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**AINOA GARCÍA MARTÍ**  
**LOW EARTH ORBIT SATELLITE**  
**COMMUNICATION NETWORKS**

Bachelor of Science thesis

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# ABSTRACT

**AINOA GARCÍA MARTÍ: LOW EARTH ORBIT SATELLITE  
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Low Earth orbit (LEO) communication networks are the near future of the communication services. What started off as something merely for scientists and students has become an attractive solution for commercial communication. The massive market competition and the huge cost of developing, building and launching conventional satellites, as well as the need of global coverage, have forced the communication industry to look for alternatives and, thanks to the developments in nanotechnology and microtechnology, LEO communication networks are a promising one, since LEO are the closest orbits to the Earth, allowing the setting up of polar orbits and the use of smaller satellites, known as small satellites or SmallSats.

The increasing interest in LEO communication systems is the main reason to write this thesis. Previous work has mainly been limited to analyzing and solving the interference of LEO networks with the geostationary ones. However, LEO are not stationary orbits, which means that satellites are not fixed. This fact, together with the small coverage area due to the low altitude, forces us to set up large satellite constellations. The big amount of satellites also causes interference to occur within the system itself, since the number of visible satellites at a point on Earth is often greater than one. The parameter intended to analyze this issue is the signal-to-interference-plus-noise ratio (SINR).

This thesis offers an overview of satellite communication, focusing on low orbit communication networks further on. Then, a simulator is developed to analyze the SINR of a polar satellite constellation. The results show a significant decrease of SINR at polar regions. In order to improve SINR value, we decrease the inclination but it does not solve the problem as the low SINR values move to different Earth latitudes. Finally, we simulate the polar constellation using dipoles as ground antennas, obtained a light but promising increase of SINR at the conflict regions.

## PREFACE

This thesis, written during the four months I spent at Tampere University of Technology, is made as a completion of the bachelor's degree in Telecommunication Systems Engineering. Although this project has been a fairly challenge, it has been rewarded at the end.

I would like to thank the following people for their support, without whose help this work would never have been possible. First, thanks to Universidad Politécnica de Madrid and Spanish government for the opportunity to benefit from an Erasmus scholarship. I gratefully acknowledge the help provided by D.Sc. Taneli Riihonen, as the supervisor of this thesis, who has been always available and prepared to give support and guidance. Thanks are also due to Adrian Garcia Baños, who gave me much valuable advice in the early stages of this work.

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Tampere, January 13, 2018

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## LIST OF ABBREVIATIONS AND SYMBOLS

CDF	Cumulative distribution function
dB	Decibel
dB <sub>i</sub>	Gain decibel
GEO	Geostationary orbit
LEO	Low Earth orbit
SmallSat	Small satellite
SNR	Signal-to-noise ratio
SINR	Signal-to-interference-plus-noise ratio
$d_k$	Distance to Earth surface from satellite $k$
$LatE$	Earth latitude
$LonE$	Earth longitude
$L_{FS}(d)$	Free space loss at distance $d$
$f$	Frequency
$G_{TX}$	Gain of the transmitter antenna
$G_{RX}$	Gain of the receiver antenna
$G$	Gravitational constant
$\sigma$	Incidence angle of the satellite $k$
$r_e$	Main radius of Earth
$\alpha$	Nadir angle
$k^*$	Nearest satellite to a point on Earth
$h$	Orbit altitude
$i$	Orbit inclination
$T$	Orbit period
$L_{RX}$	Receiver loss
$P_{RX}(d)$	Received power at distance $d$
$LatS_k$	Satellite $k$ latitude
$LonS_k$	Satellite $k$ longitude
$\phi_k$	Satellite $k$ elevation
$a$	Semi-major axis of the orbit
$\mu$	Standard gravitational parameter
$L_{TX}$	Transmitter loss
$P_{TX}$	Transmitted power

# 1. INTRODUCTION

Since the first human beings until now, we have had the necessity to communicate amongst ourselves. The media or communication channels have changed and evolved over time, beginning with the voice, passing through the paper and ending in space. In the field of wireless communications, the objective of space technology is to put two very far-away points in contact. At first, space communication had a military purpose. However, thanks to the technological advances, the usage of space communications has extended to user level, making them one of the most demanded ways of communication.

Space communication is possible thanks to satellites orbiting around Earth. Since today, most of those satellites are located at 35,786 kilometers from the Earth's surface, it is what we call geostationary or GEO satellites. They turn around the Earth following an orbit pattern above the equator and with the same orbit period as the Earth, guaranteeing an almost total coverage of the Earth surface with only three satellites [25]. However, since GEO satellite orbits are above the equator, they do not cover well the polar regions.

From year one of space communications history, GEO satellites have dominated the market, however, the current demand of global coverage and the increase of the market competition have forced space communication industry to look for alternatives to reduce the high cost involved in the production and placed in orbit of GEO satellites, and to provide good coverage at the polar regions. Considering LEO allow polar orbits and the use of smaller satellites, they are a promise solution.

Small satellites or also known as SmallSats have been always present. Nonetheless, until now and thanks to the developments in micro and nanotechnology, their role had not gained importance. Their small size reduces their development time and costs and allows us to place them in LEO orbits, reducing as well the launch costs. However, because they are launched closer to Earth, their coverage area is smaller than that of the GEO satellite one. Besides, they are not geostationary, which means that they are moving very fast around the Earth. Those disadvantages force us to establish satellite constellations to guarantee total and continuous coverage.



## 1.1 Motivation and Scope

The lack of polar coverage, the delay problems and the high cost of geostationary communication systems make necessary to investigate and develop alternatives. Low Earth orbits possess the ideal characteristics to solve the above mentioned problems. In contrary to GEO, LEO can be polar, which means that satellites cross periodically the Earth poles allowing polar regions coverage. The delay problems are solved by the reduction of the distance between the satellite and the users while the reduction of the cost of the systems lies on the satellites used, the small satellites or also knew as Smallsats. However, LEO orbits present two main disadvantages. First, their satellites are not geostationary and second, the coverage area is limited because of the shorter distance. Those facts force us to establish satellite constellation to guarantee global and continuous coverage. The scope of this thesis is the low Earth orbit satellite constellation networks as a solution of the lack of polar coverage of the geostationary communication systems.

## 1.2 Objectives

As mentioned earlier, satellites in LEO orbits cross the poles and therefore, it is possible to achieve polar region coverage through them. However, LEO orbits features, specially their low altitude and non geostationary, require the use of large satellite constellation to guarantee global and continuous coverage. The first objective of this thesis is to acquire the knowledge necessary in space communication system, in order to applied it to LEO communication networks. Since they need satellite constellations to work properly, our second step is to learn how to design them and how their defining parameters affect the communication systems in terms of coverage, quality and cost. One of the problems of polar constellation is the satellite interference at the ground stations. Therefore, thanks to the knowledge acquired about constellation design and satellite communication operation, we develop a simulator designed to represent the behavior of constellations in terms of signal-to-interference and noise ratio (SINR). The objective that we want to achieve with it is to prove that SINR of polar constellations at the polar region is very low, which reduces the quality of the communication systems. Likewise, it allows us to change some parameters of the communication network, which enables us to offer a possible solution.

## 1.3 Organization of the Thesis

This thesis is organized into five chapters. The second chapter examines how satellite communications work, providing the equations that determine the power received at the ground station and the equations that regulate orbit behaviour. Furthermore, this chapter provides information about the classification of orbits by their altitude and the main characteristics of each one. Chapter 3 looks at the question of LEO satellite network, providing a description of the satellites used in this type of orbits, the small satellites. Then, we describe the parameters that define a small satellites constellation and finally, we explain the method used to design it. The analysis of SINR is developed in Chapter 4, previously explaining what SINR is and its equation. In this chapter, we also clarify how to determine if a satellite of the constellation is visible at a point on Earth, as well as the distance between them. Besides, Chapter 4 includes the results and the possible solution. Finally, the conclusion obtained from the whole thesis is elaborated in the final chapter. The main objective of which is to highlight the objectives achieved through this thesis.

## 2. SATELLITE COMMUNICATIONS

The requirements of communication service can be met by terrestrial or satellite-based networks. Nowadays, the former ones are on the limit of their capacity and they are oriented to give service to urban and metropolitan areas, leaving rural areas without properly access to communication service. This fact makes necessary establish a global network. Nevertheless, satellite-based networks are more expensive and they are used as a supplement and a way of reducing the use of the terrestrial networks in urban areas [18].

