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Cubesat Constellation
Astrea

Report

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1 | Aim of the project

To design a **satellite constellation** dedicated to communications relay between LEO satellites and between LEO satellites and the ground.

2 | Scope of the project

This section establishes the scope of the project.

Satellite development

- Select the proper satellite's weight and size, taking into account the next constraints: the launch system cost, the relation between the weight, size and the orbit decay time and, lastly, the interdependency with the selected subsystems.
- Deep study of the market and of the state of the art so that later choice on which subsystem to include is done accordingly. The most important subsystems will be analysed. These are: the structural subsystem, the power subsystem, the thermal control subsystem, the attitude control subsystem and the data handling subsystem. The information is going to be extracted mainly online. Also, prestigious magazines can be taken into account as well as contacting some satellite companies.
- Eventually, a subsystems choice will be done taking into account the cost, the ease of integration and the need to fulfil the project's requirements.

Orbital design

- The orbit design will be accomplished according to the results of several studies such as visibility between satellites and between satellites and ground stations. Also, collision and orbital decay avoidance is going to be taken into account. Finally, stated requirements as low latency or the possibility to act in case of a network's failure are going to be contemplated due to their tight dependency on the selected orbit.
- The number of satellites and the number of orbital planes will be deducted from those studies.
- A study will be carried out to clarify if the Earth is the only celestial body that will influence the satellites or others, for instance, the Moon or the Sun will also have to be considered. It will consist in the inclusion of empirical or physical models in the orbit

calculation software and evaluate the level of significance of these cellestial bodies in the results.

- The specific existing legislation will be taken into account and followed during all the orbit development.

Constellation Deployment

- A comparison among the existing launch platforms will be carried out to find out the one that fulfils the mission requirements with a reasonable economic conditions.
- A launching date will be reserved if the chosen launch platform requires it.
- The recommendations of *Joint Space Operation Center* will be followed and their application form will be followed up to ensure all the launch procedure accomplishes the legislation.
- An end of life strategy will be designed according to the CubeSats lifespan, orbit decay, replacement stratagem of the company and legislation procedures.

Operation

- An analysis will be done to clarify how many ground stations must operate and the possibility of placing a central one in UPC ESEIAAT.
- The requirements and costs of the ground station will be determined.
- Communication logistics will be defined. Thus, how the satellites decide whether to send the data or to store it, and if they are to send, where they should do it, is going to be approached. In other words, a high level communications protocol is going to be defined.

Exhibition

- It will consist on a simulation of the constellation. Basically, the results from the orbit's calculations are going to be used here in order to show the client the final state of the product. A CAD of the Satellite node is going to be used as well.

3 | Requirements of the project

Feature	Description
1	Provide communication relay between two LEO nanosatellites with a latency **lower than 1 minute**.
2	Provide communication relay between a LEO nanosatellite and the ground with a latency **lower than 5 minutes.**.
3	Back-up system prepared to handle **up to two major failures** in the system. A major failure can be defined as the loss of a client's satellite coverage because of a failure in the network.
4	Switch time after major failure happens, shall be **below 6 hours**.
5	Each Satellite Node volume should be equal or **lower than a 3U Cubesat.**
6	Each Node should be able to handle **at least 25 Mbit/s** of data rate.

Table 3.0.1: Project Requirements

4 | Background

One of the major drawbacks of satellites is their poor temporal resolution. Although they can gather high quality data, they frequently lose contact with ground stations as they orbit. Therefore, their connection is limited to once every few hours. Astrea's objective is to solve this issue by creating a network between ground stations and LEO satellites providing near real-time communication to the customer. A network like the aforementioned is ideal for a CubeSat constellation because they are economical and easily reproducible satellites, making their mass production affordable.

Another problem which is normally faced when designing a satellite is that the systems that contains become obsolete in a relatively short period of time. In order to prevent this premature obsolescence, a constant refilling of the constellation is proposed, possible due to the low cost of CubeSat. The preliminary study leads to the fact that the orbit decay would make the CubeSats fall after 2 years of operation making it capable of updating the systems as the technology evolves.

Since 2013 CubeSat launches have experienced an incredible raise (as shown in Figure 4.0.1) mainly because of their economic advantage. The future projection shows that the launches are going to continue increasing. However, more than the half of these CubeSat constellations are going to be focused on Earth monitoring or become multiple-point sensors [10]. In these situation, Astrea has the opportunity to take a unique position in the market, sharing the communication segment only with Kepler Communications [3].

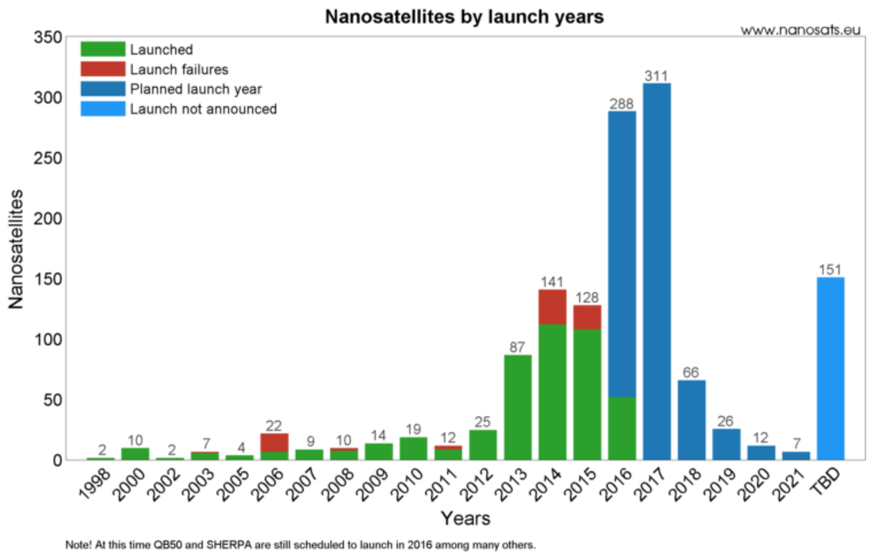


Figure 4.0.1: Nanosatellites by launch years. Extracted from [14]

Currently, there isn't any mission involving a large number of satellites implementing inter-satellite connection. However, missions like **QB-50** and **Keppler** are going to use this technology. The objective of these missions and other small satellites related projects is exposed at the Table 1 . For Astrea, this is an intrinsic advantage since normally, the CubeSat that connects with ground won't necessary be the same that the one establishing a link with the customer satellite. This will enable client's satellites to configure and maintain dynamic routes and manage intermediate nodes.

Mission Name	Number of satellites	Launched/Projected launch year	Products or Services
Spire	+100	2012	Weather monitoring system.
GHSat	1	2013	Greenhouse gas and air quality and gas emissions monitoring.
SpacePharma	-	2013	Microgravity service with 3U CubeSats.
Sky and Space global	200	2015	Communication service (voice,data and M2M)
Astro Digital	20	2015	Earth Obervation (Landmapper-HD).
EDSN	8	2015	Demonstration of small satellite applications using consumer electronic-based nano-satellites.
QB-50	50	2016	International network for thermo sphere exploration.
PROBA-3	2	2017	Demonstrate the technologies needed for formation flying.
Keppler	50	2017	Coordinate and relay the communication between satellites and ground.

Table 4.0.1: Current and future small satellites missions. Adapted from [14, 21]

5 | State of the art

The objective of this chapter is to make a overview of the current state of the technology covered by this project.

CubeSats

The main reference of this information is [18], a complete analysis done by NASA which describes the state of the art of the small spacecrafts technology and how it is expected to develop.

Power

Driven by weight and size limitations, small spacecraft are using advanced power generation and storage technology such as $> 29\%$ efficient solar cells and lithium-ion batteries. The higher risk tolerance of the small spacecraft community has allowed both the early adoption of technologies like flat lithium-polymer cells as well as commercial-off-the-shelf products not specifically designed for spaceflight. This dramatically reduces cost and increases flexibility of mission design. However, despite these developments, the small spacecraft community has been unable to use other, more complex technologies. This is largely because the small spacecraft market is not large enough to encourage the research and development of technologies like miniaturized nuclear energy sources.

Propulsion

A significant variety of propulsion technologies are currently available for small spacecrafts. While cold gas and pulsed plasma thrusters present an ideal option for attitude control applications, they have limitations for more ambitious maneuvers such as large orbital transfers. Other alternatives such as hydrazine, non-toxic propellants and solid motors provide a high capability and are suitable for medium size buses and missions that require higher ΔV budgets. Some spacecrafts have already flown with these systems or are being scheduled to fly in the next year. For the near future, the focus is placed on non-toxic propellants that avoid safety and operational complications and provide sufficient density and specific impulse. The application of this technology in cubesats is still in development as some of the components need to be scaled down to comply with volume, power and mass constraints. Electrosprays, Hall Effect thrusters and ion engines are in an active phase of development and active testing and technology demonstrations are expected for different bus sizes. These propulsion technologies will allow spacecrafts to achieve very high ΔV and, therefore, to perform interplanetary transfers with low thrust.

Structures, Materials and Mechanisms

The landscape for small spacecraft structural design is expanding and the firms developing and offering solutions for spacecraft designers are expanding as well. Most of the developments have been in the 3U CubeSats and there are now some examples of designs for 6U and 12U CubeSats.

Thermal Control System

As thermal management on small spacecrafts is limited by mass, volume and power constraints, traditional passive technologies, such as MLI, paints, coatings and metallic thermal straps, still dominate thermal design. Active technologies, such as thin flexible resistance heaters have also seen significant use in small spacecraft, including some with advanced closed-loop control. Passive louvers and sun shields have been proposed and developed for small spacecraft and will tentatively fly in 2016 (Dellingr and CryoCube-1). Deployable radiators and various types of composite thermal straps have also been fabricated and tested for small spacecrafts. Thermal storage units are being developed in order to have better control of the amount of heat dissipation.

Communications

There is already a strong flight heritage for many UHF/VHF and S-band communication systems for CubeSats. X-band systems are less common but its use is growing in the last years. The use of even higher RF frequencies and laser communications already has been implemented on CubeSats, but with limited performance. Ka-band systems are currently in development, but are still low matured. On the other hand, laser communication is technology that will most likely see increased performance in the near future for onboard laser systems.

Integration, Launch and Deployment

There is a wide variety of integration and deployment systems. While leveraging excess payload space will continue to be profitable into the future, dedicated launch vehicles and new integration systems are becoming popular to fully use the advantages provided by small spacecrafts. Dedicated launch vehicles may be used to take advantage of rapid iteration and mission design flexibility, enabling small spacecrafts to decide the mission parameters. Advanced systems may be used to host secondary payloads on orbit to increase mission lifetime, expand mission capabilities, and enable orbit maneuvering.

Ground Data Systems and Mission Operations

Depending on the requirements and priorities of the user, different types of solutions to build and assemble a ground station are available in the market. If the user wants to focus more on the payload and the system engineering of the spacecraft, some companies have pre-defined solutions, which provide full capability and support for the spacecraft-ground communications. Other possible solutions are customizing the ground station with specific components (such as antennas, transceivers, modems and software) provided by different manufacturers. Finally, another valuable solution for small spacecrafts to communicate with Earth is using inter-satellite communications relays. Some CubeSat missions have already demonstrated these capabilities.

Constellation of CubeSats

The raise of these small satellites has let to the research of new possibilities for CubeSats, such as satellite constellations. This concept has been discused for the last years. One of the examples is the QB50 Project, a mission that wants to facilitate the access to space through a constellation of CubeSats [**?**]. There are also planned missions, like the BIRDS constellation from the Kyushu Institute of Technology. It consists of five 1U CubeSats, that are going to do experiments on radio communications [15]. However, the most interesting case is the already operative Spire. It is a constellation of CubeSats that collects data of the Earth through a network of small satellites [**?**].

Despite all the constellations, there are no precedents in a constellation that communicates with satellites other than the ones of its own network.

6 | Main alternatives, decision and development of the best one

6.1 Orbits

6.1.1 Coverage

6.1.1.1 Orbit Geometry

Throughout this section, the bases of orbital geometry will be introduced in order to correctly understand the parameters that will later be exposed when dealing with the constellation orbits (or the position of the satellites in them). To understand the movement in space is enough to apply the Newton's laws. You can find a detail on the approach to the equations in [REF TO ANNEX I. Section 1.2].

These equations, however, need an inertial non-rotating frame to be correctly described. When dealing with Earth-orbiting, one usually chooses a reference system called *geocentric-equatorial system* which is shown in the figure 6.1.1.a.

