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Nanosatellite Networks and Applications

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Declaration of Authorship

I, Juan Misael Góngora Torres, declare that this thesis titled, "Nanosatellite Architecture and Applications" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Juan Misael Góngora Torres

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Monterrey Nuevo León, May 6th, 2019

To my parents
Juan & Blanca

Acknowledgments

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Abstract

Small satellites are increasing their and number capabilities to perform missions in the Low Earth Orbit and beyond. This project presents requirements of a satellite network for the low Earth orbit to modernize data gathering and decision making for agriculture fields in Mexico through satellite communication, integrating topics of several areas to show the characteristics of the satellite communication problem.

This work starts giving a brief review of satellite communications concepts and then continues with a definition for the mission, a brief state of the art about the agriculture fields in Mexico, and the required devices to achieve the proposed network. A survey performed contains topics such as the requirements for the communication, frequencies for space applications, available frequencies in Mexico for space research application, the requirements in terms of hardware for both the space and ground including some commercial options, a description of physical layer, and available protocols for the data link layer, network layer, and transport layer.

The project also includes simulations for comparing two type of orbits and to determine the best suited for the desired geographical zone of coverage. More simulations contains scenarios of communication with a proposed constellation of 30 satellites at different elevation angles. This constellation of 30 satellites provides permanent coverage below one particular elevation angle and partial coverage at higher angles. The project also includes strategies to modify coverage and the feasibility for achieving permanent coverage in Mexico with a low Earth orbit satellite constellation.

A link budget developed shows the feasibility of communication between a satellite as the proposed for the permanent coverage and the ground. Additional considerations for a satellite such as the communication impairment due to the rain effects are also part of this project. A brief description of the channel, which also affects the link budget, is part of the project and a proposed topic for future research. Related topics with this project that and research opportunities are part of the last chapter.

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Chapter 1

Introduction

Mexican history of modern Satellites begins in the decade of 1960 for providing worldwide coverage of the Summer Olympic Games of 1968 and for the FIFA World Cup in 1970. Those first services supplied by Intelsat [6] continued expanding and in in the decade of 1980, the first two Mexican Satellites (Morelos I and Morelos II) developed by Hughes Space and Communications Industries and launched from the USA provided communication services to Mexico until 2004, when the last of those satellites stopped working [7].

Solidaridad I and Solidaridad II were the next generations of Mexican satellites launched in the 90s. Mexsat Satellites (acquired by EUTELSAT some years later), Eutelsat 117 West A, Eutelsat 115 West B and the QuetzSat-1 followed those first satellites [2].

Big satellites for high altitude orbits provides great value communication capabilities for Mexico; however, large systems of this kind implies significant costs since the development of spacecraft for a high altitude orbit have a price in the order of hundreds of millions of dollars. Usually, large satellites also require several years for their construction, launch, calibration and technical probes before starting operations; furthermore, those satellites represent a substantial financial risk [8], [9].

The Centenario, a Mexican satellite intended to be part of a constellation to three satellites, became lost during its launch stage in 2015. Even though the insurance covered the $390 million USD of the cost of the Centenario, this loss, considered as a large project failure [10, 11], is vast. The case of the Centenario contrasts with the loss of smaller satellites where replacement is quicker and with a much lower cost.

Small satellites are much faster and cheaper to build and launch than big satellites [12]. Even though there are limitations like onboard computing [13], propulsion, and available power, the constellations of small satellites are becoming more capable of performing missions that were previously only thought for big satellites [14]. Ambitious projects of small-satellite constellations like OneWeb of Airbus propose global access to the Internet [15] which is one of the market segments for the space industry. Other essential market segments like traffic and fleet management, commercial aviation, agriculture, fishing, and maritime transport are part of the 64 market segments identified in the Roadmap for Mexico Space Industry and are achievable with a flexible satellite platform of small satellites in the low earth orbit [16].

Important social applications for small-satellites constellations in Mexico are communication in rural areas, monitoring of agricultural lands and natural disasters surveillance. Closer observance of natural disasters could help to prevent casualties by giving timely alerts to specific areas and having a quick response in case of accidents or human life threat.

1.1 Motivation

Space is one of the natural resources that we could exploit more in Mexico. There are a lot of ideas and opportunity areas related to the utilization of this natural resource, some of them are the observation and communication using satellite systems. Mexico, as previously mentioned, get its big satellites from other parts of the world but it is also possible to entirely design and generate satellites systems in Mexico. Minimization of high costs and risks associated with geostationary satellites is achievable thanks to nanosatellites; the scope of a mission using them is variable but also increasing with time.

A good proposal or appropriate implementation of a nanosatellite or small satellite mission could increase the interest to space from the Mexican academic and private sector and even create regional interest to design and manufacture new components for use in satellite missions at space or ground scenes.

1.2 Research Questions

Do a communication network with small satellites in low Earth orbit allows communication with agriculture sensors in a field?

What are the required subsystems and its characteristics at ground and space that allow communication between a ground station and a small satellite orbiting in the low Earth orbit?

What are the communication parameters for the link budget that guarantee reliable communication from ground to a small satellite in the low Earth orbit?

What are the main characteristics of orbits to guarantee total coverage in Mexico through a communication network enabled with small satellites?

What are the lessons learned from previous small satellite projects that would improve the design of a small satellite communication network for collecting measurements of sensors in agriculture fields at the ground?

1.3 Problem Statement and Context

Space is an exploitable natural resource for communication purposes. Satellites are the primary space technology for communication, but they are costly. Nanosatellites helps to reduce economic costs and time for development compared with big satellite projects and are continuously increasing their capabilities; some missions have even reached longer distances than the terrestrial orbits.

For defining a satellite communication project it is necessary to identify the hardware and operational requirements for the satellite mission, then it is essential to have in mind a mission. Equipment and operations vary according to each mission, but there is a base of systems and protocols usually found in related satellite communication projects; thus, the mission would serve as a reference point to guide the project and the selection of resources and operations.

A satellite project requires of some physical resources at space and ground; also requires of other resources like frequencies for communication, orbits, and a series of evaluation of communication parameters to ensure link availability from its orbit to Earth and vice versa.

Given the diversity of necessities for a satellite project as previously stated, it is essential to have a complete reference of requirements in terms of hardware, operations, practices, problems, restrictions, and the establishment of communication between Earth and the spacecraft.

Simulations and specific analysis are necessary to identify the right physical and operational resources for a nanosatellite system; thus, it is also fundamental to include simulations including both analysis of the ground, space, and link to form an integral project that could serve as a basis for a nanosatellite project or a specific part of it.

Lessons learned from previous satellite projects of different sizes, budgets and for different missions could serve with a significant role in designing a nanosatellite project since it could help to avoid repetition of mistakes and guide to an improved implementation. It is essential to identify some of those lessons learned and understand how they apply to the particular nanosatellite project.

1.4 Objectives

The primary objective of this project is to show the feasibility of a nanosatellite system in the low Earth orbit to provide a communication network for agriculture applications in Mexico.

Specific Objectives:

1. To describe the required characteristics of the satellite system from an integral point of view; including both communication aspects, hardware requirements, and operational considerations.

2. To understand the integration of hardware and operations in a small satellite project, identify the functional components of a small satellite and describe how they inter-operate to achieve the proposed mission.

3. To identify the technical requirements of the network to achieve the proposed mission.

4. To describe the wireless link characteristics and it how it is affected during the communication between a particular location in Mexico and a small satellite in the low Earth orbit.

5. To determine the orbital characteristics of a small satellite in the low Earth orbit and its influence in the coverage for a particular location in Mexico.

6. To discuss lessons learned from previous satellite and small satellite projects to improve the mission design.

1.5 Main Contribution

This project proposes a way to modernize agricultural activities utilizing a robust and flexible small-satellite network following some requirements of the Internet of Things. The proposed mission tries to show that satellites and space have not only purely scientific purposes and that space and satellite technology could bring benefits and innovation to Mexico on sectors like agriculture.

This thesis includes a definition of the desired specific mission as well as a discussion of available resources, possible configuration, standard practices, expectations for the following years and opportunities to implement similar approaches to solve other problems. The project aims at providing an overall background and general guide as a kind of a survey that could be useful for future research and or implementation of this project in Mexico by a research institution like a university as well as simulations to some key sections.

1.6 Scope of the project

This project aims to provide a comprehensive outline of the requirements for satellite communications, including surveys of space and ground requirements for communicating with small satellites in the low Earth orbit. The thesis includes a definition of the mission; this proposed mission proposes to provide communication for agriculture applications including communication with sensors and actuators, but, it is not the intention of the project to go further in the area of agriculture but in satellite technology and enabling strategies. As part of the definition of the mission, tables of available hardware for agriculture applications accompany the project, mainly with information of sensors, data loggers and transmitters.

The thesis includes a survey of different topics like hardware for space and ground, communication protocols, overall network requirements, communication strategies, frequencies, and suitable orbits to provide communication on Earth; however, deep research of any of those topics is not part of the work since the intention of the project is to board multiple involved areas providing relevant information. Simulations for orbits were performed in two different software packages to evaluate the options of coverage.

A link budget analyzes the transmitted and received power and requirements for reception of the signal at the ground and at the satellite, but no transmission impairments were included in the calculation. A rain attenuation model, which is one of the greatest causes of attenuation, is also developed as part of the thesis but it is taken into the calculations of the link budget since it is calculated for a particular location and the link budget aims to provide a general idea of the reliability of satellite communication with LEO satellites at different places. Effects of the channel are not included in the link budget calculations and it is proposed as a further topic for research and continuation of this project.

1.7 Methodology

The project started with a survey of communications and then with a survey of satellite communication systems with primary sources as [Bosquet2011]. After understanding the basic concepts of satellite communications the project continued with a study of low Earth orbit satellites, a review of communication protocols for satellites and an examination of the available hardware for the satellite, the ground station, and the agriculture fields.

After the first period of study of satellite technology, protocols, and practices, the project continued with the use of the open software GMAT by NASA to perform analysis of orbits. Then, GMAT and the STK software by AGI were the primary tools to evaluate orbits, coverage, and to propose a satellite constellation to provide permanent coverage.

At the same period than the simulations, took place evaluation of the link and communication impairments such as the attenuation by the rain, which is developed in chapter 4. Fig. 1.1 illustrates the process followed during the project.

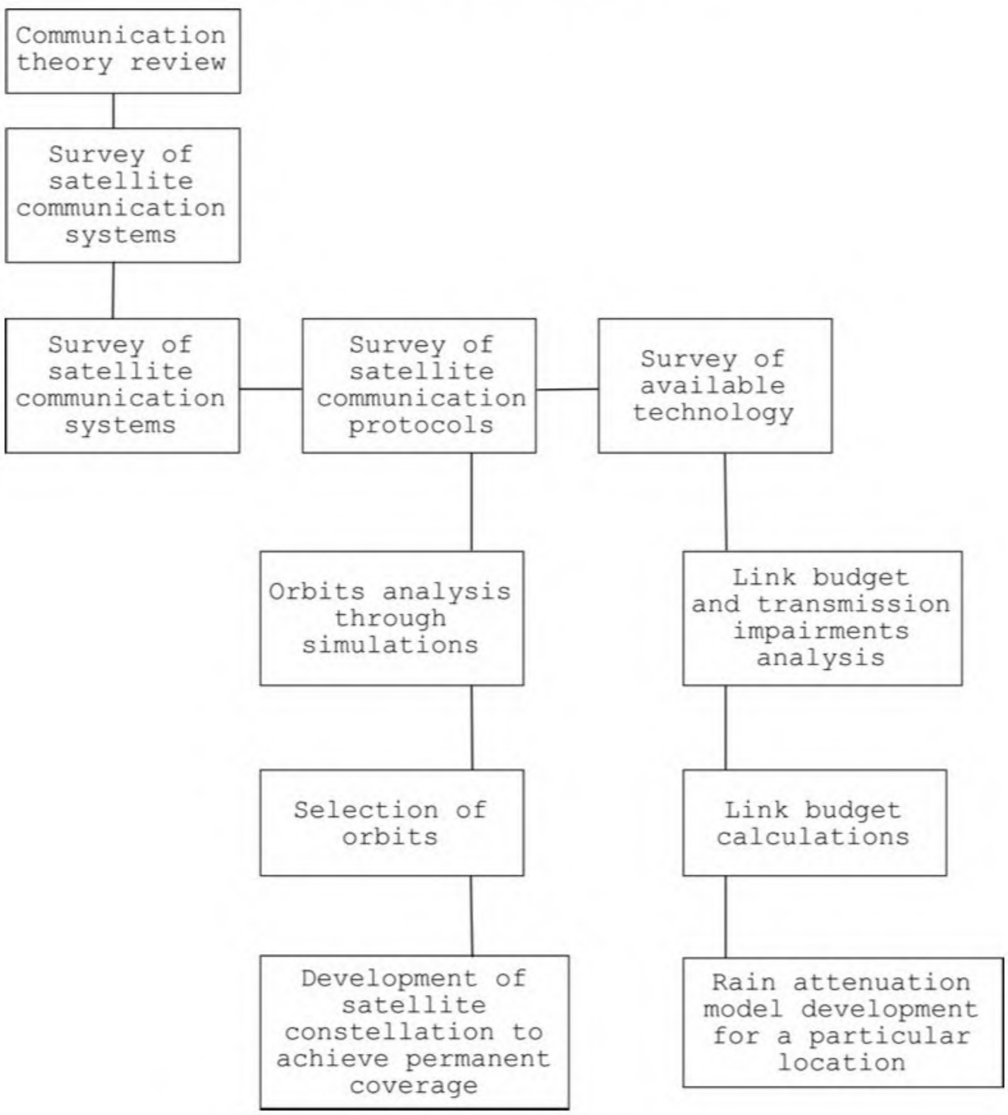


Figure 1.1: Sequence followed during the project.

1.8 Dissertation Organization

This first chapter contains the motivation and the main contributions of the project. The second chapter provides descriptions of basic concepts of satellites and communication networks and concludes with the proposal of the desired network. The third chapter begins introducing the specific mission and continues mentioning available devices and some case studies. The second part of this section contains the proposed orbit, required subsystems, and payload for the satellites to achieve the mission, as well as commercial examples of those subsystems. The last part of chapter three contains a coverage analysis and an overview of communication protocols that have been used or proposed for space missions. The fourth chapter includes applications attainable with the same project or doing some modifications. Fig. 1.2 shows a diagram with the main contributions of the document. The diagram starts with the main topic at top and continues with a second row of main sections which contains a tag in parenthesis indicating the type of contribution expected at each section. After the second row the diagram continues with several boxes describing the specific topics and activities inside each of the categories of the second row.

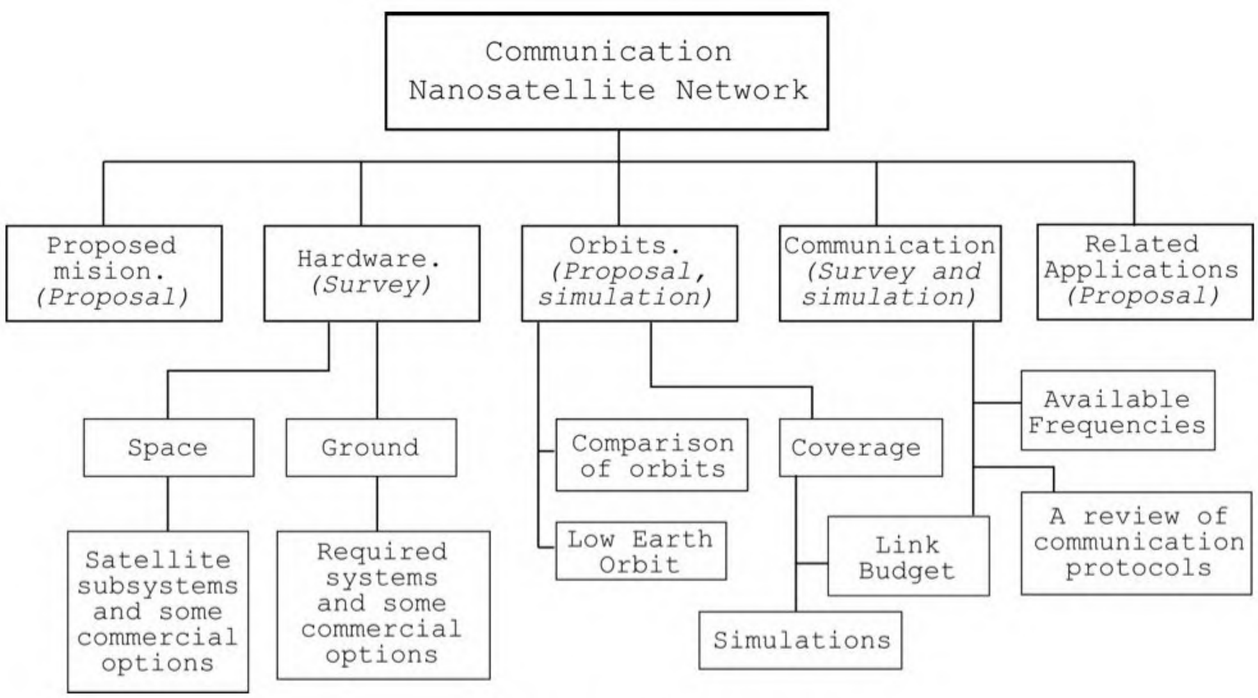


Figure 1.2: Main contributions of the document.

Chapter 2

Background

This section starts describing an orbit and its parameters and a scale to classify the technology level of space hardware; then continues with a brief definition of the Internet of Things (IoT) and some primary concepts of information theory and digital communications. Finally, the section concludes presenting the desired network architecture which idea will be the base for the following chapters.

2.1 Orbits

Orbit is related to the region of coverage and also with the available time for communication with a ground station or user. In a polar Low Earth Orbit (LEO) circular orbit, a satellite passes over the same region in Earth around two times per day, limiting the time for communication with a ground station in that region to usually less than 1 hour per day. An orbit with an inclination close to the 90 °from the Earth equator is called a polar orbit. Polar orbits are one of the most common and usually found with a circular shape (eccentricity close to zero).

Satellites can have different topologies or arrangements in space. Satellites can operate like individual entities doing all the work alone, or operate accommodated like a swarm with multiple close neighbors that help others to achieve the mission or placed in a constellation. Satellites in a constellation are well located, and they can have neighbors in the same orbit and at adjacent orbital planes. A constellation allows establishing of inter-satellite links and cooperation between satellites to achieve the mission and to provide broader coverage at Earth. A brief description and summary of the advantages of each of those topologies and its corresponding diagrams are included in [17].

Satellite coverage depends on the orbit of the satellite. Description of an orbit contains orbital parameters that define both the orbit and its orbital plane. This topic is extensively covered in the first chapters of [18, 19] and also briefly described in [17], among others. The following list contains a brief description of the orbital parameters and some illustrations.

According to the first law of Kepler, we can describe the orbit like an ellipse and the first two orbital parameters relates to the shape of the orbit, seen as an ellipse.

1. Length of the semi-major axis, a. Fig. 2.1 shows the semi-major axis and the semi-

minor axis. Concerning to the orbit, the Perigee or argument of Perigee (AOP) is the maximum distance from the Earth that the satellite reaches in its orbit, this distance and the length of the semi-major axis goes from the center of the Earth to the spacecraft. Let define this radius of the Earth like $R_{\text{Earth}} = 6371\text{km}$.

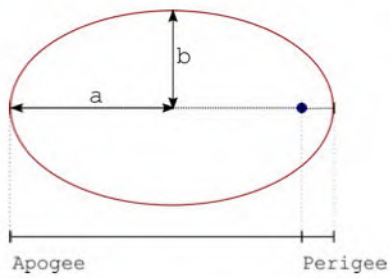


Figure 2.1: The ellipse shows the semi-major axis a and semi-minor axis b. The lines of the Apogee and Perigee represent the distances from the Earth (one of the focus) to the furthest and closer points of the orbit.

2. Eccentricity of the orbit, e. The calculation of this parameter involves the semi-major an semi-minor axis and takes values between zero and one. When this value is closer to zero the orbit is closer to a circular shape.

$$e = \sqrt{1 - \frac{b^2}{a^2}}$$

The following parameters describe position and orientation of the orbital plane:

3. Inclination, i. Taking like reference the equatorial plane, the inclination is the angle between the equatorial plane and the plane of the orbit. Fig. 2.2 shows the inclination of the orbit.

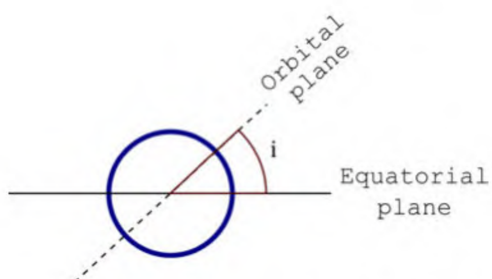


Figure 2.2: The inclination is the angle between the orbital plane and the equatorial plane. Lines used instead of planes.

4. Longitude of the ascending node or Right ascension of the ascending node (RAAN), Ω. This angle measures the angle between the Vernal Equinox (or vernal point) and the ascending node. The ascending node is the point when the satellite crosses up the equatorial plane.

The previous orbital parameters describe the geometry of the orbit but the description of the position of the satellite at any moment in its orbit requires of two more parameters which are the argument of Perigee (AOP) and the True Anomaly (TA). With all those parameters the description of the orbit and its plane is complete, as well as the position of the satellite at any moment.

5. Argument of perigee, ω. Is the angle from the ascending node to the perigee.

6. True anomaly, θ. This is an angle from the perigee to the current location of the satellite.

The Low Earth Orbit (LEO) is a kind of orbit with a typical altitude of few hundred kilometers above the ground but reaches heights up to 5000km. Satellites at LEO have a higher velocity than the Earth rotation velocity, accomplishing a full orbit around the Earth in roughly 100 minutes for altitudes close to 1000km. Important considerations related to the selection of the semi-major axis are the radiation belts around the Earth and the space trash belts or debris belts which are an increasing concern to space missions [19].

The two-line orbital element format (TLE) is a usual format to write the orbital parameters of a satellite. This format contains three lines with the name of the satellite at first; the second line includes relevant information about the satellite, its orbit and the year of launch. Finally, the third line contains the information which describes the orbit. A complete description of the TLE format is available at [20] and [21]. Fig. 2.3 shows an example of the TLE format retrieved from an open-access online database called Celestrak. This website contains a large amount of information (in TLE format) of the satellites that are orbiting the Earth; the data is available by characteristics of the mission, orbit or size (e.g., communication satellites, geostationary satellites, cubesats). The URL for this website is in [22].

```
ALTAIR PATHFINDER
1 42711U 98067LS  18304.22472673  .00014465  00000-0  13008-3 0  9999
2 42711  51.6357  32.9940 0004001 340.2566  19.8275 15.68503708 82793
         (a)      (b)     (c)     (d)       (e)     (f)
```

Figure 2.3: Description of the two-line orbital element format (TLE). (a) Inclination i, (b) Right ascension of the ascending node (RAAN) ω, (c) eccentricity of the orbit e assuming a leading decimal point, $e = .0004001$, (d) argument of perigee ω, (e) mean anomaly M, (f) mean motion n. Incises a, b, e are given in degrees.

The altitude of the satellite is one of the main parameters to define an orbit, and it corresponds to the semimajor axis the orbit when the eccentricity is zero. The calculation of the semi-major axis from a TLE format requires the mean motion shown in point (f) of Fig. 2.3. The mean motion is the number of revolutions per day of the satellite around its orbit, and the semimajor axis is determined from the equation of mean motion

$$n = \sqrt{\frac{\mu}{a^3}} \tag{2.1}$$

then

$$a = \frac{\mu^{1/3}}{n^{2/3}} \tag{2.2}$$

where $\mu = G\ (M + m)$. G is the gravitational constant and M the mass of the Earth and m the mass of the satellite (negligible compared to the mass of the Earth). It should be noted that the value of n is in rad/s instead that in $revolutions/day$ as given in the two-line orbital element (TLE), this change can be easily performed by multiplying the given value of the mean motion by $2\pi/86400s$ (86400 seconds equals one day and 1 revolution equals $2\pi\ radians$).

$$a = \frac{\mu^{1/3}}{(n \cdot 2\pi/86400)^{2/3}} \quad \text{meters} \tag{2.3}$$

Definition of the constants used in the previous equations.

$$\begin{aligned} \mu &= G * M \\ G &= 6.674 \cdot 10^{-11} \quad \mathrm{N} \cdot \mathrm{kg}^{-2} \cdot \mathrm{m}^2 \\ M_{\mathrm{Earth}} &= 5.972 \cdot 10^{24} \quad \mathrm{kg} \end{aligned}$$

The parameters of an orbit as discussed in this section will serve in the next chapter with the two-line orbital element (TLE) format. A detailed description of an orbit whit additional illustrations of the orbital plane and its parameters are covered in the first chapters of satellite communication books such as [18] and [19], among others.

