. This is due to the wavelength, because the longer the wavelength, the lower the frequency, and the longer the range equals to lower data rates. However, increasing the frequency leads to increased noise, but lower interference is achieved. All these results are based on equations and laws about communication channels and links. Some of these equations will be seen below, but the main scope of this thesis is not to specify how communication metrics work.

2.5.3 Radio and mmWave frequencies for video transmission

Although, there are some basic radio frequencies used by UAS to transmit video. This RF are:

- **2.4 – 3 GHz:** not so-good data rates for video, but big coverage is an advantage while penetration is good.
- **4 GHz:** lower coverage area than $2.4 - 3\,GHz$ and penetration with acceptable data rates.
- **8 GHz:** lower penetration than the two previous bands, but the video quality is good enough.

- **Satellite bands:** no penetration at all, very good data rates due to directional antennas, can transmit on extremely big areas.

Having these in mind, choosing the best communication protocol is not that simple. One must be sure about the priorities and tasks that wants to be done and after that, user must be ready to decide about the transmitting and receiving way of data. A trade-off between the metrics and the features of the link must be considered.

2.5.4 Satellite operations

Entering areas such as big data for almost every application, the demand for the high data rate of a communication system keeps increasing. Although most commercial UAVs communicate based on Line-of-Sight (LoS) fields when it comes to high-altitude drones, and links with the need for high data rates, LoS-based communication is not suitable other than global positioning system (GPS), which is accomplished via a satellite system. One way to solve the problem of long distances, high altitudes, and many Mbps or even Gbps of transmitting data, is to apply a geosynchronous earth orbit (GEO) relay satellite. A communication link between a UAV and a GEO satellite would be extremely helpful because the data shall be first collected by the relay satellite and then transmitted back to the ground station with better link performance. Satellites are an obvious choice for BLoS communications. However, the choice of the satellite orbit, as it's mentioned above, i.e., geosynchronous earth orbit (GEO), distinctly affects the latency, atmospheric turbulence, link budget parameters, Doppler effect, and handoffs/handovers. Simply because of the much larger link distances, for currently planned BLoS frequency bands (above $5\ GHz$), other problems are shown in addition to terrestrial prototypes, close the link between a UAV and satellite will very likely require the use of directional antennas and adaptively focused beams, i.e., mechanical, or electronically steered antenna beams with gimbals and other solutions like encoding and modulating the transmitted data and so on. To make everything more understandable and clear the way out for satellite communications, available frequency bands used for UAV missions are presented. [4] [11]

Table 1: Frequencies used by UAV among with some features

Frequency name	***Frequency band (GHz)***	***Features***
Ku	*12-18*	*1. BLOS communication 2. Direct satellite links*
K	*18-26*	
Ka	*26-40*	
X	*8-12*	*Military operations*
C	*4-8*	*1. Wi-Fi band 2. Used by small UAVs*
S	*2-4*	*1. Used by NASA to communicate with ISS 2. Weather and surface ship radar 3. Good penetration*
L	*1-2*	*1. GPS and satellite mobile phones 2. Good penetration into buildings*
Below	*<=1*	*Low power and long-range UAV operations*

Image 10 below indicates everything noted about satellite communication until now with a more schematic way.

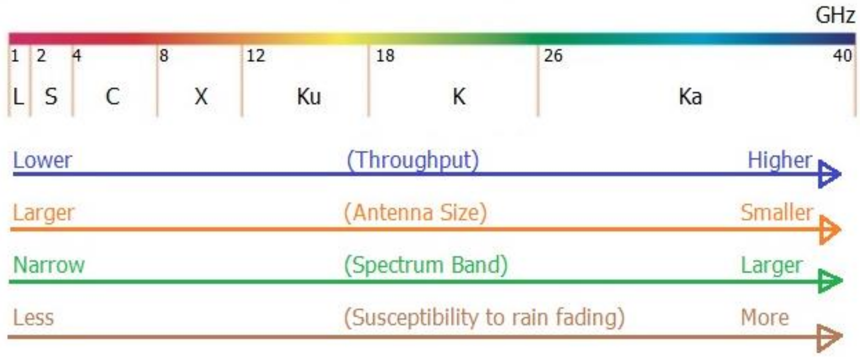

Image 10: Frequency bands and basic features of satellite communication *[11]*

In general, as the study will show later in the next Chapters, high-altitude UAVs are preferable to be controlled via cellular or satellite networks, while low-altitude UAVs can be controlled both from cellular or satellite networks and by radio frequency protocols such as wireless fidelity (Wi-Fi). All the
information shown before with the characteristics of the satellite protocols going to be discussed in more detail later, thus there is no need to analyze and explain everything about satellites in this Chapter. Optimization for every possible solution will be provided, while focusing on the satellite communication model for UAV operations is the main concept of this thesis.

3 TERRESTRIAL COMMUNICATIONS

Terrestrial communications in easy words are everything that communicates on the ground with the basic Internet protocol, without that meaning that the end-to-end communication link establishes over an IP address. Simply it's communication relative to 2D and not 3D like aerial communications. For example, you have a vehicle that moves on the Cartesian space and that means that it cannot move in any $[-Z \quad +Z]$, direction and go up or down. However, many UAV operations are based on terrestrial data links called air-to-ground communication and as it's going to be proved later it's not the same thing due to the reason for movement in 2D and 3D as mentioned above, and that's what is discussed in this Chapter.

3.1 Cellular

A cellular network or mobile network, it's a network where end-to-end communication is wireless but not over Internet protocol (IP). It is generally accepted for the reasons of big data and interference that cellular technologies cannot support large-scale UAV communications in a cost-effective manner. On the other hand, it is also economically nonviable to build new and dedicated ground networks starting from zero for achieving this goal. So, the interest relies upon leveraging the existing cellular network for enabling UAV-ground communications. Due to the very high coverage of the cellular network worldwide, both CNPC and payload communication requirements for UAVs will be able to meet. For example, fifth generation (5G) cellular network is expected to support the peak data rate of $10\,Gb/s$ with only $1\,ms$ round-trip latency, which, in principle, is adequate for high-rate and delay-sensitive UAV communication applications, such as real-time video streaming and data relaying. Even if these numbers are just in theory and not in real-life scenarios and there is deviation, 5G will still provide better communication than 4G generation links.

3.1.1 Types of cellular networks

There are some types of cellular networks called generations. For example, 5G means the fifth generation. However, below in Table 2, some characteristics of these generations are presented to justify the possible scenarios that could be implemented. Many researchers are working on beyond 5G networks with even bigger data rates, but it is not implemented in Table 2 because it is not defined yet as it isn't existed at the time of writing.

Table 2: Generations of cellular networks

Name of generation	Band type	Channel bandwidth	Data rate	Latency
2G	*Narrow band*	*25 MHz*	*144 kbps*	*692 ms*
3G	*Wide band*	*25 MHz*	*2 Mbps*	*200 ms*
4G	*Wide band*	*100 MHz*	*100 Mbps*	*50 ms*
5G	*Ultra-wide band*	*Up to 1 GHz*	*10 Gbps*	*1 ms*

3.1.2 Advantages and disadvantages of cellular networks

Although, cellular technology, which belongs to terrestrial communication, is an obvious candidate for UAV CNPC links. However, problems still exist because of the limitations of these terrestrial links. For example, in a world full of UAVs, when the operations require full scalability and flexibility, it will be important that UAVs can maneuver in the sky. Thus, an instant change in the orientation of the antenna will affect the total performance of the system in a way that will be impossible to have a reliable communication with directional beamforming antennas. Also, a challenge that cellular networks must solve is the need for multi-users at the same time and the same frequency, to access the ground station (GS) without channel collision between users. An easy solution for the problem described is using mmWave communication with high directly array antennas while users are separated based on their departure angle and transmission in dedicated time slots. Based on these problems forming steerable beams using antenna arrays, results in a higher antenna gain compared to an omnidirectional antenna which is most of the time used. Furthermore, steerable beams at any side of transmitting or receiving reduce the probability of the radioactivity being detected and jammed. But nothing is perfectly implemented, so those advanced antennas also introduce system-level challenges such as antenna-array calibration or the need for location and attitude information required for beam steering. Despite the promising advantages of cellular-to-UAV communications, there are still cases where cellular services are unavailable to perform in areas, such as the ocean, desert, high mountains, or forests. In such scenarios, other technologies, such as satellite links, can be used to support UAV communications beyond the terrestrial coverage of the cellular network. One more advantage of a cellular link is the ability to transmit video (and data) in near real-time. It is designed not to uplink the data, but to downlink the data to a ground station with small latency times compared to satellite and for that reason, it’s resulting in aviation operations.

3.2 Wi-Fi

Wi-Fi stands for Wireless Fidelity and it’s a part of Wireless Local Area Networks (WLAN). IEEE 802.11 standards, which are the protocols that Wi-Fi is based on, have been used worldwide since they can function in a wide range of frequencies. Wi-Fi is a networking technology that allows computers, smartphones, tablets, and other devices to connect through the Internet or communicate with each other wirelessly within the specified range. Each Wi-Fi device must be connected to the WLAN network and to a wireless Access Point (AP) to be able to access the Internet (cellular data does not connect to an AP). Due to the global usage of these systems, there is no need to implement new equipment, so it is low-cost and easy to set up. Although, this should be a negative parameter because the more users belong to an area more the interference will be, thus less coverage area and that might cause problems for long distance mission-critical UAV applications. However, considering their disadvantages from the aeronautical standardization point of view, this network is considered as a short-range wireless local area network (LANs). [4] Also, they have not been tested officially for aeronautical use by any official standardization body yet. Moreover, these standards were not designed for aeronautical or aviation purposes, although they have been widely tested for commercial and private small unmanned aerial applications and it is still faster than cellular ones.

3.2.1 Types of Wi-Fi standards

In the last paragraph, it is mentioned that Wi-Fi relies on the 802.11 standard protocol. But what is 802.11 and what should anyone expect from it? Below are presented the 802.11 protocols used now: [12]

- **Wi-Fi 1&2:** known as $802.11a/b$ and it was first created back in 1997. The data rate was $2\ Mbps$ at $2.4\ GHz$ frequency. A newer version came up later to achieve in $5\ GHz$ rates of $54\ Mbps$. The maximum coverage distance was $100\ m$ and for the newer version was $5\ km$.
- **Wi-Fi 3:** known as $802.11g$ and it was released in 2003 achieving $54\ Mbps$ of throughput in the $150\ m$ range, while the band was $2.4\ GHz$.
- **Wi-Fi 4:** known as $802.11n$ back in 2009. It operates in dual band $2.4\ \&\ 5\ GHz$ with $600\ Mbps$ speed and a coverage area of $250\ m$. It was the first standard that used multiple-input multiple-output (MIMO) a wireless technology that uses multiple transmitters and receivers to transfer more data at the same time.
- **Wi-Fi 5:** known as $802.11ac$ in the 2013 year. It is mostly used right now -with Wi-Fi 4- achieving $1300\ Mbps$ data rates in $5\ GHz$ in addition to the small coverage area of $40\ m$. It also supports $2.4\ GHz$.
- **Wi-Fi 6:** known as $802.11ax$ first implemented in 2019. Extremely big data rates of $10\ Gbps$ for $5\ GHz$ frequency in addition to the small coverage area of $10\ m$. It supports $2.4\ GHz$, while it is implementing multiple users - MIMO (MU-MIMO) with orthogonal frequency-division multiple access technologies (OFDMA), so that enables many devices to use the same access point at the same time while sequentially it increases speed, capacity, and throughput while reduces latency.

3.2.2 Advantages and disadvantages of Wi-Fi standard

Like every protocol has its pros and cons, so does it. The most important parameter before someone sends traffic to the network, is security issues. Someone must be sure that the network which is connected on is secure, even if the network is a home network which the user can have everyday access. Even riskier is when using the public network so awareness is a must on this standard because data can be easily jammed or spoofed. Plus, if the internet speed is a manner, then it is necessary to use Wi-Fi instead of cellular networks, especially if someone is making international travel where roaming is available. Also, when a phone has a strong Wi-Fi signal and there is a need for video streaming, it could be more efficient and suitable for the usage of Wi-Fi instead of cellular protocols. Although, 802.11 allows connecting many devices over a network while in cellular this is impossible. However, this might lead to interference and noisy scenarios where the power density of a transmitting user is not acceptable. Thus, there are limitations and trade-offs to be taken before the correct choice of a standard. Using Wi-Fi may be faster, but without a router or low distance between the transmitter and receiver, connection will never establish.

3.3 Results

In this section, some metrics are provided to clarify the results and the comparison between the terrestrial networks. Two Tables will be given and the first one (Table 3) will indicate the commonly used frequencies for UAV operations regardless of whether throughput is control or payload. The other Table (Table 4) will show the communication technologies used for UAV missions. The latter Table includes satellite as a connection link just to show its performance. More details will be given in the next chapter. Both Tables are based on [6].

Table 3: Frequencies used for traffic messages in UAV operations

Frequency	Description
2.4 – 2.484 GHz	*Both wideband and short-range transmission*
5.03 - 5.091 GHz	*Assigned by ITU to passenger and cargo traffic. Cannot use for ground-based UAVs.*
5.47 – 5.725 GHz	*High power is mostly used for radars and LANs*
5.725 – 5.875 GHz	*Based on short-range devices*

Table 4: Technologies used for UAV operations

Technology	Frequency band	Channel bandwidth	Coverage	Data rate	Latency	Mobility support	UAV support
UMTS	*0.7-2.6 GHz*	*5 MHz*	*10 km*	*2 Mbps*	*80 ms*	*high*	*Likely*
LTE-4G	*0.45-5 GHz*	*100 MHz*	*30 km*	*1 Gbps*	*10 ms*	*Very high*	*Likely*
5G	*5-64 GHz*	*2.16 GHz*	*35 m*	*10 Gbps*	*1 ms*	*Ultra-high*	*Likely*
Wi-Fi	*2.4 & 5.2 GHz*	*20 & 40 MHz*	*100 m*	*54 Mbps*	*50 ms*	*Low*	*Yes*
GPS (Satellite)	*1.176-1.576 GHz*	*2 MHz*	*Unlimited*	*50 bps*	*500 ms*	*Quite high*	*Yes*

To sum up, cellular networks use cellular signals to connect to the Internet but in Wi-Fi, protocols signals are radio frequency waves. Wi-Fi and cellular standards are similar - even if the connection establishment differs between them- because they both let you wirelessly connect to the Internet. Thus, it is hard to say if one of these two is better. At the end of the day, Wi-Fi allows you to connect to the Internet more freely -since it is wireless- accessible by many devices, more secure, and cheaper than cellular data. Since Wi-Fi is a local area network, it can only operate within a specified range, unlike cellular networks, which operate outside boundaries. However, anyone can broadcast Wi-Fi signals via cellular networks with a cellular modem, which task is to convert cellular signals to Wi-Fi signals. This is out of the scope of this thesis so there is no need to analyze how this works.

While the implementation of UAVs in terrestrial protocols is important, optimization in link can’t be performed. This is due to the Beyond Line-of-Sight (BLoS) that a drone can fly. In these cases, it is important to transmit and receive data from the aerial vehicle even when ground stations are unable and even if the drone relay on non-visible areas. Hard tracking and communicating scenarios like these are promised to be solved through satellite communications. Satellite work is limited to transferring the traffic from the ground station to UAVs when the first cannot do it by itself. Occasionally it is possible and more optimal that a UAV transmits the data through the satellite and then the satellite routes the data back to the ground station, even if there is a Line-of-Sight communication between the UAV and ground station.

4 SATELLITE COMMUNICATIONS

In telecommunications, the phrase satellite communications refer to the links created between a satellite and an aerial or terrestrial object at high frequencies. The use of these satellites mostly is to provide communication links in various areas globally on Earth and also for offering aircraft tracking. However, in the last years, these links due to the aviation industry could serve aerial users too, like UAVs or drones. This thesis is going to study the use of satellite communications in UAV operations. However, that doesn't mean links will held only in aerial areas but can also orient in terrestrial base stations. In this way, the contribution of Satcoms will be thoroughly investigated. Image 11 and Image 12 indicate what the satellite link is between terrestrial and aerial units respectively.

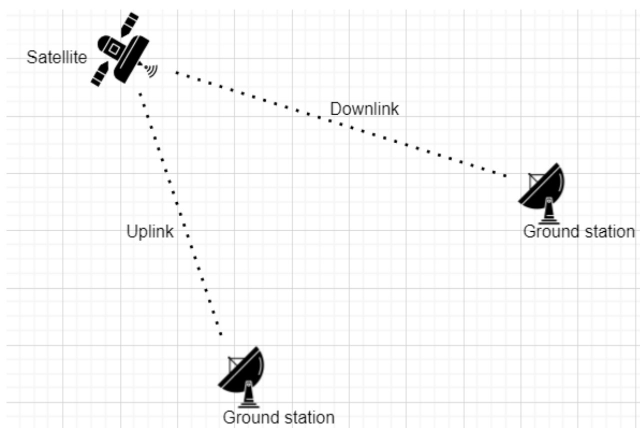

Image 11: Satcoms to ground stations

The above Figure gives an idea about ground communication. For example, one ground station may be in Australia, while the other one is in the USA and because they are in BLoS communication they transmit/receive data through a satellite. Uplink is called the channel where a ground station is transmitting traffic and downlink when the entity is receiving traffic data.

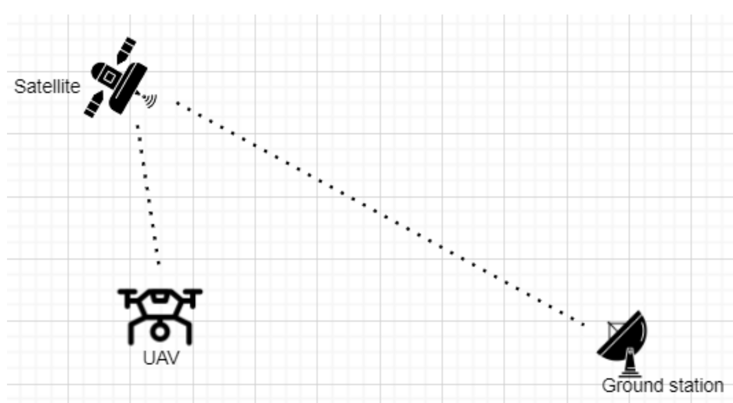

Image 12: Satcoms to both aerial and ground station

Image 12 shows aerial communication where UAVs transmit data to a satellite and ground communication where satellite downlinks the data to a ground station. Due to the earth's curvature, the LoS links can restrict the performance of the mission, which forces UAVs to go to higher altitudes.

It is normal and completely understandable that Satcoms can be very helpful with BLoS communication when cellular and Wi-Fi standards fail to achieve good and reliable data links, like over oceans or forests. Even now, many autonomous vehicles operate with satellite cooperation because these type of system offers a more comfortable ride, manage traffic in better conditions, improve safety, etc. The use of satellite connections may be a complementary or required feature to improve or allow coverage and reliability both for commercial applications and for tactical missions. This is a possible approach to smoothly integrate UAVs into the 5G systems via BLoS links where using low earth orbit (LEO) satellites is the concept of 5G relay nodes. [13] The UAV Satcom system is reliable, and fast enough, with regards to the mission and it is always available to the users, while they can view streaming video, use drone cameras, and can download UAV collected data. However, it is acceptable that somehow regardless of the conditions that exist, a communication link may fail for multiple reasons. Even in these scenarios, UAVs can act as a relay for broken links, and this can only be succeeded using satellite implementation. [14]

The good thing about Satcoms is the flexibility of using different frequencies. For example, one is free to use X-band for their mission plan, while other can use Ka-band, as Image 10 reviewed earlier. So, Satcoms may be an important parameter to localize and navigate a UAV beyond only transmitting/receiving data. Another useful topology that could be succeeded, is the flight ad-hoc network topology the so-called FANET. [10] In this way, many UAVs create an ad-hoc network, they communicate with each other via a routing path, and a user may communicate with a satellite to optimize the performance of the system. In general, the best choice for channel models is relative to the study and operation of UAV communications which depends on the communication scenarios and the purpose of the mission that one is called to do so, since they offer different tradeoffs between analytical tractability and modeling accuracy. In the next sector bands with their usage in depth are summarized.

4.1 Satellite frequencies and their use

Image 10 refers to all available frequencies used for satellite communications. As before said, frequencies may have pros and cons based on distance, latency, and data rates parameters. So, it is good to understand what frequency should be used on what operations. For that reason, it is applied: [4]

- K-band: it is a powerful band that allows big data rates. However, the power consumption for antennas is big enough, while the environmental effects affect the performance of the link. It is used basically for terrestrial microwave communications and for radar purposes.
- Ka-band & Ku-band: the most important characteristic of these bands is the extremely big data rates. These bands are commonly used when BLoS communication is the only solution, because an object obstructs the

communication between the endpoints or if endpoints are far away and the path losses are bigger than the power density of the gain of antennas. NASA's Kepler spacecraft used Ka-band, while television satellites are using Ku-band.

- X-band: is used for military purposes with high security and data rates. ExoMars mission will use this type of band.
- C-band: is the most known band for LoS communications. The frequency is smaller in addition to the K-band, thus both the data rates and the environmental effects are smaller. However, due to its relatively short wavelengths, the signal attenuation is relatively high, which leads to a considerable amount of power consumption. SpaceX SES-22 is using C-band for communication.
- S-band & L-band: these bands have the less big data rates, due to their low frequency, but these frequencies can penetrate more obstacles than any other band. Power consumption is not big enough compared with other bands because distances are not extremely big so there is no need for a big amount of transmitting power for a signal. Global navigation satellite system (GNSS) is using S and L bands so a signal can be easily and safely transmitted regardless of the weather conditions.

After this analysis, it is now known that not all satellite bands can be used for the same purposes. Based on the UAV application, some may be better than others. None can say which is the best band, because none can know the purposes and the tasks the mission must do. Although, last years, the implementation of even lower frequencies, like 433 or $868\ \mathrm{MHz}$ has attracted the attention of researchers. The distances that these bands can travel are bigger than every other band and the penetration is more than good optimal. Problems may be shown up with the small data rate that these bands indicate, but these rates will be enough and reliable for normal use (no big data applications) of transmitting/receiving control messages or even payload data.

4.2 Satellite orbits for UAV links

Except for available bands that someone may use based on the mission application of UAV, some problems must be addressed relative to the orbit of a satellite. Probably these two references, called orbit and satellite bands are relevant, but sometimes maybe not. So, if for example there is a need for BLoS or near real time communication in a UAS, it is better to use a service from LEO constellations due to its lower communication latency. In addition, if the purpose of the flight is the autonomously of the system, then latency is not the biggest and the most important factor that someone has to lay all the applications on. In that way, satellite orbits affect the performance of the system, but it is important to be clear that due to big distances from the antenna mast and the earth's face, real-time operations are impossible with satellite links. For the sake of truth, near real time communication is suitable for Satcoms, where time delays are close to real-time communication, but never the same which sometimes may be critical. Having these in mind, Table 5 presents the most common orbits used for Satcoms: [6] [13]

Table 5: Features of Satcom orbits

Orbit	Elevation	Period	Lifetime	Handoff	Doppler	Path loss	Round trip delay
LEO	*500-1500 km*	*115 min*	*max 7*	*high*	*High*	*least*	*max 30 ms*
MEO	*2000-24000 km*	*3-7 hours*	*max 15*	*Low*	*medium*	*medium*	*max 200 ms*
GEO	*35.800 km*	*24 hours*	*15+*	*none*	*low*	*high*	*0.5 s*

The elevation is the distance a satellite orbits from the sea level, the period indicates how much time a satellite in specific needs to operate an orbit around the earth, while the lifetime indicates the years of a satellite in orbit. The most important fields are the last four. Handoff indicates the possibility to transfer an active data stream to another ground station or other UAV. Doppler is the well-known effect of frequency difference at the destination due to high traveling speeds that it is negatively affecting the communication link as path loss propagation. The path loss is the power attenuation of an electromagnetic wave as it travels in the free space and below is given its equation to make it clearer and more understandable about the metrics that affect it. [15]

$$FSL = -147.55 + 20\log_{10}(f_c) + 20\log_{10}(d_{3D})$$

$$d_{3D} = \sqrt{(H_{GEO} - H_{UAV})^2 + d_{2D}^2}$$

where,

$FSL =$ free space losses.

$f_c =$ frequency of the carrier.

$d_{3D} =$ distance between base station and drone in 3D space.

$H_{GEO} =$ height of the GEO satellite.

$H_{UAV} =$ height of the UAV.

$d_{2D} =$ distance between the base station and drone in 2D space.

because of the huge difference in distances between H_{GEO} and d_{2D}, is applied:

$$(H_{GEO} - H_{UAV}) \gg d_{2D}$$

,d_{3D} can be written as:

$$d_{3D} = \sqrt{(H_{GEO} - H_{UAV})^2 + d_{2D}^2} = \sqrt{(H_{GEO} - H_{UAV})^2} = |(H_{GEO} - H_{UAV})| = d_{2D}$$

So finally, Free Space Losses can be calculated as:

$$FSL = -147.55 + 20\log_{10}(f_c) + 20\log_{10}(d_{2D})$$

Last, the round trip delay is called the delay that a satellite faces when it sends a packet until the response of the same packet is received back by the same satellite.

Consequently, the choice of the satellite orbit depends mostly on the tasks the UAV and of course the satellite call to do.

4.3 Satcom features

Before, is mentioned that satellite bands and orbits must be chosen based on the applications of UAV operations. But what are the features of Satcoms? When must someone choose satellite communications and what must expect from this implementation? Answers to these questions are going to be provided in summary through Table 6, as in basic level are discussed previously:

Table 6: Satcom features

Features	Description
Suitable for UAV operations	1. *Surveillance* 2. *Agriculture* 3. *Disaster management* 4. *Remote area coverage* 5. *Near real time*
Unsuitable for UAV operations	1. *Law enforcement* 2. *Real time operations* 3. *Delivery* 4. *Internet coverage*
General level	1. *Good for BLOS but high propagation losses* 2. *Reliable links but not always available* 3. *Allow mobility but provide low data rates* 4. *No congested frequency bands compared to cellular networks*

However, it is worth mentioning that Satcoms cannot only operate in a single UAV but a swarm of UAVs. On the other way, UAVs may share the resources of a satellite and there is a master UAV that is the only aerial vehicle that communicates with the satellite as previous Figures showed. There is no need to explain these in detail, but it is good to understand at entry level the characteristics of these systems. Thus, Table 7 with some features is extracted.

Table 7: Features for single and multiple UAV

Features	**Single UAV**	**Multiple UAVs**
Failure possibility	*High*	*Small*
Survivability	*Low*	*High*
Speed of mission	*Low*	*Fast*
Cost	*Medium*	*Low*
Antenna	*Omnidirectional*	*Highly directional*
Complexity	*Low*	*High*

One field that must be discussed in Table 7 is the cost, while the other ones are discussed in previous sectors. The cost is not as simple as it probably sounds. The metrics that affect cost are many, like distance, data rates, directional antennas, etc. Therefore, single

UAV seem to be more expensive than many UAVs, and that's based on the link performance. For example, many UAVs equals more equipment cost than having only one, but in addition, many drones indicate many communication paths and links, thus less power consumption and smaller transmit gains for the antennas. Although, the expensive equipment is offset by the optimization of the link performance, so the cost is more economical in the long run. Talking about the cost it is important to know that Satcoms are not always the cheapest communication way compared to terrestrial communication but depends on the distance. Figure 4 shows when it is good to use satellites and when terrestrial bands.

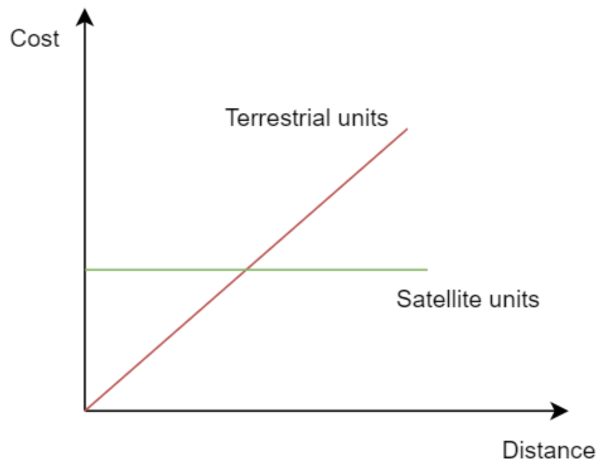

Figure 4: Terrestrial vs satellite cost and distance

From the Figure 4, one can observe that the cost for satellite units is constant, and it does not depend on the UAV regardless of the distance. However, the cost of terrestrial equipment is relative to distance, and as distance increases, so cost does because for long distances you need directional antennas, beam forming, and increment of transmitting power. In general conclusion for small distances, terrestrial units are cheaper than satellites, while for long distances the opposite happens.

4.4 Modelling in telecommunication budget estimations

As technology constantly develops and evolves, telecommunications follows the same pattern. Researchers are slowly moving away from traditional communication networks and leaning towards more promising protocols such as optical fibers and optical communications. The latter sounds promising for satellite communications in drone applications as its performance promises to bring changes to the design and modeling of an already existing system. To be able to study the performance of a system, as far as aerial and optical communications are concerned, one must consider three factors related to the Doppler effect, atmospheric turbulence, and the pointing factor. Doppler effect refers to the change in frequency waveform received by an observer who is moving relative to the signal source. For example, the change in frequency of an ambulance siren as it approaches its listener and the difference compared to when it moves away from it. Atmospheric turbulence is relative to the chaotic movement of the atmosphere and wind gusts due to the atmosphere and a vehicle's geographical location, which leads to reduced performance with the possibility of poor transmission rate and poor quality of service. Pointing factor/error is relative to the angle of inclination of the antenna towards the terminal so that it leads to maximum reception rates and on the other hand it has to do with the structural deformation of the antenna reflector where large antennas, big powers and torques based on the conditions of the system are responsible. For example, in lift-off due to gravity and the acceleration of the satellite rocket, a satellite has to deal with bending, twisting moments, etc.

Typically, in the uplink stream (from the ground station to drone or from drone to satellite), intensity scintillation and beam wander are the main problems, whereas, in a downlink stream (from satellite to drone or from drone to ground station), only intensity scintillation is the effect that must considered. Intensity scintillation causes the received optical signal -power, and phase of the signal- to vary randomly due to rapid changes in the ionospheric electron density, and beam wander is the effect that will result in the random deviation of the beam center in time. In general, the Doppler effect can cause frequency shifts in the received signals. The atmospheric turbulence can cause random fluctuations of the received data and power signal, while the pointing error effect can cause the beam center to deviate. To understand how these parameters affect the link budget, some equations are going to be provided. To be fully understandable, the equations below represent worst-case scenarios where all the relative parameters are obtained. For example, the height and angle of UAV, signal obstruction, scattering, fading, shadowing, etc are parameters that need to be calculated and determined. Of course, it is impossible to consider all parameters that may affect link performance -like the height of the building, a flying bird that may bother the connection, a burst of wind that may affect the attitude of the UAV and so on- but the equations below are something more than a good calculation of some metrics and provide a globally acceptable result under many circumstances.

4.4.1 Doppler effect

According to [16], Doppler effect equation is given by:

$$F_s = \frac{F_B D_{SE}(R_E + H_U)\omega_F \sin(\omega_F t)}{c\sqrt{(D_{SE}^2 + (R_E + H_U)^2 - 2R_{SE}(R_E + H_U)\cos(\omega_F t))}}$$

Equation 1. Doppler equation

where F_B is the beam frequency of the antenna, R_{SE} is the distance between the satellite and the earth center, R_E is the radius of the earth, H_U height of UAV, ω_F angular velocity, t is the current running time and c is the speed of light.

Although, when the UAV is fixed over a place so its velocity is zero, there will be no Doppler effect, thus such higher the UAV velocity will be, a much larger frequency shift of the received optical signals will occur. The maximum frequency shift caused by the Doppler effect in a UAV-to-satellite optical communication system is $70\ MHz$ based on the experiments that took place in [16], while the extra background noise caused by the increased $70\ MHz$ in the bandwidth will not significantly deteriorate the communication performance. Thus, the Doppler effect will be relied on both uplink and downlink systems, but it is negligible for GEO satellites where their position is fixed, while for LEO satellites this is not happening.

4.4.2 Pointing error effect

The point error effect considers a Rice distribution, which is out of the concept of this thesis, so no relative study will be done. Equation is: [16]

$$PE(d) = \frac{d}{\sigma_i^2} exp\left(-\frac{d^2 + BE^2}{2\sigma_i^2}\right) I_o\left(\frac{dBE}{\sigma_i^2}\right)$$
$$\sigma_i^2 = \sigma_j L$$
$$BE = BE_j L$$
$$L = (H_S - H_U) sec(\zeta)$$

Equation 2. Pointing error equation

where d is the distance deviation of the beam center, σ_i is the scale parameter of jitter, BE is the boresight error which is the difference between port-to-port voltage ratios, σ_j and BE_j refers to angular deviation, H_S is the height of the satellite, H_U is again the height of the UAV, ζ is the zenith angle, L is the length of the link and I_o is the Bessel function of rank zero.

It is sometimes possible the pointing error effect can be neglected because of the great stability of the two terminals. But when a UAV is used as a terminal or a middle node, due to high mobility and random movements of weather conditions the pointing error becomes important and a must count factor. Based on the experiments of [16], when the pointing error effect is determined, the beam wanders effect leads to receiving optical signals not in the right position, but away from the beam center, which will impact the performance of the system.

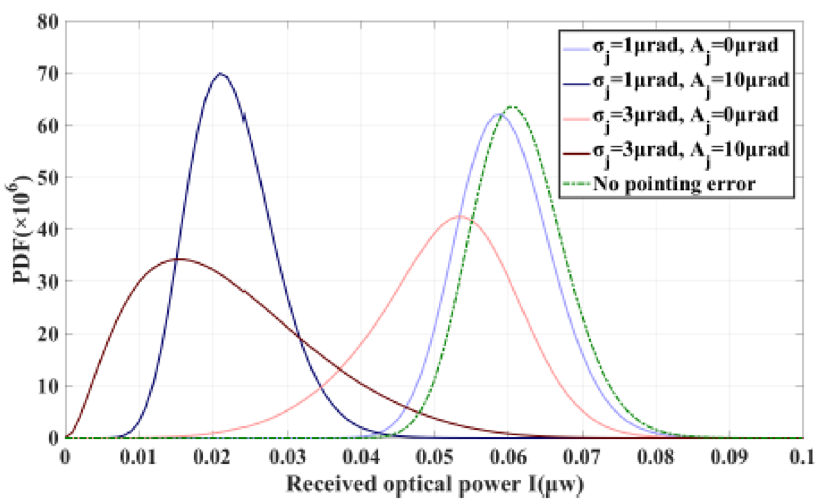

Figure 5: PDF for both pointing and no-pointing error for uplink channel

Figure 5 shows the results whereas long angular deviation is small and proceed zero values, the PDF will be at the same levels and the received power will converge to the received power of no pointing error which is the optimal performance. Both σ_j and BE_j (which is the same as A_j) indicate that as the pointing error becomes larger (either jitter increases or boresight error increases), the receiver is more likely to receive a lower optical power. Thus, when designing a UAV, we should consider the effect of pointing errors thoroughly. The same metrics could be shown for the downlink channel too, such as Figure 6 that indicates the results were previously discussed.

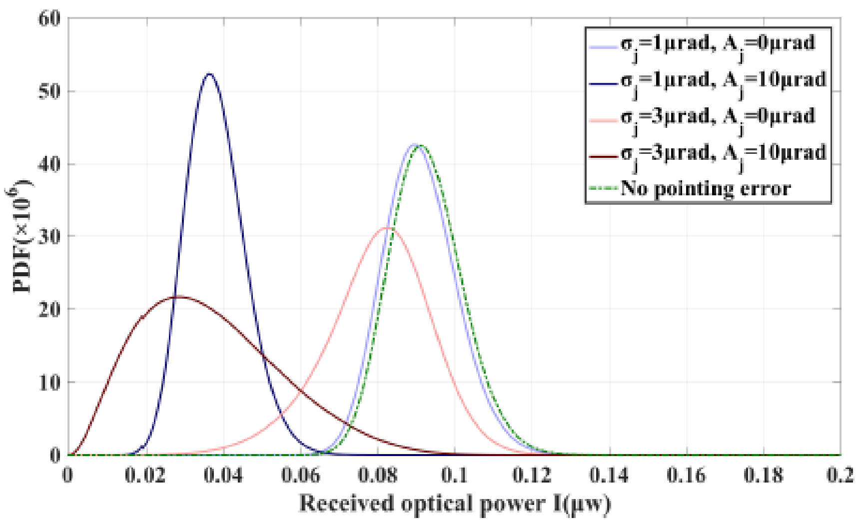

Figure 6: PDF for both pointing and no-pointing error for downlink channel

The difference between uplink and downlink channels is that the later beam wander is a factor that it doesn't have to consider. It is important to mention that $\sigma_j = 3\ \mu rad$ means high jitter relatively to $\sigma_j = 1\ \mu rad$, while $BE_j = A_j = 10\ \mu rad$ means big boresight error regard the value of $BE_j = A_j = 0\ \mu rad$.