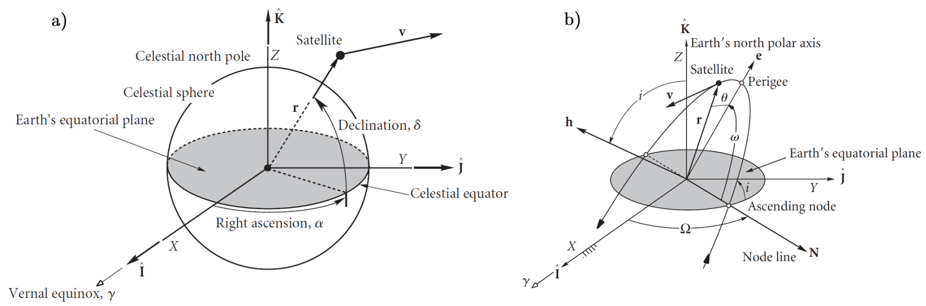


Figure 6.1.1: a) Geocentric-equatorial frame and b) Classical Orbital Elements. Extracted from [8].

By defining this system, any point in the space can be depicted by its position vector r and its movement can be studied by the velocity vector $\dot{r}$. These elements are useful especially for computational work but they nearly do not provide information about the orbit. For these reason, the orbital elements were developed. More information on orbital elements in [REF TO ANNEX I. Section 1.1].

6.1.1.2 Parameters of Satellite Coverage

The design of the constellation depends mainly on the coverage that a single satellite can provide. The parameters that define this coverage need to be deeply studied since their influence in the final constellation design is very significant. They can be listed below:

Satellite - Ground Visibility main parameters

- **Footprint:** Defined as the region of Earth where a single satellite can be seen. Details on its computation found in [REF TO ANNEX I. Section 2.1].
- **Elevation Angle:** The angle between the Ground Station beam pointing to the satellite and the horizontal local plane. Usually described as the minimum elevation angle necessary to avoid atmospheric absortion of the signal. A deep analysis on this influence and the implications of the constellation design can be found in [REF TO ANNEX I. Section 2.2]. The geometry of the setup can be seen in figure 6.1.2
- **Minimum Plane Inclination:** If the goal is to provide global coverage, then there is a minimum latitude in which the satellites can orbit. This minimum inclination is assessed in [REF TO ANNEX I. Section 2.3].

Satellite to Satellite Visibility

In this case, the conditions are set by direct linear communication between the two satellites. The details on the determination of this limitation is found in [REF TO ANNEX I. Section 2.4].

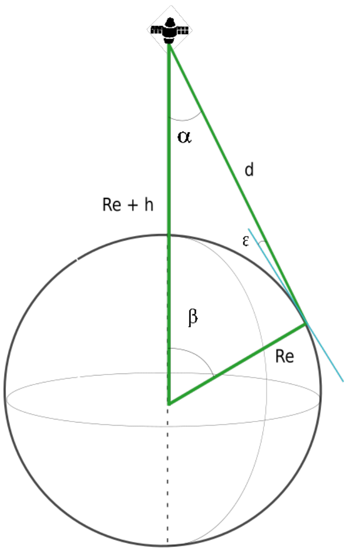


Figure 6.1.2: Single satellite coverage geometry

6.1.1.3 Market Study: Current Nanosatellites in Orbit

Criteria for the orbital height of the satellites

Satellites currently in Orbit

If only geometric considerations were to be applied in the design of a satellite constellation, it is clear that the higher the orbit the broader is the footprint, leading to a smaller number of satellites. However, if the service of communications is to be offered, the satellites currently in orbit or in design phases need to be at higher orbit than the one of the constellation. The purpose of that requirement is to intersect the field of view of the satellites that nowadays point to Earth.

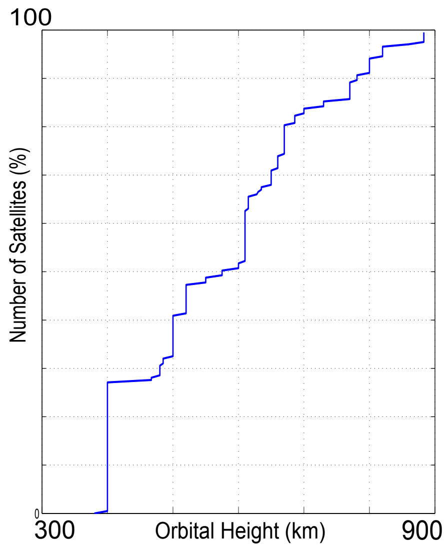


Figure 6.1.3: Distribution of the currently in orbit nanosatellites. Data on the 203 operative satellites from [14]

The most interesting potential clients

Lots of satellites are orbiting at heights lower than 500km, mainly because one of the most feasible way of launching a small satellite is from the International Space Station. However, this very low LEOs are related to very high speeds and specially to low lifetimes, since drag affects them in a more significant way. To the interest of the constellation, the satellites at higher altitudes are a better commercial target, since they are going to be in orbit for longer missions.

New Space: Adapting to new society needs,

In the future, the possibility of using the Astrea constellation to contact Earth can reduce the requirements for the antennas and AOCSs to communicate with ground, leading to a new level of resources for the satellite payload. That is just a way in which Astrea is in the New Space Generation. The Generation that brings space closer to mankind.

In conclusion, in the decision process one of the statistics considered with certain weight will be the following: the ratio of satellites at which the constellation will be able to provide service considering that nowadays all of them point down to Earth.

6.1.2 Constellation Configuration

Depending on the application the Space Segment of a mission can vary in an infinite number of ways. Probably the most famous and widely used satellite constellation is the the Global Positioning System satellite network. In this case, it uses an irregular geometry. The example is detailed in [REF TO ANNEX I. Section 3.1].

6.1.2.1 Polar Orbit Constellation

Polar Orbits are probably the simplest way to configure an evenly spaced constellation. As it will be seen in the section **Orbit Perturbations** when the inclination is the same for all the planes, the deviations tend to be the same for all the satellites. An example of near polar orbits is the constellation Iridium [12]. You can find the example in detail in [REF TO ANNEX I. Section 3.2]

General Configuration

The Polar Orbits configuration consists in the distribution of plains with inclination equal to 90 degrees. Note that the satellites will be travelling parallel to the satellites of the next plain except for the communications between the first and the last plane, hence the separation between this two is smaller. The plains are splitted in the pattern of figure 6.1.4:

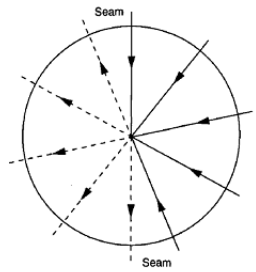


Figure 6.1.4: Distribution of the planes for Polar Orbits design.

The Streets of Coverage Method

The Street of Coverage Method is a way to compute the necessary plains and satellites to construct a Polar Orbit Constellation that provides global coverage. It is obtained from [7] and described in [REF TO ANNEX I. Section 3.3]

Results of the Streets of Coverage Method

A MATLAB routine detailed in [REF TO ANNEX VII. Satellite Number Computation for Polar Orbits] has been designed to compute the algorithm. The program is run in a broad range of parameters to see the evolution of the number of satellites. As it can be predicted, as the height increases the number of satellites is reduced. The reason is that the footprint of the satellites increases with the height. In addition, as the minimum elevation over the horizon to contact the satellites is reduced, the number of satellites is also reduced for the same reason.

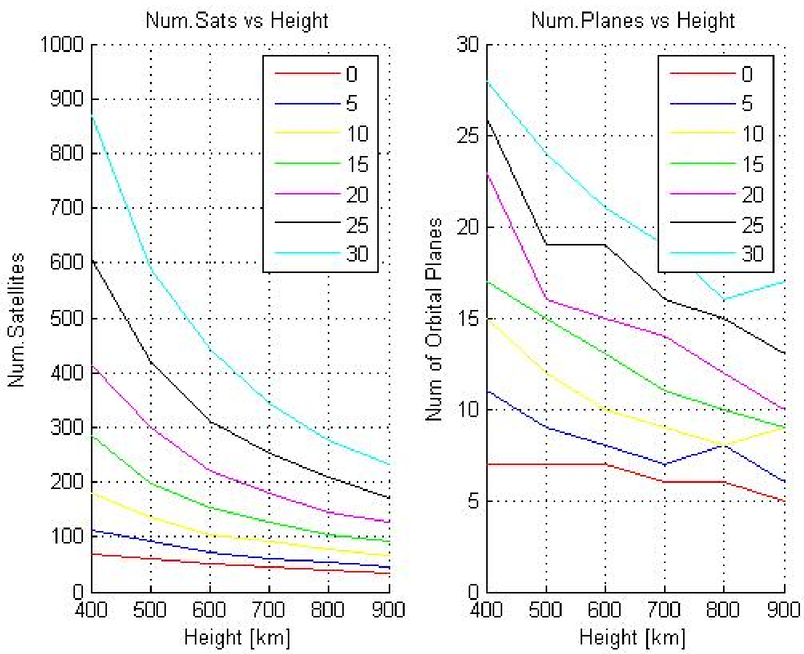


Figure 6.1.5: Variation of number of satellites for different heights and elevation angles

Conclusion

The computation and the design of this constellation requires small computational and conceptual effort. However, the number of satellites and planes is greater than expected. Even though the technical complexity can be reduced, the availability of small launchers to reach this particularly inclined orbit is also small. In conclusion, more constellation configurations need to be assessed to compare and select the most feasible one.

6.1.2.2 Walker-Delta Constellation

Walker Delta Pattern constellations are a type of symmetric, inclined constellations made of equal-radius circular orbits, with an equal number of satellites on each orbital plane.

Full Walker-Delta Constellation

A typical delta pattern has the following characteristics:

- The constellation contains a total of T satellites evenly spaced in each of the P orbital planes. All planes have the same number of satellites, defined as S, equally distributed on the orbit. Thus:

$$T = SP \tag{6.1.1}$$

$$\Delta\varphi = \frac{2\pi}{S} \tag{6.1.2}$$

Where $\Delta\varphi$ is the angle between satellites in the same plane.

- All orbits have equal inclinations δ to a reference plane. If this plane is the Equator (it usually is), then the inclination δ equals the orbital parameter inclination *i* [25].

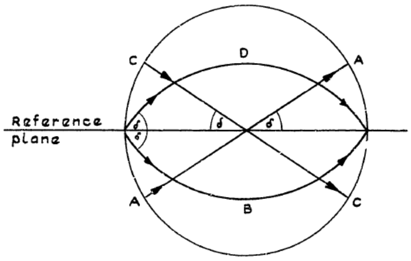


Figure 6.1.6: Definition of the inclination δ. Extracted from [25]

- The ascending nodes of the orbits are equally spaced across the full 2π (360° of longitude) at intervals of:

$$\Delta\Omega = \frac{2\pi}{P} \tag{6.1.3}$$

- The position of the satellites in different orbital planes is measured through the factor *F*. When a satellite is at its ascending node, a satellite in the most easterly adjacent plane has covered a relative phase difference *F*, and a real phase difference of:

$$\Delta\Phi = F\frac{2\pi}{P} \tag{6.1.4}$$

In order to have the same phase difference between all orbital planes, *F* is defined as an integer, which may have any value from 0 to (P-1).

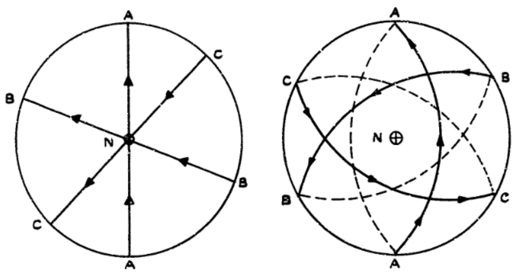


Figure 6.1.7: Comparison of a polar constellation and a delta pattern seen from the North Pole. Extracted from [26]

With these characteristics, delta constellations are more complex than polar constellations. Because of the inclination of the orbits, the ascending and descending planes and the coverage of the satellites continuously overlap. This characteristic is a constraint on intersatellite networking because the relative velocities between satellites in different orbital planes are larger than in a polar constellation. Consequently, tracking requirements and Doppler shift are increased [**?**].