2.2 Technology Readiness Level (TLR)

The Technology Readiness Level measures the level of development of a technological device. The scale goes from TLR 1 to TLR 9, being TLR 9 the highest level; it is common to find this scale in technical reports and datasheets of devices for small satellites. Table 2.1 lists a brief description of each TRL level for space technology.

TRL Description	
TRL 1	Research level. Basic research.
TRL 2	Little or no experimental proof of concept. Applied research. Potential applications are found.
TRL 3	Analytic and laboratory studies suggest the technology is viable.
TRL 4	The proof of concept is ready and small parts of the system are being tested together. Current experiments and results predicts the technology could be successfully used.
TRL 5	More rigorous testing than at TRL 4.
TRL 6	Fully functional prototype or model.
TRL 7	Prototype or model working in an space environment.
TRL 8	Sucessfull tests have been made and the device is ready to be used.
TRL 9	The technology has been successfully used in a space mission.

Table 2.1: Brief description of each state of the Technology Readiness Level scale [2].

2.3 The Internet of Things

The Internet of Things (IoT) is the main topic of several papers, like [23], that give a definition or discuss some specific matter of the IoT. Given the number of publications it is a good idea to describe the IoT for the following sections of this project.

The Internet of Things (IoT) proposes a model of integration, processing, and accommodation of data from physical devices and services that are connected to the Internet, to provide help for decision making or offer high-value information for the users. IoT implies essential concepts like security and privacy but also more ambitious characteristics like always availability [23].

This description of the Internet of Things (IoT) is the one that will be referred on the following sections. A more detailed presentation of the structure of the IoT is addressed in [23].

2.4 Information theory and digital communications

Some basic concepts of information theory are introduced in this section for later discuss the amount of information and channel capacity for the network architecture. Chapter 9 of [24] contains more details about information theory and digital communications.

Starting with a definition of information, the measure of information of a message i with probability of occurrence P_i defined by

$$I_i = \log_2 \frac{1}{P_i} \quad \text{bits} \tag{2.4}$$

The entropy H is an average information that is calculated by the expected value of the measure of information associated with a message i with probability P_i [24]. Obtaining the expected value from the previous equation we have

$$H = \sum_{i=1}^{n} P_i \log_2 \frac{1}{P_i} \quad bits \tag{2.5}$$

and the information-transmission rate R is defined by

$$R = rH \quad bps \tag{2.6}$$

where r is the symbol rate of the symbols related with H and

$$R \leq C \tag{2.7}$$

being C the channel capacity of a white band-limited gaussian channel defined according to the Hartley-Shannon theorem as

$$C = B \ log_2(1 + S/N) \quad bps \tag{2.8}$$

2.5 Defining a Network Architecture

The scale and transmission technology are two needed parameters for networks classification. The first refers to the physical distance between the elements inside the network. It is important to notice that if a connection establishment of two or more networks is called internetwork and the worldwide Internet is an example of internetwork [25].

The transmission technology refers to the way packets arrives at the final user. It can occur by using broadcast networks (all users share the same channel, and all users receive the same packets) or using point-to-point networks. Point to point consists of a connection between a pair of machines usually using more devices as intermediates; this kind of connection is preferable in larger networks [25].

A wide area network or WAN covers a large geographical area and contain a set of machines, called hosts, running user applications. Packets are carried from host to host using a subnet which usually includes transmission lines as the medium to move the packets and switching elements, sometimes called routers, to connect two or more transmission lines and choose one of them as the outgoing for its incoming packets. Fig. 2.4 shows an illustration of the interaction of the host with a subnet [25].

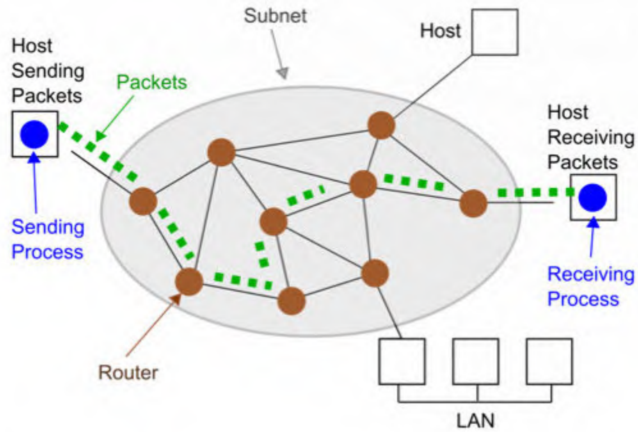


Figure 2.4: Interaction of a host sending packets with the subnet. Note that each router selects the forwarding route to send the packets to the final destination host.

A Network Architecture is a collection of layers and protocols. There are two famous models of network architecture, the OSI Model and the TCP/IP Model; the OSI Model serves as a generic model to network design, but it is the TCP/IP Model the widely used in terms of application [25].

The OSI Model consists of seven layers. Each layer interacts directly with the superior and inferior layers a protocol defines and the communication between two identical layers in different hosts. During the traveling from the Application Layer of one host to another, the information receives and detach additional information that is necessary to guarantee the arrival from the information of one host to another [26, 25]. Fig. 2.5 shows the general structure of the OSI Model.

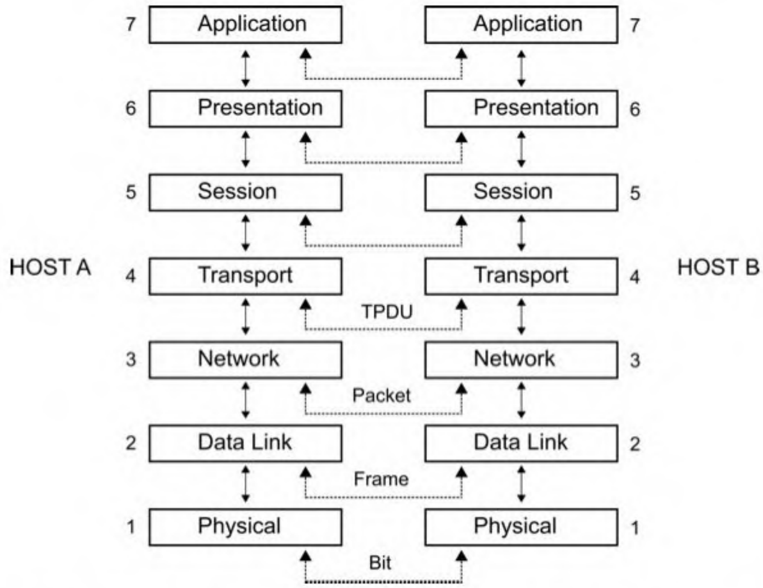


Figure 2.5: The OSI Model. The interactions of a layer the superior and inferior layers is shown with the double arrow line. The communication protocol is alluded with a dotted line, the name that receives the data due to its shape is written over the dotted line indicating the protocol for the first four layers.

Bandwidth, latency, and speed

The bandwidth, latency, and speed are crucial parameters to evaluate the network. Differing of other characteristics, those parameters are directly perceived by the user.

Bandwidth refers to the number of bits that can flow through the network; high bandwidth networks are often called high-speed networks. Generally, increasing the bandwidth can also increase the amount of transferred information that per unit of time [27].

Latency refers to the time elapsed from a request of information to the moment when this information arrives. Low latency in a network is desirable, but routing problems or inefficient data packing are factors that increase it and gives the impression of a slow communication even if the bandwidth is high [27].

The speed of the network considers both the bandwidth and latency that is present in the network; common measurements for this parameter are usually in Mbps and Gbps for terrestrial communications [27].

2.6 The proposed network architecture

The proposed network architecture is an open network that can interact with a wide range of devices with minor or without modifications. It is flexible and robust in the way that can overcome to fail at one point or part of the network without ending the availability of communication for the users, and it also has a broad coverage even in remote places. Fig. 2.6 shows the interaction of packets over the satellite and devices as desired for the Network Architecture.

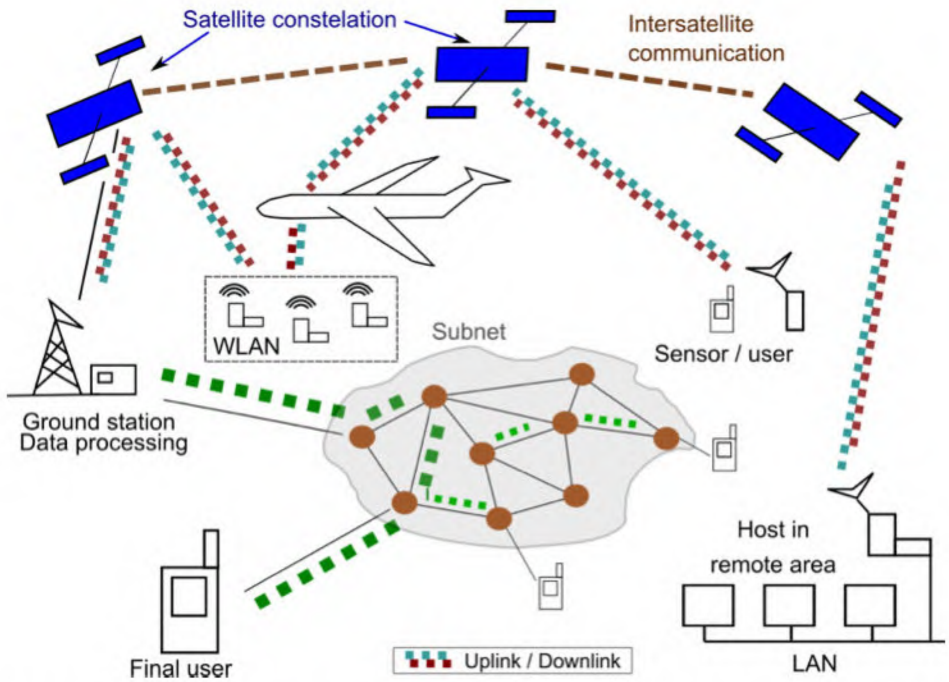


Figure 2.6: The proposed network architecture enables communication through a ground station connected to the Internet or directly at a mobile device, sensor or vehicle, even in a remote area such as a rural community.

With a network architecture as proposed in Fig. 2.6, a user can have communication with any of the devices of the network such as sensors at any moment and at any place, and those are two of the main characteristics included in the internet of things definition and a desirable communication scenario: to have always available service and at any place. The proposed network exhibits also flexibility since it is accessible from multiple devices and methods (e.g. through a subnet or with a mobile receiver) and allows communication with a variety of devices like sensors.

To achieve flexibility, the design of the network requires to have open or common protocols of communication, preferably, already included at the devices of the network. The architecture at 2.6 is also useful to provide more services than just services for the agriculture segment, allowing more opportunities for success in case of project implementation. Finally, that kind of network is a robust network since satellites can overcome many of the problems that cause disruption of communication between Earth-based transmitters and receivers such as natural disasters.

Chapter 3

Defining the Mission

Defining a mission is the first step for proposing or designing a network architecture. The mission definition tells us what is to be done and helps to understand some critical design parameters like how often to take measurements of some variables and estates why a satellite is required.

The mission in this project will serve as a reference point to guide some general ideas. For example, an observation mission that requires taking high-quality pictures from a defined area of the Earth surface, in general, would need more bandwidth or throughput to transmit the high-quality images than a mission transmitting or collecting measurements of some ground or attached sensor.

The proposed mission is to provide a communication network for taking measurements of agriculture fields at any place of Mexico, sending the retrieved information to centers or a cloud to be processed and then deliver it to the farmers. This kind of structure will allow farmers to know the state of their fields, make smart decisions, and control some actions like irrigation or adding of pesticides remotely with satellite communication or from the Internet.

This network should be able to carry the information generated by a given number of sensors and packets from the user containing orders to some actuators like valves. According to the Internet of Things Definition (IoT), the instructions from the user to some actuator comes after the user has received added value information and decided to execute some action, or performed automatically after some set of conditions have been met.

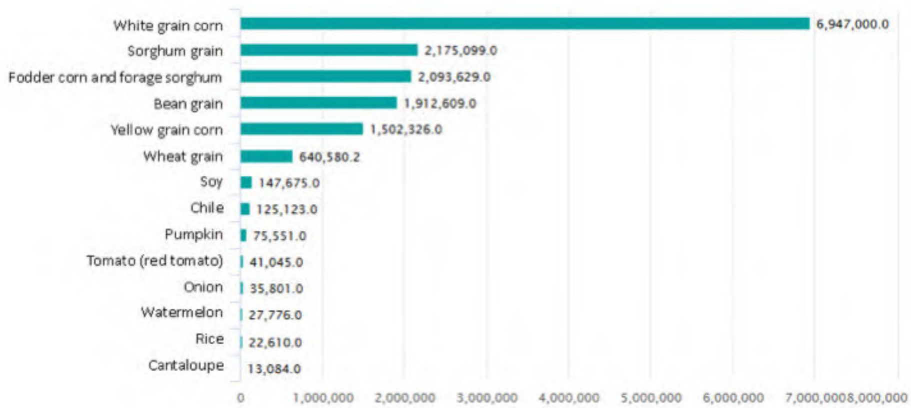
The purpose of the mission is to provide a flexible and robust communication network to farmers to monitor their fields even if they are dispersed or have a great extension, also, to give a platform to control an execution of actions from a single site. Those processes, has previously mentioned, could be directly ordered by the farmer just with the information of his field, but also mixing the info of his crop fields with additional information at the data center (like the weather forecast) and in this manner implemented actions could have more accuracy.

A mission like this would help to develop ideas to modernize the Mexican agriculture practices and to give a proposal to include the Mexican soils and farmers in the Internet of Things. The scope of this project is to discuss some of the challenges and the required elements for enabling the development of such a flexible and robust communication network for this mission.

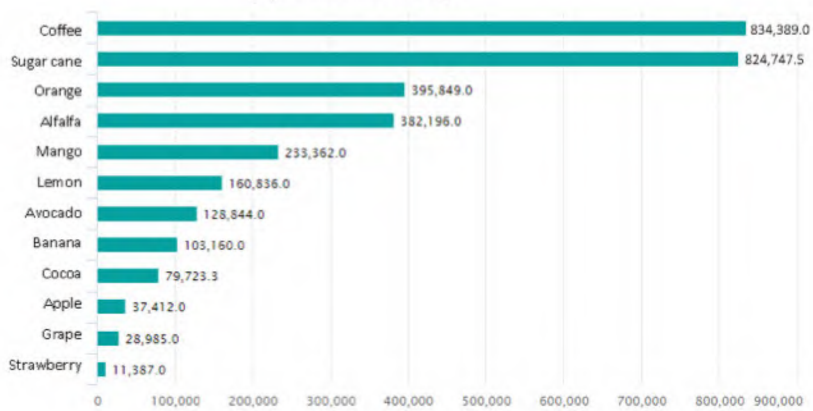
3.1 State of the Art

Agriculture in Mexico

According to SAGARPA (Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación), a governmental agency in Mexico, in 2017 the total surface planted in Mexico was 21.6 millions of hectares and the states with most planted hectares in that year were Jalisco, Veracruz, Tamaulipas, Chiapas and Oaxaca [28]. From the total number of acres for agriculture in 2017 just 21% had a system of irrigation and 79% depended of seasonal rains [1]. From the Fig. 3.1 shows a graphic from INEGI (Instituto Nacional de Estadistica y Geografia) of the most sown crops in Mexico.



(a) Annual Crops



(b) Plants that live more than two years.

Figure 3.1: This graphs generated by INEGI with data collected by them in the 'Encuesta Nacional Agropecuaria 2017' shows the number of hectares used by some of the leading annual crops in Mexico and also some crops produced by plants or trees which lives more than two years. Image retrieved from [1].

3.1.1 Case studies on similar applications

This section introduces two case studies published by the companies Campbell Scientific and MeterGroup which are related to this project. More case studies are available at [29].

California Irrigation Control

Flood irrigation is the common method of irrigation for alfalfa, and in this case study, a field of alfalfa of 60×220 m^2 was initially irrigated with two valves by flood irrigation from the highest part of the crop field and personally supervised by employees to determine when to close the valves. MBK Engineering and two universities installed 12 water sensors close to the lowest end of the field, a data logger and a full-duplex modem to transmit measurements of the sensors using the Internet to cellular towers. After the installation, the employees monitored the readings of the sensors and avoided waste of water which was in the order of thousands of gallons. More details of this case study are accessible at [30].

Trans-African Hydro-Meteorological Observatory (TAHMO)

Weather is a crucial factor to decide when to plant, and this case study aims to provide a platform to decide when to plant by installing thousands of ground weather sensors across Africa. Those sensors will help to complement other observations (such as satellite observations) and help determine farmers when is the best moment to plant, thinking in achieving a higher volume of crops and avoiding a loss of time and resources by planting in the wrong epoch of the year. More information about this case study is available at [31].

A network of sensors including communication through a satellite channel is proposed to modernize the production of agriculture fields and to provide better resources utilization. This network could also be used to quantify and record in some way the levels of soil degradation, allowing modernization of agriculture activities with less harm to the soil.

3.2 Devices of the Network

A network may allow devices such as sensors, actuators, data loggers, transmitters, receivers or intermediate devices for communication to the satellite. Additional elements required for the network are the ground station and ground installations for control and telemetry. Some of those devices could be transparent to users (e.g., not noticed, with no direct interaction) and its location could be far outside an agriculture field. This section includes a list of some available devices. The requirements for the ground station are discussed in the next chapter.

3.3 Existing and required devices

The physical elements to be located in the bottom of the proposed network are sensors to collect information of the field like humidity, water content, actual nutrients in the soil, soil degradation, wind velocity, rain intensity and more. The parameters to monitory may vary for different farmers, but equipment with similar standards have been developed by some companies like Campbell Scientific and MeterGroup, among others.

The actual level of technology allows transmission of the information collected by the sensors primarily through wires, wireless networks of small coverage and commercial cellular networks. Figure 3.2 shows the overall idea for communication with those already developed devices and with required devices that need to be developed.

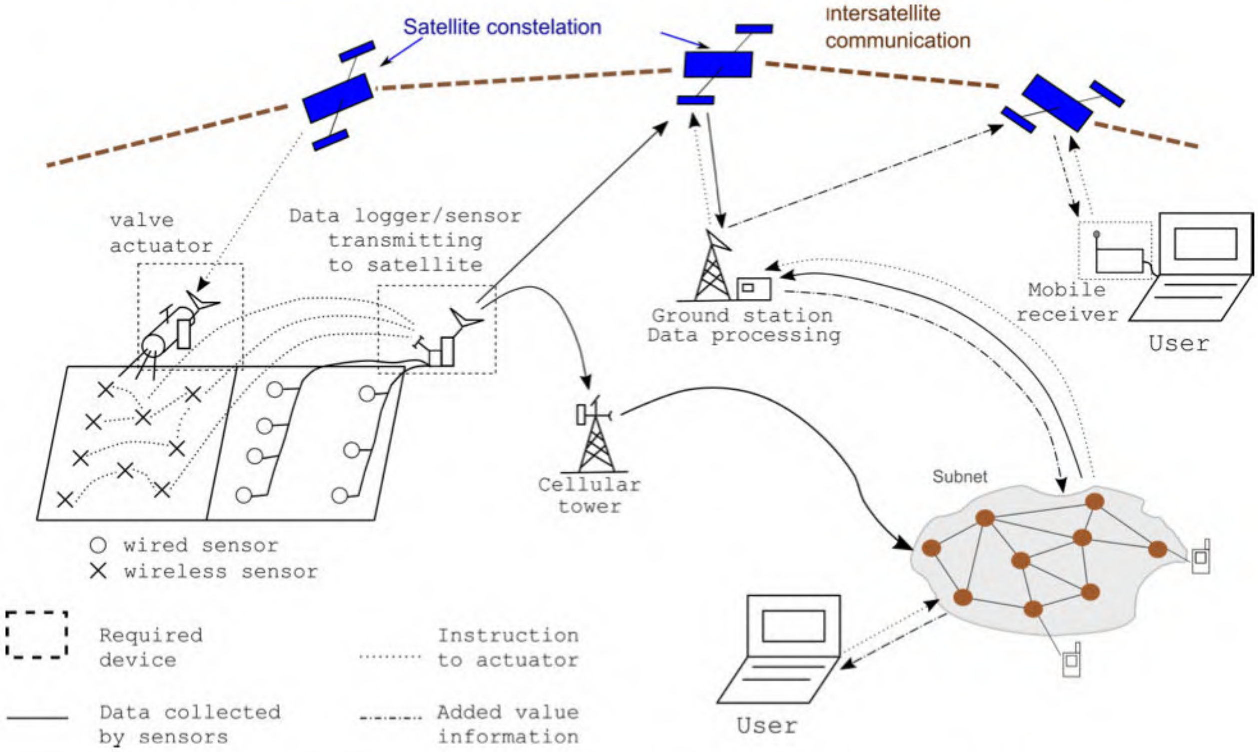


Figure 3.2: Communication between devices and required devices.

Tables 3.1 and 3.2 contains a list of some available devices such as sensors, data loggers and transmitters with a brief description and features. The tables are in groups according to the company that produces them and to their primary function. Fig. 3.3 shows a possible array of wired sensors as those provided in the previously mentioned tables.

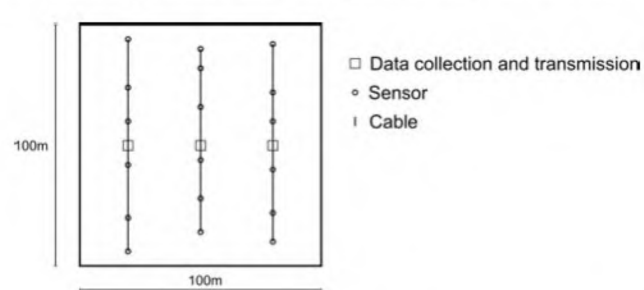


Figure 3.3: Possible array of sensors to take measurements in a hectare.

Meter Group Hardware		
Device Name	Type	Description
Atmos 41	Sensor for weather monitoring	This sensor or station for weather monitoring is part of the family of devices Atmos and has the capacity of monitoring several weather parameters as precipitation, wind velocity and direction, air temperature, solar radiation, humidity, pressure, and other relevant variables. This small station is one of the physical elements in the case study THAMO in the following subsection.
Phytos 31	Leaf Wetness Sensor	This sensor with a shape of a leaf behaves similarly to a natural leaf to collect measurements of the wetness that actual leaves have. This sensor collects measurements that help to decide when is the best moment to apply fungicides and to detect the moments when the plants are more susceptible to diseases. The approximate volume of the sensor is 120 $\times$ 58 $\times$ 8 mm^3, requires a voltage supply of 2.5 to 5 Vdc and the cable length availability goes from 5 to 40 m.
Teros	1	1
ECH_2O EC-5	Sensor of volumetric water content	Wired sensor for large sensors networks with approximate dimensions of 90 $\times$ 20 $\times$ 5 mm^3, required voltage and current of 2.5 to 3.5 Vdc and 10mA, length of the cable from 5 to 40 meters.
ECH_2O TM	Sensor of volumetric water content and soil temperature	Wired sensor with approximate dimensions of 110 $\times$ 35 $\times$ 5 mm^3, required voltage and current of 3.6-15.0 Vdc and 0.03-10mA, length of the cable from 5 to 75 meters, DDI serial and SDI-12 communication protocols.
ZL6	Data Logger	This data logger requires few setups since it automatically recognizes the attached sensors, and includes solar panels for uninterrupted use for months and even several years with good sun view. This data logger has GPS, pressure and temperature sensors, and make use of cellular towers to send data to a cloud service of the company where the user will have access to the information. Up to six sensors can be attached to the data logger of dimensions 149 $\times$ 250 $\times$ 63 mm^3.

Table 3.1: Meter Group Hardware. A complete list of available hardware from this company is available at [3].

Campbell Scientific Hardware		
Device Name	Type	Description
CS650	Sensor of volumetric water content	Wired sensor with approximate dimensions of $300 \times 32 \times 3$ mm^3, sensing volume of 7800 cm^3, requires a voltage of 6 to 18 Vdc, maximum cable length of 610m, SDI-12 and serial RS-232 communication protocol at the output. This sensor needs a warm-up time of 3s and less than one additional second for communication through its communication protocol.
CWS655	Wireless sensor of volumetric water content and soil temperature	This sensor with approximate dimensions of 145 $\times$ 60 $\times$ 45 mm^3 with 2 thin rods of length of 120 mm uses 2 AA batteries with an estimated life of one-year taking measurements every 10 minutes. This sensor acts as a router also, to retransmit readings of other sensors up to three hops
CWS900	Wireless sensor interface	Similar to the CWS655, this device can incorporate one sensor; wind, soil and surface temperature, solar radiation, relative humidity, and rain intensity are examples of sensors developed by Campbell Scientific that are compatible with this platform.
CWB100	Wireless base station	This hub for the wireless-sensor network collects the measurements of sensors like CWS655 or the attached to the CWS900 according to the parameters configured in the data logger. This station can poll up to 50 sensors, the data is stored and then transmitted to the data logger. This station works in the 902-918 MHz band, have dimensions of $108 \times 44 \times 44$ mm^3, requires a voltage supply of 4.5-22 Vdc.
CR1000	Data Logger	This data logger has 16 analog inputs, 4 Mb of storage, and communication capabilities supporting TCP/IP, email, FTP and a web server; up to 4 devices as the CBW100 can be connected. The capacity for connecting sensors is in the range of several tens, being the required time to poll each sensor the main limitation to add more of them. Data can be transferred using direct connect, Ethernet, various kinds of modems, RF telemetry and even satellite transmitters for some specific communication satellites as Iridium and Inmarsat.