4.4.3 Atmospheric turbulence effect

Atmospheric turbulence is more complicated due to the intensity of scintillation and beam wander. It is assumed that the laser beam follows Gaussian distribution, then the effect of beam wander which as previously mentioned affects the beam center deviation can be modeled as a Rayleigh distribution and intensity scintillation which is responsible for the random variation of the receiving signal can be modeled with probability distribution function. The below equations digitize the atmospheric turbulence parameters and are based on [16]:

$$AT\,(d, RP) = \frac{1}{RP\sqrt{2\pi\sigma_{RP}^2(d,\ L)}} exp\left(-\frac{\left(\ln\frac{RP}{\langle RP(0,L)\rangle} + \frac{2d^2}{BR^2} + \frac{\sigma_{RP}^2(d,L)}{2}\right)^2}{2\sigma_{RP}^2(d,L)}\right)$$

Equation 3. Atmospheric turbulence equation

Where AT is the atmospheric turbulence, d is the distance deviation of the beam center as indicated before, RP is the received power, σ_{RP} refers to angular deviation, L is the length of the link, BR is the beam radius and $\langle RP\rangle$ is the mean received power.

$$\sigma_{RP}^2 = \kappa^{\frac{7}{6}}(H_S - H_U)^{\frac{5}{6}} sec^{\frac{11}{6}}(\zeta)\left[8.702\mu_3 + \ 14.508\lambda^{\frac{5}{6}}\mu_1\left(\frac{d^2}{BR^2}\right)\right]$$

$$\lambda = \frac{2L}{\kappa BR^2}$$

Equation 4. Intensity scintillation equation

Where σ_{RP} refers to angular deviation, κ is the wave number, H_S and H_U refers to the eight of the satellite and UAV respectively, ζ is the zenith angle, μ_3 and μ_1 are two parameters which depend on the link parameters, d is the distance deviation of the beam, BR is the beam radius and L is the length of the link.

$$BW(d) = \frac{d}{\sigma_d^2} exp\left(-\frac{d^2}{2\sigma_d^2}\right)$$

$$\sigma_d^2 = 2.07\int_{H_U}^{H_S} C_n^2(L-z)^2 BR(z)^{-\frac{1}{3}} dz$$

$$BR(z) = \ BR_0 + \frac{a_z}{2}$$

Equation 5. Beam wander equation

Where BW is the beam wander, d is the deviation of the beam, C_n is the refractive index structure parameter at the position z, BR is the beam radius and a_z is the divergence angle at the z position.

Therefore, a GEO satellite where the position is constant at a time can be used to transmit data to a UAV to avoid strong atmospheric turbulence. A good approach to increase the performance of the system is a laser emitter to receive the frequency-shifted optical signals caused by the Doppler effect which is placed on the satellite whose limitations of payload are not so restricted, and it results in more transmission power in a downlink system. However, it is good to know that a UAV should be kept at a certain height of $400\,m$ to avoid atmospheric turbulence. Furthermore, when transmission power and receiver diameter are determined, an optimal divergence angle can be configured to optimize the communication budget to further achieve better performance. Finally, even a different type of modulation for bit streams, like BPSK should be indicated to achieve better performance of the UAV-to-satellite communication, when jitter or boresight error is weak. BPSK conveys data by modulating, two different phases of the carrier signal and it’s used in OFDM systems, like 5G implements. However, there is no reason to study more about the types of modulations as the main purpose of this Chapter is to implement some techniques to improve the performance of the Satcoms and not to find the best approach for every technique.

4.5 Advantages and disadvantages

In this section are going to be discussed some of the advantages and disadvantages of Satcoms. Probably some of these features described below have been mentioned in previous subsections but will be mentioned again so that they are partially organized and consolidated into one subsection. The description will start by mentioning the disadvantages, while the advantages will be analyzed afterward as solutions to many of the former ones.

First, a very important parameter is that orbit affects latency, and an example of this is the Doppler effect or air turbulence in a way that as the orbit altitude increases, so does latency. LEO faces less latency than GEO, in the case of GEO the latency can reach $0.5\ seconds$ due to high distance, but the Doppler effect is negligible for GEO satellites because velocity is zero. Based on that, often apply that as the altitude increases the coverage probability is decreasing due to a low signal-to-interference (SIR) ratio, which is determined as receiving power divided by the white noise plus interference, caused by high interference and low receiving power leading to path losses and multi-path fading. As a result, latency can strain the autonomous function of the UAV if and only if there is a need for real-time scenarios. Another problem that satellite links must deal with is the high frequencies. The high-definition video and photos have led to big data technologies and provided a long delay which requires more capacity to be served at the right time. The high-frequency bands can manage problems relative to big data rates but are sensitive to signal degradation because they are absorbed by weather conditions like fog, rain, snow, etc. Also, from the perspective of UAVs limitations for size, weight, and power due to their small size exist, and that occur to inability of carrying a directional antenna which will be heavy and energy-consuming. Another issue that need to be addressed is the problem of mobility. In general, aircraft have flying speeds much bigger than ground vehicles. So, antennas based on terrestrial vehicles cannot perform optimally for UAVs and aircraft that fly in 3D instead of 2D, because variables like azimuth and elevation angles must be considered more carefully than before on 2D planes.

On the other side, some of these problems shall be addressed with the advantages and solutions below. Directional antennas with narrow beams seem to be an effective way to reduce interference and handovers related to UAVs. But another reason for lowering interference is the definition of a specific bandwidth for aviation purposes -so no user interferes with another user- by the authorities. Furthermore, multi-hop links may solve the problem of collision and interference. Since the altitude of a UAV is much lower than a satellite many UAVs can be used both to de-load the traffic from one UAV and to route the traffic among the many UAVs of the network. Thus, maybe a UAV has less coverage area compared to a satellite, but it can provide broadband service to a subset of users

(not to everyone) in a very reliable, safe, and good-performance way. Now, from the perspective of satellites, the antennas
that are carrying, are designed optimally and not to add extra weight. Problems according to signal degradation should be easily solved by using signal processing in association with advanced processor/calculation functions and with maximum throughput rates. For those reasons, limiting energy consumption is achieved and UAVs are placed in positions that could stay stationary at the assigned location as near as possible to the ground station. Intuitively, the closer the UAV flies to a ground station, the less energy is needed for the latter to transmit its data. Also, the high-capacity wireless connection between the access node and the core network is needed for the reason of real-time UAV applications. An interesting solution for latency is the automation of the mission. In that way, UAVs would be completely autonomous, and time-related issues will not be manner while this approach will also eliminate the need for low latency links.

To sum up, in this Chapter the analysis of satellite communications was discussed. Information about satellite links, orbits, pros and cons, and many more were ejected to make it easy to understand what a satellite link is and how it works. Another goal of the Chapter was to keep it as readable, condensed, and organized as possible without tiring the reader but encouraging him to do more of his work.

5 ANALYSIS AND DESIGN OF SATCOMS

This chapter condenses the previous information and formats it in such a way that some advantages and disadvantages of satellite communications are clearly understood. In the following, some techniques applied to the previous Chapter will be analyzed in simpler terms to maximize the link performance. So, this chapter will study the design and modeling of satellite systems without tiring and discouraging the reader. Additional work will be required from the reader in case he wants to delve deeper into a technique as it is impossible to thoroughly study all optimization models, as well as the possible combinations of applying them to communication links.

5.1 Hardware and software architecture solutions for SatComs and drones

5.1.1 Multi-UAV and multi-hop links technique

It is assumed a swarm of UAVs connected both with terrestrial and satellite units to maximize performance. The reason for having multiple links through multiple UAVs is for supporting the central management of UAV communication behaviors. Moreover, it enables frequency hopping when some frequency resources are congested, e.g., operation in urban areas so link performance must be optimized. Although, three technical gaps concern the scientists relative to the resources of a system. How this information will be safely transmitted to each UAV, then how to allocate these resources equal to each other while each linked resource must be allocated by one UAV and the last thing is to switch to another customer when and only when the link resource time is finished for the previous vehicle, so it is now free and ready to allocated by other UAV. [3] But what happens if a UAV must transmit its information in a specific time rather than when the resource is free? What if a UAV wants to transmit rescue messages -which is high priority message- while another one wants to send just a photo? To answer these questions a variable that represents the highest priority is used. In that way, the most important messages will be first transmitted. The algorithm is greedy based and below the pseudo-code is presented. This algorithm is calculating the priority from the first UAV and each UAV is starting to calculate the maximum value. In the end, if only one UAV has the max value it can allocate the channel, otherwise -if for example are three UAVs have the same value- the channel will be allocated in this UAV which will optimize the performance of the link. The optimization is substituted with two cases: (1) minimizing the time interval time between the start time and the end time of the resource which leads to maximum throughput, (2) maximizing the remaining time duration of the resource in interest which leads to using the resource as much as possible.

```
Initialization of parameters
while available_UAVs do
    Calculate the priority for the UAV with the closest opportunity.
    Select a value T = max(priority) according to the maximum value of
objective functions.
```

```
    Find link opportunities for each UAV that satisfies priority >=
max(priority).
    if Only one UAV is allocated to this opportunity then
        Save link opportunity T to n-th UAV.
        Remove previous UAV when Tprevious <= Tn.
        Update parameters.
    else
        Save link opportunities Tcurrent with the maximum link_performance
value to n-th UAV.
        Remove previous UAV when Tprevious <= Tn.
        Update parameters.
    end if
end while
return T
```

Image 13: Pseudo-code for an effective resource allocation

5.1.2 Radome antenna design

Another implementation for providing a better quality link is the use of radome for the antennas, in a way that also decreases the electromagnetic interferences of a Satellite terminal station. However, this design fit better to large unmanned aerial vehicles (UAVs) which use a bidirectional SATCOM link for communication with the ground station and they don't have too much restricted limitations to mass and power consumption. A radome is a structural, weatherproof enclosure that protects a radar antenna [17] and it's constructed of a material transparent to radio waves. The aim is to use radome in a manner that minimizes radio-frequency (RF) signal loss which is big due to long distances. Image 14 shows a radome.

Image 14: Radome on a ground station

Another example of a radome is the radome of a yacht which is used to protect the directional antennas/dishes which carry for its telecommunication. The optimizations to be made are, the weight, the thickness of the outer wall, the aperture illumination of the antenna as well as the focus or direction of the antenna it carries to always mark the terminal point of information reception. So basically, to achieve directional communication and not too many losses, the antenna is mounted on a gimbal that provides two degrees of freedom to move freely in a two-dimensional frame. This factor is quite important because if the transmitted power is not maximum at the receiving point, the $3\ dB$ problem is created which means that if the power is reduced by $3\ dB$ the communication efficiency drops to 50%, [18] while this can be seen from Image 15 which presented below. Also, be mentioned, in 3D space, it is more commonly, that a UAV is not served by the main lobe of the antenna graph, but from one of the side lobes due to high altitude relative to the ground antenna. So, it is important to use the sidelobe which transmits more power and optimizes the performance of the link.

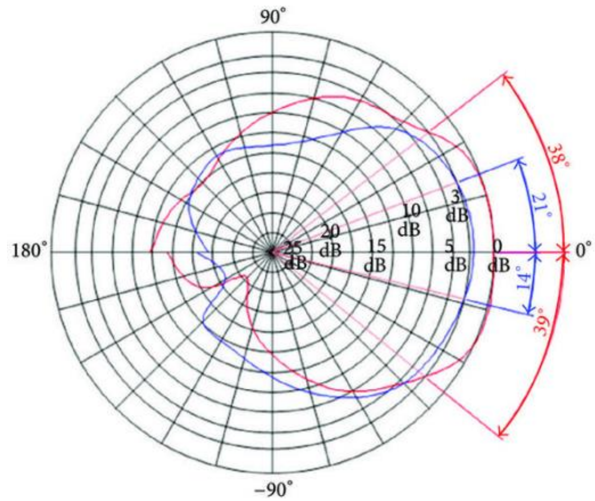

Image 15: 3dB rule

As a result, depending on the location (latitude, longitude, and altitude) and attitude (pitch, roll, yaw) of the aircraft, the antenna beam passes through a different portion of the radome every time. The outer wall is created by several layers of dielectrics, thus, to remain transparent to electromagnetic waves of the transmitting/receiving frequencies of the antenna. Lastly, it is necessary to optimize the weight of the radome so there would not be degeneration of the radio frequency signal due to the induced losses. A good mass constraint to have in mind is that the radome must have less than three plies of quartz/epoxy as older experiments from other case studies provide. [19]

5.1.3 Material used for structure

When talking about design and modeling, it is important to understand where the problem of optimization starts and how changes should not only be addressed in parts of a system but often in the system itself. This means that the structure material of satellites or even more of drones, must change. Recent research [2] shows that airframe performance is optimized when composite materials are used, like glass (plexiglass) and quartz fiber. This is an innovation that most aircraft use nowadays to achieve better quality. For example, plexiglass is stronger than plastic for bending torques. Another example of this new material is its weight, which is less than plastic, while it provides better noise cancellation. One important parameter that anyone shall not forgive is the environmental effects, while glass is 100% recyclable, but plastic must be processed to be recycled. These were just some common advantages, but below are presented all the advantages compared to the airframes used until now:

- More endurance refers to lifetime and torques without bending.
- More payload capacity while it can carry heavier cargo equipment due to the previous bullet.
- Short lead time and built time for spare parts. This happens because of the Use of Computer-Aided Design (CAD) of models and computerized numerical control (CNC) machines which do very fast and effective manufacture.
- Well-tested and not out-of-date materials validated by the International Civil Aviation Organization (CAO) and the airline industry.
- Better performance and studies for airfoil coordinates, while it provides better metrics for signal pulses and dynamometer engine tests, when with the old frame metrics were about to control level and how to proceed with some vulnerabilities.

5.1.4 Intercommunication between multi UAVs system

Establishing and maintaining efficient communications among the UAVs is challenging. High mobility among the network, leads to many handovers, congested frequencies, and bottlenecks at the receiving station. In this way, it is possible a fluid station like a satellite which is constantly in a move, serves a UAV and after a small period will need to serve another UAV, but the previous UAV must be served by another station seamlessly, without disrupting the user sessions. Traditional network topologies cannot solve these types of problems, but inter-communication for a swarm of UAVs can. This provides safety and communication links with every UAV given a path, even if the communication link from terminal to drone has a failure. However, for the sake of truth, this technique will probably lead to various changes in the layer levels of packets. For example, both media access control (MAC) and Network layers should change in a way that links will be tolerant to delays and maybe some packet losses, and have a more flexible and automated control characteristics, while power consumption shall be reduced -something like sleep mode- where the UAV will wait for the link to be up/available again.

Thus, it is important to use a store and forward algorithm for packets, where the UAV waits to receive a packet and then (when successfully receives it) moves on the next packer reception. Otherwise, if the packet was lost, UAV resends a message which informs the terminal for not receiving the packet that it was waiting and if possible, to re-transmit it. For multi-UAV systems, the concept is the same. The algorithm is store-carry-forward where a UAV can act as the middle node, so the specific UAV must first store the message so it cannot be lost and then carry and forward it to the next UAV.

Delays are also an important field for this communication, although if the data cannot be delivered under a specific time slot, then the node chosen to carry the message is the node that has the highest probability of delivering the message. [20] That means, the intermediate node is figuratively and unable to carry the message to the next one, so the bearer is more likely to carry it to the end-user terminal than the one who would like to forward it if the delay wasn’t a problem. Although the results show that as the number of UAVs increases, the throughput increases too, since the number of contending -users who have been served by the same UAV- decreases. Plus, it is also observed that the packet delivery ratio and the average delay improve significantly as UAVs increase, due to redundancy vehicles for optimizing the metrics of the system. Don’t forget the possibility of a short-time blockage, where the stream can be paused shortly and resumed when the path is not blocked again, or for long-time blockages, like blockage from a building, where the only way is to physically resort to another UAV from a non-blocked direction. In these scenarios, multi UAVs or even intercommunication between these UAVs can be very helpful to still perform a good connection even with some added latencies due to new routing paths that must be created to allow traffic flow among the networks. In the worst case, if all UAVs are blocked from a specific user who wants to be served at a given moment, then one UAV could change its route and location to where the transmission is not blocked, thanks to its maneuverability. [21]

5.1.5 Multi UAV for energy efficiency

Related to the previous technique of multiple UAVs in a close area, is the research of source [4] for power consumption-related problems. Swarm UAVs solve many problems related to link budget, power consumption, and safety obstacles. Thus, a popular approach is to employ a large number of small, low-cost UAVs to cooperate and make a large-scale network, like 5G network implementation does. For example, it is better to have five (5) antennas in $1\ km$ with a range of $200\ m$, rather than one (1) antenna with a range of $1\ km$, like UAVs should follow the same approach. As it mentioned before, multiple UAVs optimize resource allocation, so there is optimization on the link budgets like transmit power, frequency multiplexing, multiple access, etc. Systems with few subcarriers would provide better performance in high-frequency UAV applications, due to large Doppler shifts. These systems are called orthogonal Frequency Division Multiplexing (OFDM) where data stream (or users) can be served at the same time in separate sub-channels. Someone can imagine this technique as a pulse where from 0 to 1 there are two edges (orthogonal) so more than one user can be served. In the end, users are orthogonally placed to each other, requiring less bandwidth since more users are using a channel, thus the interference is less than a one user who constantly binds the data channel. Finally, it should not be underestimating the latency of the network which is relative not only to the distance between two endpoints. The bandwidth of a given channel, the traffic load on the network, and the constellation's capacity are some examples of other factors that affect the latency and someone has to be very careful about implementing more and more drones in a small area cause the network may be more congested than never before.

5.1.6 Design of aviation standards

Another technique for optimizing the link estimations is to do changes in data aviation link standards. Although, as it is going to be shown later, the best solution from the perspective of performance metrics, is to design/implement an aviation standard with many features necessary for different types of missions, offering different levels of quality of service (QoS), data rate, latency, and robustness. A good mention example called ADS-B and which is a modified Automatic Dependent Surveillance-Broadcast (ADS-B) system in which an aircraft determines its position via satellite navigation or other sensors and periodically broadcasts it to the ground section, enabling it to be tracked. [22] This channel is used from many transponders between UAV and ATC, so this technique requires both terrestrial and satellite entities to be implemented, and it is an alternative to a common radar by sharing the situational awareness information of its place, position, and height among all the aircraft and it also could be for collision avoidance. Transponders are going to be analyzed later on. Many possible standards for the use perform better than the common one (802.11 protocol), but the best protocols to examine their behavior include AeroMACS, L-DACS, ADSB, IEEE 802.11, and VDL Mode 2. [4] In Table 8 below, some pros and cons of these standards are provided.

Table 8: Aviation standards

Standard	Frequency	Pros	Cons
AeroMACS	*5091-5150 MHz*	*Flexible*	*Low mobility*
		Adaptable	
L-DACS	*164-960 MHz*	*High mobility*	*No flexible*
		High coverage	
ADS-B	*978 and 1090 MHz*	*High mobility*	*High cost*
		High coverage	
		Situational awareness	*No flexible*
IEEE 802.11	*915 MHz or 2.4 and 5.8 GHz*	*High throughput*	*Low mobility*
VDL Mode 2	*117 and 137 MHz*	*High mobility*	*No flexible*
		High coverage	

Although, using cellular stations concerning small coverage areas by tower cells, while UAV compromising high mobility leads to multiple handovers and traffic among the channel link, and this cause both data and frequency bands congestion. Increasing the transmitted power -as shown above, for specific frequencies- is usually considered as wasting power and causes interference with others. However, implementing cognitive radio UAVs can establish instant connectivity in a multi-UAV system to form a wireless topology with devices in the affected area. The cognitive radio concept is based on changing the spectrum access dynamically by observing the occupied channels and moving to the vacant ones. Another advantage of ADS-B is the operating frequency which belongs to 978 & $1090\ MHz$. [4] Thus these frequencies can easily penetrate buildings and walls and also there is no signal propagation because frequencies are not that high on the scale. As the previous Chapters study provided, the use of cellular communication is only possible for UAVs flying under $125\ m$ due to better signal-to-noise (SNR) and signal-to-interference (SIR) ratios. At higher altitudes, satellite data links are mostly used, thus it is a combination of both ground and satellite units concerning the mission tasks. When UAVs need to travel a long distance, each one of these will be served by multiple cell towers. In this technique, two or more base stations coordinate the transmissions and the receptions to the end-user to improve the availability. At the end of the day, the best standard provided by studies and experiments is to use ADS-B instead of the 802.11 protocol.

5.1.7 Connection technique between control and communication

In previous sections reference was made either to the altitude of the UAV or to the angle of inclination of the antenna with the terminal or to some other design and modeling techniques that are worth considering for an improved model. However, there was no correlation between altitude and communication. So, this is what this section is about, where it tries to emphasize the interrelationship between these two, where communications and control are highly coupled in the UAV systems as previously said. Until now, communications and flight control systems appeared as two different entities, but in reality, for UAVs, this is not the case and there is a need to integrate these two. This can be achieved by trajectory design or some other techniques that calculate the position and state of the components of a UAV at any given time and moment. By trajectory design, it means the fundamental laws of orbital mechanics, perturbations, the height of the satellite, its velocity, atmospheric drag, etc, and that parameters help to produce a robust and based in real conditions design. To realize how dependent the relationship of one is on the other, some examples are presented which affect the performance of the link as a function of altitude and control.

- gain of the antenna.
- transmit power of the antenna.
- azimuth and elevation angle.
- doppler effect.
- sampling ratio.
- steering vector.
- carrier frequency.

In Image 16 below, the procedure one should follow to optimize the performance of the communication link regarding the beam's direction is indicated. [21] It is possible to not just need a PDI microcontroller but a hybrid like an LQR so that finally a stable and reliable result is achieved.

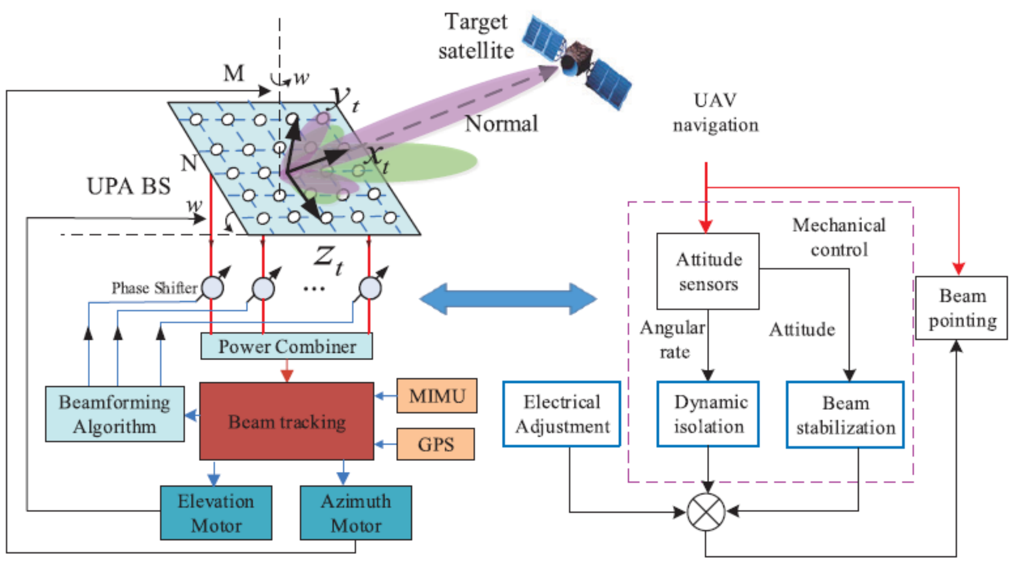

Image 16: Beam tracking for Satcoms

This Figure shows that to have a direct communication link between a base station and a satellite there is a need for both electrical and mechanical joints. For example for the satellite perspective, sensors and gimbals are the most important components. These two can provide information about altitude determination, beam pointing, and stabilization where a servo motor can be used too, which will direct the beam of the antenna based on some calculations of a micro-controller. On the ground station side, it is important to know the altitude of the aircraft so one can indicate the elevation and azimuth angles, while a necessary component is the GPS and miniature inertial measurement unit (MIMU) components which integrate navigation and filtering algorithms for a vehicle. Also, there is a need for phase shifters which will shift the phase of each signal to be in or out of phase with another signal, and mostly encoders, decoders, modulation, and demodulation components are needed to transmit/safely receive payload. Thus, trajectory design could make things less complicated and improve the performance of both control and communication layers which seems to be autocorrelated by combining both electrical and mechanical joints.

5.1.8 Compression and software design

Previously an indicative reference was made to the encoding of the data and therefore also its compression. The section examines a system entitled Adaptive System for Image communications in Global Networks (ASIGN) which promises fast real-time data rates at a very low cost compared to the existing satellite communications system. [23]

A major disadvantage of satellite communications, as seen in previous examples, is on the one hand the low data rates and on the other the cost for the traffic that a user must send, which is charged by the $Mbyte$ or by some equivalent unit. Imagine someone needs to take high-definition video and photos in real-time and wants to send the data to a ground station via a satellite link. The cost for such an eventuality which is quite feasible always talking about UAVs and aerial communications is quite high. It is estimated that for each Mbyte for high-resolution images or streams the providers charge $15-20$ €, [24] while an image could be up to $10\,Mbytes$. Therefore, it is completely normal and understandable that for many hours of flight surveillance and monitoring the cost becomes extremely high, in the order of tens of thousands of euros. Below a formula for the quantification of the transmission cost and its dependencies is provided: [15]

$$^{Cost}/_{day} = number * time * data * [cp_c a + s(1-p_c)(1-a)]$$

where,

$number =$ number of operational UAVs in flight.

$time =$ number of hours in a day.

$data =$ flight time given in hours multiplied by data rates given in Mbytes.

$c =$ cost for cellular Mbytes.

$p_c =$ average percentage of UAVs in flight using the cellular network.

$a =$ average percentage of flight time in which the cellular network was used.

$s =$ cost for satellite Mbytes.

To simplify the above equation, eventually it would be true:

$$\frac{Cost}{day} = cD_c + sD_s$$

where,

$c =$ cost for cellular Mbytes.

$D_c =$ total data per UAV using cellular network.

$s =$ cost for satellite Mbytes.

$D_s =$ total data per UAV using satellite network.

So, the strategy behind ASIGN to minimize cost due to expensive $Mbytes$ from satellite providers is simple and supports that data is not for everyone but for those who need them and will use them at the moment they request them. Otherwise sending data to many terminals that are not going to use it at the time of recording leads to wasted spectrum and increased costs. The ASIGN UAS concept for UAV and aerial communications optimizes access to data while the UAV is in flight and also allows situations with an economical framework to be used. ASIGN is a hardware-agnostic, software-based solution innovated by AnsuR which is using a push-pull methodology like client-server to transfer relevant high-definition photos and streaming procedures. Its advantage is the resource management that is applied where a network coding scheme is implemented to achieve better throughput rates by multi-hop routing links for critical data packets. Its modulation and compression are beyond the already known techniques and provide full accessibility of high-quality images in relatively economical and low latency ways. The key steps of this innovation are the observation from sensors, photos, videos, and cameras, the decision taken by signal processing of previous metrics and data, and the act where specific commands and data are sent to the end user to start acting based on data retrieved on the OBC. The compression of a high-resolution image is about 300 times which from $10\,Mbytes$ is going to be $20\,kbytes$, while it allows transmitting a high-quality spatial segment of the original information if it is necessary with lower compression rate. The same thing happens with live stream video, where quality can be degraded down to 1000 times but it could also be transmitted with high resolution at specific frames based on the needs of the application. Further ASIGN can be fitted and adapted to changes in channel capacity for a given time without collision and bottlenecks on the terminal, while it allows the transmission of the video with many terminals but can be used only by the one who needs the data most. For example, the video streams will be transmitted to all terminals by sharing the video frames but can be processed only from terminals that need these data and not from all terminals that watched the video. Finally, it lies on the 7^{th} layer of the OSI model called the application layer, and also has dedicated protocols while this combination of layers and protocols is called (GR4-COMS). Thus, its implementation is easy and could be done over a PC, smartphone, or even from Linux distributions, while low bandwidth, low cost, and effective transmission rates over different protocols like SMS, email, Wi-Fi, etc are met. To sum up, the features of ASIGN that can be successfully met are: [23]

- Automatic push of the images and video.
- Pull video and data from the server.
- Remote control of the cameras of the object that ASIGN is set.
- Full control of video streams for the day, night, gimbals, etc.
- Share the streaming video with other terminals.
- Adaptation to network bandwidth capacity limitations.
- Network coding frame protection against erasures and for better control of data.
- Quality over specific frames or segments of a photo.
- Air-traffic-control (ATC) radio integrated with Satcom.
- Transmit data through different protocols.
- Prioritization of resources and data networks.
- Remote controlled multi-hop routing management.

5.1.9 Skytrac UAV-to-satellite connectivity

The Canadian company called Skytrac [25] is a company that appeared for the first time in 1986 but has been mainly established since 2013 until now and it brings innovation to the aviation hardware market. Its track record so far is excellent and it focuses on missions that are mostly aerial, but that doesn't mean it has no interest in government, oil & gas missions. However, its interest in recent years has also focused on UAVs where for this purpose it has created four instruments that facilitate communication between a ground station and a satellite. The reason this company is worth mentioning is that it has products for UAV missions which, due to reliability and ease of use, are number one in sales worldwide. Below are four products Skytrac sells as well as some of their technical features.

- **SDL-350:** it is a device for broadband satellite connectivity. The upload speed from the aircraft is $350\ kbps$ and the download is $700\ kbps$ and over the most important part is the reliability and the improvement in cost units. It is an Iridium-Certus terminal with even more capabilities such as live video freed, image and large file transfer, VoIP communications, etc.
- **ISAT-200A-08:** it is a satellite communication system for mid-band satellite connectivity which offers about 10 times more efficient allocation of bandwidth. It is one of the cheapest transceivers updated by Iridium Certus, while the upload and download speeds from and to the aircraft are $22\,kbps$ and $88\,kbps$ respectively. May the speed be lower compared to the previous one, but this is cheaper and for mid-band connections and not broadband.
- **IMS-350:** This is a very interesting device because having this, anyone can use it for broadband Satcom, cellular, Wi-Fi, and integrated server applications. Also, except for the different protocols someone may have, it provides both data and control links in real-time UAS applications. Finally, due to the variety of protocols, the capabilities are many, such as live video streaming, and beyond visual line of sight (BVLoS) communications, but it is also doable for BLoS communication and

sensor fusion, where the speed from and to the aircraft are $350\ kbps$ and $700\ kbps$ respectively.

- **DLS-100:** This device is like ISAT-200A-08, but with an extra feature which is the GPS for mid-band UAV data link connectivity. It is optional for telemetry data such as video streaming, photos, and command and control packets due to $22\ kbps$ and $88\ kbps$ download and uplink speeds related to the aircraft. Last, it is easily integrated with the sensors and the servers of the system.

Above, the products indicated for satellite communications in conjunction with UAV missions were presented. However, the products provided as a whole for aviation missions are more, as the background of each company is quite large but not all products were showed.

5.1.10 Celera motion hardware solutions

Celera motion is an American company in Novanta that also places its little stone in the purchase and manufacture of hardware pieces for UAV to Satellite communications. However, this is only a part of the range of fields it covers, which are quite a few, such as robotics, aviation, semiconductor equipment, etc. It is a leading global supplier of core technology solutions that combines the expertise of both photonics and motion with a proven ability to solve complex technical challenges. A wide range of products are presented for drone missions as well, but since most of it has been covered in previous architectures, only the parts that have not been reprimanded will be mentioned. These solutions are: [26]

- **Optronic systems:** there is a need for fast cameras, with smooth movement, low energy costs, and high accuracy. These cameras are usually necessary for automation systems, military missions, and healthcare. To achieve the above, the company uses transistors to reduce all possible power consumption losses, while to achieve the fast data rates required by the applications, it uses Ethernet or CAN intercommunication. Finally, the equipment goes through extreme weather phenomena, such as humidity, increased temperature, vibrations, etc, to confirm its integrity at any time and moment.
- **Antenna pointing systems (APSs):** are devices that align the antennas to have a more efficient connection between the two terminals since in this way the transmission and reception energy is maximized. Many times, it can be misinterpreted with the term servo-motor which refers to microcontrollers that correct the deviation from the maximum emission point by always targeting the antenna. However, this system is different and involves motors that are placed on the outside of the plane and can move in a circle and align the antennas. Image 17 shows such a system of a Direct Drive motor (DDR) where the load is directly connected to the motor. These types of motors themselves drive the load, thus there is no need to be a mechanical transmission element.

Image 17: Low profile DDR motor

- **UAV gimbal:** as previously mentioned, application demands are increasing and so must accuracy. To be sure to have a good photo and video reception and even telecommunication link or any other work required, gimbals need to be installed. Their role is to keep a device that is placed on them stable, such as a camera, while at the same time providing the ability to move around the three axes in the entire range of available degrees of movement. For example, even if a drone is above a roundabout and is monitoring traffic, the camera must turn towards a specific vehicle without necessarily changing the course or position of the drone. This scenario is provided by the gimbal.

What was said before, is a complementary factor in the hardware part of UAVs and satellites, covering in this way, if not all, the biggest part of the architectures that are currently available in the market. Below will be presented two versions that are more related to the software part, which has not been fully implemented.

5.1.11 Hardware and software approach for UAV payload and control messages

The following technique is a diploma thesis survey that has started to be implemented by the respective members that made it up and it concerns a small piece of hardware but it is more of software. [27] Essentially, this technique concerns a Mission Control Computer which is built as a set of embedded microprocessors connected by a local area network (LAN). Module interconnection is an additional extra benefit because there are mass and space limitations, but also because in this way it contributes to the transmission of messages faster by using real-time scenarios.

Therefore, through the network, connections are provided between different modules which provide some services/tasks to the whole system. In this way every application could create and subscribe to some provision. This architecture is reminiscent of the robotic operation system (ROS) approach, where it is used by nodes to publish and subscribe to some features they have, such as speed, acceleration, angle of view. So, a node asks to get the speed of another node and the system learns who that node is. Finally, the interested node subscribes to the node that contains the speed to see its content, while the other node publishes the value of the speed. This example is a purely personal adaptation and no relation between the respective architecture and ROS is mentioned in the sources. Therefore, it would be good not to adopt it, but to exist as a simple consideration of how the author perceives the technique. However, the architecture does not stop there. There are some optimizations to the link and its metrics.

For example, in one system, there is a choice of the most efficient and reliable communication channel, through a communication manager that has been deployed which is responsible for routing traffic efficiently, in real-time and autonomously, between the different protocols that may exist.

5.1.12 Blockchain technologies

The relevant field is an innovation that does not date back very far. Specifically, it was proposed for the first time around 2018 and the project has been dubbed the Space Communication Reconstruction and Mapping with Blockchain Ledgering (SCRAMBL). [28] There are not many sources to confirm exactly how this is implemented in a real plan, but if one judges the security that is channeled behind the blockchain like that of Bitcoin, then it is certain that the levels of security and integrity will be extremely secure. Blockchain is also among the most effective approaches for UAV/drone security and privacy and can provide very effective and enhanced security for UAVs/drones. It is a promising technology, which if implemented will bring huge changes in the field of telecommunications even for aerial vehicles. However, one should not forget the negatives that are hidden behind this technology, which are none other than the requirement of additional computational resources. Sooner or later, even with these negatives that can affect link performance, optimization will pass and end up being the dominant factor in telecommunications.

5.1.13 Honeywell

Honeywell Aerospace is located in Arizona and provides avionics, engines, systems, and service solutions. [29] The most important of all its goods, in the context of this thesis, is that it provides the smallest UAV Satcom on the market. The reason it is presented in this part of the chapter is that its expert scientists have built a complete UAV system that has many capabilities. Therefore, if not the whole vehicle, then part of it, is an innovation in the class of its size and capabilities. However, it is not an independent communication system and requires the contribution of Inmarsat for communications, covering in this way reliable rates and real-time video streaming globally. So, a user can see the video stream in real-time even in BVLoS. Its technical specifications are the maximum data rate is about $200\ kbps$, it allows connection with GPS and the transmission power is $11.5\ dBm$. Its antenna weighs only $500\ g$ and the maximum energy consumption reaches $45\ W$.

5.2 Transponders

It was previously reported about some kinds of channels can be used under the assumption that some important UAV message control information is transmitted from the UAV to the satellite or ATC. These channels are handled by transponders and every transponder is built with some different channels/protocols, as routers do. The messages exchanged over these links (that are created from the transponders) are defined as signaling messages that a phone would send to a cellular network, such as its exact location, but in this particular application the information is not only about the location but also information for the aviation safety and regularity of the flight are shared. But what exactly are transponders, why are they important, who manufactures them, and what are their selection criteria to optimize an application? These are all questions that should be answered to ensure individual knowledge.

5.2.1 Questions to be addressed

Before deciding whether a transponder is needed, some questions must be answered regarding the type of shipment. The answer to the question 'Do I need a transponder' does not have only one nature and the correct answer is 'Depends'. This implies that several questions must be considered before one decides to place a unit that consumes energy and money on a UAS and the first question is what a transponder is. The question manual that has been followed [30] is made by a transponder manufacturing company which is listed below and goes by the name of Sagetech.

5.2.1.1 What is a transponder?

A transponder is sometimes confused with the transmitter. However, transponder means transmitter-responder so it does more than transmit. The main concept behind this equipment is that it produces a response when it receives an electromagnetic signal, such as a frequency signal. It is called a transponder because when it receives a signal, it responds to that by transmitting a different signal and not the same one and these devices are used on aircraft to share information about location, altitude, etc. The way it works is that a secondary surveillance radar (SSR) uses the transponder to respond to a message it has received from another interrogation radar. Thus, it authenticates itself by using the unique ID it has (4 digits), and at the same time it sends information about the altitude of the respective UAV, because a primary radar is not able to send such information because it works in a passively way, which means that it is reflecting a radio signal of the aircraft and not transmitting one. The 4 digits code is created with numbers between $1 - 7$ and that allows 4096 possible combinations.

If a UAV is not equipped with a transponder, it is impossible for the air-traffic control radar beacon system (ATCRBS) to get the information from this aircraft. Also, in order to receive the signal back to the ATC, UAV may receive many interrogation signals but it responds only to those that are being received in the mode in which the transponder is set. Thus, even if a UAV is equipped with a transponder, it is calibrated with a specific mode and code to respond to the specific signal. Most transponders are equipped on a UAV to have collision detections and to provide a safe aviation distance between aircrafts by sharing their location. Furthermore, due to the small size of some UAVs, it is possible that the ATC is not able to localize them in the radar screen, so a transponder can make the whole process easier.

