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Cubesat Constellation

Astrea

Report

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Constellation Deployment

1.1 Constellation Deployment Department

This introductory section aims to present the Constellation Deployment Department and its duty.
The mentioned department is composed of four members of the Astrea Constellation. It is created in order to asses all the issues related to the launcher which will put the constellation into orbit and the different strategies to be followed to ensure the adequate set up and posterior maintenance of the constellation. In the Project Charter document, four tasks are assigned to the department:

- A comparison among the existing launching platforms to find one that fulfills the requirements of the constellation at a reasonable economic conditions.
- The booking of a launching date if the selected launcher requires it.
- The following of the Joint Space Operation Center regulation to ensure that the launch procedure accomplishes the legislation.
- The design of an End of Life and a Replacement strategy.

In order to simplify the accomplishment of this assignments, the department decides to divide its tasks into six parts each of one is a section of this report:

- Launching System
- Deployer
- First Placement
- Replacement Strategy
- Spare Strategy
- End of Life Strategy

1.2 Launching System

The aim of this section is the selection of a launching platform. First of all, a review of the available ones on the market is carried out, secondly a small group of launchers is chosen and finally, an optimization is developed in order to find the most suitable system.

1.2.1 Launch site and vehicle analysis

Now a days there is such a great amount of launchers available over the world. Nevertheless, most of them are designed for very specific missions. In addition, the space career of a country is usually highly attached to the government, for both economic and political reasons. When searching for a launching system, some parameters have to be taken into an account like payload mass, possible inclination angles, launching site, etc. This analysis only considers those rockets which parameters seem adequate for the Astrea constellation launching.

A general research is done in order to filter all the launchers that can be discarded without any study. The result of this research is that there are seven potential rockets in the market capable of deploying the constellation as well as carrying out the replacement needs. The launchers can be divided in two categories: the powerful ones and the small ones. The first ones are capable of carrying heavy payloads, however they present high operation costs whereas the second ones are way more economic due to the reduced size. In addition, the small rockets are more focused on commercial flights without having to attend governmental issues.

The following table displays the first seven candidates.

ENTERPRISE	ROCKET	LAUNCHING SITE	TYPE
Rocket Labs	Electron	North Island (New Zealand)	Light
Kosmostras	Dpner	Baikonur Cosmodrome (Kazakhstan)	Light
Arianespace	Ariane V	Guiana Space Center (French Guiana)	Heavy
Arianespace	Vega	Guiana Space Center (French Guiana)	Light
SapceX	Falcon 9	USA	Heavy
PLDSpace	ARION-2	Huelva and Cape Canaveral	Light
LEO Launch and Logistics	-	USA	Light

Table 1.2.1: List of Launchers

1.2.2 Last candidates and selection

Once this first selection is done, more accurate information is needed so as to reach a reliable conclusion. However, none of these enterprises shows its information on the Internet or any similar divulgation channel with the exception of Arianespace. Thus, all of them must be contacted to get the needed data. The same email is sent to all seven enterprises and several days later, three of them show interest in the Astrea constellation: Rocket Labs, PLDSpace and LEO Launch & Logistics. Since the other enterprises do not answer the requests and, as a consequence, will not provide the necessary information, they can be directly discarded. Hence, the candidates list is reduced to those three who responded the enquire plus Vega, given that its information is available online. Although the needed data of Ariane V is also known, it is discarded by the fact that it presents high operation costs and it is capable of carrying about 5,000 cubesats 3U when the Astrea constellation will have 168 sats. Therefore, the four remaining candidates are studied in more detail and are subjected to an optimization.

In order to find the most suitable option achieving the project objectives, it is thought to do an evaluation process following the Ordered Weighted Average (OWA) method . First of all, the required parameters for the decision have to be determined. According to the orbit design, the range of inclinations, the number of orbital planes and the range of heights must be taken into an account. Nevertheless, more parameters are needed in order to ensure a reliable result: cost per satellite, frequency of launchings per year and number of satellites deployed per launch. Both range of inclinations and number of satellites per launch act as a restriction due to the following two reasons. First, since orbital plane changes are very expensive and are out of consideration, the minimum number of launchings must equal the number of orbital planes. In addition, being capable of deploying the constellation with the minimum number of launchings is an adequate solution. This turns the number of CubeSats per launch into a restriction: the chosen launcher must be capable of launching at least the number of satellites in an orbital plane. Secondly, the inclination is considered a restriction by the fact that if a rocket is not capable of deploying a satellite in the desired inclination, it makes no sense to use it.

Since the number of orbital planes is 8 and the inclination is 72°, any launcher which doesn't fulfills one of this restrictions can be automatically rejected.

Moreover, the following table contains all the information mentioned above which is helpful to compare the different launchers and see if they accomplish the basic features.

Parameters	Rocket Lab	PLD	LEO L&L	Vega
Satellites/Launch	24	34	150	325
Inclination(°)	39.2 to 99	116 or 140	any	any
Cost/Satellite (US dollars)	240,000	-	266,667	100,000
Orbital planes	1	1	1	1
Frequency/year	9	8	8	2
Range of heights (km)	LEO	LEO	LEO	LEO

Table 1.2.2: Criteria

It is important to point out that all the rockets available in the market can achieve the necessary amount of satellites per launch. Although all of them reach the height the CubeSats need, PLD does not attempt the inclination needed which is 72°. As a result, this launcher is not appropriate for the project purpose and it is rejected. According to the remaining 3 candidates, all of them are adequate candidates, nevertheless there is a characteristic that may interfere with the mission goals. At first instance, the frequency per year has not been considered a critical parameter. Those have been chosen regarding orbital parameters only, however, although the frequency does not influence de capability of the rocket of deploying a CubeSat in the desired orbit, it can compromise the set up of the constellation and the posterior replacements. The lower the frequency is, the slower the deployment will be. Therefore, the frequency of the three remaining candidates must be analyzed. As seen in the table, Vega presents the lowest frequency (two launchings per year). This value is not acceptable due to the intention of deploying one single orbital plane per launch. The placement of the whole constellation would last four years, this mean that de first planes would be near their replacement time while the last ones would only have been nearly a year in orbit. Thus, Vega can also be discarded.
This leaves the selection with only two options: Rocket Lab and LEO Launch&Logistics. An Ordered Weighted Average can be made between those two candidates taking the cost/satellite, the number of orbital planes, the frequency and the range of heights into account. Yet, they both present the same number of planes and range of heights, consequently the OWA can be done regarding only the two cost and frequency. The first

has to be minimized and the second maximized. Since Rocket Lab presents best values in one parameter and the other (240,000 US dollars vs 266,667 and 9 launchings/year vs 8) there is no need to develop an OWA. In addition, an e-mail from Rocket Lab is received stating that a launch per week is achievable. Thus, the chosen rocket is Electron, from Rocket Lab enterprise. This rocket fulfills all the requirements of the constellation.

Figure 1.2.1: Electron Rocket

1.2.3 Launcher overview

Following, a brief description of Electron is provided.

Figure 1.2.2: Second Stage

Shown in 1.2.1, Electron is a two stage light rocket constructed from carbon fiber composite. It is powered by ten Rutherford engines, all of them use liquid oxygen (LOX) and rocket kerosene. The first stage has nine out of the ten engines which generate 152 kN of thrust. The second one, displayed in 1.2.2, has the remaining engine which produces 22 kN. The second stage contains the fairing where the payload is placed. Electron is 17 m long and its diameter is 1.2 m. It is capable of launching 24 3U CubeSats every week at a LEO orbit with a range of inclinations from 39.2 to 99 degrees.

Figure 1.2.3: Electron Rocket Fairing

The injection maneuver is carried out following the flight profile shown in the table 2.3 . The accuracy of the injection is mission dependent, however a typical value would be ±15 Km. According to the CubeSat/Fairing interface, Electron is compatible with the standard CubeSat deployers like ISIS or P-POD, in addition, if those deployers are used, Rocked Lab is able to situate the satellites inside the rocket in a more efficient disposition.

Event	Time (s)	Altitude (km)
Lift-off	0	0
Max Q	79	11
MECO/S1 Separation	152	69
Stage 2 Igintion	159	69
Farinig Separation	183	110
SECO	457	284
Satege 2 Apogee Kick	3157	499
Payload Separation	3200	500

Table 1.2.3: Flight Profile

Rocket Lab facilities are located in New Zeland. The test laboratories are placed near the airport of Auckland and the launch site is in Mahia (1.2.4).
Finally, the cost per satellite is 240.000 US dollars or if the rocket is totally filled, 5.760.000 US dollars the entire launch.

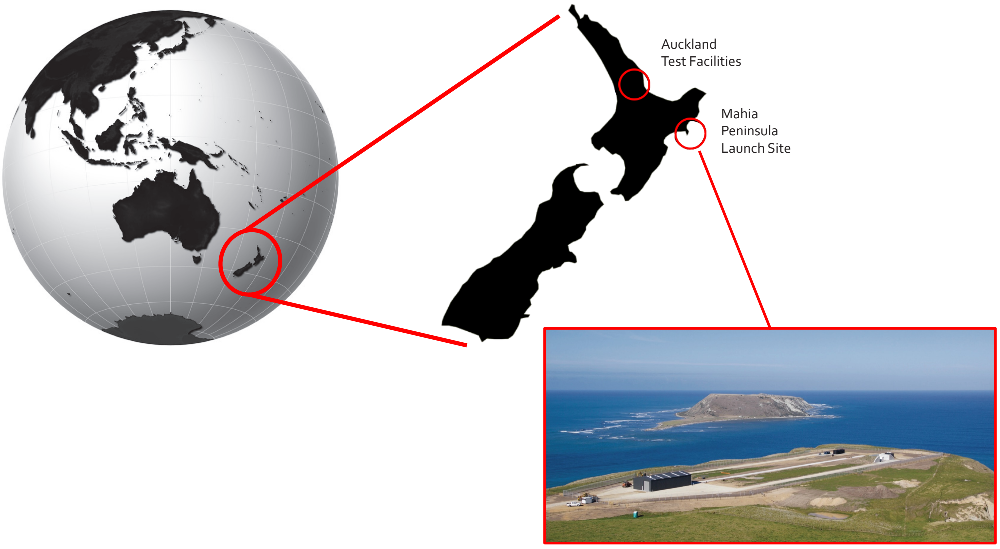


Figure 1.2.4: Rocket Lab Facilities

1.3 Deployer

The objective of this section is to give a brief explanation of what is a deployer and how it works. Additionally, some examples of available ones in the market are shown and so is the selected one.
As introduced above, there must be an adaptor between the rocket and the satellite in order to ensure subjection during the flight, efficient organization of the space in the fairing and a correct separation during the injection maneuver. This duty falls on the deployer. It consists on a prismatic structure prepared to carry the CubeSat inside. When the desired orbit is reached, the deployer uncovers one of its faces so as to let the satellite leave. There is a spring in the bottom that provides a little push to ensure that the CubeSat separates from the rocket. There are many types of deployers, some of them are designed for an specific type of mission. As stated before, Electron is compatible with the standard CubeSat deployers, hence, only this type is considered. Similar to the case of the launcher selection, almost all the enterprises don't show enough information on the internet to reach a reliable conclusion, thus, some of them are contacted. Only two answers are obtained, one from ISIS (ISIPOD Deployer) and GAUSS (GPOD deployer). POD stands for Pico-satellite Orbital Deployer.
They both present similar characteristics, however there are some differences. First, the main features that both offer are outlined, secondly, the small differences between them are pointed out.

- Main features
  - Provide deployment status signal.
  - No battery needed nor external power source
  - No pyrotechnics
  - Protect the CubeSat from external environment
  - Mechanically interfaces with the CubeSats by means of guidelines
  - Mechanically interfaces with the launch vehicle by means of standard fasteners
  - Qualified for multiple of launch vehicles
- ISIPOD
  - The satellites are fully enclosed inside the deployer, once the CubeSat is fit in, there is no access to it (see image 1.3.1)
  - Electrically interfaces with launch vehicle for telemetry
- GPOD

- Accessible panels: all the side panels allow the access to the integrated CubSat (see image 1.3.2). This means that the entire area between the guide rails over the entire CubeSat length may be freely accessed.
- The price for a single deployer 3U is 16000 euros.

In order to reach a reliable conclusion, two issues must be taken into consideration. First, the CubeSats of the Astrea Constellation are equipped with thrusters which increase the length of the satellite, thus, the deployer chosen cannot be fully closed. This condition automatically rejects the ISIPOD, nevertheless, there is a second reason for choosing the GPOD, the enterprise ISIS does not show the prices of their deployers even when a request is sent. Without this information it is decided that it cannot be taken into account.

Figure 1.3.1: ISIPOD

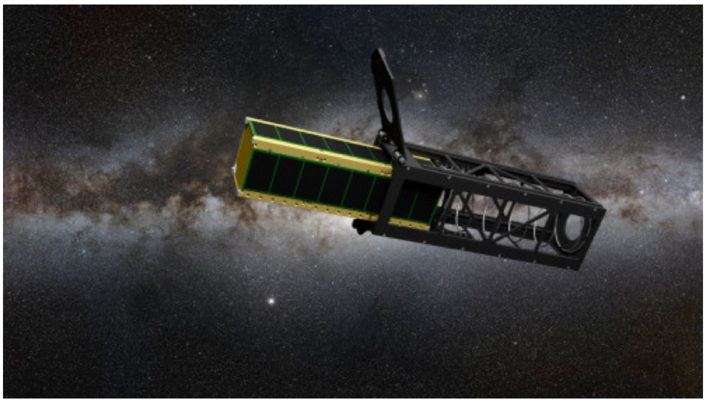


Figure 1.3.2: GPOD

1.4 First Placement

The aim of this part is to explain the first placement of the constellation. It is divided in two parts, the first one is intended to give a first approach to the logistics involved in the first placement. The second one is focused on the maneuver required so as to deploy the satellites into orbit.

1.4.1 First Placement logistics

The objective of this section is to give a general idea of the first placement logistics. Although some temporal data is provided, it is a qualitative explanation, only to clarify the order in which the different elements must be purchased, assembled, transported, etc. Rocket Lab provides two gantt diagrams on which their launching procedure is explained (images 1.4.1 and 1.4.2)

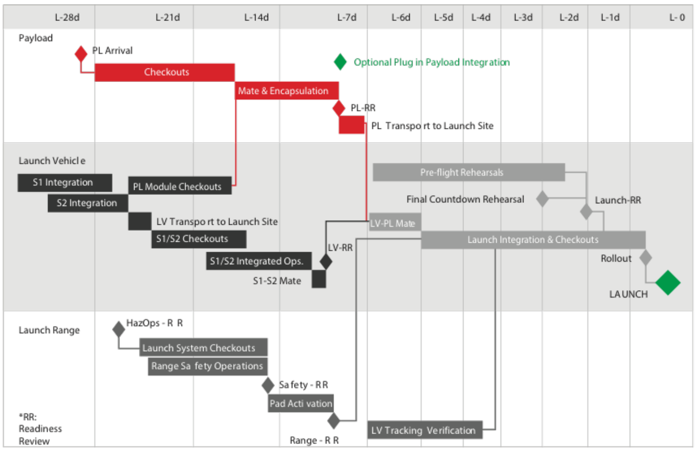


Figure 1.4.1: Launch Range Operations Flow/Schedule

The constellation has 168 3U CubeSats distributed in 8 orbital planes. One of the conclusions stated in the Launching System section is that the quickest way to deploy the whole constellation is by carrying out one launching per orbital plane, consequently, the first placement consists on 8 launchings and all the logistics around them. Rocket Lab is capable of launching once a week, therefore, the first placement takes 8 weeks. Due to the magnitude of the mission, the whole rocket is filled with Astrea satellites, hence, there is no need to share it with other missions. Also, Rocket Lab offers an online booking procedure to reserve a date, however, The Payload User's Guide (provided by Rocket Lab) recommends contacting directly with them in case of filling several rockets with a mission instead of booking online.

Since the schedule of Rocket Lab is fixed, the logistics needed in order to deliver the payload on time are going to be explained starting from the launching day, going back

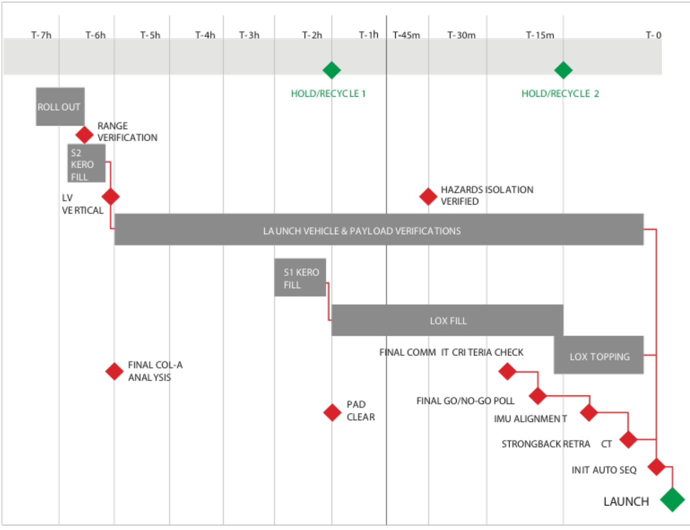


Figure 1.4.2: Countdown Operations Flow

in time until the first movements in Terrassa, where the satellites are assembled. The launching day is designed L henceforth, and all the other ones are referred to this one (eg. L-30d means 30 days before launching).

As seen in figure 1.4.1, Rocket Lab needs 28 days to prepare the payload, place it into the rocket and prepare the rocket itself. Thus, the CubeSats have to arrive at the Rocket Lab launching facilities the L-28d. The satellites are assembled in Terrassa, hence, they have to be brought to New Zealand. Due to the large amount of CubeSats, the chosen transport is sea transportation. The estimated time from Terrassa to New Zealand is 30 days, so the CubeSats have to leave Terrassa the L-58d. At this point, there is two options. First, the 168 satellites can be divided in groups of 21 (number of sats in an orbital planes) and sent separately to New Zealand so that every group arrives 28 days before its departure. The other option is to send all 168 CubeSats at the same time so that they arrive 28 days before the first launching. Each option has its pros and its drawbacks. Option one does not need to store the satellites in Rocket Lab facilites, conversely, the logistics of carrying each group of satellites separately is complicated. Option two allows to assemble all the satellites and send them in one ship, however, once they arrive to their destination, they have to be stored somewhere until their departure day arrives. Option two is selected because it is simpler and it is more likely to not cause delays delivering the payload to Rocket Lab, in addition, it is concluded that sending eight ships with one week separation is not as efficient as sending a single one.
The estimated time of assembling the satellites is twelve months, consequently, they have to be ordered the L-423d.
As clarified above, it is important to remember that the stated times are an approximation and the goal of this section is to give a first idea of the order of the different actions.

1.4.2 1st Placement Maneuver

Once the Constellation is designed, it is essential to plan a proper procedure to put it in orbit. The Constellation is configured in several planes and satellites in each plane which work and communicate together in order to give signal coverage around the globe to finally accomplish their final purpose: intercommunicate other satellites form our customers.

One of the purposes of the project is to ensure the system is able to provide partial service right from the very beginning of its life, that is since the first orbital plane is put into orbit. Therefore, along with the maneuvers required to separate satellites in a certain orbital plane, the order in which the planes are put into orbit will also be assessed in this section. This particular section is crucial as it describes how the constellation is born.

1.4.3 In-Orbit Injection

It wouldn't be fair to start without mentioning the spaceship that will bring the whole system to life, and this is no more and no less than the Electron, from Rocketlab USA in New Zealand. The Electron is able to carry 24 3U CubeSats at once. Since 21 is the number of satellites needed in 1 orbital plane, it will be able to put one orbital plane into orbit in just one launch using the procedure described in the upcoming paragraphs.

Before starting any procedure description, it is important to set a start point. The first consideration is that there are still no Astrea satellites orbiting the earth. Therefore it is the first orbital plane that will be put into orbit. It is also considered that the rocket loaded with the 21 satellites has already accomplished all necessary maneuvers after lift-off and has just been able to arrive at the satellite's orbit, that is, proper altitude above Earth and proper tangential velocity. Of course at this point only the 2nd stage of the initial Electron rocket remains. Moreover, this stage is the one responsible of carrying the payload along with every single deployer. Once the start point is set, it is possible to thoroughly describe the procedure.

At the very described moment the first CubeSat is deployed into its final orbit around the Earth, which is a circular orbit at $542\,km$ above Earth's surface. In order to deploy the second satellite at a given phase separation from the first one, the rocket must enter into an elliptical orbit with a slower period. Adopting this procedure will allow the needed phase separation between satellites given the fact that after one revolution of the rocket around the Earth, the first satellite will have gone through one revolution and a fraction more. In other words, at the very moment the rocket passes through the initial point which is tangential to the satellite's orbit, the first deployed satellite will be phase-wise ahead of the rocket. Obviously, the elliptical orbit mentioned must be accurately computed in terms of the increments in speed required to enter into it.

In a more schematic way, the procedure goes as follows:

1. The rocket goes through the procedure designed by Rocketlab USA to get to the destination orbit. The approximate trajectory during this stage is represented in 1.4.3.Right after entering into the destination orbit, the first satellite is deployed into it as seen in 1.4.3 represented with a red dot.
2. Once the latter is completed, the rocket's engine gives it the necessary ΔV in order to get to the elliptical spacing orbit. In 1.4.4 half a revolution of the rocket is represented along with the orbit of the first deployed satellite at the same point in time.
3. After one full revolution of the rocket in the elliptical orbit, the first satellite will have left the right phase spacing with respect to the rocket. At this point the rocket's engine gives the same ΔV as in 2 but negative. This will cause it to enter again into the circular orbit of the satellites. At this point the rocket deploys the second satellite as shown in 1.4.5. Right after this deployment the rocket enters into the elliptical orbit again.
4. 1.4.6 represents again half a revolution of the rocket in the elliptical orbit along with the deployed satellites so far.
5. Finally, the rocket reduces its velocity again to enter into the circular destination orbit in order to deploy the third satellite (1.4.7).
6. The procedure is iterated until the orbital plane is full.

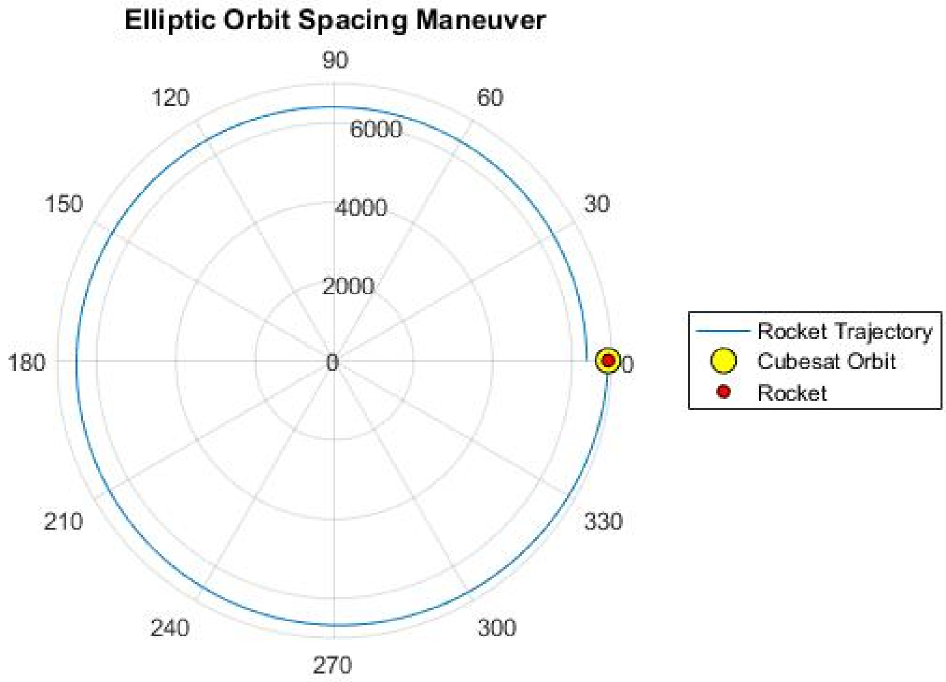


Figure 1.4.3: Rocket's trajectory from lift-off to final orbit.

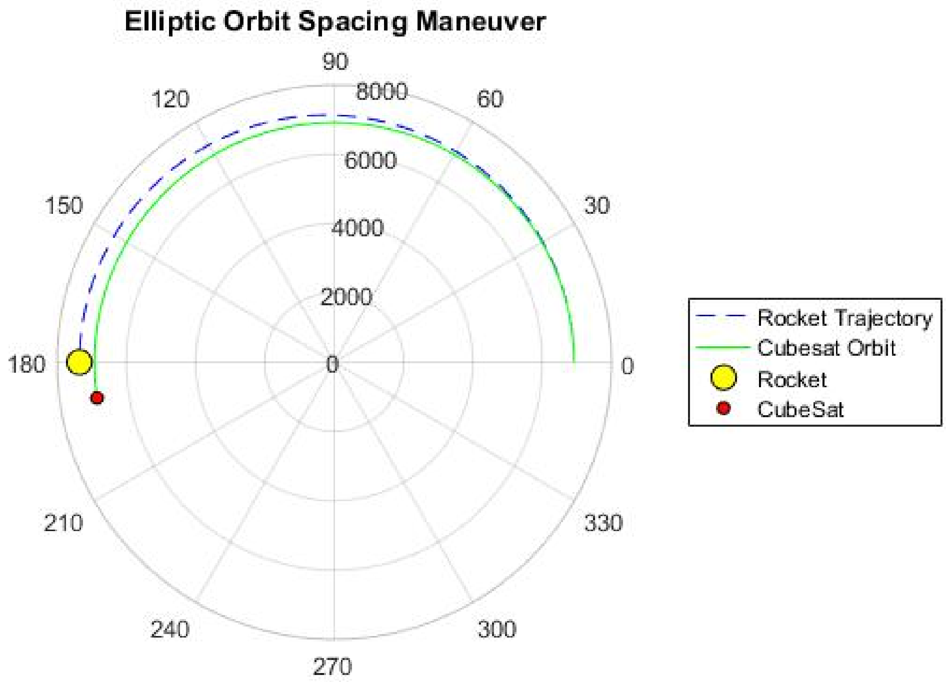


Figure 1.4.4: Half of a revolution of the rocket in the elliptical spacing orbit.

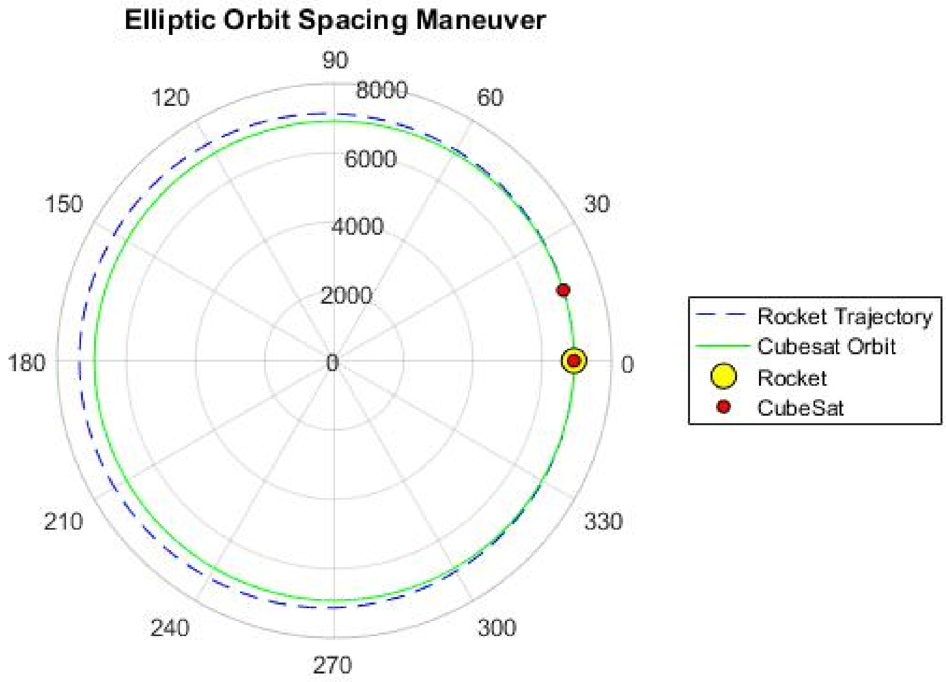


Figure 1.4.5: Deployment of the second satellite.

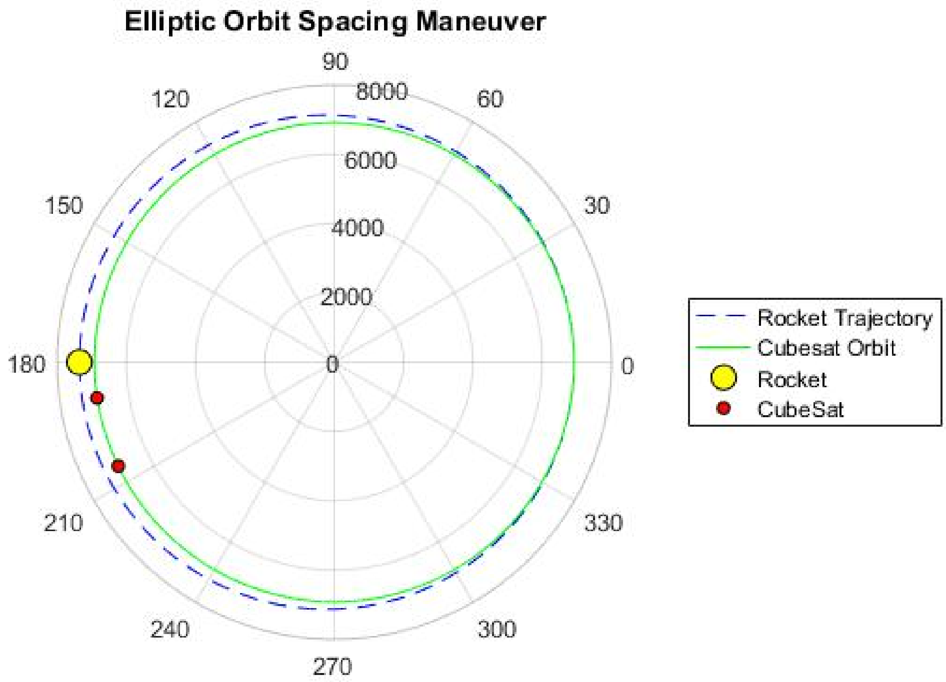


Figure 1.4.6: Half of a revolution of the rocket after the deployment of the second satellite.

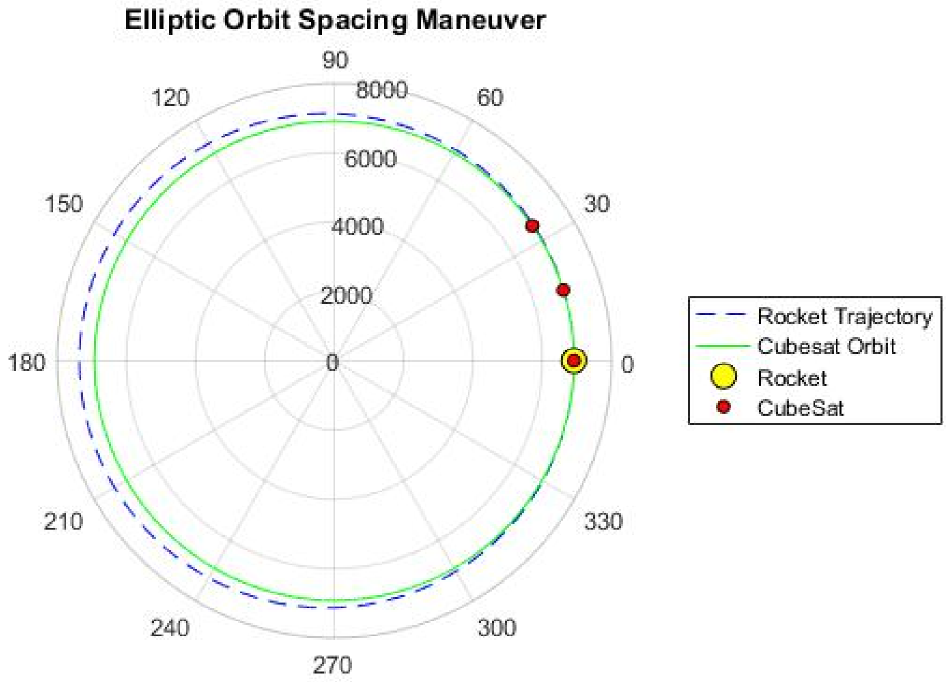


Figure 1.4.7: Deployment of the third satellite.

Having pointed all of the above, it would make no sense to proceed without thoroughly going through the calculations of every single one of the required parameters to perform the manoeuvre. The first thing to take into account is the number of satellites for orbital plane. A number of 21 satellites per plane has been established, thus, a separation of $360°/21 = 17.14°$ between satellites will have to be accomplished. The velocity of the satellites and the period of their orbit is now computed:

$$V_s = \sqrt{\frac{GM_t}{R_t + h}}$$

$$T_s = \frac{2\pi * (R_t + h)}{V_s}$$

Where R_t and h are Earth's radius and height above Earth's surface respectively. For $h = 542\,km$, the values obtained are $V_s = 7,589.6\,m/s$ and $T_s = 5,723.1\,s$. Let's call the spacing between satellites $\theta = \frac{360°}{21} = 17.14°$ and $R = R_t + h$. Using these values it is possible to compute the period of the elliptical orbit, T_r, along with the rest of the parameters:

$$T_r = T_s + \frac{\theta R}{V_s} = 5,995.6\,s$$

$$a = (\frac{T_r}{2\pi}^2 GM_t)^{\frac{1}{3}} = 7,130.8\,km$$

$$R_1 = R; \quad R_2 = 2a - R_1$$

$$c = a - R_1; \quad b = \sqrt{a^2 - c^2}$$

$$\epsilon = \sqrt{1 - \frac{b^2}{a^2}} = 0.0305$$

$$\Delta V = \sqrt{\frac{GM_t}{R1}}\,(\sqrt{\frac{2R_2}{R1 + R2}} - 1) = 115.01\,m/s$$

Astrea's main purpose when it comes to 1st placement is to provide service as quickly as possible. This means that the time it takes to put a plane into orbit is crucial. This time will be determined by the period of the elliptical separation orbit that the rocket uses between deployments and of course by the number of satellites in each plane. Since 21 are the satellites that need to be put in orbit, 21 elliptical orbits will be needed. Therefore the time needed for one orbital plane is $3200\,s + 21 * T_r = 129,191.6\,s$ which means 35.9 hours.

1.4.3.1 Plane Order

Having described the procedure used to put one orbital plane in orbit, it is now time to describe the order in which all of the 8 planes are put into orbit. The fact that establishes one path or another is the fact that satellites can only communicate with neighbours, that is, one satellite can only communicate with its neighbours from the same plane and the neighbours from the neighbour planes.

When it comes to the order in which the planes are put into orbit, there are two main ways that come to mind. The first one is putting the planes consecutively into orbit. The second one is to put the planes into orbit leaving space between them for future planes. For example plane number one is put into orbit. The second plane to be put into orbit leaves space for one plane in between them. Then the third leaves space for one plane from the second, and so on. Leaving more space than for one plane could also be an option.

On the one hand, when using the first way the satellites from each plane could communicate with the ones from their neighbourhood. Therefore the range of communication would start being narrower but as new planes are put into orbit, the range would become wider. For instance, when three planes are already working, a given satellite form a customer could communicate with satellites that are at the other side of the planet in a determined range given by the width of signal that those three orbital planes could cover. When new planes are put into orbit this width becomes bigger up until the full globe is covered. Of course the main drawback of using this consecutive way of putting planes into orbit would be the long time of inactivity right at the beginning when few planes are working.

On the other hand, when using the second described way, the satellites can't communicate with other satellites from neighbour planes but the time of inactivity for customer's satellites would be less as a gap between planes is left for future ones. Nevertheless, this kind of configuration has a huge drawback and it's that when a satellite communicates with one given plane, this one can only communicate with other satellites that are in the range of signal emission of that given plane. This is due to the fact that as neighbour planes are further apart they can't communicate with each other and therefore the range of communication is affected.

. Having pointed out all of the advantages and drawbacks of each configuration it is time to choose and it all comes down to Astrea's preferences. The configuration that fulfils these preferences for the most part is the consecutive .It allows the satellites to communicate in a broader range as the constellation grows and progressively conquer the sky.

1.5 Replacement Strategy

Due to the lifespan of the CubeSats, the whole constellation is replaced every five years, hence, a replacement strategy has to be designed. As stated in the First Placement section, the orbital planes are deployed consecutively, thus, the replacement has to be so also. One simple solution could be waiting for a plane to de-orbit and then place a new one into the same position, however, this procedure would spend to much time by the fact that the satellites approach the atmosphere in a very slow rate. Additionally, the replacement of different planes would probably overlap. Since the first placement has been carefully designed, it is thought to adapt the same procedure to the replacement process, that means, to consider the replacements as a first placement. Obviously, some differences have to be taken into account given that at this point there is a constellation providing full service to the customers. The problem remains on the fact that in order to use the same strategy, the replacement needs to be achieved in eight weeks, therefore, the new orbital planes cannot be situated into the same position than the old ones. A rapid replacement is also interesting regarding the need of providing full service to the customers without interruption. The solution adopted consists on placing the new planes between the old ones consecutively, following the order of the first placement. In order to clarify the process, a detailed explanation is shown below:
First of all, since different orbital planes are going to be taken into account in this explanation a nomenclature is set: old planes are the ones that have to be replaced, the new ones are the planes that will substitute them. If a plane is named with the number 1, it means that is the first one to be placed (old or new) and so on (2,3,..,21).