Table 3.2: Campbell Scientific Hardware. A complete list of available hardware from this company is accessible at [4].

Chapter 4

The Network Architecture

4.1 Traffic estimation

For the data loggers shown in Table 3.1 an estimation of the bits generated per measurement is calculated in this section. In the case of the data logger from Table 3.1, the manual of operation mentions that the internal storage of 8 Mb is filled with about $40,000$ to more than $80,000$ measurements depending on the configuration to collect measurements. A rough estimation of the quantity data generated by a single measurement could be approximated by dividing the total capacity of the data logger over the measurements required to fill it. Taking this approximation with the mentioned boundaries:

$$0.1 \leq I_{sensor\ measurement} \leq 0.2 \quad \text{kB} \tag{4.1}$$

Given that sensors in both Table 3.1 and 3.2 uses the same communication protocol and have a similar bit resolution for taking the measurement it would be assumed that the quantity of information generated by similar sensors is approximately equal and from this point and forward it would be assumed that the information generated by a sensor is contained in the boundaries of the previous result.

4.2 Network Requirements

Fig. 4.1 shows elements of the physical and data link layer needed for satellite communication. It is similar in various aspects to wireless communications, but it has more constraints in the techniques that can be used mainly because of the channel conditions and the restrictive hardware to perform electronic operations in space as well as in ground conditions. A similar figure is available at [**?**, Fig. 1.1].

4.2.1 Source coding

Source coding is employed to reduce the number of bits to be transmitted, and this is achieved by reducing the redundant information and thus increasing the entropy of the source. Coding and compression are employed to diminish redundancy. Coding refers to assigning a particular sequence of bits to represent information and compression refers to take

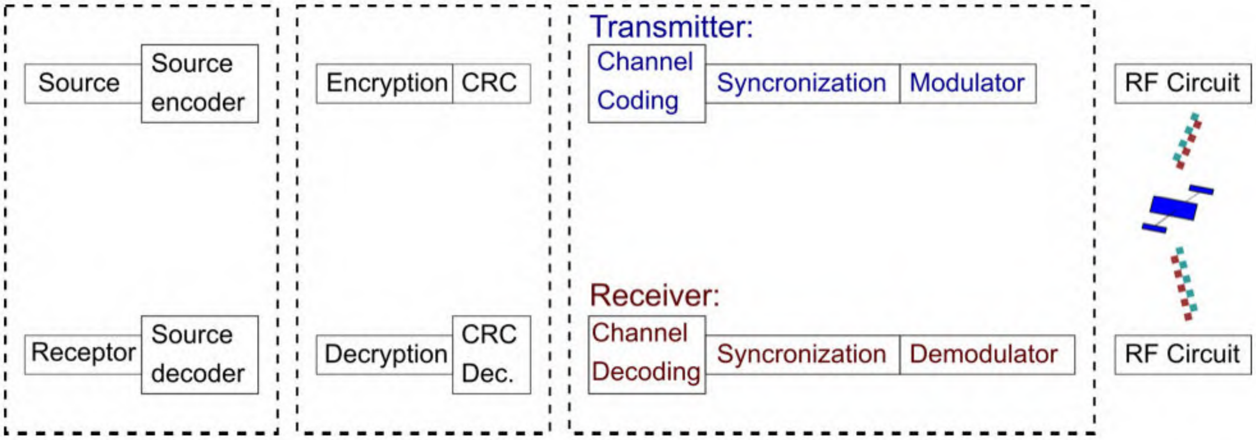


Figure 4.1: Block diagram of the necessary elements for establishing a satellite communication network in LEO.

out the redundant information. It is essential to notice that diminishing the data employed to carry some information to the receiver will increase the speed of communication.

Huffman coding is an example of source coding based on representing information with a sequence of bits of variable size according to its uncertainty. JPEG is an example of a compression method. Both of those methods are a lossy coding approach, meaning that an approximation will be recovered at the receiver.

4.2.2 Encryption and CRC

4.2.3 Channel coding

Channel coding helps to deal with noise during transmission and consist of adding redundancy to the transmitted information. Forward error correction is needed on satellite communications since transmission is unsuitable through the satellite channel. Reed-Salomon codes are one well-suited option for low data rate transmissions making them a good option even for deep space applications [32]. Convolutional codes and turbo codes are also well-suited options for coding included in some space transceivers.

4.2.4 Modulation

Phase Shift Keying (PSK) modulation is one suitable modulation for satellite communications [18]. Quadrature Amplitude Modulation (QAM) modulation have advantages in terms of SNR over PSK modulation; however, this modulation its more susceptible to problems in reception when the amplifiers in the receiver operate close to its saturation region. OQPSK, GSMK, and APSK are other types of modulation also available for LEO satellites. Details and simulation of the behavior of PSK, QAM, OQPSK, and GSMK for CubeSats systems are addressed on [33].

4.2.5 Access methods

Three classical methods to share the satellite channel over multiple users are the time division multiple access (TDMA), frequency division multiple access (FDMA) and code division multiple access (CDMA), several sources such as [34] describe those methods. Sources such as [35] mention that FDMA is the most common method for multiple access in satellite communication, but using this method usually generates interference as a result of the transmission of multiple signals [35].

Attempts to include multiple access in nanosatellites are discussed at [36], [37], [38], and [39] among few others. Power and onboard computation limitations are two of the significant barriers to achieve higher data throughput; however, as discussed at [13], nanosatellite technology and capabilities are evolving rapidly.

4.3 Space

The space segment refers to the satellite, a constellation, or a swarm or satellites orbiting the Earth. This section includes a description and recommendations of orbits, frequencies, and hardware that is suitable for the satellite to achieve the mission.

4.3.1 Orbit

Low Earth Orbit has benefits compared with geostationary orbits in terms of the round trip time and attenuation of the signal. Those factors are significant at the time to achieve low latency in communication.

Polar orbits are one of the most common orbits for satellites and are usually circular sun-synchronous orbits too. This kind of orbits is very usefully in a constellation; however, a constellation requires more satellites, launches, and usually more ground infrastructure. Iridium is an example of a constellation of Low Earth Orbit (LEO) satellite constellation with polar orbits; this constellation consists of 66 big satellites evenly distributed in six orbital planes achieving global coverage [40]. Telesat is proposing a LEO satellite constellation for communications with global coverage [41] mixing polar orbits and orbits with another inclination.

> **Lessons Learned 4.1**
>
> Although a polar orbit can provide global coverage and provide benefits of fixed position between satellites (which is usefully for inter-satellite communication), it passes only around two times per day over the same region of coverage.

An orbit with some inclination could provide more time of coverage for a specific region inside the geographical band covered by the satellite. Figs. 4.2, 4.3 and 4.4 show an orbit with an inclination of 30° while Figs. 4.5, 4.6 and 4.7 show a polar orbit. In both cases, the simulation had a duration of 24 hours, and the figures show the path covered by satellite while it is moving in its orbit.

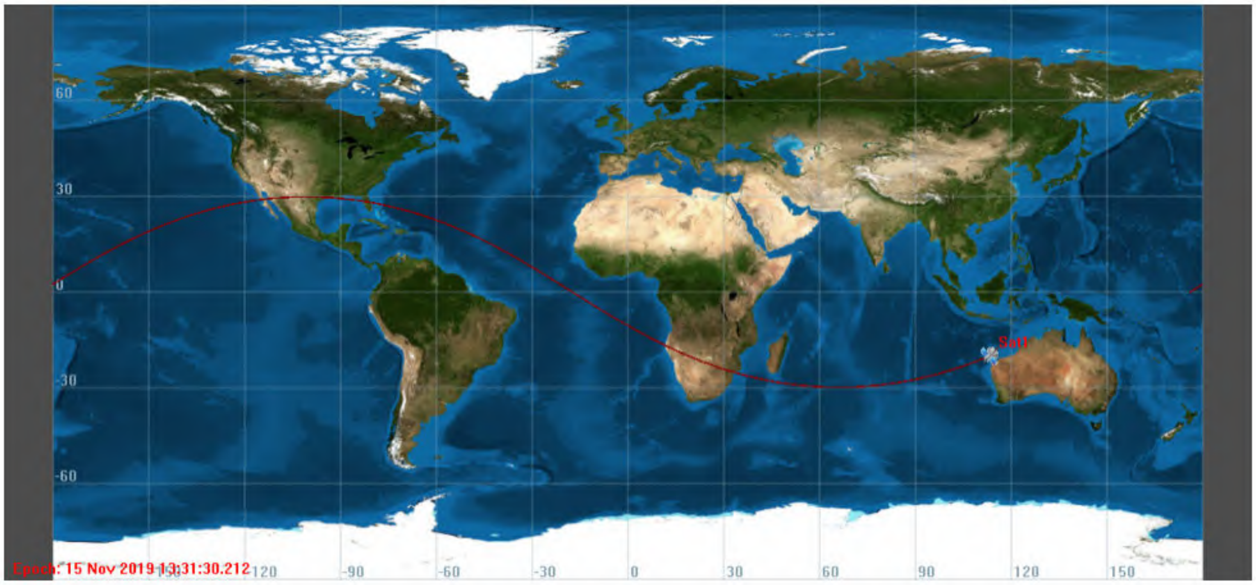


Figure 4.2: Simulation of an orbit with inclination of 30° in GMAT. The orbit was simulated for one day starting at Nov. 15, 2019, at the 12:00:00, and the picture shows the position of the satellite shortly after it starts orbiting.

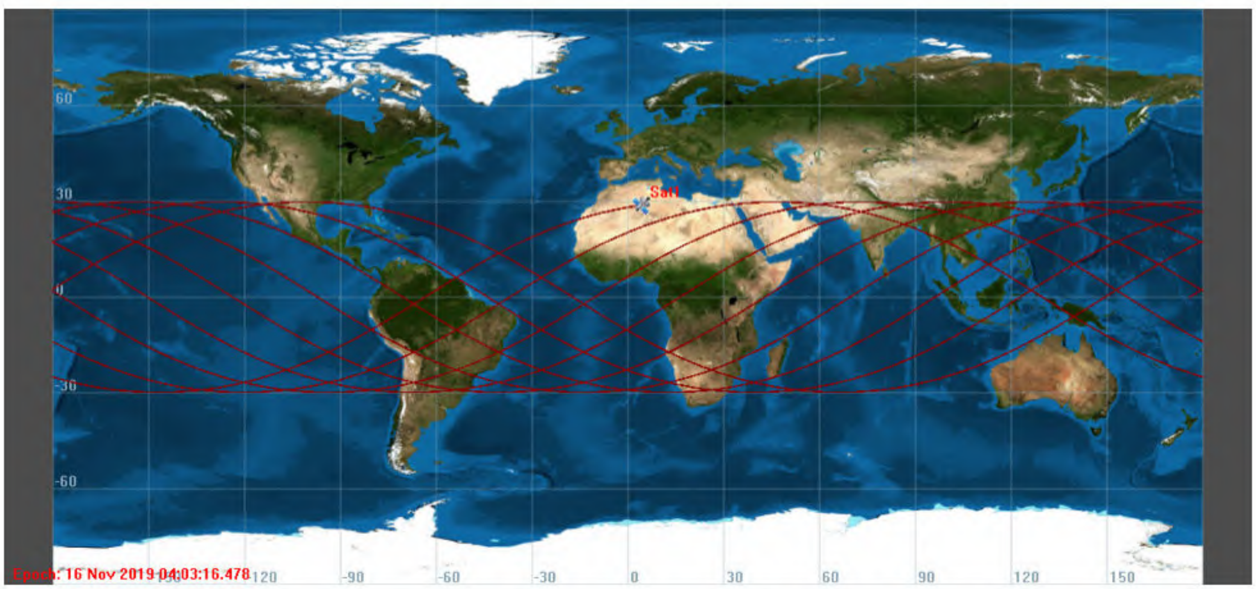


Figure 4.3: Simulation of an orbit with inclination of 30° in GMAT. The orbit was simulated for one day starting at Nov. 15, 2019, at the 12:00:00, and the picture shows the position of the satellite after 16 hours orbiting the Earth.

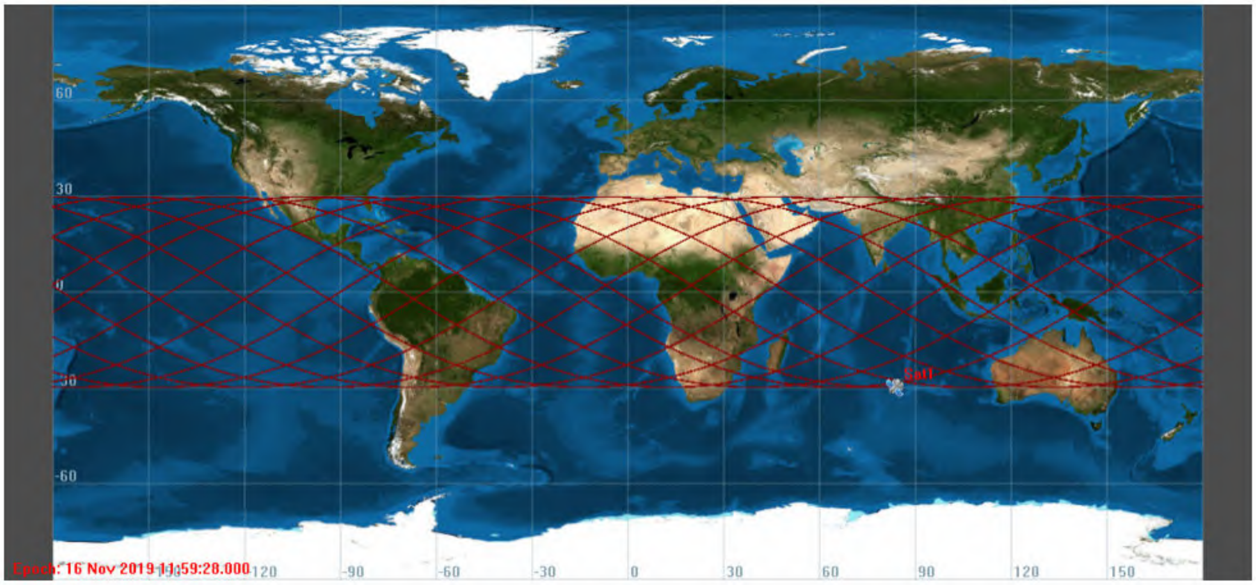


Figure 4.4: Simulation of an orbit with inclination of 30° in GMAT. The orbit was simulated for one day starting at Nov. 15, 2019, at the 12:00:00, and the picture shows the position of the satellite after 24 hours orbiting the Earth.

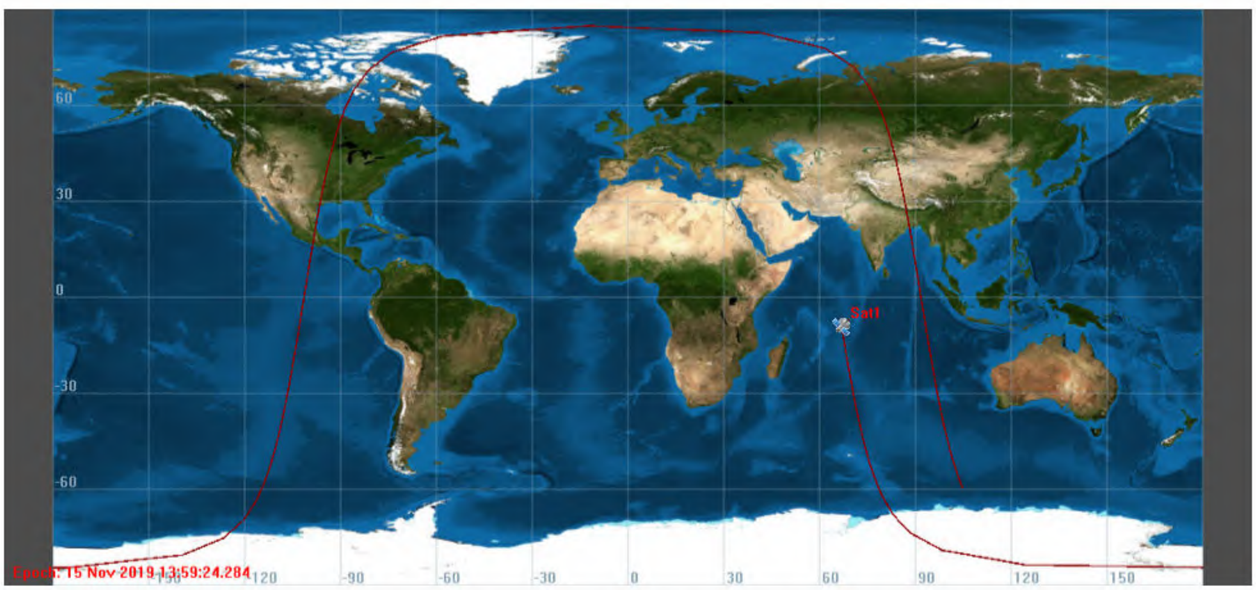


Figure 4.5: Simulation of an orbit with inclination of 97° in GMAT. The orbit was simulated for one day starting at Nov. 15, 2019, at the 12:00:00, and the picture shows the position of the satellite after 2 hours orbiting the Earth.

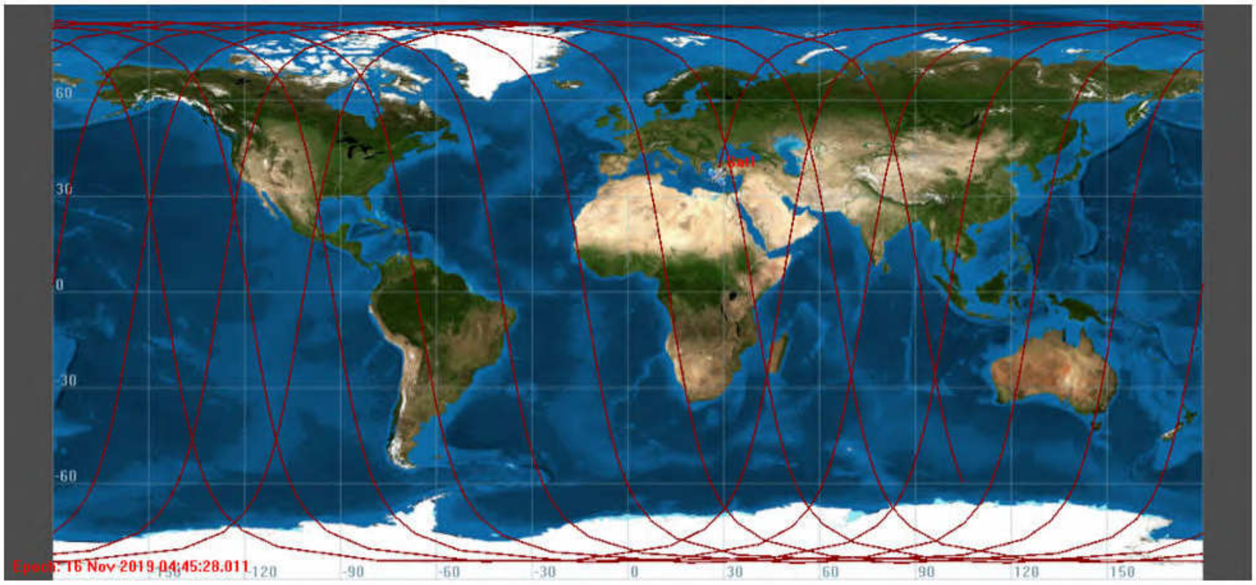


Figure 4.6: Simulation of an orbit with inclination of 97° in GMAT. The orbit was simulated for one day starting at Nov. 15, 2019, at the 12:00:00, and the picture shows the position of the satellite after 16 hours orbiting the Earth.

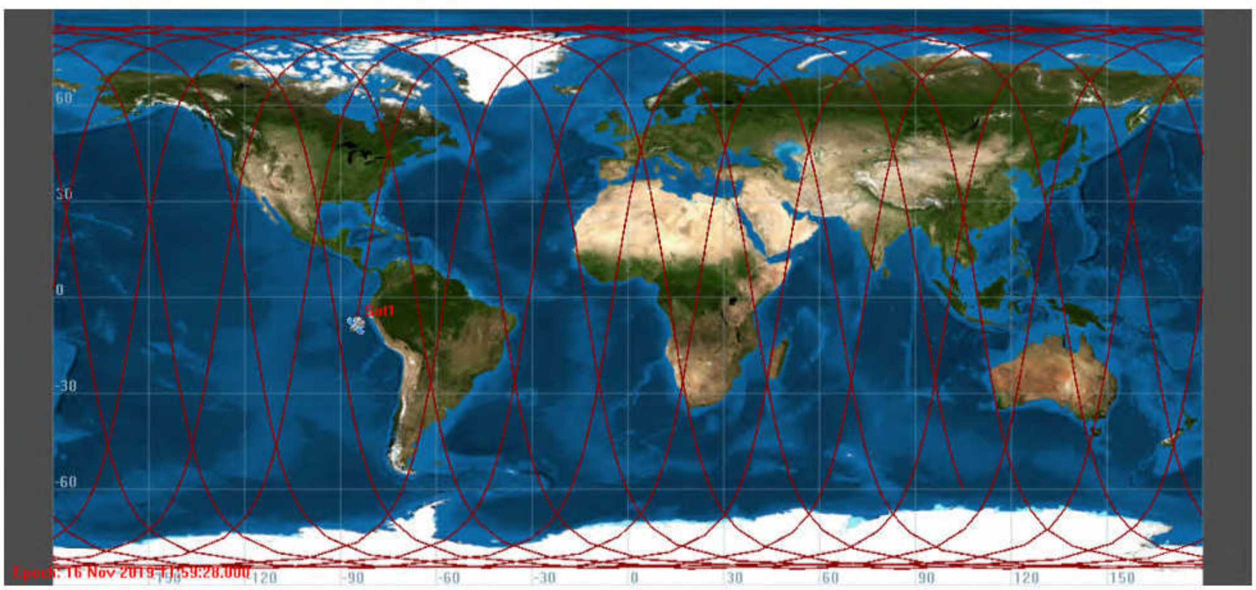


Figure 4.7: Simulation of an orbit with inclination of 97°in GMAT.The orbit was simulated for one day starting at Nov. 15, 2019, at the 12:00:00, and the picture shows the position of the satellite after 24 hours orbiting the Earth.

The inclined obit described in Figs. 4.2 and 4.4 has a semi-major axis of 7371 km. The following fragment of a two-line orbital element format (TLE) contains more information about the orbit:

```
30DEG ORBIT SAT
```

```
1 ---------------------------------------------------------------------
2 XXXXX 29.96301 44.77956 0007097 321.9822 311.1640 13.73150419XXXXXX
```

The polar obit described in Figs. 4.5-4.7 has a semi-major axis of 7371 km. . The following fragment of a two-line orbital element format (TLE) contains more information about the orbit:

```
POLAR ORBIT SAT
1 ---------------------------------------------------------------------
2 XXXXX 97.99409 330.8317 0021727 331.4197 217.5870 13.68318699XXXXXX
```

Figs. 4.8 and 4.9 contains a view from the space of the simulated orbits. With those figures, it is clear to see that the geographical coverage of an inclined orbit is more limited than the coverage of a polar orbit but can be useful to cover a specific region. Fig. 4.8 and 4.9 shows the orbits previously simulated with a view from outer space.