5.2.1.2 What's the size of the aircraft?

The truth is, in such applications, size does matter. The size of the aircraft is an important factor in whether the use of a transponder is necessary. For the most part, aircraft that need to fly in controlled airspace are those that are larger than $25\ kg$. However, this is not true and some aircraft that may weigh less than 8kg depending on the range they cover or the altitude they fly, may again need a transponder. For this purpose, the US DoD has categorized UAS into 5 groups based on weight, altitude above the ground level (AGL) or flight level (FL), and the distance that an aircraft must cover. The results are shown in Figure 7 and indicate that those in groups $2-5$ can cover missions over protected airspace as long as they are equipped with a transponder to be seen by ATC.

UAS Group	Maximum Weight (lb) (MTOW)	Nominal Operating Altitude (ft)	Speed (kn)
Group 1	0-20	< 1,200 AGL	100
Group 2	21-55	< 3,500 AGL	< 250
Group 3	< 1,320	< FL 180	< 250
Group 4	> 1,320	< FL 180	Any airspeed
Group 5	> 1,320	> FL 180	Any airspeed

Figure 7: Groups of UAS that need a transponder *[30]*

5.2.1.3 What's the type of the aircraft?

Another question that must be answered before the big question of whether a transponder system is needed, is the type of aircraft. This has a lot to do with the altitude at which it flies, but much more to do with the type of mission. For example, one needs to know if the aircraft in question is for military or commercial use. And beyond that, is this aerial object a weather balloon, is it a high altitude pseudo-satellite system, is it a medium altitude system or is it used for cargo shipments and junction traffic management? These types of aircraft affect the final answer because of different requirements and in different areas and altitudes will fly a UAV to do surveillance, different weather balloon, and different governmental system.

5.2.1.4 What's the range your aircraft has to cover?

In continuation of the previous question, comes the question which concerns the coverage range that a vehicle needs to fly. The questions do not have to be dependent on each other and this is evident in this particular point. Following on from the question at hand, the answer lies in whether the system will fly LoS or BVLoS. Regardless of the answers to the previous questions, if the vehicle's operation is for BVLoS missions, then a transponder is required. This suggests that there are scenarios where a system may weigh less than 8kg, but due to its flight which may be beyond the visual line of sight, be required to carry a transponder.

5.2.1.5 What's the altitude of your flight?

As previously discussed, altitude plays a role in whether a transponder is needed. This is because the respective aviation authorities have allocated the spaces based on altitude and how close one flies to an airport. According to the authorities and a schematic diagram that will be shown below, in almost all areas you need ATC approval and a transponder. When talking about altitude, it is not only the distance from the ground that is meant, but from the mean sea level (MSL), the altitude of the flight FL, and the distance from the sea in the horizontal plane i.e. the nautical miles (NM). The difference between the AGL and MSL is that the first one refers to the actual height an aircraft exist over the ground level, but the latter refers to the actual altitude and elevation and it's the point where to find the altitude someone has to consider the atmospheric pressure. That's different the earth is not flat, so the mean sea level is not always the same and changes around the globe. Lastly, FL is an indicator of barometric pressure and not of altitude as someone could believe.

Image 18: Flight boundaries for transponder *[30]*

So, the results of the previous scheme, indicate that aircraft belonging to these classes and altitudes -that may vary from different country authorities- need a transponder:

- **Class A:** sums up all the altitudes.
- **Class B:** until $10{,}000\ ft$ MSL but including the Class C Veil up to $10{,}000\ ft$ MSL too.
- **Class C:** from the surface up to $4{,}000\ ft$ MSL plus the horizontal boundary to $10{,}000\ ft$ MSL.
- **Class C Veil:** airspace where the distance with an airport is lower than $30\ NM$ with a distance from the MSL about $10{,}000\ ft$.

- **Class E:** only flights above $10{,}000\ ft$ MSL but without the airspace below $2{,}500\ ft$ AGL. Over the sea and especially above $3{,}000\ ft$ MSL within $12\ NM$ of the coastline.

5.2.1.6 What are the airspace rules for your mission?

This question has been implicitly created earlier. The use of the aircraft for military or governmental or commercial uses affects how a transponder should be set or not. The military authorities are a bit independent and for their areas of flights they create their requirements that must be met. However, regardless of the nature of the groups, civil or military flights have the same responsibility to avoid any collisions and keep a safe flight area. In case an aircraft is over a military area a transponder is needed because military aircraft are flying faster than UAVs and must be seen by ATC and other authorities. However, all these limitations and boundaries may change per country, so the optimal way to address these questions is to read the guides the main aviation authority provides for your country.

5.2.1.7 Is the operation and UAV highly important or are disposable?

The last question one must answer is deciding whether one needs a transponder. The question lies in the type of mission and how much one can tolerate losing their data. This is something no one wants to do because it wastes time, money, and data, but some missions can be more demanding than others. For example, a weather balloon can be lost without causing a huge problem compared to if a UAV observing the borders of a state or if a UAV mission for awareness or if search and rescue situation data were lost. Therefore, the type of mission largely depends on the choice or not of a transponder.

5.2.2 Transponder categories and specifications

However, a lie was told previously to make the operation of the transponders easier to understand. Not all transponders are the same, not all have the same capabilities, and not all transmit on the same frequencies. Regarding the latter, there is no need for a separate discussion about the different frequencies since some types of channels along with their characteristics were analyzed in Chapter 5.1.6. The categories for civilian transponders are separated as: [31]

- **Transponder A:** this is the simplest transponder it sends back to the ATC only the transponder code.
- **Transponder C:** it is like transponder A, but now it also publishes its altitude information.
- **Transponder S:** this is the most complex, as it sends information about the transponder code and its altitude, as a transponder C does, but also it is publishing the information with other transponders of the same category.

While military scenarios are separated as: [31]

- **Mode 1:** provides a 2 digit mission code.
- **Mode 2:** provides a 4-digit code created by the ground authority, which can be changed by the aircraft while in flight.
- **Mode 3:** includes the features of transponder A and transponder C mentioned before.
- **Mode4:** this is not currently used, but it is sending an electronic pulse as a reply in an interrogator signal.
- **Mode 5:** it's a version of Mode S transponder and ADS-B GPS position but it is cryptographically secured and encrypted.

However, it is required for every transponder to be tested every 2 years and it must operate in 6 different functions:

- **On:** it means that the transponder must be able to turn on.
- **Alt:** alt allows the transponder to share/transmit its altitude.
- **Sby:** means stand-by and it is used to make the transponder behave as a type A transponder which only responds with its ID to the ATC authority.
- **Off:** it turns the transponder off.
- **Ident:** transponder must send a signal to blink on the radar screen of the interrogator.
- **Squawk:** a squawk code is given by the ATC when a flight clearance is requested. It is the basic function of a transponder and it's held on transmitting an encoded signal that includes the 4-digit code.

Some of the most important codes that a pilot must recognize in dangerous situations are:

- **1200:** this is entered when the pilot is flighting in visual flight rules (VFR), which means that the aircraft is operating in weather conditions that are identical and allow for the pilot to see where the aircraft is going.
- **7500:** it is used when the aircraft has been hijacked.
- **7600:** it is used when the aircraft has no available communication abilities.
- **7700:** if nothing from the previous is happening but the aircraft is still in danger/emergency, this code Is used.

5.2.3 Market of the UAV transponders

Since the UAV market started, the need for transponders for every UAV has gradually followed. In particular, the reason for the phenomenon that more and more UAVs are in the airspace, whether they are friendly or hostile, there is a need to use transponders to identify specific objects. As attacks, demolitions, and breaches of UAVs have increased, it is more critical than ever that the use of transponders be made mandatory for all UAVs. It is mentioned in [32], that the market of UAV transponders in 2022 will reach $2.5 billion worldwide.

Some of the metrics and questions that someone has to consider and answer before using a transponder are based:

- **By the type of broadcast channel:** separated on ADS-B and non-ADS-B compatible.
- **By the type of UAV platform:** is the UAV fixed or rotary wing?
- **By fit market:** it is based on line-fit or retrofit. Line-fit refers to the items or equipment that are placed in the industry line by the manufacturer. Retrofit is referred to making improvements to the equipment that were not existing at the time of manufacturing.
- **By application:** is the UAV used for civil or military purposes?
- **By weight:** is the drone heavier than 25kg or is it lighter than 0.5kg?
- **By region:** where are you oriented? Are you in Europe, Asia, USA?

5.2.4 Transponder providers

Regardless of what has been said earlier, some dominant transponder manufacturers dominate the market and for those, some of their technical features and achievements are mentioned. Some of these manufacturers are framed both at the government level and at the commercial level, so it is quite understandable that their contribution to transponder manufacturing is extremely important and not at all insignificant. The information provided by the providers is very technical and there is no reason to do an in-depth study since the individual basic features are enough to cover the context of each diplomacy.

5.2.4.1 Sagetech avionics

Sagetech avionics [33] is an American company that promises reliable, safe, and functional solutions for various aerial missions. If not the biggest, among its biggest achievements, are the transponders which are divided into governmental and commercial, while there is no shortage of products and solutions for collision avoidance.

For governmental purposes the transponders are:

- **MX12B:** it is the first micro Mode 5 IFF (Identification Friend or Foe is a radar-based system identification) transponder designed. It is the only one with the Department of Defense (DoD) AIMS Mk XIIB certification, which is necessary for mounting military equipment. Also, there are no required additional components, as it already includes a pressure altitude encoder, antenna diversity, ethernet, and ADS-B In and Out.
- **XPC:** these transponders are easy to use, low in cost, used for military purposes, and extremely reliable with at least $1.5\ M$ of flight hours and 10 years of service. These are used for exceptional situational awareness of unmanned aircraft.

For commercial or civil uses, there are:

- **MXS:** it is a Model S transponder, that can also be used as Model A or Model C. As previously reported, it is used for both commercial and civil purposes, while it provides ease of use, command and control software, and a set of testing and integration components without implementing any further operations. Also, it is using ADS-B In and Out at $1090\ MHz$.

- **XPS:** the most important specification of this transponder is its tiny size and its ability to operate in long ranges to modern Detect-and-Avoid (DAA) systems.
- **XPG:** provides an all-in-one solution with the capability of ADS-B Out and GPS functionalities. It is used for safer and more reliable UAV operations while this transponder is operating as a Model S type.
- **XPC:** it is the same as the one previously described for governmental operations, but this version is provided for civil or commercial applications.

5.2.4.2 uAvionix

Another company that falls into the field of avionics for aerial flights and specifically for drones is uAvionix, which is based in Montana, America. This particular company was created in 2015 and therefore has made significant progress in its areas of interest and expertise, intending to bring safety solutions to the unmanned aviation industry. Beyond what it has achieved with the production of semiconductors, the design of UAS systems, its work with RF signals, etc., the manufacture of its transponders is noteworthy and a point of reference. The latter are divided into two categories, those that have ADS-B as a protocol and those that are used for defense purposes, while one could say that its range is not large, but without this being considered a disadvantage. Nevertheless, the transponders are: [34]

- **tailBeaconX:** it is used for general aviation purposes while it is compatible with ADS-B surveillance. One of the features that provide is that besides the fact of the Model S transponder to which belongs, it is also GPS integrated with a dipole antenna to maximize performance, so there is no need for additional GPS. The term 'tail' indicates its position on the aircraft and for this reason, it is also equipped with an LED light to act as a light source. One of the most important features is its power consumption needs which are $2-3$ times less than other transponders.
- **ZPX-A:** is a transponder used for defense and especially civil purposes because it is an AIMS-certified micro-transponder. As the previous one, it is categorized as a Model S transponder with ADS-B Out capabilities. It is a low-mass low power transponder that is used for traffic collision avoidance missions and operations such as safe separation information to the ATC but in cooperation with a GPS module.
- **ZPX-series:** this category of transponders is an updated version of the previous ZPX-A. That doesn’t mean the ZPX-A is not as good as ZPX-C or vice versa but indicates the different types of civil and defense transponders for different types of operations. The transponders are ZPX-B, ZPX-B2, and ZPX-C. Each of them has different specifications and the selection of the optimal one depends on the mission that someone wants to accomplish and the equipment that may have.

5.2.4.3 Meteksan Savunma

Meteksan [35] is a company in the field of defense systems since 2006, and it is based in the capital of Turkey, Ankara. Its production is limited not to a single category, but to many, such as radar and communication systems, laser and optical systems, and especially underwater acoustic systems where in 2009 it was designated as a "Center of

Excellence in Underwater Acoustics". Besides these, it also manufactures transponders for UAVs. Unlike what has been shown before, their transponder is different and the information provided is limited.

- **OKIS:** it is an automatic radar system for take-off and landing. It is based on two levels one for the ground segment which is an interrogator radar and the airborne segment which is a transponder with an antenna mounted on the UAV. It is using Ka-band for communication while its link stays reliable and trustworthy even under harsh weather situations or signal jamming. The two layer system is easily implemented and can provide tracking at $10\ km$ distances. Information about the system is not provided because OKIS is a single system and not just a transponder. The information given is minimal and the Table with the results which is given below refers to OKIS as an airborne segment and not only a transponder.

5.2.4.4 Aerobits

Aerobits [36] is a Polish company that was created in 2015, by a university when they made a miniature ADS-B implementation in conjunction with a GNSS function. The purpose of the company is to cover the needs of UAS systems and to provide solutions in the military, civil or commercial environments which solutions concern both manned and unmanned operations. Lately, they have started dealing with transponders for both ground and airborne radar.

- **TR-10:** it is a transponder that will be launched soon with low power to provide ADS-B Out solutions. It is designed to be mounted on small UAVs to provide more safety and security in the aviation space. It is a Mode S transponder that has a capability with an external GNSS source, while it has many interfaces for easy integration solutions with the flight controller.
- **TR-10i:** it is the same transponder as the previous one, with the only difference that the latter is used as ADS-B In -providing a tracking range at $10\ km$- and not as ADS-B Out transponder -with a range of $25\ km$-, meaning that TR-10i will be mounted on the ground segment. All the other technical information is the same for both transponders, while many specifications are missing because these two transponders are going to be released soon in the future.

5.2.5 Results

The results provided below in Table 9, sum up all the transponders of the previous manufacturers. Some of the entries appeared to be N/A because the values for these specific fields are not announced. That may happen due to the nature of the mission which will be military or governmental or because transponders are not yet on the market, so the technical details are not given yet. Note that Mode 5 is referred to the purpose of the mission where AIMS means for military purposes and FCC for commercial or civil missions. The best choice for a transponder is based on the mission requirements. Is the mission for military or commercial purposes, is there any weight and size limitations due to small UAV systems or is the power consumption the most important factor for the mission? These questions must be addressed before someone concludes to the optimal transponder which may not be so optimal for a client with other mission requirements.

However, there is not a single chart that indicates the requirements a transponder must respect, but ZPX-A seems a good choice for military purposes as it is lightweight, with extremely low power consumption and good transmit power. For commercial reasons, XPS seems the best option based on transmit and consumption power and size metrics.

Table 9: Results of the transponder providers

Name	Transmit power (W)	Power (W)	Mass (g)	Dimensions (mm)	Operating temperature (°C)	ADS-B standard	Mode 5
MX12B	*AIMS 17-1000 Standard / 316*	*13*	*190*	*86x64x25*	*-40 to 70*	*RTCA DO-260B*	*AIMS*
XPC	*250*	*4*	*100*	*89x46x18*	*-20 to 70*	*N/A*	*FCC*
MXS	*316*	*10*	*190*	*86x64x25*	*-40 to 70*	*TSO-C166b*	*FCC*
XPS	*250*	*8*	*100*	*89x46x18*	*-20 to 70*	*RTCA DO-260B*	*FCC*
XPG	*250*	*8*	*147*	*102X47X26*	*-20 to 55*	*RTCA DO-260B*	*FCC*
tailBeaconX	*250*	*3*	*140*	*113x105x48*	*-45 to 70*	*TSO*	*FCC*
ZPX-A	*500*	*1.5*	*50*	*88x79x20*	*-45 to 71*	*TSO-C166b*	*AIMS*
ZPX-B	*250*	*4*	*70*	*83x47x15*	*-45 to 71*	*TSO-C145e*	*AIMS*
ZPX-B2	*250*	*6*	*91*	*83x47x21*	*-45 to 71*	*TSO-C145e*	*Pending AIMS*
ZPX-C	*500*	*5*	*100*	*88x79x20*	*-45 to 71*	*TSO-C166b*	*AIMS*
OKIS	*0.1*	*30*	*2500*	*N/A*	*N/A*	*N/A*	*N/A*
Tr-10	*250*	*10*	*60*	*54x44x18*	*N/A*	*N/A*	*N/A*
Tr-10i	*250*	*10*	*60*	*54x44x18*	*N/A*	*N/A*	*N/A*

5.3 Safety needs

To succeed integration of space communication with UAVs, some measures and some decisions must be taken which will provide on the one hand a harmonious communication system without jamming problems or collisions between ground and air links and on the other hand will defend the safety of both citizens as well as the environment since the damage that can be caused by one is quite large. Below are some of the risks involved as well as some measures to take if a drone's control status becomes erratic and unsafe.

5.3.1 New aviation standards

As it has been realized from previous sections, the most important messages between the link are those related to the control of the vehicle and the link itself, where these messages are called CNPC. Thus, a communication protocol is required to guarantee the secure message exchange and ensure the integrity of the message to the recipient. It would be good if it were an independent standard that would not collide with cellular or wireless networks. This is important because the uplink control data must be received exclusively by each predetermined recipient and by no one else since they are unicast messages. Therefore, the security and integrity of the message transmission to the satellite are required. As for the downlink payload data, because they carry important information such as updates about the components of a drone etc, it must be ensured that there is no possibility of interception and falsification of the message content. Therefore, there is a need to define new standards that will reduce interference from other networks while at the same time effective frequency spectrum allocation will be made.

The International Civil Aviation Organization (ICAO) and the International Telecommunication Union (ITU) are responsible for these assignments and network designs. To meet such requirements, the C-band spectrum at $5030 – 5091\ MHz$ has been made available for UAV CNPC at the World Radiocommunication Conference (WRC)-12. More recently, the WRC-15 has decided that geostationary fixed-satellite service (FSS) networks may be used for UAS CNPC links. [10] However, terrestrial networks are not as innocent as many think and should be avoided. One can jam the intercoms of a UAS with cheap equipment on the order of 1000 €. In one incident, the Iranian military was able to take down a U.S. Lockheed Martin RQ-170 Sentinel drone by jamming the UAV's control signals. In addition to jamming, there are other types of attacks where they come into conflict with the ground stations which should be dealt with in case the ground stations need to coexist with the space communications. Such attacks will be discussed later in more detail, but now three basic categories are provided: [5]

- **UAV to UAV coordination attacks:** the main purpose of this particular attack is to disorient the formation of a group of drones. This is achieved for example by colliding two drones with each other or by sending fake messages which have no purpose and are not real information messages.
- **UAV to Command center coordination attacks:** the goal of this attack is to disorient communication between the command center and UAV. The Command center is one of the most important entities of the UAS because it sends tasks and messages to the UAV to operate autonomously. This deformation is achieved by gaining unauthorized access to a channel and after that broadcast message to the end-terminals to make the system restricted to transmitting and receiving data or by collecting data as a middle user and not as an end user, but without being noticed from anyone.
- **UAV functionality attacks:** these are the most well-known attacks where an attacker's goal is to take the entire vehicle with him. Thus, he will be able to act according to his needs and destroy a component of the drone or drop it on a target such as a building or a corresponding drone or even intercept and destroy the drone's communication with the outside world.

In general level cyberattacks on UAVs can be done in three different ways: direct access attacks like UAV-to-UAV coordination attacks do, masquerading the command center communications which is the same as the UAV to Command center coordination attacks, and denial of service (DoS) attacks which belong to the UAV functionality attacks with many more different types of attacks. Later, all these attacks will be briefly described but for this section, it was not important because the aim was to show how important are Satcoms and aviation standards to avoid terrestrial units.

5.3.2 Air Traffic Organization (ATO) measures

Federal Aviation Administration (FAA) which has as its operational manager the Air Traffic Organization (ATO) has led to the inclusion of some individual measures to secure air communications. [2]

- **En Route Automation Modernization (ERAM):** will be able to process and display complex UAS plans with automated flight profiles. Also, it provided the feature to display a routing plan of a drone in a controller display. However, another important ability of this measurement, is that it can modify or review a UAS flight plan request which is originating in an airspace environment.
- **Terminal Automation Modernization and Replacement (TAMR**): basically, it is the same as ERAM, but this first one is originating in terminal airspace environments and is not en route. The difference is that the UAV acts as a terminal like an end user and not as a routing node that will route the traffic to another UAV until the packet reaches its final destination.
- **National Voice System (NVS):** It allows a pilot (which is not on the UAV), to have direct access by messaging like Voice over Internet Protocol with the system. So, in an emergency, voice messages can be sent from the controller to the pilot and vice versa.
- **System Wide Information Management (SWIM):** it is relatively connected with the rapid apportionment of the right information to the right user in a specific time slot.
- **New learning procedures:** where techniques will be presented to be an effective implementation of the UAS systems with paradigms. Also, new facilities will be used to host coordinators, managers, and people who are working on these systems.
- **Detection and avoidance techniques:** as aerial vehicles increase, so must avoidance techniques to avoid collisions do. It is therefore necessary to have congestion management algorithms and techniques to avoid conflicts.

5.3.3 Terrestrial attacks to be addressed

It is possible in some rural areas UAV operations will likely need to employ a mix of cellular (LTE/5G) and satellite connectivity so it is somehow difficult to avoid in all manners the cellular communication. If it is necessary to use such links (in association with Satcoms) some of the below attacks must be addressed: [5] [6]

- **Spoofing:** issues related to communication links, where some data are sent decrypted so it is easily accessible to be taken, altered, or injected into the UAV software and hardware components.
- **Jamming:** packets without useful information are transmitted continuously and simultaneously and restrict the ability of the system to receive or transmit data.
- **Malware infections:** communication link issues where a UAV due to its connectivity with cellular or wireless systems is vulnerable to malware installation of software in the controller or the drone. Thus, it is necessary for the UAV to operate as much as possible with Satcoms and not terrestrial terminals.
- **Use of Wi-Fi connections:** experiments provided that will use software to control the UAV autonomously, many disconnections happened while malware users tried to control the UAV without authority or permissions.
- **Attacks on sensors:** based on the previous type of attacks it is easily controllable to manipulate or destroy sensors from a UAV. For example, by sending ultra-sonic waves to the gyroscope of the UAV.
- **ADS-B channel:** this is a channel based on Satcoms and was previously described as a new feature to implement. However, this technique also needs to be upgraded because these GPS signals are not encrypted and anyone with cheap equipment (like antennas catching the traffic over the air), can easily affect the source message and alter it in a harmful way.
- **Traffic Collision Avoidance System (TCAS):** this is a system in which the UAV is trying to avoid any given collisions that may happen in the future with the trajectory of other UAVs. The problem is that to avoid these collisions, in a highly dense area, the system doesn't have enough time to calculate the new collisions that may occur with the change of the previous trajectory, and a crash of the two UAVs is unavoidable.
- **Man in the middle attack:** in this type of attack, the attacker is aiming at the communication channel. Mostly he pretends to be the end terminal but it is only an unauthorized user who is between the two end terminals and trying to alter the control and data messages.

5.3.4 Quality of Experience (QoE)

An important factor that one must consider for UAVs and the modern data rate requirements, is that it is not enough to have enough quality of service (QoS), but there is also a strong need for good quality of experience (QoE). The difference between these two is who and what they refer to. The first concerns server availability and how available it is to cover a client's request (eg handover). The latter refers to the quality of services received by the user requesting something. For example, how satisfactory was the link's error rate according to the operation it wants to perform? This is because, for large volumes of data such as optical cameras and high-resolution video and images, it is not only sufficient to have a channel available to serve the request at any given time, but it is even more important to satisfy the request beyond the time spectrum, in the spectrum of performance without congestion in the system. Therefore, it is important to consider this factor in the design and implementation of these links.

5.3.5 Space and UAV debris

As previously presented many security aspects start from communications and as it has been understood throughout the thesis, telecommunications are closely related to energy consumption and drone control. So, when someone talks about satellite communications, is referring to high-volume data, at extremely long distances, with many losses and therefore high consumption both in energy and financial terms. So, for satellites to become a mainstay of UAVs, they need to become more efficient on many levels, as well as the sum of system entities that are implemented must be improved to achieve good performance.

However, with the growth of satellites, other environmental problems arise. Since the satellites for these kinds of technologies are small in size and life span, it means that more and more flights will be carried out with the ultimate goal of incorporating even more microsatellites, as SpaceX is already doing. Therefore, it is necessary to establish programs and regulations by all states, which oblige that when the end of the life of a satellite comes, it must move to a dead zone, otherwise there will be nets that will collect the remnants of a system and these will burn up in the atmosphere or they will land somewhere safe. It is equally important that this process will be carried out from the drones too, which are relatively close to the altitude of the citizens, so that citizens are never in danger from any damage or destruction of a drone. Already, many companies have begun to place protective plastic supports on drone propellers, which prevent direct contact with the rotating propellers of the vehicle. This, however, is only a necessary but small beginning, and further measures to ensure the integrity of citizens must be arranged.

5.3.6 General safety measures

In addition to those previously mentioned, several measures should be used for the general use of communications links and drones to implement unified and ground-based security in all sectors. So, the Civil Aviation Authority (CAA) announced some measures that should be in place:

- It is necessary that an operator or pilot always carry the license or proof of registration when operating.
- There are both upper and lower height boundaries based on the level/class of the license and normally someone could not fly over $400\ ft$ or below $140\ ft$.
- Due to the above measurement, UAV must always be on the operator’s line of sight (LoS).
- It is recommended to fly drones during the day, but if the UAV must operate at night, it shall bring lighting to be visible.
- It is prohibited to fly near military camps or airfields except if the relative authority has allowed it.
- For any illegal action by a UAV (like recording people without permission), the operator will be punished.

It is still necessary to always consider the worst-case scenario. At this point, the safety will be able to exist even in the worst scenarios. For an aerial system to be ultimately safe, even when all the above measures are taken, anti-UAV systems must be in place. These include systems where they drop the drone or catch it to avoid any damage and situations out of control. Some examples of these systems are: [6]

- **Athena laser weapon:** it is used to destroy UAVs even aircraft at long distances by ejecting laser beams.
- **Rafael drone dome:** it is kindly the same as the Athena laser.
- **Anti-UAV zapper:** it uses a very simple approach. The messages sent through it are classified, so when decrypted messages are traveling among the link that means there is a jamming condition and the UAV must be taken down.
- **Electric fences:** there are invisible fences and they are being used to restrict access in these areas while affecting the UAV power and communication layers.

With the above limitations, one concludes that the problems do not concern telecommunications to a huge extent but much more the integration of flying vehicles in communication systems and in everyday life. However, there are also restrictions on telecommunications and especially on the protocols for the links as mentioned earlier.

5.4 Satcom providers

Last years, since the advent of aerial communications and streams of big data, many providers started implementing and adapting to these technological rules to serve the needs of their customers. This section refers to the available Satcom providers along with some of their best specifications for the communication link they provide. In the end, an attempt will be made to conduct the characteristics and weaknesses of each provider in a single Table.

Russian satellite communication [37] and Kronshtadt company are companies based in Russia that will start to be applied in UAV missions. The first one is capable of transmitting TV, mobility, and maritime signals and has already started signing contracts related to UAV flights. The second has already started to build a satellite system, which it aims to implement by the end of 2022, exclusively for UAS systems where communication will reach distances of the order of $300\ km$. Similar companies like these are Thaicom which, based on its most recent statements, promises a low-orbit satellite system, that will provide 'beyond broadband' capabilities, while the link budget from end-to-end satellite points will be capable to support low latency, high data rates, and reliability. [38] Companies with relevant goals are Hugues which signed a contract to build a satellite communication system with the U.S. Army's MQ-1C Gray Eagle. There is a need for both air and ground modems for the U.S. Army Gray Eagle with a software solution to maintain continuous operational resiliency. Thus, Hughes will collaborate with Comtech Telecommunications Corporation on the production of ground equipment and waveform technology in support of the program. [39] The reason these companies are not shown below is that their satellite systems for aviation and UAS systems are still in the early stages and no technical specification analysis has been done because they were focusing on different types of applications. Therefore, they are more of an information and research axis rather than a computational of their capabilities until something comes to market. A similar satellite communications provider is AsiaSat [40], which has not yet ventured into UAVs. However, it has functions for maritime and aero, but there are some key differences, such as the size of equipment that a drone can carry versus a civilian plane or a large ship, the speed of movement and change of position and course, etc. Therefore, although it provides satellite coverage for various missions in Asia, Africa, and Europe, it is not a reference and analysis in the context of each diplomacy, due to its lack of participation in UAV missions.

New technological developments are expected to compound the data explosion problem. Substantial satellite bandwidth is required to support many UAV missions. These aircraft use satellite bandwidth to ship sensor data over areas. In this way, they transmit the data to a satellite so they can off-load the traffic between a UAV and a ground station. In 2009, U.S. UAVs alone generated 24 years' worth of video if it watched continuously, according to Defense Industry Daily. [41] Today's is more likely to ask, not if there is available bandwidth but "How much bandwidth is available?" however the answer has been, "Not enough bandwidth to fully exploit the UAV fleet." These days, links must promise characteristics such as good security, improved coverage area, efficient use of spectrum with multiple users using the bands without interference to each other, and also support a variety of complex sensors for high-definition video and imaging radar. Crossing this path, it is necessary to examine the strategic moves and projects that providers have started working on to cover the needs of UAVs. [4]

5.4.1 Inmarsat

Inmarsat stands at the forefront of an exciting new age for the commercial unmanned aerial vehicle market. It was the only provider for a long time, but after digitalization, many other providers appeared. Their satellites operate in bands like L-band, Ka-band, and S-band. [42] For that reason, Inmarsat is unsuitable for real-time operations as the latency is not optimal. For the sake of the truth, Inmarsat is one of the biggest providers that have many collaborations such as with Honeywell, Cobham SATCOM [43] and other companies from where it is equipped with materials such as antennas, servo-motors, etc, but there is no need to do a detailed analysis for such events.

- **I-6 Satellites:** These are the first hybrid, largest, and the more sophisticated satellites that operate in both L and Ka-bands. On December 2021, I-6 F1 satellites were launched by JAXA and in 2023 a new optimized version of these satellites will be released. They are suitable for mobility, military purposes, and IoT commercial usage. The I-6 satellites will also provide a key role in the geostationary earth orbit (GEO), low earth orbit (LEO), highly elliptical orbit (HEO), and 5G in one harmonious solution to redefine global, mobile connectivity.
- **ELERA band:** also known as L-band which they use for their satellites. They keep developing ELERA's secure narrowband network to meet the global, mobile connectivity needs of their clients. ELERA offers the fastest L-band speeds available to customers.
- **Global XPRESS:** it operates in the Ka-band and is the first mobile broadband network. This service is useful for applications that require high availability at any given time and seamless connectivity. GX5 which is the latest updated satellite was launched in 2019 with an ulterior purpose to meet growing demand across

Europe and the Middle East, for aviation Wi-Fi and commercial maritime services. The performance and flexibility of the GX satellites make the total throughput of each satellite to be around $12\ Gbps$. The GX can achieve downlink speeds up to $50\ Mbps$ when the uplink is about $5\ Mbps$.

- **European aviation network:** it is deployed in S-band frequencies to cover the need of Europeans. It combines satellite coverage with Deutsche Telekom's 4G LTE ground network to achieve cost-effective in-flight connectivity while transforming the passenger experience in new levels.

5.4.2 Iridium

While Inmarsat is suitable for BLOS communications, Iridium is better for LoS communications. Its LEO positioning, combined with L-band frequency, creates a line of sight from remote operations centers to UAVs operating anywhere in the world. Also, it extends the reach of terrestrial infrastructure with truly mobile communications capabilities, making it ideal for supporting the connectivity needs of autonomous systems anywhere in the world. Low-latency data services provide the ideal solutions for transmitting data messages between remotely piloted aircraft and centralized operations centers near real-time. Data rates are about $50\ kbps$ for Time Division Multiple Access (TDMA) modulation. A new project called Iridium Next was released in 2018: [4]

- **Iridium Next:** it's the second generation of satellite constellations that operate in the L-band. The data rates are almost three times bigger than the old fleet and about $150\ kbps$. Latency is improved too, from $180\ ms$ to $40\ ms$. An advantage of this project is the low latency and neglectable Doppler effect, but this leads to bigger antennas and slower data rates due to the operation on L-band.

5.4.3 Globalstar

Created by Qualcomm and operates since 1999. Its constellation is oriented from LEO satellites with dual-band antennas where the uplink belongs to L-band and the downlink to S-band. The antennas are active phase arrays which means each antenna element has an analog module that helps to steer and stabilize the antenna beam. Furthermore, follows the bent pipe technique, where the data are received, then amplified, and then pushed to the downlink without the need for demodulation or decoding of the data. Like Iridium, the latency is about $40\ ms$, but data rates approximately are $7.2\ kbps$ per user. A relatively new project, since 2015, for UAV operations, is described below. [44]

- **ALAS aviation:** a collaboration of Globalstar with ADS-B Technologies to provide a simple and low-cost satellite-based ADS-B system called ADSB Link Augmentation System (ALAS). When the aircraft is not in the LoS concerning the ground station, then the satellite provides a non-Line-of-Sight (NLoS) communication link for command and control messages, so a highly reliable air traffic management (ATM) system is guaranteed without neither performance degradation nor interference to other aircraft's transmissions. It is robust against Doppler shifts, while it can support high mobility networks, in that case, UAVs, with only a few disconnections and fast reconnections.

5.4.4 OneWeb

OneWeb was first created to provide Internet connection to under-developed regions. They invented a technique called progressive pitch, where the antennas of the satellite -so and the satellite too- will turn occasionally to avoid interference with other satellites operating in the same frequency bands (Ku band).

- **Aviation:** its goal is to provide connectivity at any given place even above the ocean, with LEO satellites and hybrid GEO. The customers will be both from the business and commercial markets, while the company promises feasibility, sustainability, and reliability for their on-air communication links. They will use in-flight user terminals that are significantly lighter and smaller than existing aviation antennas, and suitable for all aircraft types. Data rates are about $200\,Mbps$ and the latency is low so airlines can connect all their passengers without conflict or compromise issues. [45]
- **Government:** provided air connectivity regardless of if the vehicle is an unmanned or rotary-wing or any other type. Their flexibility is based on their networks which can be easily adapted and aggregated with medium earth orbit (MEO) and GEO satellites, 5G networks, or even with ad-hoc networks, so optimization of the link budget will be successful. One big advantage is the LEO network solutions which support stable and trustful communications for command and control, positioning, and even more in affordable prices and easy deploy setup. Their goal beyond communication is to make equipment as lighter, cheap, reliable, and power consumed as possible.

5.4.5 SpaceX

SpaceX is one of the most famous space companies in the world. It was founded by Elon Musk and the accomplishments as much as the hard work provided by the scientists are extremely big. One of the most innovative things is Starlink which calls to provide Internet globally.

- **Starlink:** low-cost Internet about $100€$, with data rates of max $200\,Mbps$ and latency lower than $20\,ms$, due to LEO satellites. The goal is to create a mega constellation of 42.000 objects even if the scientists believe that these numbers and the debris that is going to create will affect the climate. The satellite weighs about $0.25\,kg$ with an operation time maximum of 5 years while the setup of the terrestrial antenna is a very easy implementation. [46] Commonly the satellites operate both in the X and Ku bands which means $8 - 18\,GHz$.

Many industries are working on air communication right now, so more and more companies will start providing air solutions to their customers. Many times, satellite communication is more expensive than terrestrial, but the promises that are going to satisfy are much more than terrestrial-based systems do. LEO satellites also implement some pros and cons, like low latency but they have high Doppler shifts respectively.

5.4.6 European Space Agency

Away from the big players of the space agencies, ESA has given many tries to satellite communications for UAV tasks and operations. Probably they were one of the first industries which tried such things because they first implemented and worked on projects in 2010. Here are mentioned two of the biggest projects which are DeSIRE I [47] & DeSIRE II [48], while another wonderful project is IDEAS et. al [9]. The project was targeting both governmental and international organizations responsible for service operations, such as civil security bodies, national coast guards, border control authorities, etc. Thus, the aim of the two former projects, called DeSIRE, was the developing and demonstrating services based on a Remotely Piloted Aircraft (RPA) flying Beyond the Radio Line of Sight (BRLoS) by using satellite communications. Then it comes the successful deployment of the relay of Air traffic control (ATC) and the transfer of the payload data to the ground in near real-time. In general, their goal -a successfully settled goal- was to demonstrate the contribution of the Satcoms in civil traffic for RPAs applications for BRLoS communication types. More information about the whole procedure, planning, and aims of both projects could be retrieved from the links provided above. There is no reason to investigate the project thoroughly because on the one hand it was a demonstration project which is closed and completed and not something that is working now in the real world, like Starlink.

5.4.7 Eutelsat

Eutelsat is a company of French origin and is the third largest company in terms of income based on satellite operations, while it is the first European company to broadcast to European homes. Its coverage is global and not limited to the European level, while its missions do not only concern aviation, but also radio coverage, television, and space coverage as previously mentioned. For this reason, it has begun to upgrade and develop its fleet to cover more and with better performance for the users requirements, especially those on air flights. For this reason, the satellite fleets that have already started to launch are: [49]

- **Konnekt VHTS:** built by Thales Alenia and launched on $7/9/2022$ to provide government, mobile, and broadcast coverage in Europe. The band that will be used is Ka-band with a capacity of $500\ Gbps$, hence the name VHTS which means Very High Throughput Satellite. This mission will carry the most powerful onboard digital processor ever put in orbit, to support great flexibility, optimal spectrum use, and reliable ground network deployment.
- **EUTELSAT 10B:** this particular array is again a collaboration with Thales Alenia and has a launch plan to take place in 2022 and cover areas not only of Europe and America but also of Asia and Africa. The purpose of this mission will be to provide strong connections and communications for maritime and beyond since the usage band will be Ku-band. Also, in this way the satellite will be able to process more than $50\ GHz$ of bandwidth, offering a throughput of approximately $35\ Gbps$. In addition, it will be possible for redundancy reasons to use a combination of C-band and Ku-band to ensure service continuity.