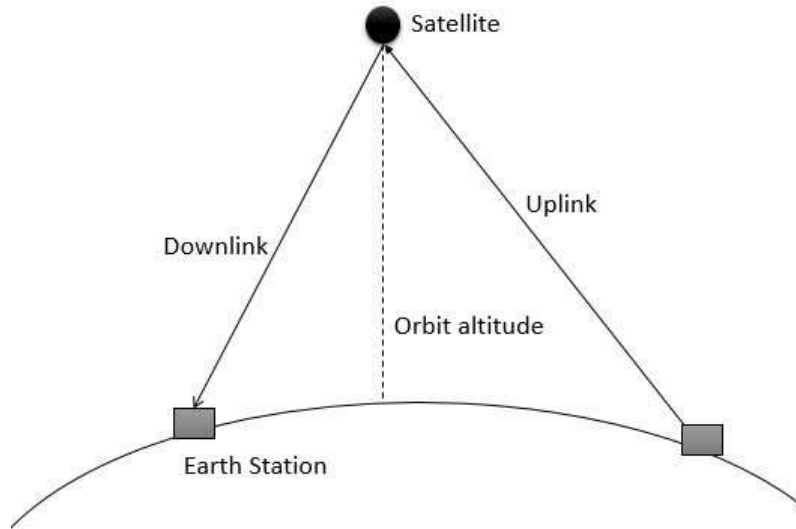
Signal used in satellite communication can be analog or digital. However, digital signals are the most employed because their parameters can be adjusted to the system requirements, which increases their efficiency. Once the signals are adjusted to the communication requirements, they are modulated on a radio-frequency carrier and transmitted by the Earth station.

This chapter provides an overview of the functioning of satellite communication systems, including the equation that determines the power received in the ground stations and the orbit behavior; and an overview of the classification of the orbits by their altitude, adding the main characteristics of each one and a brief comparison of them.

### 2.1 Satellite Link Design

Satellite link design contemplate all the parameters that interfere in the transmission system. The objective of it is to achieve a minimum signal-to-noise ratio (SNR) at the received station. In other words, the emitted signal must arrives to the receiving station with enough power to guarantee the quality of the system, assuming the losses and noise that deteriorate it. SNR will be explain in more detail in chapter 4.

Through the link budget it is possible to design the system to meet the quality requirements. It allows us to determine the received power at the received station, accounting all the gains, what increases power; and losses, what decreases it; that take part in the transmission system. The following equation includes the most



**Figure 2.1** Uplink and Downlink

important variables of a link budget:

$$P_{RX}(d) = P_{TX} - L_{TX} + G_{TX} - L_{FS}(d) + G_{RX} - L_{RX}, \quad (2.1)$$

where

$P_{RX}(d)$  is the received power in dBm at distance  $d$ ;

$P_{TX}$  is the transmitted power in dBm;

$L_{TX}$  is the transmitter loss in dB;

$G_{TX}$  is the gain of the transmitter antenna in dB;

$L_{FS}(d)$  is the free space path loss in dB at distance  $d$ ;

$G_{RX}$  is the gain of the receiver antenna in dB;

$L_{RX}$  is the receiver loss in dB.

Path loss is calculated as

$$L_{FS}(d) = 32.45 + 20 \log d + 20 \log f, \quad (2.2)$$

where  $d$  is the link distance in kilometers and  $f$  is the frequency in GHz.

## 2.2 Orbit Mechanics

Orbit mechanics is the part of classical physics that studies the movement of artificial satellites and rockets. It allows, inter alia, the design of the trajectory and the constant control of the position of the satellites. Kepler described the motion of planets around the sun while Newton developed the reasons for that motion [6].

Although Kepler's laws are suitable for planet orbits around the sun, they can be applied for artificial satellite orbits around the Earth. The first law proves that satellites do not draw circular orbits, but they had elliptical shapes, being the Earth one of the ellipse focus. Second one verifies that the velocity of the satellites depends on the distance between them and the Earth, as the following equation shows:

$$v = \sqrt{\frac{GM}{R+h}}, \quad (2.3)$$

where

$G = 6.67384 \cdot 10^{-11} \text{ m}^3/(\text{kg}\cdot\text{s}^2)$  is the gravitational constant;

$M = 5.97237 \cdot 10^{24} \text{ kg}$  is the mass of Earth;

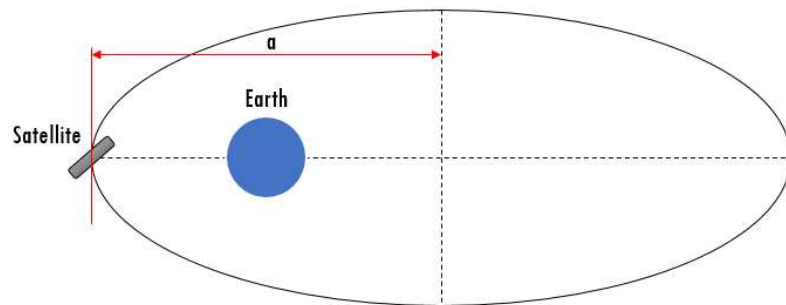
$R = 6371.0 \text{ km}$  is mean radius of the Earth;

$h$  is the orbit altitude.

Third law announces that all the satellites comply with the following equation

$$\frac{T^2}{a^3} = \text{constant}, \quad (2.4)$$

where  $T$  is the orbit period and  $a$  is the semi-major axis of the orbit, as fig. 2.2 shows.



**Figure 2.2** Semi-major axis  $a$

The orbit period of a satellite orbiting around the Earth is

$$T = 2\pi\sqrt{\frac{a^3}{\mu}}, \quad (2.5)$$

where  $\mu = 3.986004418 \cdot 10^{14} \text{ m}^3 \cdot \text{s}^{-2}$  is standard gravitational parameter.

On the other hand, Kepler parameters allow us to determine the satellite position in its orbit. Eccentricity,  $\epsilon$ , determines the shape of the orbit. It is the quotient between the semi-distance between the two focuses of the ellipse and the semi-major axis. If  $\epsilon = 0$ , the orbit is circular. In communication systems, LEO are typically considered circular orbits.

## 2.3 Types of orbits

Satellite orbits could be classified by its inclination, its eccentricity  $\epsilon$  or its distance from Earth. By its inclination, orbits can be equatorial, if its inclination is 0; polar, if its inclination is 90; or low, high or critical inclination. Eccentricity determines the shape of the orbit, so attending at this parameters, orbit can be circular ( $\epsilon = 0$ ), elliptical ( $0 < \epsilon < 1$ ) or parabolic ( $\epsilon = 1$ ).

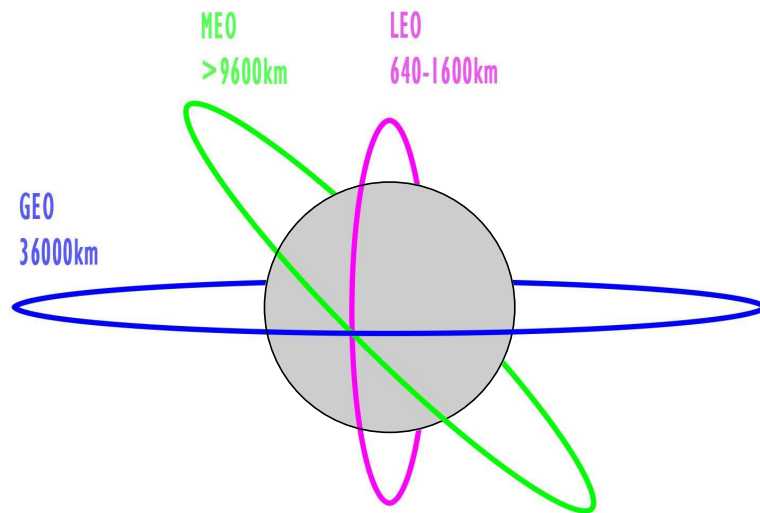
This thesis is focused on the orbit classification based on its altitude. In that way, orbits are classified in low Earth orbit (LEO), medium Earth orbit (MEO) and geostationary orbit (GEO) [15]. Table 2.1 summarize the main characteristics of each one.