- The new plane 1 is placed between the old plane 1 and the old plane 21.
- The new plane 2 is placed between the old plane 1 and the old plane 2 to ensure that at the very moment the first old plane begins to decay, it does not appear a gap.
- At this point, the following new planes are deployed consecutively between the old ones until the constellation is fully renovated. This maneuver is repeated every five years to ensure the continuity of the Astrea Constellation. The following images show the process explained above.

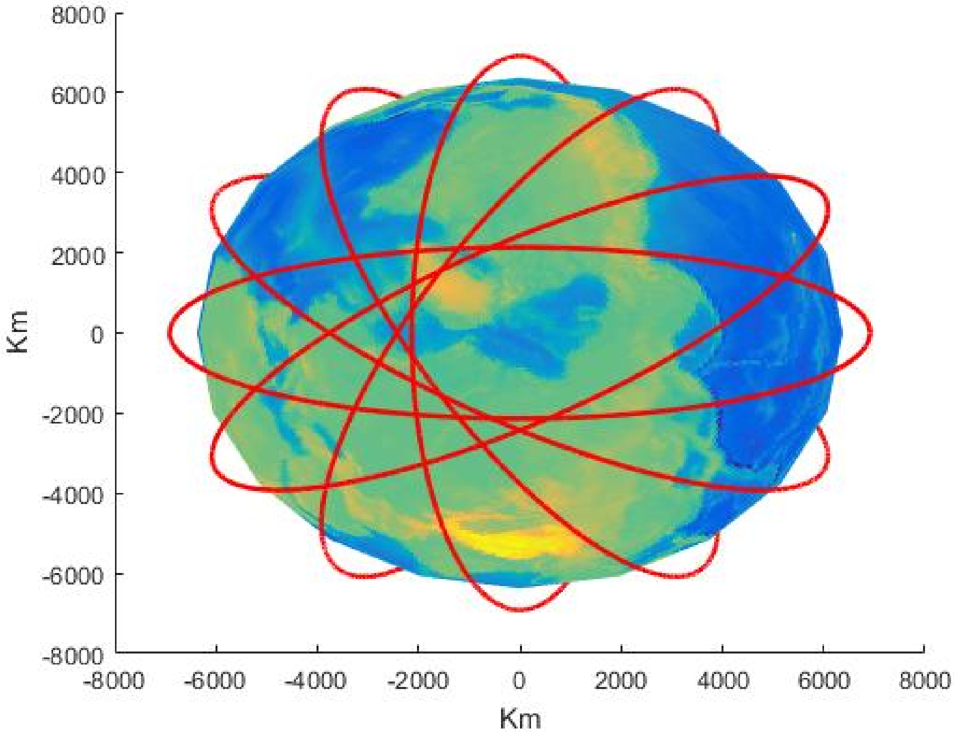


Figure 1.5.1: Old Constellation

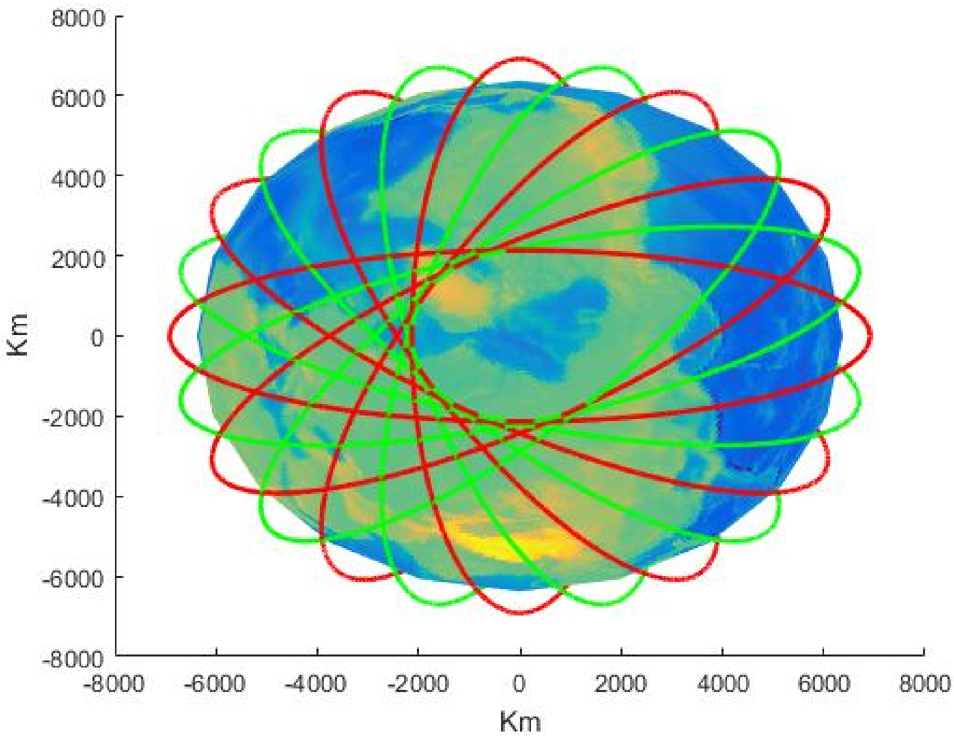


Figure 1.5.2: Old and New Constellations

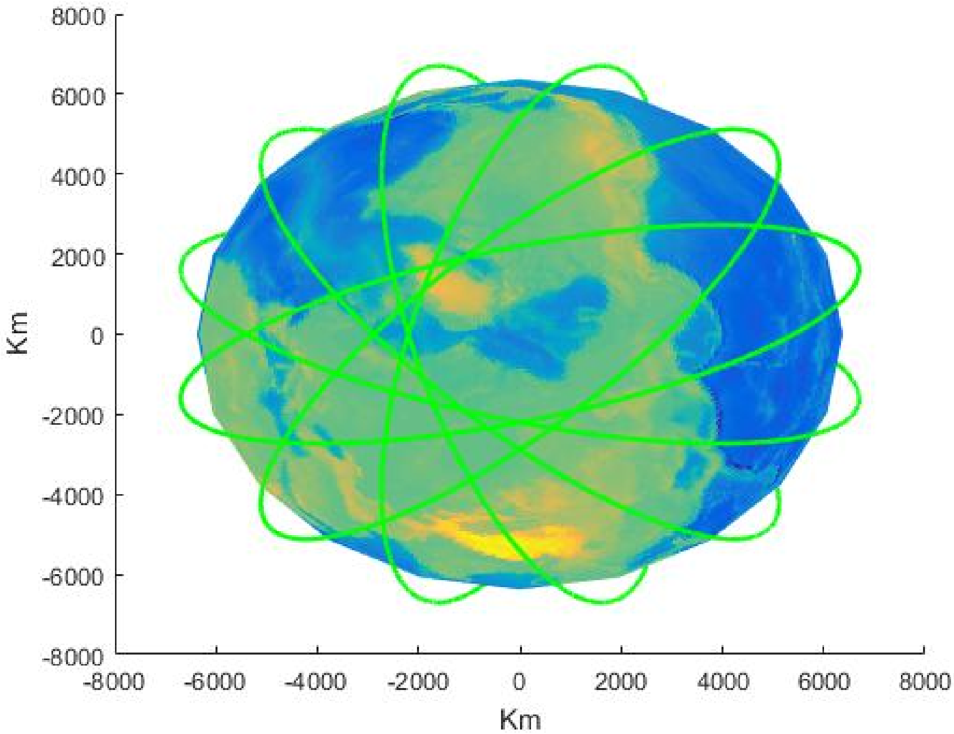


Figure 1.5.3: New Constellation

1.6 Spare Strategy

1.6.1 Introduction

When building a satellite constellation with the target to provide global coverage communication relay between LEO satellites and between LEO satellites and the ground, it is crucial to avoid any deterioration of the service. In order to ensure that any possible fail from the satellites would not spoil the constellation operation for more than 6 hours; a spare strategy has to be done. Nowadays, four different types of spare strategies are known:

- Spare satellites in constellation
- In-orbit spare
- Spare satellites in parking orbits
- Spare satellites on the ground

Each existing spare strategy is valid. Despite, depending on the enterprise priopritics the most suitable has to be choosen. In addition, the decision taken is related to the constellation flexibility to degrade the service to a lower performance level during a certain period and to its cost.

1.6.2 Spare Strategy Alternatives

Spare satellites in constellation:
This configuration consists on designing the constellation to be *"overpopulated"*. As it sounds, this means that the system is established with *extra* operative satellites already orbiting within the constellation. For instance, only two overpopulating configurations had been pictured: ovepopulated by one satellite or overpopulated by two satellites per orbital plane.

- One extra Satellite:
  By adding an extra satellite to the primary design of the orbital plane configuration, one satellite failure is covered with little time delay to recover the plan. In this way, the constellation continues to work at maximum capacity after a short interruption and at a suitable cost.

- Two extra Satellites:
  Usually, by adding two extra satellites per orbital plane the reliability of the service achieves values around the 99.99%. This configuration increases considerably the cost of the project and it is mainly neccessary in cases where the availability of the satellite is essential for the proper operation of the constellation.

Therefore, when designing an overpopulated constallation, the first decition to be made is the number of extra satellite per orbital plane. To guarantee the most optimal configutation a feasibility study is needed.

In-orbit spare:
The main diference between this strategy and the previous one is that in this case spare satellites are not operative. So the idea is to put some spare satellites in a orbit close to the principal one of the constellation in order to avoid possible collisions between operative satellites and spares.

A few things have to be taken into account when using this method. Firstly,even though the spare satellites are not operative, by being in orbit they deteriorate and by the time they are needed their operative lifetime and performability will not be such as the ones of brand new satellites.Secondly, as their are non-controlled satellites their orbital decay has to be predicted to be aware of possible collitions and avoid them. Thirdly, once any spare satellites is needed, it has to be able to do a two Hohmann transfer to achieve the performance orbit; the first one to reach a phasing orbit and the second one to end in the operational altitude.

Spare satellites in parking orbits:
By mading this choice it has to be assumed that the spare satellites can be keeped in parking orbit until they are needed. Two different option are valid: keeping the rocket in a *"parking"* orbit and then try to send it to the corresponding orbit; or keeping it in in-orbit satellites parkings such as the ISS. The main drawback is that the performance takes a long time until the constellation is recovered and depending on the orbit parameters and the launcher it is not possible to use this strategy.

Spare satellites in parking orbits:
The simpliest and easiest one; the only thing that has to be done is to build extra satellites. The spares will remain on ground when the constellation is launched. Only in case the structure collapses due to a satellites failure, an emergency launch will put the spares in orbit. Moreover, this method is expensive because every extra launch has a high cost and it can take weeks to recover the constellation performance.

1.6.3 Spare Strategy Selection

From all those alternatives, two of them are quickly discarded: in-orbit spares and in parking orbit spares. The first one is having a non-working satellite in orbit because not only the satellite has to be purchased, but also it has to be launched to a different orbit than the principal one. That fact will increase the cost of the launch or even worst it could create the necessity of an extra launch. Although, the satellites needs to reach the operative orbit and it is known that cubesats propulsion is not really powerful. Furthermore, this satellites might never be needed. So it is highly probable this investment to be a waist of money and sources and this are the main reasons why it has benn discarded.

The second is not available in the *Astrea Constellation* case. On the one hand, the main parking in orbit will be the ISS which is at an altitude of 400km above the earth and the constellation is situated at among 550km above the earth. Knowing that, this option is immediately discarded. On the other hand, the Electron the rocket that will accomplish the mission to put the satellites in orbit cannot stay in parking orbit before arriving to its final destination. Definitely, the service cannot rely on this option.

Two possible spare strategies remain: pare satellites in the constellation or on ground. In spite deciding if both ones are useful or only one of them is, a feasibility study is done. The objective is analise the diferent kind of failure that have to be covered and determine how the constellation will collapse. Only after that the most suitable strategy method can be designed having as reference the alternatives presented above.

1.6.3.1 Feasibility Studies

The following studies are based on the probability of failure of the satellites and how the different combinations of failure could become a critical or not for the constellation operations. Furthermore, the main parameters needed during this studies are the number of satellites per plane, the probability of failure of a single satellite and the number of planes.

Let's quantify the parameters presented above. The probability of failure of the satellite during the first five years is about **FALLABILITAT** and there are 21 satellites per orbital plane per 8 orbital planes. As a result, it means the whole constellations contains 168 satellites which have a 95% of probability not to fail. By doing quick calculations, firstly it could be assumed that around 8 satellites would fail during the mission. However, this are simple calculations with low reliability.

As CubeSat communicate between other satellites and ground, two different cases of failure are observed. On the one hand, the constellation has been designed to offer global coverage of the Earth's surface, so once a satellites fail its footprint disappear and a small hole appears. On the other hand, a sophisticated network of communication between satellites has been created, so once a Cubesat fails it creates a hole in the communications network and entails the creation of new paths which avoid the non-operative satellite. Therefore, the collapse situation for each state has to be determined.

- Communication with ground: The main problem with ground communications is the appearance of a big gap in the footprint the satellites leave. This gap is formed by the failure of several neighboring satellites and has to be big enough to cut all communication with the corresponding ground station to consider the failure as critical. Nevertheless, even if the communication with a single ground station was not possible for a short period of time the information could be transmitted to another ground station with the only drawback that the travel time of the data increases.

- Communication between satellites: Once the communication of a satellite fails, it creates a gap in the communication network. Although any satellite outside the constellation (referring to the ones that use *Astrea* services) tries to communicate, it will not have any problem to communicate with neighboring CubeSat to the one it failed if it is necessary. So the real problem could appear when two or more neighboring CubeSats fail. Additionally, the failure of a single satellite is not critical at all for the constellation because the data can still travel through other paths.

1.7 End-of-Life Strategy

1.7.1 Introduction

The main objective is to determine the best strategy to implement at the end of the operational lifetime of the satellites forming the constellation. In this way, it is possible to avoid an increase in space debris and in the collision risk between satellites positioned in the same altitude band or nearby.

1.7.2 Space Debris

The Space had been a virgin environment until the middle of the twentieth century. However, it has already been exploited by humanity. During the last sixty years many space research centers –such as NASA, ESA or ROSCOSMOS- have been sending rockets and satellites to explore and understand its foreign environment without thinking on the consequences it could have. Fortunately, at the twenty-first century the concern about space debris has appears. Due to this fact, all those space research centers have begun to develop end-of-life strategies for all the missions that generate debris to restrict its lifetime.

The term Space Debris implicates all man-made objects that are orbiting with no human control. The problem arises from the fact that depending on the orbital parameters this space stuff is subject to more or less perturbations from either the Earth, the Moon, the Sun or the atmospherically drag and, after their operability's death, they might never disappear or completely disintegrate. As the quantity of space debris is huge and varied, they have been classified in four categories: fragmentation debris, non-functional spacecraft, rocket bodies and mission related debris.

The category that concerns the project is the non-functional spacecraft because it refers to all intact structures which have completed their mission. It is noticed that once satellite's operative lifetime arrives to its end, the satellites stop maneuvering and counteracting perturbations to maintain the current orbit. Consequently, they tend to deviate from their nominal orbital parameters, starting an unknown trajectory and important repercussions.

Therefore, by increasing the number of uncontrolled *"dead"* satellites the probability of collision between working satellites and space debris increases at LEO as it is overcrowded. Space debris is small usually and its location can be followed from earth but is impossible

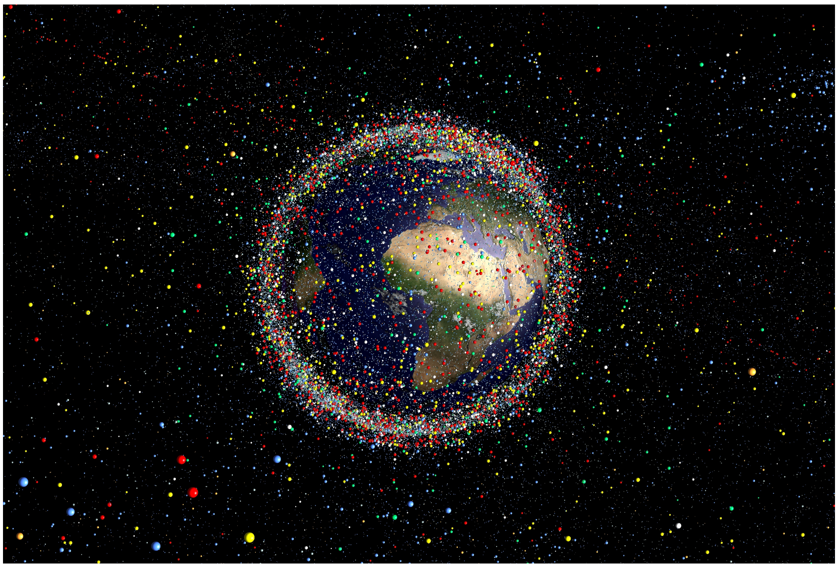


Figure 1.7.1: View of the Space Debris around the Earth

to control it. Meanwhile, it is essential for space assets to be free of any impact because avoidance maneuvers are too complicated to have real success. Thereby, the increasing risk of collision becomes the big threat everyone is fighting against.

1.7.3 End-of-Life Types

End-of-life strategies where implemented taking into account three factors: the time the satellite can orbit, the technical feasibility of active de-orbiting in terms of propellant and sub-systems enhancements and the altitude of its nominal orbital plane.

The first one is related to the fact that the current recommendations say that any space asset that can become a non-functional spacecraft must de-orbit and disintegrate at its twenty-fifth birth on orbit. The second refers to the magnitude of the maneuver that can be developed with the power the thruster system can achieve. The third one is relevant because perturbations in space change according to the distance to the Earth's surface. The closer it is the more perturbations from Earth and drag forces from the atmosphere the satellite suffers and perturbations help to de-orbit and disintegrate space assets.

Based on these premises, two different end-of-life groups had been determined:

- Controlled de-orbit:

  It consists on carrying out a maneuver that leads to steep, controlled re-entry and burn-up in the atmosphere or ground impact. It must be done in a relatively short period of time, usually 1 revolution and it involves significantly high ΔV. This sophisticated maneuver is initiated by a large increment of potential energy to make change the orbital altitude to a lower one well into the atmosphere where the satellite burns. A few calculations are useful to have a numerical result of that ΔV: The velocity in the initial orbit is:

$$V1 = \sqrt{\frac{GM_t}{R_t + h}} = 7593.4m/s$$

Then the semi major axis of the elliptical orbit is obtained:

$$a = \frac{r1+r2}{2} = 6672km$$

The speed at apogee of the elliptical orbit is:

$$V2 = \sqrt{GM_t(\frac{2}{r} - \frac{1}{a})} = 7455m/s$$

Finally, the ΔV is computed:

$$\Delta V = V1 - V2 = 138.4m/s$$

- Uncontrolled de-orbit:

  A simpler and cheaper way to de-orbit satellites is to induce a reduction of the orbit altitude in order to cause a decay and ,finally, a re-entry to the atmosphere. The process is initiated by one or several arc maneuvers at apogee passes and it is carried out without controlling the trajectory. This procedure is appropriate for low-thrust systems and small satellites.
  In addition, when considering satellites placed at LEOs, this strategy takes advantages of the perturbations present in this altitudes (atmospheric drag). This force contributes to the decay increasing the rate of approach to the atmosphere.

In order to make a decision, it has to be considered that the constellation is compounded of very small satellites (3U CubeSats). Those kinds of satellites cannot contain high thrust systems, consequently, the controlled de-orbit is out of its range. Also, the fact that the constellation is placed at LEOs makes easier the application of the uncontrolled de-orbit because of the given reason above. A reason that could force to adopt the controlled de-orbit could be the replacement strategy. If it had been designed so that the de-orbit was rapid, the uncontrolled one would provably not be adequate, nevertheless, the replacement strategy has been designed so as to avoid the need of a quick de-orbit (see Replacement Strategy section). Given all the stated reasons, it is decided to use the uncontrolled de-orbit.

1.8 Conclusions

This final section is intended to put and end to the Constellation Deployment Department activities. First of all, a brief summary of the work done is carried out, secondly, the compliance of the tasks assigned to this department in the Project Charter document is verified. Accomplished tasks:

- Launching System: a launching platform has been chosen regarding all the important parameters. Electron, from the enterprise Rocket Lab is the rocket that will bring Astrea Constellation to life.
- Deployer: a suitable deployer has been selected according to the standards of CubeSat deployment. GPOD deployer, developed by the enterprise GAUSS is in charge of the separation of the CubeSats from the rocket.
- First Placement: the assembly of the satellites will begin approximately 420 days before the first launching. The first placement will consist on eight launchings (one per orbital plane) and will last eight weeks.
- Replacement Strategy: similar to the first placement strategy, new orbital planes are placed between the old ones avoiding the formation of gaps during the decay of the satellites that are being renewed.
- Spare Strategy:
- End of Life Strategy: an uncontrolled de-orbit procedure has been chosen.

The summary shown above demonstrates that the Constellation Deployment Department has fulfilled the requested duties. According to the Joint Space Operation Center regulation, it can be noticed that it is not mentioned in the report. The reason of this fact is that both Electron and GPOD follow the current standards and legislation of space mission, since the JSOC also does, there is no need to check the JSOC regulation.

Part II

Communications

Chapter 2

Space Segment Protocol Stack

"The wonder is, not that the field of stars is so vast, but that man has measured it."

Anatole France, 1894

2.1 Introduction

Over this chapter, the **space communication protocols** are going to be defined. That is, a set of rules are going to be established in order to achieve the actual node-to-node communication. Altough the scope of the chapter is limited to the space segment, this inital introduction on the protocol definition is usfeul for the ground segment. Having said that, several factors constrain the design of this relation of rules:

- **Speed:** As it has already been mentioned, each node should be capable of handling at least **25** Mbit/s. Even though this doesn't mean that the design should be able to fit 25 Mbit/s of pure costumer data, it is still a strong requirement with many effects over the system. For example, some protocols are just too slow establishing the connection; those will be directly discarded.
- **Reliability:** The protocols have to assure that the messages are going to arrive to their destination. In order to achieve this, a routing protocol has to be used as well.
- **Security:** Messages are not just required to arrive to their destination but they also must be ordered and coherent when they reach the client. That is the reason why error control is taken into consideration very seriously along the design process.

In the diagram 2.5.1, it can be clearly seen the structure of a protocol stack. Each layer has an underlying protocol, designed to achieve a specific task. There are **low-level** protocols, dealing with *hardware* or with the establishment of the *physical* path between two nodes. Also, there are the **high-level** protocols, dealing with session control, optimum *logical* paths generation and bridging the application layer with the physical layer.

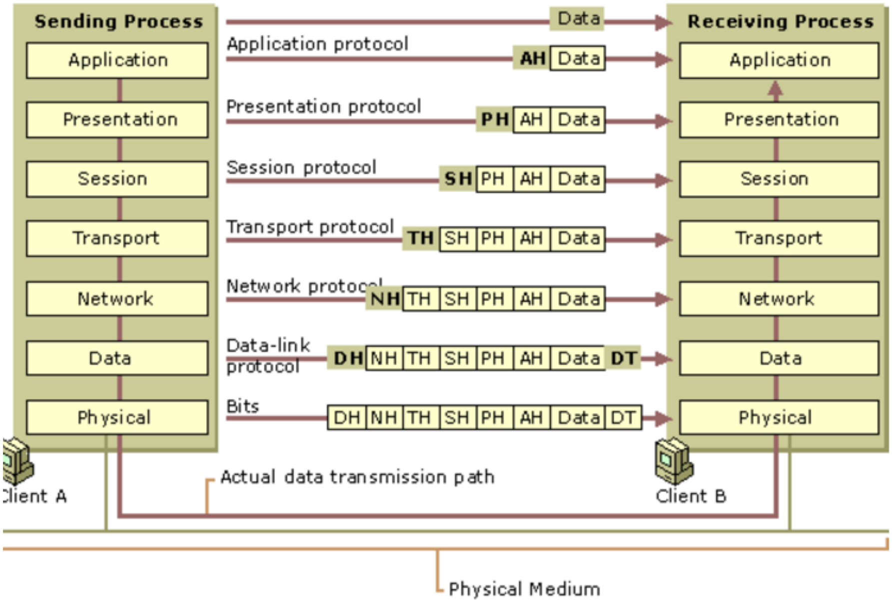


Figure 2.1.1: OSI Model layers

As it can be deducted, both the sending and the receiving node have to work in coordination. Also, each layer is designed with encapsulation in mind. Therefore, each layer does not depend on the others and develops its own task independently.

This philosophy has been started by the *International Telecommunications Unit* or **ITU** who first proposed, in the late 1970, the previously depicted **OSI Model**. Basiaclly, it establishes a conceptual framework for when new protocols are to be designed. Each layer can be understood easily if one thinks as the act of sending mail by post, for instance.

As far as *Astrea constellation* is concerned, the physical layer is already defined in detail in the **Satellite Desgin** part. Since the **Data Link layer**, the **Network layer** and the **Transport/Session layer** are of vital importance for the communication to work, the aim of the next sections will be to define the protocol that the constellation will be using for each one of those layers.

The presentation and the application layer are more client oreinted. In other words, if one client's satellite sends some data formatted with an unknown application protocol, *Astrea* will not be affected in any way. What astrea will do is add to this stream of bits, some headers, in order for the message to arrive in time to its destination. This methodology is undoubtedly positive for *Astrea* since the respobility of the application data will be solely for the customer.

2.2 Layer 2: Data Link

2.2.1 Functions of the DLL

The Data-Link layer is the protocol layer in a program that handles the moving of data in and out across a physical link in a network. The Data-Link layer is layer 2 in the Open Systems Interconnect (OSI) model for a set of telecommunication protocols. According to the IEEE-802 LAN standards, the DLL can be divided into two sublayers:

- Logical Link Control (LLC): Deals with protocols, flow-control, and error control.
- Media Access Control (MAC): Deals with actual control of the media.

The DLL is responsible for converting data stream to signals bit by bit and to sent that over the underlying hardware.At the receiving end, DLL picks up data from hardware which are in the form of electrical signals, assembles them in a recognizable frame format, and hands over to upper layer. The DLL also ensures that an initial connection has been set up, divides output data into data frames, and handles the acknowledgements from a receiver that the data arrived successfully. It also ensures that incoming data has been received successfully by analyzing bit patterns at special places in the frames. The specific functions of the DLL are explained in the following lines.

- **Framing**: Data-link layer takes packets from Network Layer and encapsulates them into Frames.Then, it sends each frame bit-by-bit on the hardware. At receiver end, data link layer picks up signals from hardware and assembles them into frames.
- **Adressing**: Each device on a network has a unique number, usually called a hardware address or MAC address, that is used by the data link layer protocol to ensure that data intended for a specific machine gets to it properly.
- **Synchronization**: When data frames are sent on the link, both machines must be synchronized in order to transfer to take place.
- **Error control**: Sometimes signals may have encountered problem in transition and the bits are flipped. These errors are detected and attempted to recover actual data bits.
- **Flow control**: Stations on same link may have different speed or capacity. Data-link layer ensures flow control that enables both machine to exchange data on same speed.

2.2.2 Working procedure

In the previous section, the functions of the DLL have been determined. Now, the way it is achieved will be exposed. To do so, a list of possible protocols from the simplest one to the more complex will explained. A ranking of the prefered working procedures will be done. All the images have been extracted from [?].

2.2.2.1 Simplest Protocol

This protocol has no error or flow control. It is supposed that the frames are traveling only in one direction, from the sender to the receiver. It is also supposed that the receiver can immediately handle the frames received, so there is no overwhelming. The DLL of the sender site gets data from its network layer, makes a frame out of the data and sends it. The DLL at the receiver site receives a frame from its physical layer, extracts data from the frame and delivers the data to its network layer. The problem here is that the sender site cannot send a frame until its network layer has a data packet to send and the receiver site cannot deliver a data packet to its network layer until a frame arrives. There is the need to introduce the idea of events in the protocol. The procedure at the sender site is constantly running; there is no action until there is a request from the network layer. The procedure at the receiver site is also constantly running, but there is no action until notification from the physical layer arrives.

```
while (true)                          // Repeat forever
{
  WaitForEvent()i                     // Sleep until an event occurs
  if(Event(RequestToSend»             //There is a packet to send
  {
     GetData()i
     MakeFrame()i
     SendFrame()i                     //Send the frame
  }
}
```

Figure 2.2.1: Sender algorithm for the simplest protocol.

```
while(true)                          // Repeat forever
{
  WaitForEvent()i                    II Sleep until an event occurs
  if(Event(ArrivalNotification»      IIData frame arrived
  {
      ReceiveFrame()i
      ExtractData()i
      DeliverData ()i                //Deliver data to network layez
  }
}
```

Figure 2.2.2: Receiver algorithm for the simplest protocol.

2.2.2.2 Stop-and-Wait Protocol

If data frames arrive at the receiver site faster than they can be processed, the frames must be stored until their use. Normally, the receiver does not have enough storage space, especially if it is receiving data from many sources. This may result in either the discarding of frames or denial of service. To prevent the receiver from becoming overwhelmed with frames,we somehow need to tell the sender to slow down. There must be feedback from the receiver to the sender.

In the Stop-and-Wait Protocol the sends one frame, stops until it receives confirmation from the receiver and then sends the next frame. We still have unidirectional communication for data frames, but auxiliary ACK frames (simple tokens of acknowledgment) travel from the other direction. We add flow control to our previous protocol. In this case the algorithms of the sender and the receiver are the following ones.

```
while(true)                          IIRepeat forever
canSend = true                       IIAllow the first frame to go
{
 WaitForEvent()i                     II Sleep until an event occurs
 if(Event(RequestToSend) AND canSend}
 {
    GetData()i
    MakeFrame()r
    SendFrame()i                     I/Send the data frame
    canSend = false;                 I/cannot send until ACK arrives
 }
 WaitForEvent()i                     II Sleep until an event occurs
 if(Event(ArrivalNotification)       /I An ACK has arrived
  {
    ReceiveFrame();                  I/Receive the ACK frame
    canSend = true;
  }
}
```

Figure 2.2.3: Sender algorithm for the Stop-and-Wait Protocol.

```
while (true)                          IIRepeat forever
{
  WaitForEvent();                     II Sleep until an event occurs
  if(Event(ArrivalNotification)}      IIData frame arrives
  {
     ReceiveFrame();
     ExtractData(}i
     Deliver(data};                   /IDeliver data to network layex
     SendFrame();                     IISend an ACK frame
  }
}
```

Figure 2.2.4: Receiver algorithm for the Stop-and-Wait Protocol.

The two protocols explained are protocols that can be suitable for noiseless channels. However, noiseless channels are nonexistent. There is a need to add error control to the protocol. Three protocols are discussed with the aim of doing so.

2.2.2.3 Stop-and-Wait Automatic Repeat Request

The Stop-and Wait ARQ adds a simple error control mechanism to the Stop-and-Wait Protocol. To detect and correct corrupted frames, we need to add redundancy bits to our data frame. When the frame arrives at the receiver site, it is checked and if it is corrupted, it is silently discarded. The detection of errors in this protocol is manifested by the silence of the receiver. Frames are also numbered so if the receiver receives a data frame that is out of order, this means that frames were either lost or duplicated. What is done to solve the error is that when the sender sends a frame, it keeps a copy of the sent frame. At the same time, it starts a timer. If the timer expires and there is no ACK for the sent frame, the frame is resent, the copy is held, and the timer is restarted. Since the protocol uses the stop-and-wait mechanism, there is only one specific frame that needs an ACK even though several copies of the same frame can be in the network. Since an ACK frame can also be corrupted and lost, it too needs redundancy bits and a sequence number. In the following figure is possible to see more clearly what is going on with this protocol.

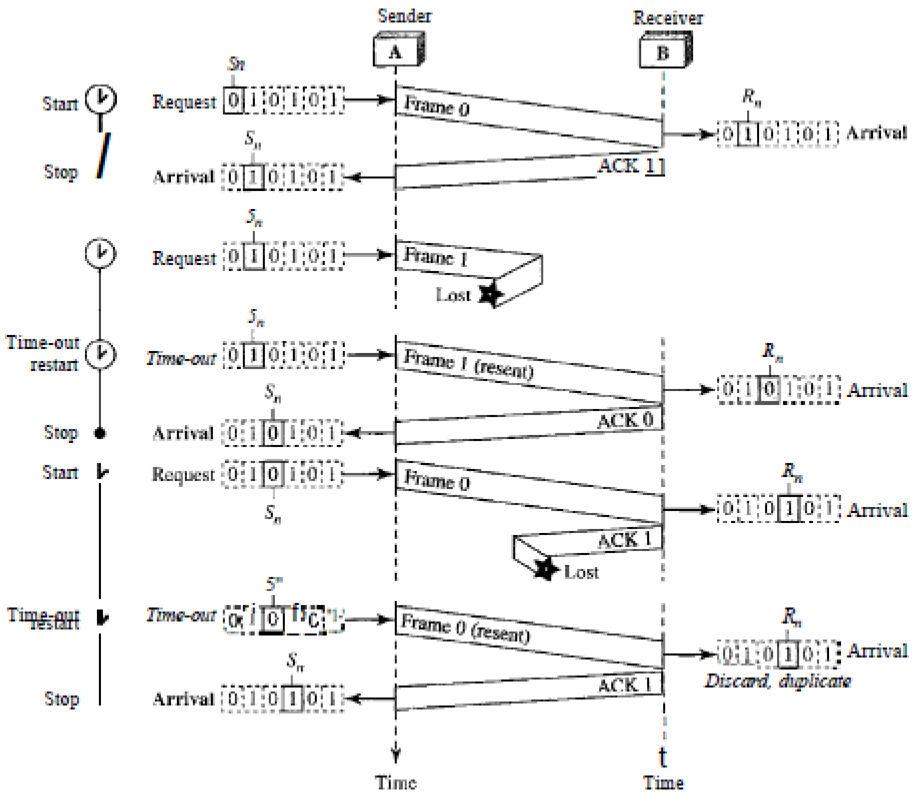


Figure 2.2.5: Flow diagram of the Stop-and Wait ARQ.

The main problem of this protocol is its efficiency. The Stop-and-Wait ARQ is very inneficinet if our channel is thick and long. The product of thickness and longitud is called the bandwidth-delay product. We can think of the channel as a pipe. The bandwidth-delay product then is the volume of the pipe in bits. The pipe is always there. If we do not use it, we are inefficient.

2.2.2.4 Go-Back-N Automatic Repeat Request

To improve the efficiency of transmission (filling the pipe), multiple frames must be in transition while waiting for acknowledgment. In other words, we need to let more than one frame be outstanding to keep the channel busy while the sender is waiting for acknowledgment. In the Go-Back-N Automatic Repeat Request the sender sends several frames before receiving acknowledgments. It also keeps a copy of these frames until the acknowledgments arrive. Although there can be a timer for each frame that is sent, in this protocol only one is used. The reason is that the timer for the first outstanding frame always expires first and then all outstanding frames when this timer expires are sent again. The receiver sends a positive acknowledgment if a frame has arrived safe and sound and in order. If a frame is damaged or is received out of order, the receiver is silent and will discard all subsequent frames until it receives the one it is expecting. The silence of the receiver causes the timer of the unacknowledged frame at the sender site to expire. This, in turn, causes the sender to go back and resend all frames, beginning with the one with the expired timer. The receiver does not have to acknowledge each frame received. It can send one cumulative acknowledgment for several frames. That is the reason why the protocol is called Go-Back-N. The flow diagram and the and algorithms of the sender and the receiver are shown next.