- **ELO:** Eutelsat's fleet of LEO satellites, called ELO, will be used for the Internet of Things -or IoT- to transfer data from sensors and other instruments from one end to the other by using narrowband connectivity. One of its biggest capabilities is its low-power consumption, and wide-area wireless technology (LPWA network). Launches of the two fleets named ELO 1 and ELO 2 have already been carried out, while in late 2022 and early 2023 the ELO 3 and ELO 4 missions will also be carried out where they will be used to improve the formation of the already existing satellites.

5.4.8 Results and conclusion

In Table 10, a sum up for the characteristics of previous providers is shown.

Table 10: Characteristics of the Satcom providers

Provider	Latency	Mobility	Country of Origin	Bandwidth	Satellite Mass	Frequency Band	Dimensions
Inmarsat	*Medium*	*High*	*London, UK*	*500 Kbps*	*5470 kg*	*L & Ka band*	*7m*8m*33m*
Iridium	*Medium*	*Medium*	*Virginia, USA*	*150 Kbps*	*50 kg*	*L band*	*0.3m*0.4m*0.7m*
Globalstar	*Low*	*Medium*	*Louisiana, USA*	*7.2 Kbps*	*450 kg*	*L & S band*	*11m*4m*
OneWeb	*Low*	*Low*	*London, UK*	*50 Mbps*	*150 kg*	*Ku band*	*1m*1m*1.3m*
SpaceX	*Low*	*Low*	*California, USA*	*100 Mbps*	*260 kg*	*X & Ku band*	*3.2m*1.6m*0.2m*
Eutelsat	*Low*	*Low*	*France, Europe*	*100 Mbps*	*80 kg*	*C & Ka & Ku band*	*0.7m*0.7m*0.7m*

Latency is the delay for end-to-end point link, reliability is how safe and trustworthy is the link, while mobility indicates the ability that a UAV has so it can move freely in the 3D space. Based on this Table, one can choose the satellite provider which prefers to associate the UAV and terrestrial communications. As mentioned before, there is no right or wrong choice of provider, but there are ideal and less ideal based on the functions and capabilities of each mission. For example, someone may prefer a European provider even if it has less performance or may prefer a high data rate for live streaming over high mobility, while at the same time another application may have limitations in terms of link costs and interference.

5.5 UAV providers

Besides the SatCom providers, there are also some quite large companies/industries that manufacture UAVs. For the most part, military UAV manufacturing companies will be studied, since DJI has a monopoly on commercial drones, so there is no point in comparing such metrics. What must be understood, is that the UAV providers are not responsible for the satellite link and the rates they will receive. It may sometimes be contractually possible to require more things due to government and military missions, such as link decongestion, not interference losses, and many more, but this leads to system adjustment capabilities unless SatCom providers can bring changes in their honor. Therefore, the way to use satellite communications is the same and it is about transferring data from the UAV to the base station when there is no LoS communication and the signal cannot reach the terminal directly, thus the contribution of satellite communications is required. Apart from this, satellite communications are also used due to the added security and avoidance of jamming techniques applied to intercept the data.

Most of the technical characteristics of each system will be presented in a table at the end of the section, while previously a small historical review and some basic satellite data regarding drone-satellite communication will be made.

5.5.1 DJI

DJI [50] is a Chinese company that has a wide range of uses for its equipment, such as drones, components, cameras, and gimbals. The drones it produces, depending on their size, can be used either at an amateur level, for detection and situational awareness, but also government operations, since many use this type of drone for policing, telecommunications and agriculture. What is interesting and noteworthy is that the company is not only committed to the production of drones but also to all the peripheral parts that can be used for a mission. This means that it produces and sells cameras of various kinds such as HD, thermal, optical, etc., while also manufacturing the stabilizers/gimbals that may be required to move the camera in the whole space plane. The same manufacturing strategic applies from the pilot's side, where additional components are manufactured for the remote control, its range, spare parts for it, etc. Based on these, one can conclude that it justifiably has a monopoly on amateur and professional drones, while its reliability and technical support are quite good and inspire confidence for any situations that may happen. Regarding its models, there are several drones such as the Mini-2 or the Matrice-300. Nevertheless, a study will not be conducted regarding this particular company because it does not rely on satellite technologies for network communication. It has a satellite connection via GPS and GLONASS, but the transfer of data is carried out by cellular or wireless network and not by satellite. Therefore, this unit will deal with military Drones which are the most widespread and will mention the satellite communications they support.

5.5.2 Bayraktar

The Turkish company Baykar Makina manufactures a UAV named Bayraktar TB2 [51] which is a medium-altitude high-endurance UAV for its domestic military forces as Image 19 shows. TB2 model is the newest version of TB1, while in 2022, the first flight of TB3 is planned. However, Ukraine and Azerbaijan have also equipped themselves with these drones. The Bayraktar TB2 platform has a blended wing body design with an inverted V-tail structure while the propeller is mounted between the tail booms and driven by an internal combustion engine located in the body. The mobile unit supports three personnel: pilot, payload operator, and mission commander, and these three are placed in a NATO spec shelter. The satellite link is an added benefit for Bayraktar since 2020 when it was introduced as an additional function of TB2 named TB2S since at first there was only communication with the ground station. The satellite station is Turksat which uses Ku-band with 24 transponders to transmit the signal to Turkey and Europe. Its price is about $\$5 - 5.5\ million$ and it is six times cheaper than the US-Reaper UAV.

Image 19: Bayraktar TB2 *[51]*

5.5.3 Global Hawk

The Global Hawk [52] given in Image 20 is if not the most well-known, one of the most well-known UAVs of the US military which is TIER II+ and concerns large vehicles with high range, while it is using high-resolution synthetic aperture radar, that also can read and scan areas equal the size of Korea in one day. Although, the US military intends to retire the specific models in 2027 since the cost of a flight is quite high, while it had attempted the same procedure again in the past but there were possibilities for a restructured program. For this reason, the number of them decreases as a function of time. From communication and telemetry exchange, a military X-band band is used in case it is necessary to transfer the data from the vehicle to the ground central control unit, while if there is LoS then it is possible to transmit the data directly from the UAV. At the same time, when there is congestion or the area is quite dense, the pilots manage the UAV through a satellite link and not straightforward.

Image 20: RQ-4 Global Hawk *[52]*

5.5.4 MQ-1 Predator

The MQ-1 or RQ-1 Predator [53] is a drone of American origin that is used by the US military but also has operations with the CIA. While at first, the missions were more for aerial reconnaissance, later it turned out that they could also equip it with missiles. It is a category smaller than the Global Hawk and specifically Tier II medium altitude. It is no longer in use as it has been replaced by a more advanced UAV, namely the MQ-9 Reaper as discussed below in a subsequent sub-section. The "R" is the United States Department of Defense designation for reconnaissance and the "Q" refers to an unmanned aircraft system. The communication between the base station and the drone was done in two ways depending on the flight point. There was a slight delay in the response of the UAV during remote control and C-band was used for LoS communications, while Ku-band was used for BLoS.

Image 21: MQ-1/RQ-1 Predator *[53]*

5.5.5 MQ-9 Reaper

The MQ-9 Reaper [54] or as it is called Predator-B is an evolution of the RQ-1 (without changing the way of the remote control and tele-control between these two aircrafts) and more specifically it was the first UAV that was used for combat missions and it the reason belongs to high endurance class at high altitude. To understand the difference in power between the RQ-1 and the MQ-9 one must be able to know that the latter has a payload capacity of 15 times greater and is approximately three times faster than the former. There were different models from time to time such as B-002 and B-003 where they brought variations in the engines and at the same time in the thrust the engines produced and the load they could carry. It is reported that the camera he carried was so powerful that he could read a license plate at a distance of $3.5\ km$. The satellite link it used was Ku-band, with a delay of $1.2\ s$ from end to end, and is used to acquire and pass real-time imagery data to ground users by operating in beyond-line-of-sight (BLoS) scenarios. The project will terminate in 2035.

Image 22: MQ-9 Reaper *[54]*

5.5.6 RQ-170 Sentinel

For stealth UAV missions, the CIA and US military use the RQ-170 Sentinel [55]. This particular model has been manufactured by Lockheed Martin and is an evolution of the older stealth UAV named RQ-3 DarkStar, which mainly carries the same components but is larger than the previous model. This specific aircraft is not used for combat missions and does not carry military equipment like the Global Hawk or the MQ-9 Reaper, but as its name indicates, it is used for R for reconnaissance and Q for unmanned. The reason it is dark gray in color and not black is because it indicates its altitude capability where it is a medium altitude drone and not high altitude (where it would be black in color), but some sources are saying that this drone is HALE meaning high altitude long endurance [56]. The reason that makes it difficult to detect by enemy radars is the zigzag-edged landing gear doors and sharp leading edges, and due to the architecture of the exhaust which is not shielded by the wing. Also, it is using satellite links for BLoS communications, but it is not known its operating frequency.

Image 23: RQ-170 Sentinel *[55]*

5.5.7 Sukhoi S-70 Okhotnik-B

The cooperation of the two Russian military companies, namely MiG and Sukhoi brought to the market a drone named Okhotnik-B [57] that means “Hunter” in Russian, which was a new heavy unmanned reconnaissance and attack drone in 2011. One could claim that this particular drone is an answer to the RQ-170 Sentinel, with a different use, however, they were both stealth UAVs since the Russian vehicle is made of synthetic and hard-to-trace materials and fabrics respectively, which makes it difficult to detect during its flight. It has been used for military uses respectively, while it is known that it operate over satellite link, but it is impossible to find at which band it uses.

Image 24: Okhotnik-B drone *[58]*

5.5.8 BAE Systems Mantis

In addition to the drones that the two major belligerent countries have, Britain also has some drones such as the Taranes and the Mantis, where the latter will be specifically mentioned [59]. This particular drone has been used for combat missions, so it belongs to the unmanned combat aerial vehicles and is the equivalent of the RQ-9 Reaper where their shape is identical. One of its most important features is that it is considered as an autonomous vehicle, able to pilot itself and construct its path while in parallel it can communicate with personnel on the ground regarding its observations and metrics it receive from the sensors. However, information about its technical characteristics is not known. For example, it is known that it is used for bombing attacks or research and data collection but the frequency of the satellite link and the transmission range or the price, remain unknown.

Image 25: BAE Systems Mantis *[59]*

5.5.9 Soar Dragon WZ-7

China, with the American RQ-4 Global Hawk in mind, has built its drone called the Soar Dragon WZ-7 [60], which is a high altitude and long endurance UAV and is mainly used for military purposes, such as aerial reconnaissance and to provide targeting data for anti-ship ballistic missiles and cruise missiles. Its structure is thus designed to provide less flex but more ease of flight and a greater lift-to-drag ratio which makes it useful enough for a variety of missions.

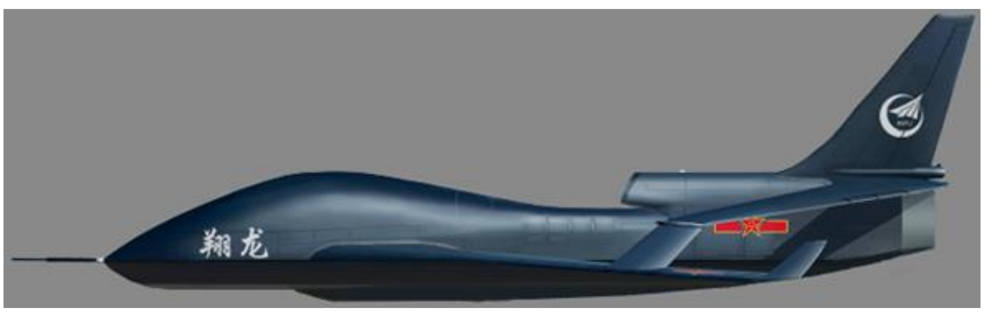

Image 26: Soar Dragon *[60]*

5.5.10 Specifications and conclusion

Based on what has been discussed in this section, one can understand that America is a dominant power in drones since it owns the most powerful and sophisticated drones. However, this does not mean that other countries are weak and indifferent, but they are not leading in this industry sector. Generally, due to the content of the missions some values are unknown as shown in the table below (Table 11), where the term NA means not announced and some other values vary from research to research. Each UAV has its use and there is no definition of 'the best drone' because it depends on the type of operation one wants to achieve. For example, is cost a criterion for shipments? If not, does the country of origin of the drone matter? It is needed for combat missions or monitoring and data collection, etc.

Table 11: Characteristics of the UAV providers

Name	Dimensions (m)	Mass (kg)	Max. speed (km/h)	Frequency band	Range (km)	Country of origin	Altitude (km)	Price ($M)
Bayraktar TB2	*12*6.5*2.2*	*500*	*220*	*Ku*	*300*	*Turkey*	*8.2*	*5*
RQ-4 Global Hawk	*40*14.5*5*	*6781*	*580*	*X*	*2000*	*USA*	*18*	*70*
RQ-1 Predator	*14.8*8.2*2.1*	*1000*	*217*	*C & Ku*	*740*	*USA*	*7.6*	*20*
MQ-9 Reaper	*20*11*3.8*	*2200*	*480*	*Ku*	*1850*	*USA*	*16*	*57*
RQ-170 Sentinel	*20*4.5*1.8*	*3900*	*950*	*NA*	*NA*	*USA*	*15*	*6*
Okhotnik-B	*20*14*3*	*20000*	*1000*	*NA*	*6000*	*Russia*	*1.6*	*20*
Mantis	*22*18*4*	*9000*	*560*	*NA*	*NA*	*UK*	*17*	*NA*
Soar Dragon	*25*14*5.4*	*7500*	*750*	*NA*	*7000*	*China*	*18*	*2*

5.6 Satcom services

In a previous section, it has been linked to the use of drones as a mean of dealing with several different types of missions and how they can contribute to a more efficient information system. However, the current diplomacy, beyond UAVs, also studies satellite links concerning UAV protocols and frequency bands, so it is necessary to mention the important satellite services provided. The reference will be made in a general context, which will concern not only aero services, but also general-type services, such as military, naval, etc, to clarify how they contribute to a better solution and what satellite communications providers are used. Mostly, it will be researched on Satcom global [61], a provider that has abundant satellite services to ensure excellent end-to-end communication with high efficiency at all times. There will be no reference to various providers such as Eutelsat since on the one hand they have been discussed previously and on the other hand some benefits will be mentioned which are not only limited to the provision of television coverage but something much bigger and more complex as system.

Broadband Satellite Solutions (BSS), which is the subsidiary company of Satcom global, is a company of English origin founded in 2012, with the ultimate goal of creating and implementing satellite communications in areas that not only did not have a communication connection but also are areas that are difficult to access, providing a reliable and stable connection throughout the day. Some of the features BSS promises to bring to the market are:

- Upgrading the already existing equipment in the frameworks that will satisfy the demands of the customers.
- Providing software and the network easily and understandably to be representative for everyone.
- Connectivity all over the world either for streaming, video games or for transmitting important information.
- Trying to create the most successful satellite system at low cost and high end-to-end performance.

However, in addition to the objectives, it is worth mentioning the services provided at the moment and some products that have been placed on the market to successfully meet the needs of the users.

5.6.1 Maritime

The provision of services at sea is a very developed provision for Satcom Global which has been active for at least 45 years. Fishing, offshore, yacht itineraries, entertainment, and shipping services are of vital importance for various ports of the world in which each company operates in collaboration with Iridium and Inmarsat projects. The services it offers are software for real-time monitoring and data management, tools for cyber security, and internet services. One of the most important advantages is the ability to communicate through customer support around the clock, where engineering and installation services, IT services, and prepaid solutions are provided. The products suitable to support this service are Aura VSAT, Fleet Xpress, Thuraya Maritime Broadband, Iridium Certus 700, Inmarsat XpressLink, and others. However, the services are not limited there, since there are many contexts in which the company operates such as providing products for marine spares, fishing technology, entertainment systems like TVs, navigation and anti-piracy systems, and other system designs and integrations. However, no in-depth analysis is required since these systems do not persepertain to satellite communications, but large suppliers such as Bosch, Cobham, Furuno, Intellian, Lars Thrane, etc are manufacturing these products.

5.6.2 Land

The provision of terrestrial coverage is also part of the services covered by Satcom Global beyond maritime. Its purpose is to provide reliable and high-performance connections in remote and extremely hard environments. For example, one may observe a leak of a fluid pipe, in a noisy environment, while he is in America, either in his office or driving on the road, while the pipes are in Asia, providing not only visual contact with the pipes but also acoustics. Some additional services provided are the robust network infrastructure with messaging, web-based solutions and also software solutions for monitoring and data management. The products used are BGAN Link, Iridium Push to Talk, Inmarsat Global Xpress, and IsatPhone Link.

5.6.3 Handheld

Handheld services are also provided by the respective organization, covering in this way the provision of telephone communication in extreme locations and environments for reasons of vital importance, for monitoring, for information, or even for entertainment covering high durability and reliability of the link. The highlight of this service is the call security that exists, coupled with high voice data rates for any region, without limitations. The way to complete this process is through Iridium 9555 phone, Thuraya XT-LITE phone, IsatPhone 2 Vehicular antenna, and Iridium Push to Talk.

5.6.4 Smartphone to Satphone

An interesting innovation is the conversion of the mobile phone into a satellite phone. This can take place when for example you are using a mobile network such as cellular 4G and want to connect via satellite coverage for any reason. Then by using one of the available sleeves you can turn your smartphone into a satellite phone. The benefit of this provision is that you can use your normal phones, such as Apple or Android, and with a single sleeve your mobile will receive a satellite signal and not a terrestrial one, while there is high reliability, good data and voice rate. These sleeves can be any of the following: Thuraya SatSleeve+, IsatHub iSavi, and Iridium Go.

5.6.5 Machine to Machine

As technology moves towards smart devices and internet of things (IoT) it is expected that there will be a need for remote access and control of specific devices. Satcom Global tries to meet these needs through this specific service where it provides IP network capabilities and data collection in remote areas only with satellite coverage and without of ground stations assosiation. This application finds many monitoring and data extraction needs not only in small devices such as the smart refrigerator or the smart dehumidifier but also in real-time systems such as leaks in fluid pipes, monitoring, information for ships carrying products, and also for vehicles moving on the road, so it can be used for infrastructure operations too, where time and response are critical parameters. Iridium has a primary role in this through Iridium Burst, Iridium LRIT, Iridium RUDICS, Iridium Short Burst Data products, and then IsatData Pro and BGAN M2M follow.

5.6.6 Defense

The use of space and specifically of satellite communications is a one-way and vitally important according to CEO of SES, Karim Michel Sabbagh [62], who bases his opinion on two points regarding the use and availability of bandwidth by the US military which has grown $150x$ in the last 15 years and how “hungry” devices are for extra bandwidth and data rate, such as UAVs where for example Global Hawk wants data rates of $10 - 50\ Mbps$. Therefore, security and connectivity will be realized through three axes of reference, assurance, accessibility, and acceleration.

Assurance is achieved by the exclusive location of the satellite. Being a mass $36{,}000\ km$ away from the surface of the Earth, one might think that performance and delay issues are created, but in reality, there is security in terms of any earthly physical and territorial disasters, such as war, earthquake, fire, hurricane, etc. Also, when there is an overload of the terrestrial systems or when there is no visual contact between the terminals, then the best solution is to provide satellite communications, which as it is found covers all worst-case scenarios. Finally, thanks to geostationary location capabilities, interference and anti-jamming measures can be put in place immediately.

Accessibility is a big and decisive factor since continuous and uninterrupted access of military units to satellite communications is required. About 60% of the available spectrum is provided by military SATCOM, while the remaining 40% is provided by commercial Satcom providers. This means that such movements are very important to be carried out both for the security of the country and for the improvement of the lives of its citizens, since the delivery of e-education, e-health networks, and search and rescue missions is achieved.

Acceleration of this appears in its sense and takes the form of rapid adoption and development in new improved technologies and more traffic requirements. One such example could be LuxGovSat, i.e. the launch and the operation of a satellite for the provision of both governmental and military communication services, where it will be able to cover the spectrum and capacity needs for both military operations and political/social activities.

5.6.7 General satellite services

What was mentioned before, constitutes satellite communications and the benefits that they offer to space and Earth. However, gradually in the context of diplomacy, further functions of satellite communications have been mentioned, but an allusion will be made again to have a collection of information that will be clear and easily readable.

Without satellite links, the world would be more difficult and less safe to live in. For example, has anyone ever imagined what it would be like to have no television coverage or radio station? Ever wondered how to make withdrawals and deposits from automated teller machines (ATMs) that require a satellite signal to operate? How are you sure you are going on the right way when you are not able to use your GPS? What one concludes is that satellite communications are hidden behind many daily activities, where a person has learned to use some of these benefits to improve the pace and performance of his/her life. So, if one day all satellites stopped providing their services, would mean absolute chaos in many layers of social class, whether in entertainment, weather, or payments.

But even this is a small version of the possibilities of satellite communications. Year after year, user demands on data, mobility, and reliability are increasing. In other words, there is a transition from the age of the Internet in the home, to the Internet of Things and the Internet outside the home. This means that whether people, airplanes, or UAVs, require a stable connection link with the outside world at any time and moment, without high delays and with great security. These criteria are met by satellite communication, which is not only safer and more reliable than terrestrial means, but can transmit information from very distant places, i.e. BLoS, and support the high mobility of its users. So, whether it's UAVs, airplanes, or automated vehicles, users will be able to utilize all the amenities and services they would have at home, even if they are now miles away from it also with a great advantage which is high mobility.

6 MODELLING OF A SATELLITE LINK

What has been said before, is the theoretical part of satellite communications, while the mathematics presented are based on as real as possible scenarios. However, it needs some experimentation on the side of the reader, as what has been studied is not only literature work, but also documented and tested/experimented knowledge. Therefore, in this Chapter, some parameters that affect the satellite link will be studied and tested, and some conclusions and results will be obtained for the individual values of these parameters. A comparison will be made between the values while the performance of each link will be tested.

However, to do this, all available tools on the Internet will be used, but the emphasis will be placed on a simple code that will show at a very basic level some parameters and how they affect the link, as well as values from the previous Chapters dealing with losses and reductions due to Doppler, atmospheric turbulence, etc, will be considered. Finally, MATLAB Simulink and specifically the Satellite Communications library will be used to create an experiment that will be based on as real values as possible, concerning finding a finite solution.

6.1 Parameters to be declared

To draw some quantitative conclusions, some variables must be established and defined which determine the performance of the link and how these values are related to link's behavior. The term link is meant end-to-end communication, which is divided into two parts, the uplink from the ground station to the satellite and the downlink where the reverse happens, that is from the satellite to the base station. Indeed, instead of a ground base station, it may be the case that there is an aerial terminal such as a UAV, as will be studied later. Nevertheless, another link exists and it is between two satellites for transmitting the data as it is going to be showed later. However, may another definition will be given later with the forward and return link, where the forward refers to the link until the data reach the uplink end-terminal (the terminal that the information must be received to make some operations) and the return link refers to all the hops the data shall make in order to be received by the requested end-terminal (the terminal which requested some specific operations).

6.1.1 Transmission from eNB to satellite – EIRP

EIRP is used to send the signal from the source to the destination (satellite), after it first converts it to the correct frequency, i.e. some of those mentioned such as Ku, C, X, band. The variable is called Effective Isotropic Radiated Power or power flux density (EIRP) and this is because it emits the signal with a gain that is the same for all directions. However, there are directional or parabolic antennas that emit different power density in different directions, but the EIRP is considered in isotropic direction estimations. The following parameters are taken from the previous chapters and also from the [63].

$$EIRP = P_t * G_t \qquad (Watt)$$

otherwise,

$$EIRP = P_t + G_t \qquad (dB)$$

and G_t can be expressed as:

$$G_t = \eta(10472 * D * F)^2 = -42.2 + 20\log F(MHz) + 20\log D(m)$$

so finally,

$$EIRP = P_t + G_t - L_t \qquad (dB) \tag{1}$$

where:

P_t: transmitted power

G_t: antenna gain

η: apperture efficiency (0.5-0.65)

F: carrier frequency

D: reflected antenna diameter

L_t: transmitted losses from cables, modulation, process

6.1.2 Space section – Free Space Losses

Free space losses or Free space path losses (FSL or $FSPL$) are one of the most important factors of link budget and this is because specific losses affect the coupling to a greater extent, because it includes losses due to distance, weather, directionality, etc.

$$FSL = 32.4 + 20\log R(km) + 20\log F(MHz) \qquad (dB) \tag{2}$$

However, the total losses of the system are expressed as:

$$TL = FSL + AML + AAA + PML \qquad (dB) \tag{3}$$

where:

R: distance between end-to-end terminals

F: frequency of transmission

AML: antenna misalignment losses

AAA: anais atmospheric absorption

PML: polarization mismatch losses

6.1.3 Both terminals – Noise Figure

It is known that there are no devices without noise. In theory, this can happen, but in practice even if a device has no noise on its own, it gets noise from other factors, such as thermal noise, environment, white noise, etc. Now it is required to consider the receiver noise which can be thermal, short, or flicker noise.

$$T_S = T_{rf} + T_{in} + \frac{T_m}{G_r}$$

but Noise Figure (NF) is:

$$NF = \frac{T_S}{T_0} + 1$$

And Noise Power (NP) can be calculated from:

$$NP = k * T_0 * NF * B$$

and finally, noise power is given from:

$$NP = -174 + 10\log B(Hz) + NF(dB) \qquad (dB) \tag{4}$$

where:

T_{rf}: temperature on the front end of receiver

T_{in}: input temperature of receiver

T_m: mixer/frequency converter temperature

G_r: receiving antenna gain

T_0: room temperature, given as 290K mostly

k: Boltzmann's constant $1.38 \times 10^{-23}\, JK^{-1}$

NF: noise figure

B: bandwidth of the receiver

6.1.4 Received efficiency – Figure of Merit

Through this variable one can check the link performance from the receiver side. Here, it can get results for received power:

$$\frac{G}{T} = G_r - 10\log T_s - R_x \qquad \left({}^{dB}/_{K}\right)$$

and the signal power received, which must be greater than the lower boundary of the accepted signal that receiver can accept, is given by:

$$PR = EIRP - TL + \frac{G}{T} \tag{5}$$

where:

R_x: losses on the receiver due to cables and connectors

6.1.5 Link budget analysis

In order to properly evaluate the results regarding the satellite link budget, what really matters is not the SNR also known as Signal to Noise Ratio, but the C/N, i.e. carrier to noise ratio. This is calculated as the carrier power to noise power on the receiver.

$$\frac{C}{N} = PR - NP \qquad (dB) \tag{6}$$

In conclusion, it follows that all the variables required as well as their measurement units are those presented in Table 12 as inputs and those that result are presented in Table 13 as outputs.

Table 12: Input parameters for satellite link budget

Symbol	Parameters	Units
η	*Aperture efficiency*	$real\ number$
F	*Operating frequency*	MHz
P	*Output power*	W
D	*Transmitted antenna diameter*	m
L_t	*Transmitted losses*	dB
R	*Slant range*	km
AML	*antenna misalignment losses*	dB
AAA	*Anais atmospheric absorption*	dB
PML	*polarization mismatch losses*	dB
B	*Operational bandwidth*	MHz
T_s	*Equivalent temperature*	K
T_0	*Reference temperature*	K
$-$	*Threshold level*	dBm

Table 13: Output parameters for satellite link budget

Symbol	Parameters	Units
λ	*Wavelength*	cm
G_t	*Antenna transmitted gain*	dBi
G_r	*Antenna received gain*	dBi
$EIRP$	*Power density*	dBm
FSL	*Free space losses*	dB
TL	*Total losses*	dB
G/T	*Figure of merit*	dB/K
P_r	*Received power*	dBm
NF	*Noise figure*	dB

C/N	*Carrier to noise ratio*	dB

6.2 Simple link code

With the previous explanation and having in mind the basic idea of the previous features, it is possible to derive a very simple script that calculates link estimations for the satellite and the ground station. The code is based on [64], and it's a basic idea to understand how some (if not all) of the previous variables are connected. This script is written in MATLAB, and no further checks have been made for the safety of the values. The user must be careful with the input values since the program waits for user input for both uplink and downlink before displaying the results. It is assumed for the calculations that the satellite is in a GEO orbit of about $36{,}000\ km$, with a frequency of $30\ GHz$.

Cable losses can be declared, based on the below script, such as:

$$Cable\ losses = branching\ loss + feeder\ loss + back\ off\ loss$$

Free space losses are:

$$FSL = 32.4 + 20\log R(km) + 20\log F(MHz) = 143$$

G/Te is based on:

$$\frac{G}{T} = G_r - 10\log T_s - R_x$$

and from:

$$NF = \frac{T_S}{T_0} + 1$$

1. Earth station Transmitter output power = 40 *2. Earth Station back-off loss = 3* *3. Earth station branching and feeder losses = 3* *4. Earth station Transmit antenna gain = 40* *5. Additional uplink atmospheric losses = 0.6* *6. Free-space path loss = 143* *7. Satellite receiver G/Te ratio = -5* *8. Satellite branching and feeder losses = 0* *9. Bit rate = 150*(10^6)*	*1. Earth station Transmitter output power = 15* *2. Earth Station back-off loss = 0.1* *3. Earth station branching and feeder losses = 0.4* *4. Earth station Transmit antenna gain = 40* *5. Additional uplink atmospheric losses = 0.3* *6. Free-space path loss = 143* *7. Satellite receiver G/Te ratio = 40* *8. Satellite branching and feeder losses = 0* *9. Bit rate = 150*(10^6)*
Data for uplink	**Data for downlink**

The results are very optimal and that means that there is a very strong and reliable connection between the ground station and the satellite because the output values are quite big relative to noise levels and losses. In this section there is no further explanation of the link results, as the main aim for now is to provide the fundamentals of a satellite link, so reader can digest the given information from a basic code example and not to dive into difficult things as this is going to be done later. Furthermore, results depend on the inputs of the user, so having in mind the previous equations someone can built a reliable connection without any further help. Image 27 provides the output values:

```
OUTPUT
---------------------------------------
---------------------------------------
UPLINK BUDGET
---------------------------------------
EIRP (Earth Station) = 74.000000 dBW
Carrier power density at the satellite antenna = -69.600000 dBW
C/No at the satellite = 154.001209 dB
Eb/No : = 72.240297 dB
for a minimum bandwidth system, C/N = 77.980609 dB
---------------------------------------
DOWNLINK BUDGET
---------------------------------------
EIRP (satellite transponder) = 54.500000 dBW
Carrier power density at earth station antenna = -88.800000 dBW
C/No at the earth station receiver = 179.801209 dB
Eb/No : = 98.040297 dB
for a minimum bandwidth system, C/N = 103.780609 dB
---------------------------------------
OVERALL RESULTS
---------------------------------------
Eb/No(overall) : = 72.228888 dB
```

Image 27: Results of the basic script for link estimations

The script is:

```
clear all;
clc;
disp('----------------------------------------')
disp('ENTER UPLINK PARAMETERS')
disp('----------------------------------------')

earth_transmitted_power=input('Earth station Transmitter output power in
dBm:');
earth_back_off_loss=input('Earth Station back-off loss in dB: ');
earth_branching_feeder_loss=input('Earth station branching and feeder
losses in dB:');
earth_transmit_antenna_gain=input('Earth station Transmit antenna gain in
dBi: ');
uplink_atmospheric_loss=input('Additional uplink atmospheric losses in
dB: ');
earth_fsl=input('Free-space path loss in dB: ');
earth_receiver_gte=input('Satellite receiver G/Te ratio: ');
satellite_branching_feeder_loss=input('Satellite branching and feeder
losses in dB: ');
bit_rate_1=input('Bit rate: ');
```

```
disp('---------------------------------------')
disp('ENTER DOWNLINK PARAMETERS')
disp('---------------------------------------')

satellite_transmitted_power=input('Satellite transmitter output power in
dBm:');
satellite_back_off_loss=input('Satellite back-off loss in dB: ');
satellite_branching_feeder_loss_2=input('Satellite branching and feeder
losses in dB:');
satellite_transmit_antenna_gain=input('Satellite Transmit antenna gain in
dBi: ');
downlink_atmospheric_loss=input('Additional downlink atmospheric losses
in dB: ');
satellite_fsl=input('Free-space path loss in dB: ');
satellite_receiver_gte=input('Earth station receiver G/Te ratio: ');
earth_branching_feeder_loss_2=input('Earth station branching and feeder
losses in dB: ');
bit_rate_2=input('Bit rate: ');

disp('---------------------------------------')

earth_EIRP=earth_transmitted_power+earth_transmit_antenna_gain-
earth_back_off_loss-earth_branching_feeder_loss;

disp('---------------------------------------')
disp('OUTPUT')
disp('---------------------------------------')

disp('---------------------------------------')
disp('UPLINK BUDGET')
disp('---------------------------------------')



fprintf('EIRP (Earth Station) = %f dBW \n',earth_EIRP);

satellite_carrier_power=earth_EIRP-uplink_atmospheric_loss-earth_fsl;

fprintf('Carrier power density at the satellite antenna = %f
dBW\n',satellite_carrier_power);

satellite_cn0 = satellite_carrier_power + earth_receiver_gte -
(10*log10(1.38*(10^(-23))));
fprintf('C/No at the satellite = %f dB\n',satellite_cn0);

satellite_ebn0 = satellite_cn0 - (10*log10(bit_rate_1));
fprintf('Eb/No : = %f dB\n',satellite_ebn0);

bandwidth_cn = satellite_ebn0 - 10*(log10((40*(10^6))/(bit_rate_1)));
fprintf('for a minimum bandwidth system, C/N = %f dB\n',bandwidth_cn);
```

```
disp('---------------------------------------')
disp('DOWNLINK BUDGET')
disp('---------------------------------------')


satellite_EIRP = satellite_transmitted_power +
satellite_transmit_antenna_gain - satellite_back_off_loss -
satellite_branching_feeder_loss_2;
fprintf('EIRP (satellite transponder) = %f dBW \n',satellite_EIRP);

earth_carrier_power = satellite_EIRP - downlink_atmospheric_loss -
satellite_fsl;

fprintf('Carrier power density at earth station antenna = %f
dBW\n',earth_carrier_power);

earth_cn0= earth_carrier_power + satellite_receiver_gte -
(10*log10(1.38*(10^(-23))));
fprintf('C/No at the earth station receiver = %f dB\n',earth_cn0);

earth_ebn0 = earth_cn0 - (10*log10(bit_rate_2));
fprintf('Eb/No : = %f dB\n',earth_ebn0);

bandwidth_cn_2 = earth_ebn0 - 10*(log10((40*(10^6))/(bit_rate_2)));
fprintf('for a minimum bandwidth system, C/N = %f dB\n',bandwidth_cn_2);


disp('---------------------------------------')
disp('OVERALL RESULTS')
disp('---------------------------------------')

a = 10^(satellite_ebn0/10);
b = 10^(earth_ebn0/10);
ebn0all = (a*b)/(a+b);
ebn02db = 10*log10(ebn0all);
fprintf('Eb/No(overall) : = %f dB\n',ebn02db);

```

6.3 MATLAB Simulink

The MATLAB satellite communication toolbox is a manual that has many aspects that can be adapted to produce measurable results for a satellite link. To begin with, one can visualize the created link, check the satellite's orbit, whether it meets the needs of the ground base station, how long it will transmit and so more features can be computed and visualized from this library. Then, while you have this setup, next step is the evaluation of the link budget trade-offs using your parameters including losses, gains, distances, etc. Then, after the results of the link budget have been obtained, one can choose the waveform that will be used for communication from the station to the satellite as well as what transmission protocol will be used, etc. There are several protocols, such as GPS, Digital Video Broadcasting, 5G, etc, so the options provided by this toolkit are many and depend on the needs of each organization. Therefore, it is not necessary to use all the individual features of the toolkit, one is enough and can be used according to the requirements of each user. So, in summary, one would say that the following features are provided: orbit propagation and visualization, link budget analysis, waveform generation, and finally end-to-end link simulation. The difference between visualize and link budget is that the former answers the question 'Can you see the satellite?', while the latter answers the question 'Can you hear the satellite?'

To begin with, the experiment to be carried out will be between two base stations and two low-orbit (LEO) satellites, where one will be used to transfer the data from one ground station to the other satellite, there will also be an intercommunication and the data will relay between the two satellites, while the second satellite will be also used to send the data to the other base station that for this experiment is the reception terminal. The two base stations cannot communicate by direct link because they are not in the line of sight (LoS), so the use of satellite communications is mandatory.

Also, tests have been done to use one satellite to receive data from two ground stations, but the tests failed because an antenna shall be calibrated at the ground station location and direction, so the satellite needs two receiving antennas and one more antenna for transmitting the received data, and in a real scenario at a certain point in time the satellite can serve and receive data from one endpoint and not many. However, depending on the timing and different parameters and conditions, it is possible to transfer data from one ground station to another for various purposes, whether research or educational, without requiring a satellite link. In the context of this Chapter, satellites as a mean of data transmission are mandatory.

So below, the experiment that will be followed will be presented and an extensive analysis of the code used will be made to make it fully understandable. However, MATLAB and specifically the Satellite Communications Toolbox [65] that was used has quite satisfactory material and videos, which ensure the understanding of the code and its parts.