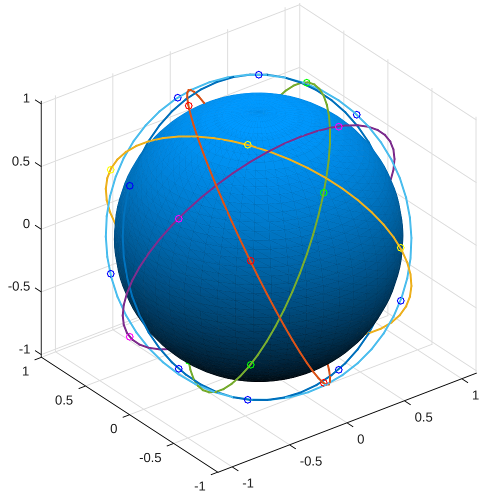


Figure 6.1.8: Delta pattern 65°: 30/6/1

The notation and coverage of this kind of constellations is developed in Annex REF TO ANNEX NOTATION SECTION ORBITAL DESIGN and annex REF TO ANNEX COVERAGE SECTION ORBITAL DESIGN.

Custom Walker Delta Configuration

In order to reduce the necessary costs to design this satellite-based constellation, some other configurations have been discussed. The Walker Delta Configuration (WDC) represents the most general constellation for a given inclination different to 90 degrees, i.e. 75 degrees. The WDC is a uniform based 360 degree generated configuration with equidistant orbits, which implies a certain redundant Earth coverage as described in the previous chapter. However, this can be solved by generating a 180 degree constellation - Semi Walker Delta Configuration (SWDC) - which can also fulfill global coverage although having some inconvenients. One of these inconvenients is the fact that a gap is obtained, as it is discussed in Annex REF TO ANNEX SEMI WALKER DELTA CONSTELLATION SECTION ORBITAL DESIGN.

To avoid the gap, adding planes to the SWDC can be contemplated. In result, different configurations distributed around the Earth can be described and set in order to fulfill global coverage. As discussed before, the SWDC constellation is generated around 180 degrees whereas the Walker Delta Constellation is a 360 degree generated configuration. This Mixed Walker Delta (MWDC) is the result of adding some planes to the SWDC, thus a constellation can be generated for different degree values, such as 200, 225, 240, etc.

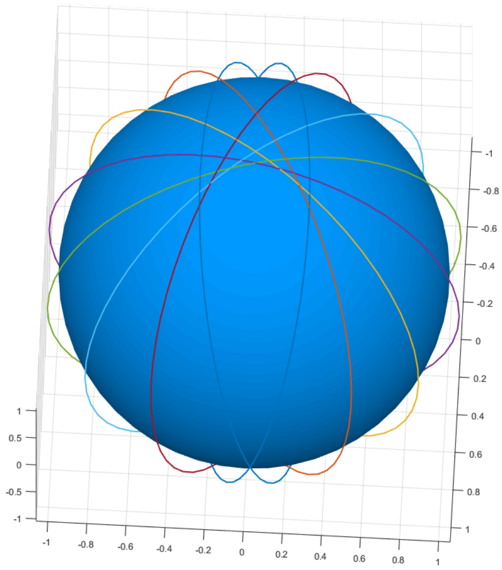


Figure 6.1.9: 8 plane based MWDC generated for 210 degrees

6.1.2.3 Testing Method

To design Astrea constellation the orbit parameters must be decided following the established requirements. As seen in the previous sections, there are different types of constellation that must be considered when selecting those parameters. The main requirement in the bases of this chapter is to fulfill global coverage of the Earth. Therefore all the possibles solutions have to be tested to ensure they pass this specification.

Method Bases and Results

The method consist in evaluating all the possible combinations between the variables listed in the table 6.1.1 within established margins and testing them to know if they fulfill the determined conditions than ensures global coverage. The conditions considered to asses this global coverage and the details of the method can be reviewed in [REF TO ANNEX I. Section 3.4].

typeC	Type of constellation	in	Inclination angle [°]
ε	Elevation angle [°]	n_p	Number of Planes
h	Height [km]	N_{pp}	Number of Satellites per plane

Table 6.1.1: Coverage Testing Method main Variables

A MATLAB routine has been developed (see details in the same attachment) to see the evolution of a satellite network configuration regarding the variation of the orbital parameters. With this code, the optimum configuration can be obtained given the chosen requirements. The configurations that will be later considered to perform an analysis of weighted parameters are extracted from this routine.

To visually check the coverage obtained, the ground track of three of them had been plotted. The figure 6.1.10 shows one of them, the others can be found in the [REF TO ANNEX I. Section 2.4].

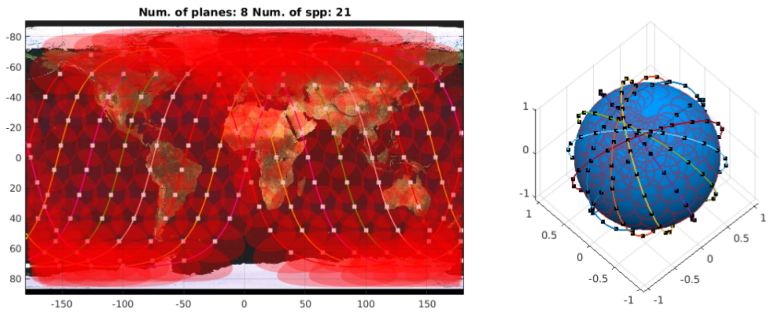


Figure 6.1.10: Ground track and spherical representation for a 210° Walker Delta configuration

6.1.3 Perturbations

6.1.3.1 Sources of Perturbation

Introduction to Orbit Perturbations [24]

In this chapter it is seen how the designed orbit configuration varies in time due to external perturbation sources. While some of them can be neglected, there are other of major importance to the future of the constellation.

Even though most of the outter space is vacuum, the ideal models need to consider some factors that escape the typical two body problem. To enumerate, here is a typical list of the main perturbation sources:

- **Gravity Field of the Central Body:** due to the Earth's aspherical shape as seen in [REF TO ANNEX I.Section 4.1.2]. This perturbation will not be considered because it does not affect Astrea's constellations as shown in [REF TO ANNEX I.Section 4.3.1]
- **Atmospheric Drag:** It is the perturbation caused by the remaining atmosphere. The study of the satellites orbit decay can be found in [REF TO ANNEX I.Section 4.3.3].

Even so, this effect is not taken into account because the satellites are equipped with thrusters.

- **Third Body perturbations:** Perturbation computed in [REF TO ANNEX I.Section 4.1.4]
- **Solar-Radiation Pressure:** Explained in [REF TO ANNEX I.Section 4.3.2]
- **Other Perturbations**

6.1.3.2 Significant Perturbations

Algorithm

Given the definitions and approximations to compute perturbations described in the previous section, a propagation in time for the change in orbital parameters is solved. The results are plotted in the graph below:

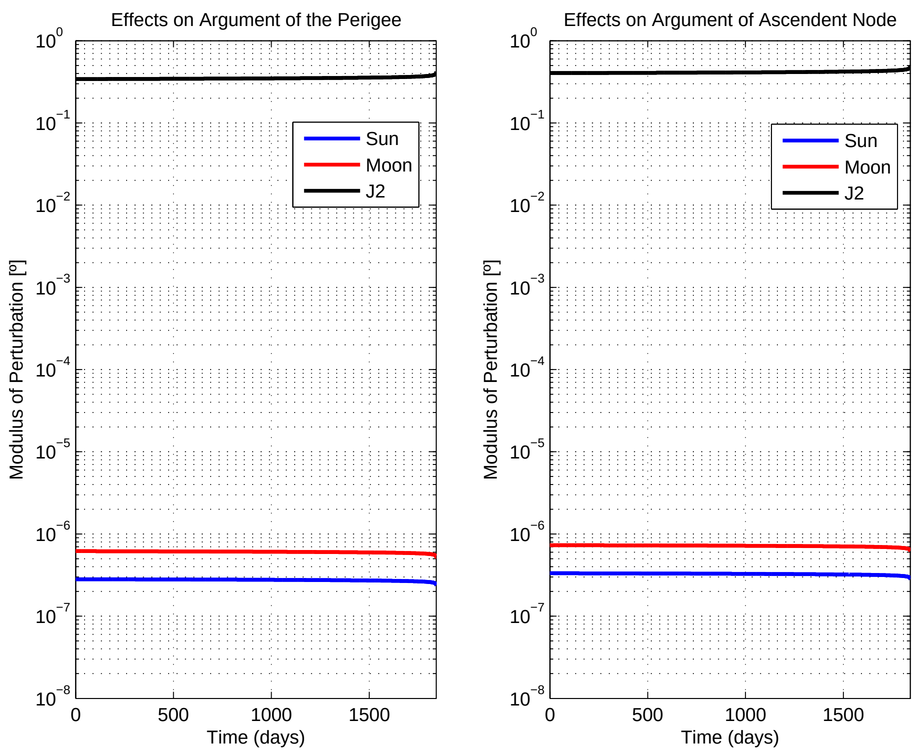


Figure 6.1.11: Logaritmic plot of the modulus of the increases in Angular Arguments of the orbit

As it can be seen, the perturbations caused by 3rd bodies are several orders of magnitude below the order of magnitude of the variation caused by Earth's oblateness. It is also remarkable that the moon has a higher effect than the sun given the relative distance to Earth, even if the sun is way more massive.

Another important observation is that given the very low eccentricity being considered, the deviation of the argument of the perigee does not affect the performance of the constellation. In other words, since the orbits are considered almost circular there is not a defined Perigee for the orbit.

Conclusion

The effects of the Moon and the Sun are neglected in comparison with the effects of J2 for the Argument of the ascendent node as well as for the argument of the Perigee.

6.1.3.3 Orbital Station-Keeping

One of the main problems of putting a satellite in a low Earth orbit, is that its lifetime is very reduced. The easiest way to solve this problem would be increasing the height of the orbit, as it is discussed on the Annex REF TO ANNEX ORBIT DESIGN SECTION RAISING THE ORBIT HEIGHT TO INCREASE LIFETIME. However, there is another proposal that is useful for Astrea Constellation.

Using Thrusters to increase Lifetime

In order to maintain the configuration of the constellation for a longer time, a thruster is installed in each satellite to correct the decrease in altitude due to the orbit decay. To maintain the altitude the thruster will apply a velocity increment to the satellite to change its orbit and, consequently, its altitude. This is a maneuver. It can be an impulsive maneuver, in which the velocity increment is added instantaneously, or non-impulsive, in which ΔV is applied during a significant amount of time. The optimal maneuver is an impulsive one, the Hohmann transfer, a single-impulse maneuver. Hohmann has the best relation between propellant consumed and time required to do the maneuver. However, non-impulsive maneuvers like low-thrust maneuver require lower velocity increments and are less propellant-consuming.

To maintain the altitude, Astrea satellites will compute a low-thrust maneuver. However, since this is a preliminar study, the calculations will be computed for a Hohmann transfer maneuver, which is simpler and requires more propellant and greater increases of velocity. That is, by computing the velocity and propellant needed for a Hohmann maneuver, the results will be safe for a low-trust maneuver, because the late one requires less energy.

Orbit maintenance

The method proposed begins when the satellite is deployed at a given height. This height will decrease due to the orbit decay, reaching a critical value, a limit altitude. Once this critical altitude is achieved, the satellite is put once again at its initial height through a Hohmann maneuver. The process is repeated several times until the satellite runs out of propellant or until it reaches its desired lifetime. All the calculations needed are developed in Annex REF TO ANNEX ORBIT DESIGN SECTION USING THRUSTERS TO INCREASE LIFETIME.

As mentioned before, in reality the satellite will perform a low-thrust maneuver, which is more practical for an electric thruster. In this non-impulsive maneuver, the thruster is constantly providing a velocity increment to the satellite, but it is so small that the whole transfer maneuver requires a lot of time. This means that it is not necessary to wait until the satellite reaches the critical altitude. The maneuver will start when the satellite is deployed or when it reaches a given altitude (higher than the critical altitude) so that it counteracts the effect of the orbital decay.

Results

The results are computed for a 3U CubeSat with an ion thruster. The characteristics of the thruster are the ones shown on table 6.1.2. For more information on the thruster refer to section 6.2.3.

Thrust	100 μN
Specific Impulse	2150 s

Table 6.1.2: Simulation Thruster Parameters

The first parameters to be defined are the maximum and minimum height of the orbit, mesured from the surface of the Earth. The maximum height is the altitude at which the satellite is deployed, and minimum height is the altitude at which the Hohmann transfer maneuver is applied.