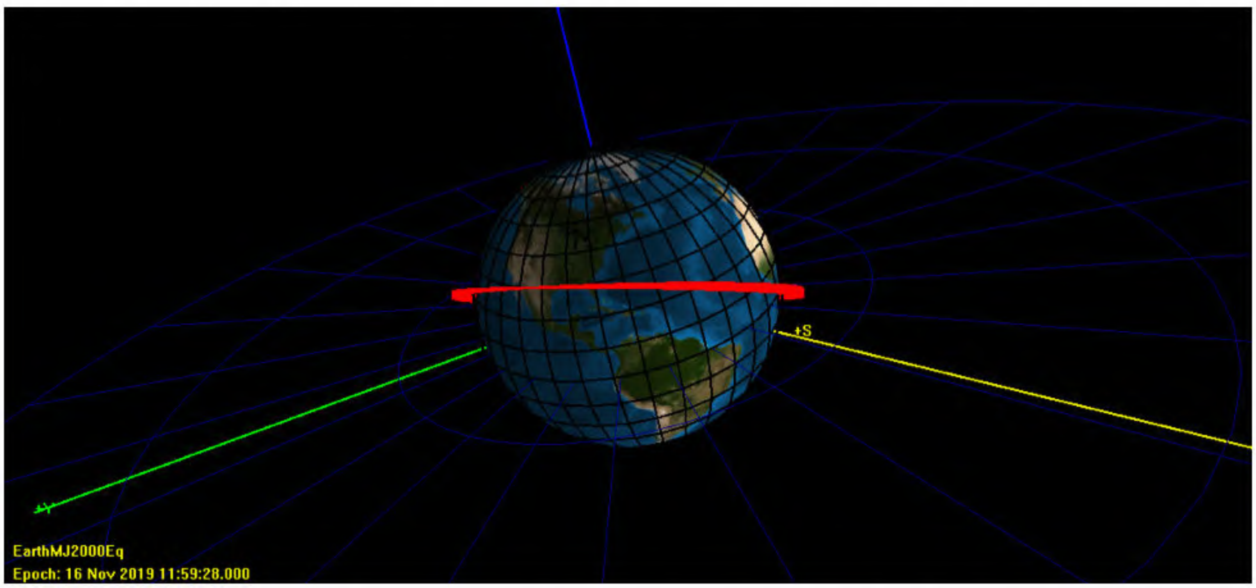


Figure 4.8: Simulation of an orbit with inclination of 30° with view from the outer space.

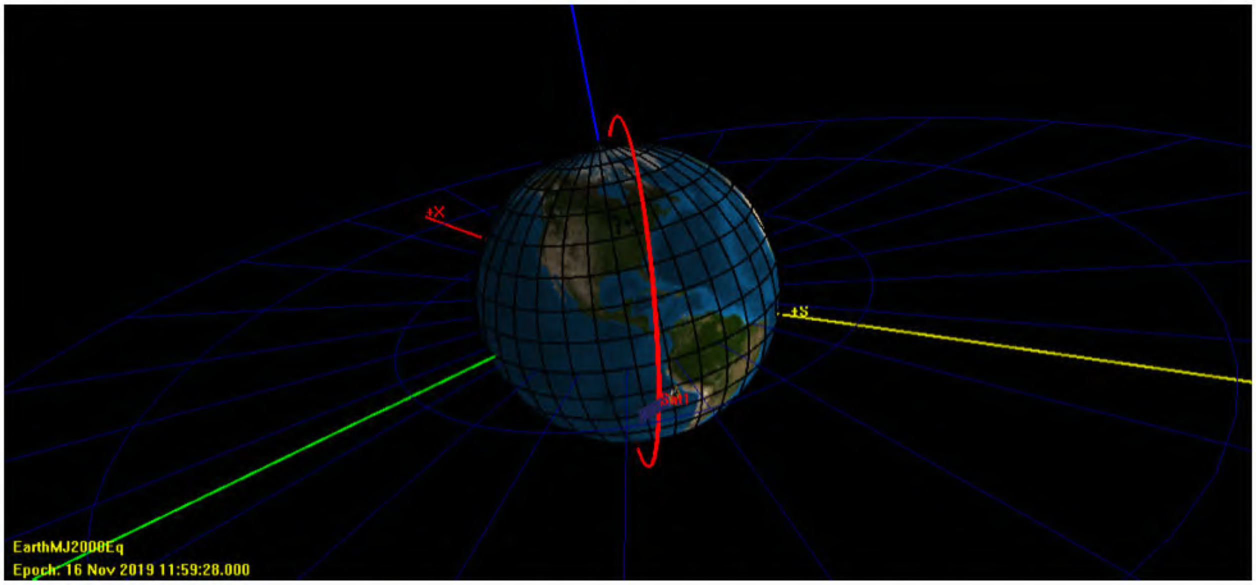


Figure 4.9: Simulation of an orbit with inclination of 97°with view from the outer space.

4.3.2 Frequency bands for the mission

Satellite communications use frequency bands above 100 MHz since the atmosphere conditions represent higher difficulties below this range. Some frequency bands could contain satellite and terrestrial links; others could contain just satellite links or terrestrial links, this means that some caution is necessary to avoid interference with other signals especially in those bands. Fig. 4.10 shows the frequency bands mainly used in satellite communications and its classification according to the IEEE Radar Band Designations [42].

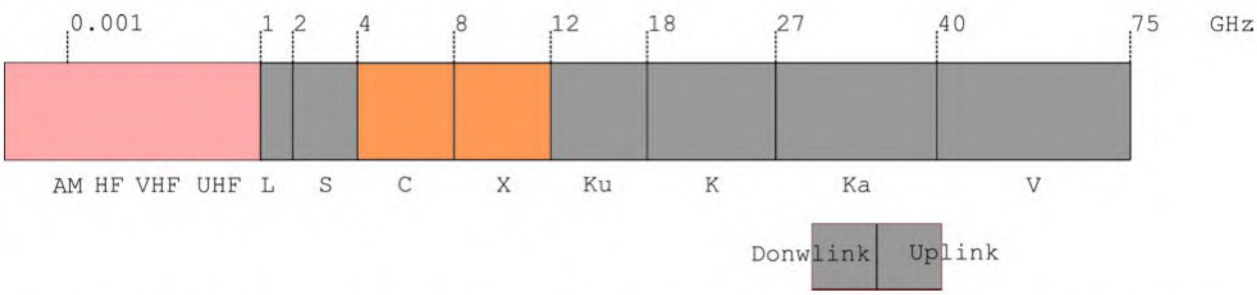


Figure 4.10: Mainly used in satellite communications. Terrestrial bands are red colored; satellite bands are in gray and shared bands in orange. Generally, the uplink is slightly above the downlink for satellite communications.

Three options of frequency bands to use in a network of satellite communications are the S, K and Ka bands. Each of those frequency bands has some advantages described in the following paragraphs.

The K and Ka bands

The K-band contains frequencies in the range of 18-27 GHz and the wavelength associated to those frequencies varies between 1.67-1.11 cm while the Ka-band contains frequencies in the range of 27-40 GHz and the wavelength associated to those frequencies varies between 11.1-7.5 mm. One of the advantages of those frequencies is that they generally contain more available bandwidth; also, the antennas operating at those frequencies can have a higher gain than antennas of similar size operating at lower frequencies.

At the K and Ka frequency bands, Mexico has assigned portions of the radioelectric spectrum for research purposes that a university could obtain. Even though high throughput is achievable at those bands, they are also more affected by atmospheric attenuation than lower-frequency bands.

When considering the frequency band to operate it is also necessary to consider the intended geographical region of coverage by the satellite, and the characteristics of the rain or other phenomena that could attenuate the propagated signal at that particular region. The high attenuation caused by rain is the greatest challenge for satellite communications in the Ka-band; however, some approaches like multiple ground stations can be implemented to minimize the rain effects, receiving and transmitting from a place far enough from the rain [43]. Fig. 4.11 shows a graph obtained from [19] of the atmospheric attenuation at different frequencies.

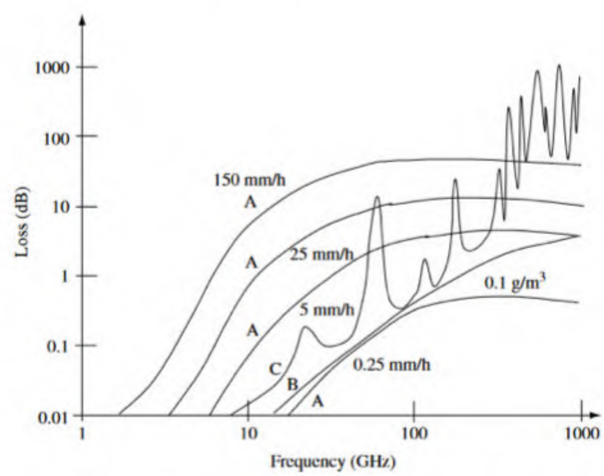


Figure 4.11: Atmospheric attenuation by various factors A: Rain, B: Fog, and C: Gas, and to different rain average intensity. Graph retrieved from [19]

The S band

The S-band contains frequencies in the range of 2-4 GHz, and the wavelength of a signal in this band varies between 30-15 cm. This band is more suitable than the K and Ka bands to cover regions with regular high-intensity rain. Fig. 4.12 obtained from [42] shows the attenuation effects by rain in the S, K, and Ka frequency bands.

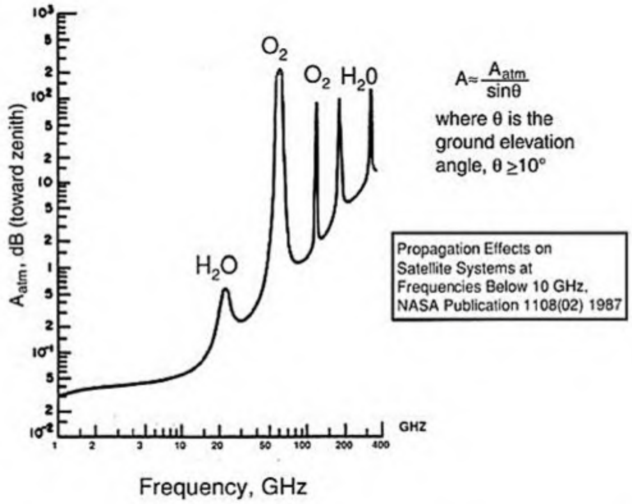


Figure 4.12: Attenuation caused by rain. The attenuation caused by rain (H2O) is visible in the frequencies corresponding to the K-Ka bands and are much higher than in lower frequency bands such as the S-band. Graph obtained from [42]

Lessons Learned 4.2

Different organizations including the NASA [44] consider the K and Ka bands as the band for the future for space communications, but commercial communications subsystems for nanosatellites at those bands are more hard to find than for lower such as those between the VHF and the C-band.

Available frequencies in Mexico for space research

The radioelectric spectrum in Mexico contains several portions dedicated to satellite communications such as space research, fixed and mobile satellite services, inter-satellite communication, satellite amateur, Earth exploration with satellites. Governmental regulations, definitions, and a description of the whole regulated radioelectric spectrum in Mexico are available at [45], and a map describing the uses for each portion of the spectrum in Mexico is provided at [5]. Table 4.1 lists some portions of the spectrum at the S, K and Ka bands, which contains available bandwidth for space research and amateur purposes. The bandwidth indicated in the table contains at least one smaller portion dedicated to amateur or research applications.

Bandwidth Research and Amateur Purposes in Mexico		
Frequency band	Available bandwidth within	Category
S	2025 - 2110 MHz	Space Research (Earth-Space and Space-Space)
S	2200 - 2290 MHz	Space Research (Earth-Space and Space-Earth)
S	2290 - 2300 Mhz	Space research (Deep space and Space-Earth)
S	2300 - 2450 Mhz	Amateur
S	2690 - 2700 MHz	Space Research
S	3100 - 3300 MHz	Space Research
S	3300 - 3500 Mhz	Amateur
K	18.6 - 18.8 GHz	Space Research
K	21.2 - 21.4 GHz	Space Research
K	22.21 - 22.5 GHz	Space Research
K	22.55 - 23.15 GHz	Space Research (Earth-Space)
K	23.6 - 24 GHz	Space Research
K	24 - 24.25 GHz	Amateur
K	25.5 - 27 GHz	Space Research (Space-Earth)
Ka	31 - 31.3 GHz	Space Research
Ka	31.3 - 31.8 GHz	Space Research
Ka	31.8 - 32.3 GHz	Space Research (Deep space and Space-Earth)
Ka	34.2 - 34.7 GHz	Space Research (Deep space and Earth-Space)
Ka	34.7 - 35.2 GHz	Space Research
Ka	35.5 - 36 GHz	Space Research
Ka	36 - 37 GHz	Space Research
Ka	37 - 37.5 GHz	Space Research (Space-Earth)
Ka	37.5 - 38 GHz	Space Research (Space-Earth)

Table 4.1: Radioelectric spectrum in Mexico for space research and amateur purposes in the S, K and Ka frequency bands. Information gathered from [5]

4.3.3 Satellite Subsystems

The satellite includes a variety of subsystems, some of them can vary according to the mission, and others are almost always present. This section describes classical subsystems for satellites, some of them with greater detail than the others according to their relevance to the proposed mission and constraints of a nanosatellite. Chapter 5 of [35] contains more information about this topic, while chapter 4 of [46] and publications like [17] contain more information for the particular case of CubeSats.

Attitude control subsystem

The satellite experiences disturbances in its orientation once it has been deployed and entered its operative life. Causes of this disturbances are, among others, forces generated by the solar radiation and the gravity of the Earth. The attitude control subsystem has the function of restoring the orientation of the satellite around its axes to keep aligned the satellite and the antenna to the right position [35].

Reaction wheels and magnetorquers are two types of technology employed to keep the small satellite with the right orientation, both of those technologies usually have a TRL (Technology Readiness Level) of 9 and are commonly found in CubeSats. In general, the technology associated with this subsystem has been successfully proven and successfully used in the past. A description of the technology used in this subsystem is discussed at [47] with descriptions and tables containing relevant details and technical data.

Lessons Learned 4.3. Attitude determination and control subsystem available in the market.

It is crucial to include this subsystem in a nanosatellite that will perform a mission of communication by the reasons stated in the two previous paragraphs. Additional constraints like the needed accuracy in the position, mass or cost will help to determine the best attitude determination and control (ADCS) board for the mission.
A board can be designed and programmed to control one or several actuators bought in the market or directly bought to some companies like ISIS (based on the Netherlands) or Maryland Aerospace (from the US) which are specialized companies in nanosatellites, and small satellites and aircraft. Several tables and a description of this subsystem are available at [48, Chapter 5]

Two ADCS commercial subsystem boards are included in this section. The first one, shown in Fig. 4.13 is an ISIS Magnetorquer Board offered by a company from the Netherlands called Innovative Solutions In Space (ISIS). A full description of this board and datasheets are available on the web page of the provider [49]. The second ADCS subsystem is the MAI 400, shown in Fig. 4.14,by Maryland Aerospace; it is much more expensive than the board from ISIS, also bigger and heavier, but contains a potent computer, 3-axis magnetometers, sensors for position determination (such as star tracker) and one or more reaction wheels according to request to the provider. Information of MAI 400 is available on the web page of the provider [50], and datasheets are also available at [51]. Table 4.2 lists some critical technical aspects of both boards.

Figure 4.13: This magnetorquer PCB offers 3-axis magnetic actuation. Images retrieved from [49]

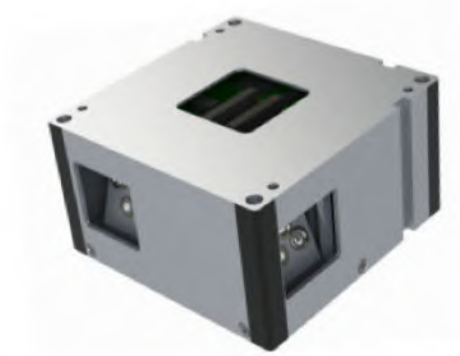


Figure 4.14: This Attitude Determination and Control System contains reaction wheels and can include some sensors for guidance functions as star trackers. Image retrieved from [51]

ADCS Subsystem		
	ISIS board	Maryland A. board
Mass (gr)	$\sim$ 196	694
Dimensions (mm)	95.9 x 90.1 x 17	100 x 100 x 516
Supply voltage (V)	5	5
Power consumption no actuation	175mW (@20°C)	0.82W
Power consumption full actuation	less than 1.2W (@20°C)	1.1-2.05W
Cost (Euros)	8000	more than 15000
TRL	9	9

Table 4.2: Comparative table of two ADCS boards.

Propulsion subsystem

The propulsion subsystem generally consists of thrusters, motors or other devices to place the satellite in the correct orbit once ejected from the launch vehicle, to perform orbital corrections and to modify the attitude of the satellite. This subsystem is critical because it can help to extend the satellite life by keeping it in its orbit or deorbiting after ending its mission life. In addition, when the satellite is part of a constellation, it is necessary to maintain a certain distance between satellites and this subsystem deals with such position corrections [52].

Some categories for propulsion are the chemical, electric, propellantless, solid, and hybrid propulsion [52]. Tables including technical details and describing technologies with different types of thrust corresponding to each of these categories are included on [47]. Not all small satellites include this subsystem, but it is essential to know that this subsystem offers benefit to the satellite life cycle and to its capability to achieve a mission.

Power supply subsystem

The power supply system for satellites consists of solar panels, rechargeable batteries, regulators with different output voltage levels, inverters, and a system to recharge the batteries. Solar panels can be flat for 3-axis stabilized satellites or cylindrical panels for spin-stabilized satellites [46].

Generally, the batteries have a longer life when their cycle of charge and discharge is longer and when the level of discharge of the batteries is lower. Batteries are usually connected with an unregulated line (batteries are in parallel to the solar array) or in regulated line with a regulation system between the solar array and the batteries [46].

The number of required solar cells by a satellite is given by

$$n = \frac{P}{\phi s \eta} \tag{4.2}$$

where P is the required generated power in Watts (W), ϕ is the solar flux in a normal direction to the solar cells in W/m^2, η is the efficiency of conversion associated to the cells, and s is the area of the surface of the solar cell in m^2. The energy in the form of solar radiation available when orbiting the Earth is about 1370 W/m^2, but it is necessary to consider in the design of the power system the eclipses and the time without solar radiation.

There are different kind of suitable batteries for nanosatellites, but lithium-ion batteries are the most popular. Those batteries have high specific energy (power per unit of mass) and energy density (power per unit of volume). The Lithium manganese nickel (LMC) battery is one of the preferred lithium batteries for aerospace applications with specific energy around 150 to 200 Wh/kg. A table comparing different lithium batteries and a performance analysis is provided at [53]. Tables and descriptions of different batteries, solar panels, and power management and distribution hardware is found at [48, Chapter 3]

Structural subsystem

The structural system weights around 7 % to 10 % of the satellite and some constraints for its design are the low mass, resistance to vibrations during the launch, resistance to cyclical changes in temperature and resistance to collision with charged particles and small objects in the space. Some of the preferred materials are aluminum alloys and some composite materials [46]. The structural system can be found in the market for some recommended altitudes and sometimes including solar panels. A discussion of the materials, weights and some commercial options of this subsystem is available at [48, Chapter 6], and techniques for the deployment of antennas and solar panels after the launch are addressed on [54].

Thermal control subsystem

There are two classical techniques for thermal control, the first is called passive thermal control and the second is called active thermal control. Passive thermal control consists of covering the satellite with layers of adequate materials to avoid extreme temperatures inside the satellite [46].

> **Lessons Learned 4.4**
>
> Passive thermal control looks adequate for nanosatellites since it can be achieved with layers of materials covering the structure to diminish the elevated and cyclical changes of temperature while the satellite is in operation instead of adding a thermal system adding more mass and volume.

Telemetry-command subsystem

The telemetry command subsystem is in charge of supervising and control the satellite. Telemetry refers to the communication with the ground station to give information about the health and current state of the nanosatellite while command refers to the received instructions from Earth to execute some task [46]. The control of the tasks and supervision is executed through an onboard computer, microcontroller or embedded system; onboard computing and options are discussed at [13] and at [48, Chapter 8].

4.3.4 Payload

The payload refers to the primary device of the satellite concerning the mission. In this case, the payload is a communication system to collect and transmit the measurements of the sensors on Earth.

> **Lessons Learned 4.5**
>
> Selection of protocols can profoundly influence the selection and operation of the payload and other subsystems. For example, selecting the TCP SNACK protocol, as proposed in Section 4.7, would help improving reliability during communication but more storage capacity would be required for a buffer than for other transport layer protocol, thus increasing the onboard requirements of the satellite.

Overview of an S band communication systems

Fig. 4.15 and Fig. 4.16 show two communication systems from IQ Space and Syrlinks for the S band. Details of this communication system are listed in Table 4.3. The transponder EWC31 is radiation hardened and designed to a two years lifetime in LEO. Those communication systems are compatible with patch antennas designed for them with gains of about 6 dB.

Figure 4.15: Commercial transceiver SLink by IQ Wireless.

Figure 4.16: Commercial transponder EWC31 by Syrlinks.

Three communication systems for the S band			
	SLink	Slink-Phy	EWC31
Mass (gr)	~ 420	< 190	< 400
Dimensions (mm)	$65 \times 65 \times 137$	$55 \times 55 \times 94$	$90 \times 96 \times 39$
Supply voltage (V)	7-18	7-18	8-18
Power consumption TX	8-12 W	4-8 W	7-11
Power consumption RX	3-5 W	3-4 W	1.5
Data rate uplink	30-200 kbps	up to 256kbps	up to 256kbps
Data rate downlink	0.6-4.0 Mbps	up to 20 Mbps	up to 2 Mbps
Data rate inter-satellite	27-150 kbps	N/A	
Supported Modulations	BPSK/QPSK/ 8PSK/QAM16	QPSK, BPSK	OQPSK/QPSK/ PCM/PM/SP-L
RF output	up to 27 dBm	up to 27 dBm	up to 33 dBm
TRL	9	8 (Dec. 2018)	9

Table 4.3: Details of a S band transceiver by IQ Space

4.4 Ground Infrastructure

The ground data system are divided into control centers and ground stations; contacts with the satellites and processing of the information takes place at those sites. The ground segment or ground stations refers to the terminals available for communication purposes with the satellite, and those terminals can be fixed, transportable or mobile. For small satellites such as nanosatellites, the control centers for the payload, spacecraft, and mission are usually at a single adapted room; however, ground architecture expands according to the complexity of the satellite missions [48]. The following list contains some essential elements associated with a ground station and a brief description of them.

- Parabolic antennas are common to the reception of the signal. Those antennas can operate with software and coupled steering systems to schedule and track the pass of the satellite. Typical commercial diameters for the S-band managed by Innovative Solutions In Space company start at more than 2 meters with gains above 15 dBi [55]. Fig. 4.17 shows two antennas for the S-band by Innovative Solutions In Space.

(a) Diameter of 3 m, gain of 35 dBi and a noise figure of 0.9 dB. Image retrieved from [56]

(b) Diameter of 3 m, gain of 31 dBi and a noise figure of 1.6 dB. Image retrieved from [57]

Figure 4.17: Receiver antennas for ground for the S band

- The receiver and transmitter equipment is required to receive and transmit data to the satellite. Its function is similar to the satellite transponders but with a higher RF output ranging in tens of Watts. Fig. 4.18 shows a receiver for the S-band and a transceiver to the VHF, UHF bands both commercialized by Innovative Solutions In Space.

(a) Transceiver for the VHF/UHF band. Image retrieved from [58]

(b) Receiver for the S band. Image retrieved from [59]

Figure 4.18: Two receivers for ground for the VHF and S band

- Low noise amplifier. The signal from the satellite arrives at its lowest level to the receiver antenna at the ground making it more vulnerable to noise distortion. The function of a low noise amplifier (LNA) is to amplify the received signal without adding more noise in the process; this means a high gain and a very low noise figure is desirable. Fig. 4.19 shows a LNA by Norsat for the Ka-band with a noise figure of 1.5 dBm, a gain of 55 dB and dimensions of $116 \times 49 \times 40\text{mm}^3$. The description of a LNA for the S-band with similar dimensions, a minimum gain of 50 and a lower noise figure ranging from 45 K to 70 K is available at [60]

Figure 4.19: Norsat Low Noise Amplifier with gain of 55 dB and a noise figure of 1.5 dB. Image retrieved from [61]

- Transmission lines. Even though transmission lines look as standard equipment they take relevance as closer they are to the receiver antenna. The closer and extensive the transmission lines are to the receiver antenna the more noise temperature could be added to the overall receiver system, decreasing the figure of merit of the overall receiver system.

Lessons Learned 4.6. Ground segment and ground installations.

A single room equipped with commercial-off-the-shelf (COTS) technology can provide an adequate platform for managing data retrieved from a small satellite and the Telemetry, Track and Command (TT&C) actions for the satellite and its payload can be executed from a single computer. For multiple satellites, a more complex mission or to increase the bandwidth and throughput more antennas should be considered and also a more complex set of installations.

4.5 Coverage

Permanent coverage of a region is achievable with small satellites, a few tens can be enough to cover some area, but the number of required small satellites can vary from hundreds to thousands to provide global coverage. By using big satellites in the Low Earth Orbit (LEO) global coverage is possible with some tens of satellites, e.g., the Iridium constellation employes 66 big LEO satellites to provide coverage at any place of the globe [17].