6.3.1 Access and link analysis

First, it is necessary to define the time in which the experiment will take place, and anyone can set any start and end dates for the experiment. The experiment was set to take place at $12{:}45$ on February 20, 2023, its duration would be two days to completion, and the sampling seconds would be 120 samples.

```
startTime = datetime(2023,2,20,12,45,0);
stopTime = startTime + days(2);
sampleTime = 120;
sc = satelliteScenario(startTime,stopTime,sampleTime);
```

Subsequently, the technical characteristics of the two satellite orbits are defined as well as the coordinate system that will be used where in the specific example it is the two-body-Keplerian. The satellite() function is used to convert these arguments into an actual satellite body concerning these parameters. The input data of these satellites can be any imaginary values or even data from real satellites. In particular, values from the Galileo services satellites were used [66]. If the first case were the situation that someone may has, the data must not be completely arbitrary so that there is communication between the satellites and the ground base stations, even for a very short time. However, before the code appears, it is good to know what the Keplerian orbital parameters that define each satellite are and are shown in Image 28.

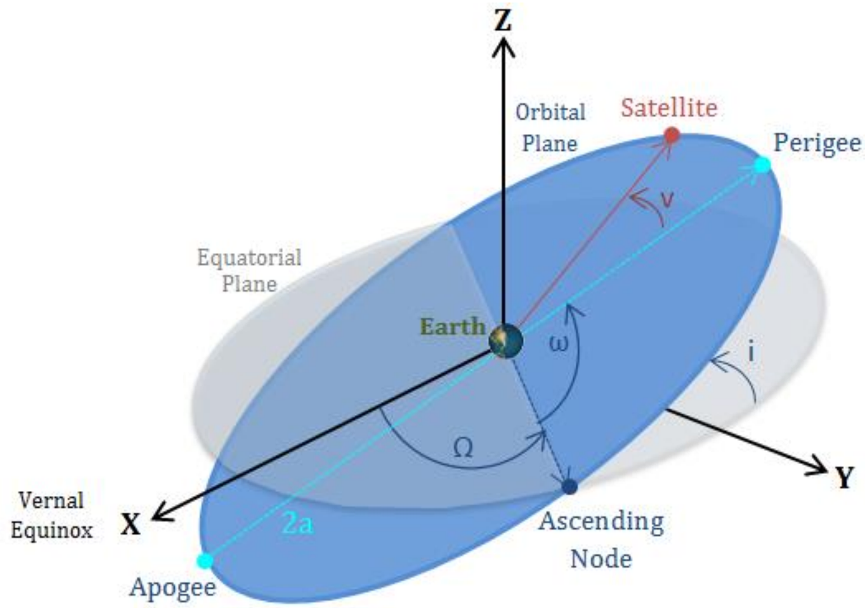

Image 28: Keplerian orbital parameters *[66]*

6.3.1.1 Semi-major axis

It is also called an orbital ellipse and it is referred to as the half length of the major axis, starting from the center of the ellipse and finishing on the longest possible edge of the orbit. It is thus the longest possible radius for the orbital ellipse as Image 29 provides. However, the semi-minor axis is the orthogonal line starting at the center of the ellipse and finishing at a right or left edge which is perpendicular to the semi-major axis, so it ends at the center of the conic section. For the special case of a circle, the lengths of the semi-axes are both equal to the radius of the circle.

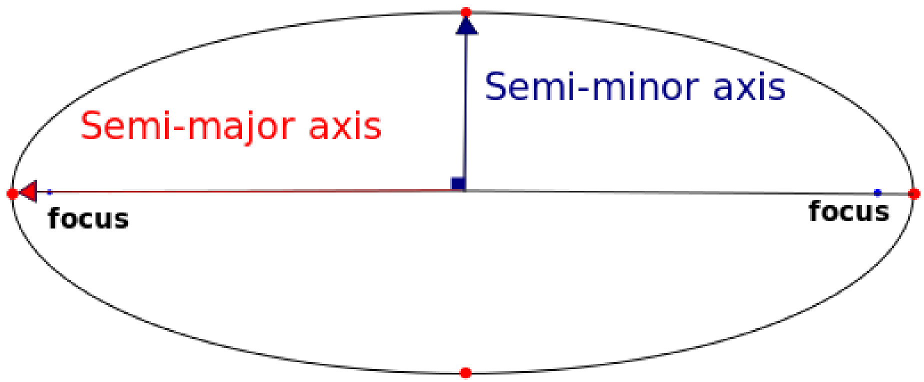

Image 29: Semi major and minor axis *[67]*

6.3.1.2 Eccentricity

It provides information on how circular or elliptical an orbit is. The larger the value of the concentricity, the flatter the orbit will be, therefore more elliptical, while the smaller the value, the more circular the orbit. The minimum value is 0 and specifies a perfect circle, while the maximum value is 1 and refers to the largest possible elliptical orbit. Eccentricity is seen in **Image *30***.

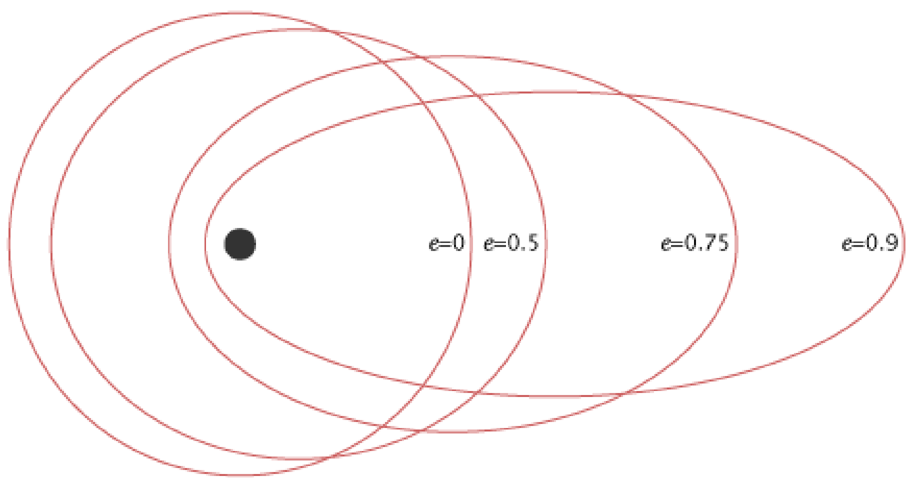

Image 30: Eccentricity of an orbit *[68]*

6.3.1.3 Inclination

The term is a straightforward meaning word and refers to the inclination of a body's orbit compared to the equator, as shown in **Image *31***. When the inclination is $90°\ (degrees)$, the orbit is exactly perpendicular to the equator and passes over the pole, while if the orbit is 0 or $180°$ it is parallel to the equator, therefore passing through it.

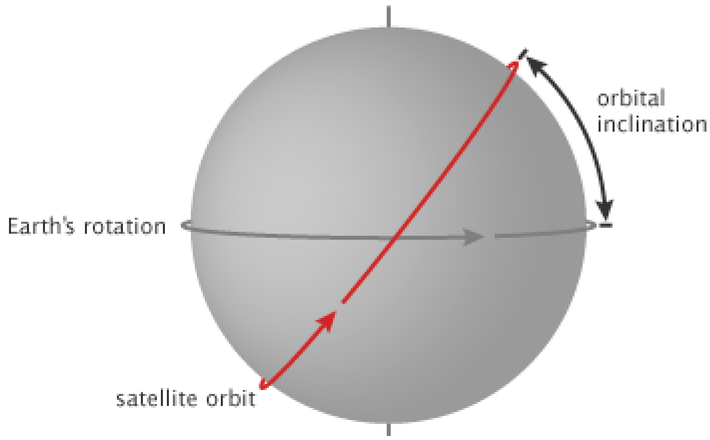

Image 31: Inclination of an orbit *[68]*

6.3.1.4 Right ascension of Ascending Node (RAAN)

It is the angular phasing between the orbital plane and the Vernal Equinox, which is the point of intersection between the Sun's trajectory and the Earth's equatorial plane. The intersection of the equatorial plane and the orbital plane is called the "Nodal Line". Its intersection with the unit sphere defines two points: the "Ascending Node", through which the satellite crosses to the region of the positive Z-axis, and the "Descending Node". "Right Ascension" is a counter-clockwise sense viewed from the positive Z-axis. Due to the Oblateness of the Earth, the RAAN is decreasing by about 10° per year. [66]

6.3.1.5 Perigee and apogee

In an orbit that has an eccentricity other than zero and a satellite moves around a body, then perigee is defined as the point closest to the body around which the satellite moves (for example the point where the satellite is closest on Earth), while the apogee is the point at which the satellite, while on its orbit, is farthest from any other point on that orbit as defined by **Image *32***. If the eccentricity is zero, then the perigee and apogee are the same size and this is because the circle is assumed perfect, so all points are the same distance far from the center of the orbit.

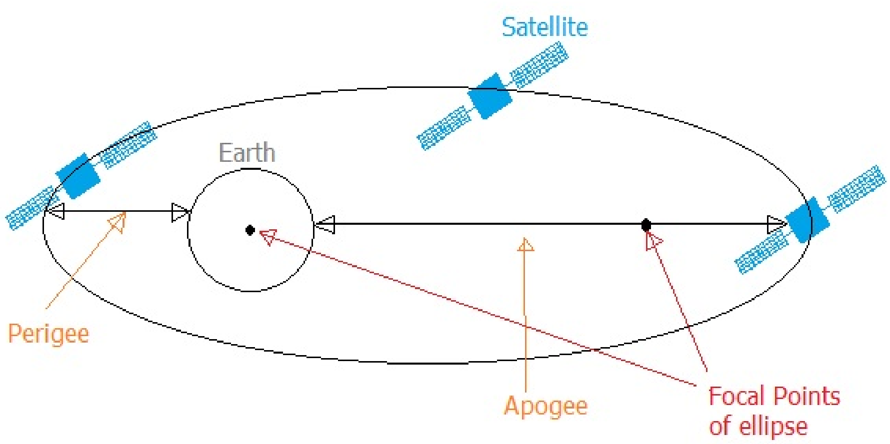

Image 32: Perigee and apogee *[69]*

6.3.1.6 True anomaly

Based on **Image *33***, a true anomaly defines the angle that the satellite has with the perigee of its orbit and takes values from 0 to $360°$.

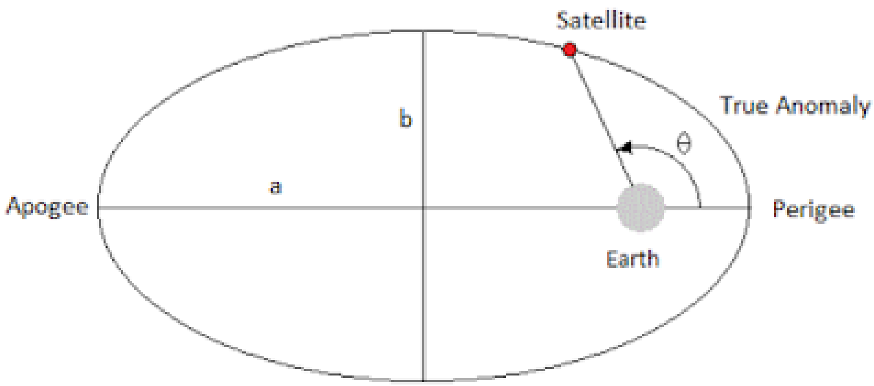

Image 33: True anomaly of an orbit *[70]*

Having in mind the previous parameters and the source [59], the following values are defined for two satellites, which concern the technical orbital characteristics of the GSAT0101 and GSAT0208 satellites, respectively.

```
semiMajorAxis = 12000000;
eccentricity = 0;
inclination = 56;
rightAscensionOfAscendingNode = 77;
argumentOfPeriapsis = 0;
trueAnomaly = 15;
sat1 = satellite(sc, ...
    semiMajorAxis, ...
    eccentricity, ...
    inclination, ...
    rightAscensionOfAscendingNode, ...
    argumentOfPeriapsis, ...
    trueAnomaly, ...
    "Name","Satellite 1", ...
    "OrbitPropagator","two-body-keplerian");

semiMajorAxis = 12000000;
eccentricity = 0;
inclination = 56;
rightAscensionOfAscendingNode = 197;
argumentOfPeriapsis = 0;
trueAnomaly = 120;
sat2 = satellite(sc, ...
    semiMajorAxis, ...
    eccentricity, ...
    inclination, ...
    rightAscensionOfAscendingNode, ...
    argumentOfPeriapsis, ...
```

```
    trueAnomaly, ...
    "Name","Satellite 2", ...
    "OrbitPropagator","two-body-keplerian");
```

Now that the orbital characteristics of the satellites have been added, the gimbals that will hold the antennas for both receiving and transmitting must be installed. The purpose of the gimbal, as previously mentioned, is to have two on each orbital body, with the purpose of each of them supporting the transmitter or receiver and at the same time their antennas. Each satellite acts as a regenerative repeater. A regenerative repeater receives an incoming signal, and then demodulates, re-modulates, amplifies, and retransmits the received signal. However, the MATLAB function requires the use of Cartesian coordinates in space ie $[\hat{x}_s, \quad \hat{y}_s \quad \hat{z}_s]$ where are referred as roll, pitch and yaw angles of the satellite respectively as Image 34 illustrates.

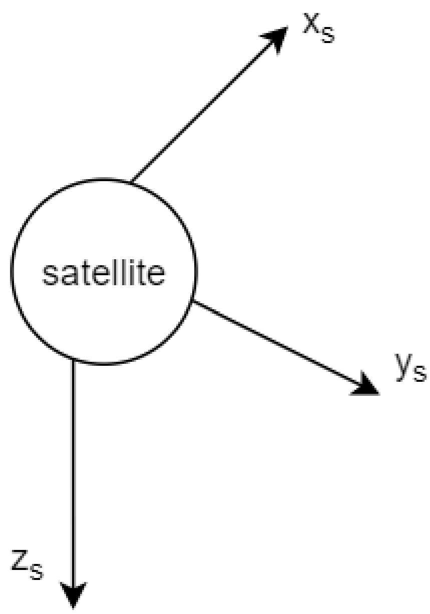

Image 34: Cartesian coordinates in 3D space

Thus for this experiment which is currently taking place, it is initialized that $[\hat{x}_s, \quad \hat{y}_s \quad \hat{z}_s] = [1 \quad 2 \quad 1]$ for the transmitter gimbal and $[\hat{x}_s, \quad \hat{y}_s \quad \hat{z}_s] = [1 \quad -2 \quad 1]$ for the receiver gimbal, for both satellites. One, could use whatever realistic values he/she wants, but the gimbals have to be in opposite directions. Image 35 shows how the gimbals are mounted.

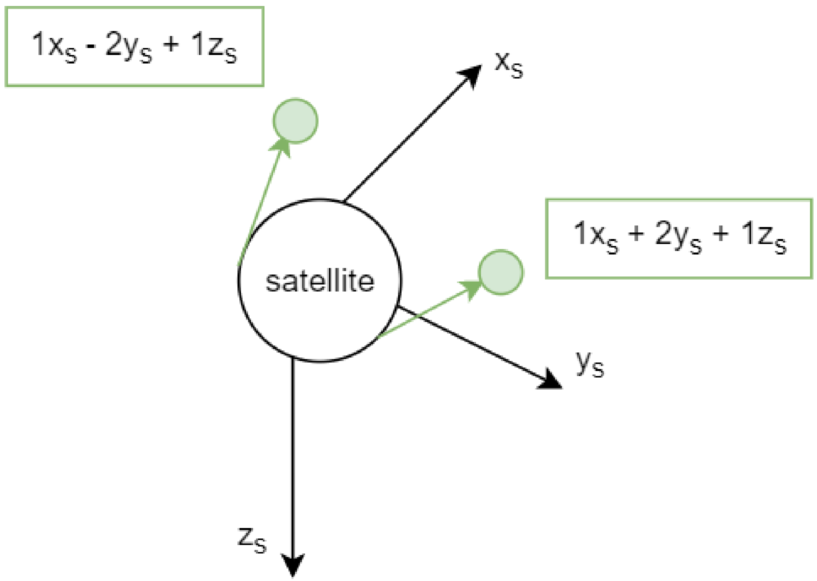

Image 35: Cartesian coordinates of the gimbals

The code for the above explanation is given below:

```
gimbalSat1Tx = gimbal(sat1, ...
    "MountingLocation",[1;2;1]);
gimbalSat1Rx = gimbal(sat1, ...
    "MountingLocation",[1;-2;1]);

gimbalSat2Tx = gimbal(sat2, ...
    "MountingLocation",[1;2;1]);
gimbalSat2Rx = gimbal(sat2, ...
    "MountingLocation",[1;-2;1]);
```

Afterward, the coordinates of the transmitter and receiver must also be defined so that the system can be fully defined. The specific objects have been placed to $\hat{z}_s = 1,$ as **Image *36*** shows, while the schematic diagrams cannot fully render the 3D representation of the components. However, with a rudimentary knowledge of the layers, one can imagine how the figure will look.

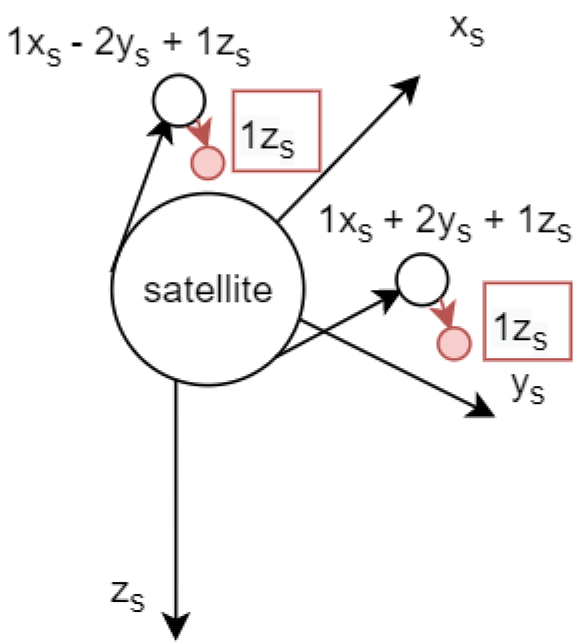

Image 36: Transmitter and receiver cartesian coordinates

However, the components for the transmitter and the receiver, in addition to the exact placement of their Cartesian elements, also need further information regarding their technical characteristics. Specifically, transmitters need arithmetic values for the parameters of frequency (Hz) and radiation power (dBW), while receivers need values for the performance of receiving the transmitted signal, and these values concern two ratios, one for Gain-to-Noise temperature ratio with a unit of measurement $^{dB}/_{K}$ and the last variable is set as $^{E_b}/_{N_0}$, given in dB. The values are set arbitrarily but always based on possible values that may exist in a system and not completely random values that make no sense. So the code is as follows:

```
sat1Tx = transmitter(gimbalSat1Tx, ...
    "MountingLocation",[0;0;1], ...
    "Frequency",30e9, ...
    "Power",15);
sat1Rx = receiver(gimbalSat1Rx, ...
    "MountingLocation",[0;0;1], ...
    "GainToNoiseTemperatureRatio",5, ...
    "RequiredEbNo",4);

sat2Tx = transmitter(gimbalSat2Tx, ...
    "MountingLocation",[0;0;1], ...
    "Frequency",27e9, ...
    "Power",15);
sat2Rx = receiver(gimbalSat2Rx, ...
    "MountingLocation",[0;0;1], ...
    "GainToNoiseTemperatureRatio",5, ...
    "RequiredEbNo",4);
```

Finally, before explaining the parameters for terrestrial means such as base stations, it is required specifically for satellites, to define the distribution of antennas as well as their diameter, where the code below performs for both satellites as well as for two components of the transmitter and the receiver. The radiation pattern of a Gaussian antenna is based on peak gain at its boresight, while the peak gain is a combination of the dish diameter and aperture efficiency. Also, this type of antenna decays radially-symmetrically based on a Gaussian distribution while moving away from boresight. The code is shown below.

```
gaussianAntenna(sat1Tx, ...
    "DishDiameter",0.5);
gaussianAntenna(sat1Rx, ...
    "DishDiameter",1);

gaussianAntenna(sat2Tx, ...
    "DishDiameter",0.5);
gaussianAntenna(sat2Rx, ...
    "DishDiameter",1);
```

Since now the two satellites have been fully defined in terms of their orbits and their technical characteristics, it’s time to initialize ground stations (GS) too. This is simple since, to begin with, their position depends on the longitude and latitude. The values were set arbitrarily, not representing real satellite communication stations, while their unit of measurement is given in degrees. The code is shown below.

```
latitude = 52.9436963;
longitude = 57.6906568;
gs1 = groundStation(sc, ...
    latitude, ...
    longitude, ...
    "Name","Ground Station 1");

latitude = 53.7974039;
longitude = 21.1768208;
gs2 = groundStation(sc, ...
    latitude, ...
    longitude, ...
    "Name","Ground Station 2");
```

Then the gimbal must be placed together with the transmitter or the receiver depending on the type of station and whether it is receiving or broadcasting the data. The strategy behind the frame is the same as that presented in previous schemes. There are two differences between the two groups of terrestrial and satellite units and it is on the one hand that the satellite has two gimbals for transmission and reception, while the ground station has only one gimbal because it is required to carry out only one of the two functions. The second difference lies in the delimitation of the frames where although the process is the same, the initial reference frames are defined differently. Also important for the base station antenna is that two metrics are required to fully define it and these are the elevation (meters) and tilt or pitch (degrees) angle. Therefore, based on Image 37 one has to set the mounting pitch angle to $180°$, so that $\hat{z}_G$ points straight up when the gimbal is not steered.

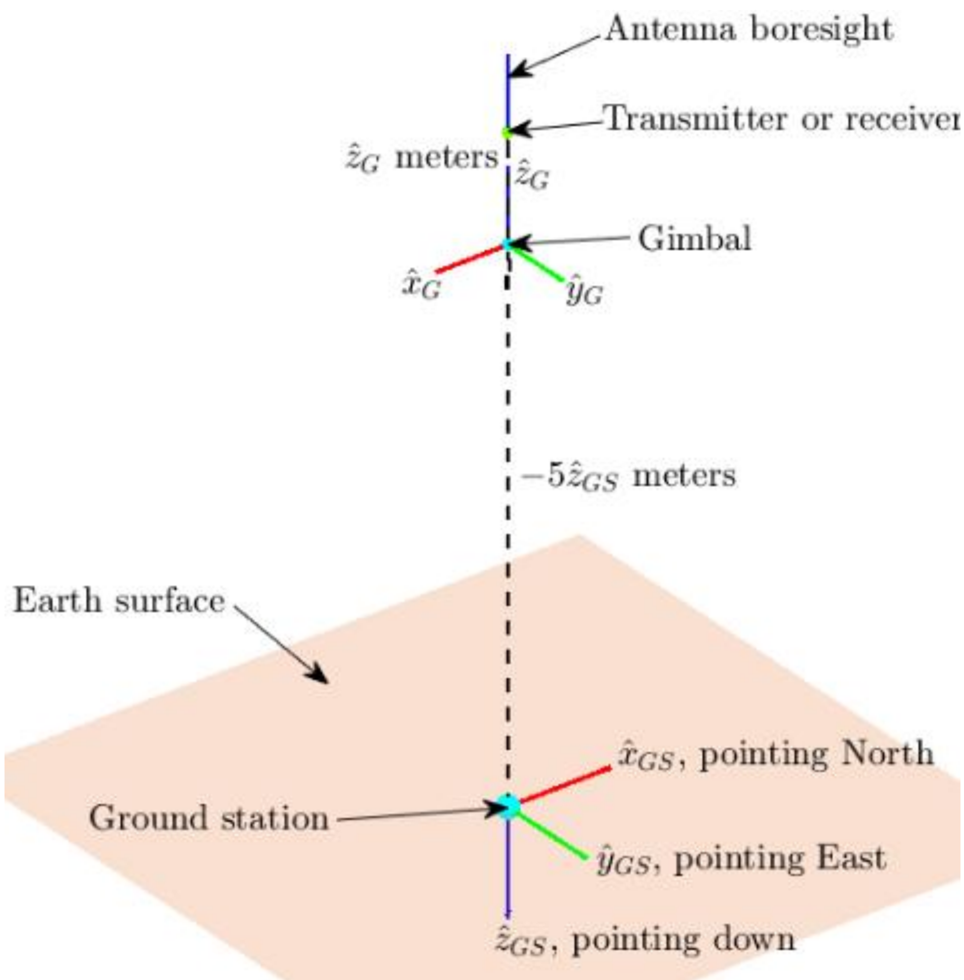

Image 37: Cartesian coordinates for both gimbal and transmitter/receiver for the ground station *[65]*

The result is the code shown below.

```
gimbalGs1 = gimbal(gs1, ...
    "MountingAngles",[0;180;0], ...
    "MountingLocation",[0;0;-5]);

gimbalGs2 = gimbal(gs2, ...
    "MountingAngles",[0;180;0], ...
    "MountingLocation",[0;0;-5]);
```

The same procedure will be followed now for the transmitter of Ground station 1 and the receiver of Ground station 2, as previously for the satellites. There is no reason to explain again how the parameters and their units resulted. Keep in mind that Image 37 fully illustrates what is happening on both base stations, so the code for them is given below:

```
gs1Tx = transmitter(gimbalGs1, ...
    "Name","Ground Station 1 Transmitter", ...
    "MountingLocation",[0;0;1], ...
    "Frequency",30e9, ...
```

```
    "Power",30);

gs2Rx = receiver(gimbalGs2, ...
    "Name","Ground Station 2 receiver", ...
    "MountingLocation",[0;0;1], ...
    "GainToNoiseTemperatureRatio",3, ...
    "RequiredEbNo",1);
```

Then, type of the antennas and their diameter must be provided.

```
gaussianAntenna(gs1Tx, ...
    "DishDiameter",2);

gaussianAntenna(gs2Rx, ...
    "DishDiameter",2);
```

At this point, both ground stations and satellites are fully addressed. The problem now is that MATLAB wants to know the flow of the data traffic to route the data among the objects. To do it so, one can use a function called 'pointAt' and 'link'. The first function helps to continuously point the gimbals of each object to each other to have an optimal link connection. The gimbals can be steered independent of their parents (satellite or ground station) and configured to track other satellites and ground stations. For these functions, there are six connections between the four objects that must be specified.

- Ground station 1 (transmitter of this station) points at the receiver of satellite 1.
- Based on the previous bullet, the receiver of satellite 1 points to the transmitter of ground station 1.
- The transmitting antenna of satellite 1 points at satellite 2.
- The receiver antenna of satellite 2 aims at satellite 1.
- The transmitter of satellite 2 aims for the 2nd ground station.
- Finally, ground station 2 points at satellite 2.

The code is given below.

```
pointAt(gimbalGs1,sat1);
pointAt(gimbalSat1Rx,gs1);

pointAt(gimbalSat1Tx,sat2);
pointAt(gimbalSat2Rx,sat1);

pointAt(gimbalSat2Tx,gs2);
pointAt(gimbalGs2,sat2);
```

Now, it is time to use the function called 'link'. This function helps to track the traffic flow of the data and it comes after the call of the 'pointAt' function. For this experiment, the flow starts from ground station 1 which wants to transmit something from its antenna to an end terminal called ground station So, the first and the last argument of the function will be the transmission from GS1 and the reception on GS2. Also, the signal arrives at the receiver of satellite 1 which is associated with the transmission of the signal to satellite 2. Satellite 2 receives the signal and then it transmits it to the GS2, where the link terminates. Thus, the flow is:

- Transmission gimbal of GS1 to reception gimbal of Sat1.
- Reception gimbal of Sat1 to transmission gimbal of Sat1.
- Transmission gimbal of Sat1 to reception gimbal of Sat2.
- Reception gimbal of Sat2 to transmission gimbal of Sat2.
- Transmission gimbal of Sat2 to reception gimbal of GS2.

Code is a one-line function and it is given below.

```
lnk = link(gs1Tx,sat1Rx,sat1Tx,sat2Rx,sat2Tx,gs2Rx);
```

If someone wants to see the results of the above code, MATLAB provides two ways to do it so. One is with a live scenario where you can adjust the speed of motion, days, angle of perception, etc. The other way is more for observation of the data transmissions and where these took place. Method ‘linkIntervals’ is used to determine the times the link is closed in a Table. It presents the intervals between link closures and especially the times that GS1 can send data to GS2 in association with the existing satellites. Names such as ‘source’ and ‘target’ refer to the first and last nodes in the link, respectively.

```
linkIntervals(lnk)

play(sc);
```

The results are given below at Image 38 and Image 39.

Source	Target	IntervalNumber	StartTime	EndTime	Duration	StartOrbit	EndOrbit
"Ground Station 1 Transmitter"	"Ground Station 3 receiver"	1	20-Feb-2023 12:51:00	20-Feb-2023 13:07:00	960	NaN	NaN
"Ground Station 1 Transmitter"	"Ground Station 3 receiver"	2	20-Feb-2023 16:29:00	20-Feb-2023 16:45:00	960	NaN	NaN
"Ground Station 1 Transmitter"	"Ground Station 3 receiver"	3	21-Feb-2023 14:17:00	21-Feb-2023 14:33:00	960	NaN	NaN
"Ground Station 1 Transmitter"	"Ground Station 3 receiver"	4	22-Feb-2023 12:05:00	22-Feb-2023 12:21:00	960	NaN	NaN

Image 38: Transmitting results of the end-to-end link channel

According to MATLAB [58], if one of the Source or Target is on a satellite, StartOrbit and EndOrbit provide the orbit count of the source or target satellite that they are attached to directly or via gimbals, starting from the scenario start time. If both Source and Target are attached to a satellite, StartOrbit and EndOrbit provide the orbit count of the satellite to which Source is attached. Since both Source and Target are attached to ground stations, StartOrbit and EndOrbit are NaN. IntervalNumber is just an ID that shows how many times something happened, StartTime and EndTime are coherent with the Duration and provide info about the exact time transmission of the data happened.

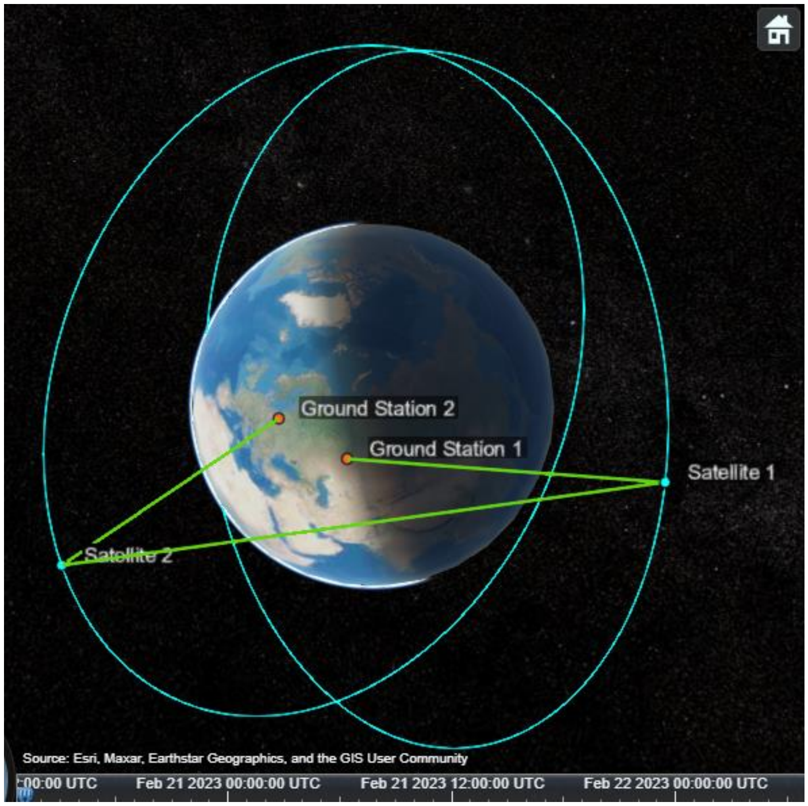

Image 39: Visualization of the experiment

Some comments are that for the two days that the simulation took place, it appears four times that end-to-end information is transmitted. However, this is not always a good thing. On the one hand, there is an open communication channel for about 15 minutes each time, which is considered sufficient time for satellite communication for LEO satellites and not for MEO as they could operate for about 2 hours, but for these scenarios a lot of things matter such as elevation, orbit, locations, etc. Also, as previously mentioned, the satellites are in MEO orbital positions, with technical characteristics that marginally touch GEO satellites. Therefore, although low in orbit compared to GEO satellites, the individual technical characteristics do not allow more data time frames transmissions. Nevertheless, on the one hand, this is not the best, but it is not always bad, and it depends on the information and the type of mission that one wants to carry out. If, for example, a near-real-time mission is required, then more LEO satellites are needed to transmit enough information continuously over time. Nevertheless, if earth observation is being done to see if a stadium is being built or not, then even once a day can be a pretty good chance of getting information.

6.3.1.7 Extra code for access on a ground station

One may want to see specifically for a sensor, which is in a certain position on the satellite, its characteristics and field of view based on this position, and how long it can send information (or receive) concerning the GS1 that serves it. A ground station and a conical sensor based on a satellite are said to have access to each other if:

- the ground station is inside the conical sensor's field of view.
- the conical sensor's elevation angle concerning the ground station is greater than or equal to the latter's minimum elevation angle.

Thus, firstly it is recommended to allocate the name of the camera sensor which is a canonical sensor mounted on the satellite. Its angle of view is $70°$ and specifies the ability and the angle in the cartesian system to take pictures in these degrees. Then, to capture good quality pictures with minimal atmospheric distortion, the satellite's elevation angle concerning the site should be at least $30°$, and for this experiment, the value is set to $70°$.

After that someone has initialized the characteristics of the sensor it is time to add a ground station, which represents the geographical site to be photographed.

Then in a case where multiple cameras and satellites exist, it is necessary to use the 'access' function so the access analyses will be used to determine when each camera can photograph the site.

Functions called 'satelliteScenarioViewer' and 'fieldOfView' are used to visualize the range of the camera and how the orbits with these fields of view affect the communication link.

'accessIntervals' is the same as 'linkIntervals' but this time it provides the times when there is access between each camera and the geographical site and not the times when the ground and space units can transmit data as it may differs based on the radius of the sensor.

Code is summed up and provided below. A result of the conical sensor connected to the GS is seen in Image 40.

```
names = sat1.Name + " Camera";
cam = conicalSensor(sat1,"Name",names,"MaxViewAngle",70);


minElevationAngle = 40;
gs1 = groundStation(sc, ...
"MinElevationAngle",minElevationAngle, ...
    "Name","Ground Station 1");

ac = access(cam,gs1);

v = satelliteScenarioViewer(sc,"ShowDetails",false);
sat1.ShowLabel = true;
gs1.ShowLabel = true;

fov = fieldOfView(cam([cam.Name] == "Satellite 1 Camera"));

accessIntervals(ac)

play(sc);
```

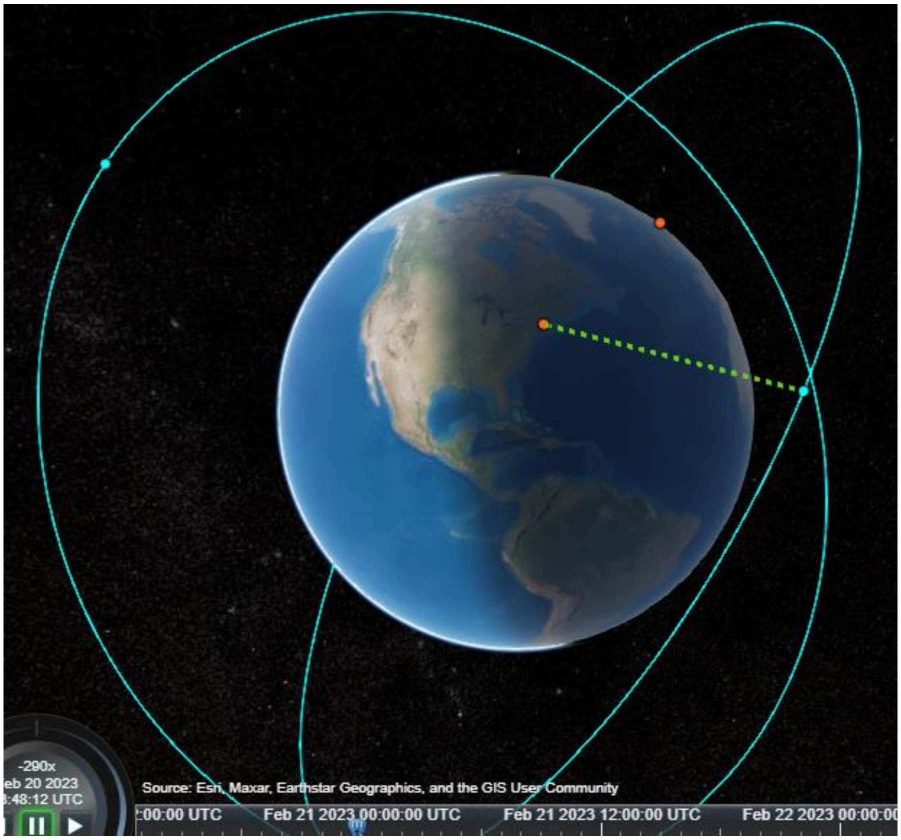

Image 40: A canonical sensor connected to a GS

6.3.2 Satellite budget link analysis

Beyond the modeling and basic operations of the link and when the data is sent, MATLAB provides an APP to be able to do an in-depth analysis from both the satellite and ground station sides. Therefore, one can adapt the technical characteristics of the link and terminals based on a real system or at least based on some specifications that one wants the link to provide. This implies that characteristics such as longitude, latitude, type of antenna, power, EIRP, etc are variables that the application user is asked to initialize to obtain valid and reliable information about the performance of his/her link. A feature of this APP is also that in addition to the results obtained for the performance of the link, it is possible to realize various plots which can clarify and explain more specifically the whole system.