Figure 6.1.12 is an example of the height variation of the satellite using the Hohmann maneuver to reach the maximum height once the satellite is in the minimum height. The results of this maneuver are:

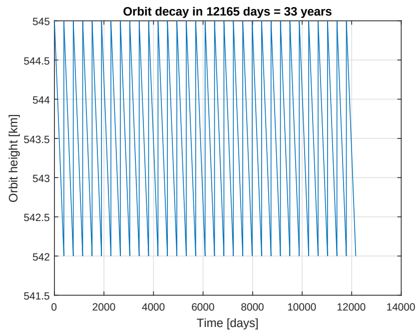


Figure 6.1.12: Height variation of the satellite

Maximum height	545 km
Minimum height	542 km
Number of Hohmann Maneuvers	32
Maximum ΔV_1	0,8237 m/s
Maximum ΔV_2	0,8236 m/s
Total ΔV Budget	52,7116 m/s
Propellant mass	10 g
Lifetime of the satellite	33,3288 years

Table 6.1.3: Station-Keeping with Thrusters Simulation 1 Results

Since the thruster used is an ion thruster, the specific impulse is big, and the mass propellant is very low. In this case, the variation of height due to the orbit decay is approximately 3 km per year, so the thruster needs to do a Hohmann maneuver per year. With only 10 g of propellant, the lifetime of the satellite is over 30 years.

Figure 6.1.13 is another example of the Hohmann maneuver with the same amount of propellant but with a more restrictive range of operational heights, only 80 m. It should have the same shape as Figure 6.1.12, but since a lot of maneuvers are applied, the lines have overlapped. The characteristics of this maneuver are:

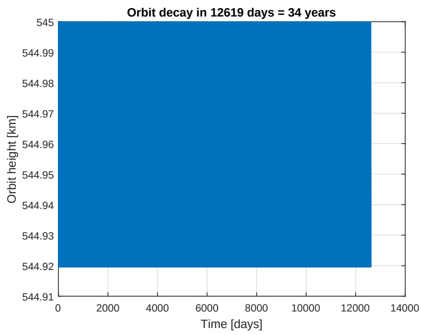


Figure 6.1.13: Height variation of the satellite with a more restrictive minimum height

Maximum height	545 km
Minimum height	544,92 km
Number of Hohmann Maneuvers	1200
Maximum ΔV_1	0,0221 m/s
Maximum ΔV_2	0,0221 m/s
Total ΔV Budget	52,7570 m/s
Propellant mass	10 g
Lifetime of the satellite	34,5726 years

Table 6.1.4: Station-Keeping with Thrusters Simulation 2 Results

Comparing these results with the previous ones, it can be seen that with a more restrictive range of heights, the lifetime of the satellite is practically the same. The velocity increments are lower because the difference in the heights is extremely low, but at the same time, the satellite reaches before the minimum height and the number of maneuvers needed to maintain the satellite in this range are many more than on the other case. Since the ΔV budget is practically the same in both cases, it can be assured that the only difference between them is the number of maneuvers computed.

As mentioned earlier, the results obtained are for a Hohmann maneuver when in reality the satellite will compute a low-thrust maneuver, that requires less velocity increments and less propellant. In conclusion, taking into account these results, it can be stated that the lifetime of the satellite will not be determined by its orbit decay but for the failure of its systems or other external causes. It can also be assured that the satellite is capable of carrying enough propellant to maintain its altitude and to compute other maneuvers if necessary.

6.1.4 Constellation Design Decision

6.1.4.1 Considered Designs

Introduction

In this chapter it is seen how the final constellation decision is made. To do that an analysis of weights will be performed.

The constellation candidates selected to their later evaluation are the following:

Candidate 1: Polar - Global Coverage

This polar constellation (Figure 6.1.14) came from the street coverage method explained in 6.1.2.1. It is a network of polar orbits that provides global coverage. This constellation is generated as follows:

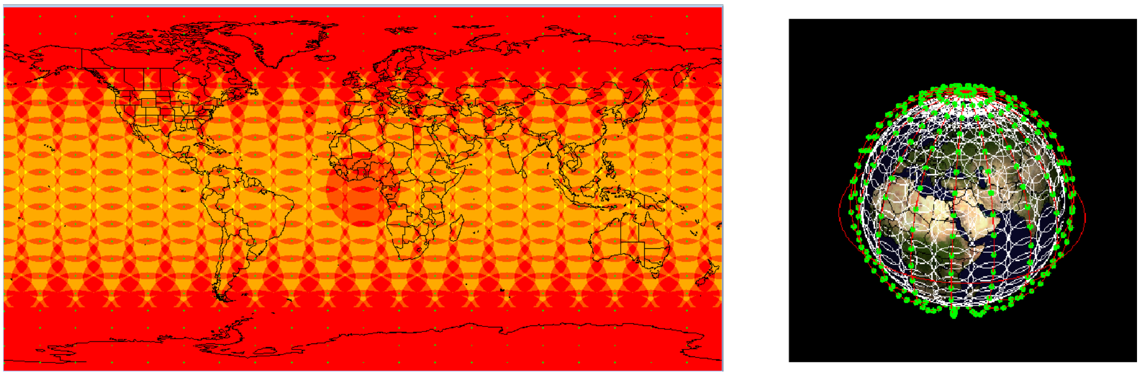
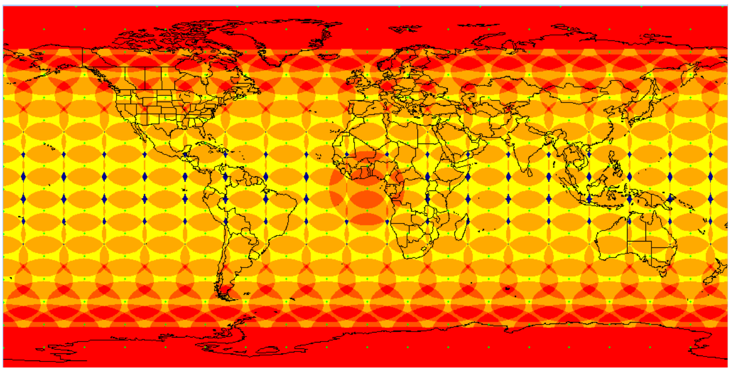


Figure 6.1.14: Candidate 1. Full Polar constellation with global coverage. h= 560km; Np=20; Npp=21; Tsat=420

Candidate 2: Polar - GS Coverage

The second candidate that will be compared is a polar orbit extracted from the coverage method explained in 6.1.2.1 (Figure 6.1.15). This constellation provides total coverage to the Astrea's team ground stations. The constellation distribution is set as follows:



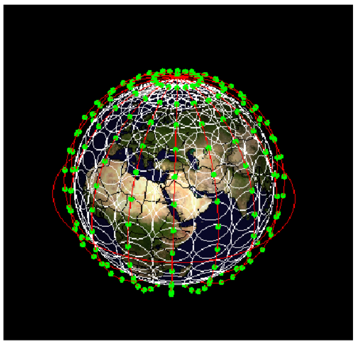


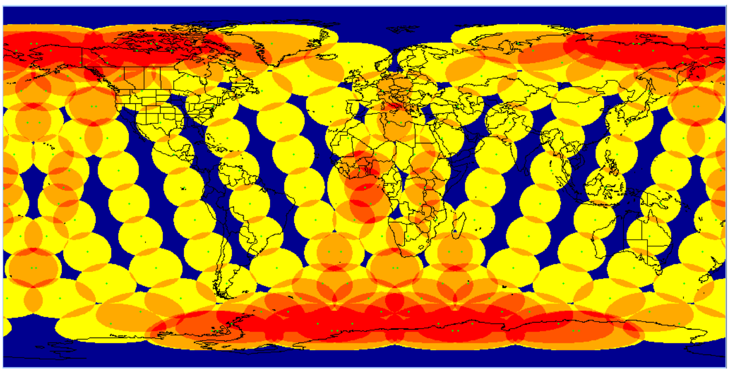
Figure 6.1.15: Candidate 2. Full Polar constellation with total ground station coverage. h= 550km; Np=18; Npp=20; Tsat=288

Candidate 3 and 4: Walker-Delta GS Coverage

Two Walker-Delta constellation configurations have been also chosen due to their reduced number of planes and satellites while being able of providing total coverage on the lattitudes where the ground stations are located.(Figures 6.1.16 and 6.1.17).

These constellations have been obtained with the algorithm explained in 6.1.2.3. The distribution of these constellations is described below:

Candidate 3



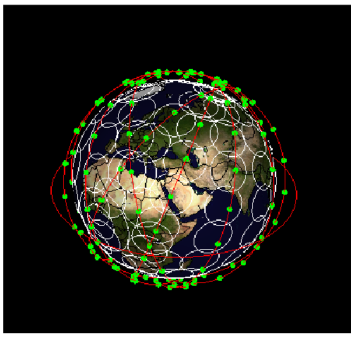


Figure 6.1.16: Candidate 3. 210° Walker-Delta constellation configuration. h= 542km; in=72; Np=8; Npp=21; Tsat=168

Candidate 4

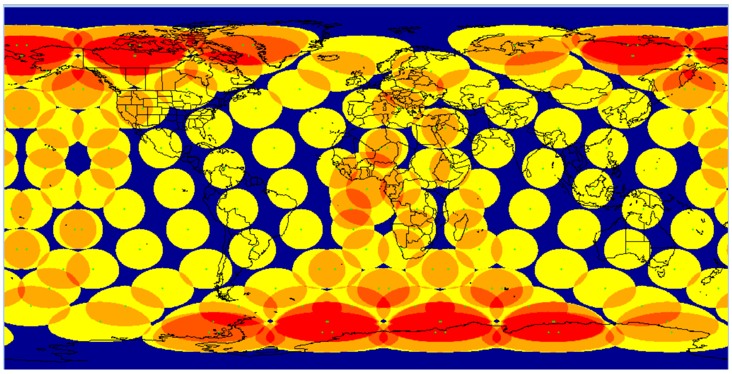
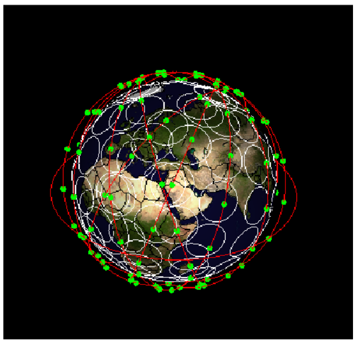
 

Figure 6.1.17: Candidate 4. 225° Walker-Delta constellation configuration. h= 542km; in=72; Np=9; Npp=17; Tsat= 153

Candidate 5: Walker-Delta Lat: 0-58

Another Walker-Delta constellation has been selected with the criteria of total coverage of a range of lattitudes going from 0 to 58 (Figure 6.1.18). Therefore, the distribution needed to fulfill this particular condition of the constellation obtained from 6.1.4.2 is the following:

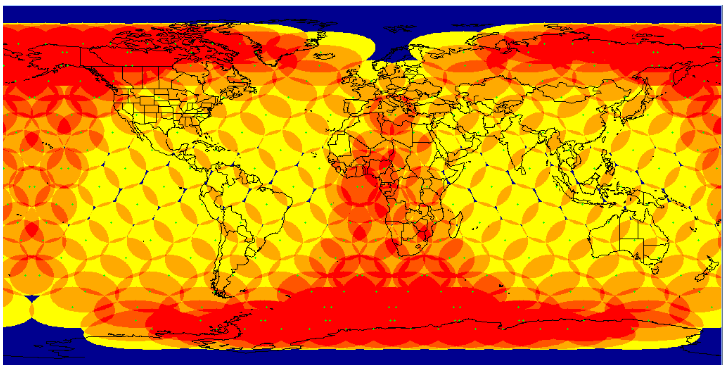
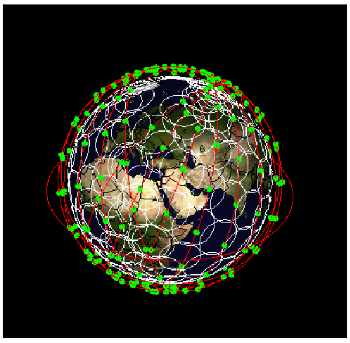
 

Figure 6.1.18: Candidate 5. 210° Walker-Delta constellation configuration with total coverage of the lattitudes from 0 to 52 degrees. h= 560km; in=72; Np=14; Npp=19; Tsat= 226

Candidate 6: Walker-Delta J2 + Rotació

With the goal of providing constant coverage at the Ground Stations a constellation that takes profit of the rotation of the Earth can be designed. If Earth's oblateness that causes another Ω variation is also considered, the longitudinal position of a plane after an orbit has passed can be computed. Now, if the constellation is designed in a way that this deviation after an orbit matches the separation between planes, a line of satellites will always be on the GS. (Figure 6.1.19)