**Table 2.1** Types of Orbits

Main Characteristics	LEO	MEO	GEO
Altitude (km)	640-1600	>9600	3600
Period	10-127 min	2-14 hours	24 hours
Satellite Lifetime (years)	5-8	10	15

Low Earth orbits are the closest to the Earth as fig. 2.1 displays. Since their radio is the smallest, their period is the shortest, which means that satellites in LEO take the least time to circle the Earth. Satellite lifetime determines the time between a satellite is placed in the orbit and it ceases to operate. There is a huge difference between the lifetime of LEO and GEO satellites. Satellite lifetime is mainly limited by two factors: orbit decay and satellite batteries. At the altitude of LEO satellites, there are atmospheric molecules which collision causing the atmospheric

drag. Atmospheric drag is translated in the orbit decay, which means a reduction of the altitude of the satellite orbit. There comes a point where the orbit altitude is enough low to cause the re-entry of the satellite in the Earth's atmosphere. The temperature reached at that point is so high that most of the satellite disintegrates [2]. Batteries are also a determining factor of satellites lifetime. Artificial satellite use solar panels as energy font and store it in batteries. During the solar eclipses, they use the energy stored in the batteries. The problem is that batteries need time to recharge once their power is over and the charge-recharge cycles reduce their lifetime [5]. In the case of LEO satellites, the eclipse time can be over 30% of satellite period [16] and therefore, the rate of charge-discharge is high, limiting the life of batteries and thus, satellites, to 3-5 years [5].



*Figure 2.3 Types of Orbits*

### 3. LEO SATELLITE COMMUNICATION NETWORKS

Although satellite communication systems in LEO have been present since the beginning of space communication, GEO orbits have been the most exploited. However, GEO faces two main problems. The first one is the distance between the users and the satellites, which increase the delay and the cost of the systems, as well as the size and power requirements. The second one is the bad coverage at the polar regions due to the fact that, to achieve geostationary satellites, they must be placed above the equator and thus, their elevation angle at the Earth poles is very small. The need of low cost systems has increased due to the huge expansion of the competition in the communication market and the current demand of global communication force us to solve the lack of good coverage of the polar regions. As a way of reducing the cost and improve the global coverage, LEO communication networks has become a real and attractive solution [18].

The smaller altitude of LEO orbits reduces the transmission power required, making possible the use of smaller satellites: the SmallSats. Their advantages can be summarized under the slogan "faster, better, cheaper" [11]. Faster because they have shorter development times, better because of the reduction of latency and cheaper because of their size and the launch requirements [27].

However, LEO orbits have also disadvantages. Due to the lower altitude, LEO satellites have a limited coverage, since their coverage area is smaller than the GEO satellites one, and they are not geostationary, causing the constant movement of satellites, which is translated in the appearance of Doppler effect and the not fixed coverage area of the satellite. These facts force us the usage of a larger number of satellites, or in other words, a satellite constellation [18].

In this chapter, we provide an overview of the classification of small satellites as well as an explanation of their main characteristics. Furthermore, this chapter included the information necessary to implement a satellite constellation: its parameters and the design method.



### 3.1 Definition and Classification of Small Satellites

A satellite is considered as a SmallSat when its mass is between 10 and 500 kilograms compared to 1000 kilograms of the big satellites. Focusing on its mass, a small satellite can be mini satellite, if its mass is between 100 and 500 kilograms; microsatellite, if its mass is between 10 and 100 kilograms; and picosatellite if its mass is between 0.1 and 1 kilograms [21]. Table 3.1 summarizes small satellite classification by its size [21].

*Table 3.1 Small Satellites Classification*

Group name	Mass (Kg)
Large	>1000
Medium	500-1000
Mini	100-500
Micro	10-100
Pico	0.1-1
Femto	<0.1

### 3.2 Features of Small Satellites Networks

Determining small satellite network features is a difficult task as each company uses its own technology. However, it is possible to find some common features between them, as follows.

#### Modulation

Sound waves have a low frequency and they cannot travel through the space. They are the modulating signals. On the other hand, the carrier signals have high frequency and they can travel through the space, but they are empty, they do not have the information that we want to transmit. Modulation is the set of techniques that allows us to combine both signals and therefore, transport the information of the modulating signal using the carrier one. These techniques allow a better use of the communication channel, which makes it possible to transmit more information in a simultaneous way, protect the wave from interference and noise and the use of smaller antennas.

#### Frequency Band

As for the frequency band, most satellites work in L-band (1 to 2 GHz) except OneWeb's satellites, which will operate in the Ku band (12 to 18 GHz). The

higher the frequency, the better the communication is. The user terminals who work in Ku bands are made by little and cheap antennas (30cm-75cm). Therefore, it will be easier and faster to deploy the user terminal [8, 19].

#### Latency

Latency, also called lag, is the parameter that measures the time that takes the information to go from the user terminal to its destination. In telecommunication field, the term round-trip delay is used to allude to the time that the information sent by a sender takes to return to this same sender having passed through the destination receiver. The propagation delay associated in satellite communication depends on the orbit in which the satellite is orbiting. Hence, the lower the orbit, the lower the latency [13].

#### Weight

The mass of satellites varies greatly from one constellation to another. The oldest SmallSat (those that are already in orbit) weigh about 680 kg [10] while the satellites of the future constellation do not exceed 200 kg [19].

#### Lifetime

As with the weight, the lifetime of small satellites is not a constant value. Globalstar satellites have a lifetime of 7.5 years, while the future OneWeb constellation estimate 25 years [9].

#### Power Generation

One of the major limitations of SmallSats is the power generation. As large satellites, SmallSats employ photo-voltaic cells for power generation. The area of the spacecraft surface meant for solar cells is little, what limits the power production capacity. That is why small satellites are only capable of transmitting with a power of between 10 and 20W [28]. If we include deployable solar panels it is possible to achieve 36W of transmitted power [3].

#### Satellite Antenna

SmallSat's antenna design has certain challenges. If we want smaller, cheaper and smarter satellites, their antennas should be such too. The high data rates required imply the use of high gain antennas because transmit power is strictly limited. However, its compact size also poses a challenge to the accommodation of this type of antenna. Some projects have been improving the gain of SmallSat antenna and the maximum value achieved is 15 dBi in the direction of maximum radiation [20].

### 3.3 Satellite Constellation Design

As it has been mentioned above, LEO features force us to set up satellite constellations to ensure global and continuous coverage. It is an important part of the communication system design, since it determines the main cost of it. Unfortunately, there is not a predefined set of steps for designing satellite constellation because they change considerably depending on the constellation purpose. The goal is to achieve the communication requirements through the optimal parameters that reduces to a bare minimum the overall cost of the operation. As a result of this aim, it is necessary to set the minimum number of satellites that guarantee global and continuous coverage. Not only the number of satellites is a cost factor but also the number of orbits influences in the constellation amount. If satellites are placed on significantly differing orbit planes, the complexity of the launch will increase, as multiple launches will be necessary, increasing the cost of the system [24].

#### 3.3.1 Parameters of Satellite Constellation Design

##### Orbit inclination

Orbit inclination is the angle between the equator plane and the orbit plane. It determines how the coverage latitude is distributed and it is defined according to the coverage demand [24]. The different inclination values give rise to two different orbit types: polar orbits and inclined orbits.

Satellites orbiting in polar orbits cross periodically the Earth poles. Its inclination is near  $90^\circ$ . In polar orbit constellations, not all the satellites move in the same direction, their movement depends on the side of the Earth. On one side, they move in northerly direction, while on the other side, they move on southly direction. Due to this particularity, when two satellites lie on orbit planes which are next to each other and have different directions, we call the region in between counter-rotation interface. However if they have the same direction, we name it co-rotation interface. The advantage of this type of orbit is that it improves the coverage in low latitude regions while the high ones are also covered [14].

Inclined orbits differ from polar ones, as expected, by their inclination. Usually, it is less than  $90^\circ$  but it could be larger, changing the rotation direction of satellites. Although they guarantee uniform global coverage, the coverage area changes its shape, making more complex the changes between connections [17].