This particular experiment is a combination of the previous values used and values found online from more specific examples. The values are compatible with real scenarios for the most part and are not values that are impossible to achieve. For example, values may be used in some parameters that do not exist from some space vehicle or some solved examples of the Internet, but the resulting results will have realistic values and not extravagant and utopian ones. Also, for the propagation loss, a model called ITU-R P.618-13 [71] is used, which helps for the availability of the satellite communications link through, where MATLAB gives the option to use but it is not applied by default and one has to choose it. Below, we will present the values imported into each variable, which as previously mentioned have been drawn from previous examples, but also the results with some graphs are presented too.

Apart from the previous ones, the MATLAB APP is quite peculiar, and while it provides many features that one can use, the other hand it lags in a few things. For example, it allows the addition of a different link between two terminals but does not change the names of the stations. For this reason, it is worth noting that within the APP S3 and S4 are hypothetically two different additional satellites (S), but for our example, they are S1 and S2, respectively. Also, an attempt was made for the experiment to remain on a low level of difficulty, both for the time limit to complete the task, but more so to introduce and facilitate the reader with the basic use of the program and encourage him to do something innovative on its own, based on its own processing needs. Equations and results provided below can be used for every satellite link and most of these equations and formulas have been provided earlier. Below are the values used to perform the experiment and derive the results for the three links, between the transmitting station to satellite 1, satellite 1 to satellite 2, and satellite 2 to receiving ground station respectively. The values are taken from previous examples and equations, from the paper [65], but also can be computed based on previous sections via customer's needs.

6.3.2.1 Receiving terminal equations and estimations

First of all, it is necessary to compute the gain of the antenna. It is assumed that the antenna panel and the broadside vector are horizontal too, so the gain of the antenna depends only on the peak gain of the antenna. Otherwise, the gain can be calculated as:

$$G\ (dBi) = Peak\ (dBi) - \cos(roll\_off) \times 10 \times \log(\cos\theta)$$

Where the $roll\_off$ is an antenna coefficient for the reduction in gain caused by scan angle (θ) and it is given by the provider, which is called scan angle. Also, θ is the angle between the boresight vector and the broadside vector and the φ is the second angle coordinate that determines the direction of the boresight vector. The above variables are provided in Image 41.

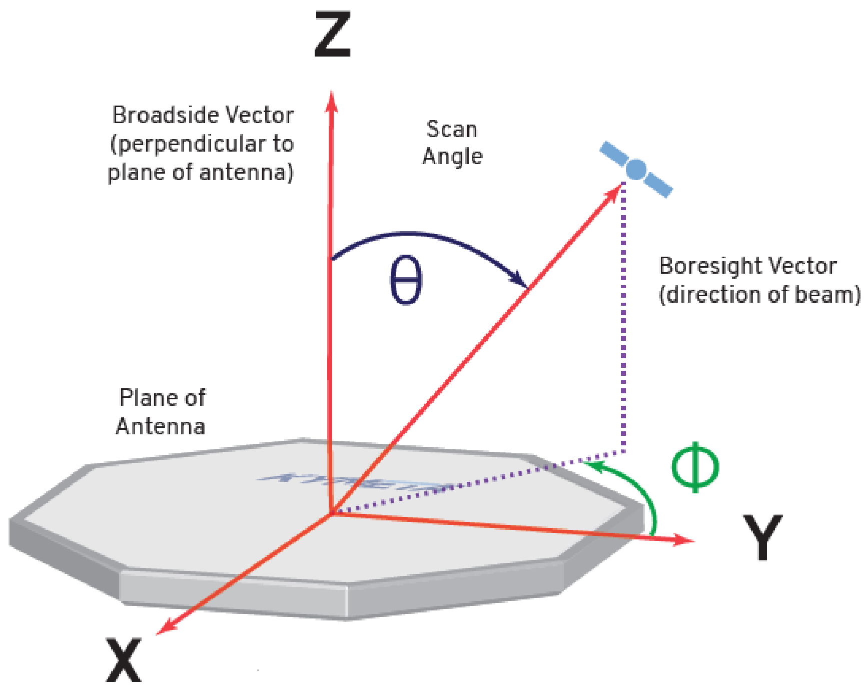

Image 41: Configuration for the gain of the antenna *[72]*

For the example that is provided in this thesis, it is given:

$$G\ (dBi) = Peak\ (dBi)$$

Sometimes calculating the noise temperature is difficult and most of the time providers are given this information to you, considering it as a known variable. However, below is provided the equation used to measure the noise temperature of the passive component such as a diplexer and it is calculated from:

$$T_p = T_e * (L - 1)$$

Where T_e is the ambient temperature of the component while a good estimation is $290K$, and L is initialized as the linear attenuation of the component, thus $L - 1$ gives the payload. A diplexer is something different than a duplexer. Diplexer, it's the only component between the RF chain and the end terminal and it is used with filters to separate the signals concerning their different frequencies. However, a duplexer is used to separate two signals both received or transmitted that operate in the same frequency. A typical value for diplexers losses depends on the operating frequency, and it is about $2\ dB$. Thus, it is applied:

$$T_p = T_e * (L - 1) = 290 * \left(10^{\frac{2}{10}} - 1\right) = 290 * (1.5848 - 1) = 170K$$

Having in mind that the satellites and ground stations used in this example are operating between $25 - 30\ GHz$ frequency based on if the link is uplink or downlink, which means Ka-band, the $Noise\ Figure$ of a ground station antenna with $2.4\ m$ diameter, is approximately in a good case scenario such as $1.5\ dB$. Thus the temperature of the noise figure, keeping in mind the previous equation is given as:

$$T_{NF} = T_e * (L - 1) = 290 * \left(10^{\frac{NF}{10}} - 1\right) = 290 * (1.4125 - 1) = 120K$$

Furthermore, it is possible to calculate the gain of antenna relative to the temperature of the noise figure:

$$G/_T = G\ (dBi) - T_{NF}\ (K) = 27.69\ {}^{dB}/_K$$

Knowing the antenna gain and the $Transmitting\ power$ for a common $2.4\ m$ diameter antenna operating in $25\ GHz$ frequency for uplink, which means Ka-band, equals $100\ W$ or $20\ dBW$ it is possible to calculate the Equivalent Isotropic Radiated Power (EIRP). Someone can also use the linear attenuation loss (diplexer loss) L to be more specific about the result, even if it is very small compared to the other metrics. Apply these to the EIRP equation:

$$EIRP = G(dBi) + T_x(dBW) - L\ (dB) = 98.42\ (dBm)$$

6.3.2.2 Transmission link equations and estimations

After all, it is important to calculate the Free Space Losses (FSL) of the data link. These losses represent how the electromagnetic signal attenuates through the distance in a free space environment with a Line of Sight view between two end-points. So, this parameter depends on the spread of the signal in the 3D space and the efficiency of the antenna to receive the incoming signals. Thus, FSL is given by:

$$FSL = \frac{P_t}{P_r}$$

The transmitting power, called Pt is a function of the power density Pd given in Wm2 and the distance between transmitting and receiving antennas in m, so:

$$P_t\ (W) = P_d * 4\pi d^2$$

While the receiving power Pr depends to the power density Pd given in Wm2 and the wavelength of the signal given in m, and it equals to:

$$P_r\ (W) = \frac{P_d \lambda^2}{4\pi}$$

Thus, FSL is known due to c=λ∗f, where f is the frequency in Hz, as:

$$FSL = \frac{P_t}{P_r} = \frac{P_d * 4\pi d^2}{\frac{P_d \lambda^2}{4\pi}} = \frac{(4\pi df)^2}{c^2} = \left(\frac{4\pi df}{c}\right)^2$$

However, this is calculated in $Watts$, so the logarithmic formula can be written based on c=3∗108 ms as:

$$FSL = 20\log d + 20\log \mathrm{f} - 20\log\left(\frac{4\pi}{c}\right) = 20\log d\ (km) + 20\log f\ (GHz) + 92.45$$

For the experiment, d is $12{,}000\ km$, without calculating the distance of the ground earth to the ground station antenna and from the satellite to its antenna, because these distances are extremely small compared to the distance between the two antennas, so approximately $20\ m$ will not affect the result. Also, the operating frequency is $30\ GHz$.

$$FSL = 20\log(12000) + 20\log(30) + 92.45\ (dB)$$

$$FSL\ = 20 * 4.07 + 20 * 1.47 + 92.45 = 81.4 + 29.4 + 92.45\ (dB)$$

$$FSL = 203.25\ dB$$

However, not only do Free Space Losses occur on the link but at such distances, there is also exist atmospheric loss, like molecules that absorb energy and reflect the signals in different ways. Figure 8 provides information about the losses per km for the different frequencies and wavelengths. Someone can observe that as the frequency increase, so does the atmospheric loss, and that leads to the conclusion that it is very difficult to transmit a signal in very high frequencies.

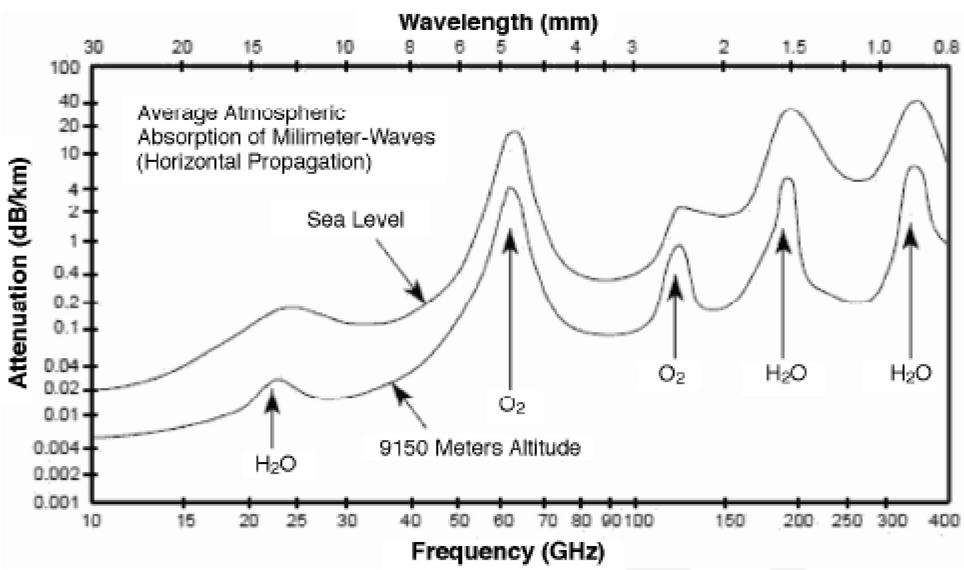

Figure 8: Atmospheric loss relative to frequency and wavelength *[72]*

For $30\ GHz$ uplink frequency and especially Ka-band, the loss is about $0.01\ {}^{dB}/_{km}$, thus for $12{,}000\ km$, it is applied as:

$$Atmospheric\ loss = 12000km * 0.01\ {}^{dB}/_{km} = 120\ dB$$

Someone could assert that clouds or rain also affect the link estimations and that’s true. However, for the experiment, this is considered as something that is not happening because the rain and clouds losses are calculated through the longitude and latitude values and the location of a satellite/GS and it’s something that’s not always happening due to different weather conditions per location. For more information, someone could study the source [72].

6.3.2.3 Satellite equations and estimations

It is important now to calculate all the parameters of the satellite that affect the link budgets that are previously shown. That means that saturation flux density (SFD) is something that must be taken into account because it is a metric that shows how much must the density be in the receiving antenna, to feed and saturate the high power amplifier (HPA) of the transponder in a way that reproduces the maximum available output power. This parameter depends on the bandwidth of the channel and typically ground earth antenna cannot saturate the satellite antenna. The difference between these values SFD and PFD, meaning saturation flux density and received flux density respectively, is called input back-off to the HPA. Also, to compute these two variables (SFD and PFD) someone must know that the first one is provided by the operator based on a ${}^{G}/_{T}$ ratio. Mostly, it is applied as:

$$SFD = -88\ {}^{dBW}/_{m^2} \rightarrow for\ a\ {}^{G}/_{T} = 0\, {}^{dB}/_{K}$$

and that means the lower ${}^{G}/_{T}$ ratio is, the more transmitted power requires to achieve HPA saturation. Thus, for the experiment that currently computing, is applied:

$${}^{G}/_{T} = 27.69\ {}^{dB}/_{K}$$

so,

$$SFD = -88\ {}^{dBW}/_{m^2} - 27.69\ {}^{dB}/_{K} = -115.7\, {}^{dBW}/_{m^2}$$

Now, the PFD variable is remaining and it can be expressed in real/true numbers as:

$$PFD = \frac{P * G}{4\pi d^2}\ ({}^{W}/_{m^2})$$

and for the logarithmic estimations it is expressed as:

$$PFD\ ({}^{dBW}/_{m^2}) = EIRP_{terminal} - 20\log d\ (m) - 10\log 4\pi = EIRP_{terminal} - 20\log d\ (m) - 10.99$$

For this experiment, $EIRP_{terminal}$ is given as 70 dBW and d is given as $12.000.000\ m,$ so the power density received by the ground station can be calculated.

$$PFD\ = 70dBW - 20 * 7.07 - 10.99 = 70 - 141.58 - 10.99 = -82.57\ {}^{dBW}/_{m^2}$$

Thus back-off to the HPA is given as:

$$Input\ back-off\ to\ HPA = SFD - PFD = -115.7\, {}^{dBW}/_{m^2} - (-82.57)\ {}^{dBW}/_{m^2}$$

$$Input\ back-off\ to\ HPA = -33.13\ {}^{dBW}/_{m^2}$$

Furthermore, input back off it is also affected by the channel bandwidth and the HPA compression. So,

$$SFD_{terminal} = SFD - 10\log\left(\frac{BW_{transpoder}}{BW_{channel}}\right)$$

The difference between $SFD_{terminal}$ and SFD is that the $BW_{channel}$ is greater than $BW_{transpoder}$, then only a part of the available bandwidth is allocated, so not whole power density is committed.

Let's not forget the HPA compression when operating near saturation, which is given as $2.7\ dB$ and it is important to include it on the saturation power needed because if you do not, the system will not reach saturation as this limit is the lower boundary. For example, if $20dB$ is needed, then in fact the system must have at least $22.7\ dB$ to attain saturation.

Finally, having in mind that $BW_{channel}$ for a Ka-band is about $0.5 - 1\ GHz$ and the BW for a satellite transponder is approximately $36\ MHz$. Thus, the saturation flux density of the terminal can be found by:

$$SFD_{terminal} = SFD - 10\log\left(\frac{36}{1000}\right) = -\,115.7 - 10 * -1.44 = -130.13\ {}^{dBW}\!/_{m^2}$$

6.3.2.4 Transmitting earth station equations and estimations

For a specific transmitting station, this information is not always given to a user but can be calculated based on the previous equations, otherwise sometimes providers publish some of their data and it is possible to be gathered from them. The key differences now are that noise temperature increases due to atmosphere and precipitation, there also exist contributions from interfering ground and cosmic radiation sources and finally gain of the antenna is coherent with its diameter of its panel.

For this experiment data are considered as:

- $G = 51.5\ dBi$
- $Antenna\ diameter = 3\ m$
- $Operating\ frequency = 25\ GHz$
- $Antenna\ noise\ temperature = 150\ K$
- $Additional\ losses = 90\ K$
- ${}^{G}\!/_{T} = 51.5 - 10\log(150 + 90) = 27.7\ {}^{dB}\!/_{K}$

Now it is important to calculate the SNR ratio between transmitting and receiving antenna. So, the formula for this equation is given as:

$$SNR = EIRP_{sat_{transponder}}(dBW) - BW_{transponder}(dBHz) - FSL\ (dB) - Atmospheric\ loss\ (dB) - {}^{G}\!/_{T_{transmitter}}\left({}^{dB}\!/_{K}\right) - k\left({}^{dBW}\!/_{KHz}\right)$$

$$SNR = 70 - 45.56 - 203.25 - 120 - 27.7 + 228.6 = 22.09\ dB$$

One of the most important parameters to be calculated is the spectrum efficiency (SE), which refers to the amount of data that can be transmitted in a given bandwidth and is measured in bits per second per Hz (bps/Hz). To calculate this value, someone needs to know the SNR of the link due to Shannon limitations that don't allow the SE to operate near these SNR limits. Table 14 shows these restrictions, where the rightmost column refers to the minimum SNR, and the leftmost column provides information about the modulation of the codewords used. Knowing these two parameters, someone can calculate spectrum efficiency. However, here are not summarized all modulation schemes, but some of them, that will be used in this example. Modulations like QPSK and so on exist, with higher spectrum efficiencies as well.

Table 14: Spectral efficiency based on SNR and modulation code *[72]*

MODCOD	SPECTRAL EFFICIENCY bps/Hz	SNR for QEF (dB)
APSK 1/2	0.4	-2
CPSK 1/4	0.5	0
CPSK 1/2	0.6	1
CPSK 3/4	0.65	2
DPSK 1/4	0.75	3
DPSK 1/2	0.9	4
DPSK 3/4	1.05	6
DPSK 5/6	1.25	7
DPSK 7/8	1.5	9

Now, bit rate can be calculated. Channel bandwidth is about $36\ MHz$ for uplink Ka-band of $30\ GHz$ frequency. Spectral efficiency based on this experiment is given by considering as modulation scheme the DPSK $5/6$ with $1.25\ {}^{bps}/_{Hz}$. Finally:

$$Bit\ rate = spectral\ efficiency\left({}^{bps}/_{Hz}\right) * channel\ bandwidth\ (Hz)$$

$$Bit\ rate = \ 1.25 * 30 * 36 * 10^6 = 1.35\ Gbps$$

6.3.3 Implementation and discussion of the above theory and examples

The problem with the above calculations is that MATLAB APP does not use all of the above parameters so the results that are going to be calculated will be different from the real scenario. Thus, an example based on MATLAB will be used just to see the basic properties of the app and see how it works. Also, previously the ESA terminal - hub and how it works among with the parameters and the values of these parameters were presented, so the reader can use either the ESA or MATLAB scenario based on its constants and what serves more his/her procedures. There is no reason to try customized inputs/outputs because the data provided are not fully addressed, so importing values on arguments out of the box will lead to not doable results. At the end of the day, values, as seen below for each parameter, are based both on different types of providers for their antennas or satellites, examples provided above on previous Sections and also on some imaginary values that are randomly inserted but based on possible systems and scenarios. That happened because no one publishes the full data used by each provider and it is difficult to concatenate two or three different data from providers that lead to a reasonable result. Thus, the results are not optimal and lead to some not optimal connection budgets as it going to be shown later, but this is not something that anyone has to worry about because in a real system you will know all the available data and you could be able to adjust the inputs/outputs of the system.

Before starting using the MATLAB Analyzer it is necessary to do a recap for the variables that will be used, so the user and the reader will be able to implement the necessary values for each field represented below and also to understand how the link is used. For the recap, it is known:

- **Feeder losses:** indicates the losses that resulted due to the existence of different devices on the path of the antenna to the end-point receiver
- **Other losses:** indicates the losses for different reasons, such as white noise, cable noise, over-the-air transmission, etc. Here are not included the free space losses or the rain or propagation losses.
- **HPA transmitting power:** this is the transmit chain also called a high-power amplifier and how energy/radiation it transmits.
- **HPA back-off losses:** these losses indicate how much the amplifier will be under saturation levels, but it will still operate in linear mode instead of saturation mode.
- $\boldsymbol{E_b/N_0}$**:** it's so-called 'SNR per bit' and indicates how strong the signal is at the receiver in the arrival time. Different modulation schemes give different ratios because the bit error rate (BER) is a parameter that affects the result.
- **Polarization mismatch losses:** leads to electromagnetic power losses. That happens when receiver and the polarization of the electromagnetic field are not coherent, and are not matched.
- **Implementation losses:** refers to satellite links and especially it is the degradation that a signal has before and after the trip/pass from the uplink and downlink equipment. It is the losses from input to output of the whole equipment in both uplink and downlink.
- **Antenna mispointing losses:** this is the error of the misalignment of the antenna due to big distances that lead to an attenuation of the signal strength.
- **Radome losses:** since the signal has to pass through the wall of the radome, then occur insertion loss and scattering loss through the panel that blocks the aperture of the antenna.
- **Interference losses:** can be happened due to other objects transmitting on the same band and interfering with the signal of interest.
- $\boldsymbol{G/T_e}$: gain received divided by the system noise received. It helps to clarify the performance of the antenna, where the bigger the value, the better the performance.

Also, as one would notice by using the MATLAB Analyzer, each station has different properties and this is because one is used for broadcasting while the second one is used for receiving information. Therefore, this implies that they cannot have the same properties since one can have $Transmiting\ power$ parameter, and the other could have $power\ density$ of the received signal. It is also worth noting that the two satellites, are not expressed in the form of geographic coordinates, i.e., longitude and latitude. The following code is used to print the geographic coordinates on the screen, while the Keplerian orbit parameters of the previous part are known, namely the inclination, the argument of periapsis, the right ascension of ascending node (RAAN), and the true anomaly variables.

```
incl_sat = 56;
argp_sat = 0;
raan_sat = 77;
ta_sat = 15;
lat_sat = asind(sind(incl_sat)*sind(argp_sat+ta_sat));
L_sat = atand(cosd(incl_sat)*tand(argp_sat+ta_sat));
if lat_sat >=0
    if L_sat>0
        lon_sat = L_sat + raan_sat - 360;
    else
        lon_sat = L_sat + raan_sat - 180;
    end
else
    if L_sat>0
        lon_sat = L_sat + raan_sat - 180;
    else
        lon_sat = L_sat + raan_sat;
    end
end
lon_sat
lat_sat
```

In the experiment that took place for this thesis, there are three links (L) to transmit the data from one ground station to another. That happens because the first link refers to the ground station which wants to transmit data and to do it so it uses a satellite. The second link is for the connection between the two satellites and the third one is for the data to be transmitted to the end-point ground station from the satellite. Thus, to get started below will be provided information and values for every argument that used as input for the MATLAB Analyzer. Image 42 shows the connection link, while Image 43, Image 44 and Image 45 contain the values for the fields used. All the data provided below is taken from examples or providers that publish some of their antenna and space mission features. Otherwise, some existing data are based on real scenarios but are not taken from specific missions or operations.

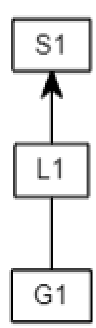

Image 42: Transmitting ground station to receiving satellite

6.3.3.1 Ground station 1 (G1) – Transmitter

- $Transmiting\ feeder\ losses = 0.4\ dB$
- $Transmitting\ losses = 2.5\ dB$
- $HPA\ transmitting\ power = 20\ dBW$
- $HPA\ Back\ off\ losses = 4\ dB$
- $Antenna\ gain = 56.6\ dBi$

- $Longitude = 52.9437°$
- $Latitude = 57.6906°$
- $Altitude = 5\ m$

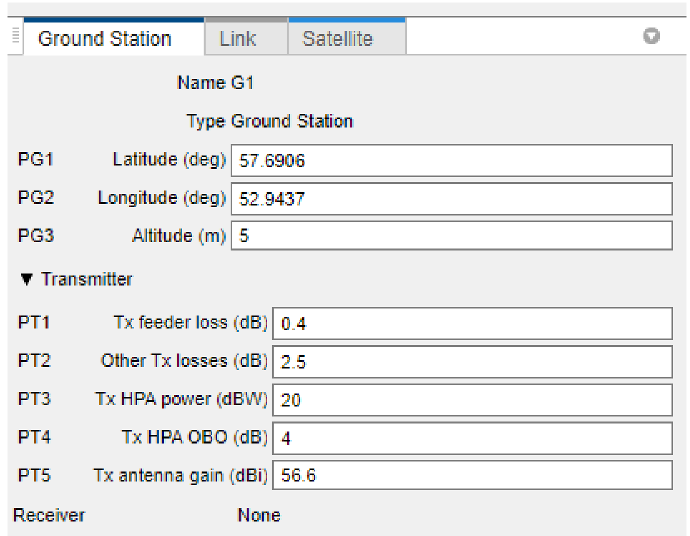

Image 43: Data imported in the MATLAB APP for the G1

6.3.3.2 Link 1 (L1) – between transmitter and a receiving mid-point satellite

- $Frequency = 30\ GHz$
- $Channel\ bandwidth = 600\ MHz$
- $Bit\ rate = 120\ Mbps$
- ${E_b}/{N_0} = 8\ dB$
- $Availability = 99.9\ \%$
- $Polarization\ mismatch\ loss = 45°$
- $Implementation\ loss = 2\ dB$
- $Antenna\ mispointing\ loss = 2\ dB$
- $Radome\ loss = 1\ dB$

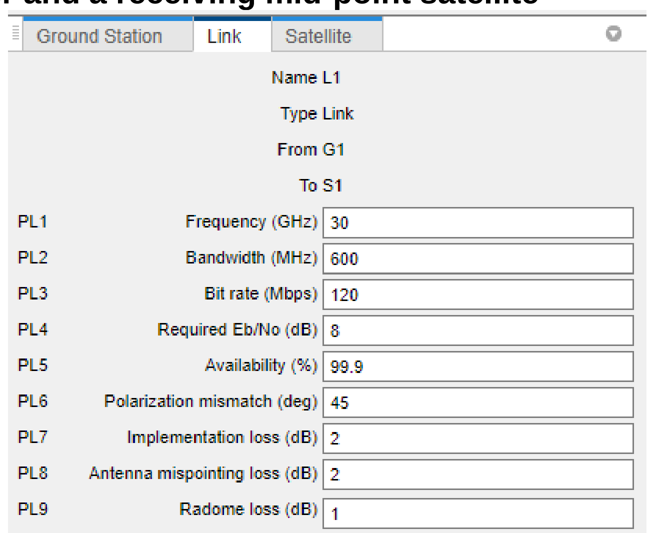

Image 44: Data imported in the MATLAB APP for the L1

6.3.3.3 Satellite 1 (S1) – mid-point receiver

- $Interference\ loss = 3\ dB$
- $^{G}/_{T_e}\ ratio = 27.5\ ^{dB}/_{K}$
- $Received\ feeder\ loss = 3\ dB$
- $Received\ losses = 2\ dB$

- $Longitude = 27.0847°$
- $Latitude = 45.8869°$
- $Altitude = 12{,}000\ km$

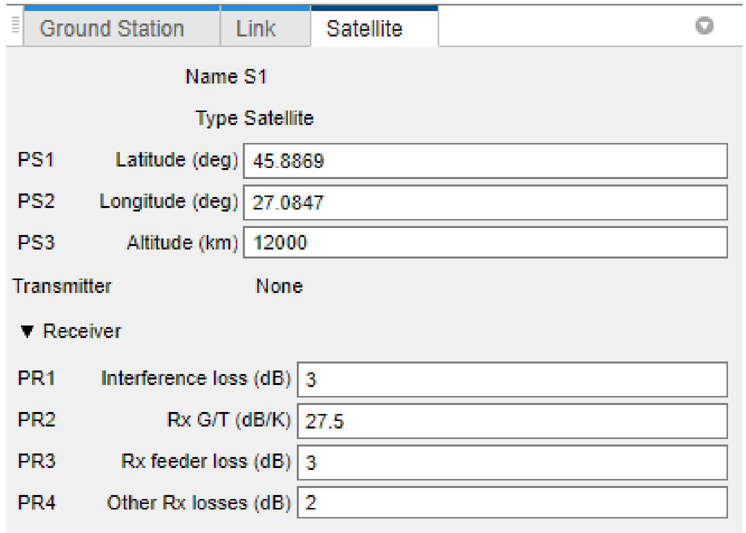

Image 45: Data imported in the MATLAB APP for the S1

Now, the first link between the transmitter and the receiver is fully addressed, so the connection between the two satellites acting as relays has to be computed. Image 46shows the middle connection between the two satellites, while Image 47, Image 48 and Image 49 provide the data used for the link described. As previously mentioned, MATLAB does not allow to have from Satellite 1 direct communication to Satellite 2 as it is happening to transmit the data from Ground station 1 to Ground station 2. That occur because S1 is acting as a receiving point and S3 as a transmitting point. Thus, MATLAB does not know what parameters to allocate in a satellite acting as both terminals (transmitting + receiving) and that's why it allocates two different satellites (S1 and S3) to receive and transmit the data to another satellite. The same operation is happening with the S2. To successfully receive and transmit the data MATLAB is constructing a receiving satellite and a transmitting one called S4 and S2 respectively.

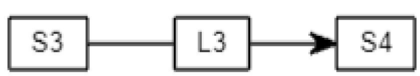

Image 46: Transmitting satellite to receiving satellite

6.3.3.4 Satellite 3 (S3) – transmitter of the S1 satellite information

- $Transmiting\ feeder\ losses = 2\ dB$
- $Transmitting\ losses = 3\ dB$
- $HPA\ transmitting\ power = 17\ dBW$
- $HPA\ Back\ off\ losses = 3\ dB$
- $Antenna\ gain = 50\ dBi$

- $Longitude = 27.0847°$
- $Latitude = 45.8869°$
- $Altitude = 12{,}000\ km$

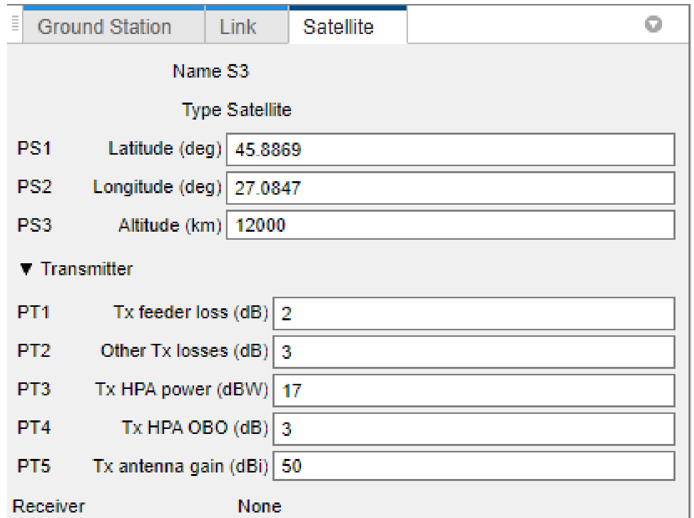

Image 47: Data imported in the MATLAB APP for the S3

6.3.3.5 Link 3 (L3) - between transmitter and receiving mid-point satellites

- $Frequency = 25\ GHz$
- $Channel\ bandwidth = 36\ MHz$
- $Bit\ rate = 120\ Mbps$
- $E_b/_{N_0} = 7\ dB$
- $Availability = 99.9\ \%$
- $Polarization\ mismatch\ loss = 45°$
- $Implementation\ loss = 1\ dB$
- $Antenna\ mispointing\ loss = 1\ dB$
- $Radome\ loss = 0\ dB$

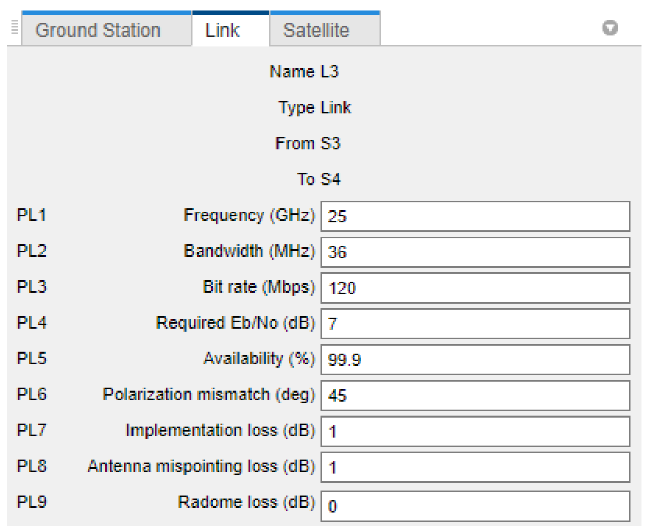

Image 48: Data imported in the MATLAB APP for the L3

6.3.3.6 Satellite 4 (S4) - transmitter of the S3 satellite information

- $Interference\ loss = 2\ dB$
- ${}^{G}/_{T_e}\ ratio = \ 25\,{}^{dB}/_{K}$
- $Received\ feeder\ loss = \ 1\ dB$
- $Received\ losses = 2\ dB$

- $Longitude = -94.4785°$
- $Latitude = 12.3903°$
- $Altitude = 12{,}000\ km$

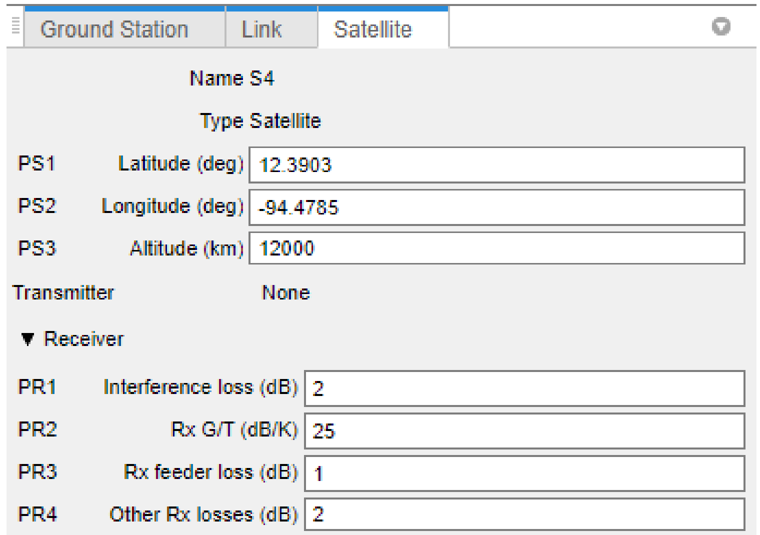

Image 49: Data imported in the MATLAB APP for the S4

The connection link below is the most important of the three. That's because Ground station 2 is the final terminal that receives the data transmitted from Ground station 1. Also, Satellite 2, which is Satellite 4 as said before, is the satellite that has to do the transmission of the data. The link is described in Image 50, while Image 51, Image 52 and Image 53 present the data used for the end-point transmission/reception of the data.

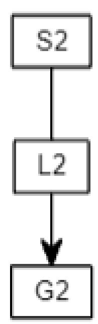

Image 50: Transmitting satellite to receiving ground station

6.3.3.7 Satellite 2 (S2) – transmitting the data to the end-point terminal

- $Transmiting\ feeder\ losses = 0.2\ dB$
- $Transmitting\ losses = 1.5\ dB$
- $HPA\ transmitting\ power = 22\ dBW$
- $HPA\ Back\ off\ losses = 6\ dB$
- $Antenna\ gain = 50\ dBi$

- $Longitude = -94.4785°$
- $Latitude = 12.3903°$
- $Altitude = 12{,}000\ km$

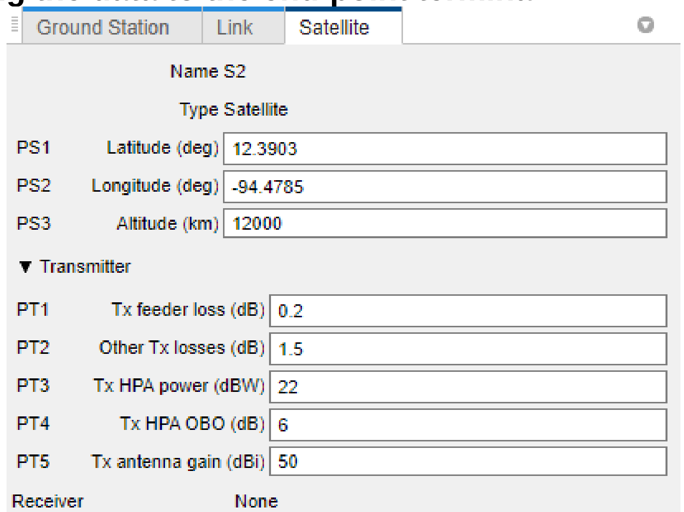

Image 51: Data imported in the MATLAB APP for the S2

6.3.3.8 Link 2 (L2) - between transmitter and end-point Ground station terminal

- $Frequency = 25\ GHz$
- $Channel\ bandwidth = 36\ MHz$
- $Bit\ rate = 150\ Mbps$
- $E_b/N_0 = 10\ dB$
- $Availability = 99.9\ \%$
- $Polarization\ mismatch\ loss = 45°$
- $Implementation\ loss = 2\ dB$
- $Antenna\ mispointing\ loss = 2\ dB$
- $Radome\ loss = 0\ dB$

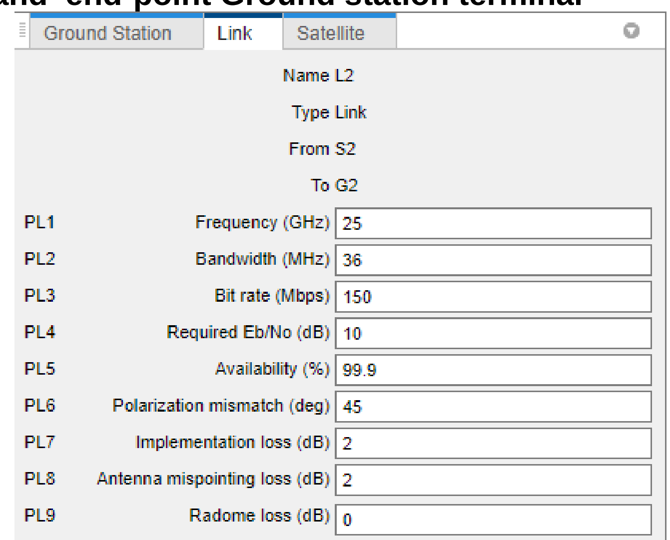

Image 52: Data imported in the MATLAB APP for the L2

6.3.3.9 Ground station 2 (G2) - Receiver

- $Interference\ loss = 2\ dB$
- $G/_{T_e}\ ratio = 27\ ^{dB}/_{K}$
- $Received\ feeder\ loss = 2\ dB$
- $Received\ losses = 3\ dB$

- $Longitude = 53.7974°$
- $Latitude = 21.1768°$
- $Altitude = 5\ m$

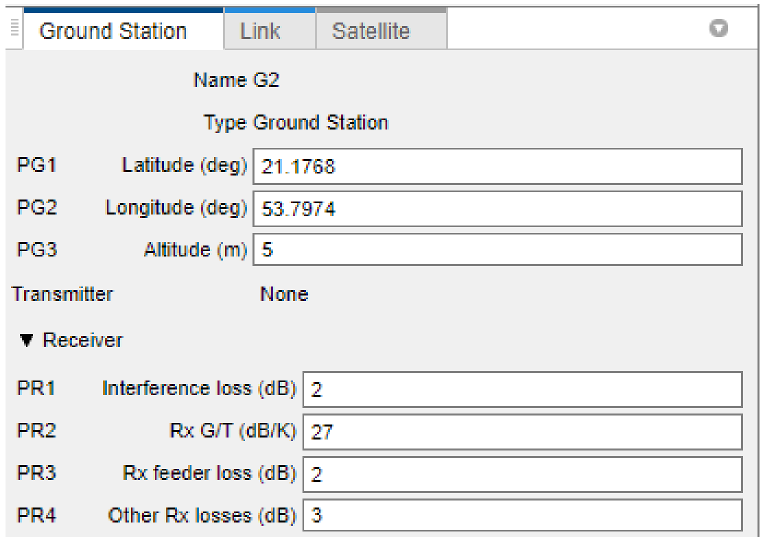

Image 53: Data imported in the MATLAB APP for the G2

6.3.4 Results from the MATLAB Simulink

Using the data provided previously, MATLAB APP is doing some calculations and formulas, so the correct results are extracted from the inputs, as Table 15 provides.