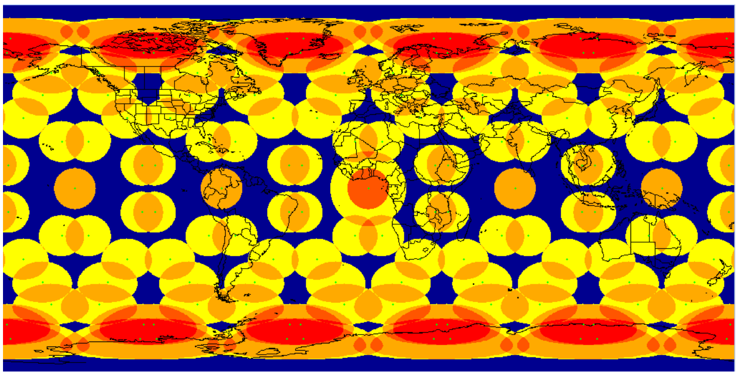
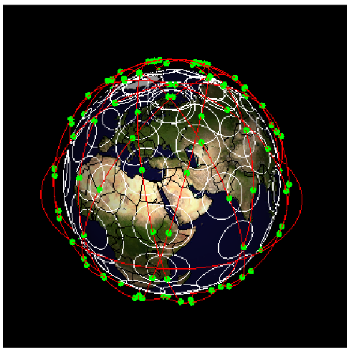



Figure 6.1.19: Candidate 6. 225° Walker-Delta constellation configuration. h= 542km; in=72; Np=14; Npp=19; Tsat= 226

Candidate 7: Walker-Delta GS Coverage 3

The last configuration to be studied is a Walker-Delta constellation configuration designed to provide total coverage to the ground stations (Figure 6.1.20). It came up from candidate 3 constellation adding one more plane in order to increase its global coverage and minimize the gaps. As can be seen below, its parameters are the same as candidate 3 adding an extra plane.

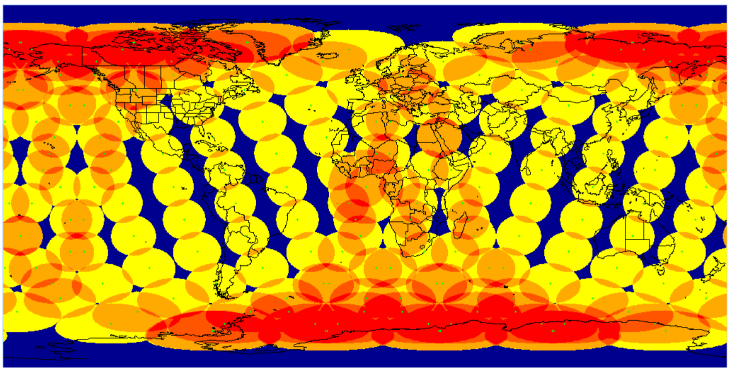
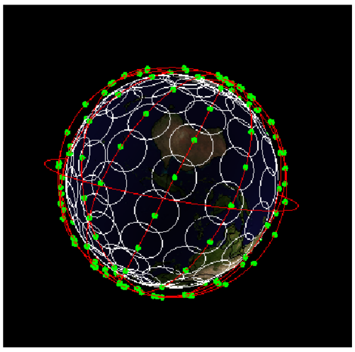



Figure 6.1.20: Candidate 7. Full Walker-Delta constellation configuration.h= 542km; in=72; Np=9; Npp=21; Tsat= 189

Final candidate constellation paramater comparison.

The different parameters for the 7 candidate constellations are defined in table 6.1.5. These are essential in order to compute further calculations regarding the final constellation design.

Candidates	1	2	3	4	5	6	7
Height of the satellites(km)	560	550	542	542	560	542	542
Inclinations of the plane (deg)	90	90	72	72	72	72	72
Number of planes	20	18	8	9	14	14	9
Satellites per plane	21	16	21	17	19	19	21
Total number of satellites	420	288	168	153	226	226	189
Range of argument of ascending node(deg)	360	360	210	225	210	210	225

Table 6.1.5: Key parameters of the different candidate constellations

6.1.4.2 Constellation Performance Analysis

Even though the design requirements are included in the computation of the different configurations, it is necessary to evaluate how does the constellation perform when deployed. With this purpose, another MATLAB routine was developed.

Time factor It is important to remark that the design methods used so far did not consider coverage in a certain period of time, but the coverage at a given instant. This section summarizes a method to compute this variation.

Quality Time Another factor that was not considered in the design process was the pass times of the satellites. If a pass is too short the contact with the satellite cannot be produced.

Performance Evaluation In order to determine if the performance of the Constellation is good enough and to compare different constellations, the following parameters that are to be used in the weighted ordered average decision6.1.8 are defined.

Simulation parameters important to clarify:

- Simulation time: 25h. This time is enough to observe the motion of the whole constellation on Earth considering its rotation and the rotation of the plains due to the Earth's oblateness.
- Minimum contact time: 3 minutes. Time enough to download data, tracking and Telecommanding the satellite.
- Time precision: 10 seconds. It is empirically observed to be precise enough.

The computed parameters:

- Fraction of time with flybys on the GS: Ratio between the time in which there is any satellite in the field of view of the Ground Station and the total simulation time. (Referred in table 6.1.8 as % Coverage)

- Mean number of links with the satellite

- Fraction of time with flybys longer than 3 minutes: In this case the ratio is with the time in which there is a satellite doing a useful pass, since a full contact can be done. (Referred in table 6.1.8 as %Quality Time)

- Mean pass time: This parameter is used to guarantee a minimum of quality and to compare different configurations. (Referred in table 6.1.8 as Average Pass Time)

- Number of gaps: Gaps are in this chapter defined as periods of time without a pass that is lasting/will last more than 3 minutes. (Referred in table 6.1.8 as Num Gaps)

- Maximum gap time: At high latitudes all the Walker-Delta configurations show a characteristic gap that can last even for hours, which is not admissible. This parameter will tell if a maximum defined as 3 minutes for this study is exceeded. (Referred in table 6.1.8 as Max Gap Time)

- Mean gap time: As it is obvious, a minimum or a 0 is desired.

You can find below an example of the analysis, for a constellation in a Semi Walker-Delta configuration.

Constellation	Full WD
Number of Planes	$p = 8$
Satellites per plane	$spp = 18$
Inclination	$i = 75°$
GS Latitude	$\lambda = 80°$
GS Longitude	$\phi = 0°$

Table 6.1.6: Constellation parameters for the Example Constellation

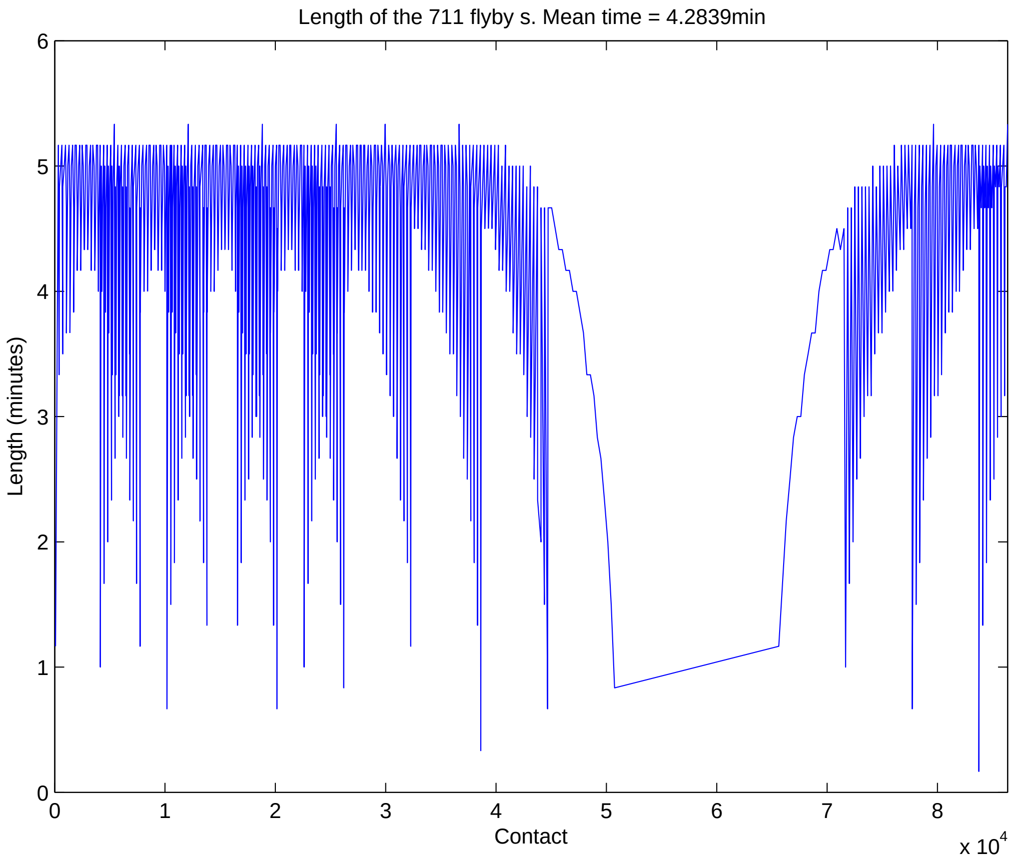


Figure 6.1.21: Length of the passes on the example GS.

Pass Time Ratio	77.53%
Quality Time Ratio	75.77%
Mean Pass Time	$4.28min$
Number of gaps	37
Maximum Gap Time	$314.33min$

Table 6.1.7: Performance Parameters for the Example Constellation

Given the high latitude of the Ground Station plus the Semi Walker-Delta Configuration there is an enormous gap. In addition, between planes some gaps are also observed.

6.1.4.3 Ordered Weighting Average based Decision

The Described Constellations are weighted and averaged in the table below. The detailed explanation of the parameters can be found in 6.1.4.2:

		Candidates						
Criteria	W	1	2	3	4	5	6	7
Price	15	1	2.35	5	4.94	3.21	3.92	4.67
% Coverage	4	5	4.77	2.94	2.14	4.43	1	3.86
Max Gap Time	3	3.12	3.62	1	2.88	3.51	5	4.75
%Quality time	5	4.91	4.49	4.05	1	3.19	5	4.98
Average Pass Time	5	1.21	1.14	1.14	1	1.90	5	4.72
Num Gaps	2	4.73	4.44	4.23	1	3.03	4.99	5
% Sats above	6	1	1	5	5	1	5	5
SUM (p*g)	40	90.42	108.17	154.19	133.29	113.94	167.71	188.21
OWA		0.452	0.541	0.771	0.666	0.570	0.838	0.941

Table 6.1.8: Constellation Configuration OWA Decision

With this comparison table, the optimum Constellation is option number 7:

The Astrea Constellation

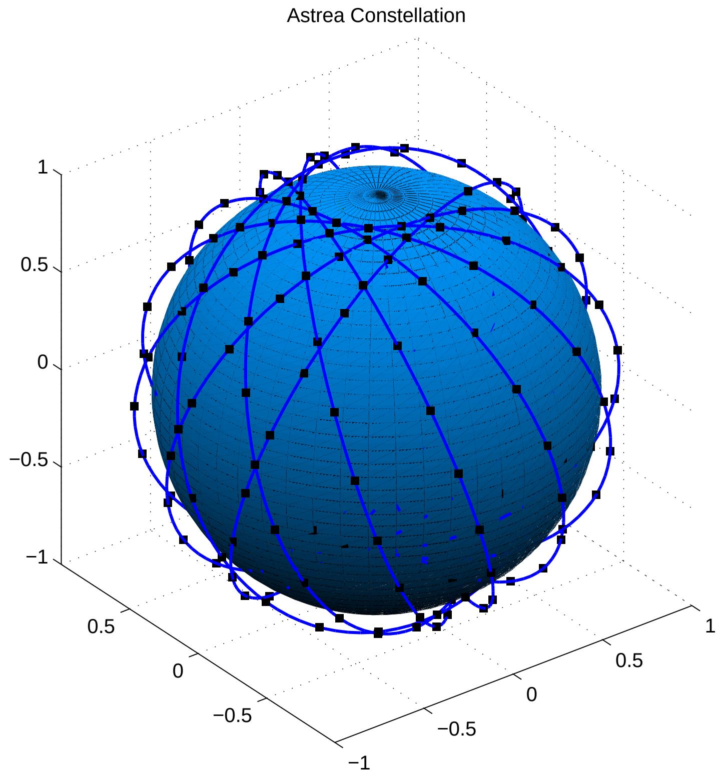


Figure 6.1.22: Astrea Constellation Final Configuration.