Simulations in GMAT were performed to evaluate the inclined orbit at 30° described in Section 3.2.1. A ground station was simulated in Monterrey, Mexico, with coordinates 25.6563 North, 100.28708 East, and 520 meters of ellipsoidal height to establish contact with the satellite. The available time for transmitting and receive a signal was measured for the orbit inclined at 30° varying the parameter of minimum elevation from 8° to 11°. This minimum elevation is the elevation above the horizon when the satellite can effectively transmit to the ground station; this elevation depends on factors such as the irradiated power, and the link budget (further described) helps to determine this amount.

Fig. 4.20 shows the available time for communication in seconds with a different parameter of minimum elevation for seven different days. Figs. 4.21 and 4.22 contain boxplots comparing the duration of contacts of the inclined and polar orbit in seconds for one day and seven days. The number of contacts and its length vary according to the chosen orbital inclination and the box plots helps to compare the polar and inclined orbit and the effect of the minimum elevation angle. The duration of the contacts represent the maximum achievable time for communication at a given elevation angle when the channel and finally the link budget allows it. Table 4.4 and 4.5 contains more information about the number of contacts, mean, median and standard deviation for the periods of contact of the boxplots.

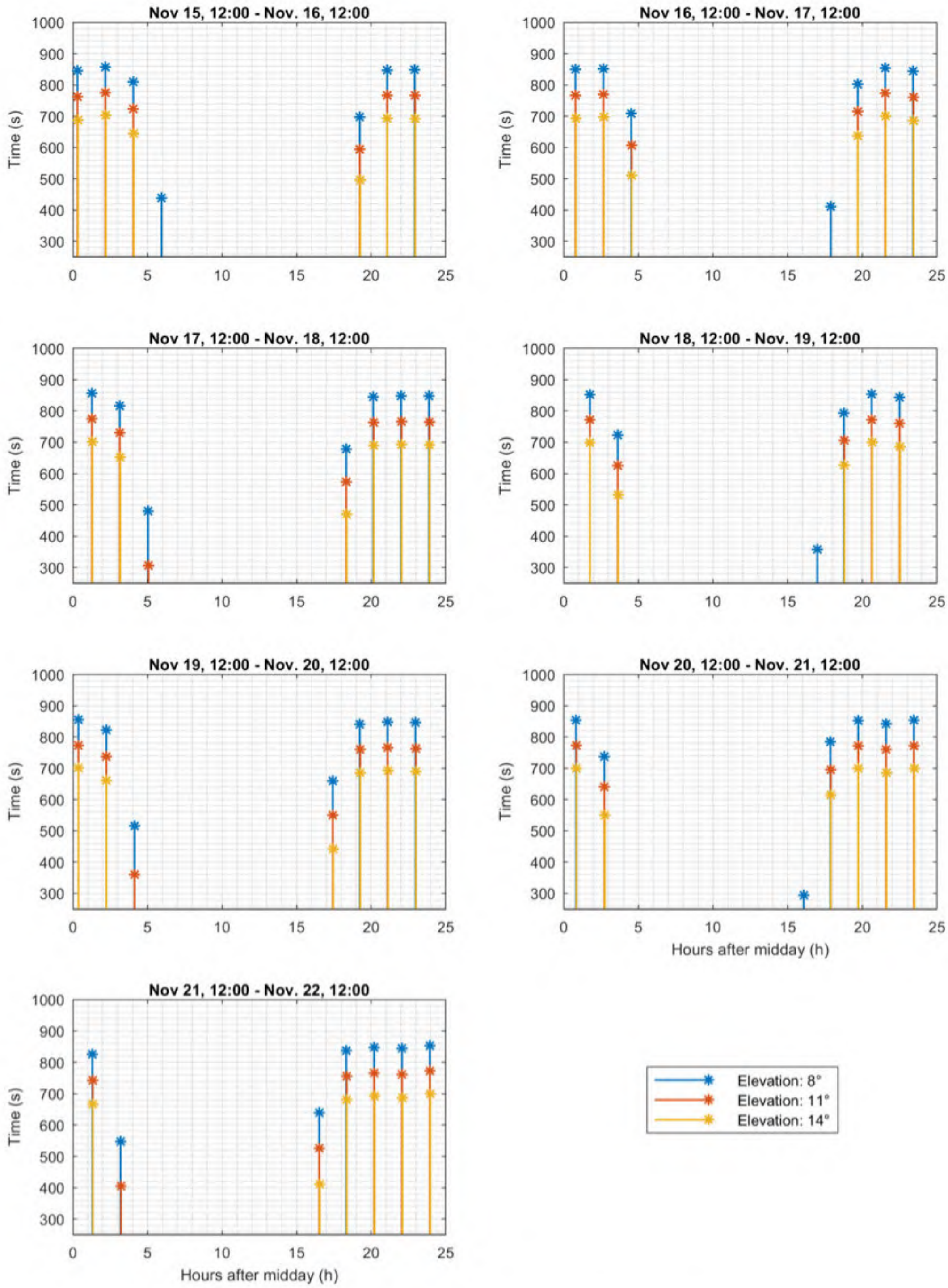


Figure 4.20: The minimum elevation starts at 8°, 11° and 14° and the communication time is given in seconds. When the required elevation angle increases the available time for communication reduces.

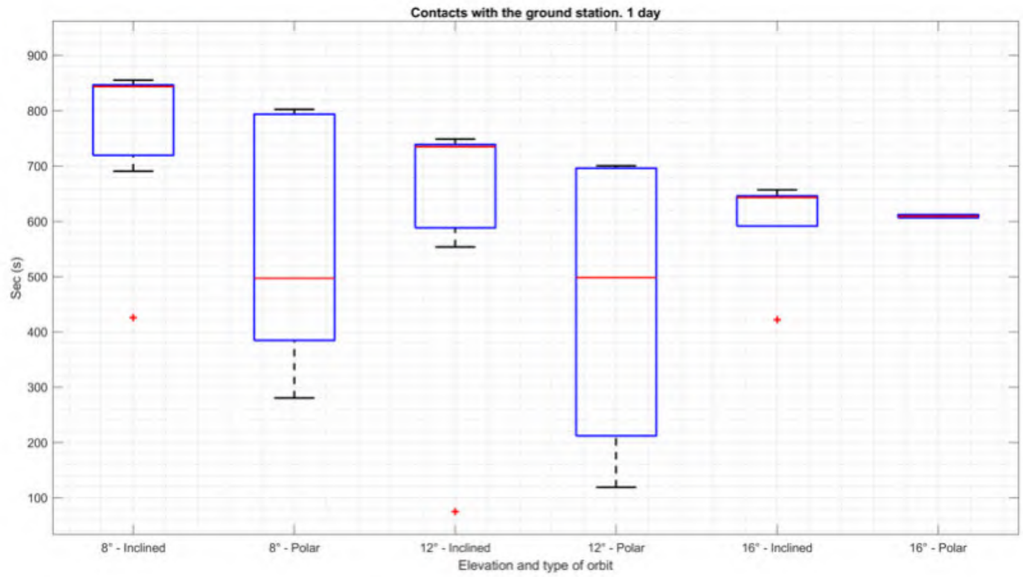


Figure 4.21: Those plots show the contact duration for one day of the two orbits defined in Section 3.2 with the ground station defined in this section.

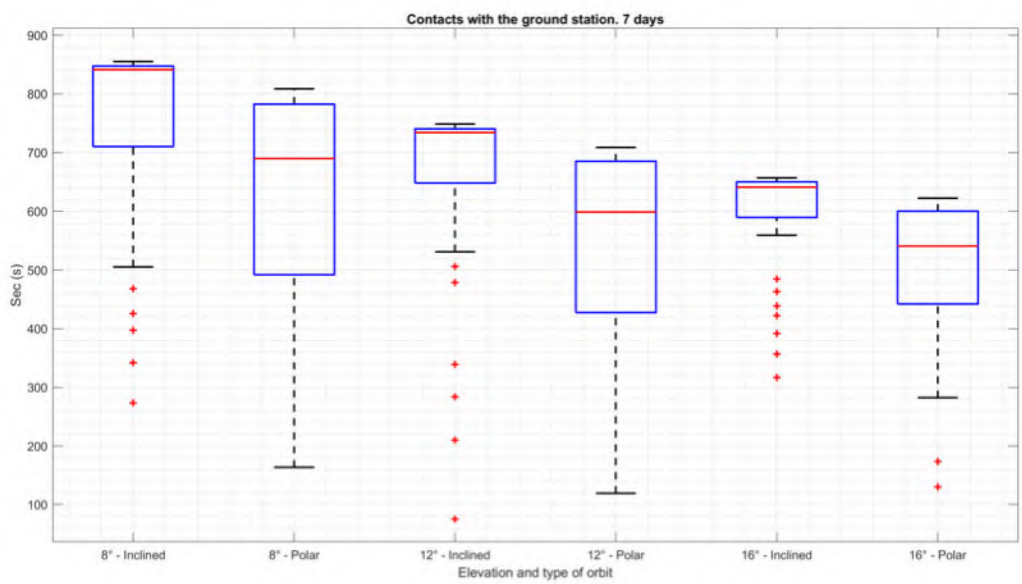


Figure 4.22: Those plots show the contact duration for seven days of the two orbits defined in Section 3.2 with the ground station defined in this section.

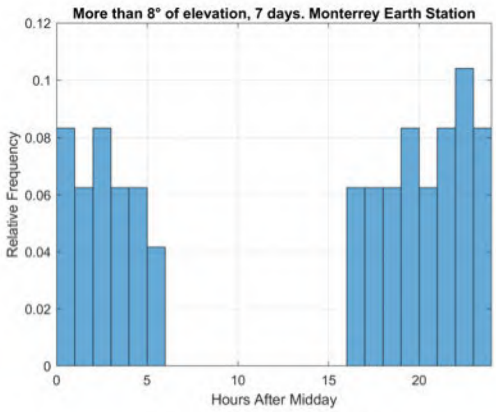
Simulation results, contacts per one day					
Inclination	Elevation	Contacts	Mean (s)	Median (s)	SD (s)
30 deg	8 deg	7	759.0	843.7	157.8
98 deg	8 deg	5	558.0	497.2	231.2
30 deg	12 deg	7	611.7	735.0	246.1
98 deg	12 deg	4	454.2	498.5	289.6
30 deg	16 deg	6	600.6	643.3	90.3
98 deg	16 deg	2	609.3		

Table 4.4: Contact information. The mean, median and standard deviation of the contacts are given in seconds.

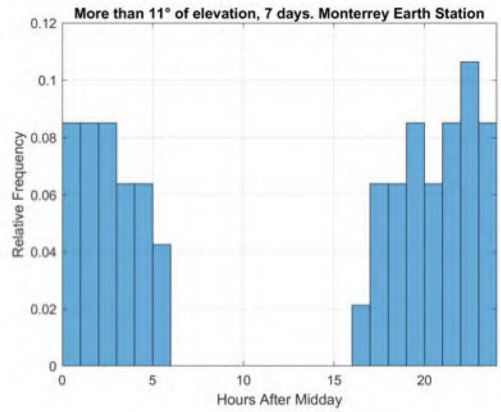
Simulation results, contacts per seven days					
Inclination	Elevation	Contacts	Mean (s)	Median (s)	SD (s)
30 deg	8 deg	48	755.0	841.4	154.2
98 deg	8 deg	29	627.0	689.9	181.9
30 deg	12 deg	45	656.4	734.2	155.9
98 deg	12 deg	25	547.0	598.8	170.4
30 deg	16 deg	41	596.9	641.2	91.6
98 deg	16 deg	21	493.3	540.9	144.6

Table 4.5: Contact information. The mean, median and standard deviation of the contacts are given in seconds.

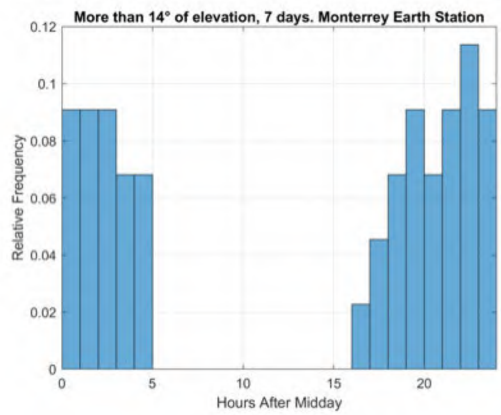
Even though the available time for communication with the satellite sums an average between 1 and almost 2 hours per day for any of simulated the seven days, it is clearly in Fig. 4.20 that there are hours without coverage for all the seven days. This period without coverage is between the 5 and 20 hours after the midday (5 pm to 8 am) for those simulated days. Fig. 4.23 shows the normalized histograms of the hours with available communication for the plots shown in Fig. 4.20; those histograms show that there are hours without contact with the satellite for several days.



(a) Elevation of 8°.



(b) Elevation of 11°.



(c) Elevation of 14°.

Figure 4.23: Normalized histograms for the same simulation of the results shown in Fig. 4.20 which shows the frequency of hours at which communication started to be possible at the indicated elevation angle.

The distribution of hours with available communication tends to be uniform after several days as shown in Fig. 4.24. If the number of satellites and orbital planes increases then will be more hours with coverage in a single day. Considering the time of coverage that is provided by only one small satellite looks feasible that tens of satellites should be enough to provide coverage at all time with a minimum elevation angle close to 8°.

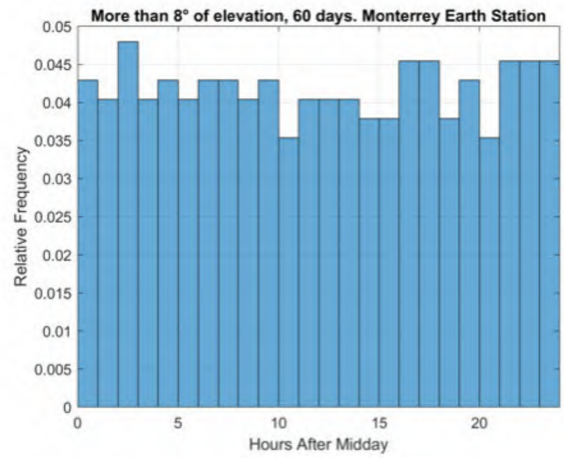


Figure 4.24: Hours with coverage in a period of 60 days when the minimum elevation is set to 11°.

Simulations were performed in STK to find scenarios of permanent coverage. A proposed array of 30 satellites at an altitude of 1000 km offers at least one satellite always visible from the proposed Earth station location with an elevation angle of 8°. Fig. 4.25 shows the available time for contacts of those 30 satellites with the ground station. In this case, the Earth station always sees at least one communication satellite (and sometimes more than one), meaning that if the link budget allows a minimum elevation angle of 8° communication is feasible between a satellite and the ground station at any moment of the day with this proposed array. The small satellites, distributed in five orbital planes, follow each other with a separation of 35° in its true anomaly, a full description of the array of satellites is available at Appendix 1.

Fig. 4.25 shows the distribution of 30 satellites to provide continuous coverage to the Earth station. At the left of the vertical axis is a name for each of the 30 small satellites starting with a number that represents one of the five orbital planes simulated and then a number that serves as an identifier of the spacecraft within the orbit. A bounded horizontal line withing the graph indicates the available periods for contact between each satellite and the ground station. Figs. 4.26, 4.29 and 4.32 contain similar information than Fig. 4.25 but for elevation angles of 12 °, 16°, and 20°.

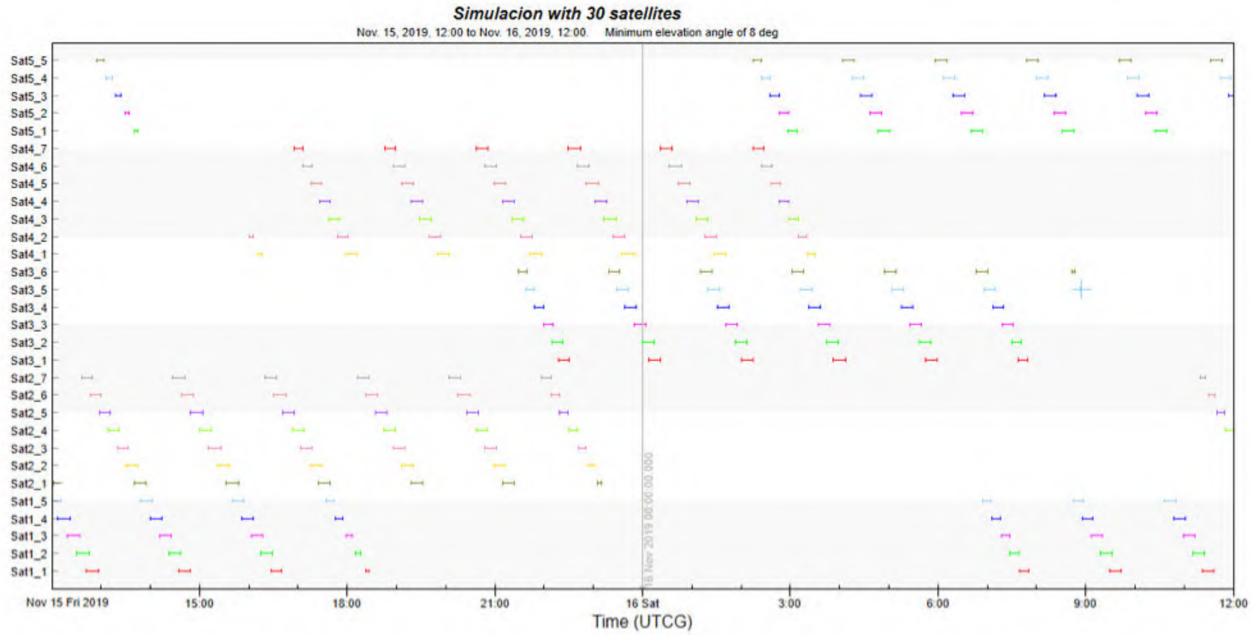


Figure 4.25: Distribution of 30 satellites to provide continuous coverage to the Earth station with and elevation angle set at 8°.

As mentioned in the previous paragraph, Fig. 4.25 shows a scenario in which at least one satellite is always visible from the ground station with a minimum elevation angle of 8°; however, if communication is only feasible at a higher elevation angle the previous array of 30 satellites stop offering continuous availability to the Earth station and more satellites would be required. Simulated satellites have even separation as described in Appendix 1, and more satellites can be added in each orbital plane to increase redundancy or coverage at a higher elevation angle. Fig. 4.26 shows the same array of satellites than in Fig. 4.25 but with a higher elevation angle of 12°.

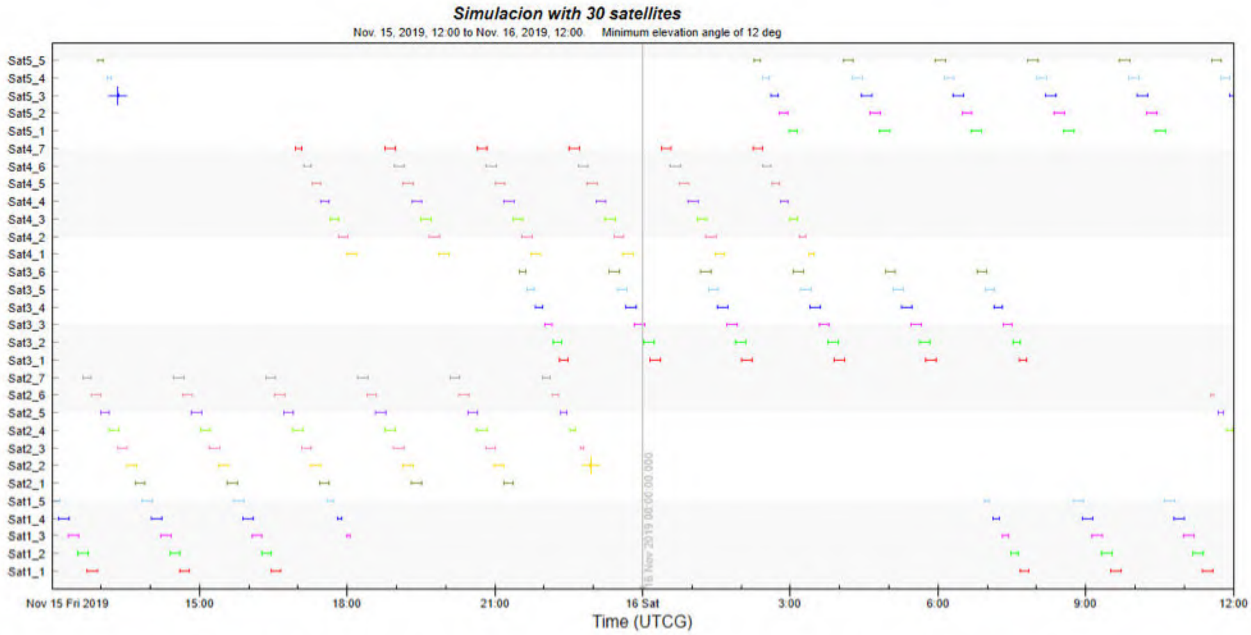


Figure 4.26: Distribution of 30 satellites to provide continuous coverage to the Earth station with and elevation angle set at 8°.

Given the scale of the graph contained in Fig. 4.26 it is hard to see that the period that each satellite is available for the ground station has decreased or even disappeared in comparison with the results offered at Fig. 4.25. Table 4.6 provides some numerical results derived from the simulations. Periods with availability to a satellite are shown in Fig. 4.27 and the intervals without availability from the ground station for the given elevation angle are shown at Fig. 4.28. For this proposed array of satellites and with a required minimum elevation of 12° the available time for establishing contact with at least one satellite corresponds to 99.46% of the day

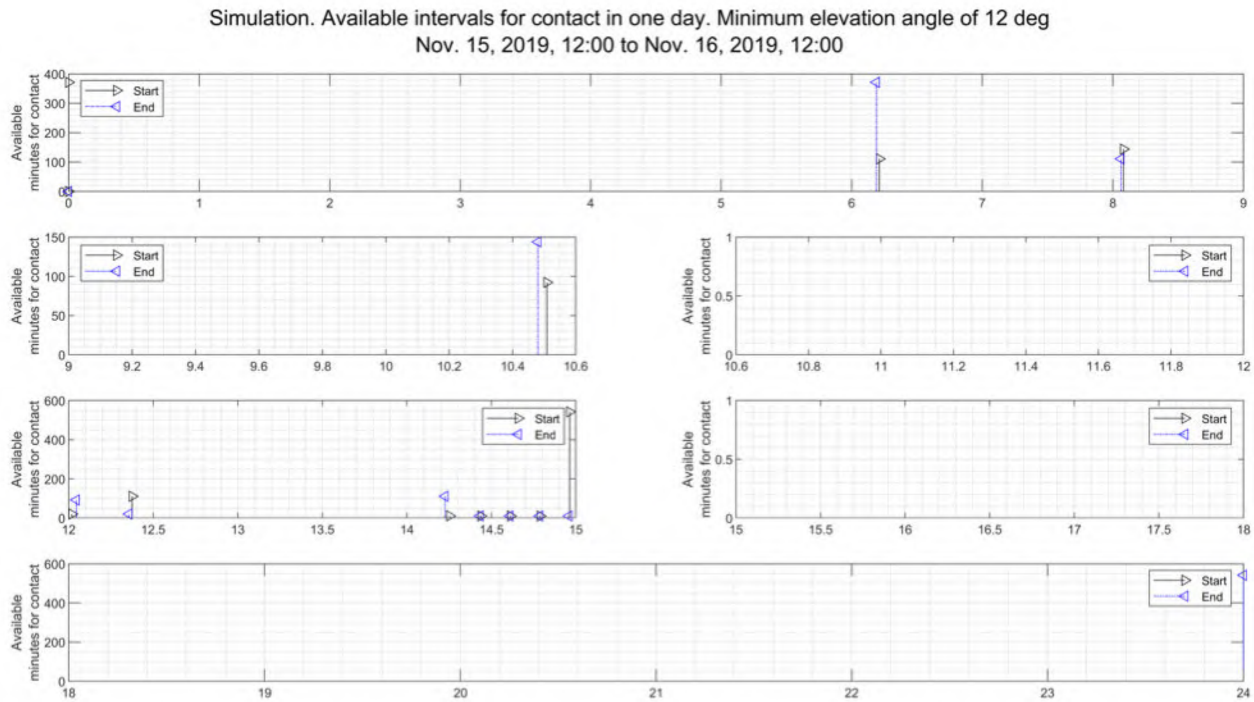


Figure 4.27: This figure shows the periods at which contact with at least one the satellite of the proposed array of 30 satellites is not possible.