If the orbit is not polar, coverage at poles is not always guaranteed. There is a minimum orbit inclination angle below which the satellites are not visible (its elevation is less than  $10^\circ$ ) at the poles. It will be called  $\delta$  and it depends on the orbit altitude. Solving trigonometrically fig. 3.1, we get the following equations:

$$\phi = 10^\circ = 90 - \alpha - \theta \quad (3.1)$$

$$\alpha = \tan^{-1} \left( \frac{R \cdot \sin(\theta)}{a - R \cdot \cos(\theta)} \right) \quad (3.2)$$

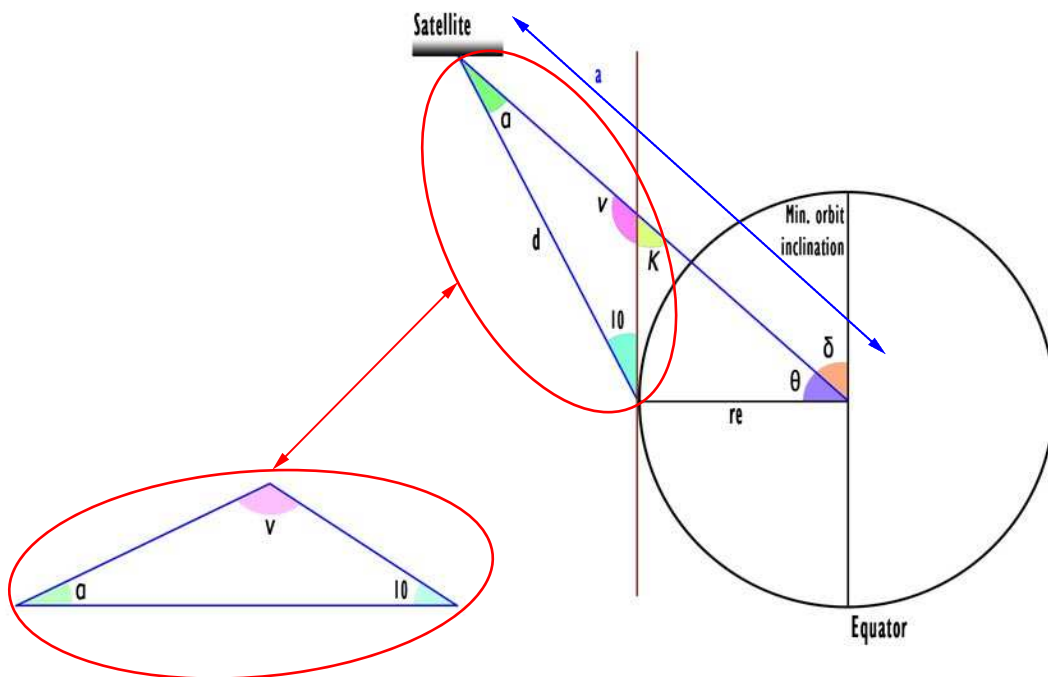
$$10 + \alpha + v = 180 \quad (3.3)$$

$$\omega + v = 180 \quad (3.4)$$

$$\omega + 90 + \theta = 180 \quad (3.5)$$

Substituting with equations ( 3.2), ( 3.3), ( 3.4) and ( 3.5), we get

$$\delta = 90 - 80 - \alpha \quad (3.6)$$



**Figure 3.1** Minimal Orbit Inclination

### Orbit altitude

Coverage and launch cost are directly proportional to the orbit altitude. The higher the altitude, the larger the coverage area and the lower the number of satellites needed [14], therefore, the construction cost is lower. Nevertheless, "not all that glitters is gold" and the launch cost increases as well. Not only this but also, the transmitted power required increases, rising the whole cost of the communication system. The choice of the orbit altitude should keep the balance between the system development cost and the quality of the communication [14].

Nonetheless, there are two environmental parameters that should be considered in the choice of orbit altitude:

- Effect of the Earth's atmosphere: the satellites cannot be inside the atmosphere because the oxygen atoms will erode the satellite, reducing its lifetime [17]. Besides, the atmospheric drag disturbance decrease the orbit altitude [4].
- Van Allet belts influence: Van Allet discovered that there are two belts orbiting the Earth, composed of high-energy charged particles and depleting electromagnetic radiation. The belts are located at an altitude of 1,500 – 5,000 km and 13,000 – 20,000 km. The selection of the orbit altitude should avoid those belts as well as their electromagnetic radiation [17].

### Number of satellites and number of orbits

The most critical factor of the constellation cost is the number of satellites. Furthermore, the coverage area also depends mainly on this parameter. The primary condition that the constellation should achieve is the global coverage. Considering that, the number of satellites and the number of orbits are two determining factors of the coverage, it is necessary to establish first the minimum pair of values that guarantee it. The number of orbits varies depending on the coverage requirements and its impact on system cost is due to the number on launches required. Satellites of the same orbit have similar launch characteristics and therefore it is possible to place them all in just one launch. However, the characteristics of the launch vary from one orbit to another, so the number of launches increases, the cost also increases [24].

### 3.3.2 Walker Constellations

The complexity of the design of satellite constellations lies on the huge number of different possible combinations of the six Keplerian orbit parameters. Fortunately, various constellation design methods have been proposed to reduce the challenge of the task. The most distinguished is the Walker constellations, developed by first name. Their main advantage is that satellite orbits at a common altitude and inclination are distributed symmetrically [22]. All satellites in Walker constellations have the same inclination  $i$ , the same semi-major axis  $a$ , and zero eccentricity  $\epsilon$ , as their orbit is circular [7].

Walker's notation is  $T/F/P i$  [29] where

$T$  is the total number of satellites in constellation;

$P$  is the number of commonly inclined orbit planes;

$F$  is the relative phasing parameter;

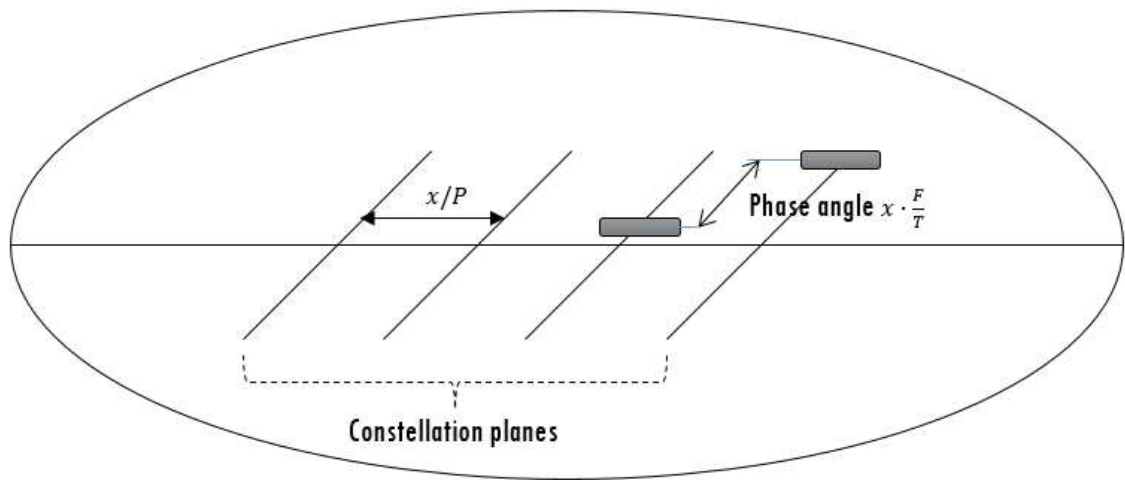
$i$  is the orbit inclination in relation to the equatorial plane.

The value of the  $i$  parameter leads to two types of Walker constellations: Walker delta and Walker star. Orbits in Walker delta constellations are inclined and distributed throughout the Earth globe with a  $360^\circ$  span. On the other hand, Walker star constellations are made up of polar orbits. If we keep the same span as for the delta ones, orbits in star constellations will be overlapped, and that is why their span is  $180^\circ$  span [1].

Considering the prior information, it is possible to define also the number of satellites per plane as  $T/P$  and the phase between planes as  $x/P$ . The phasing parameter  $F$  relates the satellite position in one orbit plane to those in an adjacent plane. The units of  $F$  are  $x/T$ . The phase difference between satellites from consecutive planes is [26]

$$x \cdot F/T, \tag{3.7}$$

where  $x$  is  $180^\circ$  if it is a Walker star constellation or  $360^\circ$  if it is a Walker delta one.



*Figure 3.2 Walker Delta Method*

## 4. ANALYSIS AND SOLUTIONS

The experimental part of this thesis is to simulate the behavior of a polar constellation and analyze the quality of the communication in terms of SINR across the Earth's surface. For achieving that, we develop a simulator able to show the SINR values through the Earth latitudes given the parameters that define a low earth communication system: orbit inclination, number of satellites per orbit, number of orbits, orbit altitude, transmitted power  $P_{TX}$ , frequency  $f$  and antenna gain of the satellites and ground stations.

For developing the simulator, the MATLAB software tool has been used. It is the most appropriate tool for solving mathematical problems related to matrices. It is convenient to add that the function that generate the orbit constellations has been implemented from the function developed by Adrian Garcia Baños [12].

In this chapter, we explain the concept of SINR and present the results obtained for a polar constellation. Since then, we observe that SINR has a low value at polar regions. In order to improve SINR, first we try, unsatisfactorily, to reduce the orbit inclination. In view of that the orbit inclination does not solve the SINR constellation problem, the results by changing the ground antennas' directivity will be also presented.

### 4.1 Signal-to-Interference Noise Ratio

Signal-to-interference noise ratio (SINR) is one of the parameters that defines the quality of a communication process. On account of LEO communication systems need huge satellite constellations, usually, more than one satellite interfere with a point on the Earth. This interference has a negative impact in the quality of the communication provided by the constellation.