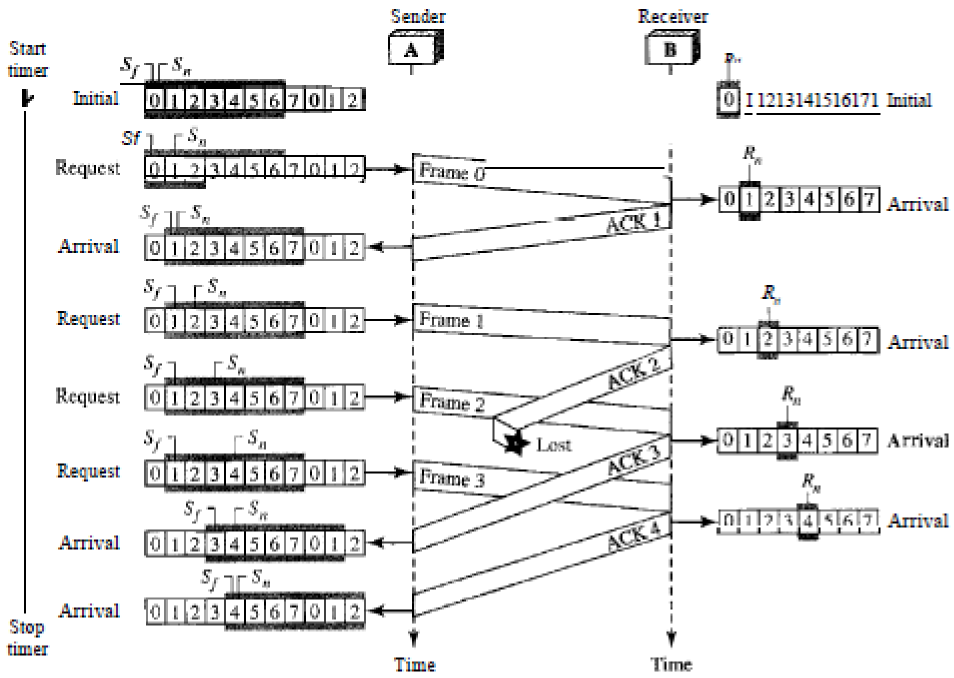


Figure 2.2.6: Flow diagram of the Go-Back-N ARQ.

```
Rn = 0;

while (true)                              IIRepeat forever
{
  WaitForEvent();

  if(Event{ArrivalNotification»           /Data frame arrives
  (
     Receive(Frame);
     if(corrupted(Frame»
          Sleep();
     if(seqNo == Rn)                      IIIf expected frame
     {
       DeliverData()i                     IIDeliver data
       Rn =Rn + 1;                        IISlide window
       SendACK(Rn);
     }
  }
}
```

Figure 2.2.7: Receiver algorithm for the Go-Back-N ARQ.

```
Sw = 2m - 1;
Sf = 0;
Sn = 0J

while (true)                          //Repeat forever
{
 WaitForEvent():
  if(Event(RequestToSend»             //A packet to send
  {
      if(Sn-Sf >= Sw)                 ///f window is full
            Sleep () ;
      GetData() ;
      MakeFrame (Sn) ;
      StoreFrame (Sn) ;
      SendFrame(Sn) ;
      Sn = Sn + 1;
      if(timer not running)
           StartTimer ():
  }

  if{Event{ArrivalNotification»       IIACK arrives
  {
      Receive (ACK) ;
      if{corrupted{ACK»
           Sleep ():
      if{{ackNo>sf)&&{ackNO<=Sn»      ///f a valid ACK
      While(Sf <= ackNo)
       {
        PurgeFrame{Sf):
        Sf = Sf + 1;
       }
       StopTimer():
  }

  if{Event{TimeOut»                   liThe timer expires
  {
   StartTimer() ;
   Temp = Sf;
   while{Temp < Sn);
     {
      SendFrame(Sf):
      Sf = Sf + 1;
     }
  }
}
```

Figure 2.2.8: Sender algorithm for the Go-Back-N ARQ.

2.2.2.5 Selective Repeat Automatic Repeat Request

Go-Back-N ARQ simplifies the process at the receiver site. The receiver keeps track of only one variable, and there is no need to buffer out-of-order frames; they are simply discarded. However, this protocol is very inefficient for a noisy link. In a noisy link a frame has a higher probability of damage, which means the resending of multiple frames. In the case of these protocol, the Selective Repeat ARQ, the processing at the receiver is more complex but is more efficient for noisy links. The Selective Repeat Protocol allows a number of frames to arrive out of order and be kept until there is a set of in-order frames to be delivered to the network layer. The handling of the request event is similar to that of the previous protocol except that one timer is started for each frame sent. The arrival event is more complicated here. An ACK or a NAK frame may arrive. If a valid NAK frame arrives, the corresponding frame is resent. If a valid ACK arrives the corresponding timer stops. When the time for a frame has expire, only this frame is resent.

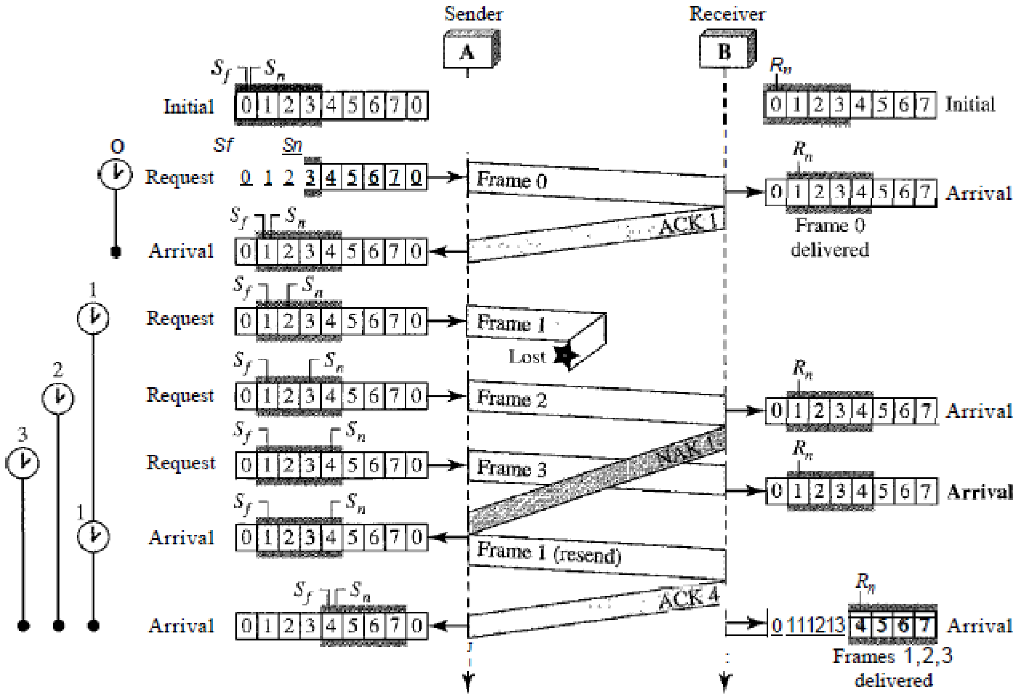


Figure 2.2.9: Flow diagram of the Selective Repeat ARQ.

```
    = 2m-1 i
    = Oi
    = Oi

 hile (true)                    //Repeat forever
{
  WaitForEvent()i
  if(Event(RequestToSend)}      //There is a packet to sen
  {
```

```
    if{Sn-S;E >= Sw)                     I/If window is full
          Sleep ();
    GetData () ;
    MakeFrame (Sn) ;
    StoreFrame{Sn);
    SendFrame (Sn) ;
    Sn = Sn + 1;
    StartTimer{Sn);
 }

 if(Event{ArrivalNotification»       IIACK arrives
 {
    Receive{frame);                      I/Receive ACK or NAK
    if{corrupted{frame»
         Sleep ();
    if (FrameType == NAK)
       if (nakNo between Sf and So)
       {
        resend{nakNo);
        StartTimer{nakNo);
       }
    if (FrameType = ACK)
       if (ackNo between Sf and So)
       {
         while{sf < ackNo)
         {
          Purge (sf);
          stopTimer (Sf) ;
          Sf = Sf + 1;
         }
       }
 }

 if(Event{TimeOut{t»)                 liThe timer expires
 {
  StartTimer{t);
  SendFrame{t);
 }
}
```

Figure 2.2.10: Sender algorithm for the Selective Repeat ARQ.

```
Rn = 0;
NakSent = false;
AckNeeded = false;
Repeat(for all slots)
    Marked(slot) = false;

!while (true)                          IIRepeat forever
{
  WaitForEvent()i

  if{Event{ArrivalNotification»        jData frame arrives
  {
     Receive(Frame);
     if(corrupted(Frame»&& (NOT NakSent)
     {
      SendNAK(Rn);
      NakSent = true;
      Sleep{();
     }
     if(seqNo <> Rn)&& (NOT NakSent)
     {
      SendNAK(Rn);
      NakSent = true;
      if {(seqNo in window)&&(IMarked(seqNo»
      {
       StoreFrame{seqNo)
       Marked(seqNo)= true;
       while(Marked(Rn)
       {
        DeliverData(Rn);
        Purge(Rn);
        Rn = Rn + 1;
        AckNeeded = true;
       }
        if(AckNeeded);
        {
        SendAck(Rn);
        AckNeeded =false;
        NakSent = false;
        }
      }
     }
  }
}
```

Figure 2.2.11: Receiver algorithm for the Selective Repeat ARQ.

2.2.2.6 Bidirecional links: Piggybacking

Piggybacking is not a protocol, is a technique. All que protocols explained until now are all unidirectional: data frames flow in only one direction although control information such as ACK and NAK frames can travel in the other direction. In real life, data frames are normally flowing in both directions: from node A to node B and from node B to node A. This means that the control information also needs to flow in both directions. Piggybacking is usedto improve the efficiency of the bidirectional protocols. When a frame is carrying data from A to B, it can also carry control information about arrived (or lost) frames from B; when a frame is carrying data from B to A, it can also carry control information about the arrived (or lost) frames from A.

2.2.2.7 Working procedure ranking

Now its time to choose the working procedure that best fits the needs of the mission. To do so, an OWA (Ordered Weighted Average) will be used. The criteria to consider is the following one:

- Efficiency: This fact deals with how the channel is being used. Protocols will be classified as non-efficient or efficient.
- Time: This fact deals about the time needed to transmit the data satisfactory.
- Error correction: Deals about whether a protocol can correct an error of transmission or not.

It is important also to take into account that the protocol to use should have a flow control, that is, should know if the receiver is available or not to receive the data. For this reason the Simplest Protocol is rejected and won't be studied in the OWA. Regarding the factors of the OWA, all of them will be rated from 0 to 1. In this project the fact of transmitting the data without errors is more important than transmitting it fast, as is possible to appreciate un the project charter (the latency can be relative high, but incorrect information is useless). The efficiency of the protocol is very important too, because the less the efficiency the less power provided by the CubeSat is being used. Since the CubeSat has limited space, ideally al the power it can gives for transmittion will be used for it. Then, the weights of the different factors are the following ones:

- Efficiency: 40
- Time: 30
- Error correction: 60

In the following table the rating of each protocol together with the corresponding OWA is shown.

Protocol	Efficiency	Time	Error correction	OWA
Stop-and-Wait Protocol	0	0	0	0
Stop-and-Wait ARQ	0	0	1	0,46
Go-Back-N ARQ	1	0	1	0.69
Selective Repeat ARQ	1	1	1	1

Table 2.2.1: OWA of the DLL protocols.

Then, the ranking of working procedures is the following one:

1	Selective Repeat ARQ
2	Go-Back-N ARQ
3	Stop-and-Wait ARQ
4	Stop-and-Wait Protocol

Table 2.2.2: Ranking of working procedures

It has to be said that when dealing with bidirecional links piggybacking technique will be used if possible.

2.2.3 Protocols

The standards of the CCSDS will be followed in order to allow interoperability with other satellites such as the one of the client. The CCSDS has developed four protocols for the Data Link Protocol Sublayer of the Data Link Layer [**?**]:

- TM Space Data Link Protocol
- TC Space Data Link Protocol
- AOS Space Data Link Protocol
- Proximity-1 Space Link Protocol-Data Link Layer

These protocols provide the capability to send data over a single space link. TM, TC, and AOS can have secured user data into a frame using the Space Data Link Security (SDLS) Protocol.
CCSDS has also developed three standards for the Synchronization and Channel Coding Sublayer of the DLL:

- TM Synchronization and Channel Coding

- TC Synchronization and Channel Coding
- Proximity-1 Space Link Protocol—Coding and Synchronization Layer

TM Synchronization and Channel Coding is used with the TM or AOS Space Data Link Protocol, TC Synchronization and Channel Coding is used with the TC Space Data Link Protocol and the Proximity-1 Space Link Protocol—Coding and Synchronization Layer is used with the Proximity-1 Space Link Protocol—Data Link Layer. This can be seen better in the following image.

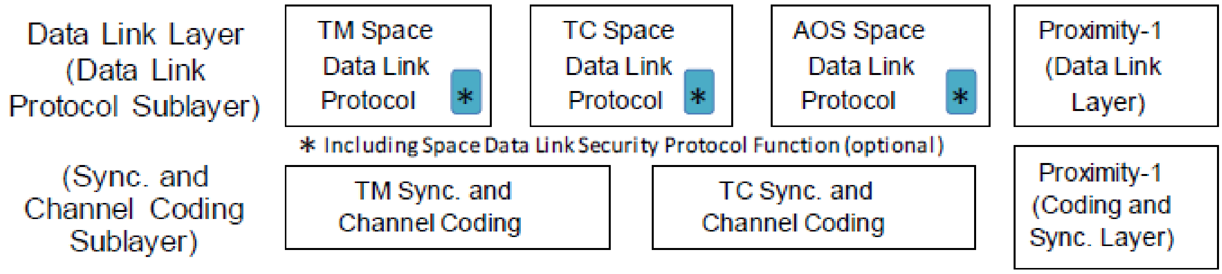


Figure 2.2.12: DLL of the CCSDS.

Now the reliability of each of the protocols of the Data Link Protocol Sublayer will be compared in order to know which one is the best of them. This will be done because reliability is the most important feature of the DLL.

Protocol	System used for reliability
TM	Stop-and-Wait Protocol
TC	Type-A: Go-Back-N ARQ, Type-B:Stop-and-Wait Protocol
AOS	Stop-and-Wait Protocol
Proximity-1	Go-Back-N ARQ

Table 2.2.3: Reliability of CCSDS protocols

According to the table and to the ranking of working procedures done previously, only TC Type-A and Proximity-1 will be considered from now on. Security is another important feature to take into account when taking this decision. TM Space Data Link Protocol has provision for inserting secured data into a frame using the Space Data Link Security (SDLS) Protocol. However, there have been no security requirements to date established for Proximity-1. The SLDS protocol can provide security services, such as authentication and confidentiality for TC Transfer Frames (it can also do it with TM and AOS, that have been previously discharted). Both the TC and the Proximity-1 use variable-lenght

Transfer Frames to facilitate reception of short messages with short delay. Another key feature to take into account when deciding a protocol, is the concept of "Virtual Channels". The Virtual Channel facility allows one Physical Channel (a stream of bits transferred over a space link in a single direction) to be shared among multiple higher-layer data streams, each of which may have different service requirements. A single Physical Channel may therefore be divided into several separate logical data channels, each known as a Virtual Channel (VC). The TC has the following identifiers: the Transfer Frame Version Number (TFVN), the Spacecraft Identifier (SCID), and the Virtual Channel Identifier (VCID). It also uses an optional identifier, called the Multiplexer Access Point Identifier (MAP ID), that is used to create multiple streams of data within a Virtual Channel. In contrast, the Proximity-1 uses a triad of multiplexing capabilities, which is incorporated for specific funcionality within the link. The Spacecraft Identifier (SCID) identifies the source or destination of Transfer Frames transported in the link connection based upon the Source-or-Destination Identifier. The Pysical Channel Identifier (PCID) provides up to two independently multiplexed channels. The Port ID provides the means to route user data internally to specific logic ports, such as applications or transport processes, or to physical ports, such as onboard buses or physical connections. Now a table with the identifiers of the TC and the Proximity-1 will be shown:

Identifiers	TC Space Data Link Protocol	Proximity-1 Space Link Protocol- Data Link Layer
TFVN	00	10
SCID	0 to 1023	0 to 2013
PCID	N/A	0 to 1
VCID	0 to 63	N/A
MAP ID	0 to 63	N/A
Port identifier	N/A	0 to 7

Table 2.2.4: Identifiers of TC and Proximity-1 Space Data Link Layer Protocols

Having Virtual Channels is important for the mission that is exposed in this project because it allows having more than one stream of bits to take place at the same time, that is to say that more than one client can communicate with their satellite without having to wait for another client to finish.

The decision taken is to use the TC Space Data Link Protocol with the TC sync. and channel coding together with the Space Data Link Security Protocol. The reasons for doing so are mainly:

- Security: Incorporing the SLDS authentication and confidentality is provided.
- More virtual channels: This feature allow more clients communicating with their satellites at the same time.

2.2.4 TC Space Data Link Protocol

Now some specifications of the chosen protocol will be exposed in order to know how it is structured and how many bits it adds to the original data. Further information of the protocol can be found in [?]. The protocol specifications will be explained when it is used with the support of the SDLS protocol. In this section is important to know that 1 octet is an eight-bit word. The structure of the transfer frame in this protocol is the following one:

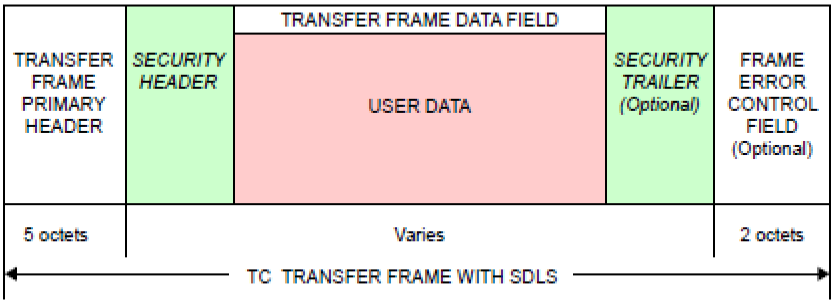


Figure 2.2.13: Transfer frame structure of the TC Space DL Protocol with SDLS.

In the transfer frame primary header, the following information is contained:

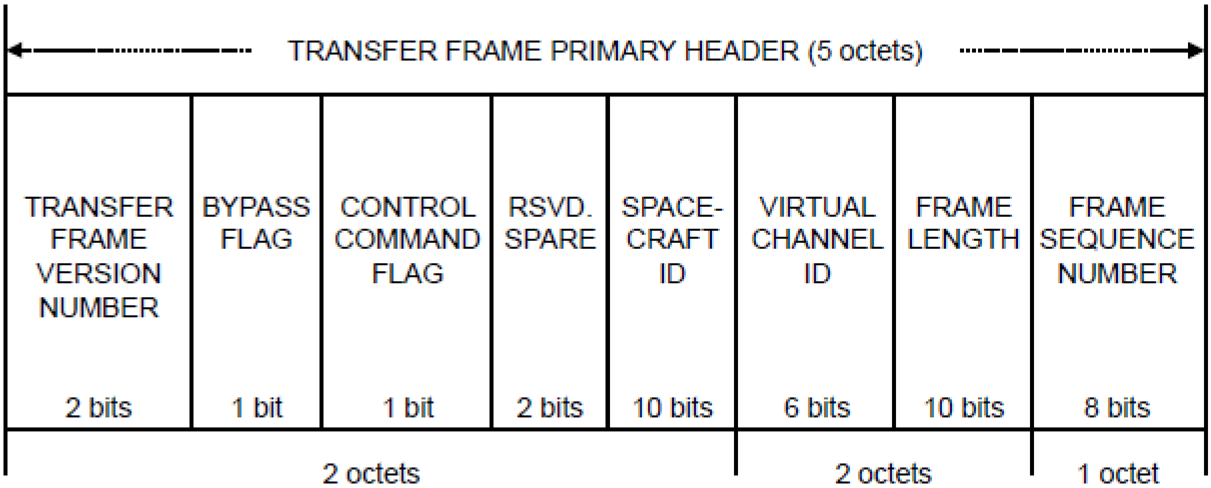


Figure 2.2.14: Transfer frame primary header.

With this data, is possible to say that the TC Space Data Link Protocol will add to data coming from the Network layer at least 5 octets (40 bits).

2.2.5 TC Sync and Channel Coding

This protocol is the corresponding to the Synchronization and Channel Coding Sublayer that has be used with the TC Space and Data Link Protocol. It has functions as for example, encapsuate the data units so that the start and end can be detected by the receiving end, ensure there are sufficient bit transitions in the transmitted bit stream so that the receiver can mantain bit synchronization during the reception of the data unit, etc. In a nutshell, one instance of the Synchronization and Channel Coding Sublayer processes the data stream for a single Physical Channel, making it a stream of bits that can be transferred over a space link in a single direction. The procedures can be differenciated between the ones that occur in the sending end and the one that occur in the receiving end. The procedures are the following ones:

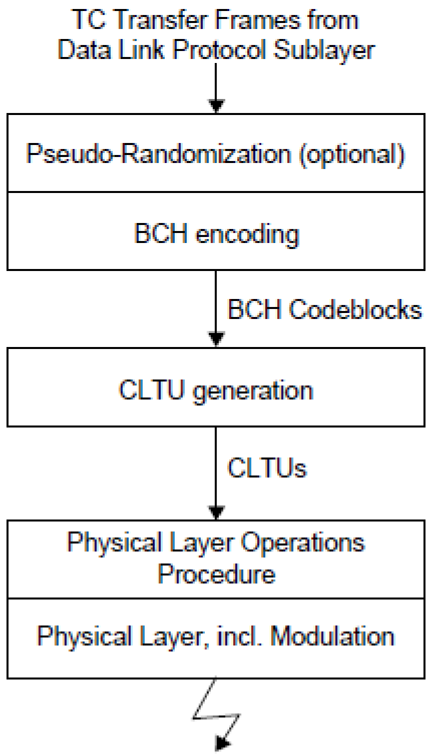


Figure 2.2.15: Procedure at the sending end.

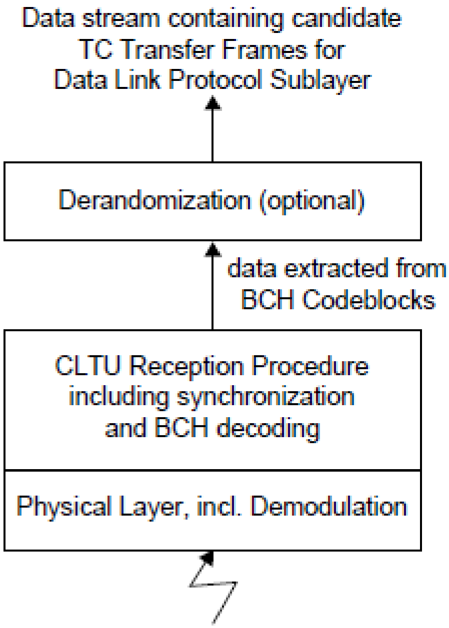


Figure 2.2.16: Procedure at the receiving end.

Is possible to see that two packets of data are created, BCH Codeblocks and CLTUs. From the point of view of the Synchronization and Channel Coding Sublayer, the content of the Frames parameter is a single block of data. For a single Channel Access request, the Synchronization and Channel Coding Sublayer generates a set of BCH Codeblocks, and that set of BCH Codeblocks is placed in a single CLTU. One of the managed parameters for the Physical Channel is the maximum length of a CLTU. The lenght of the CLTU can be calculated as follows (in octets):

$$LenghtoftheCLTU = 10 + 8 \cdot (\frac{Totallenghtoftheframes + 6}{7}) \tag{2.2.1}$$

Since with the TC Space Data Link protocol the frames can have different sizes, the CLTU can also have different sizes. More information about this sublayer of the DLL can be found in reference [?]

2.3 Layer 3: The Network

2.3.1 Functions of the Network Layer

According to [?], the Network layer is the third layer in the Open Systems Interconnection (OSI) model. It is located above the Data link layer and below the Transport layer. This layer is used for transmitting data sequences called datagrams between a sender and a reciever than may not be directly connected through only one link. The Network layer provides the following functions:

- **Routing**: Selects the best path between two nodes in a network, often using itermediate nodes called routers.
- **Network fow control**: Routers may indicate a transmitting node to reduce its transmission when the router's buffer becomes full.
- **Package fragmentation**: If the message to be transmitted is too large to be transmitted in the Data link layer, the network may split it into several packages in one node, send them independently an reassemble them in another node. Optionally, it can provide error control.
- **Logical-physical adress allocation**: Translates the logical adress (or names) of the network nodes into a unique physical adress.
- **Message forwarding**: A network may be divided into subnetworks, connected through specialized hosts, called gateways or routers, that forward packets between those subnetworks.

2.3.2 Protocols

The Consultive Comitee for Space Data Systems (CCSDS) [?] has two standards for using in the Network layer in conjuction with the Space Data Link Layer Protocols recommended by the CCSDS. Those two standards are the Space Packet Protocol (SPP) [?] and the Encapsulation Service [?]. With the Space Packet Protocol, application processes generate and consume Protocol Data Units (PDU). The Encapsulation Service encapsulates PDU of recognized protocols defined in a Space Assigned Number Authority (SANA) [?] registry into two types of packets, either Space Packets or Encapsulation Packets. External protocols data units, such as the Internet Protocol datagrams, can be transmitted by CCSDS Space Data Link Protocols, although they cannot be directly encapsulated by the Encapsulation Service, and an intermediate service, such as IP over CCSDS (IPoC) [?], must be used.

Figure 2.3.1, shows the recommended protocols by the CCSDS for Space Communications. In Figure 2.3.2 those protocols arearranged in some possible combinations. As it can be seen, IP cannot be directly used neither by the protocols in the Data Link layer nor the Encapsulation Service.

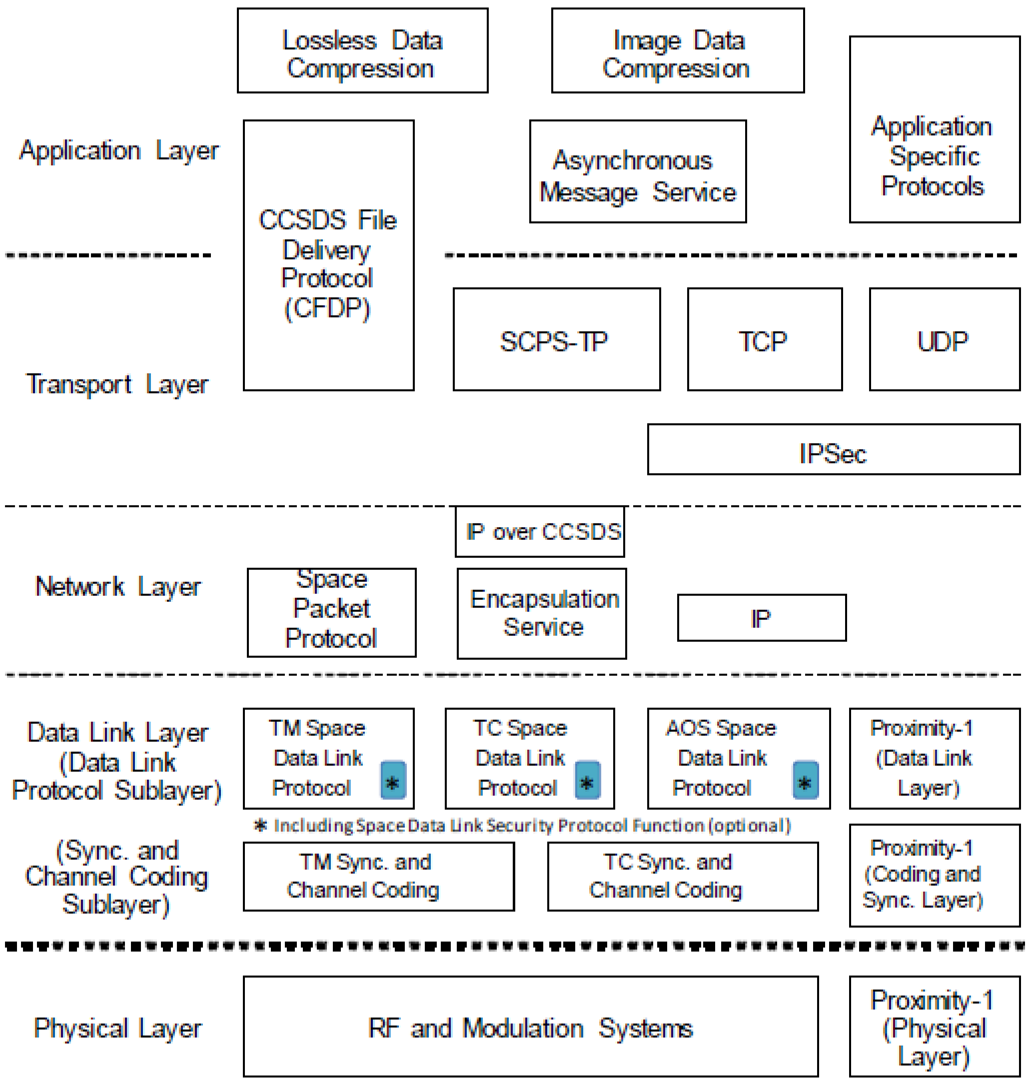


Figure 2.3.1: Protocols recommended by the CCSDS, classified in their respective OSI layers. Extracted from [?].

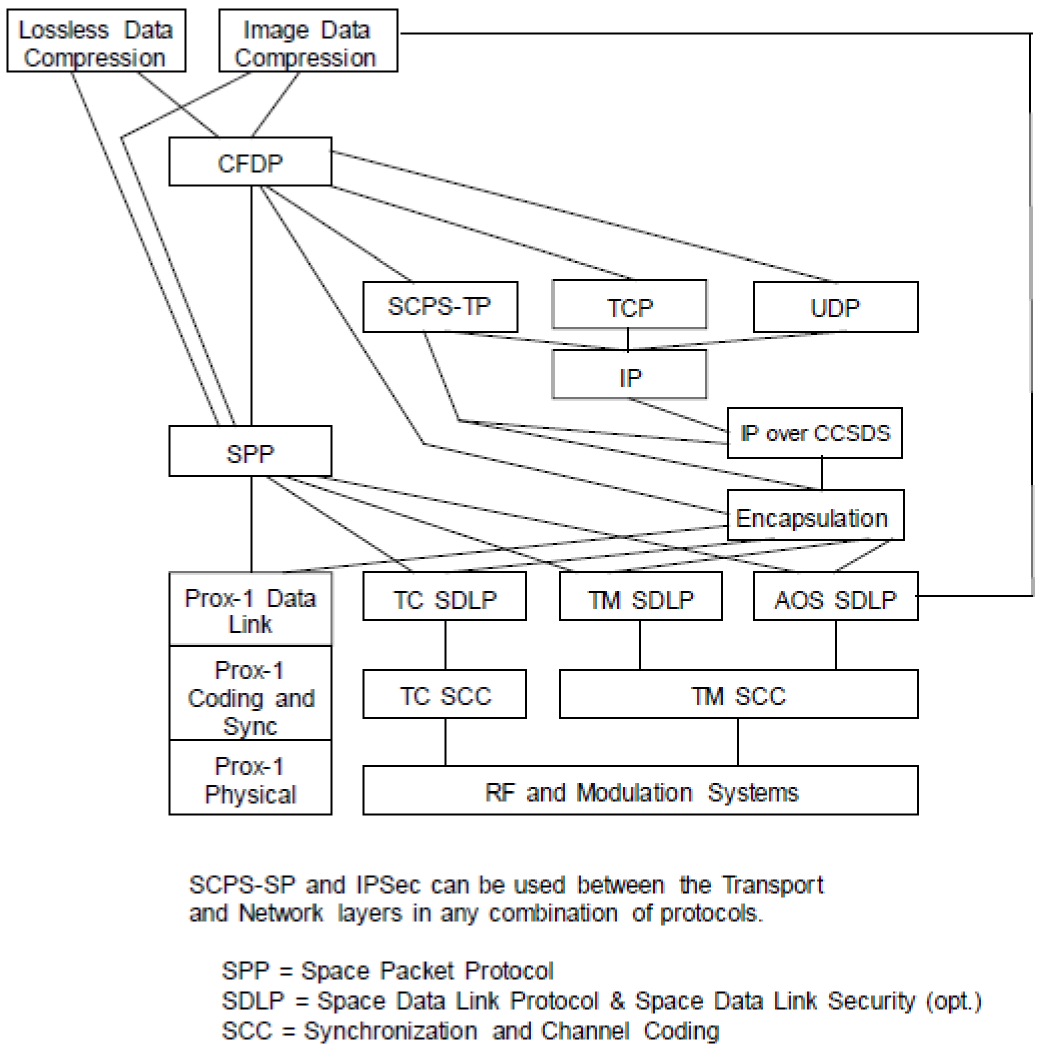


Figure 2.3.2: Possible Combinations of the CCSDS recommended protocols. Extracted from [?].

Protocols in the Network Layer can be classified according if they are the main protocol (SPP or IP, for example) or they provide additional features so that the main protocol can work efficiently. An example of the latter are routing protocols, and also for IP, IPoC and Encapsulation Service.

In the following pages, a brief review of distinct protocols on the Network layer will take place. Since CCSDS ecommends using SPP or Encapsulation Service, only SPP and protocols that can be encapsulated by the Encapsulation Service, eiyher directly or indirecly, will be reviewed. The protocols reviewed will be classified according if they are the main protocol, auxiliary protocols, or routing protocols.

2.3.2.1 Main protocols

Space Packet Protocol (SPP) [?]

The Space Packet Protocol (SPP) is a protocol designed to efficiently transfer application data over a network of space links. SPP provides a unidirectional data transfer service from a single source user application to one or more destination user applications through one or more subnetworks. The path from the source user application to the destination user application is called a Logical Data Path (LDP). Every LDP is uniquely identified by a Path Identifier (Path ID). The protocol data unit used by this protocol is the Space Packet. Each Space Packet is defined by a header section and a data section.

Each LPD is uniquely identified by a Path ID. A Path ID consists of an Application Process Identifier (APID) and an optional APID Qualifier. APID Qualifiers identify the naming domain for an APID. APIDs are unique in a single naming domain. The APID is part of the header of the Space Packet, but the APID Qualifier must be carried by a protocol of an underlying layer.

The following features are common to the services of the SPP:

- Pre-configured Services. The user can send or receive data only through a preconfigured LDP established by management.
- Unidirectional Services. One end of an LDP can send, but not receive, data through the LDP, while the other end can receive, but not send. This means A can send to B through a LPD, but for B to send to A has to use a different LDP
- Asynchronous Services. There are no predefined timing rules for the transfer of service data units supplied by the service user. The user may request data transfer at any time it desires, but there may be restrictions imposed by the provider on the data generation rate.
- Unconfirmed Services. The sending user does not receive confirmation from the receiving end that data has been received.
- Incomplete Services. The services do not guarantee completeness, nor do they provide a retransmission mechanism.
- Non–sequence Preserving Services. The sequence of service data units supplied by the sending user may not be preserved through the LDP.

The following services are assumed from the underlying layers:

- Adressing and routing capabilities for establishing LDPs
- Capability for associating an APID Qualifier for each Space Packet.

The structure of a Space Packet consists of a Packet Primary Header, and a Packet Data Field, which can contain an optional Secondary Header. Figure 2.3.3 shows the structure of the SPP primary header:

Offsets	Octet	0								1							
Octet	Bit	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	0	Packet Version Number			Packet Type	Secondary Header Flag	Application Process Identifier (APID)										
4	32	Sequence Flags		Packet Sequence Count or Packet Name													
8	64	Packet Data Length															

Figure 2.3.3: Example of a header for an SPP Space Packet.

Internet Protocol version 4 (IPv4) [?]

The Internet Protocol version 4 (IPv4) is the fourth version of the Internet Protocol (IP). It is one of the core protocols of standards-based internetworking methods in the Internet. Despite the ongoing deployment of a successor protocol (IPv6), the IPv4 still routes most of the Internet traffic. IPv4 is a conectionless protocol and does not guarantee delivery, nor does it assure proper sequencing or avoidance of duplicate delivery. These aspects are adressed by a transport layer protocol.

One of the features of IPv4 are adresses. Network adresses are the identification number of any device that is part of a network. IPv4 uses 32-bit (4 byte) adresses. Therefore, the adress space is limited to 4294967296 (2^{32}) adresses. A IPv4 adress is usually represented in two ways: in binary notation, where each group of 8 bits is separated by a dot, or in decimal notation, where each 8-bit binary number is translated to decimal, as it can be seen in Table 2.3.1.

IP adress	10101100000100001111111000000001
Dot-binary notation	10101100.00010000.11111110.00000001
Dot-decimal notation	172.16.254.1

Table 2.3.1: IP adress notation in dot-decimal and dot-binary.

Packets in the IPv4 consist of a header section and a data section. There is no footer at the end of the data section since the protocols in the data link layer and the transport layer provide error correction controls. Headers in a IPv4 packet contain 14 fields, one of them being optional. The fields are packed with the most significant byte first, and the most significant bit is also the first. Headers have a lenght between 20 and 60 bytes. The data section comes after the header, and its format depends on the protocol used (for example, ICMP, IGMP, TCP, etc.). FIgure 2.3.4 shows the structure of a IPv4 header.

Offsets	Octet	0								1								2								3							
Octet	Bit	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
0	0	Version				IHL				DSCP						ECN		Total Lenght															
4	32	Identification																Flags			Fragment Offset												
8	64	Time to Live								Protocol								Header Checksum															
12	96	Source IP Adress																															
16	128	Destination IP Adress																															
20	160	Options (if IHL>5)																															
24	192																																
28	224																																
32	256																																

Figure 2.3.4: Example of a header for an IPv4 packet. In this case, it has a lenght of 36 bytes.

IPv4 provides fragmentation of packets. If size of the packet is bigger than the maximum transmission unit (MTU) of the destination, and the message allow fragmentation (the option of Do not Fragment in the header of the packet is set to 0) the transmitting router will divide the packet in fragments smaller than the MTU.

Internet Protocol version 6 (IPv6) [?]