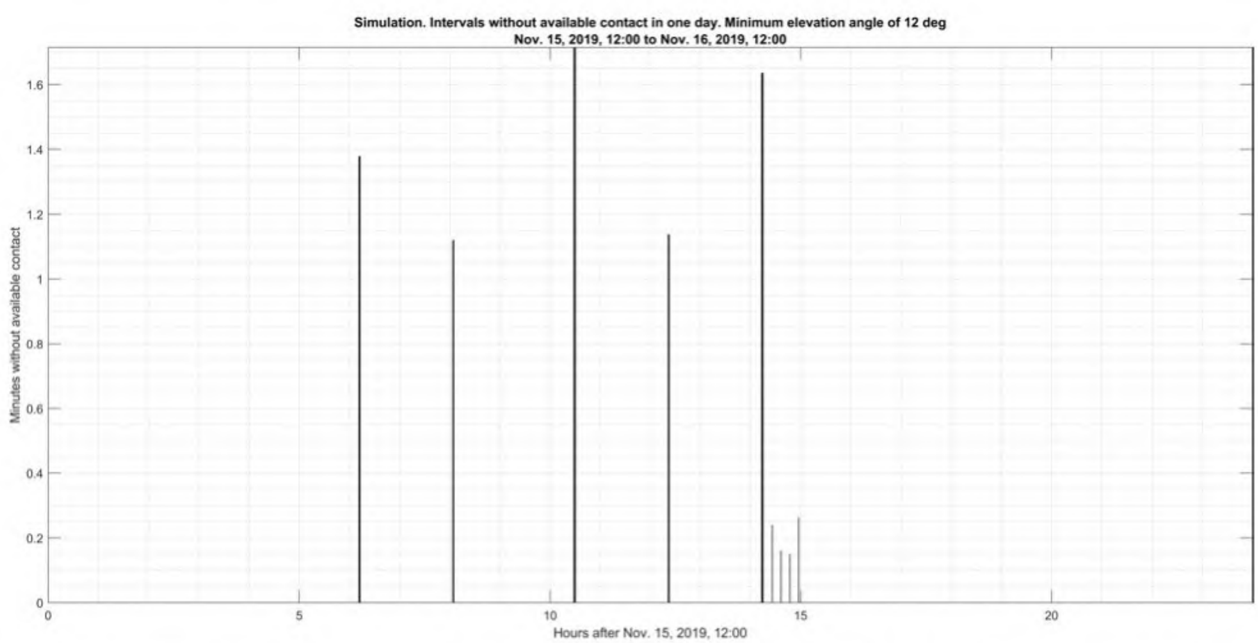


Figure 4.28: This figure shows the periods at which contact with at least one the satellites of the proposed array is not possible.

For the periods when it is not possible to establish direct communication with the satellite more satellites could be added to cover those gaps. A solution without adding more satellites or modifying the structure of transmission/reception (such as increasing transmission power) could be adding a device acting as a relay; for example, adding an aircraft or drone as shown in 2.6, or communicate through a subnet to an in-range transmitter or receiver device.

Fig. 4.29 and Fig 4.30 shows the periods of contact of the 30 satellites. Those periods provides coverage during 99% of the day with a minimum elevation angle of 16°. Fig. 4.31 shows the periods at which communication is not possible. Similarly, for an elevation angle of 20°, Fig. 4.32 and Fig 4.33 shows the periods of contact and Fig. 4.31 shows the periods at which communication is not possible, the total available periods for contact, in this case, are equivalent to 84.23% of the day.

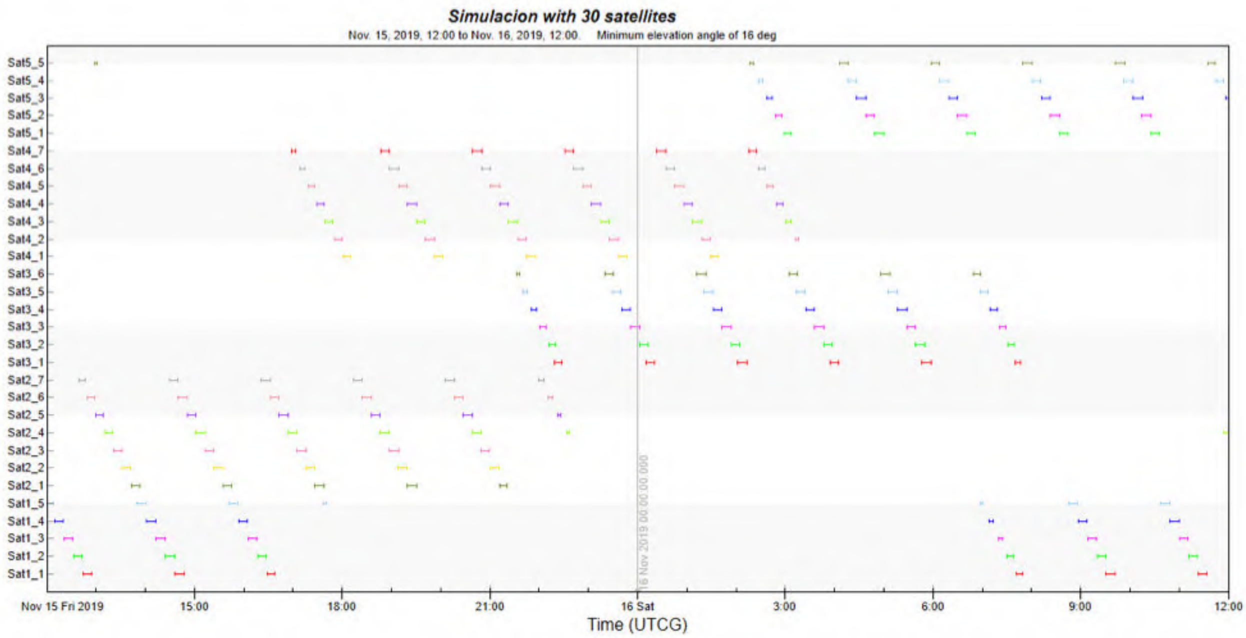


Figure 4.29: Distribution of 30 satellites to provide continuous coverage to the Earth station with and elevation angle set at 8°.

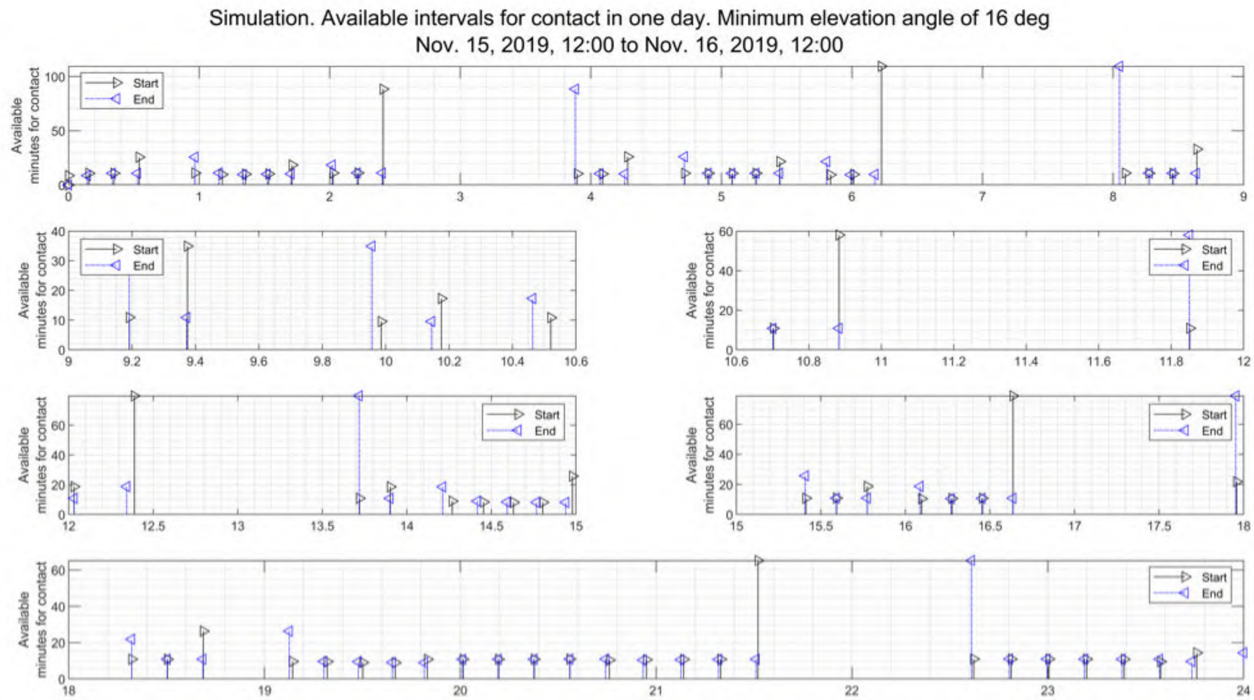


Figure 4.30: This figure shows the available periods for contact with the satellite for the proposed array of 30 satellites with an elevation angle of 16°.

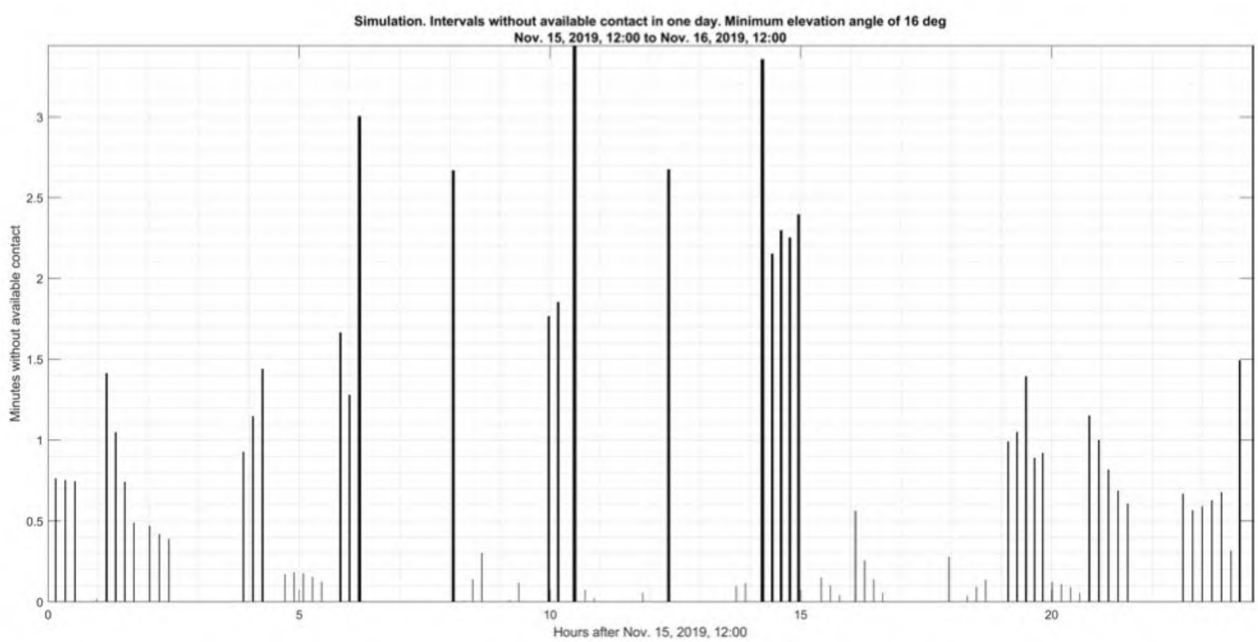


Figure 4.31: This figure shows the periods at which contact with at least one the satellite of the proposed array of 30 satellites is not possible.

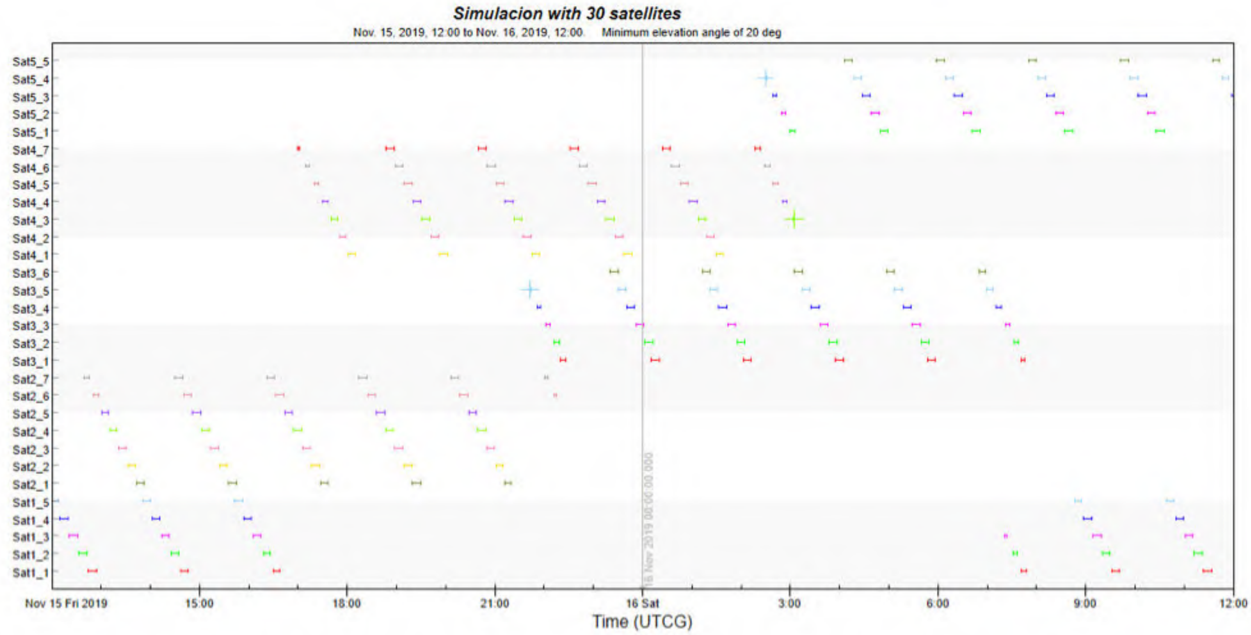


Figure 4.32: Distribution of 30 satellites to provide continuous coverage to the Earth station with and elevation angle set at 8°.

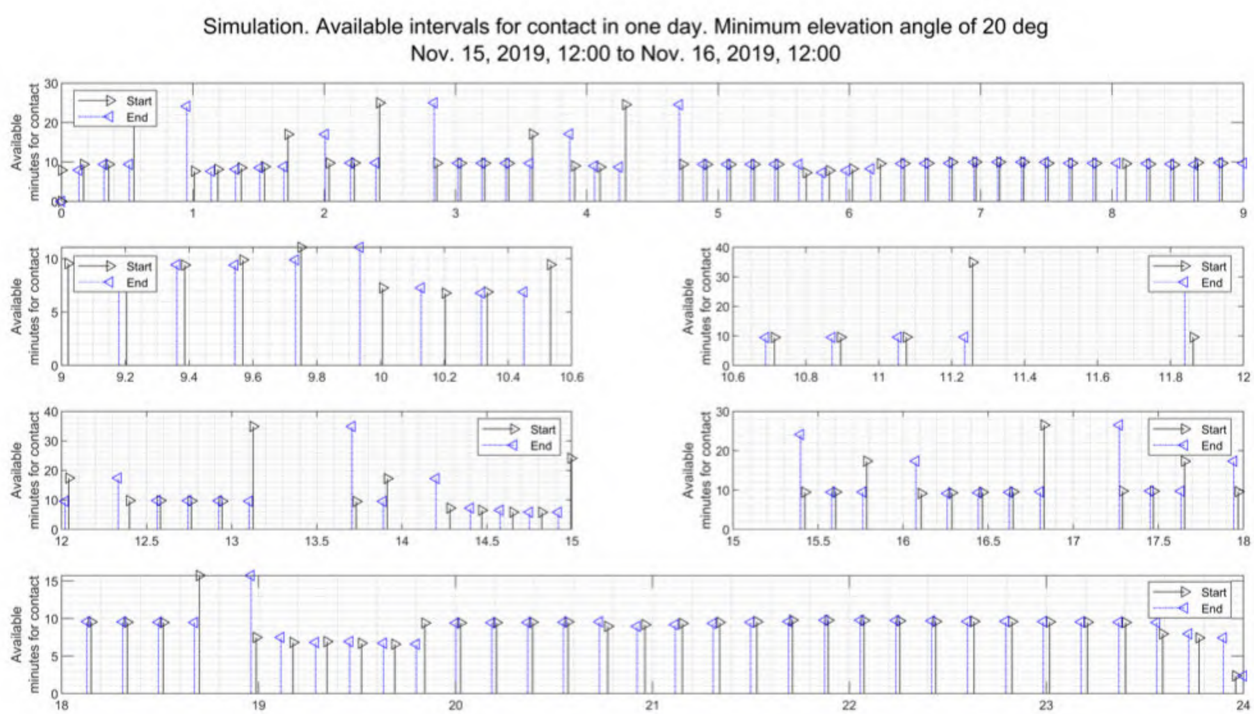


Figure 4.33: This figure shows the available periods for contact with the satellite for the proposed array of 30 satellites with an elevation angle of 20°.

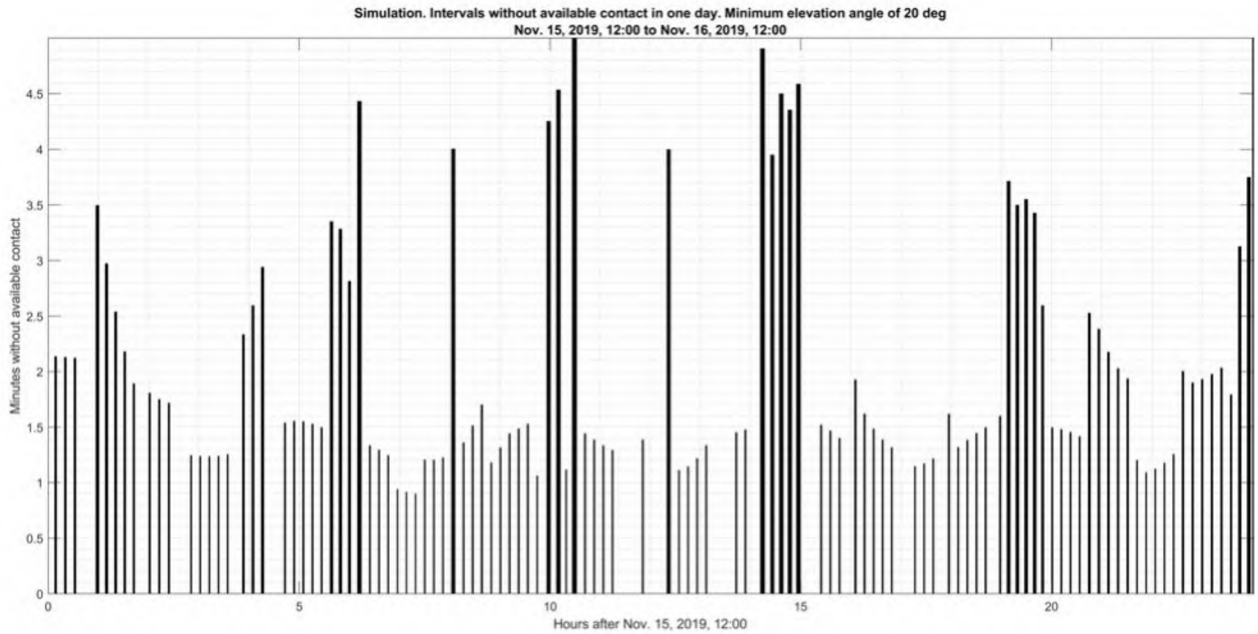


Figure 4.34: This figure shows the periods at which contact with at least one the satellite of the proposed array of 30 satellites is not possible.

Simulation results, available time per one day			
Inclination	Time per day, at least one satellite is visible from the Earth station	Time withouth available access at least one satellite	Related Figures
8°	24.00 hours 100% of the day	0.00 hours 0.00% of the day	Fig. 4.25
12°	23.87 hours 99.46% of the day	0.13 hours 0.54% of the day	Fig. 4.26, 4.27, 4.28
16°	23.00 hours 95.83% of the day	1.00 hours 4.17% of the day	Fig. 4.29, 4.30, 4.31
20°	20.24 hours 84.33% of the day)	3.76 hours 15.67% of the day	Fig. 4.32, 4.33, 4.34

Table 4.6: Contact information.

Statistics of individual contacts of the satellites						
Incl.	Sum of individual contacts	Number of contacts	Minimum duration	Maximum duration	Mean contact duration	Median
8°	41.69 hours	197	81.59 s	865.91 s	761.92 s	849.90 s
12°	34.51 hours	186	83.92 s	759.03 s	667.94 s	741.44 s
16°	28.59 hours	177	91.15 s	666.78 s	581.56 s	647.53 s
20°	23.72 hours	140	90.49 s	587.25 s	511.38 s	566.31 s

Table 4.7: Contact information

4.6 Physical Layer

4.6.1 Channel description

The free-space loss L_{FS} or free-space attenuation refers to the power attenuation suffered by a signal while traveling from one isotropic antenna to another [19].]. For satellite transmission, it varies according to the wavelength, λ, related to the frequency band used for transmission and the altitude R of the satellite.

Levels of attenuation are shown in Fig. 4.35 ffor some LEO satellite altitudes in the K and Ka bands; for a geostationary satellite, operation in the K or Ka-band would represent a free-space attenuation above of 200 dB. The free-space attenuation which comes from the analysis of the radiated and received power in an isotropic antenna is shown in the following equation:

$$L_{FS} = (4\pi R/\lambda)^2 \tag{4.3}$$

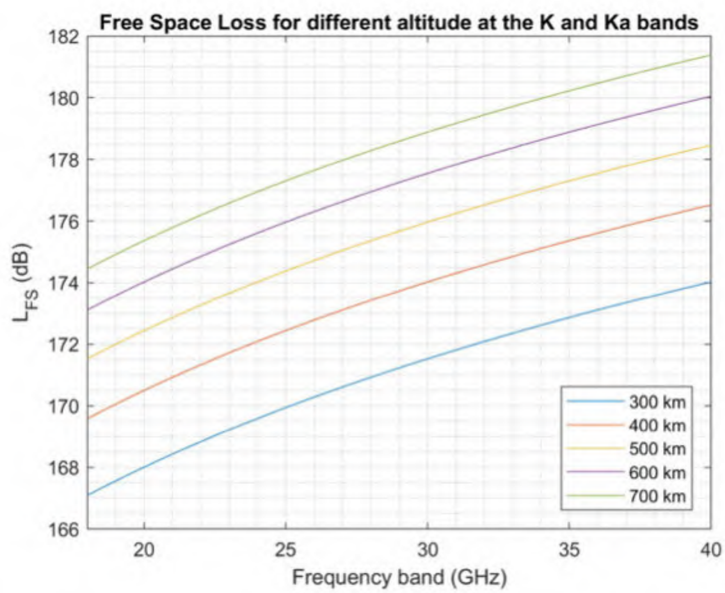


Figure 4.35: The distance and the selected frequency band are factors that introduce attenuation to the transmitted power. Distance between the isotropic antennas on earth and at the satellite must take consideration of the orbit altitude and the angle of elevation to the satellite.

Noise temperature is used instead of the noise power N since using it does not require the specifying of the bandwidth of interest. Important relations of the noise temperature are shown in the following equation.

$$N = kTB \tag{4.4}$$

$$N_O = N/B \tag{4.5}$$

The term k is the constant of Boltzmann (1.38×10^{-23} Joule/Kelvin), N_O is the noise spectral density (W/Hz), N is the noise power and B the bandwidth. The noise temperature, T, is expressed in Kelvin.

Noise temperature appears in the receiver and at the antenna. When the noise temperature is low in the section connecting those sections the noise temperature of the receiving or transmitting system can be simplified as the individual sum of the noise temperature at the antenna (T_A) and the noise temperature at the receiver (T_R). The noise temperature at the receiver (T_R) is usually much lower than 290K, and it is generated by the internal noise and the gain of the amplifier [62].

The noise temperature at the antenna is composed of terrestrial and extraterrestrial noise. Terrestrial noise tends to be the most critical part since it tends to be much higher. Some situations like the antenna intercepting the Sun can generate a large quantity of noise coming from the space, but there are recommendations of the ITU to deal with this case and similar ones [62].

ITU recommendations for transmission impairments

Additional attenuations occur at low altitudes by clouds and fog as described at [63] and at [64], also by the rain as described in the following section and according to [65]. Gasses are also a factor of attenuation, especially for the Ka-band as mentioned in section 4.3.2. Fig. 4.11 previously introduced shows the attenuation effects of gasses for different frequencies; usually, gas attenuation is mainly occasioned by water vapor and oxygen and a procedure to calculate it is provided at [66]. The sky noise is a noise contribution which affects the receiver and involves noise added by the sun, the moon, distant stars and in minor amount by galactic noise, which is characterized as a uniformly distributed noise at all the frequencies. Table 4.8 list relevant ITU recommendations of attenuation to consider in satellite communications.