6.2 Space Segment Systems. Satellite Design

6.2.1 Structure and mechanics

The design and operation of a CubeSat is a complex process that must be completed keeping in mind the huge differences between all 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). Their correct functioning has to be ensured, especially the critical systems such as the solar arrays, batteries and antennas should be fully operational for at least four years.

6.2.1.1 Structure

The mission of the structure is to sustain and protect all the electronic devices carried by the satellite. In order to ensure that all the electronic and mechanical systems can be mounted upon the structure, a high compatibility between these systems is required; therefore, the structure must be very 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 -40°C to 80°C) 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. [REF TO ANNEX IV. Section 1.1.1]

6.2.1.2 Thermal protection

The CubeSat is vulnerable to suffer extreme temperatures while operating in space, both below zero and above zero. The thermal protection system consists of a set of layers (MLI) made of insulating materials and it aims 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. Furthermore, the thermal protection system should also dissipate the heat produced by the other systems.

Dunmore Aerospace has been chosen to provide us its MLI product. The product, **Dunmore**

Aerospace Satkit, has been designed for small satellites operating in LEO and it will provide the CubeSat with the protection required during operation. [REF TO ANNEX IV. Section 1.1.2]

6.2.1.3 Options chosen for the structure and thermal protection

The options chosen are presented in the table 6.2.1.

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

Table 6.2.1: Options chosen for the structure and thermal protection

6.2.2 Electrical Power System

The Electrical Power System (EPS) of the satellite must provide and manage the energy generated efficiently in order to have all the systems operating under typical conditions during the lifetime of the mission. The role of this system is to control and distribute continuous power to the Cubesat, to protect the satellite against electrical bus failiures and to monitor and communicate the status of the EPS to the on-board computer. The EPS of the Cubesat is, probably, the most fundamental requirement of the satellite, since its failure would result in a mission failure.

6.2.2.1 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 total power required is 52W and it has been estimated considering that all the subsystems are working under typical working conditions. [REF TO ANNEX IV. Section 1.2.2]

6.2.2.2 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 fully efficient for at least four years (this is: it has to be ensured that the missions does not run out of power for at least four years).

Every cubesat will come with at least 4 deployable solar panels (manufactured by **EXA-Agencia Espacial Civil Ecuatoriana** providing it with 67.2W of power, approximately, to supply peak demands. Note that these 4 deployable solar panels are a basic requirement. If more space is available on the faces of the satellite, additional panels can be placed providing extra power. [REF TO ANNEX IV. Section 1.2.3]

6.2.2.3 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 these systems have different power and energy needs, the power management system has to be highly compatible and must have a high enough number of buses to supply the different voltage and intensity required to the systems. [REF TO ANNEX IV. Section 1.2.4]

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 and saving a lot of space.

6.2.2.4 Batteries

The role of the batteries is to provide the subsystems of the satellite 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 higher* than typical energy and power supply, since all the systems will not usually operate under peak conditions. [REF TO ANNEX IV. Section 1.2.5]

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.

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. If the satellite was in the dark during half of the period of the orbit, the estimated energy that it would need would be 50Wh. Thereby, the capacity of the batteries is more than enough to supply the energy required in the worst case scenario. Furthermore, 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.

6.2.2.5 Options chosen for the EPS

Finally, the options chosen are presented in the table 6.2.2.

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 6.2.2: Options studied for the Electric Power System

6.2.3 Propulsion Systems

The propulsion system is an important part of the satellite given the needs of the satellite to perform different maneuvers, such as reach the desired orbit after it has been deployed from the rocket, and to maintain the orbit and avoid falling into the Earth. The main parameters that have to be consider are thrust, total specific impulse, power required, weight of the propulsion system and its volume, since the size and weight of the CubeSat are very restrictive. [REF TO ANNEX IV. Section 1.3]

At the moment, the most used and modern thrusters for small 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 imply smaller accelerations than conventional propulsion systems.

The **BGT-X5**, a green monopropellant propulsion system, has been chosen as the thruster for the CubeSat. The high thrust and delta V that BGT-X5 provides (146 m/s) complies with the requirements explained in [REF TO ANNEX Const. Deployment] and they have predominated at expenses of other variables as weight or specific impulse where others options were better. With this thruster 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. [REF TO ANNEX IV. Section 1.3]

The option chosen is presented in the table below 6.2.3.

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

Table 6.2.3: Option chosen for the propulsion system

6.2.4 Attitude and Orbital Control Systems

The attitude and orbital control system (AOCS) 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 the 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 different sensors. The AOCS can also be referred as the 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 to 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 [16].

Pointing to 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 [16].

6.2.4.1 Orbital Control

Orbital control will be achieved as a combination of two systems. ADCS will orient the thrust (given by the propulsion system) and the operation will be controlled by the on-board computer. Mainly, the orbit control will be necessary to mitigate orbital debris effect on every satellite.

Taking into account several very restrictive variables: 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 and integrates also and On-Board Computer (OBC). [REF TO ANNEX IV. Section 1.1.1]

Finally, the options chosen are presented in the table 6.2.4.

System	Brand and model	Price per unit (€)	N. of units
ACDS	CUBE ADCS	15000	1

Table 6.2.4: Options studied for the AOCDS

6.2.5 Payload

The payload needs to provide a radio link with the client's satellite(s) for real time data relay with no less than 25MB/s of data rate. For achieving its purpose, the payload will consist on a pack of arrays of antennas and data handling computers.

The CubeSat will 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 used to establish the previous described links are regulated in [22] by frequency, bandwidth and type of communication . So, for the **Space to Ground link** frequencies from **70MHz** to **240GHz** will be used; 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, for **Client Space to Space link**, two cases exist; on the one hand, if the client points towards the Earth like a standard satellite, its signal is captured by a constellation satellite that acts as the data relay, since it is like a Space to Ground communication and also like a inter-satellite communication, the two previous restrictions can be combined. On the other hand, if the client satellite is below the constellation, only inter-satellite communication are avaiable, therefore **Inter-satellite Space to Space link** rules are applied.

6.2.5.0.1 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.

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. [1]

The antenna that will be equipped in the CubeSat is the patch antenna manufactured by **AntDevCov**. The satellite will come with 8 of this type of antenna; 4 of them will be placed on each side face of the CubeSat and they will occupy a 1U face and the other 4 of them will be placed on the top and the bottom.

6.2.5.0.2 Payload Data Handling Systems

Every satellite 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 nor 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 (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. The PDHS has a hard disk associated which will temporally store the client data.

The PDHS selected for the mission is the **Nanomind Z7000** because its two 667MHz processors can handle a high data payloads and processit at a high velocity velocities, reducing in last term delay between communications.

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 of several factors: the use in

The **NanoCom TR-600** by **GOMspace** has been selected as the inner-satellite tranceiver since its manufacturer offers it in combination with the **NanoMind Z7000**. 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 make it a great choice for Inter-Satellite communication.

The **SWIFT-XTS** has been selected as the space-to-ground transceiver. Its high bandwidth will make possible higher communication data rates.

6.2.5.0.3 Options chosen for the payload module

Finally, with the aim to clarify all the information of this section, the chosen systems and components are presented in the table 6.2.5.

System	Brand and model	Price per unit (€)	N. of units
Antenna	Patch antenna AntDevCo	18000 1st (7000 others)	8
Transceiver	NanoCom TR-600	8545	3
Transceiver	SWIFT-XTS	5500	1
PDHS	NanoMind Z7000	5000	1

Table 6.2.5: Options chosen for the payload

6.2.6 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 CubeSat 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 performed with a NanoCom TR-600 transceiver module attached to AntDevCo Patch antenna, both configured for S band frequency communication.

6.2.7 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**	**100 x 100 x 243**	

Is important to mention that, AstreaSAT neither exceeds the maximum weight of 4 kg or modules dimensions 100 x 100 x 300.

Additional information regarding the systems used in the CubeSat and the final configuration, calculations and decision taking can be found on the appendix.

6.2.8 Budget

System	Cost/unit (€)	Total cost (€)	N. of units
Structure and mechanics			
Structure	3900	3900	1
Thermal protection	1000	1000	1
Total		4900	
Electrical 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	50000	50000	1
ADACS	15000	15000	1
Total		65000	
Total CubeSat		276635	
Total estimation CubeSat		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 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 (such as the purchase of additional solar arrays), is added to every satellite. Furthermore, this extra 20000€ includes the costs of transport to launch site. The payload's variable expenses stand for cable, adaptors and several minor components that have to be purchased.

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 *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.

6.3 Ground Segment Systems

6.3.1 Introduction

The Ground Segment 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 is composed of Ground Stations (GS) and the Mission Control Centre (MCC) 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 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: building or renting 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. First of all, a study about building the Ground Segment will we done, analyzing the location of the GS and the MCC, the legal aspect, the costs and maintenance, and the initial investment necessary to build them. After that, an analysis about renting GS will take place. Finally, a decision will be made.

6.3.2 Localization of the Ground Stations

The place where the Ground Stations would be placed has to be studied in order to obtain maximum performance 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 latitude will 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.

6.3.2.1 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.

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. The code used can be found in [REF TO ANNEX VI. Section 14], while the study of localization can be found in [REF TO ANNEX III. Chapter 9. Section 1].

6.3.2.2 Conclusion

To summarize the results of the analysis, for an optimum performance of every Ground Station, they should be located at latitudes between -62.5° and -57.5° or between +57.5° and +62.5°. For a better performance of the system every Ground Station should be 120° of longitude away of the other GSs if they 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 6.3.1: 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.

For the Mission Control Centre, as it does not communicate with any satellite, it has no restrictions on where to build it. It is decided that it will build in Terrassa, since ESEIAAT is located there and it holds the headquarters of the UPC Space Program.

6.3.3 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 ease 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.

6.3.3.1 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 [20]. The fees can be obtained from [2] and [11]. The frequency allocation can be found in [19].

6.3.3.2 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 [4]. The fees might be estimated using [5].

6.3.4 Annual costs

6.3.4.1 Annual costs: Ground Stations and Mission Control Center

In order to know the cost that involves having three Ground Station and a Mission Control Centre always operative, an economical study will be done. In this study, parameters such as salaries, electricity and internet services will be taken into account, among othes. This study canbe found in [REF TO ANNEX III. Chapter 9. Section 2].

From this study, the following results are obtained:

- Annual cost of the three Ground Stations: 770,000€
- Annual cost of the Mission Control Centre: 460,000€
- Annual cost of the whole Ground Segment: 1,200,000€

6.3.5 Initial investment

6.3.5.1 Description of the systems

An 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 [13] and [27].

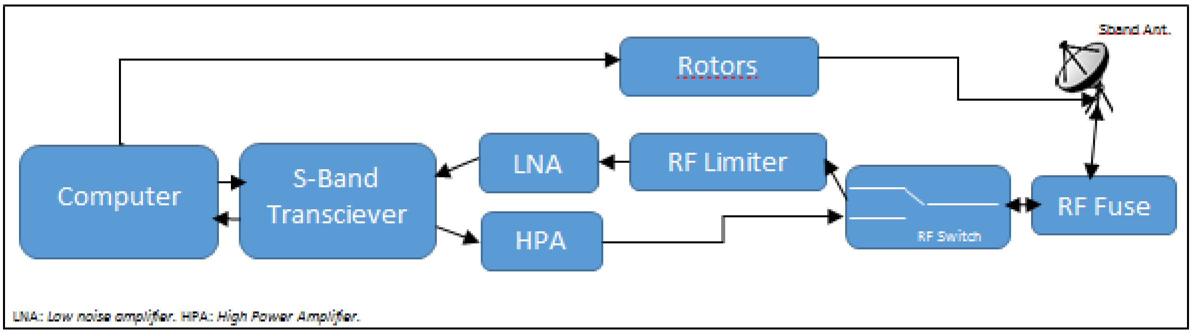


Figure 6.3.2: Equipment needed for S-band communications.

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 [9].