The Internet Protocol version 6 (IPv6) is the most recent version of the Internet Protocol, developed to solve the problem of the exhaustion of IP adresses of the IPv4. IPv6 is intended to replace IPv4. The new features of the IPv6 compared of those of the IPv4 are the following:

- Larger adress space: The length of IPv6 adresses is 128 bits, which is four times the length of IPv4 adresses. It offers a capacity of 2^{128} adresses.
- Multicasting: IPv6 acomplishes multicasting without using other protocols (such as IGMP for IPv4)
- Stateless address autoconfiguration (SLAAC): IPv6 hosts can configure themselves automatically when they are connected to a IPv6 network using the Neighbor Discovery Protocol via Internet Control Message Protocol version 6 (ICMPv6) router discovery messages. When a host is connectes for the first time, it sends a link-local router solicitation multicast request for its configuration parameters. Then, routers

respond to the request with a router advertisement packet that contains Internet Layer configuration parameters.

- Network-layer security: Internet Protocol Security was developed for IPv6 before it was adapted for IPv4.
- Simplified processing by routers: Packet headers and the process of packet forwarding have been simplified, so packet processing by routers is more efficient. Headers now have a fixed length of 40 bytes, and may have an optional section aimed for options between the header section and the data section. Figure 2.3.5 shows the structure of a IPv6 header. IPv6 routers do not perform fragmentation.
- Mobility: Mobile IPv6 avoids triangular routing (unlike IPv4) and is as efficient as native IPv6.
- Options extensibility: IPv6 headers have astructure capable of extending the protocol in the future without affecting the core packet structure.
- Jumbograms: IPv4 limits packets to (2 power 16) - 1 octets per payload. A IPv6 node can handle packets of (2 power 32) - 1 octets (called jumbograms).

<table>
<tr><th>Offsets</th><th>Octet</th><th colspan="8">0</th><th colspan="8">1</th><th colspan="8">2</th><th colspan="8">3</th></tr>
<tr><th>Octet</th><th>Bit</th><td>0</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td>19</td><td>20</td><td>21</td><td>22</td><td>23</td><td>24</td><td>25</td><td>26</td><td>27</td><td>28</td><td>29</td><td>30</td><td>31</td></tr>
<tr><td>0</td><td>0</td><td colspan="4">Version</td><td colspan="8">Traffic Class</td><td colspan="20">Flow Label</td></tr>
<tr><td>4</td><td>32</td><td colspan="16">Payload Length</td><td colspan="8">Next Header</td><td colspan="8">Hop Limit</td></tr>
<tr><td>8</td><td>64</td><td colspan="32" rowspan="4">Source Adress</td></tr>
<tr><td>12</td><td>96</td></tr>
<tr><td>16</td><td>128</td></tr>
<tr><td>20</td><td>160</td></tr>
<tr><td>24</td><td>192</td><td colspan="32" rowspan="4">Destination Adress</td></tr>
<tr><td>28</td><td>224</td></tr>
<tr><td>32</td><td>256</td></tr>
<tr><td>36</td><td>288</td></tr>
</table>

Figure 2.3.5: Example of a header for an IPv6 packet.

2.3.2.2 Auxiliary protocols

Encapsulation service [?]

The Encapsulation Service is a service used to transfer data units that can not be directly transferred by the CCSDS Space Data Link Protocols. In order to be directly transferred by a Space Data Link Protocol, a data unit must have a Packet Version Number authorized by the CCSDS (a list of PVN authorized by CCSDS is contained in [?]). With the Encapsulation Service, data units that do not have an authorized VPN can be transmitted with Space Data Link Protocols. The data unit to be transmitted must be of an integral number of octets.

A user of the Encapsulation Service is identified by the combination of the following:

- A Packet Version Number (PVN) that indicates whether Space Packets (PVN=1) or Encapsulation Packets (PVN=8) are used for encapsulation,
- An Encapsulated Protocol Identifier (EPI), whichis either:
  - An Application Process Identifier (APID) defined in reference (if Space Packets are used).
  - a Protocol ID defined in section 4 of this document (if Encapsulation Packets are used).

The APIDs used by the Encapsulation Service must be registered as 'reserved APIDs' in [?]. The Protocol IDs used by the Encapsulation Service must be registered as 'defined Protocol IDs' in [?].

If the Data Unit is encapsulated in a Space Packet, the header format of the Space Packet is the same as the one used by Space Packet Protocol, only that the values of the parameters are restricted to some values. On the other hand, if the Data Unit is encapsulated in a Encapsulation Packet, a different header format will be used. This header have a length of 1-8 octets, and for the case of 8 octet it can be shown in Figure 2.3.6

	Bit							
Octet	0	1	2	3	4	5	6	7
0	Packet VersionNumber			Protocol ID			Length of length	
1	User defined fields				Protocol ID extension			
2	CCSDS defined field							
3								
4	Packet length							
5								
6								
7								

Figure 2.3.6: Example of a header for an Encapsulation Packet of maximum length. Some parameters may vary its length in other cases.

IP over CCSDS (IPoC) [?]

The IP over CCSDS is used to transfer IP Data Units over CCSDS Space Data Link Protocols. IP Data Units are encapsulated in Encapsulation Packets and sent through

Space Data Link Protocols. IPoC uses the CCSDS Internet Protocol Extension (IPE) convention in conjunction with the CCSDS Encapsulation Service. The IPE convention is used to add IPE octecs at the beginning of a IP Data Unit, encapsulate the result in an Encapsulation Packet, and transmit it with a CCSDS Space Data Link Protocol. It is used because not all protocols that use an IP datagram have a Protocl ID used by the Encapsulation Packet.

IPoC adds a header at the beginning of the IP Data Unit, called IPE header. The sum of the IP Data Unit and the IPE header is the Data Unit used by the Encapsulation Service. In other words, for the Encapsulation Service, the IPE header and the IP Data Unit are a whole.

The structure of the IPE header will be the following. It must be of a length of an integral number of octets, with a minumum length of 1 octet. Each octet will be divided into two parts: the first seven bits (bits 0-6), and the least significant bit (LSB, bit 7). If more octets are added, the LSB of all octets except the last octet are set to '0'. The value of the IPE header is the decimal value of all the octets. The value of the IPE header must be one of the possible values in [**?**].

Internet Control Message Protocol (ICMP) [?]

The Internet Control Message Protocol (ICMP) is one of the main protocols of the TCP/IP protocol suite. It is used to send error messages to the source IP of the data packet. It is assigned IP protocol number 1. ICMP messages are typically used for diagnostic, control purposes or generated in response to errors in IP operations. They are processed differently than normal IP proceessing.

There are many types of control messages that the ICMP can send:

- Souce quench: Used to request the sender to decrease the rate of messages sent to a router.
- Redirect: Used to request the sender to send the data to another router.
- Time exceeded: Used by a gateway to inform the sender of a discarded datagram due to the time to life field reaching zero. It is also used to inform the sender that a fragment of a message has not been reassembled within the time limit
- Timestamp: Used for time syncronization. The sender sends the timestamp it last touched the packet (in miliseconds since midnight)

- Timestamp reply: Used to reply a timestamp. The reciever of the timestamp message replies the sender with the original timestamp, the timestamp when the message was recieved, and the timestamp when the reply was sent.
- Adress mask request: Used by a host to obtain the subnet mask of a router
- Adress mask reply: Used to reply the adress mass request returning the subnet mask.
- Destination unreachable: Used by the host or its inbound gateway to inform the client that the destination is unreachable.

Internet Control Message Protocol version 6 (ICMPv6) [?]

The Internet Control Message Protocol version 6 (ICMPv6) is the implementation of the ICMP for IPv6. Several extensions have been published that define new types of ICMPv6 messages, as well as new options for existing message types. One of those is the Neighbor Discovery Protocol (NDP), a node discovery protocol for IPv6 that replacesand enhances the features of the Address Resolution Protocol (ARP). Secure Neighbor Discovery (SEND) is, respectively, an extension of NDP with extra security. Multicast Router Discovery (MRD) allows discovery of multicast routers.

Internet Group Management Protocol (IGMP) [?]

The Internet Group Management Protocol (IGMP) is used by hosts and adjacent routers on IPv4 networks to establish multicast group memberships. It is a part of IP multicast, and it is used in one-to-many networking applications such as online streaming video. IGMP operates between the client computer and a local multicast router. IGMP messages are carried in bare IP packets with protocol number 2.

Internet Protocol Security (IPsec) [?]

The Internet Protocol Security (IPsec) is a protocol suite for secure Internet Protocol (IP) communications. It authenticates and encrypts each IP packet of a communication session. IPSec includes protocols for establishing mutual authentication between agents at the beginning of the session and negotiation of cryptographic keys to be used during the session. IPsec can be used in protecting data flows between a pair of hosts (host-to-host), between a pair of security gateways (network-to-network), or between a security gateway and a host (network-to-host). It supports network-level peer authentication, data origin authentication, data integrity, data confidentiality (encryption), and replay protection.

IPsec uses the following protocols to perform various functions;

- Authentication Headers (AH): Provides connectionless data integrity and data origin authentication for IP datagrams, and provides protection against replay attacks.
- Encapsulating Security Payloads (ESP): Provide confidentiality, data-origin authentication, connectionless integrity, an anti-replay service, and limited traffic-flow confidentiality.
- Security Associations (SA): Provides the bundle of algorithms and data that provide the parameters necessary for AH and ESP operations.

Protocol Independent Multicast (PIM) [?] [?]

The Protocol Independent Multicast (PIM) is a family of multicast routing protocols for Internet Protocol (IP) networks that provide one-to-many and many-to-many distribution of data. PIM does not include its own topology discovery mechanism, but instead uses routing information supplied by other routing protocols.

There are four variants of PIM:

- PIM Sparse Mode (PIM-SM): It builds unidirectional shared trees rooted at a rendezvous point (RP) per group, and optionally creates shortest-path trees per source. It is called sparse-mode because it is suitable for groups where low percentage of the nodes will subscribe to the multicast session.
- PIM Dense Mode (PIM-DM): It uses dense multicast routing. It builds shortest-path trees by flooding multicast traffic domain wide, and then pruning back branches of the tree where no receivers are present. Dense mode is ideal for groups where many of the nodes will subscribe to receive the multicast packets.
- Bidirectional PIM: It builds shared bi-directional trees. It never builds a shortest path tree, so may have longer end-to-end delays than PIM-SM.
- PIM Source-Specific Multicast (PIM-SSM): It builds trees that are rooted in just one source, offering a more secure model for a limited amount of applications (mostly broadcasting of content). In SSM, an IP datagram is transmitted by a source S to an SSM destination address G, and receivers can receive this datagram by subscribing to channel (S,G).

2.3.2.3 Routing protocols

Enhanced Interior Gateway Routing Protocol (EIGRP) [?]

The Enhanced Interior Gateway Routing Protocol (EIGRP) is a routing protocol used on a computer networks for automating routing decisions and configuration. This protocol was designed by Cisco Systems and it was only avaiable for Cisco routers. In 2003, partial functionality of EIGRT was converted to an open standard and in 2016 was published with informational status. EIGRP is used on a router to share routes with other routers in the same autonomous system.

All routers contain a routing table that lists the routes to network destinations. If a router cannot find a valid path to the destination, the traffic is discarded. EIGRP is a dynamic routing protocol, which means that routers automatically exchange information about routes and, therefore, the administrator does not have to change the routing table manually. Besides the routing table, routers adittionlly have two more tables.

- Neighbour table. It stores the IP adress of the routers that have a direct connection with this router. If a router is connectedto another with an intermediate router, it will not be recorded in this table.
- Topology table. It keeps record of routes that has learned from neightbouring router tables, and also records the distance (number of intermediate routers) of each route, the feasible successor and the successors (other routes that have the same destination and are loop free). Routes in this table are either labelled as "passive" or "active". Passive means that EIGRP has determined the path for the specific route and has finished processing. Active means that EIGRP is still trying to calculate the best path for the specific route. The router dones not use the routes in this table. A route in this table will be inserted in the routing talbe when is marked as passive, is not a feasible successor and does not have a higher distance than an equivalent path

If there is a change in the network (a link fails, or a router is disconnected), the path becomes unavaiable, and is removed from the routing table. The routing table of a router will be updated, and only the changes since the previous update will be transmitted to the neightbouring routers. The information about the changes in the routing table is not transmitted periodically, but only when a change actually occurs.

EIGRP supports the following features:

- Support for Classless Inter-Domain Routing (CIDR) and variable length subnet masking. Routes are not summarized at the classful network boundary unless auto summary is enabled.
- Support for load balancing on parallel links between sites.
- The ability to use different authentication passwords at different times.
- MD5 authentication between two routers.
- Sends topology changes, rather than sending the entire routing table when a route is changed.
- Periodically checks if a route is available and propagates routing changes to neighboring routers if any changes have occurred.
- Runs separate routing processes for Internet Protocol (IP), IPv6, IPX and AppleTalk through the use of protocol-dependent modules (PDMs).

EIGRP does not operate using the Transmission Control Protocol (TCP) or the User Datagram Protocol (UDP). This means that EIGRP does not use a port number to identify traffic. Rather, EIGRP is designed to work on top of layer 3. Since EIGRP does not use TCP for communication, it implements Cisco's Reliable Transport Protocol (RTP) to ensure that EIGRP router updates are delivered to all neighbors completely.

Open Shortest Path First (OSPF) [?] [?]

The Open Shortest Path First (OSPF) is a routing protocol for Internet Protocol (IP) networks that operates in a single autonomous system. OSPF version 2 is designed for IPv4, while OSPF version 3 is designed for IPv6. It works by gathering link state information from available routers and constructing a topology map of the network. The topology is presented as a routing table to the Internet layer which routes packets based solely on their destination IP address. OSPF detects changes in the topology, such as link failures, and creates a new loop-free routing structure. It computes the shortest-path tree for each route using a method based on Dijkstra's algorithm. OSPF does not use a transport protocol, such as UDP or TCP, but encapsulates its data directly in IP packets with protocol number 89. It implements its own transport layer error detection and correction functions. OSPF uses multicast addressing for distributing route information within a broadcast domain.

OSPF supports complex networks with multiple routers, including backup routers, to balance traffic load on multiple links to other subnets. Routers form adjacencies when they have detected each other. This detection is initiated when a router identifies itself in a Hello protocol packet. Upon acknowledgment, this establishes a two-way state and the most basic relationship. The routers in an Ethernet or Frame Relay network select a Designated Router (DR) and a Backup Designated Router (BDR) which act as a hub to reduce traffic between routers. OSPF establishes and maintains neighbor relationships for exchanging routing updates with other routers. The neighbor relationship table is called an adjacency database. Two OSPF routers are neighbors if they are members of the same subnet and share the same area ID, subnet mask, timers and authentication. OSPF adjacencies are formed between selected neighbors and allow them to exchange routing information. Two routers become adjacent if at least one of them is Designated Router or Backup Designated Router (on multiaccess type networks), or they are interconnected by a point-to-point or point-to-multipoint network type.

OSPF does not carry data via a transport protocol. Instead, OSPF forms IP datagrams directly, packaging them using protocol number 89 for the IP Protocol field. OSPF defines five different message types, for various types of communication:

- Hello: It is used to allow a router to discover other adjacent routers on its local links and networks. The messages establish adjacencies between neighboring devices. uring normal operation, routers send hello messages to their neighbors at regular intervals. If a router stops receiving hello messages from a neighbor, after a set period the router will assume the neighbor has gone down.
- Database Description: It contain descriptions of the topology of the autonomous system or area. They convey the contents of the link-state database (LSDB) for the area from one router to another. Communicating a large LSDB may require several messages to be sent.
- Link State Request: These messages are used by one router to request updated information about a portion of the LSDB from another router. The message specifies exactly which link about which the requesting device wants more current information.
- Link State Update: These messages contain updated information about the state of certain links on the LSDB. They are sent in response to a Link State Request message, and also broadcast or multicast by routers on a regular basis. Their contents are used to update the information in the LSDBs of routers that receive them.
- Link State Acknowledgment: These messages provide reliability to the link-state exchange process, by explicitly acknowledging receipt of a Link State Update message.

Routing Information Protocol (RIP) [?] [?]

The Routing Information Protocol (RIP) is a routing protocol. It uses a hop count to establish the distance between two routers and, in order to prevent loops, establishes 15 as the limit number of hops in a route. If the number of hops is 16, the distance between the two routers is considered infinite. Each router has a routing table with all the routes to each possible destination, and the number of hops to get there. There are 3 versions of RIP: RIPv1, which is the original, RIPv2, which is an updated version of RIPv2, and RIPng, which is the new generation of RIP compatible with IPv6.

The operating principle of the RIP is the following: When a RIP router comes online, it sends a broadcast message to all of its RIP enabled interfaces. All the neighbouring routers that receive the Request message respond back with the Response Message containing their Routing table. The Response Message is also gratuitously sent when the Update timer expires (by deffect, 30 seconds). On receiving the Routing table, the router processes each entry of the routing table as per the following rules:

- If there are no route entries matching the one received then the route entry is added to the routing table automatically, along with the information about the router from which it received the routing table.
- If there are matching entries but the hop count metric is lower than the one already in its routing table, then the routing table is updated with the new route.
- If there are matching entries but the hop count metric is higher than the one already in its routing table, then the routing entry is updated with hop count of 16 (infinite hop). The packets are still forwarded to the old route. A Holddown timer is started and all the updates for that route from other routers are ignored. If after the Hold-down timer (per deffect 180 seconds) expires and still the router is advertising with the same higher hop count then the value is updated into its routing table. Only after the timer expires, the updates from other routers are accepted for that route.

If the Invalid timer (per deffect 180 seconds) expires and a routing entry has not been updated, the hop counter of that route will be set to 16, marking the route as invalid. Then, if the Flush timer (per deffect 240 seconds) expires, the invalid route entry will be removed

2.3.3 Protocol Selection

2.3.3.1 Choice of the main protocol

The choice of the main protocol will be between SPP, IPv4 and IPv6. Tho make the choice, it is important to take into account that the Astrea constellation is a network that can be of more than two hundred satelites, which will communicate point-to-point. Each node can be the source ,the destination or an intermediate node of a communication route.

SPP has the advantage of being designed to work easily with the protocols of the adjacent layers, while IP needs IP over CCSDS and Encapsulation Service. However, SPP requires a parametre called Path ID, which is the identifier of a Logical Data Path. Since each satellite of Astrea constellation can be the source or the destination of a data path, this means that for a network of 200 nodes, there are 200x199=39800 possible routes. The parameter to indicate the Path ID has a length of 11 bits, which can identify 2048 different routes, which is not enough. Another issue to take into account is that since the ground station nodes of the constellation are moving respect the satellite nodes, their relative position changes and, therefore, paths also change. If the path associated to a Path ID changes during a transmission, or if is not updated for all nodes at the time of the transmission, errors can occur. This does not happen with IP, since instead of Path ID it uses the IP adress of the source and destination node. For this reason, SPP is discarded.

The main differences between IPv4 and IPv6 are the header of the datagram and the IP adresses of the nodes. Since our network is private and it is not intended to be connected to the Internet, nodes can have an arbitrary IP adress assigned. For this reason, IPv4 adresses are better, since they are shorter than IPv6 adresses. The size of the header would also be smaller in IPv4 than IPv6. However, for long datagrams, the extra length of IPv6 headers is irrelevant. Another difference is that IPv6 datagrams require less processing power, however, since the processing power is very small compared to the power required by the antennas this factor also has little importance in terms of power. However, it is important in terms of time, since less processing means less time to process. Other features of IPv6 that, in Astrea network, do not privide benefits are the multicast and mobility features, which the network ill not have. Additionally, due to the changing nature of the constellation, jumbograms will not be used because a packet so long may be interrumted when the path changes.

The real benefits of IPv6 over IPv4 is that there are less additional protocols compared to IPv4 to perform the same features, since ICMPv6 provide the features of ICMP, ARP and

IGMP, and some features of IPv6 itself and its additional protocols have been eliminated since they were already performed by other layer protocols and were redundant. All of this helps to reduce the time required to process the data and this, in long paths, is a significant factor.

If reliable adjacent layer protocols are provided, IPv6 is the best option, due to less processing in routers and more simple additional protocols. Additionally, IPv6 is progressively replacing IPv4 and, therefore, using IPv6 has no risk of being obsolete.

2.3.3.2 Choice of routing protocol

The choice of the routing protocol will be between EIGRP, OSPF and RIP.

EIGRP is a protocol compatible with either IPv4 and IPv6. Contrary to other protocols, it only sends topology changes instead of the whole routing table, allowing for less data transmitted. It also contains more information about routes than other routing protocols, and provides authentication processes.

RIP is a protocol that, compared to EIGRP and OSPF, has the drawback that its time to converge and its scalability are poor. Additionally, RIP uses the User Datagram Protocol (UDP) as its transport protocol. On the other, it is easier to configure than other protocols.

OSPF is a protocol also compatible with IPv4 and IPv6. Unlike EIGRP, each router exchanges its adjacency links with adjacent routers and then, each router creates its own map of the network and, using this map, each router creates its own routing table. However, it has mechanisms to ensure that thare are not loops in the network.

Taking into account that nodes in the Astrea network have an order of magnitude of 200 and is continously changing the data paths. Also, since Astrea is a network where a node can be the beginning or the end of a communication, this means that for a given node there has to be a route to every other node in the network, and for a network of 200 nodes, there are 199 possible routes for the 200 nodes, which is a total of 39800 different entries in the routing table only for the satellite nodes. Since RIP has longer time to converge compared to other protocols, and due to the huge size of the routing table, RIP is discarded.

EIGRP does not have this problem because it does not transmit the whole routing table, but only the changes. Although the network is continously moving, the paths between the satellite nodes remain the same. The problem happens with the ground nodes, which are continouslly changing its position respect the satellite nodes due to Earth's rotation. And since each satellite node can communicate with every ground station, the number of entries in the routing table that will be updated for a network of 200 satellite nodes and 5 ground stations is 200x5, which is 1000 entries that will be updated frequently. Since OSPF does not transmit the routing table but only the adjacencies, only 205 entries will be transmitted. This reduces the time to share the updated information to the whole network. For this reason, OSPF is chosen.

2.3.3.3 Choice of complementary protocols

The choice of which protocols include will depend on the main protocol of the network layer and the degree of services featured by the communication process.

Since IPv6 has been chosen, IP over CCSDS and Encapsulation Service are necessary. Additionally, ICMPv6 greatly expand the features of IPv6 such as flow control. Security features are already provided in the Data Link layer and, therefore, IPsec is not necessary. Also, no multicast features are required, so no multicast protocols will not be used.

2.3.3.4 Conclusion

It has been decided that IPv6 will be the network layer protocol, complemented with IPoC, Encapsulation Service and ICMPv6, and with OSPF as the routing protocol.

2.3.4 Final structure

As the protocols have already been chosen, it is time to establish how will be the headers of the different protocols.

The IPv6 header will depend greatly on the protocol of the upper layers, or the auxiliar protocol (OSPF, ICMPv6). The main parameters of the IPv6 header, that can be seen in Figure 2.3.5, are the following:

- **Version** Current version of IP, which for IPv6 is 6 (bit sequence 0110).

- **Traffic Class**. The bits of this field hold two values. The 6 most-significant bits are used for differentiated services, which is used to classify packets. The remaining two bits are used for ECN; priority values subdivide into ranges: traffic where the source provides congestion control and non-congestion control traffic.

- **Flow Label**. The flow label when set to a non-zero value now serves as a hint to routers and switches with multiple outbound paths that these packets should stay on the same path so that they will not be reordered.

- **Payload Length**. The size of the payload in octets, including any extension headers. The length is set to zero when a Hop-by-Hop extension header carries a Jumbo Payload option.

- **Next Header**. Specifies the type of the next header. This field usually specifies the transport layer protocol used by a packet's payload. When extension headers are present in the packet this field indicates which extension header follows. The values are shared with those used for the IPv4 protocol field, as both fields have the same function (see List of IP protocol numbers in [**?**]).

- **Hop Limit**. This value is decremented by one at each intermediate node visited by the packet. When the counter reaches 0 the packet is discarded.

- **Source Address**. The IPv6 address of the sending node.

- **Destination Address**. The IPv6 address of the destination node.

It has been stated that, since Astrea network is a private network that will not be connected to the Internet, IP adresses will be arbitrary assigned to the nodes of the network.

For the IPoC heaver, the value for IPv6 datagrams is 87, so the header of OPoC will be 01010111

For the Encapsulation Service, depending of the length of the data unit transmitted, the header will very. For data units up to 65531 octets, the Encapsulation Service header will be the following: 11101010-00000000-XXXXXXXX-XXXXXXXX, where XXXXXXXX-XXXXXXXX is the binary number of the total length of the Encapsulation Packet, including the Encapsilation Packet header.

2.4 Layer 4: Transport and Session

This layer is the one in charge of the free-of-error transference of data from one process to another. Therefore, its goal is to provide and guarantee a reliable and cheap flow of the data.

Whereas the network layer oversees source-to-destination delivery of individual packets, it does not recognize any relationship between those packets. It treats each one independently, as though each piece belonged to a separate message, whether or not it does. The transport layer, on the other hand, ensures that the whole message arrives intact and in order, overseeing both error control and flow control source-to-destination level.

A transport layer can be either connectionless or connection-oriented. A connectionless transport layer treats each segment as an independent packet and delivers it to the transport layer at the destination machine. A connection-oriented transport layer makes a connection with the transport layer at the destination machine first before delivering the packets. After all the data is transferred, the connection is terminated.

In the transport layer, a message is normally divided into transmittable segments. A connectionless protocol, such as UDP, treats each segment separately. A connectionoriented protocol, such as TCP and SCTP, creates a relationship between the segments using sequence numbers.

The transport layer is responsible for process-to-process delivery, i.e, the delivery of a packet, part of a message, from one process to another. Two processes communicate in a client/server relationship.

Regarding addressing, at the transport layer, it is necessary a transport layer address, called a port number, to choose among multiple processes running on the destination host. The destination port number is needed for delivery, whereas the source port number is needed for the reply.

The addressing mechanism allows multiplexing and demultiplexing by the transport layer.

2.4.1 User Datagram Protocol (UDP)

The User Datagram Protocol (UDP) is a connectionless, unreliable transport protocol. The only new feature regarding IP is that it provides process-to-process communication instead of host-to-host communication, and performs a very limited error checking. It might seem a powerless protocol, but its main point is that is a very simple protocol using a minimum of overhead. Therefore, if a process wants to send a small message and no extremely reliability is required, UDP is a good choice.

Nevertheless, regarding the aim of this project, it is unacceptable to use UDP, since reliability is a key factor and must be taken into account.

2.4.2 Stream Control Transmission Protocol (SCTP)

The Stream Control Transmission Protocol is a new reliable, message-oriented transport layer protocol. Nevertheless, it has been designed and implemented mostly for Internet applications, such as IUA or SIP. But precisely it does not fit the goal of this project.

Therefore, as there is a better choice (which will be deeply and widely explained in the following section), this protocol will not be considered.

2.4.3 Transmission Control Protocol (TCP)

The Transmission Control Protocol is again a process-to-process protocol. Consequently it uses port numbers. The main difference with the UDP is that TCP is a connection-oriented protocol, which means that creates a virtual connection between two TCP's in order to send data. Moreover, TCP uses flow and error control mechanisms. It is then a more reliable protocol that UDP. It adds connection-oriented and reliability features to the services of IP.

This will be the protocol chosen for this project, so it will be explained in detail in this section.

2.4.3.1 TCP Services

Process-to-process communication: Like UDP, TCP provides this type of communication, using port numbers. In the following image there are the main well-known port numbers used by TCP.

Port	*Protocol*	*Description*
7	Echo	Echoes a received datagram back to the sender
9	Discard	Discards any datagram that is received
11	Users	Active users
13	Daytime	Returns the date and the time
17	Quote	Returns a quote of the day
19	Chargen	Returns a string of characters
20	FIP, Data	File Transfer Protocol (data connection)
21	FIP, Control	File Transfer Protocol (control connection)
23	TELNET	Tenninal Network
25	SMTP	Simple Mail Transfer Protocol
53	DNS	Domain Name Server
67	BOOTP	Bootstrap Protocol
79	Finger	Finger
80	HTTP	Hypertext Transfer Protocol
111	RPC	Remote Procedure Call

Stream Delivery Service: as has been mentioned before, TCP, unlike UDP, is a stream-oriented protocol. UDP does not recognize any relationship between the datagrams. TCP, in contrast, allows the sending process to deliver data as a stream of bytes and allows the receiving process to obtain data as a stream of bytes. A way of explaining this would be an environment in which the two processes seems to be linked by and imaginary "tube" that carries the data across the Internet. The sending process produces the stream of bytes and the receiving process consumes them. This is, the first writes and the last reads.

Sending and Receiving Buffers: Since the sending and receiving processes might not write or read data at the same speed, there is a need for storage in TCP. Therefore, TCP includes two buffers, the sending buffer and the receiving buffer. A deeper look into those buffers can be performed by looking at the bibliography.

Full-Duplex Communication: TCP allows full-duplex service, so that data can flow in both directions at the same time. Each TCP has a sending and receiving buffer, and segments move in both directions. This feature is very important for the goal of this project.

Segments: Although buffering solves the problem of different speeds of producing and consuming, there is still one impotant feature to be discussed. The data needs to be sent in packets, not as a endless stream of bytes. Therefore, TCP groups a number of bytes together into a packet called a segment. A header is added to each segment for control purposes.

2.4.3.2 TCP features

In order to provide the services that have been explained, TCP has some features that will be briefly discussed.

Numbering Systems

TCP keeps track of the segments being transmitted or received, using the header previoulsy discussed. There are in addition two fields, the sequence number and the acknowledgement number, which refer to the byte number, not the segment number.

TCP numbers all data bytes that are transmitted in a connection. Numbering is independent in each direction. When TCP receives bytes of data from a process, it stores them in the sending buffer and numbers them. Typically, it generates randomly a number between 0 and $2^{32}-1$ for the number of the first byte. For example, if the random number happens to be 1427 and the total data to be sent are 5000 bytes, the bytes are numbered from 1427 to 6426. This system is used for flow and error control.

After the bytes have been numbered, TCP assigns a sequence number to each segment that is being sent. The sequence number for each segment is the number of the first byte carried in that segment. This is, the value in the sequence number field of a segment defines the number of the first data byte contained in that segment.

The value of the acknowledgement field in a segment defines the number of the next byte a party expects to receive. It is a cumulative number.

Flow Control

TCP provides flow control, which means that the receiver can control the amount of data that if to be sent by the sender. The purpose of this is to avoid over-whelmed receivers.

Error Control

In order to provide a reliable service, TCP implements an error control mechanism. It considers a segment as the unit of data for error detecting, even though there is also a byte-oriented control mechanism.

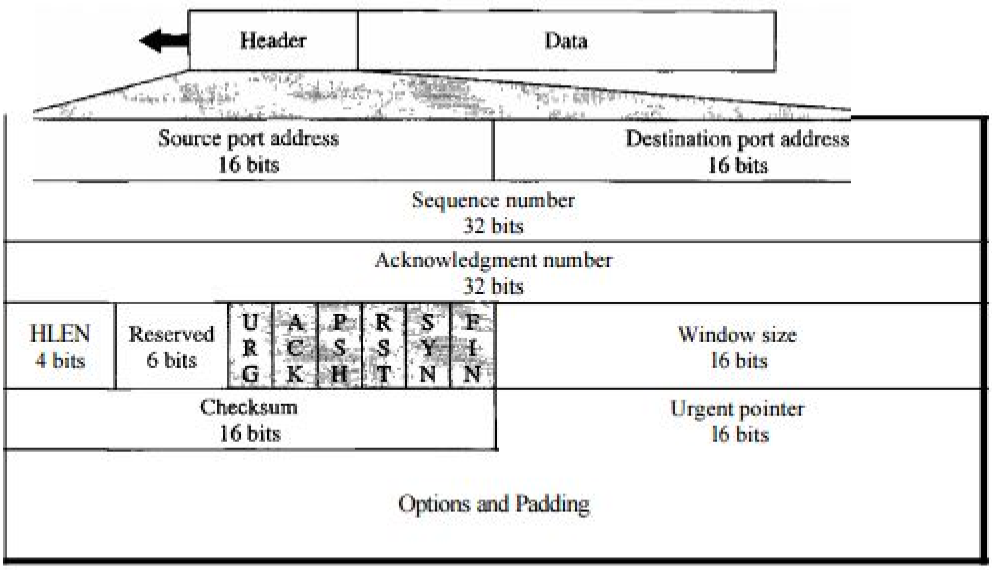
Congestion Control

TCP also takes into account congestion in the network, by the detenning of the flow depending on the level of congestion in the network.

Segment

As has been explained before, a packet in TCP is called a segment. The aim of this point is to explain in detail what a segment is and how its structure is.

The typical format of the segment is shown in the next figure.



The segment consists of a 20 to 60-byte header, followed by data frim the application program. The byte is 20-byte long if there are no options, and up to 60-bytes if there are options.

The main parts of the format are to be discussed in the following lines.

Source Port Adress

This is a 16-bit field that states the port number of the application program in the host that is sending the segment.

Destination Port Adress

It is also a 16-bit that defines the port number of the application program in the host that is receiving the segment.

Sequence Number

This 32-bit field defines the number assigned to the first byte of the data contained in the segment considered. This numeration has been previously explained.

Acknowledgement Number

This is a 32-bit field that defines the byte number that the receiver of the segment is expecting to receive from the other party. If the receiver of the segment has successfully received byte number x, it defines x + I as the acknowledgement number.

Header Length

A 4-bit field that indicates the number of 4-byte words in the TCP header. As seen, the length of the header can be between 20 and 60 bytes. Then, the value of this field can be between 5 and 15 (since $5 \times 4 = 20$, and $15 \times 4 = 60$).

Reserved

This is a 6-bit field reserved for future usage.

Control

This field defines 6 different control bits or flags. One or more of those bits can be set at a time.

Window Size

This fiels defines the size of the window, in bytes, that the other party must maintain. Since the length of this field is 16 bits, the maximum size of the windows is $2^{16} = 65535$ bytes.

Urgent Pointer

Another 16-bit field, which is only valid if the urgent flag is set, which means that the segment contains urgent data. In actually defines the number that must be added to the sequence number to obtain the number of the last urgent byte in the data section of the segment.

Options

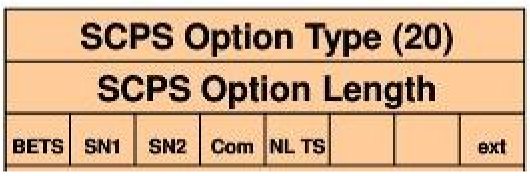
As has been explained, there can be up to 40 bytes of optional information in the TCP Header. This is the purpose of this last field.

Adaptation to space needs

TCP was estblished for wired connections initially. Therefore, in order to be eligible for the purpose of this project, it is highly recommended that some slight modifications are done. The Space Communications Protocols Specification (SCPS) defines a set of revisions to the protocols to enable them to operate properly. This is, SCPC-TCP becomes an "upgraded" TCP, specially designed for space application.

With SCPS, TCP the bandwidth of an existing link will be utilized to a significantly higher percentage and more efficiently. It also supports end-to-end communications between applications and is designed to meet the needs of a broad range of space missions.

This is all achieved because of an extension that is added to the header shown before. This extension header is shown next. Each line is a octet of bits; i.e, 8 bits:



2.4.4 Choice of protocol for the transport layer

Three protocols have been discussed, the UDP, the SCTP and the TCP. The first one has some disadvantages which make it not suitable for the purpose of the project, such as the fact that no reliabililty is guaranteed, for example, amongst others. The second one is designed mostly for Internet applications, which does not fit the goals of this project. Therefore, the only candidate suitable for the project is the TCP, Transmission Control Protocol, which has already been widely explained and analyzed. As it has the required features that the project demands, it is the chosen protocol for this layer. Also, as it has been established, it is very recommended to use the extension SCPS, due to adaptation to space needs.

2.5 Global Overview

For the sake of clarification, all the elected options are going to be put together obtaining the desired fully desgined **protocol stack**.

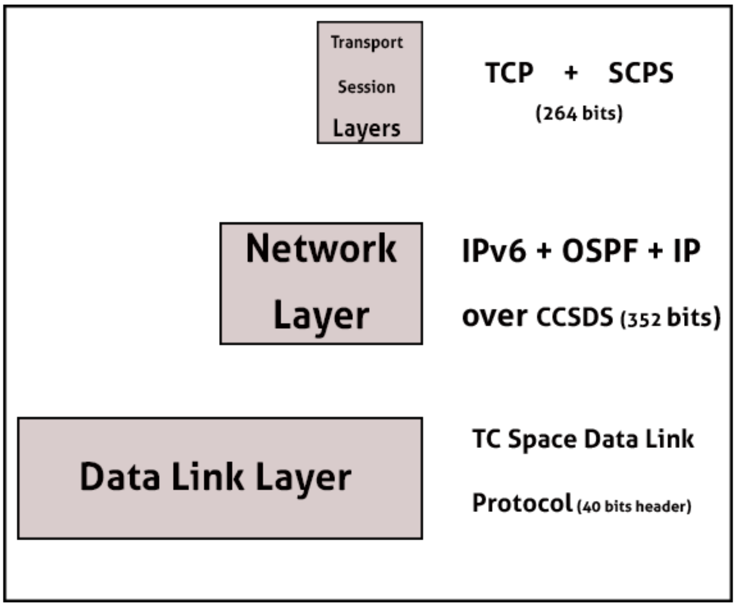


Figure 2.5.1: Overall space communication protocol stack

In total, the overhead is **656 bits**, whith conservative calculations. Hence, the quantity is negligible in comparison to the data rate.