To better understand the concept of SINR, it is necessary to define another parameter related to the quality of a communication system and linked to SINR, the



signal-to-noise ratio (SNR), which equation is

$$SNR = \frac{P_s}{P_n}, \quad (4.1)$$

where  $P_s$  is the power of the useful signal and  $P_n$  is the power of the background noise.

The difference between SNR and SINR is that SNR only considers the noise as an undesirable signal while SINR includes the interfering signals, as can be seen from its equation.

$$SINR = \frac{P_s}{P_i + P_n} \quad (4.2)$$

$$P_s = P_{TX}(d_{k^*}), \quad (4.3)$$

where  $P_s$  is the power received at the Earth point from the nearest satellite of the constellation,  $P_i$  is the interference power due to the interference satellites at point on Earth and  $P_n$  is some noise term [23]. The distance to the main satellite, the closest satellite to the point on Earth, is  $d_{k^*}$ . Basically,  $P_i$  is the sum of the  $P_s$  values of all the satellite that interference at the point on Earth, except  $P_{TX}(d_{k^*})$ :

$$P_i = \sum_{\substack{k=1 \\ k \neq k^*}}^N P_s(d_k), \quad (4.4)$$

where  $N$  is the number of satellites that interfere in a point on Earth.

### 4.1.1 Elevation and Distance of a Satellite

The elevation of a satellite determines its visibility at Earth's location. A satellite is considered visible when its elevation is higher than  $10^\circ$ . In the developed simulator, all visible satellites are also interfering ones.

Figure 4.1 shows the geometry of a satellite. For determining the elevation  $\phi_k$  of each satellite in function of a point on earth, we should follow these steps [30]:

1. Calculate the central angle  $\theta$ :

$$\cos(\theta_k) = \cos(LatE) \cdot \cos(LatS_k) \cdot \cos(LonS_k - lonE) + \sin(LatE), \quad (4.5)$$

where  $LatE$  and  $LonE$  are the latitude and the longitude of the Earth point

and  $LatS$  and  $LonS$  are the latitude and the longitude of the subsatellite point  $Z$ .

2. Calculate the nadir angle  $\alpha$  from ( 3.2).

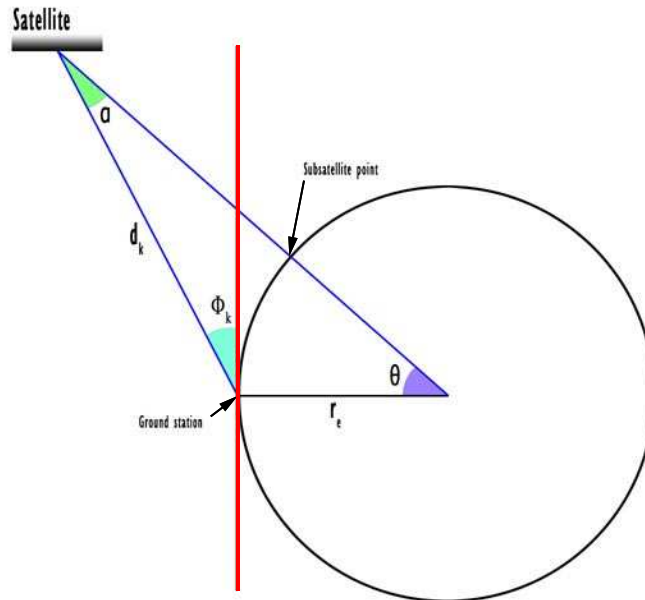
3. The elevation is:

$$\phi_k = 90 - \theta_k - \alpha \quad (4.6)$$

4. Finally, for calculating the distance between the satellite and the point on Earth:

$$d_k = a \sqrt{1 + \frac{R^2}{a^2} - 2 \frac{R}{a} \cos(\theta_k)}, \quad (4.7)$$

where  $k$  is the satellite from which  $d$  is the distance to the point on Earth.



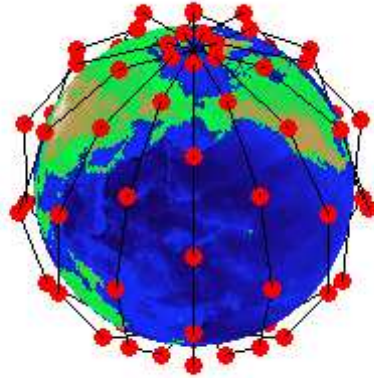
**Figure 4.1** Elevation and Distance from a Satellite to a Point on Earth

## 4.2 Analysis of the SINR

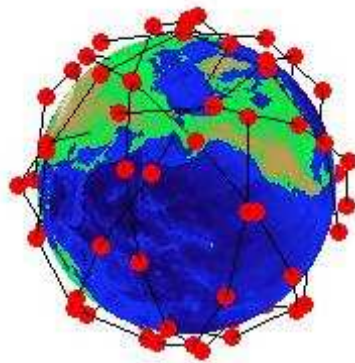
The parameters selected for the simulation are summarized in table 4.1. Parameters related to the constellation design are matched up with the ones of the Iridium constellation while the link ones have been chosen by the small satellites features information included in section 3.2. We decide to simulate this constellation because it is the only one whose parameters are available to the user. Selection of a constellation or another is not something to be taken into account, since the SINR behavior, not its values, depends basically on the orbit inclination.

**Table 4.1** *Parameters of the Simulation*

Number of satellites per orbit	11
Number of orbits	7
Phase difference between satellites of adjacent orbits	16.36°
Orbit altitude	765 km
Transmitter power $P_{TX}$	10 W
Transmitter antenna gain $G_{TX}$ (omnidirectional)	15 dB
Receiver antenna gain $G_{RX}$ (omnidirectional)	30 dB
Frequency $f$	12 GHz