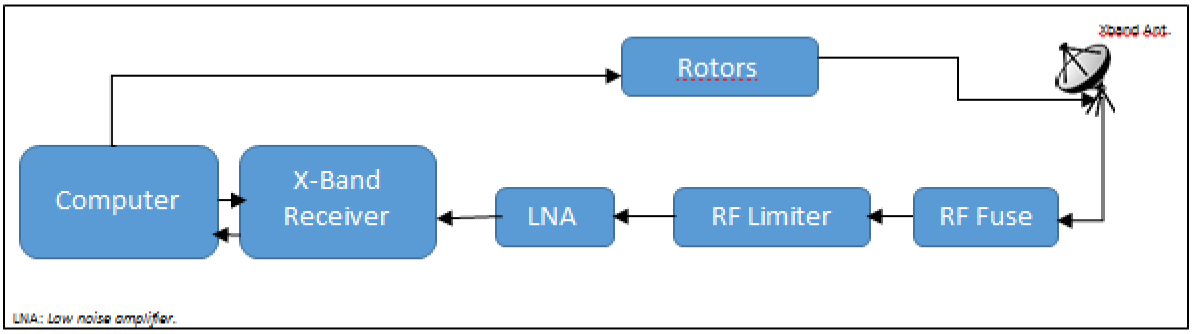


Figure 6.3.3: Equipment needed for X-band communications.

6.3.5.2 Investment

In order to calculate the initial investment necessary to build the entire Ground Segment, another economical study must be done. Same as the previous studies, this one can also be found in [REF TO ANNEX III. Chapter 9. Section 3]. The results of said study will be exposed in the following lines:

- Initial investment of one Ground Station: 356,000€
- Initial investment of the three Ground Stations: 1,070,000€
- Initial investment of the Mission Control Centre: 150,000€
- Initial investment of the whole Ground Segment: 1,220,000€

6.3.6 Renting of a Ground Station

There are a lot of ground stations spared all over the world. In [REF TO ANNEX III. Chapter 9. Section 4], a list of the most important Ground Stations and their spacifications can be found.

6.3.6.1 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.

6.3.6.2 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.

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.

Figure 6.3.4: List of planned LeafSpace Ground Stations.

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.

6.3.7 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.

The decision will be performed using an Ordered Weighted Average method (OWA) that can be found in [REF TO ANNEX III. Chapter 9. Section 5]. The conclusion of the decision process are explained in the following lines:

6.3.7.1 Decision

The results of the OWA have been the following ones:

- Building a GS: 0.83
- Renting a GS: 0.67

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

6.4 Protocol Stack

6.4.1 Space Segment

6.4.1.1 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 order to define the protocols, the standards of the Consultive Committee for Space Data Systems will be followed. The CCSDS define a set of standards that become part of ISO and enhance operatibility between different satellites. The protocols recommended by the CCSDS and the possible combinations between them are:

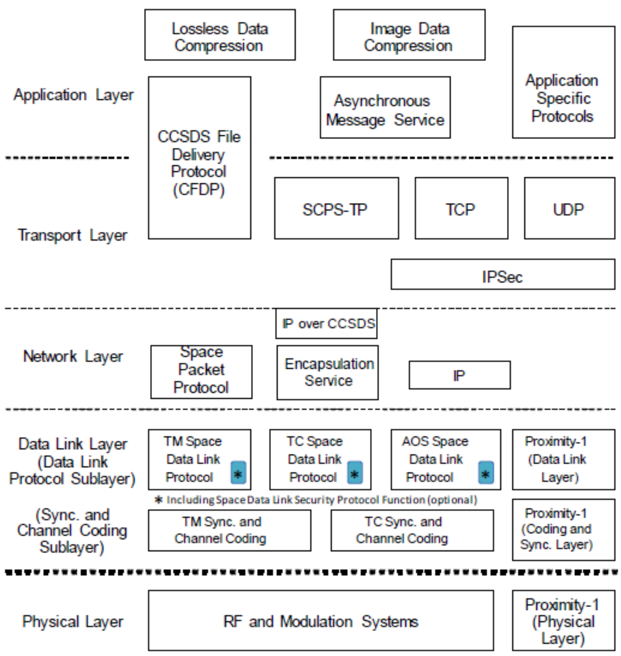


Figure 6.4.1: Protocols recommended by the CCSDS, classified in their respective OSI layer. Extracted from [6]

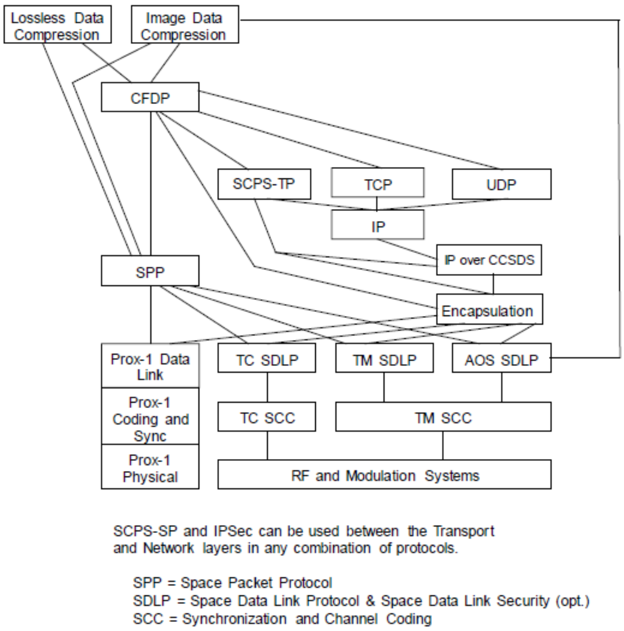


Figure 6.4.2: Possible combinations of the CCSDS recommended protocols. Extracted from [6]

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 oriented. 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.

6.4.1.2 Layer 2: Data Link

Functions of the DLL

The functions of the Data Link Layer are the following ones:[1].

- **Framing**
- **Adressing**

[1] They are explaied in [REFERENCE TO Annex II 7.1.1]

- **Synchronization**
- **Flow control**

Working procedure

There are five possible working procedures:

- Simplest Protocol
- Stop-and-Wait Protocol
- Stop-and-Wait Automatic Repeat Request
- Go-Back-N Automatic Repeat Request

They are explained in an extensive manner in [REFERENCE TO Annex II 7.1.2]. These working procedures had to be ordered according to its suitability for their application in Astrea constellation. To do so, and Ordered Weight Average (OWA) have been done. The decisive factors and its weights are:

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

Then, the results of the OWA are the following ones:

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 6.4.1: OWA of the DLL protocols.

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 [23]:

- 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.

After comparing the TC and Proximity-1 Protocols (more information at [REFERENCE TO Annex II 7.1.3]), 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.

More information about the chosen protocols such as the amount of bits occupied by the header, its configuration and total lenght can be found at [REFERENCE TO Annex II 7.1.4] and [REFERENCE TO Annex II 7.1.5].

6.4.1.3 Layer 3: The Network

Functions of the Network Layer

The Network layer provides the following functions[2]

- **Routing**
- **Network flow control**
- **Package fragmentation**
- **Logical-physical adress location**
- **Message forwarding**

Protocols

According to the CCSDS the protocols to use can be divided into three different protocols[3]

- Main protocol
- Routing protocol
- Auxiliary protocols

The possible protocols are:

- Main protocol: Space Packet Protocol (SPP), Internet Protocol version 4(IPv4) and Internet Protocol version 6(IPv6).
- Routing protocol: Enhanced Interior Gateway Routing Protocol (EIGRP), Open Shortest Path First (OSPF) and Routing Information Protocol (RIP).
- Auxiliary protocols: Encapsulation service, IP over CCSDS (IPvC), Internet Control Message Protocol (ICMP), Internet Control Message Protocol version 6(ICMPv6), Internet Group Management Protocol (IGMP), Internet Protocol Security (IPsec) and Protocol Independent Multicast (PIM).

[2]Explained in [REFERENCE TO Annex II 7.2.1]
[3]They are explained at [REFERENCE TO Annex II 7.2.2]

Protocol Selection

- **Choice of the main protocol** The choice of the main protocol will be between SPP, IPv4 and IPv6. To make the choice, is important to take into account that the Astrea constellation is a network that can be of more than two hundred satelLites, which will communicate point-to-point. Each node can be the source ,the destination or an intermediate node of a communication route. For this reason, the SPP has to be discarded, because it requires a Path ID. In Astrea constellation there are 29800 possible routes while the Path ID parameter only has 11 bits, that means that could work in a network with a maximum of 2048 routes. Between IPv4 and IPv6, is logical to choose IPv6 for its amplified benefits. Then, IPv6 will be the main protocol of the network layer. More details about this decision can be found in [REFERENCE TO Annex II 7.2.3.1].
- **Choice of routing protocol** First of all, RIP will be discarded because it has poor scalability and needs more time to converge. Then, the decision remains between EIGRP and OSPF. The difference between these two protocols is the way they update the routing table. With the EIGRP, 2000 entries are updated frequently while with OSPF, only 205 entries are needed to be updated. For this reason, OSPF is chosen. From more details about this selection, see [REFERENCE TO Annex II 7.2.3.2].
- **Choice of complementary protocols** The choice of which protocols will be included 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.

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. In [REFERENCE TO Annex II 7.2.4] the headers of the different protocols are shown.

6.4.1.4 Layer 4: Transport and Session

The objective of this layer is to provide and guarantee a reliable and cheap flow of the data. 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.

More information about the functions of the Transport Layer and of the protocols recommended by the CCSDS can be found at [REFERENCE TO Annex II 7.3].

Protocols

The protocols recommended to be used over this layer are:

- User Datagram Protocol (UDP)
- Stream Control Transmission Protocol (SCTP)
- Transmission Control Protocol (TCP)

Choice of protocol for the transport layer

The UDP 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 SCTP 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. More information had to be compiled in order to know the full suitability of it to the project. The exposition of all its parameters is not shown in this report for its large length. See [REFERENCE TO Annex II 7.3.3] for more information. As it has the required features that the project demands, it is the chosen protocol for this layer. Also, as it has been established during the deep research done, it is very recommended to use the extension SCPS, due to adaptation to space needs.

6.4.2 Ground Segment Protocols

6.4.2.1 Introduction

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.

In the following lines the characteristics of the different available protocols that can be adapted to the needs of the project are presented. More information about the suitability of them can be consulted in [REFERENCE TO Annex II 8.2].

6.4.2.2 Protocols

The protocols are the following ones:

- File Transfer Protocol (FTP)
- Secure Shell (SSH)
- Simple Mail Transfer Protocol (SMTP)
- Hypertext Transfer Protocol (HTTP)
- Transport Layer Security (TLS)
- Hypertext Transfer Protocol Secure (HTTPS)

6.4.2.3 Delivery of the data method

At first, it has to be take into 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 3 ways of working, with its advantages and drawbacks. In the following page the systems proposed are shown toguether with the decision, but in [REFERENCE TO Annex II 8.3] the advantages and drawbacks of each method are discussed in order to take the decision.

- **Web.** This system would be based in HTTP and implemented with the corresponding 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 they would sign in with an account. When the user is verified, the client could request to download information of their satellite.
- **Mail**. This method would be implemented over a SMTP with the corresponding security protocols. If the client wants to download data of his satellite, they would have to send a mail specifing the request. Then the client will receive an email with the information.
- **Application**. The idea is that the cient would operate in his computer with this software, and when they 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.

The chosen method to deliver the data is an application that would be instaled in the client's computer and where data could be extracted. This is a secure, efficient and user-friendly solution. The application will ensure a high security of the data and a robust access to it. Moreover, for the point of view of the Astrea team, the efforts in mainting a computer application are less than in other cases such as the Mail, where automatization is more difficult to implement.

This system could work with a FTP or 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.

6.5 Launcher and Deployer

6.5.1 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.

6.5.1.1 Launch site and vehicle analysis

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. A table of this seven candidates is shown in the [REF TO ANNEX 2. Section: S2-Launcher].

Once this first selection is done, more accurate information is needed so as to reach a reliable conclusion. However, none of the 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.

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 6.5.1: 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.

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, 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.

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.

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. Some images of Electron are showed in the [REF TO ANNEX 2. Section: S2-Launcher], a picture of the launching site is also showed.

6.5.2 Deployer

The objective of this section is to give a brief explanation of what is a deployer and how it works. 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. The main characteristics of the two deployers are listed in the [REF TO ANNEX 2. Section: S3-Deployer], also two pictures of them are shown there.

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. As seen in the [REF TO ANNEX 2. Section: S3-Deployer], GPOD has accessible panels whereas ISIPOD is fully closed, hence, ISIPOD is not suitable for the needs of the Astrea constellation. 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. The price for the GPOD deployer is 16000 US dollars per unit.