Chapter 3

Ground Segment Protocols

In the previous chapter the space protocols have been selected, so in this one the focus will be on the ground segment protocols. The information will be transmitted to the client using the Internet, so a part of the protocol is already established by the system. However, a secure protocol has to be defined above the Internet protocol to assure confidenciality to the client. The protocol used in the Internet is the TCP/IP protocol suite, that provides an end-to-end data communication specifying how data should be packeted, addressed, transmitted, routed and received. The layer of this protocol that can be adjusted to our needs is the application layer. The application layer is an abstraction layer that specifies the shared protocols and interface methods used by hosts in a communications network. In TCP/IP, the application layer contains the communications protocols and interface methods used in process-to-process communications across an Internet Protocol (IP) computer network. The application layer only standardizes communication and depends upon the underlying transport layer protocols to establish host-to-host data transfer channels and manage the data exchange in a client-server or peer-to-peer networking model. That means that the application layer is very important in Astrea project because it will define how the information is received by the client.
In the following lines the different available protocols for the application layer depending on the presentation of data are explained.

FTP The File Transfer Protocol (FTP) is a standard network protocol used to transfer computer files between a client and server on a computer network.
FTP is built on a client-server model architecture and uses separate control and data connections between the client and the server. FTP users may authenticate themselves with a clear-text sign-in protocol, normally in the form of a username and password, but can connect anonymously if the server is configured to allow it. For secure transmission

that protects the username and password, and encrypts the content, FTP is often secured with SSL/TLS (FTPS). SSH File Transfer Protocol (SFTP) is sometimes also used instead, but is technologically different.
Setting up an FTP control connection is quite slow due to the round-trip delays of sending all of the required commands and awaiting responses, so it is customary to bring up a control connection and hold it open for multiple file transfers rather than drop and re-establish the session afresh each time.
See more about FTP in [**?**]

SSH Secure Shell (SSH) is a cryptographic network protocol for operating network services securely over an unsecured network. The best known example application is for remote login to computer systems by users.
SSH provides a secure channel over an unsecured network in a client-server architecture, connecting an SSH client application with an SSH server. Common applications include remote command-line login and remote command execution, but any network service can be secured with SSH.
See more about SSH in [**?**]

SMTP Simple Mail Transfer Protocol (SMTP) is an Internet standard for electronic mail (email) transmission. Email is submitted by a mail client (mail user agent, MUA) to a mail server (mail submission agent, MSA). The MSA delivers the mail to its mail transfer agent (mail transfer agent, MTA). Often, these two agents are instances of the same software launched with different options on the same machine. Local processing can be done either on a single machine, or split among multiple machines; mail agent processes on one machine can share files, but if processing is on multiple machines, they transfer messages between each other using SMTP, where each machine is configured to use the next machine as a smart host. Each process is an MTA (an SMTP server) in its own right.
SMTP is a connection-oriented, text-based protocol in which a mail sender communicates with a mail receiver by issuing command strings and supplying necessary data over a reliable ordered data stream channel. An SMTP session consists of commands originated by an SMTP client (the initiating agent, sender, or transmitter) and corresponding responses from the SMTP server (the listening agent, or receiver) so that the session is opened, and session parameters are exchanged.
See more about SCTP in [**?**]

HTTP The Hypertext Transfer Protocol (HTTP) is an application protocol for distributed, collaborative, hypermedia information systems. HTTP is the foundation of data communication for the World Wide Web.
HTTP functions as a request–response protocol in the client–server computing model. A

web browser, for example, may be the client and an application running on a computer hosting a website may be the server. The client submits an HTTP request message to the server. The server, which provides resources such as HTML files and other content, or performs other functions on behalf of the client, returns a response message to the client. The response contains completion status information about the request and may also contain requested content in its message body.

TLS Transport Layer Security (TLS)is a cryptographic protocol that provides communications security over a computer network. Several versions of the protocol find widespread use in applications such as web browsing, email, Internet faxing, instant messaging, and voice-over-IP (VoIP). Major websites use TLS to secure all communications between their servers and web browsers.
The Transport Layer Security protocol aims primarily to provide privacy and data integrity between two communicating computer applications. When secured by TLS, connections between a client and a server have one or more of the following properties:

- The connection is private (or secure) because symmetric cryptography is used to encrypt the data transmitted. The keys for this symmetric encryption are generated uniquely for each connection and are based on a shared secret negotiated at the start of the session. The server and client negotiate the details of which encryption algorithm and cryptographic keys to use before the first byte of data is transmitted . The negotiation of a shared secret is both secure (the negotiated secret is unavailable to eavesdroppers and cannot be obtained, even by an attacker who places themselves in the middle of the connection) and reliable (no attacker can modify the communications during the negotiation without being detected).
- The identity of the communicating parties can be authenticated using public-key cryptography. This authentication can be made optional, but is generally required for at least one of the parties (typically the server).
- The connection ensures integrity because each message transmitted includes a message integrity check using a message authentication code to prevent undetected loss or alteration of the data during transmission.

HTTPS HTTPS is a protocol for secure communication over a computer network which is widely used on the Internet. HTTPS consists of communication over Hypertext Transfer Protocol (HTTP) within a connection encrypted by Transport Layer Security. The main motivation for HTTPS is authentication of the visited website and protection of the privacy and integrity of the exchanged data.
See more about HTTP and HTTPS in [**?**]

Conclusions At first, it has to be take in account that this layer provides the plataform in which the client will make contact with the service. At this point, not only the technical criteria should be considered, but also how do the service is presented. It has to be found a friendly use method for the client keeping the technical efficiency.
Analazyng the previous protocols, avoiding the techincal details of each one, there are considered tthis 3 ways of working, with its advantages and drawbacks:

- **Web.** This system would be based in HTTP an implemented with the corrseponding security protocols in order to ensure the privacy of the data. In this case the client wolud entry with its computer a https adress where he/she wolud sign in with an account. When the user is verified, the client could request to download informaton of his satellite.
  - Advantages:
    - It would have a really friendly use for the costumer.
    - It could include friendly information for the user us who we are, how to contact, FAQs, etc.
    - It could be very automatized.
    - The information could be protected with the adequate security protocols.
    - The client would not need any special software.
  - Disadvantages:
    - The web would be vulnerable to some type of attacks or problems that would compromise the data. This could aviod the communication between the user and the network.
    - It would need several maintenance.
    - There would be some type of data, like videos and photos, which the client would want to download as a file. So the web would have to be complemented with a file transfer protocol.
    - The web would have to be designed.
- **Mail**. This method would be implemented over a SMTP with the corresponding security protocols. If the client wants to download data of his satellite, he/she would have to send a mail specifing the request. Then the client will receive an email with the information.
  - Advantages:
    - It would be very secure and stable.
    - The mail could not fall as a web does.
    - The client would not need any special software.
    - The information could be sent and received as a text or as a file.

  - Disadvantages:
    * It could not be automatized, and this make it inefficient.
    * It is not very friendly to use for a client.
    * If there is some information missing in the request the client would have to wait for an answer and then complete the information.

- **Application**. The idea is that the cient would operate in his computer with this software, and when he/she want to upload or download something, the program would use a secure internet channel to transfer the information. This system wolud be implemented over a FTP or a SSH. For using this method it has to be implemented a plataform for the client use.
  - Advantages:
    * It would be really friendly use for the costumer.
    * It would be really secure and stable.
    * It could include friendly information for the user as: who we are, how to contact, FAQs, etc.
    * The information could be sent and received as a text or a files.
  - Disadvantages:
    * It would need to be downloaded and installed.
    * It would need some maintenance.
    * It would need to be designed.

Taking into account the advantages and disadvantages of each method it is concluded that an application is the method with the better security, efficiency and friendly-use relationship. The application will ensure a high security of the data, a robust access to it, and a friendly interface for the user.
This system could work with a FTP or with a SSH. Both would work properly in the system and have very similar characteristics, but SSH is more secure than FTP, so the system would be ruled by a SSH protocol.

Part III

Ground segment

Chapter 4

Ground Station Design

4.1 Introduction

The Ground Station is an indispensable part of almost any space mission. Such is its importance that it can even be seen as a subsystem of the mission.

This subsystem compose the Ground Segment of the mission and will be responsible of the extraplanetary communications with the spacecrafts. Furthemore, it will operate as a telecommunication port, which means that it will work as a hub, connecting the satellites to the Internet.

In order to establish communication in such high distances ($\approx$ 600km for LEO) high bands radio waves are going to be used. This is a requirement that is going to conditionate the overall Ground Station architecture.

- Since radio waves are going to be used, communication is established only when the Satellite has the Ground Staion (from now on GS) in its line-of-sight. That will affect the location. Moreover, the orbits of the satellites will affect the GS location as well. The GS should be placed in a way that it gets maximum coverage time. This point will be further explained.
- Depending on the target band to cover, which is the one used by the satellites for ground segment communication, the GS parts will vary in shape, size and prize significantly.

To use a GS there are two possibilites: build or rent one. In order to know which of the possibilities is the best, in the following lines they will be explained giving some numbers about the cost, and then a decision will be taken.

4.2 Build the GS

To start with what will involve building a GS, the parts of it will be exposed now:

- **Antenna**: For Astrea constellation a S and X band antennas will be needed in order to be able to communicate with the other nodes of the constellation.
- **Transciever**: This part is the responsibl of receiving the signal from the antennas or emitting it to them. Depending on its kind, it can interpret or generate (respectively) that signal, or it can just be seen as a ADC.
- **Rotors system for pointing the antenna**:This system should be feeded with the satellite position and they have to point the antenna towards it. Therefore, a link between the received signal going trough to the computer and then back to the rotors should be established.
- **Computer for signal generating and interpreting**

The approximated cost of a GS is shown in the following table[1]

Concept	Cost(€)
X-band system	100000
X-band maintenance	20000
S-band system	46500
S-band maintenance	10000
Building	44440

Table 4.2.1: First approximation of costs of the GS

Then, the total initial investment for a ground station will be of approximately 190940€, and the annual cost of 30000€.

[1]The data has been extracted from [?] [?]

4.3 Rent the GS

There are a lot of ground stations spared all over the world. In the following pages a list of them can be seen in order to know who owns them and their location.

4.3.1 ESA Ground Stations

- **Kiruna Station**
- **Kourou Station**
- **Maspalomas Station**
- **Redu Station**
- **Santa Maria Station**
- **Villafranca Station**

4.3.2 KSAT Ground Stations

- **Svabard Satellite Station**
- **Tromsø Satellite Station**
- **Troll Satellite Station**
- **Grimstad**
- **Hartebeesthoek**
- **Dubai**
- **Mauritius**
- **Singapore**

4.3.3 NASA Ground Stations

- **Alaska Satellite Facility**
- **McMurdo Ground Station**
- **Wallops Ground Station**
- **White Sands Ground Station**

4.3.4 SSC Ground Stations

- **Clewiston Satellite Station**
- **Esrange Satellite Station**
- **Inuvik Satellite Station**
- **North Pole Satellite Station**
- **Punta Arenas Satellite Station**
- **Santiago Satellite Station**
- **South Point Satellite Station**
- **Dongara Satellite Station**
- **Yatharagga Satellite Station**

4.3.5 Other GS

- **Goonhill Earth Station**

4.3.6 Contact with GS companies

Some companies that own a Ground Station have been contacted in order to get some information about costs and conditions of renting their stations. However, is important to notice that no answer is given for this type of project (students project). Moreover, information is not available on the Internet. If the project goes ahead, more information could be given to these companies and a cost can be obtained, so the option of renting one of the above cited GS is not discharged. Nevertheless, a cost is needed to know if is better to rent the GS or to build one. To do so, a company named LeafSpace will be used.

4.3.7 LeafSpace

LeafSpace is an italian company which provides a GS network, specifically designed to exchange data with micro and nanosatellites in a fast and simple way. Their global distribution ensures a high visibility time for a wide range of orbits, allowing their customers to download massive amounts of data.
This means that LeafSpace lets customers use their GS to download data, but does not permit to rent them in exclusive, which is the main idea of this project. Due to the

small amount of information existing, LeafSpace will be considered in order to get a first approximation and to develop an OWA to decide.

4.3.7.1 Features

Antenna LeafSpace allows to receive data from VHF (137-144 MHz), UHF (400-402 MHz), S-Band (2.2-2.4 GHz) and X-Band (8.025-8.5 GHz), but only can transmit UHF (401-403 MHz) and S-Band (2.025-2.11 GHz). The polarization is RHCP/LHCP (Right and Left Hand Circular Polarization, respectively). The moduation and the protocol are totally configurable. The datarates depend on the bandwidth: for UHF, up to 100 Kbps; for S-Band, up to 30Mbps; and for X-Band, up to 100Mbps.

Pricing The prices, expressed in euros/Mbyte, depend on the bandwidth too: for receiving, VHF 5, UHF 5, S-Band 0.4 and X-Band 0.1, while for transmitting it is UHF 20 and S-Band 2 (recall that they can only transmit in those two bandwidths).

Nevertheless, it is also stated that customized subscriptions are available for missions with large data transfers and constellations. Then, it is highly probable that a better pricing can be achieved.

Boost Performance Within 2017, 20 Ground Stations are scheduled to be implemented all around the World, ensuring a telecommunication service with a considerable increase of visibility time, together with a drastic reduction of communication latency for a wide range of Low Earth Orbits.

Way of use Data management is achieved with a user-friendly web-based interface, along with cloud storage granting direct access to download data at any time.

Since this is all granted by LeafSpace, there would be no need to develop the Ground Segment discussed before.

Services It is claimed to be 24/7 full availability of downloaded data, API access for constellations management, full redundant cloud storage for up to 10 days, advanced levels of data encrypting on demand, automatic scheduling, upling and downling, ranging and tracking, and 24/7 alert service.

Map In the following image there is the planification of Ground Stations to be built in the following years by LeafSpace.

Operation No information relative to operation is given. It is certainly stated that its working way is automatic. Despite so, some maintenance is surely required, though its cost is probably low.

4.4 Decision taking

In this subsection the decision between building GS or renting existent ones will be taken. There are a few things to be taken into account before starting to talk about the benefits and drawbacks of each of the options. First of all, the number of ground stations required is needed.If there is no communication with the satellites, the mission would not be accomplished. For this reason, the nodes of the ground stations are very important. The number of ground stations required is the minimum number that, with two failures, can still transfer the data from the satellite of the client to the client itself in less than 5 minutes. Supposing that three ground stations are built or rent, if two of them fail the communication between the client and its satelline can still be done using the left ground station. Regarding the latency, as it has been already exposed, the communication will take place with a latency of less than 5 minutes, as only one ground station that may fall will be in the communication path and is very improbable that if the ground station fails and the information is redirected to another, the latter falls too in less than three minutes. Regarding the position of the ground station, as the code developed shows, the ideal will be to have them close to the equator, because they would be capabile to stablish more links with different satellites and then the communication to the client's satellite is assured. In the following lines the factors to take into account to decide the ground stations will be explained. After doing so, an OWA will be done if needed.

4.4.1 Availability

4.4.1.1 Building a ground station

If the decision to build a ground station is taken, it will be available as soon as it is constructed. The time taken to construct the ground stations depend on the efforts employed, but the three ground stations will be surely completed at the time the satellite network is completely deployed. From the moment the ground stations are built, they are totally available to accomplish the missions of Astrea constellation.

4.4.1.2 Renting a ground station

The sections regarding the renting of a ground station will be done considering LeafSpace (as it has been already said). LeafSpace is a company that does not work only with Astrea constellation, so total availability of the antenna's and its transmissions can not be assured. For this reason, is not possible to assure that the communication rate established in the project charter will be accomplished. Moreover, LeafSpace's Ground Stations are still non-existent, and they predict that the first ones will be available next year.

4.4.2 Cost

4.4.2.1 Building a ground station

The costs of building a ground station can be divided into an initial investment an a maintenance. The initial investment have been estimated in 190940 €and the maintenance in 30000€/year. The Net Present Cost (NPC) in 10 years will be calculated in order to compare this option with the option of renting a ground station. The discount rate used to do so will be 12%.

$$NPC = +I_o + \sum_{i=1}^{10} \frac{CF_i}{(1+r)^i} \tag{4.4.1}$$

$$NPC = 190940 + \sum_{i=1}^{10} \frac{30000}{(1+0.12)^i} = 360500 \tag{4.4.2}$$

4.4.2.2 Renting a ground station

In this case maintenance is not needed as it is carried out by the owners of the ground station. The cost, however, comes from the amount of data that is transfered from the satellites to the client. The estimation of the Mbyte transfered over a whole year is difficult to calculate. LeafSpace provides a minimum cost per month of 2400 €. This has been calculated for small communications with X-band. To calculate an approximation, this number will be increased a 40% because Astrea constellation will probably has quite higher transfer of data. The cost per year is, then 40320 €. The NPC will be calculated too:

$$NPC = \sum_{i=1}^{10} \frac{40320}{(1+0.12)^i} = 227820 \tag{4.4.3}$$

4.4.3 Position

4.4.3.1 Building a ground station

In the case the ground station is constructed an operated for the Astrea constellation, there is the possibility of build them in latitudes close to the ideal ones (from 45° to 70°), so more links will be available during more time. Moreover, there is also the possibility to build them in different longitudes (approximately with a difference of 120°).

4.4.3.2 Renting a ground station

In the case the ground station is rented, there is no possibility to choose the position of the ground station. In the case of LeafSpace, most of the ground stations that will be built in 2017 are located at 45° north. This can seem quite good from the point of view of visibility and links. However, all of them are more or less in the same longitude, so at the same time the links at the different ground stations are the same. With ground station at different longitudes, the performance of the constellation would be better than having them in the same longitude.

4.4.4 Ease to improve

4.4.4.1 Building a ground station

The fact of building a ground station implies that it can be improved and adapted to the constellation and the needs of the clients along the developement of the mission.

4.4.4.2 Renting a ground station

If the ground station is rented, it can not be improved according to the needs of the constellation, and maybe the constellation will have to be adapted to the ground station in order to accomplish the mission. The improvement in this case is, then, difficult and probably impossible.

4.5 Decision

The factors used to decide will be the ones presented previously. They will be rated from 1 to 2, being 2 the best option and 1 the worst option. As there are only two options, no linear interpolation is needed. Taking into account the requirements and needs of the project, the weights are the following ones:

- Availability: 6
- Cost: 9
- Position: 6
- Ease to improve: 5

The rating and the OWA of the decision between building a ground station or renting an existent one is:

	Availability	**Cost**	**Position**	**Ease to improve**	**OWA**
Build	2	1	2	2	0.83
Rent	1	2	1	1	0.67

Table 4.5.1: OWA of the GS

Looking at the results, the fact of building a ground station is the best option for the Atrea Constellation in order to accomplish its requirements and to give a high-quality service.

4.6 Ground Station localization

The place where the Ground Stations would be placed has to be studied in order to obtain maximum rendiment of them. This decision will depend mainly of the constellation characteristics, the earth topography and the country legislation and resources. In this chapter the analysis and procedures for arriving to the final decision of where the Ground Stations would be placed are exposed.
Given the constellation topology, the coverage of a Ground Station depending on its longitude and latitudecwill be studied. The aim of this analysis is to show where a Ground Station would have more coverage and give a first approximation and proposal of the 3 Ground Station placement.

4.6.1 Method

For the purpose above explained, a Matlab algorithm is developed. This algorithm calculates, on a given moment, how many satellites can be seen from a Ground Station. This calculation will be done several times in order to obtain results along time. In order to elaborate the algorithm the steps showed below are followed:

1. Calculate where the satellites are refereed to an inertial Cartesian coordinates system, with the origin at the center of the Earth. This state analysis is done for several time periods with an adequate time-step.
2. Calculate the Ground Station position refereed to the mentioned system. Since the system is inertial, the Ground Station will describe a circle in the rotational plane of the Earth relative to this system. This trajectory depend on the latitude and longitude of the place. This position is calculated for the same time period used before.
3. Calculate, for each time step, how many links can the GS establish. It will depend on the angle between the station and every satellite, and also on the minimum elevation angle.

After seeing reasonable results modifying the parameters of the constellation and of the Ground station, the algorithm will be verified simulating the Iridium constellation. Entering the parameters of this system, the results verifies the algorithm.
Once the algorithm is tested and verified, the links during the day for several longitudes and latitudes and how this parameters affect to the coverage of the station are studied[2]

[2] The code can be found at the annexes.

4.6.2 Latitude analysis

Is easy to see that the effect of changing the latitude is practically independent for the longitude. For this reason, the links during the day for a given longitude are studied independently of the latitude and viceversa. Doing the analysis for latitudes between 0° and 90° during 2 days, with 5 minutes time-step, this are the results:

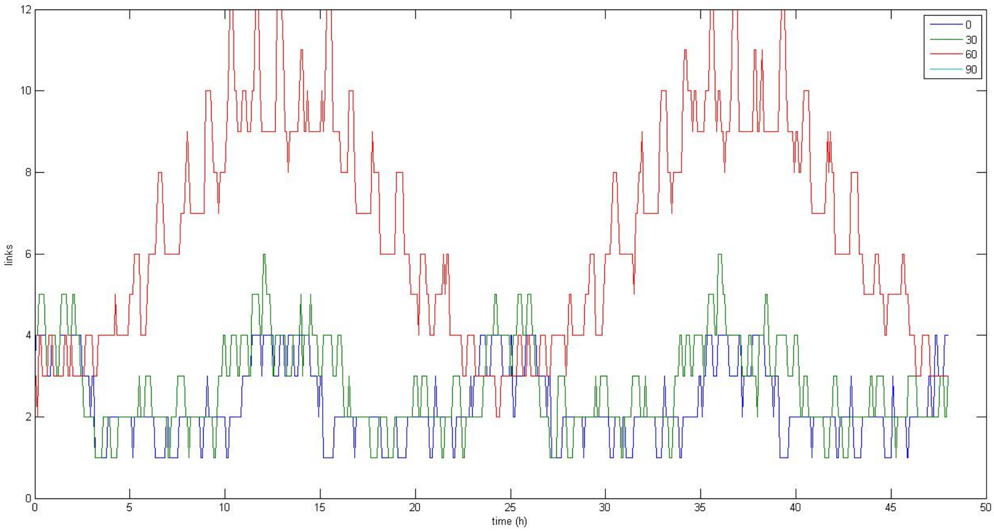


Figure 4.6.1: Links vs time for latitudes from 0° to 90°

As is shown in Figure 1.1, the behaviour is not constant during the day. For every day there is a peak and a valley. This is produced for the cylindrical asymmetry of the constellation. It can also be seen that the pole is not covered. This fact was considered and assumed at the design of the constellation since it doesn't involve any problem at the performance of the system. It can also be seen that for an equatorial latitude there is always 1 link, at least. The equator is the most critical place because is where satellites from different planes are more separated. Global coverage can be ensured, but is important to appreciate that for higher latitudes the coverage is better.

Doing the same analysis but for negative latitudes, the following results are obtained:

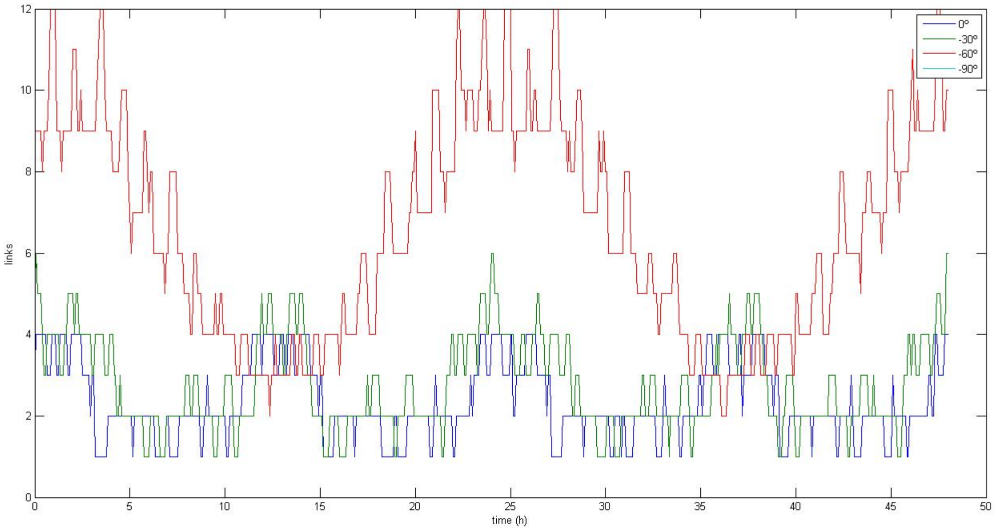


Figure 4.6.2: Links vs time for latitudes from 0º to -90º

Comparing the results of Figure 1.2 with the ones of Figure 1.1 it is seen that they are practically the same but with an offset of 12 hours. They are also seen small local deviations, but these are not much significant because of the time-step. This time-step is of 5 minutes for a first sight of the tendencies, and it do not allow extremely precise results.
Taking into account that the results of positive latitudes can be extrapolated to negative ones, the rest of the analysis will be done only for positive latitudes.Is important to know at which latitude, close to the poles, the coverage is lost due to the geometry of the constellation.

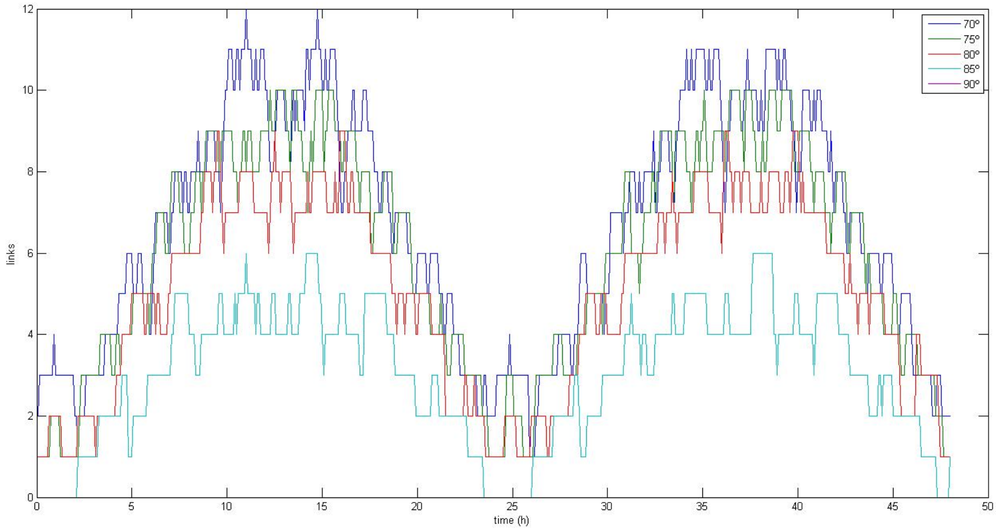


Figure 4.6.3: Links vs time for latitudes from 70° to 90°

It is seen that over 80° of latitude the system starts to lose coverage. It does not cause any problem because there are not inhabited zones over +80° or under -80°. For situating the Ground Stations it has to be considered this restriction.
Now, the latitudes that can provide more links are, around 60°:

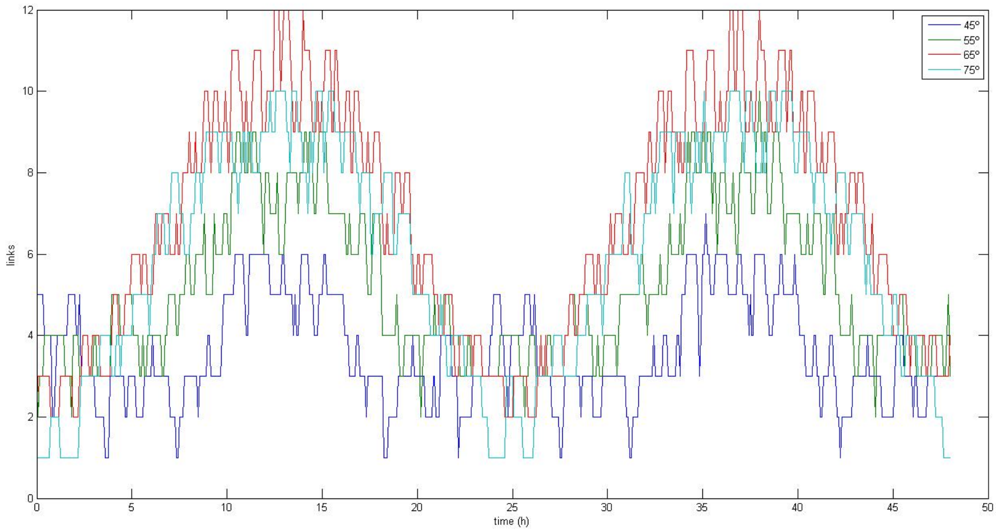


Figure 4.6.4: Links vs time for latitudes from 45° to 75°

As it can be seen in Figure 1.4, the optimal latitude must be between 55° and 75°.

Expanding the analysis:

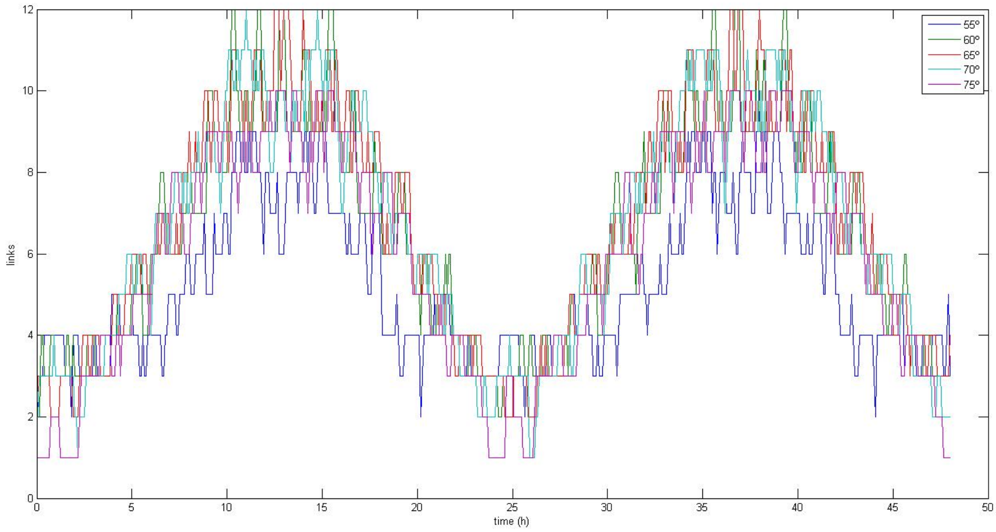


Figure 4.6.5: Links vs time for latitudes from 55º to 75º

The better performance is registered around 60º and 65º. Figure 1.5 suggest that between 50º and 60º there is always at least 1 link. But looking it carefully, at the hour 37, there is a local deviation to 0 links. This requires a more accurate analysis decreasing the time-step. For 30 seconds time-step:

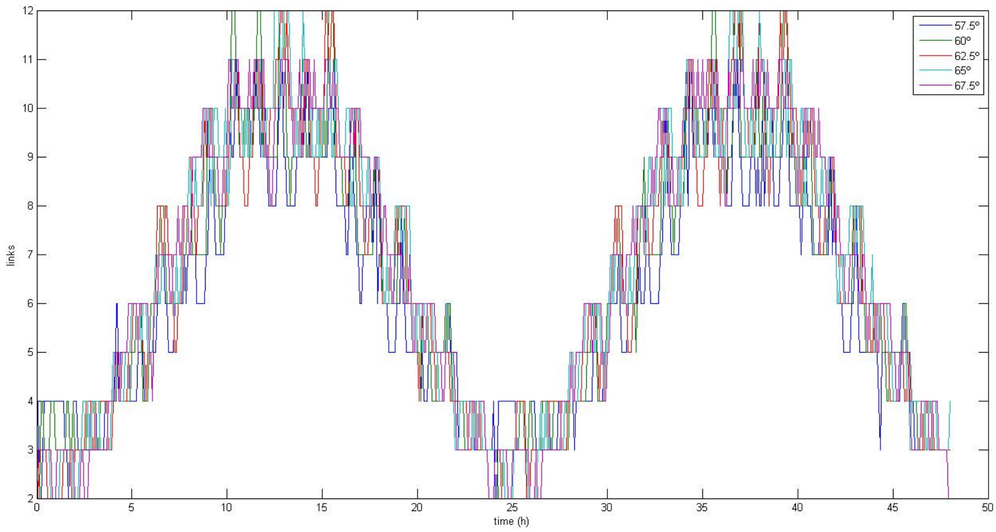


Figure 4.6.6: Links vs time for latitudes from 57.5º to 67.5º

In Figure 1.6 there is no problem with the coverage. For ensuring the results and to avoid possible loses of links locally in time, the same ragne of latitudes is analyze with a smaller time-step.

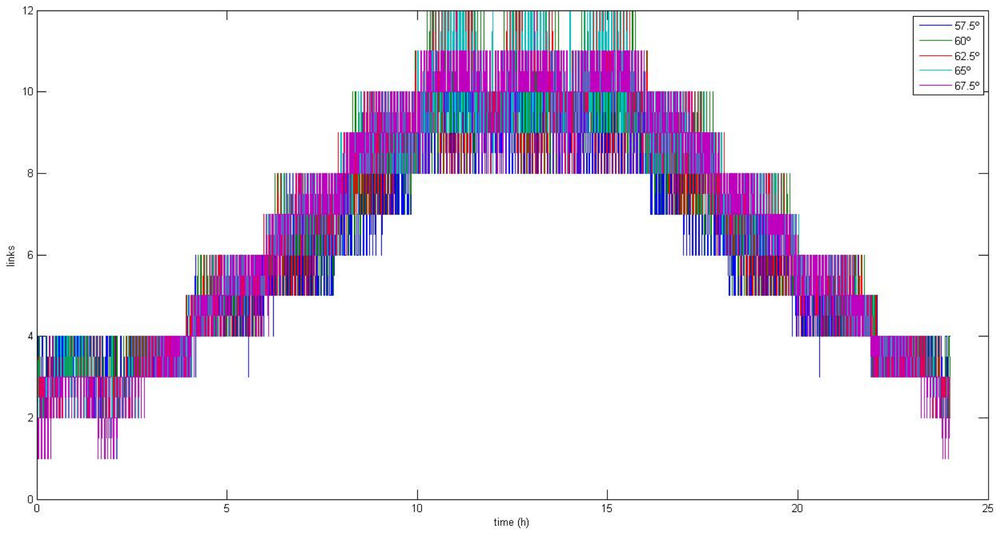


Figure 4.6.7: Links vs time for latitudes from 57.5° to 67.5° with 30 seconds time-step

It can be seen that between 65° and 67.5° the system loses the 2nd link and for a wile the station would be connected only to 1 satellite. It is optimum to place the stations between +57.5° and +62.5° of latitude. In order to verify the results for the opposite latitudes:

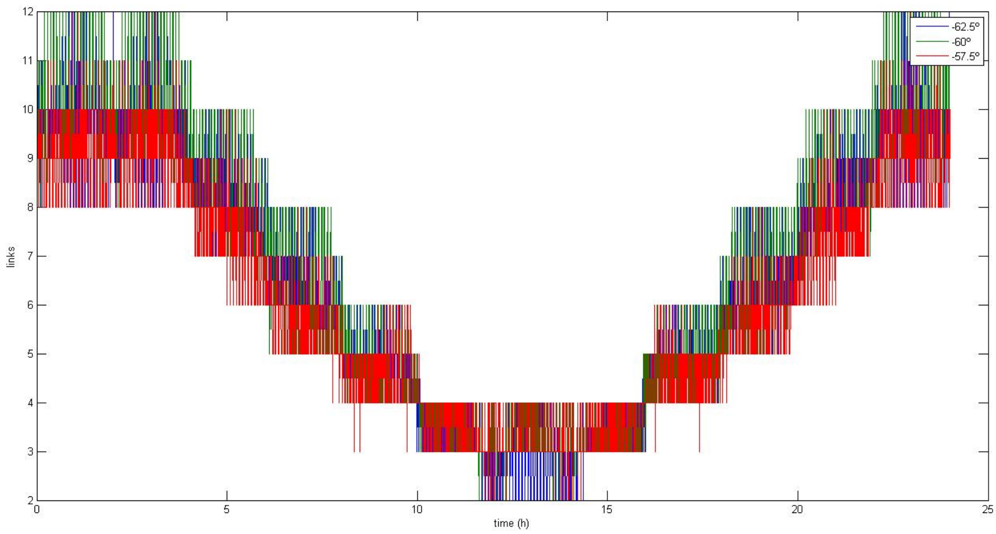


Figure 4.6.8: Links vs time for latitudes from -62.5° to -57.5° with 30 seconds time-step

In conclusion, the optimum latitudes for the Ground Station are:

- Between -62.5º and -57.5º
- Between +57.5º and +62.5º

4.6.3 Longitude analysis

It is intuitive to think that the effect of changing the longitude is delaying the evolution of the coverage. This effect is verified by the algorithm:

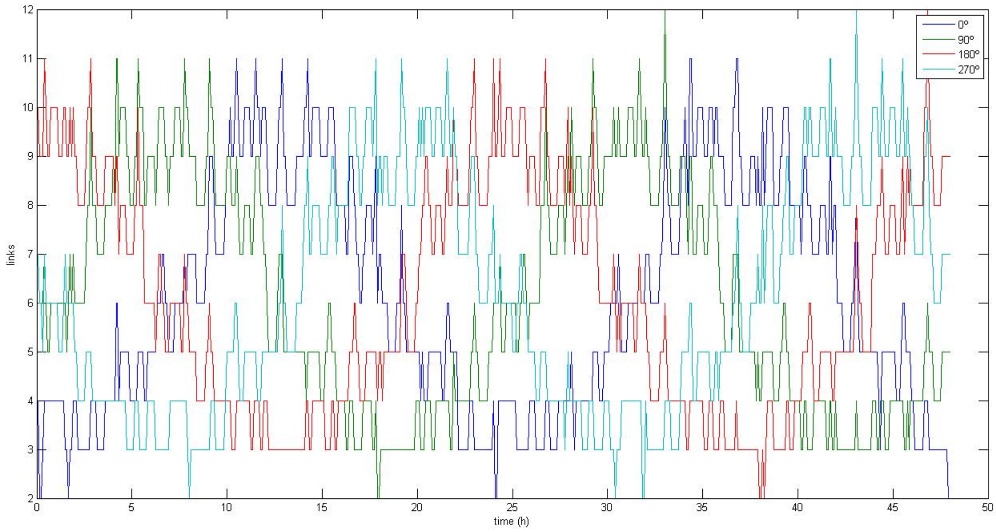


Figure 4.6.9: Links vs time for longitudes from 0º to 270º

As it is seen in Figure 1.8 the delay has a reason of 3 hours for every 45º of longitude. This effect can be used in order to optimize the performance of the Ground Stations. During the day every station will have a peak and a valley in the coverage. Placing the stations with a relative longitude of 120º would ensure that when one is at the valley another one is at the peak:

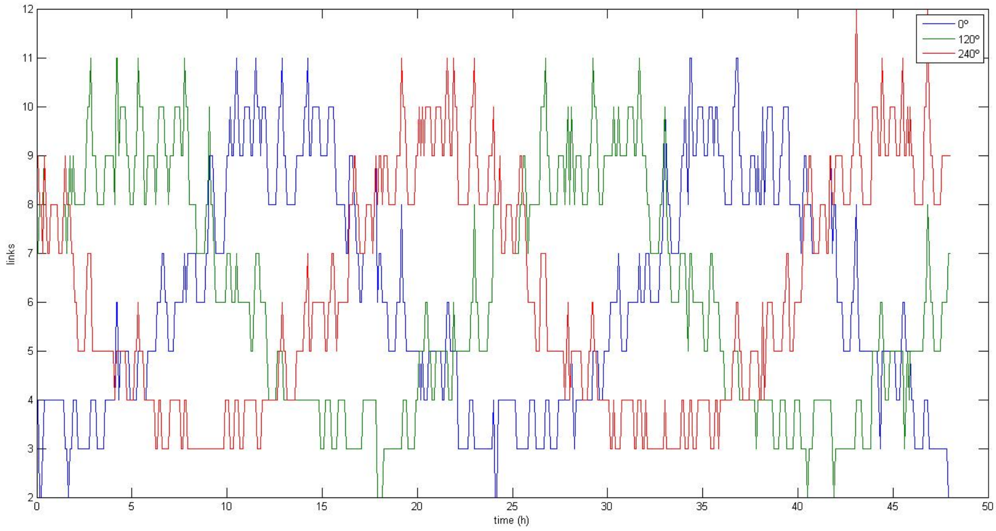


Figure 4.6.10: Links vs time for longitudes of 0°, 120° and 240°

In conclusion, the Ground Stations should be separated 120° longitude between them. It has to be taken into account that this analysis is done for stations at the same latitude. A Ground Station in a given latitude has the same coverage behaviour as an other one at the opposite latitude and 180° of longitude away. To exemplify, in the following table coordinates of equivalent places from the Ground Station point of view are showed.