(a) Polar



(b) 72° Inclined

*Figure 4.2 Polar and 72° Inclined Constellations*

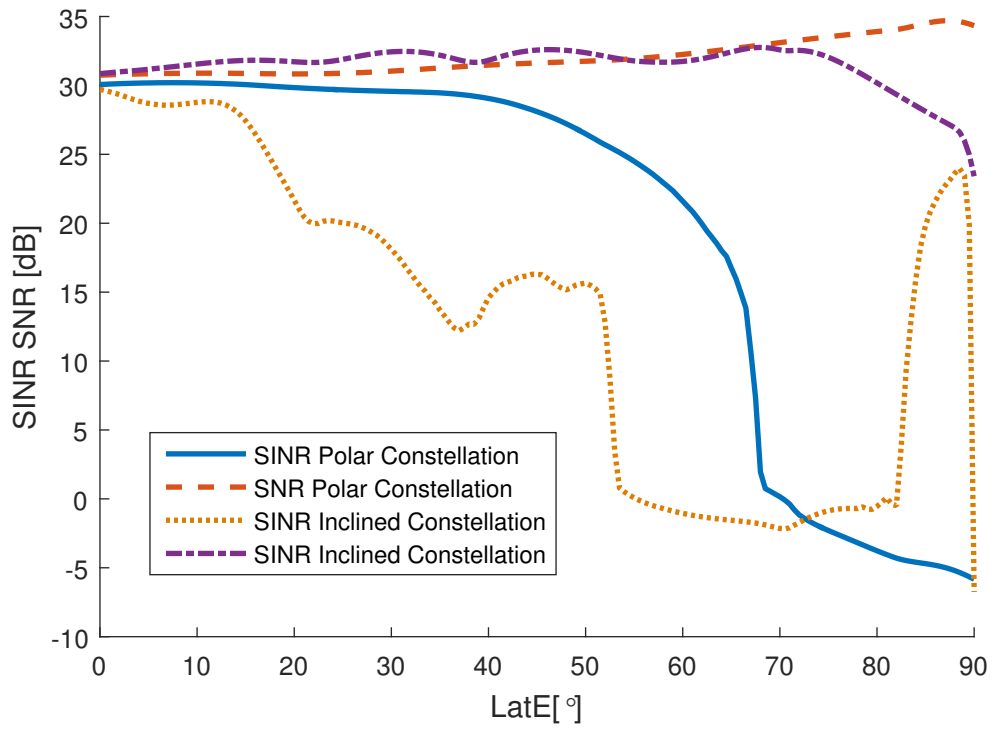


Figure 4.3 SINR and SNR of a Polar and 72° Inclined Constellations

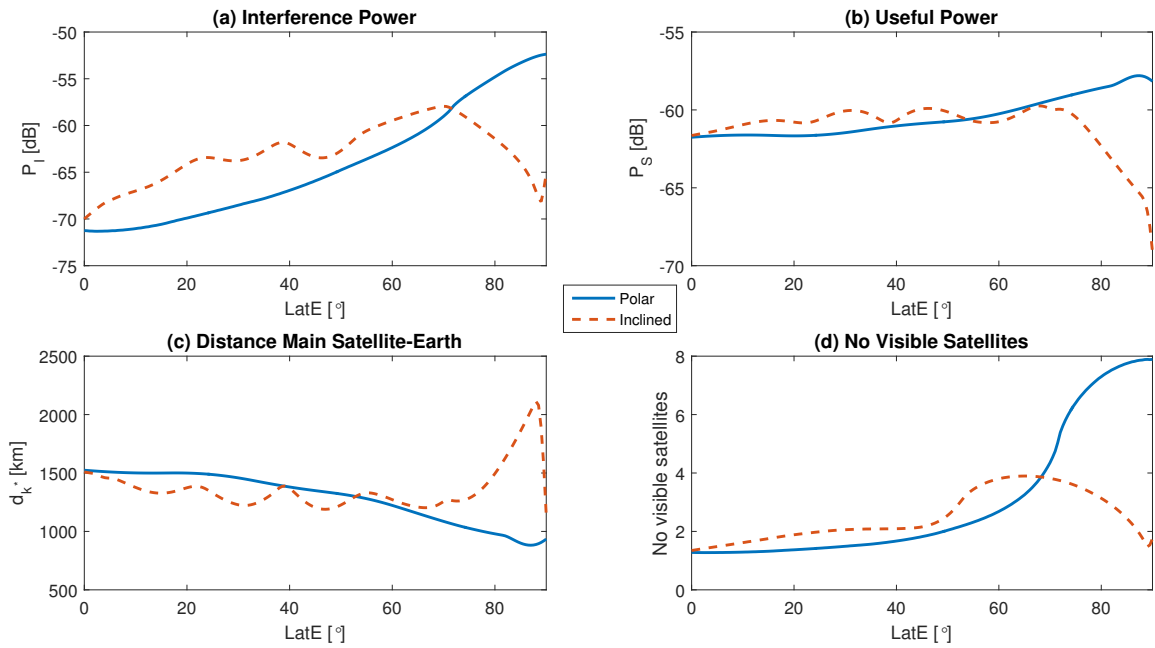
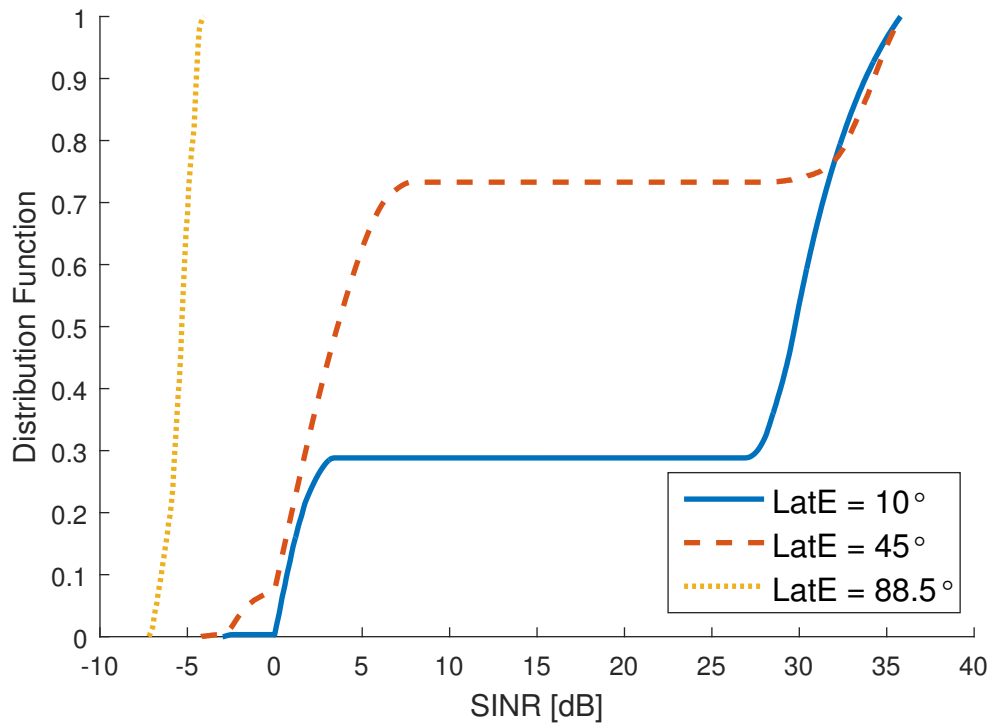
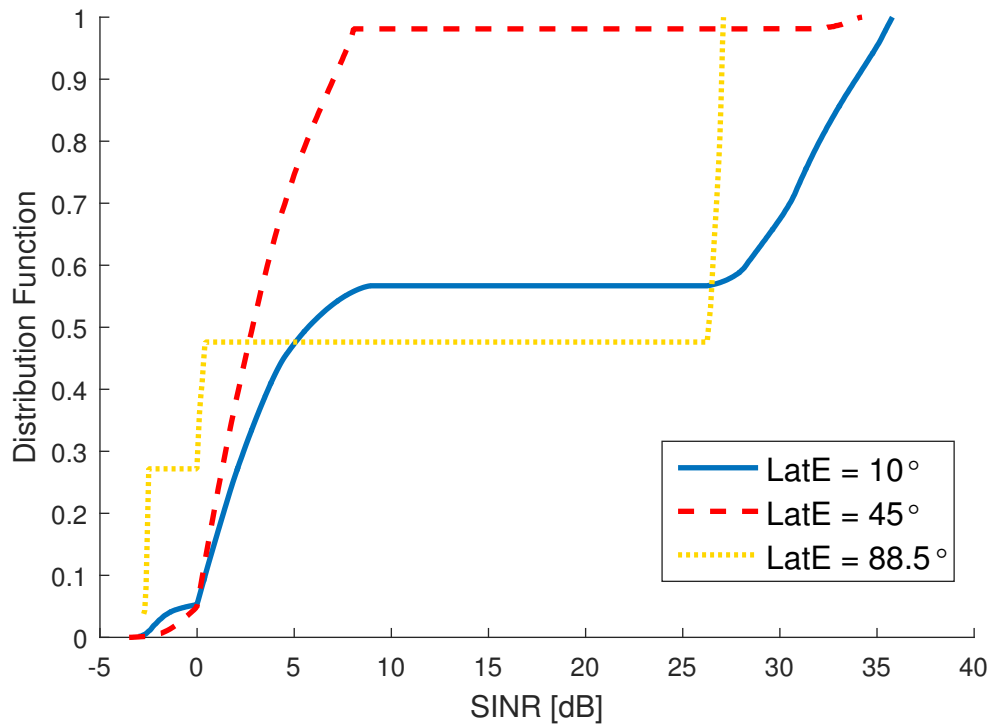


Figure 4.4 Parameters that Define SINR



(a) Polar Constellation



(b) 72° Inclined Constellation

**Figure 4.5** CDF Polar and 72° Inclined Constellations

Figure 4.2 plots how a polar and  $72^\circ$  inclined constellation look like. Figure 4.3 shows the average of the SINR and SNR of a polar constellation and a  $72^\circ$  inclined constellation versus Earth latitudes. Figure 4.5 confronts the Cumulative Distribution Function (CDF) of a polar and a  $72^\circ$  inclined constellation. CDF provides the cumulative probability of an  $x$  value, in other words, it provides the percentage of cases (vertical axis) in which the SINR is less than the abscissa (horizontal axis) at different Earth latitudes. The latitudes chosen have been  $10^\circ$ ,  $45^\circ$  and  $88.5^\circ$ . Figure 4.4 displays the average of the system parameters on which SINR of a polar and a  $72^\circ$  inclined constellation depends on. Since the satellites and the Earth are in constant movement, SINR at a point on Earth does not have a constant value. That is way that the values showed in figs. 4.3 and 4.4 are the average of the results obtained in an orbit period, it means, when the satellites have circled the Earth.

### 4.2.1 Analysis of Polar Constellations

As was mentioned in subsection 3.3.1, polar constellations allow us to better cover the polar regions as satellites pass over them periodically. Thus, they are the starting point of our experimental work. It is worth remembering that there are two possibilities when we are talking about the orbit inclination. A constellation is polar if the orbit inclination is close or equal to  $90^\circ$  and it is considered inclined when its inclination is less than  $90^\circ$ .