Relevant ITU Recommendations	
ITU Recommendation	Issue
ITU-R P.372-13	Radio noise
ITU-R P.531-13	Ionospheric propagation
ITU-R P.676-11	Attenuation due to atmospheric gasses
ITU-R P.838-3	Rain model for prediction of the attenuation
ITU-R P.840-7	Attenuation due to clouds and fog

Table 4.8: Relevant ITU Recommendations for satellite communications systems

4.6.2 Channel estimation

Free-space attenuation, LFS, shadow fading, and multipath fading causes attenuation and distortion to the signal at the receivers. Multipath fading refers to the received signal containing additional components originated by reflection or echoes of the original signal in the surroundings while shadowing refers to affections by physical obstacles the propagation [67]. The Log-normal channel and the Rice channel are the most common scenarios proposed when working with LEO satellites [17].

Rice Channel

The distribution of Rice is useful to describe the received signal in an environment that produces echo or reflection of the transmitted signal such that the receiver gets not only the original one but a superposition of the original with copies of it with a distortion in amplitude, frequency, and phase [35]. The received signal in a Rice channel can be modeled as

$$r(t) = s(t) + d(t) \tag{4.6}$$

where the component of the direct signal, $s(t)$, and the component produced by multipath fading, $d(t)$ have a random Rayleigh distribution envelope [68, Chapter 2]. Using in phase and quadrature representation the received signal can be expressed as

$$r(t) = v_I(t)\cos 2\pi f_c t + v_Q(t)\sin 2\pi f_c t + D_I(t)\sin 2\pi f_c t + D_Q(t)\sin 2\pi f_c t \tag{4.7}$$

where the in-phase direct component and direct the quadrature component are $v_I(t)$ and $v_Q(t)$, and the in-phase and quadrature components of the reflected signals are $D_I(t)$ and $D_Q(t)$ [68, Chapter 2]. The signal envelope for this case is given by

$$R(t) = \sqrt{[v_I(t) + D_I(t)]^2 + [v_Q(t) + D_Q(t)]^2} \tag{4.8}$$

and has a Rice probability density function given by

$$p(R) = 2R\sqrt{1+K}\exp\left(-K - (1+K)R^2\right) I_O(2R\sqrt{K(K+1)}) \tag{4.9}$$

where K is the Rice factor that represents the ratio of the direct component of the received signal to the multipath power components of the received signal; and I_O is a modified Bessel function [68, Chapter 2].

Rayleigh Channel

The Rayleigh distribution is useful in cases with absence of a direct line of sight between the satellite and the receiver. The Rayleigh distribution corresponds to a particular case of the Rice distribution, and it occurs when the received signal is mainly compound by waves of the original signal altered by its encounter with some obstacle and then with a lower power level [35]. The probability density function for signal envelope, ρ is

$$p(\rho) = \frac{\rho}{\sigma^2}\exp\left(-\frac{\rho^2}{2\sigma^2}\right) \tag{4.10}$$

where $2\rho\sigma^2$ stays for the mean signal power.

Log-normal fading Channel

The log-normal distribution is useful when there are moderate variations in the received power of the transmitted signal occasioned by shadowing [35]. The probability density function for the received power is given by

$$p(z) = \frac{1}{z}\frac{1}{\sqrt{2\pi\sigma^2}}\exp\left[\frac{(\ln z - m)^2}{2\sigma^2}\right] \tag{4.11}$$

where m and σ^2 are the mean and variance of z and $w = \ln z$ corresponds to the received power value.

The Corazza-Vatalaro Model

A proposal for modeling the channel for satellite communications in non-geostationary orbit was published in 1994 by Corazza and Vatalaro [69] considering the Rice and lognormal channel. Recent publications like [17] and [33], among others, give particular importance to this statistical channel model, especially when using nanosatellites. The probability density function of the received signal envelope is given by

$$p(r|S) = 2(K+1)\frac{r}{S^2}\exp\left[-(K+1)\frac{r^2}{S^2} - K\right] I_0\left(2\frac{r}{S}\sqrt{K(K+1)}\right) \quad (r \geq 0) \tag{4.12}$$

where $r$corresponds to the received signal envelope, S corresponds to the shadowing, K is the Rice factor, and I_0 corresponds to the zero order modified Bessel function. The shadowing, S, follows a log-normal distribution with a probability density function given by

$$p_s(S) = \frac{1}{\sqrt{2\pi}h\sigma S}\exp\left[-\frac{1}{2}\left(\frac{\ln S - \mu}{h\sigma}\right)^2\right] \quad (S \geq 0) \tag{4.13}$$

where the mean and variance are represented by μ and $(h\sigma)^2$, and $h = (\ln 10)/20$.

4.6.3 Link budget calculations

The link budget helps to evaluate the quality of the link, including the uplink (to the satellite) and the downlink (from the satellite). The signal-to-noise ratio (S/N), the energy-per-bit to noise density (Eb/No) and the bit error ratio (BER) are two parameters that help to evaluate the quality and reliability of the satellite communication [67].

Modulations, error correction and encoding are some of the communication strategies to choose according to the results of the link budget. The needed equipment can also be selected after an analysis of the link budget to meet the desired specifications [67].

Basic link budget for the uplink

The received power at the satellite is one of the foremost parameters to be aware, and it is defined as

$$P_R = P_T + G_T + G_R - L_{FS} - L_{Other} \quad [dB] \tag{4.14}$$

where:

P_R: received power.

P_T: transmitted power.

G_T: the gain of the transmitter antenna. For a parabolic antenna, P_R is given by

$$G_T = 10 \log \left[\eta_A \left(\frac{\pi\ d}{\lambda} \right)^2 \right] \quad [\text{dBi}] \tag{4.15}$$

where λ corresponds to the wavelength of the transmitted signal, d corresponds to the diameter of the antenna, and η_A to the antenna aperture efficiency.

G_R: gain of the receiver antenna

L_{FS}: Free-space attenuation or free path loss.

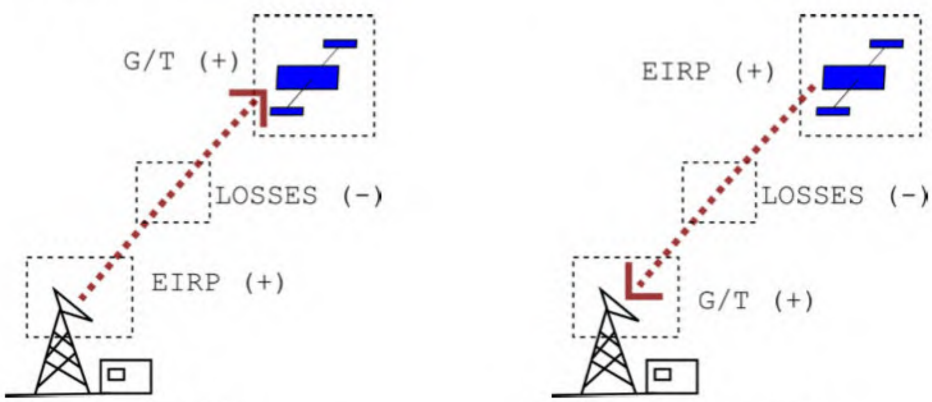
$$L_{FS} = 20 \log \left(\frac{2\pi r}{\lambda} \right) \quad [\text{dB}] \tag{4.16}$$

where r corresponds to the path length to the satellite in meters.

L_{OTHER}: Other losses such as rain, gas and oxygen attenuation.

EIRP: $P_T + G_T$

The previous equation also applies to calculate the received power at the ground station; however, receiver power varies from the uplink to the downlink mainly because of the different size and gain of the antennas at the ground and at the satellite, and to the different frequencies of transmission. The uplink frequency tends to be higher than the one for the downlink as shown in Fig. 4.10. Fig. 4.36 shows a simple example of the received power for the uplink and downlink.



(a) Uplink (b) Downlink

Figure 4.36: Received power for the uplink and downlink

One of the main parameters derived from the link budget is the carrier-to-noise ratio, and it is defined similarly to 4.14 as

$$\frac{C}{N} = EIRP + G_R - L_{TOTAL} - k - T_S - B_N \quad [dB] \tag{4.17}$$

where

L_{TOTAL}[dB]: $L_{FS} + L_{OTHER}$

T_S[dB/K]: system noise temperature

B_N[dB/Hz]: bandwidth of the noise

k[db/Hz]: constant of Boltzmann

$$k = 10\log(1.38 \times 10^{-23} = -228.6 \quad [dB/Hz]$$

The previous equation introduces the noise temperature system, which will help to define the noise figure of some device and the figure of merit of the receiver. The system noise temperature refers to the total noise produced from the addition of the noise of each device in the line of communication from the transmitter to the receiver. The system noise temperature also includes sky noise temperature.

The receiver antenna is usually the reference point to translate all the noise contributions of the different devices in the line of communication. Given that the power of the transmitted signal is at its lowest level at the receiver, the noise contributions are more critical at this point.

Several sources as [35] and [67] discuss the noise temperature system formulation from the devices that are part of the path of communication. Those formulations state clear that the further away from the receiver, generally, the less noise contribution to the total noise temperature system each device adds. The structure of the receiver where the system noise temperature, T_S, typically found as in Fig. 4.37 and equation 4.18 shows the way to calculate it

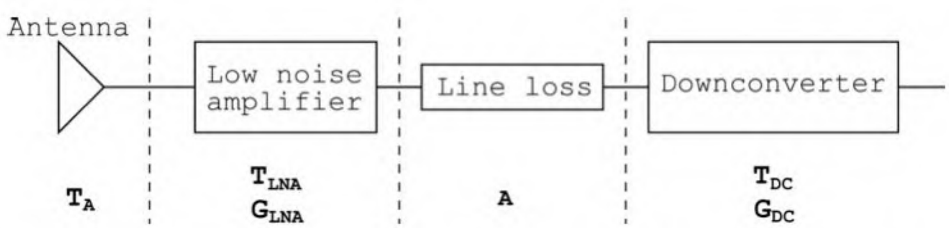


Figure 4.37: A receiver structure to calculate the noise temperature system.

$$T_s = 10\log_{10}\left(T_{Antenna} + T_{LNA} + \frac{290(L-1)}{G_{LNA}} + \frac{l\ T_{DC}}{G_{LNA}}\right) \quad \text{[dB]} \tag{4.18}$$

where:

T_a[K]: is the antenna temperature, and common values ranges according to the frequency bands, for example, for the Ka-band takes values around 50K to 80K.

T_{LNA}[K]: equivalent noise temperature of the low noise amplifier.

$$T_{LNA} = 290\left(10^{\frac{NF}{10}} - 1\right) \quad [K] \tag{4.19}$$

where NF correspond to the noise figure of the low noise amplifier in dB.

L[K]: the term L is associated to the line loss in dB of the cable connecting the low noise amplifier to the downconverter

$$L = 10^{\frac{A}{10}} \quad [\mathrm{K}] \tag{4.20}$$

where A correspond to the loss in dB of the cable.

G_{LNA}[K]: the value for the gain of the low noise amplifier.

$$G_{LNA} = 10^{\frac{NF}{10}} \quad [\mathrm{K}] \tag{4.21}$$

where NF correspond to the noise figure of the low noise amplifier.

T_{DC}[K]: equivalent noise temperature of the downconverter.

$$T_{DC} = 290\left(10^{\frac{NF}{10}} - 1\right) \quad [K] \tag{4.22}$$

where NF correspond to the noise figure of the downconverter in dB.

The noise figure helps to measure the noise produced by some device in the route of communication and can be visualized as a ratio of the power to noise ratio at the input and the output of the device as in the following equation

$$NF = \frac{\frac{P_{in}}{N_{in}}}{\frac{P_{out}}{N_{out}}} \tag{4.23}$$

The noise figure for a amplifier or device is

$$NF = 10\log\left(1 + \frac{t_e}{t_o}\right) \quad \mathrm{dB} \tag{4.24}$$

where t_e is the equivalent noise temperature associated with the device in K and t_o corresponds to an input reference temperature, usually set at the value of 290K. The following equation describes the noise figure of the receiver in terms of the noise temperature system

$$NF_R = 10\log\left(1 + \frac{t_s}{290}\right) \quad \mathrm{dB} \tag{4.25}$$

where t_s is the noise temperature system in K instead of dB.

Another parameter related to the system noise temperature is the figure of merit, G/T. The parameter G/T specifies the efficiency of a receiver or its quality, and it is defined as the ratio of the gain of the receiver antenna to the receiver system noise temperature [67] :

$$G/T = G_R - T_S \quad \mathrm{dB/K} \tag{4.26}$$

Rewriting the carrier to noise (eq. 4.17) using the figure of merit for the receiver we have the following equation

$$\frac{C}{N} = EIRP + G/T - L_{TOTAL} - k - B_N \quad [dB] \tag{4.27}$$

The carrier-to-noise density is similar to equation 4.27, and again, a more significant value for this parameter indicates a better performance of the communication link [67]. The following equations define the carrier-to-noise density using the previously developed terms.

$$\frac{C}{N_o} = \frac{C}{N} + B_N \quad [dB] \tag{4.28}$$

$$\frac{C}{N_o} = EIRP + G/T - L_{TOTAL} - k \quad [dB] \tag{4.29}$$

The energy-per-bit to noise density ratio, e_b/n_o, is useful to describe the performance of the link in digital communications, and it is defined as

$$\frac{E_b}{N_o} = \frac{C}{N_o} - R_b \tag{4.30}$$

where

R_b [dBps]: is the value in dB of the data bit rate.

Subtracting the value of the data bit rate in dB, R_b, from equation 4.29 we end with the equation 4.31.

$$\frac{E_b}{N_o} = EIRP + G/T - L_{TOTAL} - k - R_b \quad [dB] \tag{4.31}$$

In addition to free-path loss, F_S, described by equation 4.16 and at Fig. 4.35, it is necessary to consider how the elevation angle affects the distance to the satellite since it is not always over the ground station. Sometimes the satellite will be visible close to the horizon (low elevation angle) or sometimes just above the ground station.

The equation 4.32 approximates the distance from the receiver on Earth to the satellite as a function of the elevation angle and the mean altitude of the satellite. This distance is known as the slant range, S,

$$r = R_E \left(\sqrt{\frac{R^2}{R_E^2} - \cos^2(\theta)} - \sin\theta \right) \quad [\text{km}] \tag{4.32}$$

where:

θ [deg]: elevation angle

R_{Earth} [km]: radius of the Earth as defined in section 2.1

R [km]: $R_{Earth} + \bar{R}$. The radius of the Earth plus the mean altitude of the satellite around ground.

The approximation of the distance to the satellite offered by equation 4.32 will vary from the real value depending on characteristics of the orbit such as the eccentricity. In the case of circular orbits as the introduced in section 4.3.1, the mean altitude, $\bar{R}$, will have a lower variation than a orbit with greater values of eccentricity, e. Fig 4.38 shows the slant range for different values of the elevation angle, θ, for the circular orbits at 1000km of altitude introduced in section 4.3.1.

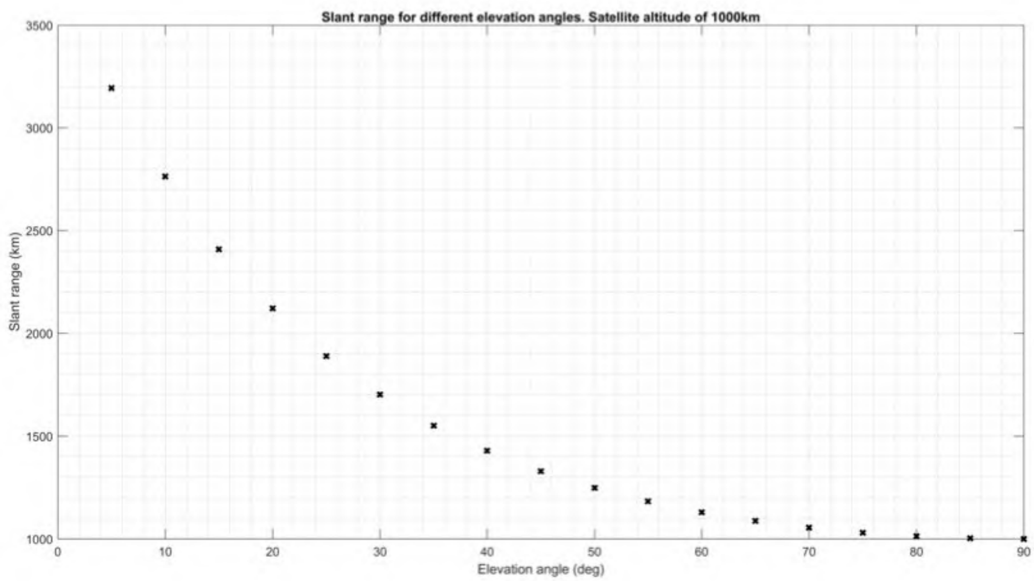


Figure 4.38: The distance from a ground station to the satellite in orbits varies according to the angle of elevation. This graph shows different values of that distance, called slant range, as a function of the elevation angle.

After determining the slant range with equation 4.32, the free-path loss, L_{FS}, can be calculated with equation 4.16. Fig. 4.39 shows a comparison of different values for the free space path loss, L_{FS}, for a mean altitude $\bar{R} = 1000$km and for different elevation angles.

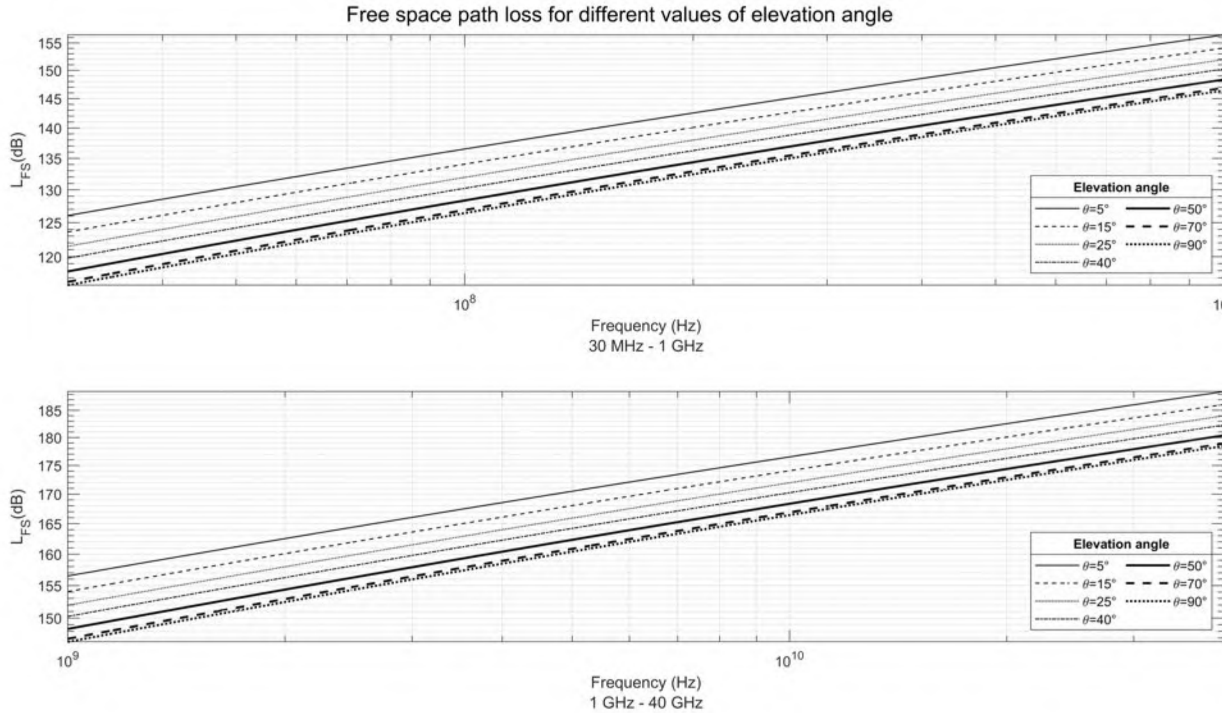


Figure 4.39: The graph shows the attenuation for different values of the slant range associated to a mean altitude of $\bar{R} = 1000km$ and different values for the elevation angle

Tables 4.9 and 4.10 show a link budget for two cases for the uplink and downlink where the distance from the satellite to the Earth station varies from the minimum to the maximum distance at 8° of elevation angle. This variation is natural of the orbit since the satellite appears at the minimum elevation of 8° above the horizon with a greater distance from the Earth station than when it is just above the ground station.

Uplink

Link budget. Uplink			
		Best case	Worst case
Parameter		Value	Value
P_T	(dBW)	17	18
G_T	(dBi)	15	15
L_T	(dB)	3	3
EIRP	(dBW)	29	29
G_R	(dBi)	6	6
T_S	(dB/K)	30.97	30.97
$(G/T)_R$	(dB/K)	-24.97	-24.97
L_{FS}	(dB)	152.56	161.38
L_{OTHER}	(dB)	0	0
k	(dB/Hz)	-228.6	-228.6
C/No	(dBHz)	80.07	71.25
Eb/No	(dB)	37.24	28.42
$(Eb/No)_{REQUIRED}$	(dB)	9.09	9.09
Link Margin	(dB)	28.15	19.33

Table 4.9: Link budget. Uplink

Description of the uplink:

f: Frequency band must be compatible with both the transmitter and receiver equipment and in this case selected according to the frequencies listed in Table 4.1. Selected uplink frequency of 2025 MHz

P_T: Transmitted power varies according to the selected transceiver for the ground station. References such as [70], [71] and [72] managed a transmitted power of 100 W or close to 100W in their link budgets. This quantity is supported by transceivers such as the VHF/UHF and S ground stations transceivers of Innovative Solutions In Space (ISIS) shown in Fig. 4.17. The transmitter power is set at 50 W.

L_T: the loss at the transmitter is set a 3 dB. This include lines losses and other losses in the transmitter. Similar values to this quantity are found at [70], [72] and [73].

$EIRP$: The equivalent isotropic radiated power sums the transmitted power and the gain of the transmitter antenna and subtracts a loss of 3dB in the transmitter.

G_T: The gain of the transmitter corresponds to the gain of the transmitting antenna. Link budgets included in [70], [72] and [73] contain values of about 15 dBi but antennas of 3 m diameter for the S band can have gains above 34 dBi as those shown in Fig. 4.17. The calculations consider a gain of 15 dBi for the transmitter antenna.

G_R: The gain of the receiver varies according to the selected antenna. In this case, gains of patch antennas of IQ space, IQ wireless for the communication systems described in Table 4.3 were the references to choose a gain of 6dBi. A description of one of those antennas is available at [74].

T_S: The noise temperature for the receiver system can be calculated once having the temperature noise of the receiver and its antenna or their corresponding figure of merit by equations 4.25 , 4.26. In this case, its employed a noise temperature system, T_S, of 1250k which corresponds to 30.97 dB as in [70], since the noise figure or noise temperature for the receiver is not given for any of the selected receivers and antennas.

G/T: The figure of merit for the receiver is given as the ratio of the gain of the receiver to the noise temperature system of the receiver.

$$G/T = 6 - 30.97 = -24.97 \quad \text{dB}$$

L_{Other}: Not considering other losses, but additional losses such as rain or atmospheric attenuation can be added here.

L_{FS}: Selecting an elevation angle of 8°, using equation 4.32 the minimum and maximum distances to the satellite and their corresponding value of L_{FS} according to equation 4.16 are

$$\begin{aligned} r_{max} &= 2763.22 \quad [\text{km}] \\ r_{min} &= 1000.00 \quad [\text{km}] \end{aligned}$$

$$\begin{aligned} L_{FS_{Max}} &= 161.38 \quad [\text{dB}] \\ L_{FS_{Min}} &= 152.56 \quad [\text{dB}] \end{aligned}$$

k: the constant value k comes from the Boltzmann constant as introduced for equation 4.17.

C/N_o: To find the carrier to noise density its necessary to substitute the previous values in equation 4.29 to have

$$\frac{C}{N_o} = 29 + (-24.97) - (152.56 + 0) - (-228.6) \quad \text{dB/Hz}$$

$$\frac{C}{N_o} = 80.07 \quad \text{dB/Hz}$$

similarly for the case with greater distance to the satellite

$$\frac{C}{N_o} = 71.25 \quad \text{dB/Hz}$$

E_b/N_o: To find the energy-per-bit to noise ratio its necessary to subtract the bit rate to the previous result as given by equation 4.31. Considering a bit rate of $R_b = 19.2$kbps its corresponding value is 42.83 dBHz.

$$\frac{E_b}{N_o} = 80.07 - 42.83 \quad \text{dB/Hz}$$

$$\frac{E_b}{N_o} = 37.24 \quad \text{dB/Hz}$$

similarly for the case with greater distance to the satellite

$$\frac{E_b}{N_o} = 28.42 \quad \text{dB/Hz}$$

The link margin for E_b/N_o is given as the difference between the obtained energy-per-bit to noise density ratio, E_b/N_o, and the required energy-per-bit to noise density ratio, $(E_b/N_o)_{REQ}$.