	GS1		GS2		GS3	
	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
Option 1	55	0	55	120	55	240
Option 2	-55	180	55	120	55	240
Option 3	55	0	-55	300	55	240
Option 4	55	0	55	120	-55	60
Option 5	-55	180	-55	300	55	240
Option 6	-55	180	55	120	-55	60
Option 7	55	0	-55	300	-55	60
Option 8	-55	180	-55	300	-55	60

Table 4.6.1: Equivalent coordenates

4.6.4 Conclusion

Summarizing the results of the analysis, for an optimum performance of every Ground Station, they should be at latitudes between -62.5° and -57.5° or between +5.5° and

+62.5°. For a better performance of the system every Ground Station should be 120° of longitude away of the other GSs if their are at the same latitude or 60° of longitude away if they are at the opposite latitude. Taking in account the topography of the Earth, the following options are proposed (every color represent the options for one Ground Station):

Figure 4.6.11: Options for placing the 3 Ground Stations.

Given this possibilities a study of the legislation of the involved countries has to be done in order to know the viability of placing there the Ground Stations. The candidate countries, as is shown in the map, are: Canada, Argentina, Chile, Falkland Islands (Islas Malvinas), United Kingdom, Denmark, Norway, Sweden and Russia.

4.7 Legislation

The legislation will determine the location of the three GS between the locations pre-selected in the previous section. This is done because all the places pre-selected are more or less equivalent, and to choose between them governamental easy will be used. After doing a research on the legislation of all the places where the GS could be placed, only two countries have available legislation: Canada and United Kingdom. For this reason, the location for the 3 Ground Stations are United Kingdom, Falkland Islands and Canada. Falkland Islands are administered by United Kingdom, so the same license must be requested.

4.7.1 United Kingdom Ground Station

Non-Geostationary Earth Stations (Non-Geo). A Non-Geostationary Earth Station is a satellite earth station operating from a permanent, specified location for the purpose of providing wireless telegraphy links with one or more satellites in non-geostationary orbit. Therefore, this is the license required for United Kingdom and Malves Islands.

The form required to ask for the license can be found at [?]. The fees can be obtained from [?] and [?]. The frequency allocation can be found in [?].

4.7.2 Canada Ground Station

The Minister of Industry, through the Department of Industry Act, the Radiocommunication Act and the Radiocommunication Regulations, with due regard to the objectives of the Telecommunications Act, is responsible for spectrum management in Canada. As such, the Minister oversees the development of national policies and goals for spectrum resource use and ensures effective management of the radio frequency spectrum.

In Canada, the fees vary depending on the zone. There are three zones:

- High Congestion Zones: There are six metropolitan areas of Canada designated as zones of intense frequency use. They are in and/or around the following cities: Calgary, Edmonton, Montréal, Toronto, Vancouver and Victoria.
- Medium Congestion Zones: There are 21 areas of Canada designated as zones of moderate frequency usage. These zones can be either stand-alone areas or areas that

are adjacent to the six intense frequency use zones listed above. These moderate zones are as follows: Calgary, Chicoutimi, Chilliwack, Edmonton, Halifax, London, Montréal, Ottawa, the City of Québec, Regina, Saint John, Saskatoon, St. John's, Sudbury, Thunder Bay, Toronto, Trois-Rivières, Vancouver, Victoria, Windsor and Winnipeg.

- Low Congestion Zones: These zones comprise all other areas of Canada.

It would be wise to choose a low congestion zone, which would have additionally less interferences.

The process to fulfill can be found at [?]. The fees might be estimated using [?].

4.8 Initial investment

4.8.1 Description of the systems

A S-band system will be used for telemetry and telecommand purposes and for receiving housekeeping data. It is intended to have uplink and downlink capabilities in half-duplex. The model can be found at [?] and [?].

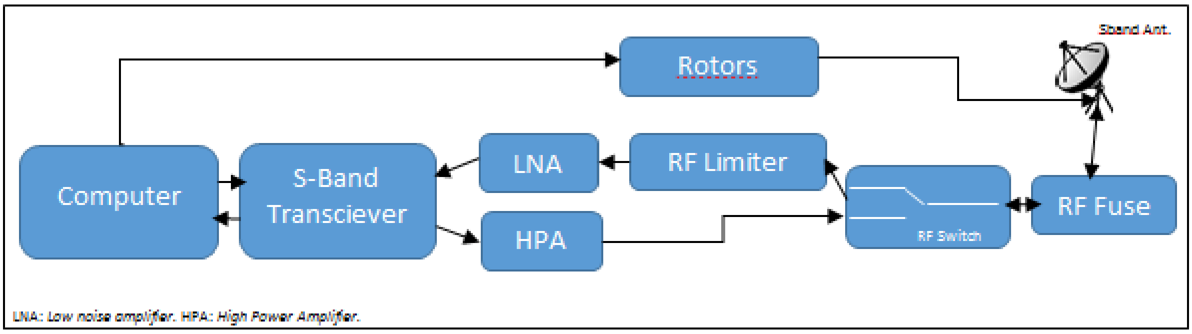


Figure 4.8.1: Equipment needed for S-band communications.

A X-band system will be used for receiving the data requested by the client from the satellites. It will only have downlink capabilities. The model can be found at [?]. beginfigure[H]

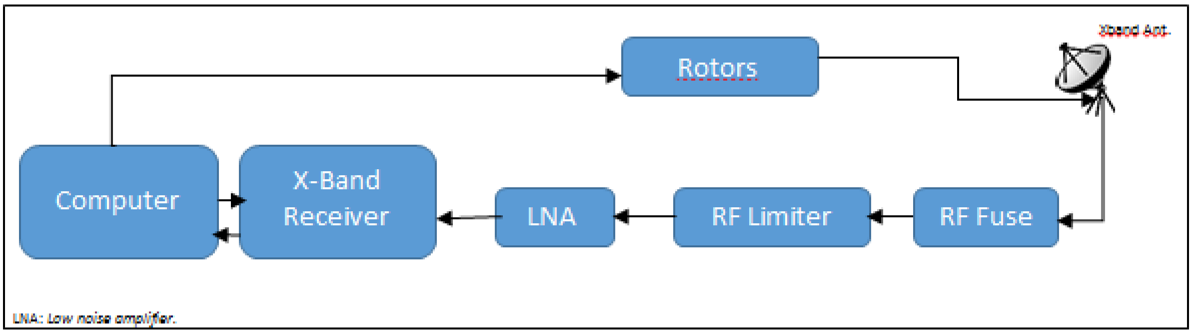


Figure 4.8.2: Equipment needed for X-band communications.

4.8.2 Costs

The following items are needed:

- S-band system: 46,500€

- X-band system: 100,000€
- Computers and office material: 13,000€
- Building: 50,000€

Because of the time interval in which an antenna will be reorientating itself to point to the next satellite when the current satellite gets out of range, that antenna will not function until it finishes the reorientation. For this reason, two S-band and X-band systes are required for each ground station to be always operative. Therefore, each ground station needs two X-band systems, two S-band systems, computers and office material and a building.

The initial investment of one ground station will be 356,000€. The initial investment of the three ground stations will be 1,070,000€.

For the Mission Control Centre, the following costs are assumed:

- Computers and office material: 50,000€
- Building: 100,000€

The initial investment of the mission control centre will be 150,000€. The initial investment of all the ground segment will be 1,220,000€.

4.9 Annual cost of GS and MCC

4.9.1 Energy and Maintenance

In this section the maintenance of the ground stations and the control center, which is located in Terrassa, will be explained and its costs will be approximated. Is important to notice that the prices are not exact numbers, but just an approximation of the real value of the costs. For these reasons, some of the calculations as for example the cost of Internet in Scotland or Canada, is done using the value of the Internet cost in Spain, as they will be of the same order but can have a slow variation.

4.9.1.1 Mission Control Center

The control center will be located in Terrassa and it will act as a center from which the activity of the Astrea group will be monitored. The most important cost in this building will be the energy consumption. To approximate the energy consumption the energy use intensity (EUI) can be used. The EUI is a recommended benchmark metric for all type of buildings and tells the amount of energy used in buildings per meter square during one year. The EUI is calculated depending on the type of building (hospital, school, etc). The type of building of the control center can be considered as a set of offices, because the most important features of it will be the computers and the internet communications. Taking as a reference an usual office floor from a building, the average surface it occupies is 500 m^2. The EUI has been obtained from [?] and is 212 kWh/m^2. The cost of a kWh according to [?] is of 0,141033 €/kWh, taking into account that the main type of consumption is of electricity. Then, doing the calculation:

$$212 \cdot 500 \cdot 0,141033 = 14960 \tag{4.9.1}$$

This is the cost of the energy consumed. However, the fixed term has also to be taken into account. This term is of 3,170286 €/month/kW. It does not depend on the kW consumed, but the ones that have been contracted. Considering a tariff of 11,5 kW, the cost per year will be of 440 €. Then, the total cost of electricity per year is 15400 €.
This is the cost without taxes. Taxes applied to the consume of electricity in Spain are the excise duty on electricity (4,864%) and the value added tax (21%). With these data, the resulting cost is of 20540 €. Another important cost is the one of the maintenance. The maintenance include cleaning service, industrial maintenance and possible failures of the systems that would need to be repaired. There are companies that offer these services, so to know the cost of the maintenance a research on the market will be done. In most of these companies, no available information about the cost can be found if no information about the exact needs is provided. However, there are some of them that have few standards

tariff that can be used. The maintenance will be divided into two: informatic maintenance and cleaning service. The cost of informatic maintenance for a business extracted from [?] is of 206 €per month. So in one year the cost will be of 2500 €. For the cleaning service, the average market cost is of 10 €per hour according to [?], for contracted maintenance. If there are 250 laborable days and every day there is 2 hour of cleaning service, the total cost of it is of 5000 €.
The other cost that has to be taken into account is the Internet connexion. To give an approximation of this cost, some Internet providers are consulted and the resulting price is of 55 €/month, that are 660 €per year. In the following table the results are exposed:

Concept	**Cost€**
Energy:	20540
Maintenance:Informatics	2500
Maintenance:Cleaning	5000
Internet connexion	660
Total cost	**28700**

Table 4.9.1: Costs per year for the control centre

4.9.1.2 Ground Stations

The same procedure as the previous one will be done. The costs of maintenance (informatics and cleaning) and of the Internet connexion will be the same, but the difference will be on the energy consumed. The EUI of the site itself, without taking into account the antennas, will also be the same: 212 kWh/m^2. The surface of the building of the ground station will be of approximately 100 m^2, enough for the comfortability of 4 people working there. Then, the energy consumption per year will be of 21200kWh. The consumption of the antennas has also to be taken into account. Each antenna consumes 770 W approximately and each GS has four antennas, considering that they will be working 24 h/day during the whole year, the consumtion during one year can be calculated.

$$\frac{4 \cdot 770 \cdot 24 \cdot 365}{1000} = 26981 kWh/year \tag{4.9.2}$$

Then the total consumption in kWh of one ground station is:

$$26981 + 21200 = 48181 kWh/year \tag{4.9.3}$$

Now the cost of the kWh is needed, and it depends on the countries, so in the following lines the cost will be calculated for each of the ground stations. The cost of kWh supplied has been extracted from [?] and is an average because it depends on many factors as for example the company selected, the type of tariff, the fixed term, taxes, etc.

Canada In Canada, the average cost of 1kWh is of 10 US cents, that are 0,0945 €. Doing the calculation:

$$48181 \cdot 0,0945 = 4550 \tag{4.9.4}$$

The total cost of energy will be of 4550 €.

United Kingdom As the other two ground stations are located under the administration of the United Kingdom, its costs will be used. In the UK the average cost per kWh is of 20 US cents, that are 0,189 €. Doing the calculation:

$$48181 \cdot 0,189 = 9100 \tag{4.9.5}$$

The total cost of energy will be of 9100€.

Total annual cost In the following table all the data that has been calculated is exposed in order to know the annual cost of the control centre (MCC) and the ground stations (GS).

Concept	MCC	GS Canada	GS Scotland	GS Malvinas
Energy	20540€	4550€	9100 €	9100 €
Maintenance	7500€	7500€	7500€	7500€
Internet	660€	660€	660€	660€
Total	28700€	12710€	17260€	17260€

Table 4.9.2: Annual costs

Total annual cost	**75930 €**

Table 4.9.3: Total annual cost of the ground segment consumption and maitenance

4.9.2 Salaries

In order to work properly, each ground station will require an electrical engineer, a computer technician, a manager and a secretary. Due to the nature of the constellation, the GS will need to be always functioning and, therefore, it can potentially fail at any moment. For this reason, the presence of an electrical engineer and a computer technician is required all the time. Four engineers and four computer technician will be hired so that for each job three of them will work all the day in 8 hours shifts while the other has the day off.

The salaries for each employee will be the average salary for each job in their respective countries. Those can be seen in Figure 4.9.4.

	Canada	United Kingdom	Argentina
Electrical engineer	47,700€	36,900€	12,300€
Computer technician	30,100€	21,800€	7,100€
Manager	34,500€	28,800€	14,100€
Secretary	28,000€	22,300€	9,500€

Table 4.9.4: Salaries for the different jobs according to the country.

Taking into account that each GS will have a manager, a secretary, four electrical engineers and four computer technicians, and that everyday will be an engineer and a technnician working during night, the total cost per ground station would be the following:

- Canada: 381,500€
- United Kingdom: 226,400€
- Argentina: 81,800€

The Mission Control Centre will consist of a building with a manager, a secretary and three aerospace engineers working. Because of the same reason as the ground station, it will be needed to hire twelve engineers, so as to have always three of them working all the time. Taking into account the average salary of each job in Spain, the cost of the salaries can be seen in Figure 4.9.5:

	Spain
Aerospace engineer	30,600€
Manager	30,500€
Secretary	23,000€

Table 4.9.5: Salaries for the different jobs in Spain.

The annual cost of all the salaries can be seen below:

- Annual cost of all Ground Stations salaries: 689,700€
- Annual cost of the Mission Control Centre salaries: 429,900€

Finally,with the frequency fees, the maintenance and the salaries, the total annual cost of all the ground segment canbe obtained.

- Annual cost of the ground segment: 1,200,000€

Part IV

Financial and Other Considerations

"The first rule is to never lose money. The second rule is to never forget the first one."

Warren Buffett

Over this chapter, the **financial study** is going to be performed. The costs and the profits will be analyzed, and some important figures will be acquired.

Moreover, some other important considerations, such as social and security issues or environmental impact will be studied too.

Chapter 5

Financial Study

The different departments have estimated the main costs of the project. It is high time to start performing a deep analysis on the economical solvency of the project. The analysis carried on will be of 10 years.

Up to this point, it is important to determine how this product will be sold, so as to quantify the benefits of the project and be able to determine some figures such as the Pay Back Time or the Net Present value, and be able to make some conclusions.

5.1 Selling the product

The aim of the project is to be able to sell to the customers the chance of both sending and receiving data from satellites. Therefore, it seems logic that the price of the product has to be somehow related to the amount of data passed on. Then, there will be a price for every Mbit, either sent or received.

From the Communications Department, there is a limitation of 3 Ground Stations operating, and each one can carry up to 25 Mbits/second. Accepting that those Ground Stations will fully operating the whole year, and calculating the amount of seconds that there are in a normal year:

$$365 \cdot 24 \cdot 60 \cdot 60 = 31536000s \tag{5.1.1}$$

It can be easily calculated the amount of Mbits that Astrea Constellation is able to either send or receive:

$$31536000 \cdot 75 = 2365200000Mbits \tag{5.1.2}$$

This means that no more than 2365200000 Mbits can be sold. This is the maximum supply.

But how can the demand be estimated? There is a need to make assumptions.

5.1.1 Estimation of demand

5.1.1.1 Universities

Firstly, it has been thought that the service offered has great academic interests. In fact, any student could build a satellite with a certain payload, send it to space and then receive data from the satellite at any time thanks to Astrea constellation.

In order to study the possible demand of Mbits, an estimation of the possible universities that would want to use the services has been done. Fortunately, the list of universities that offer studies in the aerospace field goes back a total of 400 schools approximately. Nevertheless, it is highly improbable that all those colleges become clients because not all universities have the same sources or interests. Therefore, the following list presents the number of existing colleges having an aerospace degree in each continent.

By analyzing this information, it can be determined that the continents with countries with higher PIB have more colleges interested in the space field. It is noticed that Asia is the continent with more colleges because, even if it is mostly poor, it is so big that it has rich countries such as Japan, Korea or China and the United Arab Emirates. Moreover,

Continent	Number of Universities
Europe	124
Asia	138
North America	97
South America	18
Australia	8
Africa	12

Table 5.1.1: Table. List of Universities with Aerospace Degrees

Europe and North America are not so extensive but have a higher aerospace culture and interest.

On the basis the service is affordable for many prestigious colleges and it permits to provide their students with the chance to improve their knowledge by doing their own experiments, it has been estimated that about 150 universities will end up contracting Astrea's service in the next years. If we assume that each university would be interested in sending or receiving a total of 630720 Mbits anually, therefore the number of Mbits for universities, anually, will be of 94608000 Mbits.

5.1.1.2 Particular customers

Another extremely important sector of clients are the private ones. It is harder to make an assumption on the number of Mbits consumed by this sector. Nevertheless, some figures are needed in order to perform a good feasibility study.

According to the Union of Concerned Scientists of the United States of America, right now there are about 1500 satellites orbiting around the Earth. But every day space technology is more affordable and feasible, which leads to think that in the next years a good figure of satellites would be of roughly 2000. Nonetheless, around 40% of those missions would benefit of a faster communication with their satellites. As Astrea provides a very competitive price, it seems reasonable to think that a good percentage of those satellites would be interested. In order to be conservative, a 50% of those would be potencial clients. This means that 400 full operating satellites would use Astrea, and assuming also than the average amount of data that those satellites would either send or receive anually is of 946080 Mbits, the number of Mbits for particular clients, anually, will be of 378432000 Mbits.

It can be checked that the sum of the amounts of Mbits for universities and for particular clients is lower than the maximum amount of Mbits due to the 3 Ground Stations (as has been stated before), this is, 2365200000 Mbits. In particular, it turns out to be a fifth of this quantity.

5.1.1.3 Demand

Taking into account both the universities and the particular clients, and making a conservative assumption, the estimation of the demand, in Mbits, is of a fifth of the maximum capacity of Astrea, this is, 473040000 Mbits anually. Also, in order to simulate the unceirtainty of the company during the first years (as years pass, the company gets reputation and therefore its amount of clients also enlarges, a percentage is applied during the first years. This means that first year only a 75% of the potential customers exposed before will be achieved, the second year a 80%, and so on, until the sixth year, in which a 100% is achieved.

5.1.2 Pricing the service

The determination of the price is made upon the feasibility study, in order to get a reasonable Pay Back Time and benefit. Nevertheless, it is a fact that the fare of Astrea service must fulfill a condition: it has to be competitive.

Comparing with some others constellations that offer a similar service, in order to provide a competitive fare, it seems reasonable a price per Mbit of no more than 0.5 €per Mbit, as an upper tape.

5.2 Economic Feasibility Report

In order to perform the analysis on the economical solvency of the project, following there is a table which contains the main costs of the project, as well as the numerical operations that allow to calculate some important financial parameters, such as the Net Present Value (NPV), the Internal Rate of Retorn (IRR), the Simple Pay Back Time (PBT), the Updated Pay Back Time (UPBT) and the Break Even Point (BEP). From this data, some conclusions will be drawn.

Firstly, though, there is need to take into account some costs that are not included in the other departments, and which are key to analyzing the costs and benefits.

5.2.1 Previous costs

5.2.1.1 Engineering hours

The engineering hours, which were specified in the Project Charter, are again synthesized in the following table:

Engineering hours budget	Hours (h)	Labor cost (€)
MANAGEMENT		
Meetings documentation		
Meetings	340	6800
Meetings preparation		
Agendas	10	200
Minutes	10	200
Task Tracking and scheduling		
Project Charter	170	3400
Team tasks monitoring	20	400
WBS and Gantt update	10	200
SATELLITE DEVELOPMENT		
Spacecraft subsystems	180	3600
Payload		
Antenna	40	800
PHDS	50	1000
ORBITAL DESIGN		
Constellation geometry	220	4400
Orbit parameters		
General parameters	120	2400
Drift	100	2000
Legislation	50	1000
LAUNCH SYSTEMS		
Vehicle	60	1200
Satellite deployer	10	200
Replacement strategy	100	2000
OPERATION		
Communication protocol	100	2000
Ground station	80	1600
End of life strategy	80	1600
FINANCIAL PLAN		
Costs		
Fix		
Maintenance and cost analysis	10	200
Insurance cost analysis	15	300
Administration cost analysis	15	300
Taxes cost analysis	25	500
Variable		
Manufacturing cost report	10	200
Launching cost report	10	200
Income		
Price analysis	25	500
Revenue forecast	25	500
Economic feasibility report	40	800
Marketing Plan	20	400
PROJECT EXHIBITION		

5.2.1.2 Administrarion costs

It has to be taken in account that administrating the company will require resources and manpower. To budged this costs there have been considered the following factors:

- **Manpower**. It is estimate that it will be needed 6 people working at full time. 3 for the administration of the stations, 2 more for the clients, and an other one for the purchases of new satellites and contracting launchings. The annual salary of each worker would be of 24000 €, which make a total of 144,000€
- **Financial costs**. The treasury of the company will require a bank, with its associated costs. This is estimated in 100000€per year.
- **Local** The place where the administrators will work would cost annually around 10000€
- **Supplies** The water, electricity, internet and telephone would cost 5000€

This result in 259.000€/year

5.2.1.3 Taxes

The headquarters of effective management is located in Spanish territory, so it is crucial to take into consideration the corresponding taxes. It is known that any entity that directs and controls all of its activities of effective management in Spanish territory is considered as resident. Consequently by having the residence there they are subjected to the Spanish Corporation Tax. It has to be known that this tax is an annual and proportional tribute belonging to the Spanish tax system that taxes the income of the companies.

Moreover, by following the Article 29 of the Law 27/2014 on the CT it is possible to determine the tax rate that is going to be paid. As a result, for any company located in Catalonia the annual fee to be paid is 25% of annual profits. However, for being a company of new creation, the first two years the tax will be 15% of profits only. It is important to notice that this kind of tax will be paid when the taxpayer begins to obtain benefit, in other words since the enterprise starts to be profitable.

5.2.1.4 Insurance

The responsability for possible damages or errors is an important aspect to consider. In a satellite, there are different stages that need an insurance because they have possabilities to fail and cause high damages.

From an international point of view, from 1972 there is a treaty, *The Space Liability Convention*, which says that the states must assume their responsability of their space objects launched in their territories. This liability was created to provide compensation to parties injured by space activities. This treaty was ratified in Jaunary 2013 by 89 states and signed but not ratified by 22 states. [?]

As a private company, Astrea should provide a compensation to third people if they are injured by one of the CubeSats. Furthermore, how has been explained in *Social and security considerations*, there are some little risks in differents stages of a Cubesat (launch and in-orbit) and it might be advantageous to have economic security contracting a insurance.

Currently, there are a lot of insurance companies that provide their services to space companies and specifically to satellites companies. After a market study, there are two companies to consider, *SpaceCo*, a subsidiary of *Allianz* company and *Marsh*. Both provide the main services that we need: satellite launch and in-orbit insurance and satellite third party iability insurance.

Finally, *SpaceCo* has been chosen as Astrea insurer company, due to it is considered one of the best insurer for space companies and it has more experiences than others.

This insurer provide a great coverage, in which highlights:

- Launch and commissioning – cover for the launch systems and commissioning equipment.
- In-orbit – operational life insurance for the space satellite.
- In-orbit incentives – cover for the manufacturer's obligation to the client in the event of malfunction or non-performance.
- Liability – cover for third party liability during a launch or in-orbit activities.
- Captive services – assisting cover for companies that self-insure space risks. [?]

The cost of the insurance is around a 20% of cubesat value, which is 297000 €, to pay in the 5 life-years of each. Then, the total cost of the constellation insurance would be:

N. of CubeSats	189
Cost per Cubesat	59400 €
Total cost in 5 years	11226600 €
Cost per year	2245320 €

5.2.2 Economic feasibility study

Finally, the mentioned financial table can be made. The costs are the ones taken from every department, as well as the costs just explained.

TIME	**Year 0**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**
INVESTMENT	-4,07										
INCOME											
Percentage (learning curve)		0,75	0,80	0,85	0,90	0,95	1,00	1,00	1,00	1,00	1,00
Number of Mbits hired		354.780.000,00	378.432.000,00	402.084.000,00	425.736.000,00	449.388.000,00	473.040.000,00	473.040.000,00	473.040.000,00	473.040.000,00	473.040.000,00
Gain (M euros)		35,48	37,84	40,21	42,57	44,94	47,30	47,30	47,30	47,30	47,30
Total	**0,00**	**35,48**	**37,84**	**40,21**	**42,57**	**44,94**	**47,30**	**47,30**	**47,30**	**47,30**	**47,30**
COSTS											
n planes/year	9					9					9
Satellites/year	189	0	0	0	0	189	0	0	0	0	189
Engineering hours	-0,0395										
Administration		-0,259	-0,259	-0,259	-0,259	-0,259	-0,259	-0,259	-0,259	-0,259	-0,259
Insurance		-2,24532	-2,24532	-2,24532	-2,24532	-2,24532	-2,24532	-2,24532	-2,24532	-2,24532	-2,24532
Taxes											
Percentage of profit					0,15	0,15	0,25	0,25	0,25	0,25	0,25
Cost of taxes		0	0	0	-6,38604	-6,74082	-11,826	-11,826	-11,826	-11,826	-11,826
Web hosting, maint. and promotion	-0,005	-0,005	-0,005	-0,005	-0,005	-0,005	-0,005	-0,005	-0,005	-0,005	-0,005
Launching											
Planes	-48,256	0,000	0,000	0,000	0,000	-48,256	0,000	0,000	0,000	0,000	-48,256
Satellites	-3,024	0,000	0,000	0,000	0,000	-3,024	0,000	0,000	0,000	0,000	-3,024
System											
Structure and mechanics											
Assembly (individual)	-3,78	0,00	0,00	0,00	0,00	-3,78	0,00	0,00	0,00	0,00	-3,78
Assembly (constellation)	-0,15	0,00	0,00	0,00	0,00	-0,15	0,00	0,00	0,00	0,00	-0,15
Structure	-0,737	0,000	0,000	0,000	0,000	-0,737	0,000	0,000	0,000	0,000	-0,737
Thermal protection	-0,189	0,000	0,000	0,000	0,000	-0,189	0,000	0,000	0,000	0,000	-0,189
Electric power system											
Solar arrays	-12,852	0,000	0,000	0,000	0,000	-12,852	0,000	0,000	0,000	0,000	-12,852
Batteries	-2,381	0,000	0,000	0,000	0,000	-2,381	0,000	0,000	0,000	0,000	-2,381
Power management	-3,024	0,000	0,000	0,000	0,000	-3,024	0,000	0,000	0,000	0,000	-3,024
Payload											
Patch antenna	-10,595	-0,011	-0,011	-0,011	-0,011	-10,595	-0,011	-0,011	-0,011	-0,011	-10,595
Antenna deployment	-0,567	0,000	0,000	0,000	0,000	-0,567	0,000	0,000	0,000	0,000	-0,567
Transciever inter-satellite	-4,845	0,000	0,000	0,000	0,000	-4,845	0,000	0,000	0,000	0,000	-4,845
Transciever space to ground	-1,040	0,000	0,000	0,000	0,000	-1,040	0,000	0,000	0,000	0,000	-1,040
Data handling system	-0,945	0,000	0,000	0,000	0,000	-0,945	0,000	0,000	0,000	0,000	-0,945
Variable expenses	-0,756	0,000	0,000	0,000	0,000	-0,756	0,000	0,000	0,000	0,000	-0,756
AOCDS											
Thruster	-9,450	0,000	0,000	0,000	0,000	-9,450	0,000	0,000	0,000	0,000	-9,450
CubeSpace ACDS	-2,835	0,000	0,000	0,000	0,000	-2,835	0,000	0,000	0,000	0,000	-2,835
Communications											
Maintenance GS Canada		-0,011	-0,011	-0,011	-0,011	-0,011	-0,011	-0,011	-0,011	-0,011	-0,011
Maintenance GS Scotland (UK)		-0,015	-0,015	-0,015	-0,015	-0,015	-0,015	-0,015	-0,015	-0,015	-0,015
Maintenance GS Malvines		-0,015	-0,015	-0,015	-0,015	-0,015	-0,015	-0,015	-0,015	-0,015	-0,015
Salaries GS Canada		-0,382	-0,382	-0,382	-0,382	-0,382	-0,382	-0,382	-0,382	-0,382	-0,382
Salaries GS Scotland (UK)		-0,226	-0,226	-0,226	-0,226	-0,226	-0,226	-0,226	-0,226	-0,226	-0,226
Salaries GS Malvines		-0,082	-0,082	-0,082	-0,082	-0,082	-0,082	-0,082	-0,082	-0,082	-0,082
Salaries MCC		-0,430	-0,430	-0,430	-0,430	-0,430	-0,430	-0,430	-0,430	-0,430	-0,430
Licenses		-0,010	-0,010	-0,010	-0,010	-0,010	-0,010	-0,010	-0,010	-0,010	-0,010
Total	**-105,47**	**-3,69**	**-3,69**	**-3,69**	**-10,08**	**-115,85**	**-15,52**	**-15,52**	**-15,52**	**-15,52**	-120,93
CASH FLOW	**-109,54**	**31,79**	**34,15**	**36,52**	**32,50**	**-70,91**	**31,79**	**31,79**	**31,79**	**31,79**	**-73,63**
DISC CF	**-109,54**	**29,99**	**30,40**	**30,66**	**25,74**	**-52,99**	**22,41**	**21,14**	**19,94**	**18,81**	**-41,11**
CUM CF	**-109,54**	**-77,75**	**-43,60**	**-7,08**	**25,42**	**-45,49**	**-13,70**	**18,08**	**49,87**	**81,66**	**8,03**
DIS CUM CF	**-109,54**	**-79,55**	**-49,15**	**-18,49**	**7,25**	**-45,74**	**-23,33**	**-2,19**	**17,75**	**36,57**	**-4,55**

Table 5.2.2: Feasibility Study

As it has been said, upon this financial table, in order to get a good feasibility situation, the pricing of the service is decided to be of 0.1 €per Mbit.

5.3 Conclusions of the financial study

As a result of a few iterations of this table, changing some parameters, it has been found that:

5.3.1 Pay Back Time (PBT)

From the shown table, it can be seen that between years 3 and 4, the Cumulative Cash Flow goes from a negative value to a positive one. Therefore, the Pay Back Time is between those two years. This gives a rough approximation of when will the investment be recouped. To be more precise about it, it can be linearly interpolated:

$$\frac{25.42-(-7.08)}{4-3}=\frac{25.42-0}{4-x} \tag{5.3.1}$$

Solving for x, the result is of a PBT of 3.22 years.

Nevertheless, it can also be seen that in year 5, the Cumulative Cash Flow again becomes negative, due to the increase of costs because of the re-launching of the satellites. Thus, a second Pay Back Time could be found, between years 6 and 7. Interpolating again:

$$\frac{18.08-(-13.70)}{7-6}=\frac{18.08-0}{7-x} \tag{5.3.2}$$

Solving for x again, the result is of a PBT2 of 6.43 years. However, the important one is the first PBT, since it is the point from which there starts to be benefit.

In year 10, though, the profits are high enough to cover the increase of cost due to third launching, which would make that Cumulative Cash Flow does not become negative.

The value of the first PBT found seems reasonably acceptable, taking into account that this project requires a great budget, as all space projects do, due to its own nature.

5.3.2 Updated Pay Back Time (UPBT)

Taking into account now the discount rate (6% anual), there is the Discounted Cumulative Cash Flow. It can be seen that between years 3 and 4, this value goes from a negative value to a positive one. Thus, the Updated Pay Back Time is between those two years. It can be linearly interpolated to gain some precision:

$$\frac{7.25-(-18.49)}{4-3}=\frac{7.25-0}{4-x} \tag{5.3.3}$$

Solving for x, the result is of a UPBT of 3.72 years.

Again, it can be seen that in year 5, the Discounted Cumulative Cash Flow again becomes negative, due to the increase of costs of the re-launching of the satellites, which allows to calculate a second Updated Pay Back Time, between years 7 and 8. Interpolating again:

$$\frac{17.75-(-2.19)}{8-7}=\frac{17.75-0}{8-x} \tag{5.3.4}$$

Solving for x, the result is a UPBT2 of 7.11 years.

Now, in contrast to the Pay Back Time, there will be a third Updated Pay Back Time. When taking into account the discount rate, the benefits in year 10 do not cover the increase in cost of the third re-launching, forcing Discounted Cumulative Cash Flow to be negative again, and a third Updated Pay Back Time might be found. However, this third date can not be determined with this study, since the reach of this feasibility exercise is performed for just the first 10 years.

When analyzing the NPV of the feasibility study, a graphic with those phenomenon will be shown.

Again, that first value of UPBT seems reasonably acceptable, because of the nature of the project, the space sector, a very demanding and expensive one.