Figure 4.3 represents the SNR and the SINR throughout the latitudes of the Earth, from the equator to the polar regions. For the polar constellation, it is observed that SNR has a constant value. This fact can be translated in that the useful power that we receive is always the same, independently of the latitude that we are. On the other hand, SINR suffers a decrease since latitude  $40^\circ$  and it gets worse from latitude  $70^\circ$ , approximately. It is at this point that we feel necessary note that latitude  $90^\circ$  is a conflicting point of the Earth, since it is exactly the middle point of the polar regions and it is always exposed to a higher number of satellites, as it is possible to appreciate in fig. 4.2. Consequently,  $88.5^\circ$  is the last contemplated latitude.

For bringing into light the argumentation of this result, the interference power, the main power, the distance between the main satellite and the Earth's surface and the number of interfering satellites have been also analyzed, collected in fig. 4.4. Although it is obvious, however not this one of more than specify that the useful and the interference power are directly and inversely proportional to the number of interfering satellites and the distance between the main satellite and the Earth, respectively. Results of the polar constellation offer invaluable evidence for admitting that the SINR is worse in the poles because of the increase of interfering satellites

in that region. Although the main power is better, because satellites are closer to Earth, the interfering power is worse and then, the SINR values grows less.

Since values of fig. 4.3 are the result of the average, they do not provide all the information. To know exactly how the values are distributed, we should appeal to the Cumulative Distribution Function (CDF). Therefore, fig. 4.5(a) represents the probability of having lower values of SINR at different latitudes for a polar constellation. Considering that, the value of the SINR is very much contingent on the number of visible satellites, it shows that, when we are very close to the equator (latitude  $10^\circ$ ), in 70% of the cases the number of visible satellites is very low, between one and two, while in the 30%, it is lightly higher but without being a big issue, since the SINR continues being positive. For mid latitudes (latitude  $45^\circ$ ), we realize that the cases with a very reduced number of visible satellites increases to the 70%. Besides, at this latitude, there are already moments in which the number of satellites is such that generates a negative value of SINR, approximately 10% of the cases. The shape of both lines allows us to affirm that the SINR is badly damaged from the appearance of interfering satellites, even if there is just one. At the polar regions (latitude  $88.5^\circ$ ), in the 100% of the cases the number of visible satellites is too high and thus, SINR has always a very low value.

In view of all exposed behind, it could be said that the quality of a polar constellation network, in terms of SINR, is not favorable at the polar regions. Polar orbits assemble to many satellites in the poles, which decrease the SINR value. The satellite concentration in the poles is due to the orbit inclination; therefore, it may be possible to reduce it by choosing a lower value for the constellation inclination.

### 4.2.2 Analysis of Inclined Constellations

Considering the approach described in subsection 3.3.1, if a constellation is not polar, the total Earth coverage is not guarantee. It is necessary to calculate the minimal orbit inclination that assures coverage at the polar regions. Solving eq. 3.6, the minimum orbit inclination for our constellation altitude (765 km) is approximately  $72^\circ$ .

Figure 4.3 includes the values of SNR and SINR if the inclination of the constellation is  $72^\circ$ . For the polar constellation, the value of the SNR is constant, with a lightly increase at the polar regions. However, if we reduce the inclination of the orbit, SNR decreases at the polar regions due to the fact that the distance between the Earth and the satellites increases if the orbit inclination decrease, as it is possible to see in fig.???. Once analyzed the behavior of the SNR, we focus on the concerned



parameter, the SINR. At a glance, it is more irregular in comparison with the SINR of the polar constellation. Observing the polar regions, we could affirm that reducing the orbit inclination improve the value of SINR. However, it cannot be considered an useful solution since the low values of SINR are shifted to Earth's latitudes closer to the orbit inclination.

Looking at fig. 4.4, we can explain the irregularity of the SINR. The variations or jumps are the result of the distance variations. If we reduce the inclination, the orbits overlap at different points of the Earth instead of just at the poles, as occurs if the constellation is polar. The variations of the distance are due to those overlaps. If we add the decrease of the main power because of the distance decrease, we find ourselves at the same case as the polar constellations, but shifted.

As for the polar constellation, we analyze the CDF of the inclined one. Comparing it with the polar constellation one, we can affirm that the reduction of the orbit inclination causes a general decrease of the SINR. At the nearest equator regions, the number of cases with a SINR higher than 25 dB falls by 10%. For mid latitudes, the SINR never excess the 8 dB. Fig. 4.3 shows a high improvement of the SINR at the polar regions, which would have us to think that reduction of orbit inclination is a possible solution. Unfortunately, CDF shows that SINR has a negative value in 30% of the cases and just 50% of the cases it has a value higher than 25 dB, which means that the number of visible satellites at the earth poles is also a problem for inclined constellations.

### 4.2.3 Ground Antennas Directivity

In the previous section, we try to solve the reduction of the SINR at the polar regions by decreasing the orbit inclination. However, it shift the problem to others latitudes and it does not reduce entirely the number of visible satellites at the Earth's poles. Therefore, in this section we propose increase the SINR value by changing the directivity of the ground antennas.

Antennas can be classified by their directivity in omnidirectional and directional antennas. Roughly speaking, the directivity of an antenna determines its gain at the different points of the space. Omnidirectional antennas provide the same gain in all the directions while directional ones focus the gain on one direction and it decreases with the incidence angle.

In order to reduce the  $P_{RX}$  of the interfering satellites,  $P_i$ , we decided to use directional ground antennas. Optimizing the ground antennas gain for the main satellite

and simplifying the simulator, we have implemented the ground antennas as dipoles, which means that the ground antenna gain follows the equation

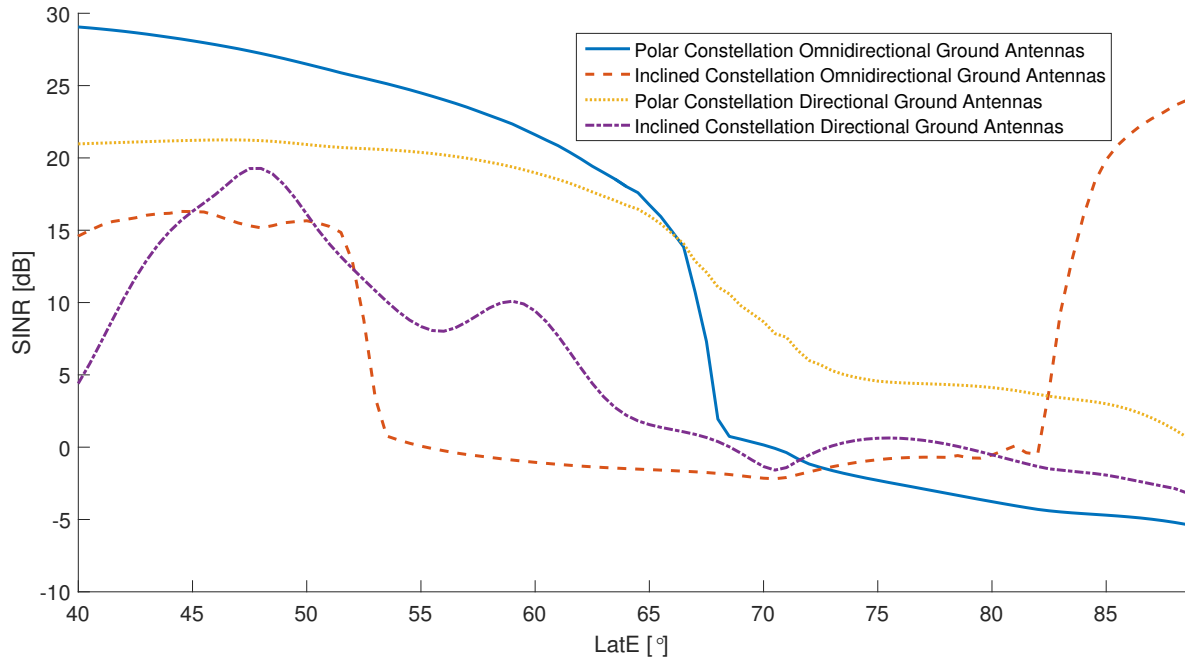
$$G_{RX_k}(\sigma_k) = G_{RX_{max}} \cdot \cos(\sigma_k)^2, \quad (4.8)$$

where  $\sigma$  is the incidence angle of the satellite  $k$ , calculated as

$$\sigma_k = 90 - \phi_k, \quad (4.9)$$

being  $\phi_k$  the elevation of the satellite  $k$ . Considering eq. 4.8, the maximum gain is at  $\sigma_k = 90^\circ$  and it is lower the smaller the elevation angle. Therefore, the  $G_{RX}$  is better for the satellite who is placed above the point on Earth (the main satellite) and worse for the interfering ones.