Table 15: Results from the Satellite Link Budget Analyzer

Link Budget

Tag	Name	L1	L2	L3
N1	Distance (km)	1.2558e+04	2.3282e+04	2.8495e+04
N2	Elevation (deg)	60.4641	-55.5202	-50.8023
N3	Tx EIRP (dBW)	68.7000	64.3000	59
N4	Polarization loss (dB)	3.0103	3.0103	3.0103
N5	FSPL (dB)	203.9689	207.7470	209.5020
N6	Rain attenuation (dB)	7.8030	-	-
N7	Total atmospheric losses (dB)	9.3774	-	-
N8	Total propagation losses (dB)	213.3463	207.7470	209.5020
N9	Received isotropic power (dBW)	-152.6566	-150.4573	-156.5123
N10	C/No (dB-Hz)	98.4426	100.1419	94.0869
N11	C/N (dB)	10.6611	24.5789	18.5239
N12	Received Eb/No (dB)	17.6508	18.3810	13.2951
N13	Margin (dB)	7.6508	6.3810	5.2951

Before start talking about the resulting values, it is good to understand what some of the parameters are doing and how are used. Below a small explanation is given.

- **Rain attenuation:** it is referred as signal attenuation due to the absorption of atmospheric rain, snow, or ice.
- **Atmospheric losses:** refers to the attenuation or absorption due to atmospheric gases and depends on the weather or clear-sky conditions.
- **Propagation losses:** depends on the frequency, location, and elevation and it is the sum of losses such as how antenna gain degrades compared to distance, the angle of arrival loss, scintillation loss, etc.
- **Received isotropic power:** it is called the EIRP on the receiver side, without calculating the losses or the gains on the reception side.
- $\boldsymbol{C}/_{\boldsymbol{N_0}}$: carrier to noise power density it is applied when the only source of noise is at the receiver and as long as the ratio is big, the quality is better and more reliable.
- $\boldsymbol{C}/_{\boldsymbol{N}}$: it is mostly used for computing the carrier-to-noise signals between two PtP (point-to-point) terminals. The difference with the previous one is on the bandwidth, where the later carrier-to-noise ratio is measured in dB and not $^{dB}/_{Hz}$.
- **Margin**: it's the difference between the minimum expected power reception and the sensitivity of the receiver and it is a metric used to counteract the fluctuations of the signal to ensure a good and reliable connection between the two end-points.

Having all this stuff in mind, results can now be discussed. The reader shall remember that values used as inputs are not based on a specific operation but are values collected from different resources, thus this results in strange values as outputs. Having the first perspective it seems that the link is well established, with some good prospects to be more efficient, but some issues need to be addressed. Until the Free Space Path Losses (FSPL) everything seems okay. The distances of the links differ because the orbits are not the same, so the distance may be bigger than the $12{,}000\ km$ altitude that is given, the elevation is changing compared to the orbit and the distance is on accepted boundaries. Furthermore, $T_x\ EIRP$ is very good, it could be more optimal, like $90 - 100\ \mathrm{dBW}$, but it is in a good and accepted width of values. Finally, polarization losses are also okay relative to satellite links and communication systems. Also, it seems that no matter what's the link metrics the polarization loss is same for all the links and that's happening because it is calculated from not from the given equations but it is a loss referring to the antenna electromagnetic field vector mismatch and it is given from the provider.

Thus, for these parameters, some plots are built. Figure 9 depicts the relation between FSPL and distance, it is obvious that as the distance is getting bigger, so do the path losses not in a linear way, but precisely with a logarithmic rate.

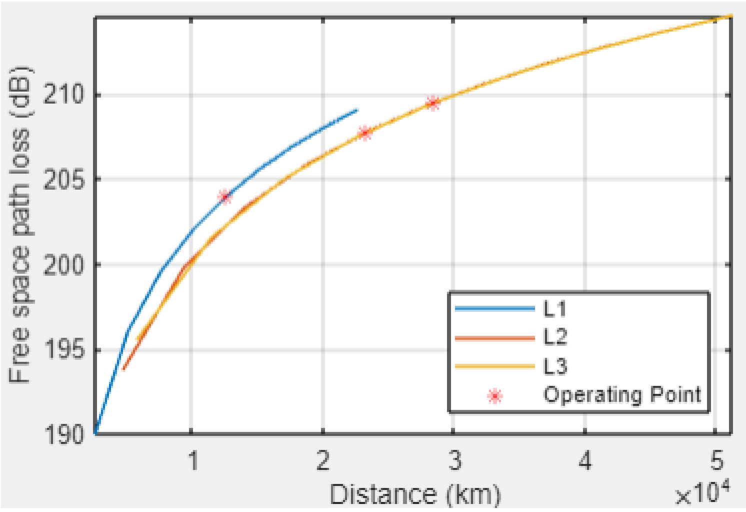

Figure 9: FSPL and distance comparison

The same behavior seems that exist between EIRP and antenna gain or HPA transmitting power. When EIRP is increased, HPA power and antenna gain do the same. The results are as expected because EIRP is directly affected by the transmitting power and the antenna gain. Figure 10 shows that L1 is the most powerful because it has the strongest antenna gain even if the HPA power as shown in Figure 11comes second on a scale of the most powerful signal strength. Based on that, it is commonly accepted that EIRP can be also affected by the losses in a linear way. It can be observed that for every 0.8 dBW decrease, other losses are increased by about 1 dB for transmission as can be seen from Figure 12, while Link 1 still has better EIRP values even after the decrease in transmitting losses.

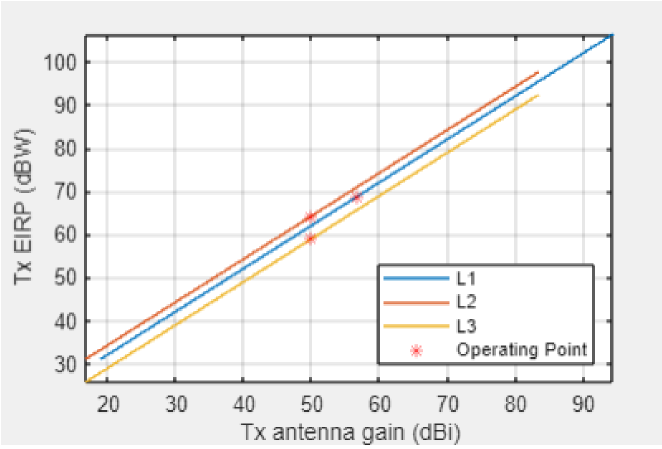

Figure 10: EIRP and antenna gain comparison

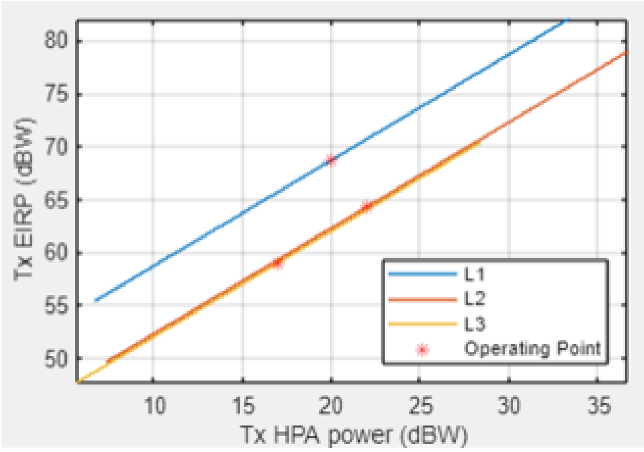

Figure 11: EIRP and HPA power comparison

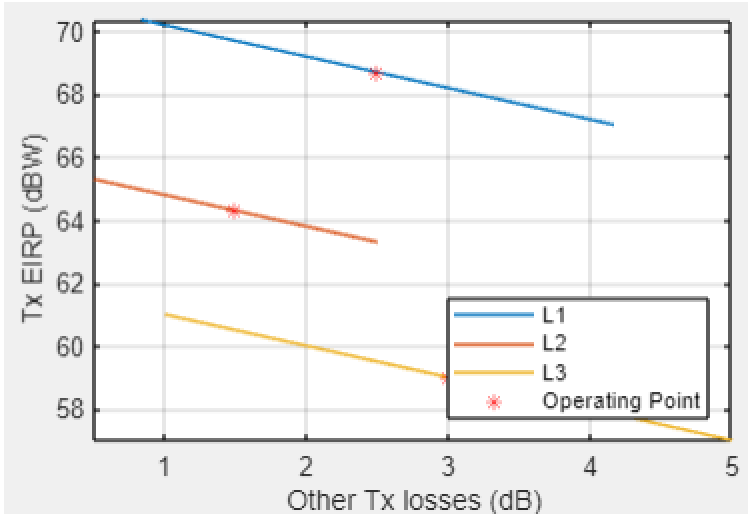

Figure 12: EIRP and other transmitting losses comparison

Having in mind Figure 12, some of the results that need to be discussed too, are the losses relative to rain, atmospheric, and propagation reasons respectively. Both rain and atmospheric loss, exist only on the earth and basically for the transmitting side. This is the reason that for L3 and L2 there are no arithmetic values because L3 is coherent to outer space and even if the L2 is directed back to earth, the transmitter is in outer space, so there are no effects of rain and atmospheric loss there. On the other hand, propagation loss is met in all links because it is a blend between FSPL and atmospheric losses, and even if the atmospheric loss does not always exist, FSPL exists no matter where the link is originated. Based on that, it is interesting to implement the relation between distance and total propagation loss as Figure 13 indicates. It is observed that as long as the distance is increased, same path follows the propagation loss. In small distances, someone can say that the relationship is almost linear, but when distance is more and more increased it follows a logarithmic scale. Even if FSPL for L3 is bigger than the other two links, propagation loss is bigger in L1 and that's because it is also affected by the atmospheric loss which only appears in L1.

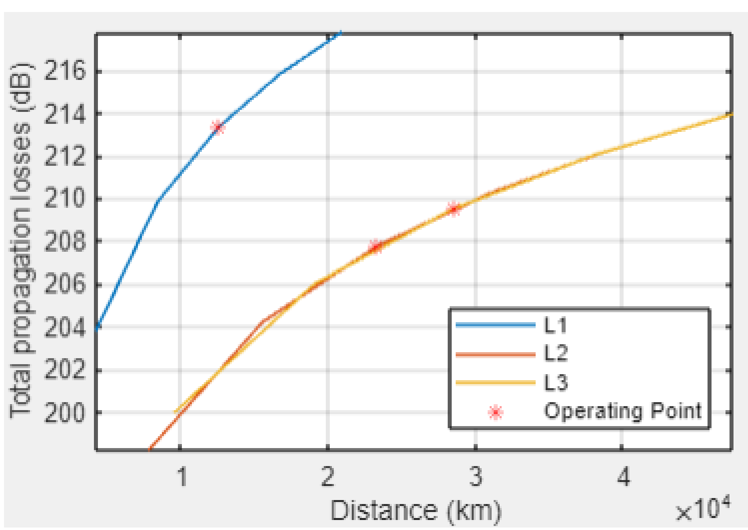

Figure 13: Propagation loss and distance comparison

Carrier-to-noise power density is also a field that shows the efficiency of the system. It is important to determine the relation that frequency has on the link budget. Someone could wait that if the frequency is increased, then the signal strength will be better and that will lead to a better connection. However, this is not true and that's a new strategy 5G is going to bring into the market. The goal behind this architecture is to build more base stations closer to each other to have better quality, not overloaded cells and not have the same distance between the already existing 4G antennas, but smaller. Therefore, it is accepted that if frequency constantly increases, the losses are bigger, and the signal can be interpreted for obstacles and easily affected by atmospheric parameters, so for long distances the carrier-to-noise is decreased. Figure 14 shows the results discussed above.

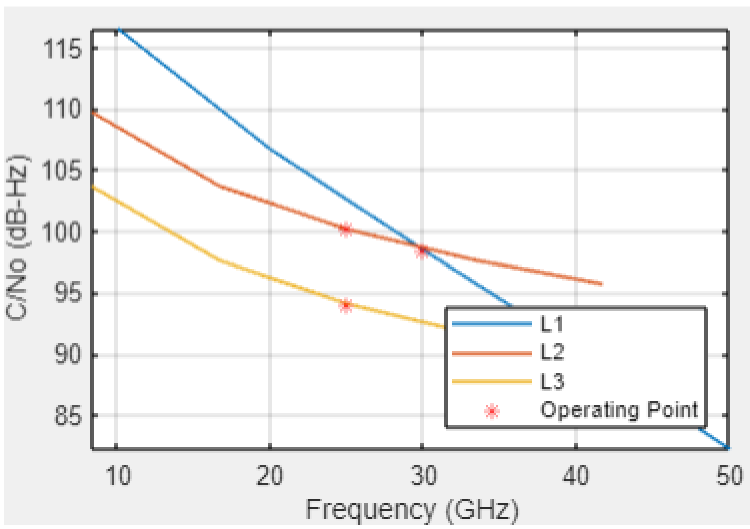

Figure 14: Carrier-to-noise power density and frequency comparison

On the other side, 'SNR per bit' it's a parameter that is extracted from the parameters of the transmitting and receiving station. So, the most important role of that is provided by the diameter and EIRP specifications of the antenna. **Figure *15***, shows the effect of antenna gain in the link budget estimation and as long as the antenna gain is increased same tactic SNR-per-bit follows up. It seems that for L2 the better quality is experienced and that's because even if the gain is not the biggest it is not a one-parameter formula and depends also on losses and so on. That's what something can be observed from **Figure *16*** where the loss from the mispointing that occurred on the antenna negatively affects the link in a linear way.

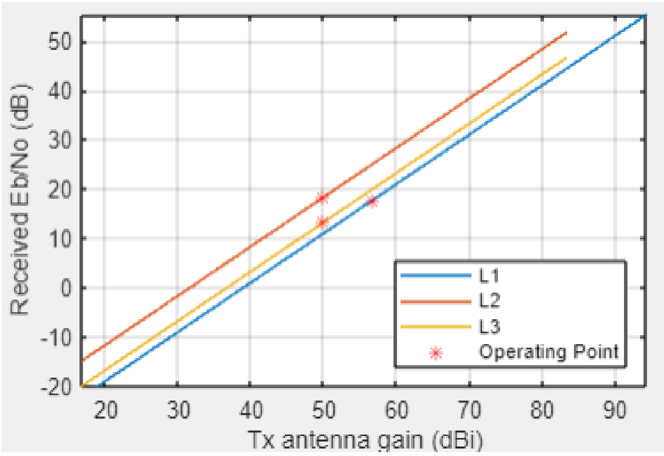

Figure 15: SNR-per-bit and antenna gain comparison

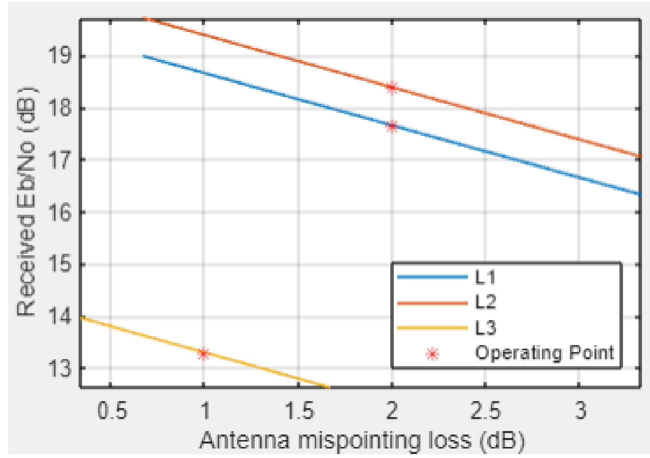

Figure 16: SNR-per-bit and antenna mispointing loss comparison

At the end of the day, results occurred from the metrics that were used as inputs, are not so bad, and could easily handle a satellite communication link. However, of course, there are always ways for improvements and someone could change the values given based on the characteristics of his/her equipment and based on what's the aim of the mission. Increasing the efficiency of the link by adding more and more gain or transmitting power, will lead to other types of problems such as power consumption, cost, bigger losses (like atmospheric), and so on. Thus, the choice of the equipment and the values implemented must be carefully chosen and not only looking for the optimal budget link but also considering cost, time, power consumption, environmental issues that may occur, etc. The reason the above example took place was more to demonstrate how the MATLAB Satellite budget analyzer is used and less to optimize a real scenario. After this example, the user will be ready to implement the desired parameters and read or analyze the results provided without any problem, while there are explained in a manner and easy way to be readable and understandable to everyone.

6.4 Link budget analysis for a UAV

Previously the essentials that one needs to know to be able to make a connection are computed. The various mathematical points and equations for the calculation of certain parameters that affect the link budget were studied separately, while some results were presented with some comments on them. Also, a script of code was presented that helped to understand and practice basic concepts for a link, while another script for calculating coordinates was implemented too. Apart from these, the code snippets that one can use to get a visual representation of a link created within MATLAB were shown, but beyond that, MATLAB and specifically the Satellite Link Budget Analyzer was again used to produce some graphs for link performance, as previously mentioned.

However, regardless of what was said before, this section studies a combination of the previous ones but this time with a UAV as an end terminal node, where before this did not appear anywhere, since simplifications were made that the distance between Earth and UAV is negligible in the relationship between Earth and satellite, as well as that the speed of the UAV relative to that of the satellite is also negligible. At this point, those simplifications don't exist and a UAV comes into play.

Image 54 shows the architecture of the system you are studying. There is a control station for the UAV, called UACS, meaning unmanned aerial control station, which does not have LoS with the UAV itself, so the satellite acts as an intermediate hub station. From there the data is sent to the UAV where it is processed for the appropriate amount of time. Then the UAV sends a response to the UACS queries, but because of BLoS communication, it sends them to the satellite which is responsible for forwarding them back to the UACS. In this example, it is clear that the satellite has the role of the mediator that connects the communication between the UACS and the UAV with its presence, where without its existence this would not be possible. From there when the data is received by the UACS it can be sent to a GS. This could be two different buildings where the data will be sent terrestrially, with terrestrial networks, but it is something that will not be studied at this point because there is no particular reason. Therefore, for the example you are studying, it will be true that the UACS is a GS. At this point, it is worth noting that the specific example and what will be studied in this section has been taken from the source [73] and is an integral source of validity and correctness as it relates to ITU-R.

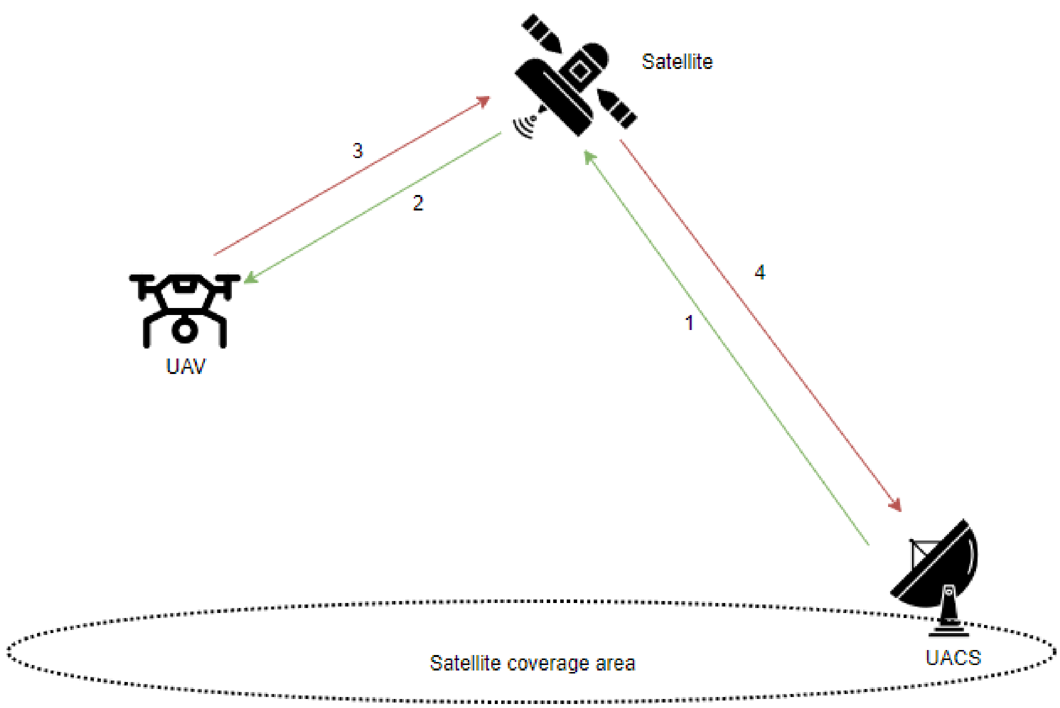

Image 54: Links for BLoS with satellite as relay

In the figure above, the communication links are listed, showing the order in which, the telecommunication takes place. Therefore, it is valid:

- **Link 1:** UACS sends the CNPC messages to the UAV. Due to BLoS communication, data are transmitted to the satellite.
- **Link 2:** following the previous step, satellites transmit the data to the end-point, meaning the UAV.
- **Link 3:** after the processing of the data, UAV replies to UACS by transmitting the requested data back to the UACS, through the satellite due to BLoS communication.
- **Link 4:** Finally, UACS receives the data through the satellite and the communication is repeated over and over based on the operation.

At this point, it is good to comment on the architecture of the UAV regarding its antenna. For performance reasons, the antenna used by the UAV is not directional as one might expect, but omnidirectional, for both azimuth and elevation. The reason this happens is that probably under normal conditions, many omnidirectional antennas would be used above and below the UAV, which may ensure the availability of the link whatever the attitude of the UAV is. Image 55 illustrates the previously mentioned pattern of the UAV's antenna.

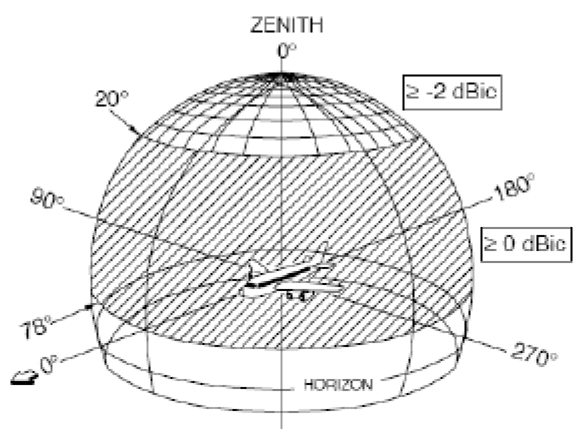

Image 55: Antenna pattern of the UAV *[73]*

Since the previous ones have been mentioned, it is now possible to use the metrics for each of the four links that must be computed and calculated. However, in a previous section, we talked about some technical difficulties created with the Satellite Link budget analyzer tool of MATLAB, where it does not allow the addition of a fourth link inside the app, therefore some small modifications will be made which will divide the whole system into smaller points to be calculated and to comment on some results at the end. Also, it is important to mention that even with the guideline used from ITU-R, some values of the fields were missing, so values based on ITU-R and different online guides were provided as input in MATLAB. The results will not be the same as ITU-R provides about each link, but an important effort will be given so the results shall be as coherent as possible.

Something that should never be overlooked is the channel width and data rate used below. The reason this point is mentioned is that it involves both type of links, and forward or backlinks characteristics, and a hint/explanation is needed to explain how they are defined. The size and rate of the return channels is higher than the forward links, but this is only one of three points to mention. The most important point is that each channel contains a carrier, since the modulation is QPSK, while if there was OFDM, more carriers could fit in one channel. Also, a carrier does not necessarily mean a user/client but can be two or even more users that correspond to a carrier. In this particular example, what is true is that one channel equals one carrier and one carrier contains two users. However, only one user can transmit per time slot and then the user receives the data, thus one user uses the full capabilities of the system. That means, the user transmits $t = 0\ ms$, the next user in the next time slot transmits too at $t = 1\ ms$, then the first user receives in a new time slot $t = 2\ ms$, and finally, the second user receives its data at $t = 3\ ms$. In this way, the antenna is working like a monopole and not a dipole, meaning that the antenna in a time instant, can only operate in one mode transmit or receive and not on two modes in parallel.

6.4.1 Forward links

As previously talked and based on Image 54 there are four available links for the round trip time (RTT) of a message. Nevertheless, in this Section, only the first two links will be discussed, because MATLAB does not allow the import of more than three links. Thus, the forward links, which mean the links from UACS until the UAV will be mentioned to provide the fundamental parameters of the message from the starting end-point until the finishing end-point. Since in previous Sections, the basic usage of Satellite Link Budget Analyzer was shown, it is not necessary to get into details about the app and the values used. However, keep in mind that throughout the duration of this experiment, source [73] was utilized, but in cases where the source provided incomplete information about the metrics of the links, values from previous experiments or some other indicative values were used to obtain as much as possible identical results to those of the ITU-R source.

The last point to be made is that the metrics and links were considered to have taken part in ideal weather conditions, that is, in clear skies and not in rainy or cloudy climates. Weather changes greatly affect the coupling since rain causes attenuation or there may be reflections due to the various ions in the atmosphere. To a large extent, cloudiness also plays a role at high frequencies where they act as obstacles for LoS communication between the satellite and another terminal.

6.4.1.1 UACS to Satellite link

6.4.1.1.1 UACS/Ground station metrics

- $Transmiting\ feeder\ losses = 1\ dB$
- $Transmitting\ losses = 3\ dB$
- $HPA\ transmitting\ power = 20\ dBW$
- $HPA\ Back\ off\ losses = 4\ dB$
- $Antenna\ gain = 59.1\ dBi$

- $Longitude = 57.6906°$
- $Latitude = 52.9437°$
- $Altitude = 7\ m$

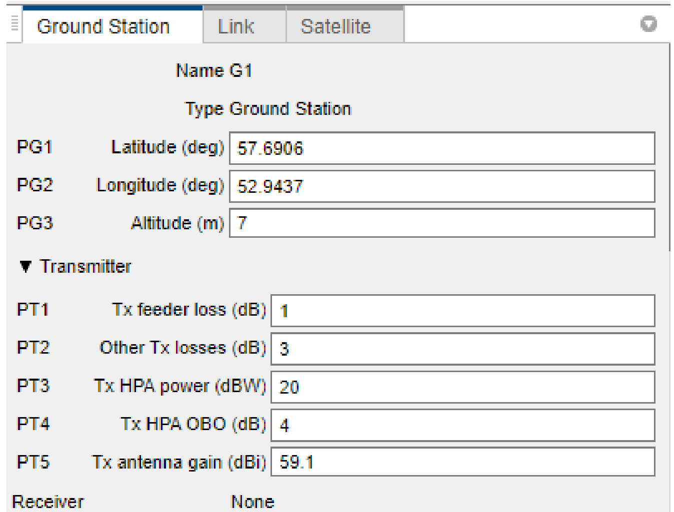

Image 56: Data imported in the MATLAB APP for the GS

6.4.1.1.2 Link metrics

- $Frequency = 14.25\ GHz$
- $Channel\ bandwidth = 0.01\ MHz$
- $Bit\ rate = 0.01\ Mbps$
- $E_b/N_0 = 3.8\ dB$
- $Polarization\ mismatch\ loss = 12.5°$
- $Implementation\ loss = 1\ dB$
- $Antenna\ mispointing\ loss = 0.5\ dB$
- $Radome\ loss = 1\ dB$

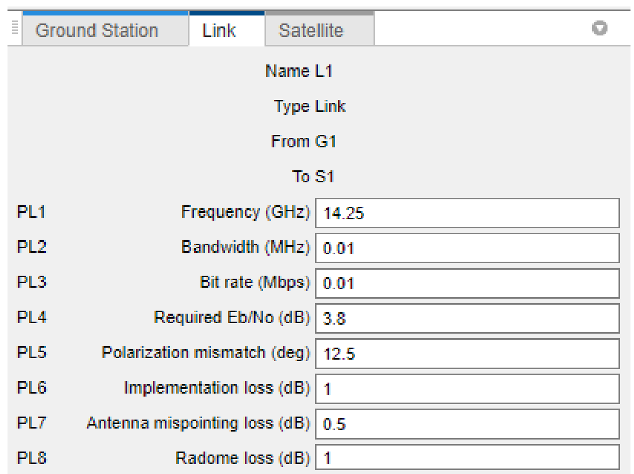

Image 57: Data imported in the MATLAB APP for the Link between GS and satellite

6.4.1.1.3 Satellite metrics

- $Interference\ loss = 1\ dB$
- $G/_{T_e}\ ratio =\ 1.4\,{}^{dB}/_{K}$
- $Received\ feeder\ loss =$ $0.5\ dB$
- $Received\ losses = 1.4\ dB$

- $Longitude = 27.0847°$

- $Latitude = 45.8869°$
- $Altitude = 36000\ m$

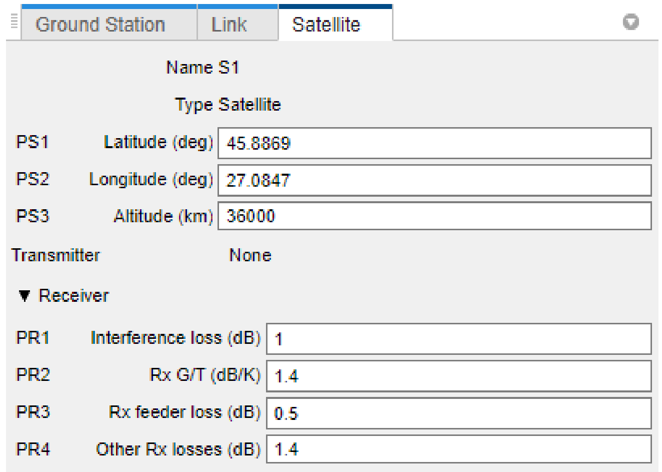

Image 58: Data imported in the MATLAB APP for the satellite

At this point, the first link between UACS and the satellite, which is a forward link, has been successfully labeled. Next, comes up the next forward link referring to the connection between the satellite and the UAV.

6.4.1.2 Satellite to UAV link

Someone must be careful and not be confused with the names given by MATLAB. These names can't be changed, so for this link, as satellite, it once referred to the real satellite but the second time is referred to the UAV that was previously discussed which is an aerial object but still it hasn't the characteristics of a satellite.

6.4.1.2.1 Satellite metrics

- $Transmiting\ feeder\ losses = 1\ dB$
- $Transmitting\ losses = 2.8\ dB$
- $HPA\ transmitting\ power = 17\ dBW$
- $HPA\ Back\ off\ losses = 4\ dB$
- $Antenna\ gain = 38.1\ dBi$

- $Longitude = 27.0847°$
- $Latitude = 45.8869°$
- $Altitude = 36000\ km$

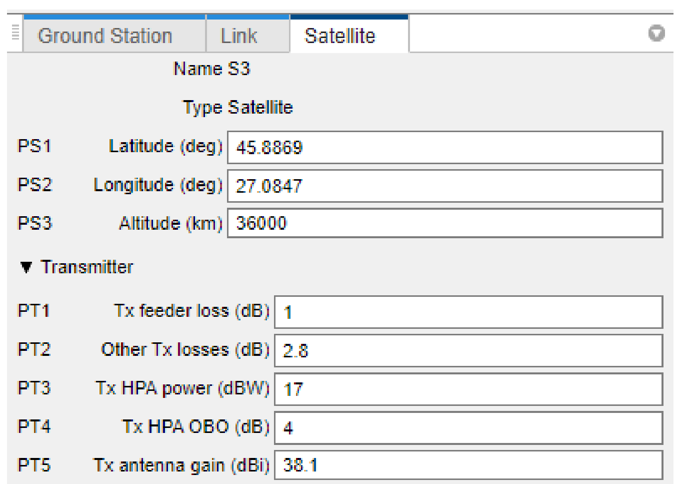

Image 59: Data imported in the MATLAB APP for the satellite

6.4.1.2.2 Link metrics

- $Frequency = 11.95\ GHz$
- $Channel\ bandwidth = 0.01\ MHz$
- $Bit\ rate = 0.01\ Mbps$
- $^{E_b}/_{N_0} = 5.4\ dB$
- $Polarization\ mismatch\ loss = 12.5°$
- $Implementation\ loss = 1\ dB$
- $Antenna\ mispointing\ loss = 0.5\ dB$
- $Radome\ loss = 0\ dB$

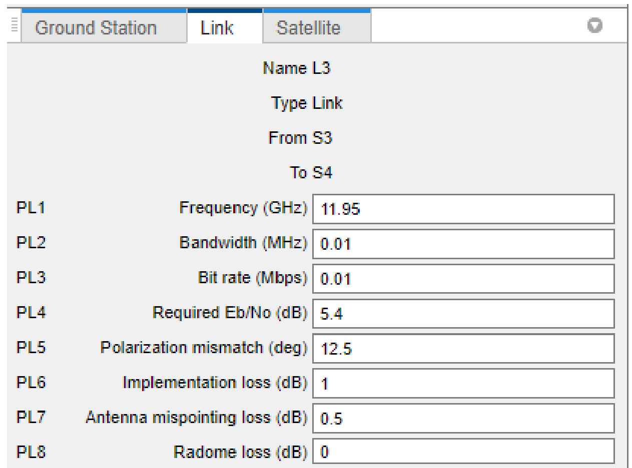

Image 60: Data imported in the MATLAB APP for the Link between satellite and UAV

6.4.1.2.3 UAV metrics

- $Interference\ loss = 1\ dB$
- $^{G}/_{T_e}\ ratio = 14.4\ ^{dB}/_{K}$
- $Received\ feeder\ loss = 1\ dB$
- $Received\ losses = 0.8\ dB$

- $Longitude = -94.4785°$
- $Latitude = 12.3903°$
- $Altitude = 0.4\ km$

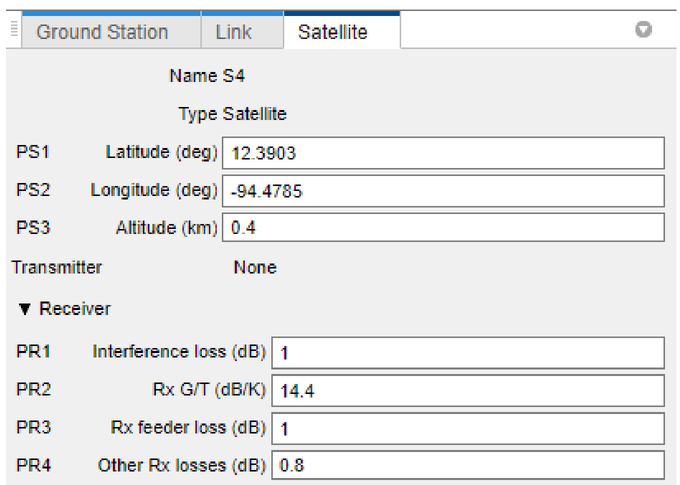

Image 61: Data imported in the MATLAB APP for the UAV

Now someone can calculate the metrics for the return links, meaning from UAV to satellite and from the satellite back to the UACS. However, it is important to see some results and discuss what is already exported for the forward links.

6.4.1.3 Forward link results

The numerical results obtained for the two link pairs are shown in Table 16. It is recalled that communication as L1 concerns the link between UACS-to-Satellite, while as L3 the link for Satellite-to-UAV is defined. The resulting results show that there is a good connection between the terminals by observing the $\mathrm{C/No}$ and the $\mathrm{Eb/No}$, while the results are the same with the source [73]. However, the logic is the same and as will be seen along the way, there may be significant differences in some values, but some others are the same as those in the report and this is explained at the end, while a significant effort has been made to make similar results when it's possible.

Table 16: Results for the two forward links

Tag	Name	L1	L3
N1	Distance (km)	3.6437e+04	4.4107e+04
N2	Elevation (deg)	66.9392	-81.8456
N3	Tx EIRP (dBW)	70.1000	47.3000
N4	Polarization loss (dB)	0.2084	0.2084
N5	FSPL (dB)	206.7548	206.8853
N6	Received isotropic power (dBW)	-138.3632	-161.2937
N7	C/No (dB-Hz)	89.7360	79.9055
N8	C/N (dB)	49.7360	39.9055
N9	Received Eb/No (dB)	49.7360	39.9055
N10	Margin (dB)	44.9360	33.5055

These results are going to be analyzed right after with various comparisons and diagrams to show and elaborate the relationship between the variables as well as how they affect the overall performance of the communications.