5.3.3 Break Even Point (BEP)

The Break Even Point is the point at which total cost and total revenue are equal, there is no net loss or gain. This figure represents the sales amount (quantity) required to cover total costs, consisting of both fixed and variable costs to the company. At this point, the total profit is zero.

In Astrea's case, the Break Even Point is the number of Mbits sold the first year so that the Cash Flow of that year is just 0 (or approximately).

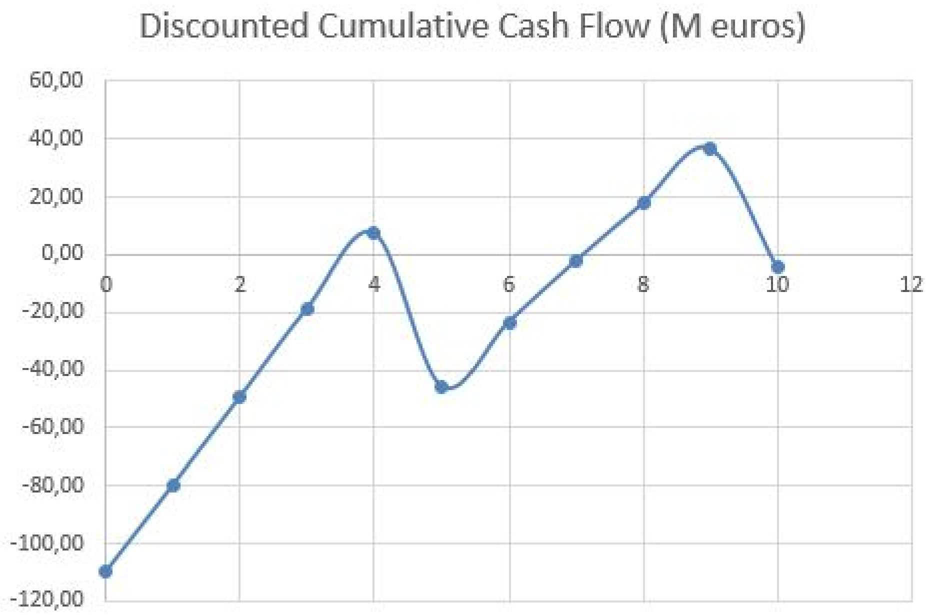
By changing manually the parameter "Number of Mbits hired" of first year, it is found that the Break Even Point is of 36907600 Mbits (with this value, the Cash Flow is approximately 0). This means that under no account there can be less Mbits hired, otherwise, the Cash Flow would be negative and the Cumulative Cash Flow, negative since first year is fully invest, would never reach a positive value, generating losses.

From the assumptions of demand already explained, it can be seen that having a greater demand than the BEP is very likely to happen.

5.3.4 Net Present Value (NPV)

The Net Present Value is the difference between the present value of cash inflows and the present value of cash outflows over a period of time (in this case, of 10 years). It is useful to analyze the profitability of a project. A positive NPV indicates that the project earnings generated by a investment exceeds the costs. The Internal Rate of Return must also be taken into account when calculating the NPV. In this project, a IRR of 6% has been considered.

From the table, it can be immediately seen that the Net Present Value (for a period of time of 10 years) is of -4.55M€. It is clearly not positive, which theorically would say that the project is not feasible within the 10 years considered. Nevertheless, as it has been explained in the pay back times, this is due to the fact that in years 0, 5, 10, 15... a re-launching of the whole constellation is performed. Therefore, just in year 9 the Discounted Cumulative Cash Flow is of 36.57M€, which means that if the period of time of the study would have been of 9 years, the NPV would be clearly positive. What is trying to be explained is that the NPV of the study is negative just because the last year coincides with a year of re-launching. Moreover, compared to the Discounted Cumulative Cash Flow of year 5, it is clearly much bigger. For sure, in year 11 it will be positive, and in year 15, of re-launching again, there won't be a Discounted Cumulative Cash Flow negative. This phenomenom is shown in the following graphic, that shows the Discounted Cumulative Cash Flow of the first 10 years so as to see the tendency of it:



In that graphic, it can be seen what has just been explained. In year 15 there will be a new decrease, but this time, its lowest point (locally) will be positive, and from that point, there will always be a positive balance.

5.3.5 Internal Rate of Return (IRR)

The internal rate of retorn is the interest rate at which the Net Present Value of all the cashflows is equal to zero. This is used to evaluate the attractiveness of a project. If the Internal Rate of Return of a project exceeds a company's required rate of return, the project is desirable, and if on the other hand the IRR falls below the required rate of return, the project should be rejected.

For the study carried on, the discount rate has been a 6% anual. Because of what has been said in the NPV, since the NPV is negative, the IRR will be a smaller quantity. According to the theory, the project should be rejected. But once again, because of the re-launching of the tenth year, it is not a good indicative figure. It should have been a better idea to perform a 9 or 11 years analysis, but it was also interesting to do a economical study of the first two completes lifes of the satellites.

Changing manually the parameter d of the table, it is found that for a discount ratio of 3.84%, the NPV is zero, which means that this is the IRR. It is smaller than the actual discount ratio, just as was predicted and explained.

Chapter 6

Environmental Impact Study

6.1 Aim of the document

This document pretends to assess the environmental consequences (positive and negative) of developing the project. The target of this study is to identify, predict, evaluate and mitigate the biophysical and social negative effects that the project could generate during the execution of it.

6.2 Ground Stations

At first sight the Ground Stations do not represent any environmental problem. The main factor that has to be taken into account is the placement of the stations. They have to be located in a place where they do not interfere with the ecosystem. The placement of the stations has to be adequate with the environmental legislation of the countries.

6.3 Satellites

For analysing the impact of the satellites it has to be studied the possible environmental impact during the fabrication and during the orbital life.

Since the fabrication of the satellites is externalized to other companies, the responsibility of the environmental consequences derived of this manufacturing is over these companies. For commercializing these products they must pass all the controls required.

During the orbital performance of the satellites, it has to be taken into account whether or not they would become orbital waste. The satellites are designed to burn out in the atmosphere at the end of their useful life. This burnt should not leave any solid residue that could precipice over the surface. The deorbit would be forced and controlled by the propulsion system of the satellite. In the case that this system fails, given that they will orbit in a LEO, they will be deorbited and burnt out naturally in a period around 5 years.

6.4 Launch system

The most critical part of the entire process, in environmental terms, is the launch of the satellites. For this reason the main relevance in this report is given to the spacecraft that will put the satellites in orbit, the Electron rocket of Rocket-Lab.

The company operate in New Zeeland, and for doing it, the Ministry for the Environment make an accurate study of the environmental impact of the Electron launching. The entire document can be seen at [**?**].

In this document are analysed the critical components of the spacecraft:

- **Structure**. The primary structural material is carbon fibre reinforced polymer. The carbon filaments are chemically inert and do not react to seawater.
- **Propellants**. Liquid oxygen and kerosene (RP-1 analogue) propellants are used on both the first and second stages of the launch vehicle. Liquid oxygen, if released to the atmosphere, rapidly boils and returns to the atmosphere as gaseous oxygen. RP-1 kerosene is a highly refined grade of hydrocarbon with low density, a thin surface film and rapid evaporation.
- **Pneumatics**.All inflight pneumatic systems use stored pressurised cold gases to provide tank pressurisation, cold-gas manoeuvring thrust in space, and for stage separation mechanisms. All gases are non-toxic.
- **Engines**. The launch vehicle uses nine engines for stage 1 and a single engine for stage 2. The engines are constructed of inconel, an inert high performance, corrosion resistant nickel alloy. At stage 1 separation, the thrust section is likely to separate from the stage, return to Earth's surface and land in the Exclusive Economical Zone.
- **Batteries**. The first stage batteries are highly likely to burn-up before returning to Earth's surface. The stage 2 batteries will entirely burn-up downrange, with only the first battery potentially landing in the EEZ. The batteries are lithium-based, and contain no lead, acid, mercury, cadmium, or other toxic heavy metals.

The document also evaluates the following possible risks:

- **Risk of toxic effects**. The toxic effects of the materials comprising stage 1, the fairings and the two stage 2 LithiumIon batteries were assessed as low at all levels of launch activity.
- **Risk of ingestion of materials and provision of floating shelter**. Floating jettisoned materials as shelter for pelagic organisms and the ingestion of jettisoned

materials were both evaluated as having low ecological risk at all levels of launch activity.

- **Environmental effect of the displacement of fishing activities.** For the demersal fish and mobile invertebrate community, marine mammals and seabirds, the effects of fishing displacement would be low because these populations could also be impacted in the areas to which fishing is displaced. In the eastern jettison zone there is less fishing activity so the consequences of fishing displacement on the seabed community, demersal fish and mobile invertebrates, marine mammals and seabirds are negligible, reaching minor impacts after 1000 or more launches.
- **Effect of the provision of hard substrates.** Another potential positive outcome for seafloor biota requiring hard substrates is that the jettisoned materials would provide further attachment sites. However, even after 10,000 launches this would provide only about 50 ha of additional attachment surface, leading to a moderate benefit at most.
- **Disturbance to marine fauna.** Noise and disturbance to marine fauna above and below water is a potential consequence of the jettisoned materials falling into the jettison zone. The chance of repeated disturbance to the same individuals or groups of marine mammals or seabirds increases with the number of launches. This was assessed as a low risk for up to 100 launches over two years, a moderate risk for up to 1000 launches over almost 20 years, and a high risk for up to 10,000 launches over almost 200 years.
- **Risk of direct strikes causing mortality to components of the ecosystem.** Direct strikes causing mortality are a low risk for all components of the ecosystem up to 1000 launches over an almost 20 year period. Direct strikes reach moderate levels of risk for the benthic invertebrate community, sensitive benthic environments, and a rare threatened species, the magenta petrel, after 10,000 launches over a period of almost 200 years.
- **Risk of smothering of sea floor organisms.** Smothering the feeding or respiratory structures of sea floor organisms by jettisoned materials was assessed as a low risk for all levels of launches up to 1000 launches and a moderate risk by 10,000 launches. This is likely to be a factor principally in areas of hard substrate where the jettisoned materials are unlikely to become buried in sediment so will be important principally on the Bounty Platform.

Chapter 7

Social and Security Considerations

7.1 Social and security considerations

The potential of the CubeSats is very high and they might be the future of satellites. Their low cost and the easiness to construct them, compared to large satellites, make them accessible to countries with fewer resources, universities and people in general, making them able to explore the space and to pursue different missions. The assembly of a CubeSat is not very complicated but requires a minimum knowledge about the subject; in other words, now "you've got a user manual, a datasheet and a 3D model that you can download, and you've got an online shop where people can buy their power systems, etc with their credit card" [**?**].

This project is based on the design of a satellite constellation dedicated to communications relay between LEO satellites and between LEO satellites and the ground. This project is helping to develop the CubeSat industry and its use and it will demonstrate that these small satellites can carry out different missions that were previously done only by large satellites, as for example the communication.

Currently, the constellations of CubeSats dedicated to the communication are in development and the market is not very extensive, this is why this project, and the global coverage that it provides, could have a privileged place in this industry. The main commitment that this project has with the customers is to ensure that they will be able to communicate with any part of the world without problems.

Another important aspect to consider is that the constellation will provide total privacity to the costumers, ensuring that they make a correct use of it and avoiding that third people interfering in the communication.

In relation to security, it must ensured the proper functioning of the constellation. To do this, it must be considered three main factors, where CubeSats could be in danger: the launch of the payload, the permanence of the CubeSats in space and the ground stations.

The launch stage is one of the most important, because it is where the mission has more probability to fail. In the next figure can be observed the succes rate of orbital launches in the last 57 years. In 2014, there were a total of 92 unmaned launches and only 4 of them were failed. This indicates that the fail rate is only a 4,34 %, which is very low.

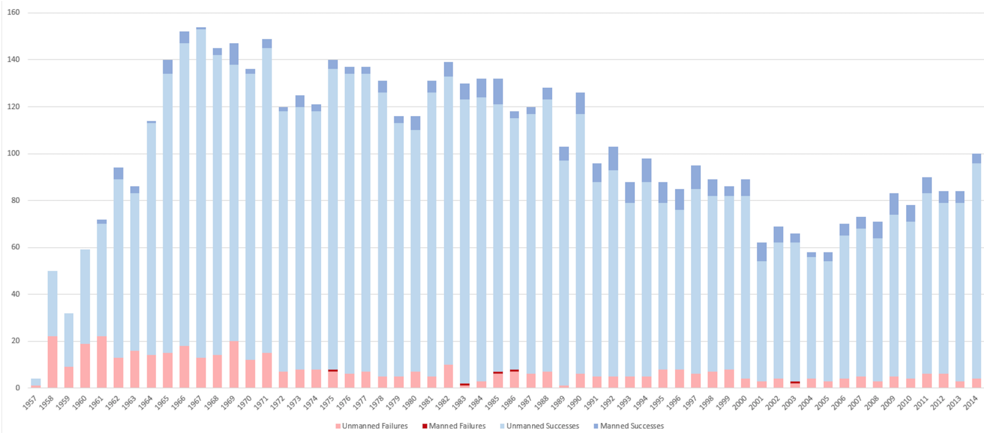


Figure 7.1.1: Orbital Launch Summary by Year

Once the constellation is in orbit, CubeSats can find dangers how colliding with other satellites or with space debris. The distances between most satellites is around hundreds of miles and there is not danger of collision, but the movement of space debris is unpredictable. In order to avoid this space debris, a CubeSat can perform a Debris Avoidance Manoeuvre (DAM). The responsible to control these fragmentation debris is *The United States Space Surveillance Network*. It consists of ground-based radars and optical sensors at 25 sites worldwide and Currently tracks more than 8000 orbiting objects.

Finally, the ground stations are a key element for the correct operation of the constellation and they must prevented from stop working. To do this, each ground station will have its operator, to control the operation of the installation, and a security system, to avoid intrusions.

7.2 Legislation

The legislation concerning activities related to space is the Space Law. Space Law is an international law comprised of international treaties and agreements. Its most important rules are the five international treaties, which have been developed under the supervision of the United Nations. The body that promotes these regulations is the United Nations Office for Outer Space Affairs (UNOOSA).

The international law is only applicable to the states that are parties to the treaties. According to the Outer Space Treaty, states are responsible for their national space activities, public or private. For this reason, each state usually adopts its national space regulations.

In the case of the Astrea constellation, since the company is based in Spain (a party of the Space Law), the current legislation is the *Real Decreto 278/1995* of 24 February 1995. According to this Royal Decree, the objects launched from Spain or whose launch has been promoted by Spain, should be registered in the *Registro Español de Objetos Espaciales Lanzados al Espacio Ultraterrestre* (Spanish Registry of Objects Launched into Outer Space). The necessary data to register the satellite must be provided to the *Dirección General de Tecnología Industrial del Ministerio de Industria y Energía* (Department of Industrial Technology of the Ministry of Industry and Energy). This department will notificate the registry to the Secretary-General of the United Nations.

The registration has to contain the following data:

a) Name of launching State or States;

b) An appropriate designator of the space object or its registration number;

c) Date and territory or location of launch;

d) Basic orbital parameters, including:

   I) Nodal period;
   II) Inclination;
   III) Apogee;
   IV) Perigee;

e) General function of the space object.

and any other useful information. For example, in the case of one of the Astrea satellites, the registration will be:

a) Spain

b) AstreaSAT 1

c) 22 February 2018,

d) Basic orbital parameters: Low Earth Orbit

   I) 95,4815 minutes

   II) 72 degrees

   III) 6.913,0 km

   IV) 6.913,0 km

e) CubeSat 3U, part of the communications constellation Astrea

Part V

Satellite design

Chapter 8

Satellite design

8.1 Structure and mechanics

The design and operation of a CubeSat is a complex process that must be completed keeping in mind the different subsystems as well as the role they will play during the lifetime of the mission. And since these systems will operate in space, they have to be prepared and certified to withstand extreme temperature and radiation conditions.

The satellite used by Astrea must have high compatibility between all the systems to avoid potential problems and has to be tested (either all the systems together or one by one) and their correct functioning has to be ensured. Given that the lifetime of the mission should be greater than four years, the critical systems such as the solar arrays, batteries and antennas should be fully operational until the end of the mission.

8.1.1 Structure

The mission of the structure is to sustain and protect all the electronic devices carried by the satellite in order to fulfill the mission requirements. In order to ensure that all the electronic and mechanic systems can be mounted upon the structure, a high compatibility between these systems is required. Given that the configuration of the current CubeSat is not as common as other configurations of actual commercial or operational CubeSats, it is a really important point that the structure is highly flexible regarding the arrangement of the subsystems.

The structure chosen is manufactured by **Innovative Solutions In Space (ISIS)**. Among its features it is worth mentioning that it can withstand the high range of temperature it will face in the space (from -40ºC to 80ºC) and it is highly compatible; almost every physical system used can be placed within the structure or on its faces (such as the antennas or the deployable solar arrays). Finally, the mass of the structure is relatively low, and given that the mass of the other subsystems is sometimes a drawback, it is plus point.

8.1.2 Thermal protection

The thermal protection system consists of various insulating materials that aim to protect the CubeSat from potential thermal shocks. The satellite must remain within an optimal range of temperature, despite of the variation of the external temperature, in order to work properly. Operating in space, the CubeSat is vulnerable to suffer extreme

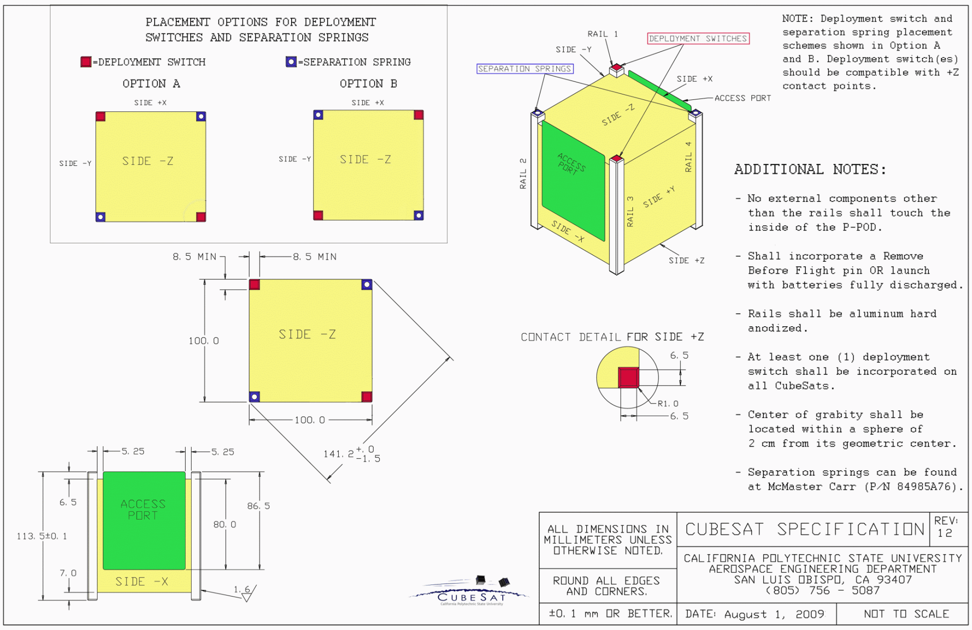


Figure 8.1.1: Dimensions of a 1U CubeSat

[?]

temperatures, both below zero and above zero, and thermal protection must guarantee that all subsystems are protected. Furthermore, the thermal protection system should also dissipate the heat produced by the other systems.

Currently, the most used element as thermal protection in the aerospace industry is the multilayer insulation (MLI), a set of multiple thin insulation layers. The MLI fulfills all the requirements that were previously stated and its main objective is to reduce the heat generated by radiation since the heat generated by convection or conduction does not have such a high impact on the on-board systems.

After a market study, *Dunmore Aerospace* company has been chosen to provide us its MLI product. Specially, the product is the **Dunmore Aerospace Satkit** and it is made for small satellites for LEO and it will provide the CubeSat with the protection required during operation

8.1.3 Study of the commercial available options and options chosen

A broad marked study is needed since all the options have to be considered. For this reason, and with the aim to show all the information and features of each system that has been considered in this section, the table 8.1.1 is presented below.

Brand and model	Features	Total price (€)
Structure		
ISIS 3U structure	Low mass (304.3g) Highly compatible High temperature range	3900
Gomspace GOMX-Platform	High mass (1500g) Comes fully equipped (basic systems) High temperature range	11000
Thermal protection		
Dunmore Aerospace Satkit	Lightweight Durability Made for small satellites	1000
Dupont Kapton Aircraft Thermal	Lightweight Durability Non-flammable	1400

Table 8.1.1: Options studied for the structure and thermal protection

Finally, the options chosen are presented in the table 8.1.2.

System	Brand and model	Price per unit (€)	N. of units
3U Structure	ISIS	3900	1
Thermal Protection	Dunmore Satkit	1000	1

Table 8.1.2: Options chosen for the structure and thermal protection

8.2 Electrical Power System

The electric power system of the satellite must provide and manage the energy generated efficiently in order to have all the systems operating under normal conditions during the lifetime of the mission. The EPS of the Cubesat is, probably, the most fundamental requirement of the satellite, since its failure would result in a mission failure.

The energy collection system and the power management and collection systems compose the EPS and their role is to control and distribute power to the Cubesat, to suppy a continuous source of electrical power during the length of the mission, to protect the satellite against electrical bus failiures and to monitor and communicate the status of the EPS to the on-board computer.

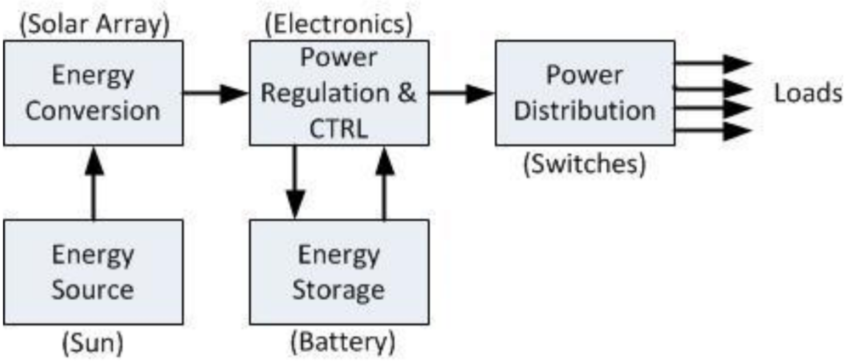


Figure 8.2.1: Basic schematics of the EPS
[?]

8.2.1 Estimation of the power required

To select the adequate electrical power systems it is essential that the power consumed by the CubeSat is known *a priori*. Thus, to select the solar arrays and the batteries, as well as the power management system, an estimation of the power consumed has to be made.

The vast majority of the time the satellite will work under typical operation conditions. However, the estimation of the power consumption provided in the table 8.2.1 has been made for typical-high conditions in order to have a power margin and a more reliable estimation.

System (number of units)	Typical power consumption per unit (W)
Payload	
Patch antenna (8)	4
Payload power consumption	32
Electrical Power System	
NanoPower P60 Power Module (1)	2
Battery (2)	-
Solar arrays (4)	-
EPS power consumption	2
Data Handling Systems	
Transceiver inner-satellite (3)	4
Transceiver space to ground (1)	4
Data handling system (1)	4
DHS power consumption	15
Propulsion and ACDS	
Thruster (1)	20
ADACS (1)	3
OACDS power consumption	3
Estimated total power consumption	52

Table 8.2.1: Estimation of the power consumption under typical working conditions

Additionally, it is worth mentioning that the thrusters are not included in the final estimated power. The thruster will only be active for shorts periods of time to maintain the orbit, and when it ignites, the other subsystems will not perform in typical conditions. The CubeSat will manage to send only the essential information to the other satellites and, since it is unlikely that their thruster is ignited, the communication is ensured during the maneuver.

8.2.2 Solar arrays

Given that the space of a 3U CubeSat is very limited, the primary source of electrical power has to be photovoltaic cells. The photovoltaic cells will collect and convert the energy of the sun into electrical energy and they have to be correctly selected to prevent failure given their importance.

The solar arrays used must have a decent efficiency and capacity to collect the energy from the sun, have to keep their mass relatively low, must have a protective radiation shield to ensure their full efficiency for at least 4 years, a proper deployment system, the ability to withstand space conditions and also must be highly compatible with all the other systems used, especially the power management system (the *NanoPower P60*).

The option selected for the mission is a set of deployable solar panels provided by **EXA (Agencia Espacial Civil Ecuatoriana)**. These solar arrays fulfill all the requirements mentioned above: they are low mass (135g per unit), they have a protective radiation shield (NEMEA Anti Radiation Shield protects the solar panels of EM, High Gamma, X-Ray, Alfa, Beta and low neutron radiation) they can withstand a very high temperature range (from -80ºC to 130ºC) ensuring that they can operate in space, they have a gentle release and deployment system with artificial muscles (developed by EXA) and they provide a power of 16.8W each (19.2V@0.5A).

Every cubesat will come with at least 4 deployable solar panels providing it with 67.2W of power, approximately, to supply peak demands during the lifetime of the mission. Additionally, it is worth mentioning that these solar arrays are compatible with the hardward used (the structure and the power management system).
Note that these 4 deployable solar panels are a basic requirement. If more space is available on the faces of the satellite, additional 1U non-deployable solar arrays (giving an extra power of 2.3W per array, approximately) or 1U deployable arrays (giving an extra power of 16.8W or 10W) will be placed. They are also low mass equipment (about 80g per array) as the deployable solar arrays and highly compatible with the CubeSat. Their current and voltage are different but given that the CubeSat will be equipped with the NanoPower P60, that should not be a problem. The only drawback of these arrays is that they may be only fully operational for 2 years in LEO. However, that does not mean they will not work anymore after these 2 years; it means that they will start losing efficiency.

8.2.3 Power management system

The role of the power management system is to distribute the power and supply the energy to the different systems used in the CubeSat. Since the systems of the CubeSat have different power and energy needs, the power management system has to be highly compatible and have a number of buses high enough to supply the different voltage and intensity required to the systems.

The selected option for the mission is the **NanoPower P60** by **Gomspace**, a high-power EPS for small satellites that comes with 1 motherboard, 1 ACU module (Array Conditioning Unit) and 1 PDU (Power Distribution Unit), allowing multiple configurations in just one motherboard; saving a lot of space.

The motherboard supports up to 4 ACU and PDU modules and has different regulated outputs (3.3V and 5V). It means that with one single motherboard, several conditioning and distributing units can be connected. That ensures that additional equipment (ACU and PDU) could be linked to the motherboard if something failed in the assembly process.

The ACU module 6 different inputs per unit with a high voltage solar input (up to 16V or 32V). Additionally, each input can withstand a maximum current of 2A and current and voltage inputs are measured on each input channel and the measurements can be communicated to the onboard computer.

The PDU module has 9 different outputs per unit that are highly configurable. Each module has 3 configurable output voltages (3.3V, 5V, 8V, 12V, 18V, 24V) and each of the outputs can withstand a maximum current of 1A or 2A (programmable). Additionally, like the ACU module, current and voltage outputs are measured on each output channel and can be effectively communicated to the onboard computer.

All these features make the **NanoPower P60** a very efficient and configurable power management unit that fulfills the mission requirements. Furthermore, given this capacity to configure each input and output channel and the high number of channels that it has, the compatibility between all the systems used in the satellite is ensured. Additionally, the communication between this system and the onboard computer in order to detect potential failures is a really adequate feature.
With the NanoPower P60 we aim to distribute the energy to all of the subsystems of the CubeSat.

8.2.4 Batteries

Batteries are essential for a proper mission operation. They will provide the spacecraft subsystems with the power needed when the solar arrays are working less efficiently or not properly. Astrea is looking for decent capacity batteries that provide a slightly high typical energy and power supply, since all the systems will not usually operate under peak conditions. Additionally, through the lifetime of the mission, the solar arrays will face an important unfavorable condition; in the worst case scenario, the satellite will be in the dark during half of the period of the orbit. So, it is clear that the batteries are a critical system of the CubeSat

Among all the commercial options, Astrea has chosen the **BA01/D** batteries manufactured by **EXA-Agencia Espacial Civil Ecuatoriana**. The CubeSat will have two of these batteries, with a total capacity of 28800mAh or 106,4Wh. Each battery has a total of 16 cells, highly stackable and with a very low mass (155g per unit). They also come with unique thermal transfer bus, that will transfer the heat of the other subsystems to the batteries to keep their temperature under efficient working conditions.

The output voltage can be configured (3.7V and 7.4V) and they are perfectly compatible with the solar arrays. Furthermore, they come with a protective radiation shield (NEMEA) that ensures at least 4 years working under full efficiency conditions in a LEO. It is also worth mentioning that if the company that will assemble the CubeSat faces problems during this part of the process, the batteries can be customized by contacting EXA.

As mentioned above, if the satellite was in the dark during half of the period of the orbit, the estimated energy that it would need would be 50W. Thereby, the capacity of the batteries is more than enough to supply the required energy in the worst case scenario. In fact, they will supply energy when the energy demand of the CubeSat is higher than the energy collected by the solar cells. And logically, they will store the energy collected by the solar arrays when the energy demand of the systems is lower than the energy collected.

8.2.5 Study of the commercial available options and options chosen

A broad marked study is needed since all the options have to be considered. For this reason, and with the aim to show all the information and features of each system that has been considered in this section, the table 8.2.2 is presented below.

Brand and model	**Features**	**Total price (€) per unit**
Solar arrays		
EXA-Agencia Espacial Ecuatoriana	Total power of 67.2W (4units) Mass of 270g (p.unit) Included thermal protection At least 4 years lifetime	17000
ISIS	Total ower of 30W (4units) Mass of 150g (p.unit) No thermal protection At least 2 years lifetime	9000
Power management		

Crystalspace P1 Vasik	Mass of 80g Full redundancy Low volume 6x outputs Up to 10W input High temperature range	5400
Gomspace NanoPower P60	Mass of 176g 9x configurable outputs 6x inputs per module EMI shielding High temperature range	16000
Batteries		
Gomspace NanoPower BP4	Total capacity of 77Wh (2u) Automatic heat regulation Highly stackable Mass of 270g (p.unit)	3250
EXA-Agencia Espacial Ecuatoriana	Total capacity of 106.4Wh (2u) Automatic heat regulation Highly stackable Total mass of 155g	6300

Table 8.2.2: Options studied for the Electric Power System

Finally, the options chosen are presented in the table 8.2.3.

System	Brand and model	Price per unit (€)	N. of units
Solar arrays	EXA	17000	4
Additional solar arrays	-	4000-12000	depends
Batteries	EXA	6300	2
Power Management	Gomspace NanoPower P60	16000	1

Table 8.2.3: Options studied for the Electric Power System

8.3 Propulsion Systems

8.3.1 Requirements

There is a big risk of a collision with space debris while a spacecraft is operating in Low Earth Orbits. The Inter-Agency Space Debris Coordination Committee recommended to the United Nations (section 5.3.2 'Objects Passing Through the LEO Region'): "Whenever possible space systems that are terminating their operational phases in orbits that pass through the LEO region, or have the potential to interfere with the LEO region, should be de-orbited (direct re-entry is preferred) or where appropriate manoeuvred into an orbit with a reduced lifetime. Retrieval is also a disposal option." and "A space system should be left in an orbit in which, using an accepted nominal projection for solar activity, atmospheric drag will limit the orbital lifetime after completion of operations. A study on the effect of post- mission orbital lifetime limitation on collision rate and debris population growth has been performed by the IADC. This IADC and some other studies and a number of existing national guidelines have found 25 years to be a reasonable and appropriate lifetime limit." [?]

Thus, a proper propulsion system is needed both for maintaining the satellite's orbit and for de-orbiting after the mission's lifetime.

Given the size of the CubeSat, not many effective options are available and a committed solution has to be found in order to follow the recommendations by the IADC.

8.3.2 Thrusters

Thruster is a main part of the structure because it is needed to allow the satellite to realise different maneuvers how incorporate it adequatly to the orbit after the deployment of the rocket, can obtain the optimal orientation or to mantain the satellite in the orbital and avoid its fallen.

The main parameters that must consider are thrust, total specific impulse,power required, weight of the propulsion subsystem and its volume.

At the moment, the most used and more modern thrusters for satellites are: ionic, pulsed plasma, electrothermal and green monopropellant thrusters. An important aspect to consider is that the goal is to reduce the mass required although this will cause minor accelerations than conventional engines but it will be suitable for small satellites.

After a market study,the best two options to consider are the green monopropellant thruster BGT-X5 and the ion thruster BIT-1, both from Busek company. These two thruster are among the most used in the aerospace industry for small satellites. The main difference between both are the thrust and the specific impulse. On the one hand, the BIT-1 thruster provides a lower thrust but with a high specific impulse. On the other hand, BGT-X5 thruster provides a high thrust, around 0.5 N but with a lower specific impulse.

Finally, BGT-X5 has been chosen how the CubeSat thruster. With the high thrust and delta V that BGT-X5 provides, the CubeSat will be able to carry out the necessary actions to keep the satellite in orbit, to relocate the satellite or to change its orbit.

The following table 8.3.1 shows the main parameters of this thruster.

BGT-X5	
PARAMETERS	**VALUE**
Total thruster power	20 W
Thrust	0.5 N
Specific impulse	225 s
Thruster Mass	1500 g
Input voltage	12 V
Delta V	146 m/s

Table 8.3.1: Main features of BGT-X5

8.3.3 Study of the commercial available options

A broad marked study is needed since all the options have to be considered. For this reason, and with the aim to show all the information and features of each system that has been considered in this section, the table 8.3.2 is presented below.

Brand and model	**Features**	**Total price (€)**
Propulsion		
Busek ion thruster BIT-1	Volume 1/2 U High Isp (2150 s) Low thrust (100 uN)	58000

Busek BGT-X5	Volume 1 U High thrust (0.5 N) High delta V (146 m/s)	50000

Table 8.3.2: Options studied for the propulsion system

Finally, the option chosen is presented in the table 8.3.3.

System	Brand and model	Price per unit (€)
Propulsion	Busek BGT-X5	50000

Table 8.3.3: Option chosen for the propulsion system

8.4 Attitude and Orbital Control Systems

Attitude and orbital control subsystem is needed to enable the satellite to keep a specific position within its orbit and to control the antennas in order to remain oriented to assigned area, because the satellite tends to change its orientation due to torque. The AOCS receives telecommands from the central computer and acquires measurements (satellite attitude and orbital position) from sensors. We will also refer to the attitude control as ADACS (Attitude Determination and Attitude control system).

Attitude control for CubeSats relies on miniaturizing technology without significant performance degradation. Tumbling typically occurs as soon as a CubeSat is deployed, due to asymmetric deployment forces and bumping with other CubeSats. Some CubeSats operate normally while tumbling, but those that require pointing in a certain direction or cannot operate safely while spinning, must be detumbled. Systems that perform attitude determination and control include **reaction wheels**, **magnetorquers**, **thrusters**, **star trackers**, **Sun sensors**, **Earth sensors**, **angular rate sensors**, and **GPS receivers and antennas**. Combinations of these systems are typically seen in order to take each method's advantages and mitigate their shortcomings. **Reaction** wheels are commonly utilized for their ability to impart relatively large moments for any given energy input, but reaction wheel's utility is limited due to saturation, the point at which a wheel cannot spin faster. Reaction wheels can be desaturated with the use of thrusters or magnetorquers. **Thrusters** can provide large moments by imparting a couple on the spacecraft but inefficiencies in small propulsion systems cause thrusters to run out of fuel rapidly. Commonly found on nearly all CubeSats are **magnetorquers** which run electricity through a solenoid to take advantage of Earth's magnetic field to produce a turning moment. Attitude-control modules and solar panels typically feature built-in magnetorquers. For CubeSats that only need to detumble, no attitude determination method beyond an angular rate sensor or electronic gyroscope is necessary (*wikipedia extract*, [**?**]).

Pointing in a specific direction is necessary for Earth observation, orbital maneuvers, maximizing solar power, and some scientific instruments. Directional pointing accuracy can be achieved by sensing Earth and its horizon, the Sun, or specific stars. Determination of a CubeSat's location can be done through the use of on-board GPS, which is relatively expensive for a CubeSat, or by relaying radar tracking data to the craft from Earth-based tracking systems (*wikipedia extract*, [**?**]).

8.4.1 Orbital Control

Orbital control will be achieved as a combination of two systems. ADCS will orient the thrust, this thrust will be given by the propulsion system and all the operation will be controlled on the On-Board Computer. Principally, the orbit control will be necessary to mitigate orbital debris effect on every satellite.

8.4.2 Study of the commercial available options

Because AOCS involve so many systems working together, full assembled module had been considered in order to avoid compatibility issues.