Using conditional probability and assuming a that a binary signal is being transmitted with white Gaussian noise being added during the process, the probability of treat a zero like if it would be a one [35] is given by

$$P_e = \frac{1}{\sqrt{\pi}} \int_{\sqrt{\frac{E_b}{N_o}}}^{\infty} \exp\left[-t^2\right] \mathrm{d}t \tag{4.33}$$

were the probability P_e can be treated as the bit error rate (BER).

The $(E_b/N_o)_{REQ}$ value of 9.09 dB, obtained as mentioned in equation 4.34, corresponds to a bit error rate (BER) of 1×10^{-6}.

$$\text{Margin} = 37.24 - 9.09 = 28.15 \quad \text{dB}$$

similarly

$$\text{Margin} = 28.42 - 9.09 = 19.33 \quad \text{dB}$$

Downlink

Link budget. Downlink			
		Best case	Worst case
Parameter		Value	Value
P_T	(dBW)	-3	-3
G_T	(dBi)	6	6
EIRP	(dBW)	3	3
G_R	(dBi)	35	35
T_S	(dB/K)	21.55	21.55
$(G/T)_R$	(dB/K)	13.45	13.45
L_{FS}	(dB)	153.28	162.10
L_{OTHER}	(dB)	0	0
k	(dB/Hz)	-228.6	-228.6
C/No	(dBHz)	91.77	82.95
Eb/No	(dB)	48.94	40.12
$(Eb/No)_{REQUIRED}$	(dB)	9.09	9.09
Link Margin	(dB)	39.85	31.03

Table 4.10: Link budget. Downlink

Description of the downlink:

f_T: Frequency band must be compatible with both the transmitter and receiver equipment and in this case selected according to the frequencies listed in Table 4.1. Selected downlink frequency of 2200 MHZ

P_T: The gain of the transmitter varies according to the selected transceiver to the satellite. In this case, a transceiver of IQ Space shown in section **??** was the reference to choose a gain of -3 dBW.

G_T: The gain of the transmitter varies according to the selected antenna for the satellite. In this case, gains of patch antennas of IQ space, IQ wireless and an helical antenna of HCT shown in section 4.3.4 were the references to choose a gain of 6dBi.

G_R: The gain of the receiver varies according to the selected antenna for the ground station. In this case, the antenna shown in Fig. 4.17a is the reference to choose a gain of 35 dBi.

T_S: Using the first terms inside the logarithm of equation 4.18 to calculate the temperature system of a receiver as the shown in Fig. 4.37 and considering as elements of the receiver the antenna shown in Fig. 4.17a with a gain of 35 dB, a low noise amplifier for the S band as the mentioned in section 4.4 and a line loss of 3 dB, the noise temperature system is

$$T_S = 10\log_{10}\left(67 + 70 + \frac{290(10^{3/10} - 1)}{50}\right) \quad \text{dB}$$

$$T_S = 21.55 \quad \text{dB}$$

The noise temperature for the antenna and the transmission line in the previous equation comes from substituting the noise figure values, NF, in equation 4.24.

G/T: The figure of merit for the receiver is given as the ratio of the gain of the receiver to the noise temperature system of the receiver.

$$G/T = 35 - 21.55 = 13.45 \quad \text{dB}$$

L_{Other}: Not considering other losses, but additional losses such as rain or atmospheric attenuation can be added here.

L_{FS}: Selecting an elevation angle of 8°, using equation 4.32 the minimum and maximum distances to the satellite and their corresponding value of L_{FS} according to equation 4.16 are

$$r_{max} = 2763.22 \quad [\text{km}]$$
$$r_{min} = 1000.00 \quad [\text{km}]$$

$$L_{FS_{Max}} = 162.10 \quad [\text{dB}]$$
$$L_{FS_{Min}} = 153.28 \quad [\text{dB}]$$

k: the constant value k comes from the Boltzmann constant as introduced for equation 4.17.

C/N_o: To find the carrier to noise density its necessary to substitute the previous values in equation 4.29 to have

$$\frac{C}{N_o} = 3 + 13.45 - (153.28 + 0) - (-228.6) \quad \text{dB/Hz}$$

$$\frac{C}{N_o} = 91.77 \quad \text{dB/Hz}$$

similarly for the case with greater distance to the satellite

$$\frac{C}{N_o} = 82.95 \quad \text{dB/Hz}$$

E_b/N_o: To find the energy-per-bit to noise ratio its necessary to subtract the bit rate to the previous result as given by equation 4.31. Considering a bit rate of $R_b = 19.2$kbps its corresponding value is 42.83 dBHz.

$$\frac{E_b}{N_o} = 91.77 - 42.83 \quad \text{dB/Hz}$$

$$\frac{E_b}{N_o} = 48.94 \quad \text{dB/Hz}$$

similarly for the case with greater distance to the satellite

$$\frac{E_b}{N_o} = 40.12 \quad \text{dB/Hz}$$

The link margin for E_b/N_o is given as the difference between the obtained energy-per-bit to noise density ratio, E_b/N_o, and the required energy-per-bit to noise density ratio, $(E_b/N_o)_{REQ}$.

Using conditional probability and assuming a that a binary signal is being transmitted with white Gaussian noise being added during the process, the probability of treat a zero like if it would be a one [35] is given by

$$P_e = \frac{1}{\sqrt{\pi}} \int_{\sqrt{\frac{E_b}{N_o}}}^{\infty} \exp\left[-t^2\right] \mathrm{d}t \tag{4.34}$$

were the probability P_e can be treated as the bit error rate (BER).

The $(E_b/N_o)_{REQ}$ value of 9.09 dB, obtained as mentioned in equation 4.34, corresponds to a bit error rate (BER) of 1×10^{-6}.

$$\text{Margin} = 48.94 - 9.09 = 39.85 \quad \text{dB}$$

similarly

$$\text{Margin} = 40.12 - 9.09 = 31.03 \quad \text{dB}$$

Rain attenuation

There are two important models for rain attenuation, the Crane model for rain attenuation and the ITU model for rain attenuation described at ITU-R P.618-8. The ITU rain attenuation model consists of 10 steps implemented in this section to a particular location to predict the rain attenuation for an average year. Fig. 4.40 shows the rain attenuation calculations for different percentages of availability, elevation angles, and frequencies up to the Ka band. The location for the calculations corresponds to Monterrey, Mexico.

Initial required data:

h_s[km] : height above mean sea level of the earth station

$$h_s = 0.54 \quad [\text{km}]$$

θ [deg] : Elevation angle

$$\theta = 8 \quad [\text{deg}]$$

$\varphi[deg]$: Latitude of the earth station

$$\varphi = 25.656[\text{deg}]$$

f[GHz] : Frequency

$$1 \text{ to } 40[\text{GHz}] \tag{4.35}$$

Procedure:

Step 1
Calculate the rain height, h_R, according to Rec. ITU-R P.839 [75]. The parameter h_0 corresponds to the yearly average 0°C isotherm height above mean sea level obtained from [76, Fig. 1]

$$h_R = h_0 + 0.36 \quad [\text{km}] \tag{4.36}$$

$$h_R = 4.5 + 0.36 = 4.86 \quad [\text{km}]$$

Step 2
Calculate the slant-path length below the rain height, L_S. For a graphical description of this length refer to [77, Fig. 1].

$$L_s = \frac{h_R - h_s}{\sin\theta} \quad [\text{km}] \tag{4.37}$$

$$L_s = \frac{4.86 - 0.54}{\sin\theta} \tag{4.38}$$

Step 3
Compute the horizontal projection of the slant-path length.

$$L_G = L_S \cos\theta \tag{4.39}$$

Step 4
Obtain the rainfall rate $R_{0.01}$ of an average year. This quantity is available in the maps contained at Rec. ITU-R P.837-4 [78] and a world color intensity map at Rec. ITU-R P.837-7 [79].

$$R_{0.01} = 33$$

Step 5
Calculate the specific attenuation γ_R

$$\gamma_R = k(R_{0.01})^{\alpha} \quad [\text{dB/km}] \tag{4.40}$$

where

$$k = [k_H + k_V + (k_H - k_V)\cos^2\theta\cos 2\tau]/2; \tag{4.41}$$

and

$$\alpha = [k_H \alpha_H + k_V \alpha_V + (k_H \alpha_H - k_V \alpha_V) \cos^2\theta \cos 2\tau)]/2k \tag{4.42}$$

The frequency-dependent coefficients k_H, k_V, α_H and α_V are available at the Recommendation ITU-R P.838 [65] and utilize a polarization tilt angle, $\tau = 45$, which is corresponds for circular polarization transmissions; for a wider discussion about the tilt angle refer to sources like [80] and [81].

Step 6

Compute the horizontal reduction factor, $r_{0.01}$, for 0.01% of time.

$$r_{0.01} = \frac{1}{1 + 0.78\sqrt{\frac{L_G}{\gamma_R}} - 0.38\,(1 - \exp(-2L_G))} \tag{4.43}$$

Step 7

Calculate the vertical adjustment factor, $\nu_0 1$, for 0.01% of the time

$$\nu_{0.01} = \frac{1}{1 + \sqrt{\sin\theta}\left(31\left(1 - \exp\left(\frac{-\theta}{1+\chi}\right)\right)\frac{\sqrt{L_R\ \gamma_R}}{f^2} - 0.45\right)}; \tag{4.44}$$

where

$$\chi = \begin{cases} 36 - |\varphi| \quad [\text{deg}] \quad \text{for} |\varphi| < 36 \\ \\ 0 \quad [\text{deg}] \qquad\qquad \text{for} |\varphi| \geq 36 \end{cases} \tag{4.45}$$

$$L_R = \begin{cases} \dfrac{L_G\ r_{0.01}}{\cos\theta} \quad [\text{km}] \quad \text{for} \zeta > \theta \\ \\ \dfrac{h_R - h_S}{\sin\theta} \quad [\text{km}] \quad \text{for} \zeta \leq \theta \end{cases} \tag{4.46}$$

and

$$\zeta = \arctan\left(\frac{h_R - h_S}{L_G\ r_{0.01}}\right) \tag{4.47}$$

Step 8

Calculate the effective path length, L_E

$$L_E = L_R\ \nu_{0.01} \quad [\text{km}] \tag{4.48}$$

Step 9

Calculate the attenuation exceeded for 0.01%, $A_{0.01}$, of an average year

$$A_{0.01} = \gamma_R \; L_E \quad [\text{dB}] \tag{4.49}$$

Step 10

For other attenuation exceeded percentages in the range 0.001% to 5% the $A_{0.01}$ serves as base as described in the following equations

$$A_p = A_{0.01} \left(\frac{p}{0.01}\right)^{-[0.655+0.033\ln(p)-0.045\ln(A_{0.01})-\beta(1-p)\sin\theta]} \quad [\text{dB}] \tag{4.50}$$

where

$$\beta = \begin{cases} 0 & \text{if } p \geq 1\% \text{ or } |\varphi| \geq 36^\circ \\ -0.005(|\varphi| - 36) & \text{if } p < 1\% \text{ and } |\varphi| < 36^\circ \text{ and } \theta \geq 25^\circ \\ -0.005(|\varphi| - 36) + 1.8 - 4.25 \; \sin\theta & \text{otherwise} \end{cases} \tag{4.51}$$

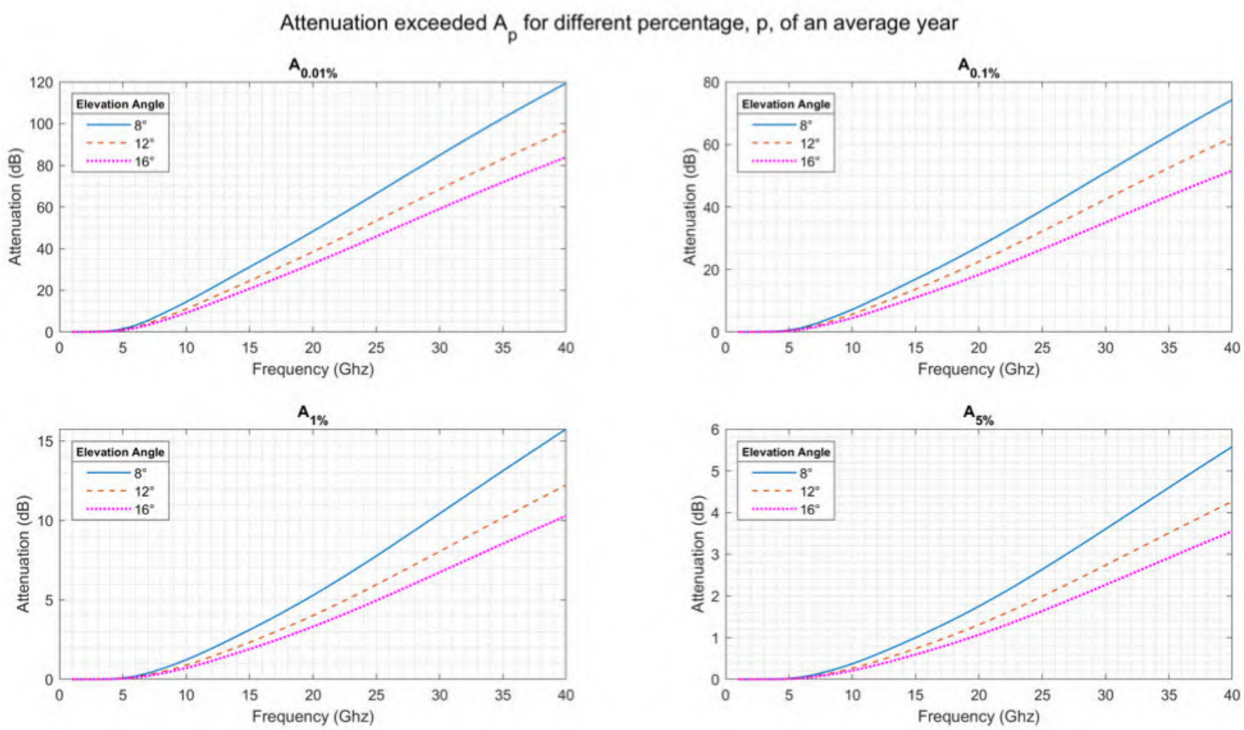


Figure 4.40: This figure shows the total rain path attenuation for a link availability of 99.99%, 99.90%, 99% and 95% for an average year. Location: Monterrey, N.L., Mexico

4.7 Transport Layer

The Transport Control Protocol (TCP) with minor modifications and User Datagram Protocol (UDP) are widely studied and implemented in satellite and space communications. Licklider Tansmission Protocol mentioned at [17] and specified at RFC 5326 serves to provide reliability based on retransmissions in environments with long delays or frequent interruptions.

4.7.1 TCP over satellite

To important approaches has being developed to implement TCP over satellite communications; the first one makes use of selective acknowledgments (SACK) while the second uses selective negative acknowledgments (SNACK). SACK is originally defined at RFC 2028 while SNACK is defined at [82], [83], negative acknowledgments are defined at RFC 1106. Different approaches has been proposed to deal with stages like the slow start and congestion avoidance; one of this approaches given as an example in [84] is to use characteristics of other TCP implementations such as TCP-Reno and adding Selective Acknowledgments (SACK). Table 4.11 contains some of the characteristics of two TCP implementations for satellite communication.

TCP Satellite Implementations		
	TCP SACK	SCPS-TP
Relevant characteristics	Selective Acknowledgments (SACK) Up to three missing segments can be detected	Selective Negative Acknowledgments (SNACK) Multiple missing segments can be detected
Configuration	During the synchronization stage of TCP	During the synchronization stage of TCP
Required number of bytes per TCP header	Maximum 40 bytes in the TCP options field	Variable
RFC or normative documents	RFC2018	CCSDS 714.0-B-2 [83]
Additional strategies	Concatenated coding at lower layers for minimizing errors Algorithms for Slow Start, Congestion Avoidance	Similarly to TCP SACK, algorithms for different stages like slow start or congestion avoidance can be implemented.

Table 4.11: Relevant details of TCP SACK and SCPS-TP

Proposed transport layer protocols specially suited for nanosatellites and small satellites described at [17] are the CubeSat space protocol, and the SCPS-TP mentioned above. An overview of the CCSDS for the transport layer protocols for space communications is available at [85]

4.8 Network Layer

The space packet protocol (SPP) mentioned at [17] and developed by the CCSDS has the characteristic of guaranteed quality of service. An overview of the CCSDS for the network layer protocols for space communications is available at [85]

4.8.1 IP over satellite

IP over satellite is a well developed topic included in several works; for example, [19] includes one full chapter about IP over satellite and additional pages distributed in other chapters. Some relevant aspects about IP over satellite for LEO satellites are the encapsulation and routing.

IP over satellite requires the satellite networks to have a defined structure for the frame, to fragment the IP package when required and encapsulate it. Those frames can be based on the data link layer protocol and its already defined for networks like ATM, DVB-S and DVB-RCS [19].

Routing is an another important aspect for the network layer. LEO satellites are changing their positions over the Earth surface constantly, however, the position of satellites can be computed previously and routing tables need to be updated frequently to allow routing of packets appropriately [19]. Similarly, routing in a constellation requires to consider the fixed distance between satellites and the varying distances and update routing tables according to availability to improve the employed routing algorithm [19].

4.9 Data Link Layer

Data link layer protocols for Small Satellites CubeSats such as satellite data link protocol (NSLP), low-altitude multiple satellite data link control (LAMS-DLC) are proposed at [17]. The TM Space Data link protocol is a data link layer proposed by the Consultative Committee for Space Data Systems (CCSDS) at [86]. Communication systems described at Table 4.3 includes data link protocols such as Proximity 1 also by the CCSDS. Table 4.12 offers a brief list of features of two of those suitable data link protocols.

Data link layer protocols		
	Proximity-1	Low-altitude multiple satellite data link control (LAMS-DLC)
Relevant characteristics	Designed for LEO satellite networks Reliable data delivery Allows selection of communication frequencies, data rates, modulations and coding. Designed to support link directionality, full and half duplex. Available Proximity-1 Physical Layer [87]	Designed for LEO satellite networks Reliable data delivery Integrates Automatic Repeat Request (ARQ) and Forward Error correction (FEC) Based on negative acknowledgments, selective acknowledgments and periodic responses called checkpoints to avoid packet loss.
Reference documents	CCSDS Recommended Standard 211.0-B-5 [88]	[89]

Table 4.12: Two data link protocols for LEO

Chapter 5

Discussion of related topics

5.1 Closely related applications

Evaluation of characteristics in a field could is plausible with similar resources than those proposed for the mission. Similarly to the case study TAHMO boarded in chapter 3, specific sensors such as the proposed in the same chapter could take measurements to analyze the behavior of a field and decide whether is best to plant some crop, another, or none, in all or at some portions of the available land. This proposal can complement weather observations as proposed at TAHMO with a study of conditions of the soil.

A similar application could help at cattle raising by using wireless sensors for supervising the state of resources like the grass, soil degradation, and water availability; also some sensors like those to detect heat and motion could help to monitor the proximity and the displacement of the animals. A network like the introduced in Fig. 2.6 also applies for an application like this but with different kind of required devices.

5.2 A satellite constellation

Nanosatellites can operate in constellations, swarms and different kind of arrays to improve their communication and processing capacities and to provide a reliable data transfer at any place. That improvement in capabilities takes particular relevance with smaller satellites since the small satellites usually have less available resources such as power and onboard computation capabilities.

In this project, it is mentioned the number of required satellites to provide permanent coverage. Satellites should have inter-satellite communication to exploit the benefits of a network; otherwise, each satellite would be operating individually with much more limited resources. Constellations like Iridium used inter-satellite communication, of their LEO polar orbit satellites, for satellites within the same orbit and satellites at adjacent orbital planes. The strategy to design the inter-satellite network should define the routing inside the subnet, the required number of hops that it would take to transmit data for the different cases, and a link budget analysis to determine the required power of transmission for those inter-satellite contacts.

5.3 Global coverage

Different orbits arrangements can conduct to global a coverage scenario, for example, a single satellite in a polar orbit will cover all points over Earth after enough time orbiting at Low Earth Orbit. Mixing polar and inclined orbits such as the proposed in this project will increase the coverage to higher latitudes, and including enough satellites guarantees coverage to all the globe. One of the critical points for designing a global coverage network is to guarantee that satellites will transmit with enough power to communicate to ground, to communicate with other satellites as previously mentioned, to onboard processing, and to operate the internal subsystems. The orbit design can guarantee that a receiver in Earth will always have a satellite in its line of sight, but the link budget must assure that communication is feasible.

5.4 Security

Small satellites have a little amount of available energy usually assigned to the primary payload such as the communication system. Most efficient security protocols would require some degree of data encryption thus increasing the computational on-board requirements and the energy consumption. Effective security techniques with low computational requirements are desirable for nanosatellites. Several communication systems as the proposed in chapter 3 for the payload of the satellite support certain level of encryption such as AES, however, data should also be transmitted from Earth with a certain level of encryption to increase security, meaning that all devices of the network communicating with the satellites must support some level of encryption. Systems to provide security to the network proposed in this project is a potential future work, and it is required according to the definition of the IoT as mentioned in chapter 1.

5.5 Research opportunities for nanosatellite technology

Several aspects of the satellite design provide research opportunities to extend this project. For example, even though chapter four mentions and describes the power system, there is not a developed power budget for the mission. The electrical system and power system are required to guarantee the satellite can provide enough power for the payload and the basic systems such as the attitude and control system. In chapter contains a link budget for communications including in its calculations the radiated supported power by the hardware; however, if it is desired to transmit with a given EIRP, the power design of the satellite should support that required power. The satellite requires to have enough solar panels, internal conversions for different output voltages compatible with each of the subsystems and adequate dimensions, weight, and components, which are crucial in space projects.

Deorbit is another essential aspect just slighly boarded in the project but required by regulations [90]. For the proposed altitude in this project, natural decay of satellites could not happen in decades, and an external system is required to cause the reentry of the satellite.

Proposed systems to cause the decay of nanosatellites are the topic of [48, Chapter 12], [91] and [92]. Similar systems or strategies could be designed or developed to increase the velocity of decay after the end of the mission life.

Mechanical design is an excellent opportunity to apply CAD, CAE and manufacturing resources available at the school. The structures for satellites such as CubeSats are not complicated, however, they must be able to withstand the hard conditions during the launch and as mentioned in chapter 4, and include coatings able to diminish the cyclical changes in temperature for the internal components as in the case of a passive thermal subsystem.

Projects related with nanosatellites design and construction in Mexico could lead to interest of more Mexican companies for the space sector in areas like electronics design, RF, materials science, engineering mechanics and even propulsion systems and rocket science since nanosatellites provides a more accessible entry to the space sector, and sometimes even easier if universities are part of the project.

5.6 Launch

Several companies like Innovative Solutions In Space (ISIS) take an active role in the launch of the nanosatellite, in performing tests, and at offering engineering services. Several companies can offer a variety of services to the last stage of the project as discussed at [48, Chapter 10]. A review of options for the launching, the definition of specific criteria to test (e.g. mechanical vibrations within a certain range), as well as managing regulations for frequency bands, is an important topic to complement this work and to make decisions for the design or purchase of the nanosatellite subsystems.

Some sources such as [48, Chapter 10] consider that most of the launches for nanosatellites in the future will be managed by specialized companies since the number of small satellites launches is high (above 62% of total launches in 2017 for nanosatellites), so it is important to analyze their role and tendencies and look for options to facilitate the realization of a nanosatellite project.

Apendix A

Common parameters to all the satellites	
Epoch	15 Nov 2019 12:00:00.000 UTCG
Inclination	30
Eccentricity	0.0015
Semi-major-axis	7371

Table 5.1: Details of the satellites of the constellation introduced in Chapter 4

Individual parameters to all the satellites		
Satellite	RAAN	TA
Sat1_1	50	-74
Sat1_2	50	-37
Sat1_3	50	0
Sat1_4	50	37
Sat1_5	50	74
Sat2_1	122	35
Sat2_2	122	70
Sat2_3	122	105
Sat2_4	122	140
Sat2_5	122	175
Sat2_6	122	210
Sat2_7	122	245
Sat3_1	266	55
Sat3_2	266	80
Sat3_3	266	115
Sat3_4	266	150
Sat3_5	266	185
Sat3_6	266	215
Sat4_1	194	225
Sat4_2	194	260
Sat4_3	194	295
Sat4_4	194	330
Sat4_5	194	5
Sat4_6	194	40
Sat4_7	194	75
Sat5_1	338	175
Sat5_2	338	210
Sat5_3	338	245
Sat5_4	338	280
Sat5_5	338	315

Table 5.2: Details of the satellites of the constellation introduced in Chapter 4

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Curriculum Vitae

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