Figure 4.6 illustrates the SINR of the constellations discussed in subsections 4.2.1 and 4.2.2. It is plain to see in fig. 4.6 that the directional antennas work for the polar constellation but they are detrimental for the inclined one. This is because the radiation pattern, the pattern that shows how the antenna gain is distributed in the space, is pointing up and then, you need to increase too much the inclination, until  $i = 88^\circ$ , to have values of  $G_{RX}$  good enough to provide an improvement of SINR. Fortunately, results are satisfactory for the polar constellation, since SINR increases approximately 8 dB, causing that it acquires a positive value. However, as happens in fig. 4.3, averages do not tell us the whole story and it is necessary to analyze the CDF.

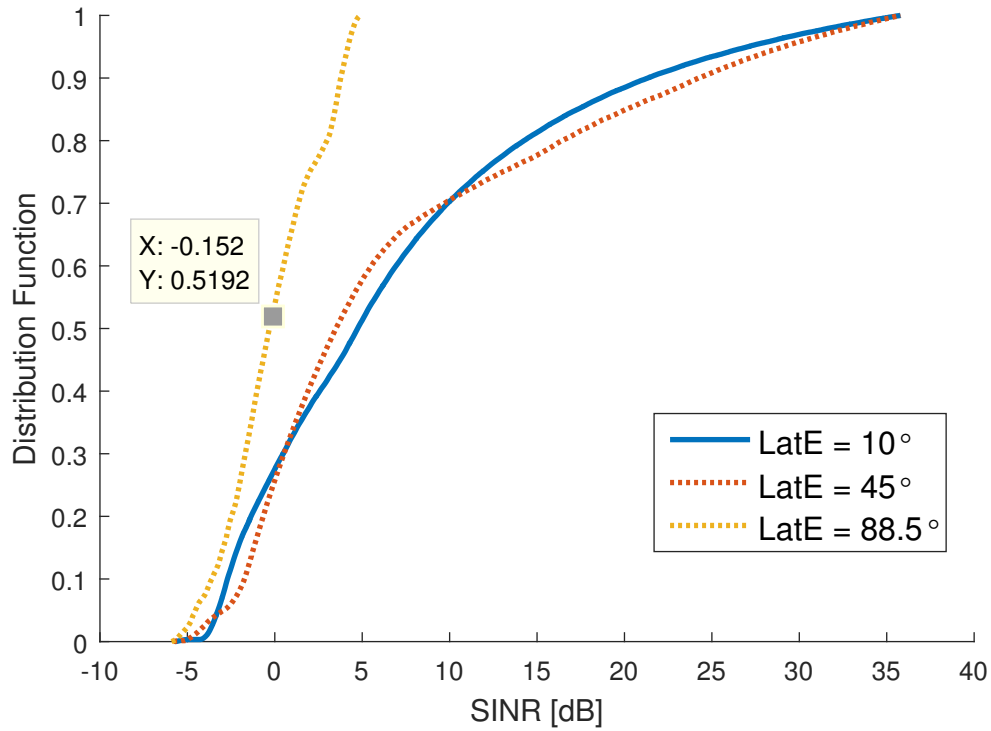


**Figure 4.6** SINR Omnidirectional and Directional Ground Antennas

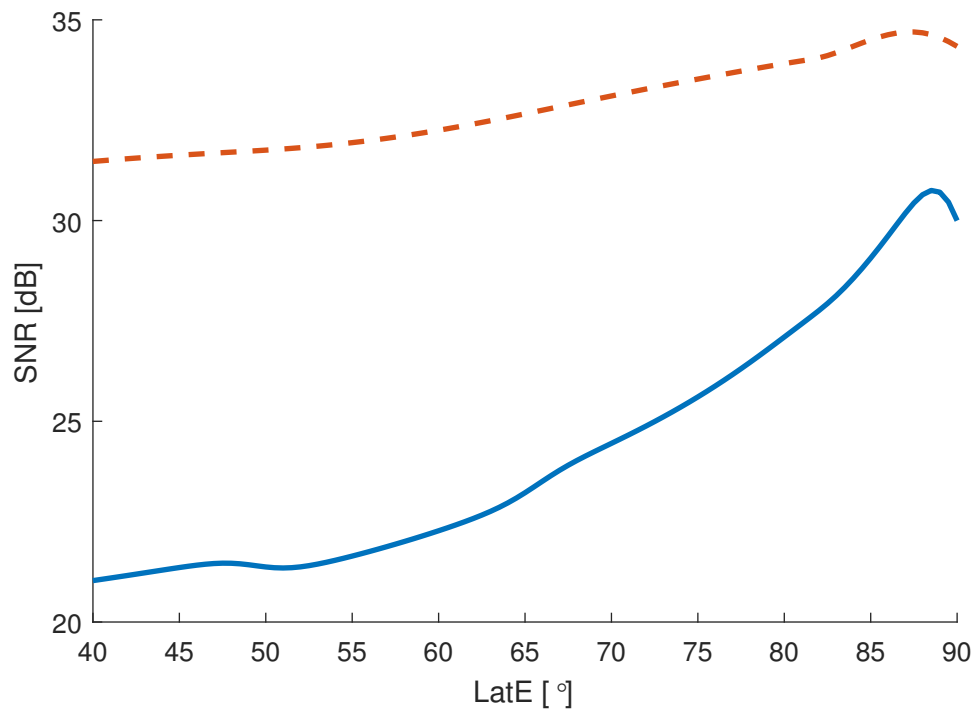
Figure 4.7 illustrates the CDF of the polar constellation when the ground antennas are directional. If we remember fig. 4.5(a), it allowed us distinguish between two scenarios: when the number of visible satellites was higher than three and when it was between one and two. We said that the appearance of a single interfering satellite was enough to decrease sharply the value of the SINR. Furthermore, the shape of the curve at equator latitudes and at mid latitudes was different, which means that SINR is not constant. However, fig. 4.7 tells us a different story. Since this graphic, we can appreciate the advantages and disadvantages of the use of directional ground antennas. When we are in a scenario where the concentration of visible satellites is low, then, the main satellite is not always just above the ground antenna, which is translated into a reduction of the  $G_{RX}$  and, thus, of the  $P_S$ . To better observe this fact, we analyze the SNR of the polar constellation using directional antennas. Figure 4.8 illustrates that SNR is higher when we are close to the polar regions, which means that  $P_S$  is higher too, while it decreases when we move towards the equator. From this and considering fig. 4.4(d), we can deduce that the downside of the use of directional ground antennas is that SNR decreases when the satellites are dispersed while it increase when they are very concentrated. On the other hand, the great advantage is that the satellites that most suffer the decrease of their  $G_{RX}$  are the interfering ones. Observing fig. 4.7 and focus on the polar regions, we realize that now, the number of cases with a negative SINR is reduced by half.

For all these reasons, we can affirm that the use of directional ground antennas

improves the quality of the system, in terms of SINR, reducing the huge negative impact of the interfering satellites. Being conscious that just in 50% of the cases the SINR improves, we consider that the increase of the directivity will increase SINR value. Therefore, it is just the point of start of future research on high directivity ground antennas as part of the LEO communication networks.



*Figure 4.7 CDF Directional Ground Antennas Polar Constellation*



*Figure 4.8 SNR Omnidirectional and Directional Ground Antennas Polar Constellation*

## 5. CONCLUSIONS

Through this thesis, the use of low Earth orbit communication networks, as a solution of the bad coverage at the polar regions provided by geostationary satellites, has been analyzed. Accordingly, it has been necessary to get to know the theoretical concepts related to satellite communications in general, as the orbital mechanics, link design and the satellite position trigonometry, as well as those related to LEO constellation design.

Once the above mentioned knowledge was acquired, a simulator has been developed for the purpose of analyze the interference problems of polar LEO constellations at the ground stations. The parameter chosen for such an evaluation was the SINR. It has allowed us to find out that SINR value decreases at the polar regions and its cause, the huge concentration of satellites above the poles of the Earth. At first, we tried to solve the problem by decreasing the orbit inclination. Nonetheless, we detected that the reduction of the orbit inclination overlaped the orbits above different points of the Earth, not just above the equator, which causes the irregular behaviour of SINR. Additionally, we discovered that the degrees latitude where SINR decreases the most corresponded with the inclination degree. For those reason, reduction of the orbit inclination was discarded and the use of directional antennas came up as another possible solution. Fortunately, this change generated a lightly increase of SINR, which allowed us to affirm that the use of high-directional ground antennas could be a possible way to improve the SINR of polar constellations at the polar regions.

To sum up, this thesis affirms the use of low Earth orbit constellations to provide coverage at the polar regions. Since the problem of this communication system is the low value of SINR at those regions, we propose the use of high directional ground antennas as a possible way to improve its value and thus, the quality of the system.

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