ADACS options		
Features	**CUBE ADCS**	**MAI-400 ADACS**
Power	3.3/5 VDC Peak: 7.045W	5 VDC Peak: 7.23W
Mass	506 g	694 g
Size	90 x 90 x 58 mm	10 x 10 x 5.59 cm
Sensors	3-Axis Gyro Fine Sun & Earth sensor Magnetometer 10x Coarse Sun Sensors Star tracker(optional)	3-axis magnetometer Coarse sun sensor EHS Camera
Actuators	3 reactions wheels 2 torque rods	3 reactions wheels 3 torque rods
Computer	4-48 MHz full ADCS + OBC	4Hz Provides telemetry
Control Board	Works as OBC included	MAI-400 not included

Table 8.4.1: Main ADACS features

Decision After the study of commercial options available, the previous two where the unique that fitted in AstreaSAT requirements, so a decision between these two must be done. Since all the features tabulated on 8.4.1 are critical, the same weights are given. Therefore, we will compare directly the two alternatives for choosing the best alternatives. Taking into account that we need: low power consumption, low, weight and size, high pointing accuracy and really versatile systems that can integrate multiple subsystems; **CUBE ADCS** is chosen. It has the lowest mass and power consumption, it also offers a higher attitude determination systems, redundancy is a key fact because we can not loose precision during the life time of each satellite. Finally, the fact that CUBE ADCS integrates also and On-Board Computer (OBC) is the turning point, because we have size and weight limitations, having and integrated, high performance OBC in this system will make able TT&C with the ground stations and the control af every system on board. http://www.cubespace.co.za/cubecomputer

8.5 Payload

Aim AstreaSAT payload, needs to provide a radio link to the client satellites, for real time data relay with no less than 25MB/s of data rate. For achieving its porpoise, the payload will consist on a pack of arrays of antennas and data handling computers.

AstreaSAT payload will have to have three types of radio links for transmitting in every condition the data received from the clients:

- **Space to Ground link**: Connection between satellite and Ground Station when it is possible.
- **Inter-satellite Space to Space link**: Communication between Astrea satellites for data relay, looking for the nearest satellite with Ground Station link available, to transmit the data.
- **Client Space to Space link**: Communication between client and Astrea satellites.

The radio frequencies that we can use to establish the previous described links are regulated in [?] by frequency, bandwidth and type of communication . So, for the **Space to Ground link** we can use frequencies from **70MHz** to **240GHz**; for **Inter-satellite Space to Space link** plus data relay type of communication, frequencies are **2-2.4GHz**, **4-4,4GHz** and **22-240GHz**. Finally, **Client Space to Space link**, they exist to cases; on the one hand, the client points towards the Earth like a standard satellite, we capture its signal and make the data relay, since it is like a Space to Ground communication and also like a inter-satellite communication, we can combine the two previous restrictions. On the other hand, if the client satellite is below our constellation, we only had inter-satellite communication, therefore **Inter-satellite Space to Space link** rules are applied.

Finally, the Payload will consist on a combination of antennas, transceivers and data handling systems which will combine to create a data relay module.

8.5.1 Antennas

The antennas are essential in this mission, since their role is to transmit and receive the data from other satellites as well as the ground stations. In order to provide fast and reliable communication, several options have been studied and information about their main parameters is presented below.

It has to be kept in mind that the mass of the antennas should be as low as possible given that there are already a lot of subsystems in the CubeSat and the mass limitation is about 4kg. Additionally, the power consumption has to be kept as low as possible given the limitations regarding to the power supply of the CubeSat. The antennas must be certified to work under space conditions (high temperature range and radiation protection shield). Preliminary, after a first satellite preliminary design, seems that patch and turnstile antennas will cover the needs of AstreaSAT.

8.5.1.0.1 Basic parameters

The **frequency range** is one of the most important parameters, since it is related to an effective satellite-satellite and satellite-ground station communication. The frequency range should be between 1GHz and 10GHz, which is a very demanding condition given that the CubeSat has a limited space and power supply. Those frequencies, assure the desired data rates an negligible atmosphere attenuations.
For an effective communication, the signal has to be able to trespass the atmosphere without a high number of losses and interference. The high frequency range allows the signal to go through this barrier and reach the ground stations.

The **bandwidth** is the frequency range in which the highest power of the signal is found. It is really important to have a high bandwidth to have a great performance and avoid extremely high signal losses.

The **gain** of an antenna is the ratio between the power density radiated in one direction and the power density that would radiate an isotropic antenna. The best option is to have a high gain.

The **polarization** of an antenna is the orientation of the electromagnetic waves when they are leaving it. There are three types of polarization: linear, circular and elliptical. For a high performance, the receiver antenna and the transmitter antenna should have the same polarization. It has been derived that the best option for the project is an antenna with circular polarization; these types of antennas are able to keep the signal constant regardless of the appearance of different adverse situations such as the relative movement of the satellites with respect to the ground station.

8.5.1.0.2 Patch antenna

A **patch antenna** is a type of radio antenna with a low profile, which can be mounted on a flat surface, It consists of a flat rectangular sheet or "patch" of metal, mounted over a larger sheet of metal called a ground plane. They are the original type of microstrip antenna described by Howell in 1972. [**?**, wikipedia]

Patch antenna AntDevCo	
Features	**Value**
Bands	L,S,C,X
Frequency range	1-12 GHz
Bandwidth	20 MHz
Gain	6 dBi
Polarization	Circular
Maximum power consumption	10 W
Impedance	50 Ohms
Operational temperature range	-65ºC to +100ºC
Mass	<250 grams

Table 8.5.1: Main features of the patch antenna

8.5.1.0.3 Turnstile antenna

A **turnstile antenna**, or crossed-dipole antenna, is a radio antenna consisting of a set of two identical dipole antennas mounted at right angles to each other and fed in phase quadrature; the two currents applied to the dipoles are 90^o out of phase.

Turnstile antenna ANT430	
Features	**Value**
Frequency range	400-480 MHz
Bandwidth	5 MHz
Gain	1.5 dBi
Polarization	Circular
Maximum power consumption	10 W
Impedance	50 Ohms
Operational temperature range	-40ºC to +85ºC
Mass	30 grams

Table 8.5.2: Main features of the turnstile antenna

8.5.2 Antenna selection

After a market study, the best two antennas to add in the CubeSat are the patch antenna AntDevCov and the turnstile antenna ANT430 Gomspace. The number of units of each antenna are 4 and 2 respectively. The 4 patch antennas will be placed on each side face of the CubeSat and they will occupy a 1U face. The 2 turnstile antennas will be placed on the upper and lower face of the CubeSat and, as they do not occupy space, other systems such as a solar panel or the thruster can be placed on those faces.

Other antenna types, like helicoidal deployable antennas, parabolic antennas or monopole antennas, had been discarded because of their big volume and mass or because the don't accomplish the preliminary requirements stated on the project charter.

Nevertheless, this is only a preselection. After the link budget study and negotiation with communications department changes can be made if it is necessary.

8.5.3 Payload Data Handling Systems

Every AstreaSAT will act as a router to transmit client data to the ground. This initial raw data, should be temporally stored into the satellite in order to process it, if necessary. Since, to down-link the data, first the satellites need to establish connection, data can not be directly retransmitted to other sources (Ground Station or satellite) as it enters to the satellite. Furthermore, non loss compression algorithms can be applied to reduce the data size load and achieve higher data transmission velocities.

To sum up, Payload Data Handling System of every AstreaSAT (PDHS) will be able to receive, process and send the client data, using the integrated transceivers (transmitter + receiver) for sending the data and the PDHS computer to process it. PDHS have a hard disk associated which will temporally store the client data.

Finally, is necessary to find the transceivers and PDHS computers compatible combination in order to achieve the specifications stated on the Project Charter.

8.5.3.0.1 Transceivers

A transceiver is a device comprising both a transmitter and a receiver that are combined and share common circuitry or a single housing. For the preliminary design, because we know that they should satisfy all the connectivity options, we are restricted to the S, K or higher bands for **Inter-satellite communication** and not restriction virtually at all for **Space to Ground** communication. Nevertheless, together with the communications department, X band is chosen as the frequency to talk to the floor because several factors: the use in

Transceivers options - Inter-satellite comm.(S band)		
Features	**NanoCom TR-600**	**SWIFT-SLX**
Band	70 - 6000 MHz	1.5 - 3.0 GHz
Bandwidth	0.2 - 56 MHz	10+ MHz
Vcc	3.3V	6 - 36V
Max. Power consumption	14W	10.8W
Dimensions	65 x 40 x 6.5 mm	86 x 86 x 25-35mm
Operational temperature range	-40°C to +85°C	-35°C to +70°C
Mass	16,4 grams	250 grams

Table 8.5.3: Main inter-satellite communication transceivers features

NanoCom TR-600 has an additional advantage, GOMspace, the supplier, offers it in combination with the NanoMind Z7000 seen in PDHS computers section. Both integrated on a board able to hold three TR-600 transceivers and one computer. The low dimensions, high bandwidth (associated to high data rates) and low mass of TR-600 versus SWIFT-SLX, makes the first, a great choice for Inter-Satellite communication.

Transceivers options - Space to Ground comm.(X band)		
Features	**SWIFT-XTS**	**ENDUROSAT**
Band	7 - 9 GHz	8.025 - 8.4 GHz
Bandwidth	10 - >100 MHz	10+ MHz
Vcc	3.3V	12V
Max. Power consumption	12W	11.5W
Dimensions	86 x 86 x 45mm	90 x 90 x 25mm
Operational temperature range	-40°C to +85°C	-35°C to +70°C
Mass	350 grams	250 grams

Table 8.5.4: Main space to ground communication transceivers features

SWIFT-XTS is pretty similar to ENDUROSAT, but presents some advantages. The higher Bandwidth, will make possible higher communication data rates. The higher mass respect to ENDUROSAT could be a problem, from the link budget analysis a decision will could be made, because the most important factor is the possibility to transmit with low losses to the ground.

8.5.3.0.2 PDHS computers

PDHS computers will process and store the clients data before the data relay is done.

PDHS computers options		
Features	**NanoMind Z7000**	**ISIS iOBC**
Operating System	Linux	FreeRTOS
Storage	4GB to 32 GB	16GB
Processor	MPCoreA9 667 MHz	ARM9 400 MHz
Vcc	3.3V	3.3V
Max. Power consumption	30W	0.55W
Dimensions	65 x 40 x 6.5mm	96 x 90 x 12.4mm
Operational temperature range	-40ºC to +85ºC	-25ºC to +65ºC
Mass	28.3 grams	94 grams

Table 8.5.5: Main PDHS computers features

The main advantage of NanoMind Z7000 over ISIS iOBC is the computing availability, because of its two 667MHz processor Z7000 can handle higher data payloads and processit at higher velocities, reducing in last term delay between communications. Also, Z7000 presents a lower mass, critical think in our mass limitation of 4kg. But the turning point is, as stated before, Z7000 comes integrated on a single board with a maximum of three NanoMind TR-600 transceivers, fact that makes it a perfect option to build a data relay module payload.

8.5.4 Study of the commercial available options and options chosen

A broad marked study is needed since all the options have to be considered. For this reason, and with the aim to show all the information and features of each system that has been considered in this section, the table 8.5.6 is presented below.

Brand and model	Features	Total price (€)
Antennas		

Patch antenna AntDevCo	High frequency range (L,S,C,X bands) High bandwidth High mass (120 g)	18000 (7000)
ISIS monopole deployable antenna	Low frequency range (10MHz) Higher mass than ANT430 (100 g) Deployable Not occupy space	17000
Turnstile antenna ANT340 Gomspace	Low frequency range (400-480 MHz) Low mass (30 g) Deployable Not occupy space	9500
Transceiver inter-satellite		
NanoCom TR-600	SDR including S band High Bandwith Low mass and dimensions Integrated with other PDHS	8545
SWIFT-SLX	Low power consumption High mass and dimensions Narrow bandwidth	7800
Transceiver space to ground		
SWIFT-XTS	High bandwith High mass Standard dimensions	5500
ENDUROSAT	Narrow bandwidth Lower mass Standard size	22500
PDHS Computers		
NanoMind Z7000	LinuxOS High processing velocity High power consumption Low mass and dimensions	5000
ISIS iOBC	FreeRTOS OS Less computing velocity High dimensions and mass	9400

Table 8.5.6: Options studied for the payload

Finally, with the aim to clarify all the information of this section, the chosen systems and components are presented in the table 8.5.7.

System	Brand and model	Price per unit (€)	N. of units
Antenna	Patch antenna AntDevCo	TO REQUEST!	8
Transceiver	NanoCom TR-600	TO REQUEST!	3
Transceiver	SWIFT-XTS	TO REQUEST!	1
PDHS	NanoMind Z7000	TO REQUEST!	1

Table 8.5.7: Options chosen for the payload

8.6 Communication module

The telemetry subsystem analyses the information of the ground station and other sensors of the satellite in order to monitor the on-board conditions. With this system, the CubeSat is able to transmit the status of the on-board systems to the ground station.

The command and control subsystem (TT&C) allows the ground station to control the satellite.

Every Astrea satellite (AstreaSAT) of the constellation, will need to report its operating status to the ground and receive commands from the ground. TT&C operations will usually be performed when the satellite flights over the coverage of the constellation ground station, but since the satellites are interconnected, there is the possibility to perform this operations via data relay links between satellites. As a collaboration with the communications department, S band frequency is chosen for TT&C operations, since there is no need for high data rates, the lower band will significantly reduce the power consumption.

Communication to the ground will be perform with a NanoCom TR-600 transceiver module attached to AntDevCo Patch antenna, both configured for S band frequency communication.

8.7 Link Budget

Astrea constellation main satellite must be able to stablish three different telecommunications link:

- Space to Ground link for payload and TT&C data.
- Space to Space link between Astrea satellites.
- Space to Space link between client and Astrea satellites.

8.7.1 Communications Basics

When evaluating a wireless link, the three most important questions to be answered are: [?]

1. How much radio frequency (RF) power is available? Up to 2W for S band or up to 12W for Xband.
2. How much bandwidth is available?
   Available 400MHz with 28 channels of 14MHz or 228 channels of 1.75MHz for inter-satellite communication at S band. For X band, there's more than 4GHz available [?]. In fact is limited by the TR-600 transceiver at 56MHz for S band and to 100MHz by SWIFT - XTS at X band.
3. What is the required reliability (as defined by Bit Error Rate, or BER)?
   Required reliability for space systems$E_b/N_o \geq 10$, so $BER = 5.5x10^{-6}$ for a MSK, PSK (worst case) modulation as shown in Fig.8.7.5.

The upper limit in terms of data rate is given by Shannon's Channel Capacity Theorem:

$$C = Blog_2(1 + S/N) \tag{8.7.1}$$

where:

$$\begin{aligned} C &= \text{channel capacity (bits/s)} \\ B &= \text{channel bandwidth (Hz)} \\ S &= \text{signal strength (watts)} \\ N &= \text{noise power (watts)} \end{aligned}$$

With all data known, the minimum required sensitivity of a receiver using the Eq. 8.7.1 will be stated in the Link Budget calculation.

Transmission Losses In any satellite transmission, there are always losses from various sources. Some of those losses may be constant, others are dependent of statistical data and others vary with the weather conditions, especially with rain.

<table>
<tr><td rowspan="13">TRANSMISSION LOSSES</td><td rowspan="10">PROPAGATION LOSSES</td><td colspan="3">FREE SPACE LOSSES</td></tr>
<tr><td rowspan="8">ATMOSPHERIC LOSSES</td><td rowspan="2">Ionospheric effects</td><td>Faraday rotation</td></tr>
<tr><td>Scintillation effects</td></tr>
<tr><td rowspan="5">Tropospheric effects</td><td>Attenuation</td></tr>
<tr><td>Rain attenuation</td></tr>
<tr><td>Gas absorption</td></tr>
<tr><td>Depolarization</td></tr>
<tr><td>Sky noise</td></tr>
<tr><td>Local effects</td><td></td></tr>
<tr><td colspan="3">POINTING LOSSES</td></tr>
<tr><td rowspan="3">LOCAL LOSSES</td><td rowspan="2">EQUIPMENT LOSSES</td><td>Feeder losses</td><td rowspan="2"></td></tr>
<tr><td>?????</td></tr>
<tr><td colspan="3">ENVIRONMENT LOSSES</td></tr>
</table>

Figure 8.7.1: Principal losses in the received signal [?]

8.7.2 Propagation losses

8.7.2.0.1 Free Space Losses

Range and Path Loss Another key consideration is the issue of range. As radio waves propagate in free space, power falls off as the square of range. For a doubling of range, power reaching a receiver antenna is reduced by a factor of four. This effect is due to the spreading of the radio waves as they propagate, and can be calculated by [?]:

$$L = 20log_{10}(4\pi D/\lambda) \tag{8.7.2}$$

where:

$$D = \text{the distance between receiver and transmitter}$$
$$\lambda = \text{free space wavelength} = \text{c/f}$$
$$c = \text{speed of light}(3\text{x}10^8 m/s)$$
$$f = \text{frequency (Hz)}$$

8.7.2.0.2 Atmospheric Losses

This kind of losses derives from the absorption of energy by atmospheric gases. They can assume two different types:

- Atmospheric attenuation.
- Atmospheric absorption.

The major distinguishing factor between them is their origin. Attenuation is weatherrelated, while absorption comes in clear-sky conditions. Likewise, these losses can be due to ionospheric, tropospheric and other local effects. [?]

Ionospheric Effects All radio waves transmitted by satellites to the Earth or vice versa must pass through the ionosphere, the highest layer of the atmosphere, which contains ionized particles, especially due to the action of sun's radiation. Free electrons are distributed in layers and clouds of electrons may be formed, originating what is known as travelling ionospheric disturbances, what provoke signal fluctuations that are only treated as statistical data. The effects are:

- **Polarization rotation**: When a radio wave passes through the ionosphere, it contacts the layers of ionized electrons that move according to the Earth's magnetic field. The direction these electrons move will no longer be parallel to the electric field of the wave and therefore the polarization is shifted, in what is called Faraday rotation (θ_F). ;
- **Scintillation effects**: Differences in the atmospheric refractive index may cause scattering and multipath effect, due to the different directions rays may take through the atmosphere. They are detected as variations in amplitude, phase, polarization and angle of arrival of the radio waves. It is often recommended the introduction of a fade margin so atmospheric scintillation can be a tolerated phenomenon.;
- Absorption
- Variation in the direction of arrival
- Propagation delay
- Dispersion
- Frequency change

These effects decrease usually with the increase of the square of the frequency and most serious ones in satellite communications are the polarization rotation and the scintillation effects, and those are the ones that will be treated in this dissertation. [?]

Tropospheric Effects [?] Troposphere is composed by a miscellany of molecules of different compounds, such as hail, raindrops or other atmospheric gases. Radio waves that pass by troposphere will suffer their effects and will be scattered, depolarized, absorbed and therefore attenuated.
Attenuation: As radio waves cross troposphere, radio frequency energy will be converted into thermal energy and that attenuates signal.
Rain attenuation: Ground stations had been chosen in order that the attenuation caused by rainfall will be very punctual. Also, the fact that there are three ground stations makes really difficult that a satellite can not communicate to the ground in all the orbit period.
Gas absorption: Under normal conditions, only oxygen and water vapour have a significant contribution in absorption. Other atmospheric gases only become a problem in very dry air conditions above 70 GHz. Thereby, losses caused by atmospheric absorption vary with frequency and the collection of data already received allows the elaboration of the graphic that follows:

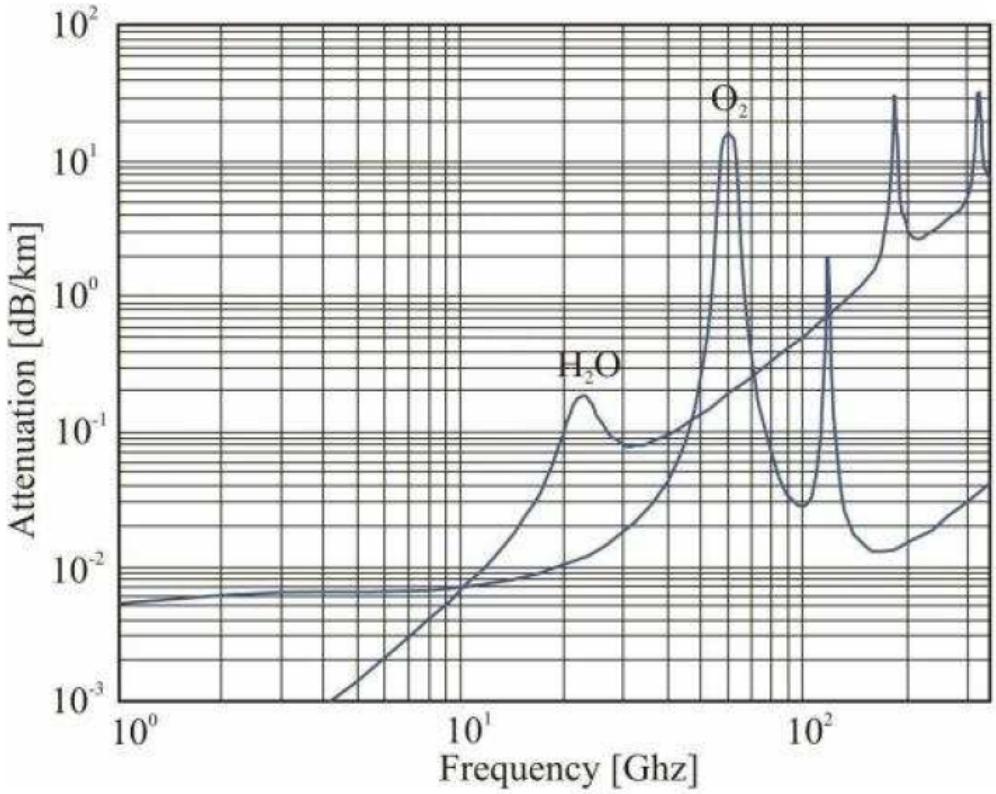


Figure 8.7.2: Specific attenuation for different frequencies [?]

Once these values depend on atmosphere thickness, it becomes necessary to perform all calculations taking into account troposphere's thickest layer (T_{trop}), which has 20 km.
It is also mandatory to refer that this graph represents the absorption for a satellite in the zenith, in other words, for an elevation angle of 90° ($\theta = 90^o$). For lower angles, the atmospheric absorption (L_{abs}) is given by [**?**]:

$$L_{abs}(dB) = L_{abs|90^o}(dB/km)\ cosec(\theta)\ T_{trop}(km) \tag{8.7.3}$$

For AstreaSAT, 5x10$^{-3}dB/km$ attenuation factor is considered for S band due to the O_2 specific attenuation. On the other hand, 4x10$^{-3}dB/km$ attenuation factor is considered for X band due to the H_2O and to the O_2 specific attenuations. An study of the critical elevation angle will lately be performed.

For AstreaSAT ground station, communication starts at an elevation angle of $\theta = 10^o$ (worst case scenario). Consequently, $cosesc(\theta)$ will go from 5.76 to 1 (best reception case). In that case, we assume:

$$L_{abs} = 2 \cdot 4\text{x}10^{-3} \cdot 5.76 \cdot 20 = \mathbf{0.92dB} \quad \text{X band}$$
$$L_{abs} = 5\text{x}10^{-3} \cdot 5.76 \cdot 20 = \mathbf{0.58dB} \quad \text{S band}$$

Polarization: Satellite communications use linear and circular polarization, but undesirable effects may transform it into an elliptical polarization. Depolarization may occur when an orthogonal component is created due to the passing of the signal through the ionosphere. There are two ways to measure its effect, cross polarization discrimination (XPD) and polarization isolation (I) [**?**]. To overcome this attenuation problems a circular polarization is the best option. AstreaSAT patch antennas will mitigate this problem, therefore this loses are considered negligible.

Sky noise: Sky noise is a combination of galactic and atmospheric effects, according as both these factors influence the quality of the signal in the reception. Galactic effects decrease with the increase of frequency. They are due to the addition of the cosmic background radiation and the noise temperature of radio stars, galaxies and nebulae. This value is quite low and a good approximation is **3 K**.

AstreaSAT noise temperature A good approximation based on Fig.8.7.3 is that Galaxy noise is 3K for S band and almost 1K for X band. Furthermore, for the previous

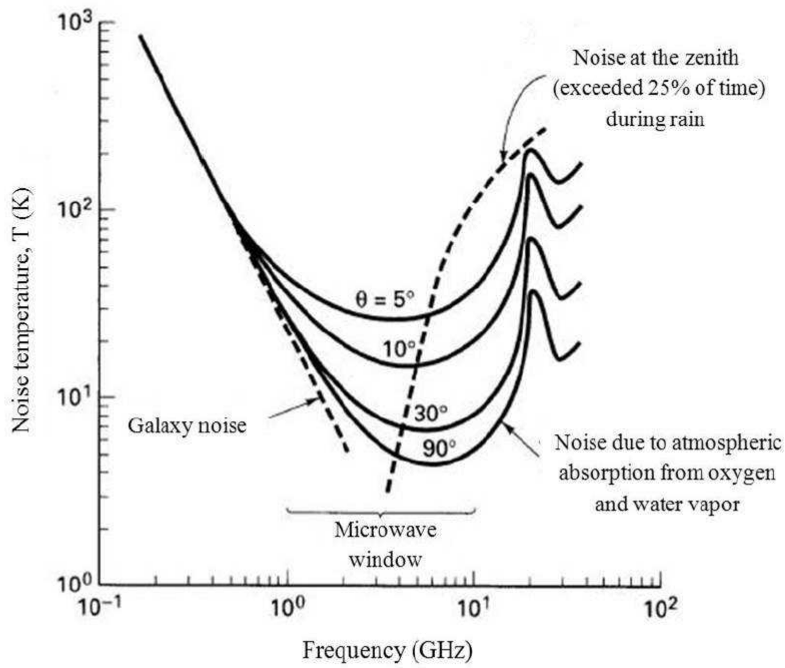


Figure 8.7.3: Galaxy noise influence in noise temperature [?]

worst case scenario stated before $\theta = 10$, noise temperature due to atmospheric absorption is 19K for both bands (S and X).

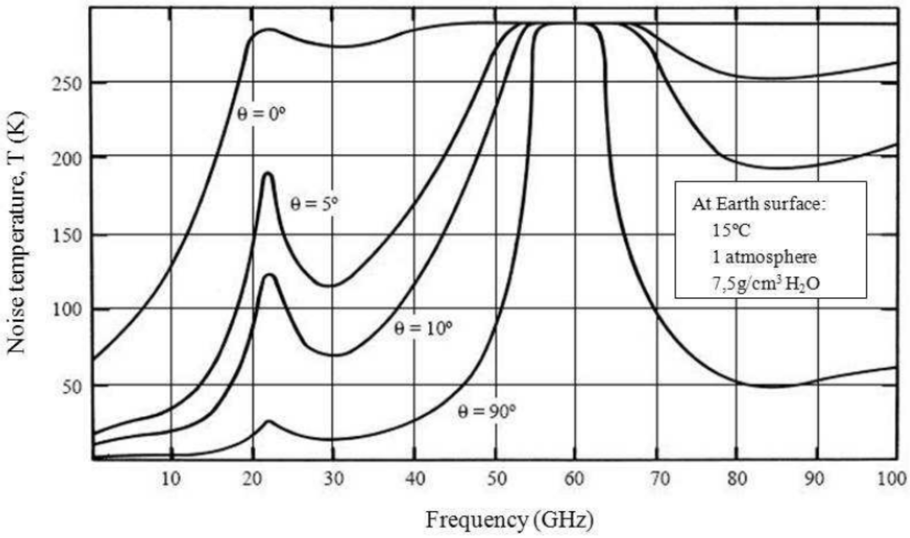


Figure 8.7.4: Noise temperature variation with frequency [?]

Local Effects These effects refer to the proximity of the local ground stations, possible sources that may interfere with the received signal and buildings that may block the signal. If the ground station is on a free external interferences zone, for satellite communications this factor may be negligible.

8.7.2.0.3 Pointing Losses

Ideal reception implies that the value for misalignment losses would be 0 dB which means maximum gain at the ground station is achieved when both the transmitter and the receiver antennas are 100% aligned. Realistically it is virtually impossible to achieve a perfect alignment between the antennas of the ground station and the satellite, especially in the case of CubeSats, due to their fast movement of nearly 8000 ms^{-1}.

Antenna misalignment losses (L_{aml}) are calculated using statistical data, so these values are an approximation based on real data observed in several GS. Ergo, these values are not calculated, but estimated. [**?**]

Based on a estimation from [**?**] a $L_{aml} = 1dB$ is a good approximation.

8.7.2.0.4 Multipath and Fade Margin

Multipath occurs when waves emitted by the transmitter travel along a different path and interfere destructively with waves travelling on a direct line-of-sight path. This is sometimes referred to as signal fading. This phenomenon occurs because waves travelling along different paths may be completely out of phase when they reach the antenna, thereby cancelling each other.

The amount of extra RF power radiated to overcome this phenomenon is referred to as fade margin. The exact amount of fade margin required depends on the desired reliability of the link, but a good rule-of-thumb is 20dB to 30dB.

8.7.3 Local Losses

8.7.3.0.1 Equipament Losses

The receiving and emitting equipments also introduces some losses to the signal.
Feeder Losses: Feeder losses occur in the several components between the receiving antenna and the receiver device, such as filters, couplers and waveguides. These losses are similar to the ones which occur also in the emission, between the emitting antenna and the output of the high power amplifier (HPA). [?]

8.7.3.0.2 Environment Losses

This item is related to the specific region of the globe where the ground station is placed (equatorial, tropical, polar…). Depending on its latitude, each region has its own characteristics (e.g. temperature, moisture, thickness of atmospheric ice layer…), which may provoke variation in signal reception. [?]

Communications department, had chosen the best locations over the globe, with stable good weather conditions to neglect this fact.

8.7.4 Modulation Technique

Modulation technique is a key consideration. This is the method by which the analogue or digital information is converted to signals at RF frequencies suitable for transmission. Selection of modulation method determines system bandwidth, power efficiency, sensitivity, and complexity. Most of us are familiar with Amplitude Modulation (AM) and Frequency Modulation (FM) because of their widespread use in commercial radio. Phase Modulation is another important technique. It is used in applications such as Global Position System (GPS) receivers and some cellular telephone networks. [?]

For the purposes of link budget analysis, the most important aspect of a given modulation technique is the Signal-to- Noise Ratio (SNR) necessary for a receiver to achieve a specified level of reliability in terms of BER.

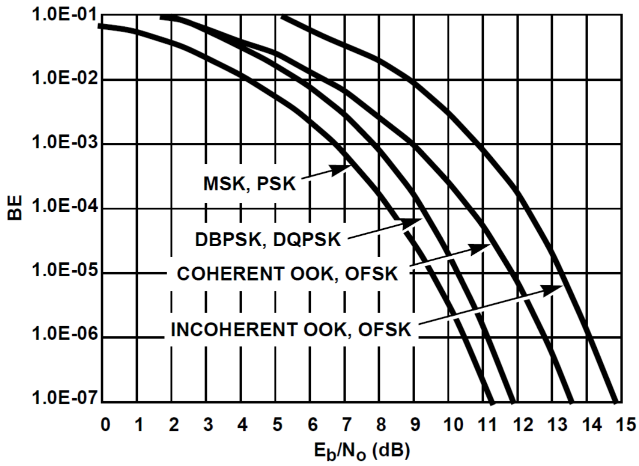


Figure 8.7.5: Probability of bit error for common modulation methods [?]

A graph of E_b/N_o vs BER is shown in Figure 8.7.5. E_b/N_o is a measure of the required energy per bit relative to the noise power. Note that E_b/N_o is independent of the system data rate. In order to convert from E_b/N_o to SNR, the data rate and system bandwidth must be taken into account as shown below:

$$SNR = (E_b/N_o)(R/B_T) \tag{8.7.4}$$

where:

$$E_b = \text{Energy required per bit of information}$$
$$N_o = \text{thermal noise in 1Hz of bandwidth}$$
$$R = \text{system data rate}$$
$$B_T = \text{system bandwidth}$$

AstreaSAT is equipped with Software Defined Radios, it has the ability to change the modulation methods when its flying, for calculus MSK and PSK modulations will be considered, because of their more restrictive conditions.

8.7.5 System Noise

The system noise temperature (T_S) is the sum of the antenna noise temperature (T_A) and the composite temperature of other components (T_{comp}), according to: [?]

$$T_S = T_A + T_{comp} \tag{8.7.5}$$

T_A may be known if the total attenuation due to rain and gas absorption (A), the temperature of the rain medium (T_m) and the temperature of the cold sky (T_C) are also known. Then, the following expression may be applied:

$$T_A = T_m\ (1 - 10^{-A/10}) + T_C\ 10^{-A/10} \tag{8.7.6}$$

Usually, for clouds it is considered $T_m = 280K$ and for the rain $T_m = 260K$. The sky noise tends to be $T_C = 10K$. Taking into account the values from Fig.8.7.3 and Fig.8.7.2 the following estimation can be made:

$$T_A = 280 \cdot (1 - 10^{-(5x10^{-3})/10}) + 22 \cdot 10^{-(5x10^{-3})/10} = \mathbf{22.29K} \quad \text{S band}$$
$$T_A = 280 \cdot (1 - 10^{-2\cdot(4x10^{-3})/10}) + 20 \cdot 10^{-2\cdot(4x10^{-3})/10} = \mathbf{20.48K} \quad \text{X band}$$

According to [?] a good components temperature approximation for a typical ground station is $T_{comp} = 65.5K$.

AstreaSAT system temperature will be considered as $T_S = 22.29 + 65.5 = \mathbf{87.79K}$ for S band and $T_S = 20.48 + 65.5 = \mathbf{85.98K}$ for X band. Since both frequencies are part of the microwave spectrum, we see that system temperatures are pretty much the same.

Channel Noise All objects which have heat emit RF energy in the form of random (Gaussian) noise. The amount of radiation emitted can be calculated by [?]:

$$N = kTB \tag{8.7.7}$$

where:

$$N = \text{noise power (watts)}$$
$$k = \text{Boltzman's constant}(1.38x10^{-23} J/K)$$
$$T = \text{system temperature, usually assumed to be 290K}$$
$$B = \text{channel bandwidth (Hz)}$$

This is the lowest possible noise level for a system with a given physical temperature. For most applications, temperature is typically assumed to be room temperature (290K). Equations 8.7.1 and 8.7.7 demonstrate that RF power and bandwidth can be traded off to achieve a given performance level (as defined by BER). [?]

8.7.6 Link Budget Calculation

Methodology From the expected requirements fixed on the Project Charter, general radio systems parameters will computed, in order to have a reference to look for the best communications system on board the Astrea satellites. As background, general losses parameters had been calculated on previous sections.

The most important concern on AstreaSAT link Budget is how far every satellite can emit on the desired frequencies. This is a key factor to know the utility of the modules selected. At least, Project Charter communication requirements must be accomplish.

$EIRP = P_T - L_T - G_T$
FRIIS EQUATION + GRAPH RANGE
SENSITIVITY CALCULUS A PARTIR DE LA DE CAPACITAT + NOISE ADJUDICANT BANDWITH

8.8 Budget

System	Cost/unit (€)	Total cost (€)	N. of units
STRUCTURE AND MECHANICS			
Structure	3900	3900	1
Thermal protection	1000	1000	1
Total		4900	
ELECTRIC POWER SYSTEM			
Solar arrays	17000	68000	4
Batteries	6300	12600	2
Power management	16000	16000	1
Total		96600	
PAYLOAD			
Patch antenna	18000 1st unit 7000 others	67000	8
Transceiver inter-satellite	8545	25635	3
Transceiver space to ground	5500	5500	1
Data handling system	5000	5000	1
Antenna Deployable	3000	3000	1
Variable expenses	4000	4000	1
Total		110135	
AOCDS			
Thruster	1350	50000	1
ADACS	280	15000	1
Total		65000	
TOTAL		276635	
TOTAL ESTIMATION		297000	
+Fixed cost	(includes all CubeSats)	150000	

The difference between the total cost and the total estimation is due to the fact that every satellite has to go through a process to be ready for operation. This is, the CubeSat has to be assembled and has to be tested as well to ensure that all the systems are working properly. Thus, an estimation of the costs related with this operation has to be made.

The fixed cost for assembling the satellites will be 150000€(cost of renting the building, the electricity, ...) and an additional cost 20000€$/unit$, which will include the wages of the people assembling and testing the satellite and also other variable costs that may appear in the process, is added to every satellite. Furthermore, this extra 20000€includes the costs of transport to launch site.

Several options have been studied for assembling and testing the satellite, and the option chosen is *OpenCosmos*. Astrea is committed to encourage the growth of the local economy and we are sure that *OpenCosmos* would be a perfect partner for the mission. They provide companies and individuals with simple and affordable access to space offering integration and testing services.

8.9 Astrea satellite Final Configuration

System	Weight/unit (g)	Sizes (mm)	N. of units
STRUCTURE AND MECHANICS			
Structure	304.3	100 x 100 x 300	1
Thermal protection	38	Covers all	1
Total	342.3		
ELECTRIC POWER SYSTEM			
Solar arrays	175	98 x 83 x 8.50	4
Batteries	155	90 x 63 x 12.02	2
Power management	126	92.0 x 88.9 x 20.5	1
Total	1136		
PAYLOAD			
Patch antenna	30	90 x 90 x4.35	8
Transceiver inter-satellite	16.4	65 x 40 x 6.5	3
Transceiver space to ground	101.5	86 x 86 x 45	1
Data handling system	28.3	65 x 40 x 6.5	1
Antenna Deployable	83	100 x 83 x 6.5	1
Variable	150	-	1
Total	652		
AOCDS			
Thruster	1350	90 x 90 x 95	1
ADACS	506	90 x 90 x 58	1
Total	1856		
TOTAL ESTIMATION	**3986.3**		