6.4.1.3.1 $\mathbf{C/N}$ and transmitting losses

One can conclude by observing the Figure 17 that the losses negatively affect the performance of the link and specifically the carrier-to-noise ratio. It seems that the dependence is linear and that as the losses increase, which can be related to increased distance, either weather conditions, or white noise environments, or other losses of the system, the ratio decreases, therefore that means the noise increases and the performance decreases. By the same token, although the rate of speech decay appears to be the same between the two channels, one could argue that L1 is more powerful and efficient, just because it achieves a better signal-to-noise ratio and not because there is a perceptible difference in reduction of each ratio.

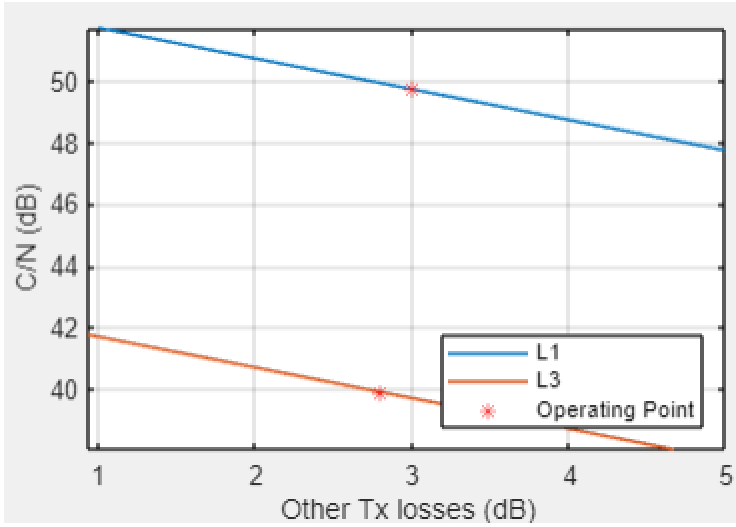

Figure 17: $^{C}/_{N}$ relative to transmitting losses

6.4.1.3.2 FSPL and $^{E_b}/_{N_o}$

Based on the previous graph and following the same strategy, one can say that the bigger the free space losses, the bigger and more noise there will be. Therefore, the ratio $^{E_b}/_{N_o}$ which is inversely proportional to losses will decrease as losses increase. This is what Figure 18 indicates, where the linearity is again observed and the reduction of the ratio with the increase of FSL is seen.

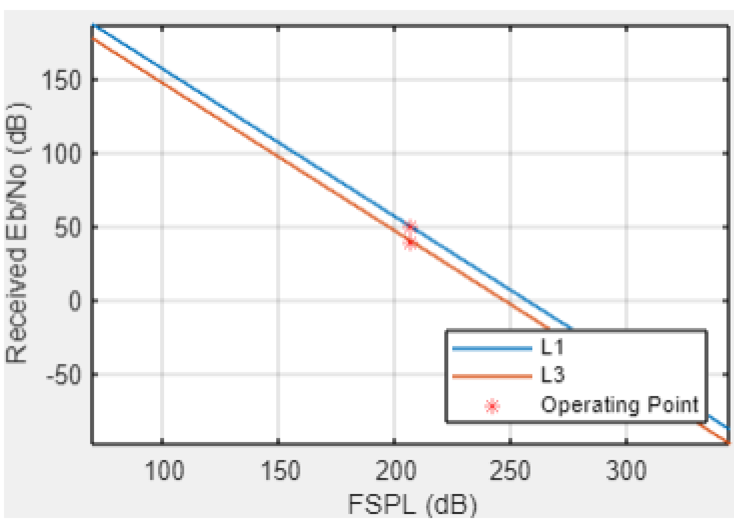

Figure 18: $^{E_b}/_{N_o}$ relative to Free space path losses

6.4.1.3.3 FSPL and distance

Something that makes sense to study for a satellite link is the free space losses. It is obvious and logical that the losses increase as the distance increases but in a logarithmic and not linear way as one would expect. However, this raises the question that the distance of L1 is greater than that of L3, but the losses are less by very little difference. This is because FSL depends not only on distance but also on other parameters such as antenna gain or radiated power. Figure 19 provides the necessary information.

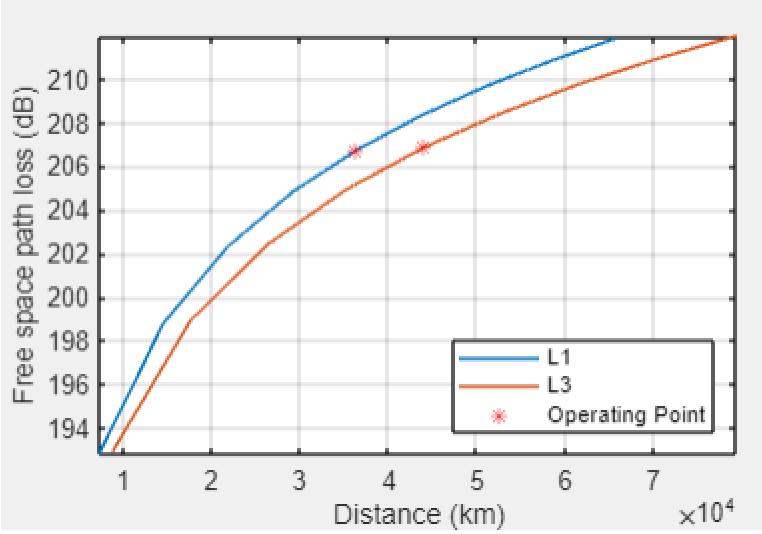

Figure 19: Free space path losses relative to distance

6.4.1.3.4 Margin and Received G/T

A quite interesting diagram is the one below, which concerns the Link margin. As a link margin, the difference between the transmitter and receiver of the system is defined which indicates that if these changes occur the system will still be able to function. For example, if the margin is equal to $15\,dB$, then the system could handle an extra $15\,dB$ of attenuation, and it would properly works. If the margin is close to zero, zero, or below zero, it means that it is already overloaded and cannot accept more fades. In Figure 20 the relation between the margin and G/T is given. It is observed, that as the G/T ratio is increasing, the margin also increases linearly. It is understandable that as the power-to-noise ratio increases, the more reliable and loss-tolerant the link can be, that's why the margin increases. Because of this and based on the diagram studied, L1 can withstand more attenuation than L3.

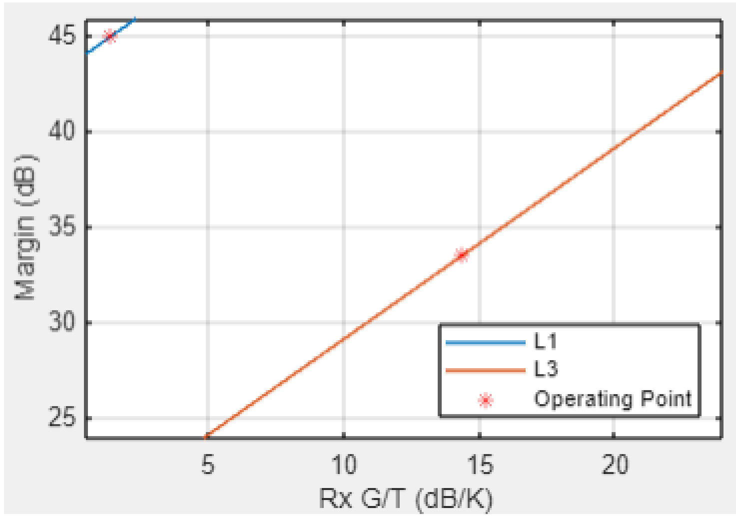

Figure 20: Margin relative to received $^{G}/_{T}$

6.4.1.3.5 Received EIRP and transmitted HPA power

A diagram that has been studied in a different way in a previous Section is the EIRP as shown in Figure 21. It is observed that as the transmission power of the high-power amplifier increases, so does the received isotropic power radiation. In general, EIRP depends on the gain of the antenna and its transmit power, so it is expected that the stronger and more powerful one transmits a signal, the stronger it will be at the point of reception, and the rate that follows appears to be linear.

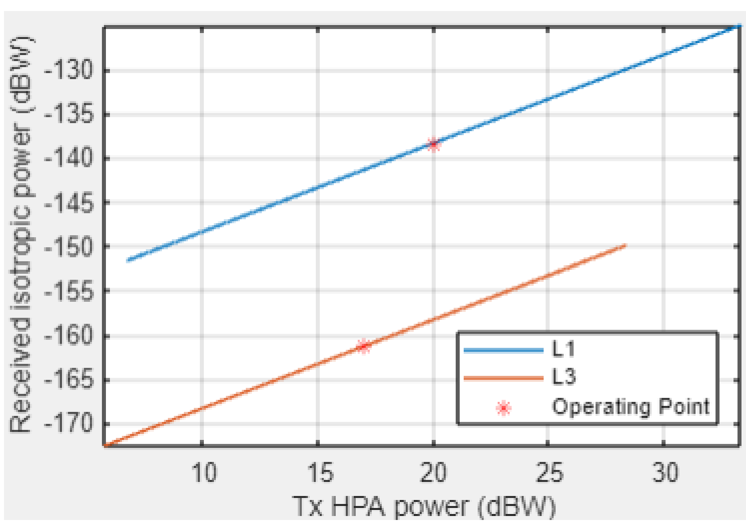

Figure 21: Received EIRP relative to transmitted HPA power

6.4.2 Return links

Nothing different happens here, based on the previous calculations. That means the same tactic and same sources were used to provide as many reliable results as possible. Return links are the links of the response of the system, for example, the response from the UAV to the satellite and the response of the satellite back to the UACS. In this way, the whole RTT between the two end-terminals, meaning UACS to UAV and vice versa is completed.

6.4.2.1 UAV to Satellite link

6.4.2.1.1 UAV metrics

- $Transmiting\ feeder\ losses = 1\ dB$
- $Transmitting\ losses = 3.5\ dB$
- $HPA\ transmitting\ power = 10\ dBW$
- $HPA\ Back\ off\ losses = 3.5\ dB$
- $Antenna\ gain = 39.7\ dBi$

- $Longitude = 12.3903°$
- $Latitude = -94.4785°$
- $Altitude = 0.4\ km$

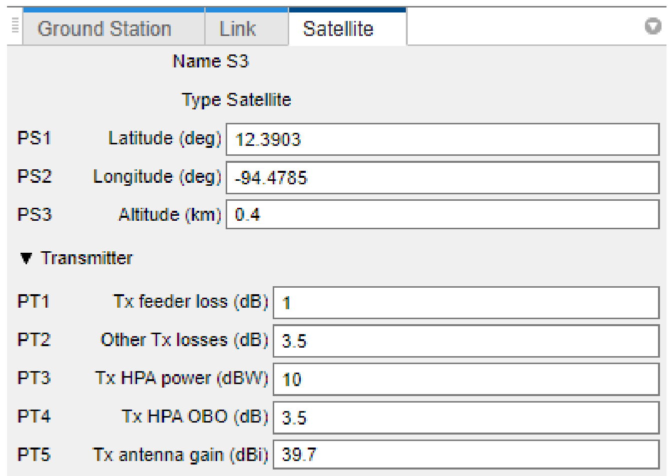

Image 62: Data imported in the MATLAB APP for the UAV

6.4.2.1.2 Link metrics

- $Frequency = 14.25\ GHz$
- $Channel\ bandwidth = 0.32\ MHz$
- $Bit\ rate = 0.32\ Mbps$
- ${E_b}/{N_0} = 3.8\ dB$
- $Polarization\ mismatch\ loss = 12.5°$
- $Implementation\ loss = 1\ dB$
- $Antenna\ mispointing\ loss = 0.5\ dB$
- $Radome\ loss = 0\ dB$

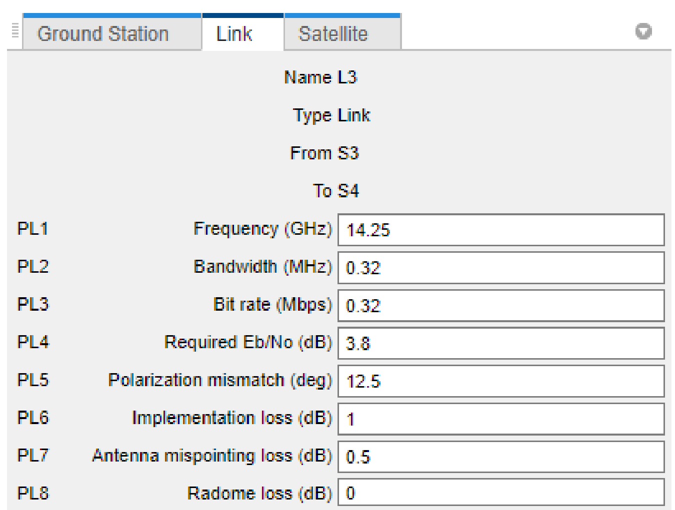

Image 63: Data imported in the MATLAB APP for the Link between satellite and UAV

6.4.2.1.3 Satellite metrics

- $Interference\ loss = 1\ dB$
- ${}^{G}/_{T_e}\ ratio = \ 1.4\,{}^{dB}/_{K}$
- $Received\ feeder\ loss = \ 1\ dB$
- $Received\ losses = 1\ dB$

- $Longitude = 27.0847°$
- $Latitude = 45.8869°$
- $Altitude = 36000\ km$

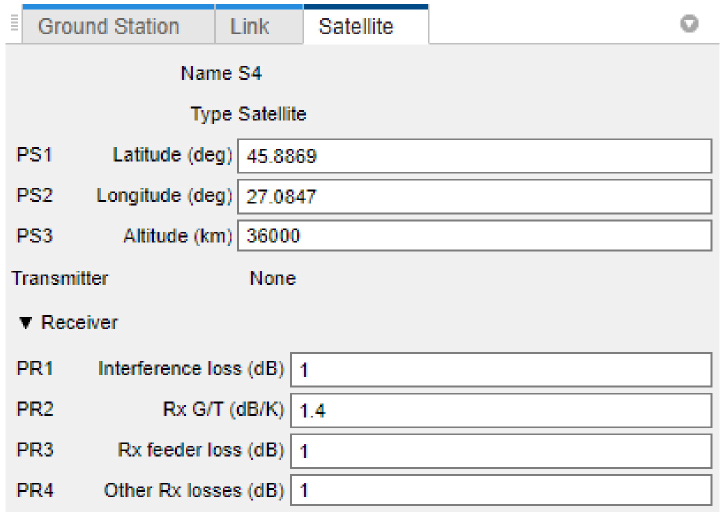

Image 64: Data imported in the MATLAB APP for the UAV

That's where the values for the fields for the 3rd link took place while is still remaining the values of the 4th link, which is presented below.

6.4.2.2 Satellite to UACS link

6.4.2.2.1 Satellite metrics

- $Transmiting\ feeder\ losses = 1\ dB$
- $Transmitting\ losses = 1.5\ dB$
- $HPA\ transmitting\ power = 15\ dBW$
- $HPA\ Back\ off\ losses = 4\ dB$
- $Antenna\ gain = 57.6\ dBi$

- $Longitude = 27.0847°$
- $Latitude = 45.8869°$
- $Altitude = 36000\ km$

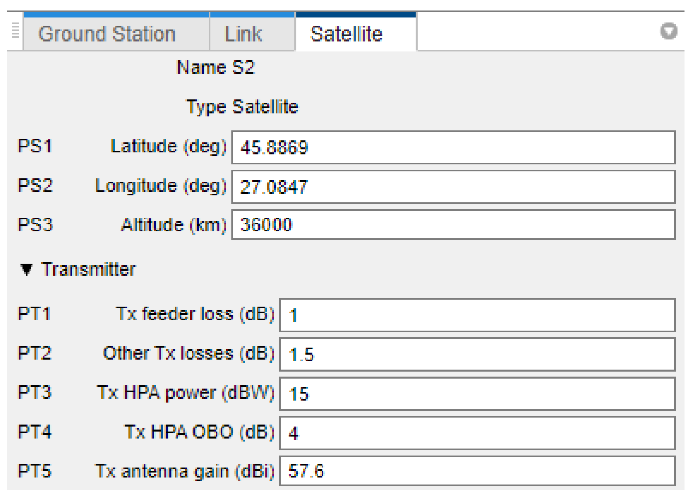

Image 65: Data imported in the MATLAB APP for the UAV

6.4.2.2.2 Link metrics

- $Frequency = 11.95\ GHz$
- $Channel\ bandwidth = 0.32\ MHz$
- $Bit\ rate = 0.32\ Mbps$
- $E_b/_{N_0} = 8.4\ dB$
- $Polarization\ mismatch\ loss = 12.5°$
- $Implementation\ loss = 1.5\ dB$
- $Antenna\ mispointing\ loss = 0.5\ dB$
- $Radome\ loss = 1\ dB$

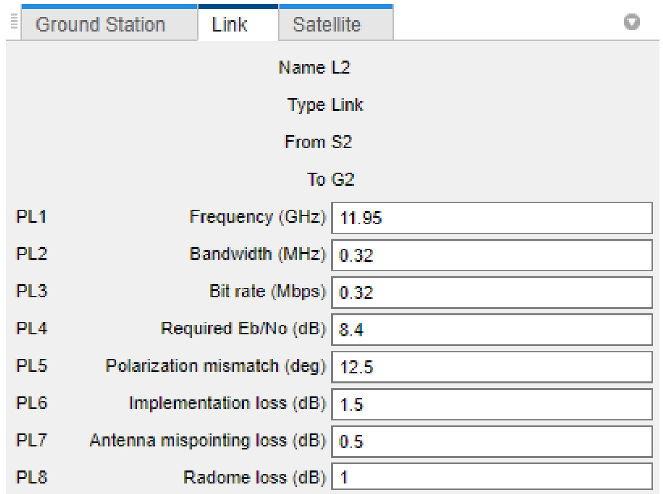

Image 66: Data imported in the MATLAB APP for the Link between satellite and UAV

6.4.2.2.3 UACS/Ground station metrics

- $Interference\ loss = 3\ dB$
- $G/_{T_e}\ ratio = 33.5\ {dB}/_{K}$
- $Received\ feeder\ loss = 0.5\ dB$
- $Received\ losses = 0.7\ dB$

- $Longitude = 57.6906°$
- $Latitude = 52.9437°$
- $Altitude = 7\ m$

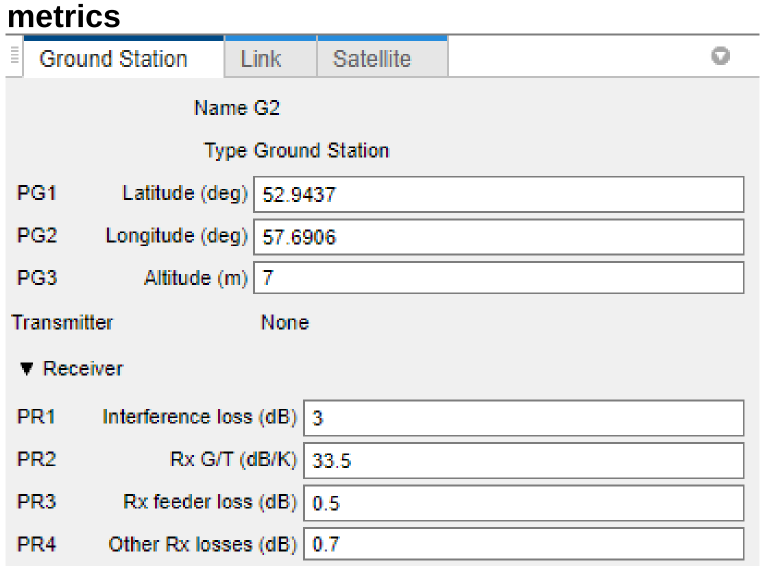

Image 67: Data imported in the MATLAB APP for the UAV

6.4.2.3 Return link results

Based on the metrics used, some results emerge which are understandable in Table 17, where with some diagrams below an attempt will be made to render the specific values obtained. It seems that margin on the L3 is below zero and this is not good enough because that means the link is not able to handle any additional losses. The results shows that L3 (link between UAV and satellite) is not as strong and reliable as L2 (link between satellite and UACS) and this can be observed from the C/N and C/No ratios except of the margin.

Table 17: Results for the return links

Tag	Name	L2	L3
N1	Distance (km)	3.6493e+04	4.4107e+04
N2	Elevation (deg)	65.4796	-19.7974
N3	Tx EIRP (dBW)	65.1000	41.7000
N4	Polarization loss (dB)	0.2084	0.2084
N5	FSPL (dB)	205.2394	208.4143
N6	Received isotropic power (dBW)	-143.8478	-168.4226
N7	C/No (dB-Hz)	117.0514	59.5765
N8	C/N (dB)	61.9999	4.5250
N9	Received Eb/No (dB)	61.9999	4.5250
N10	Margin (dB)	52.0999	-0.2750

6.4.2.3.1 FSPL and distance metrics

What has been analyzed before, is the relationship between the FSL and the distance, since it is the default diagram that is proposed and studied by MATLAB itself. Figure 22 shows the relation between these two metrics, but there is no need for further explanation about the trajectory the FSL follows as it is described before. However, L2 seems to be more efficient than L3, because the FSL is lower on the first one than on the latter.

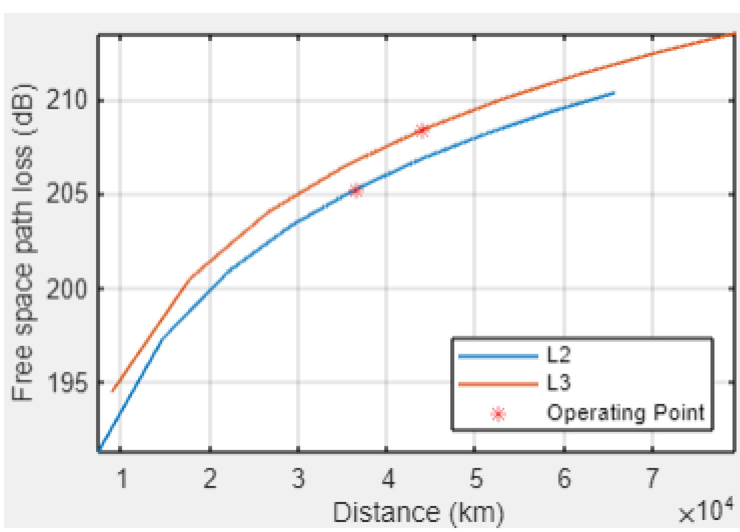

Figure 22: FSPL relative to distance

6.4.2.3.2 FSPL and frequency metrics

Whereas previously the relationship between FSL and distance was shown, now it is shown between FSL and frequency, as indicated by Figure 23. It is observed that the distribution is constantly increasing and this implies that as the frequency increases, so do the FSLs, because higher frequency implies higher attenuations in the space that mediates from one terminal to another. More efficient in terms of frequency and FSL, it seems to be the L2 link.

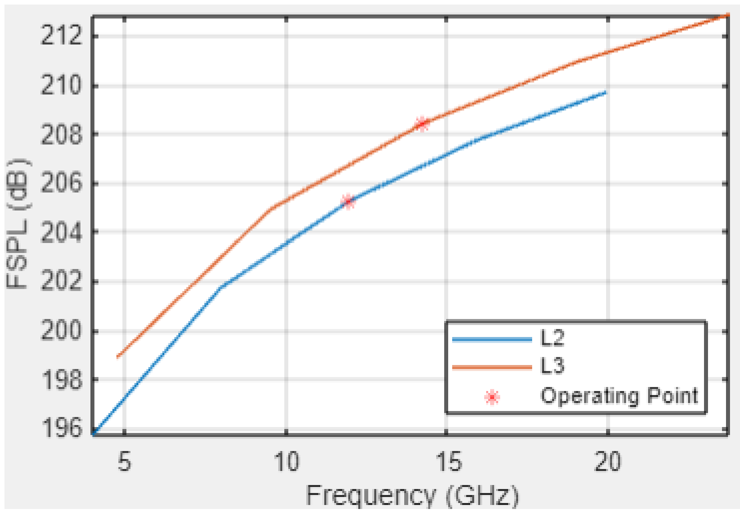

Figure 23: FSPL relative to frequency

6.4.2.3.3 Margin and received losses metrics

Previously it was discussed what the margin means for a satellite link and now the relation of this relative to the reception losses is given. It is observed in Figure 24, that as the losses increase, the range of a good and reliable operation -given in dB- of the system decreases. However, the rate of decrease is quite small, which suggests that coupling is indeed affected but not to a huge extent, since for an $2x - 3x$ increase in losses the profit can drop about $0.5\ dB$.

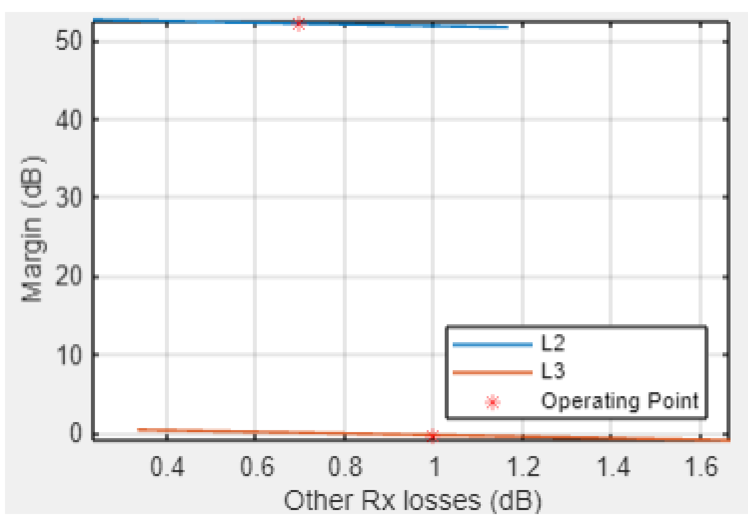

Figure 24: Margin relative to received losses

6.4.2.3.4 $C/_{N}$ and transmiiting gain metrics

The $C/_{N}$ ratio is a metric that depends on multiple variables, and one of those is the transmitting gain of the antenna. One would expect that as the gain increases, the stronger the signal is at its transmit output, therefore the stronger the signal will be at its receive point, which is shown in the diagram below, Figure 25, for which it is said that L2, which concerns the link between UAV and satellite, is more powerful.

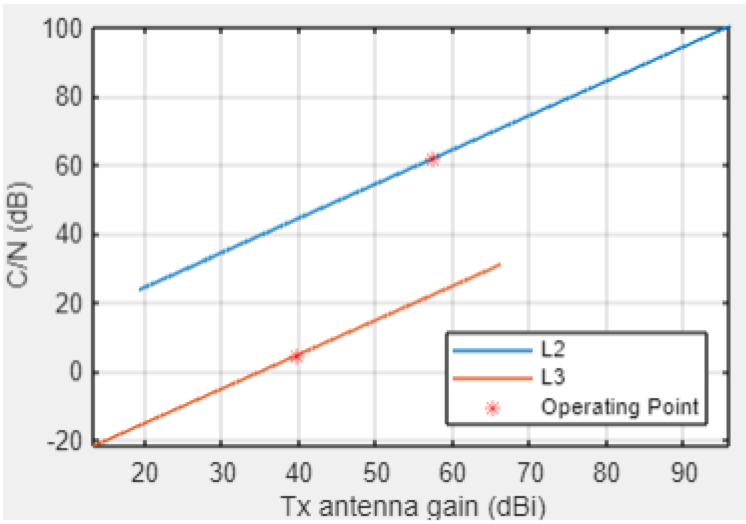

Figure 25: $C/_{N}$ relative to transmitting antenna gain

6.4.2.3.5 $C/_{N_o}$ and frequency metrics

In Figure 26 the correlation between $C/_{N_o}$ and the frequency is given, where it is observed that the higher the frequency the lower the ratio. This is something that might confuse some, as they think that the higher the frequency, the better in terms of data and latency, but that's not exactly the case. While the former may be true, the higher the frequency, the greater the losses and interference from various noise sources and it is inversely proportional to the noise, and this is why its reduction is seen as the frequency increases.

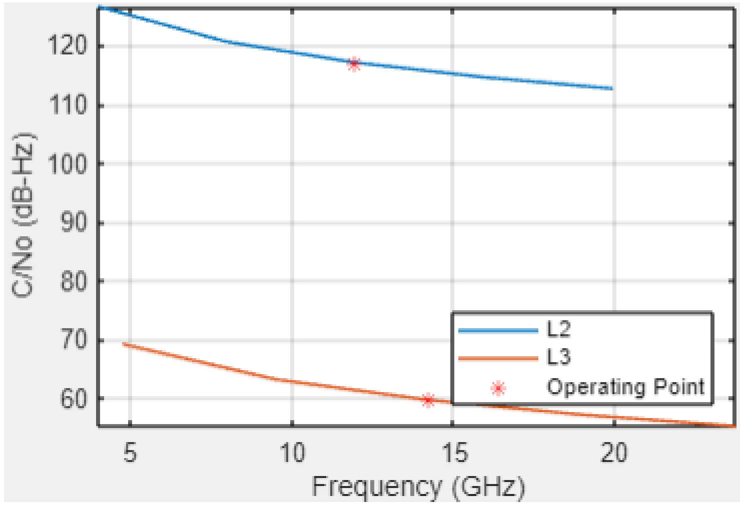

Figure 26: $^{C}/_{N_o}$ **relative to frequency**

6.4.3 Discussion and general results

The diagrams showed what one would expect to see since the results are very similar to those reported in the report [73] of ITU-R for the FSL, EIRP, and so on. It is to be expected that the values are very difficult to be exactly the same, but the architecture followed is quite close to the results of the main example and that lead to similar performance specifications. A problem to be mentioned is that MATLAB and specifically the Satellite Link Budget Analyzer, does not distinguish between UAVs and GSs, but it behaves them as a transmitter-receiver entities without caring if the receiver is a satellite, a UAV or a ground station. This, as anyone understands, is not optimal, since the variables and parameters may change between a UAV and a GS, such as the movement speed of each object, if they have losses due to internal or background noise, etc. However, the purpose of this example is not to fix the problems that may exist for each link, but to show some basic functions and equations between UAV links. Also, the equations have been mentioned in a previous Section, while also the exact values between the links are given in the ITU-R report, so there is no any point in confirming the results of their examples. For this reason, it was preferred to keep the basic structure of MATLAB and build on it the ITU-R example, in the most efficient way possible to study specific metrics and specific charts and graphs.

Based on the previous ones, observing the resulting Figures, one can explain the basic functions of telecommunications, specifically the links between satellites and UAVs. The results are in line with what has emerged in the ITU-R report and this is a strong guarantee of the results. However, as it has already been known, each mission has its elements and the user, depending on the functions he/she wants to achieve, can make changes both in the equations given for the link budget and in MATLAB libraries.

7 RETROSPECTIVE & CONCLUSIONS

The purpose of this thesis was the analysis, design, and modeling of satellite communications for UAV operations, while it was part of a study both in literature and at α research level. For the sake of truth, as will be presented in the results and the commentary of what emerges, the work aimed not only at satellite communications but in general at the whole system considering the ground and aerial means as well as their optimization techniques. Specifically, the reader shall have understood the basic principles of aerial vehicles, such as what their categories are, based on what criteria they are divided, what missions they are called to solve, etc. Then there is a study and report about the telecommunication part of aerial vehicles which was the main purpose of this research. The analysis and comparison between terrestrial and satellite systems also took part. For the former, no extensive analysis was given since the basic principles of telecommunication traffic were taken for granted. In contrast, the satellite networks were analyzed as much as possible, within the frameworks allowed so as not to deviate from its original objectives. For the most part, it covered most of the work in an understandable and readable way even for someone without the necessary telecommunication knowledge background. Following this structure, modeling and design techniques were developed for the entire telecommunication system, both for the satellite as a structure and a traffic terminal and for the UAV which plays the main role for the system that studied. However, based on the previous ones, some emerging security and performance issues were presented that should be considered, limited, and resolved to ensure the smooth operation of the system. After that, information about satellite and drone providers was discussed with their different features of them, while in the last part of this thesis code, equations and examples took place to simulate the theory of previous Chapters and also to experiment with a real scenario between ground station-satellite and another system such as ground station-satellite-UAV.

The conclusions reached are quite clear and in line with the way the technology and research market are moving, even if mobility and channel resource allocation are more complicated in 3D than in 2D spaces. Based on what has been reported, satellite communications are the new craze for UAVs. It is not a casual communication architecture, but something that is here to stay and replace terrestrial technologies that suffer from many performance problems. Nevertheless, there are cases where terrestrial entities need to act in combination with satellite means and this is perfectly acceptable and desirable since the former will be used as a secondary factor of system integration and not as a primary one as is the case now. At a general level, due to increased congestion and security issues, terrestrial cellular and wireless networks cannot meet the needs of UAVs. On the other hand, Satcoms -and even at a more specialized level with the use of blockchain and machine learning-, while considering the missions and plans of large industries for better air traffic, can satisfy all the needs of UAV operations, in contrast to a fairly high cost. But it is proven, that the problems that need to be addressed are more than everyone can imagine. For example, what will happen when everyone owns more than one drone, where the same thing happened with the IP allocation of mobile terminals nowadays. How the system will be efficient in a way that will not interfere with other systems so the data will be transmitted safely without jamming and spoofing or hacking techniques and so on.

The biggest investment, however, that must be realized at the level of research, concerns not so much the telecommunications part, because this depends on the type of mission that someone wants to carry out, but the UAVs as an entity that must bring changes in their structure and architecture. For example, as a first step, it is more important and preferable to establish laws and measures that will provide security and propriety to citizens by ensuring a harmonious coexistence and trust between humans and a swarm of UAVs. Once these moves are made by the relevant air traffic operators, then measures will have to be taken again to guarantee and secure data exchanges between terminals without jamming or spoofing problems. Thus, the delivery system is completed with the integration of satellite communications but also the maintenance of terrestrial as a complementary network where this is required. But as mentioned, this area is relatively new and less explored. There are several issues to consider before talking about link performance and reliability.

On the other hand, differently from what was said previously, experiments and tests showed that satellite communications can provide reliable and efficient budget links when classic networks cannot. May the experiment that took place is not optimal placed, but it is a good metric to clarify how relays satellite works based on the locations of satellites and ground stations, the elevation of earth orbit, transmitting and receiving specifications, etc. Also in a deeper approach, by using the satellite link budget analyzer by MATLAB it was possible to extract results for a real satellite communication link between transmitters and receivers, while equations of such a link are described in Chapter 6. Results prove that even if the link was not optimally established, because the collection of the data is difficult due to the fact that providers do not share all the characteristics of their systems, the link was good enough to successfully transmit the data related between the two ground stations or between a ground station and a UAV. Of course, there are remaining fields to be addressed but these depend on the operation of each client and are not something that can be solved by brute-forcing different values until the optimal budget specifications are found.

The main question anyone has to answer before implementing the satellite links, which are a quite promising sector as its proof is if the scientists will be able to bring about such sweeping changes at almost all levels of the system, or will they succumb to traditional techniques at the expense of performance? Whether or not individual problems are solved is up to researchers, industries, and pioneers, but not on those who are afraid to dare.

ABBREVIATIONS AND ACRONYMS

Abbreviation	***Definition***
Satcoms	Satellite communications
UAV	Unmanned aerial vehicle
C3 messages	Command, control and communication messages
OBC	On board computer
UAS	Unmanned aircraft system
ATC	Air traffic control
WLAN	Wireless local area network
Wi-Fi	Wireless fidelity
eNB/GS	Ground station
UE	User equipment
D2D	Device-to-device
V2X	Vehicle-to-everything
NLoS	No line of sight
CNPC	Control and non-payload communication
LoS	Line of sight
AG	Air ground
BLoS	Beyond line of sight
RF	Radio frequencies
mmWave	Millimeter wave
GPS	Global positioning system
GEO	Geosynchronous earth orbit
IP	Internet protocol
AP	Access point
LAN	Local area network
MIMO	Multiple input multiple output
MU-MIMO	Multiple user – Multiple input multiple output
OFDMA	Orthogonal frequency division multiple access
LEO	Low earth orbit
FANET	Flight ad-hoc network topology
GNSS	Global navigation satellite system
SIR	Signal to interference ratio
CAD	Computer aided design
CNC	Computerized numerical control
CAO/CAA	Civil aviation organization
MAC	Media access control
OFDM	Orthogonal frequency division multiplexing
QoS	Quality of service
ADS-B	Automatic dependent surveillance - broadcast
SNR	Signal to noise ratio
MIMU	Miniature inertial measurement unit
BVLos	Beyond visual line of sight
APS	Antenna pointing system

DDR	Direct drive motor
ROS	Robotic operation system
SSR	Secondary surveillance radar
ATCRBS	Air-traffic control radar beacon system
AGL	Above ground level
FL	Flight level
MSL	Mean sea level
NM	Nautical miles
IFF	Identification Friend or Foe
DAA	Detect-and-avoid
ICAO	International civil aviation organization
ITU	International telecommunication union
WRC	World radiocommunication conference
FSS	Fixed satellite service
DoS	Denial of service
ATO	Air traffic organization
FAA	Federal aviation administration
QoE	Quality of experience
HEO	Highly elliptical orbit
TDMA	Time division multiple access
ATM	Air traffic management
MEO	Medium earth orbit
RPA	Remoted piloted aircraft
BRLoS	Beyond radio line of sight
VHTS	Very high throughput satellite
LPWA	Low power wide range
HALE	High altitude long endurance
BSS	Broadband satellite solutions
IoT	Internet of things
ATMs	Automated teller machines
MATLAB	Matrix laboratory
RAAN	Right ascension of ascending node
S	Satellite
L	Link
FSL/FSPL	Free space path losses
HPA	High power amplifier
UACS	Unmanned aircraft control station
ITU-R	International telecommunication union - radiocommunication
RTT	Round trip time

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