6.6 Lifecycle Strategies

6.6.1 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 manoeuvre required so as to deploy the satellites into orbit.

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 which are included at [REF TO ANNEX 2. Section 4 - First Placement] on which their launching procedure is explained.

The constellation has 189 3U CubeSats distributed in 9 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 launch per orbital plane, consequently, the first placement consists on 9 launches and all the logistics around them. Rocketlab is capable of launching once per week, therefore, the first placement takes 9 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 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).

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 189 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 189 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 9 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 Launch minus 423 days.

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.

6.6.1.1 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.

6.6.1.2 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. A more schematic explanation can be found in [REF TO ANNEX 2. Section 4 - First Placement]

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 can be computed. [REF TO ANNEX 2. Section 4 - First Placement]

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.

Plane Order

Planes are going to be placed consecutively from the first one to the last one. This way allows a growing wider range of communication during the time the constellation is being set up. The whole discussion on which would be the best way to set up the orbital planes on the first placement can be found in [REF TO ANNEX 2. Section 4 - First Placement].

6.6.2 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.

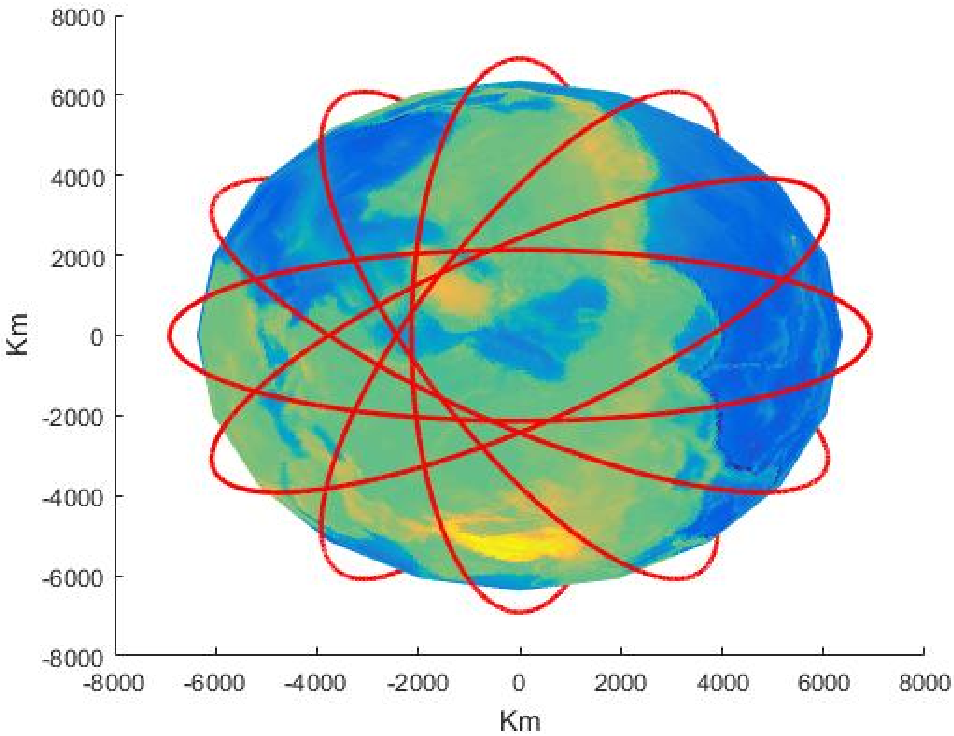


Figure 6.6.1: Old Constellation

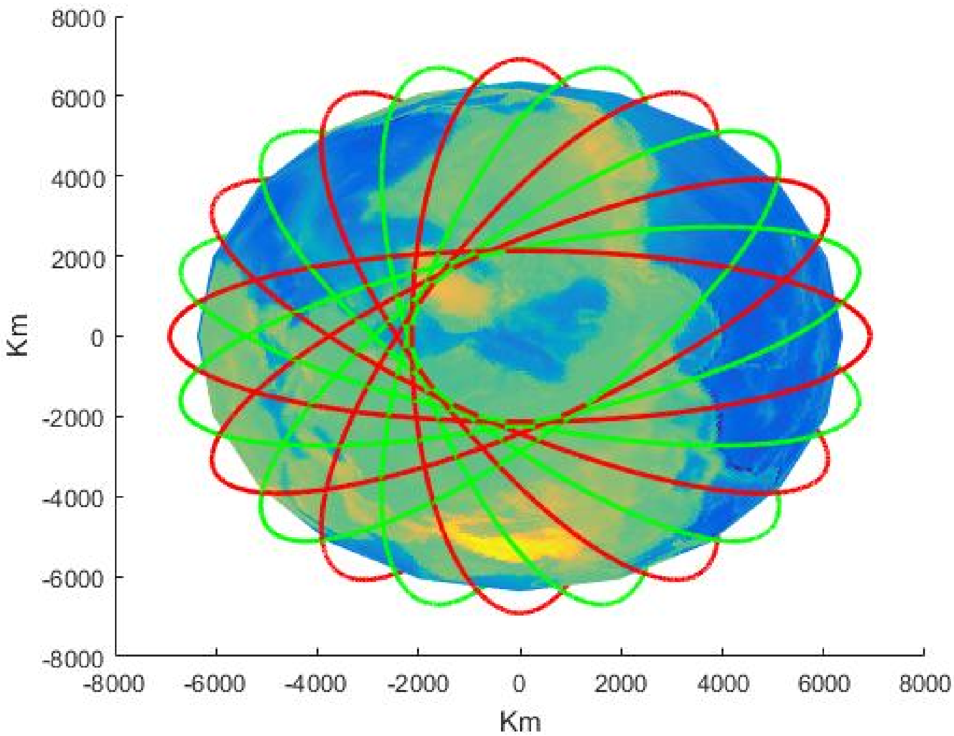


Figure 6.6.2: Old and New Constellations

6.6.3 Spare Strategy

6.6.3.1 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 priopities the most suitable has to be choosen. In addition, the decision taken is related to the constellation

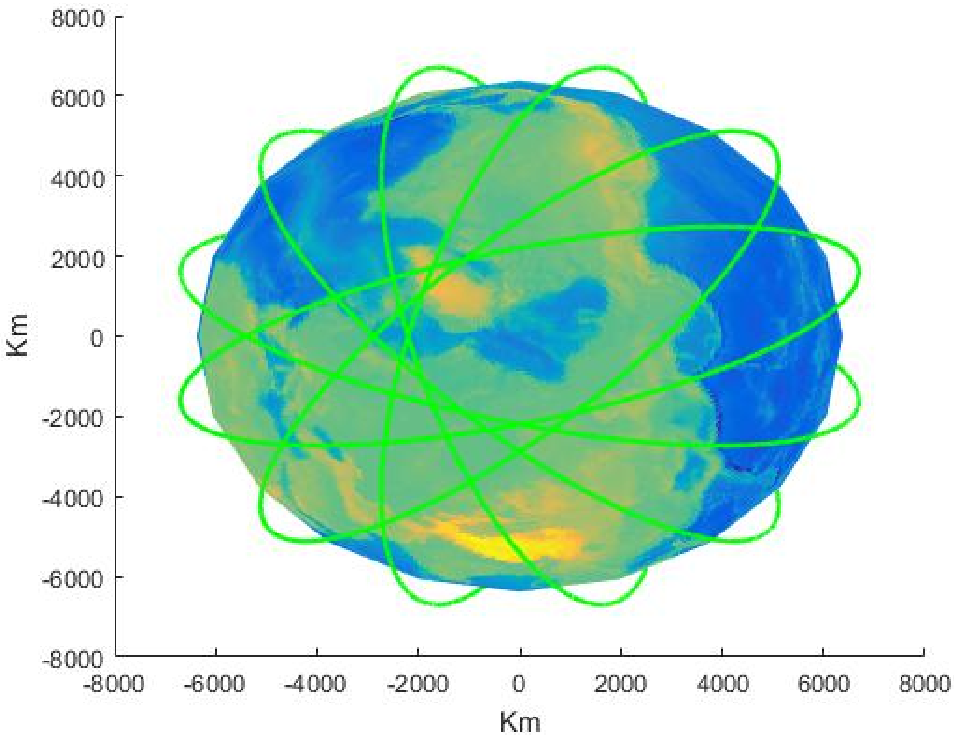


Figure 6.6.3: New Constellation

flexibility to degrade the service to a lower performance level during a certain period and to its cost.

6.6.3.2 Spare Strategy Selection

From all those alternatives explained in the annex[REF TO ANNEX 6. Section 6], 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.

6.6.4 Major failure deffinition

It can be stated that a major failure can happen due to various factors:

- The failure of at one satellites.
- The failure of all ground stations. It would be at least 3 ground stations.
- The failure of at least two satellites in a communication route in less than 3 minutes.

  For more information about the major failure definition see [REF TO ANNEX 6. Section 6]

6.6.4.1 Decision

Having studied all the possibilities of failure and taking into account that the porformance of the satellite is guaranteed for four years the conclusion is that there are no spare satellites needed in-orbit because of the fact that the constellation is dimensioned in order to have the capacity to assume some minor expected failures that will not affect the performance of the entire constellation.

However, there has to be always spares on ground for at least two planes so that in case of a major failure there can be a fast reaction to replace the planes afected. Besides, these satellites will not suppose a great increase in the cost of the constellation because if they are not used as spares they can be used for to following replacement.

6.6.5 End-of-Life Strategy

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, which is an existing problem explained in detail in [REF TO ANNEX 2. Section 4 - First Placement].

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 as it has been checked in [REF TO ANNEX 2. Section 6 - End of Life]. Moreover, due to the fact the replacement strategy has been designed so as to avoid the need of a quick de-orbit, to adopt a controlled de-orbit decay it is not necessary and the uncontrolled one is still being adequate. Finally, the fact that the constellation is placed at LEOs makes easier the application of the uncontrolled de-orbit because the perturbations present in this altitudes increase the satellites decay rate of approach. As a result, given all the stated reasons, it is decided to use the uncontrolled de-orbit.

7 | 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 **12 years**. The decision of this amount of years has been done taking into account that every 5 years there is a re-launching of the whole constellation, which means a considerable increase in the costs. In order to have a good view of the whole project, it has been decided that at least two full cycles had to appear complete (years 0 to 4 and 5 to 9) and also to see the tendency it was recommended to add some more time. This is the reason why the studied is carried on for 12 years.

From an analysis carried on by Astrea's team, it has been found that the anual estimation of the **demand** can be approximated by 7500 GB (or 59130000 Mbits) hired per year. An economical study is going to be performed using that estimation as the sales. The determination of the price of Astrea'a service is made upon this feasibility study.

When performing the feasibility study, all the costs must be taken into account. This means that all the costs derived from the different departments (communications, satellites, launching, ...) are considered, as well as other costs such as the engineering hours, which were stated in the Project Charter and the Gantt Chart. All those costs have already been explained. Nevertheless, some last costs which must be taken into account are the administration costs and the insurance service. The estimations of those costs are of 259000 and 2245320 €per year, respectively. Following there is a summary of the economical study. For further details on the studies mentioned, please refer to the [REF TO ANNEX: Annex V. Section 11]. There it can be found the full feasibility study table, with all the costs and profits broken down. All the costs can be found in the Budget as well.

In the following page, there is the summary of all the investment, benefit and cost taken into account when doing the feasibility study, as well as the anual cash flows, the discounted cash flows, the cumulative cash flow and the discounted cumulative cash flow. In the mentioned annex, it can be found the same table but much more complete. For instance, in this document there are the *system (satellites) costs* and just its global cost, whereas in the annex there is the full list of components that form the forementioned system costs.

TIME	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12
INVESTMENT (build GS)	**-4,07**												
INCOME													
Gain (M euros)		44,35	47,30	50,26	53,22	56,17	59,13	59,13	59,13	59,13	59,13	59,13	59,13
Total Income	**0,00**	**44,35**	**47,30**	**50,26**	**53,22**	**56,17**	**59,13**	**59,13**	**59,13**	**59,13**	**59,13**	**59,13**	**59,13**
COSTS													
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	-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	-2,24532	-2,24532
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	-0,005	-0,005
Launching	-51,280	0,000	0,000	0,000	0,000	-51,280	0,000	0,000	0,000	0,000	-51,280	0,000	0,000
System (satellites)	-56,21	0,00	0,00	0,00	-56,21	0,00	0,00	0,00	0,00	-56,21	0,00	-0,15	-0,15
Communications	0,00	-1,20	-1,20	-1,20	-1,20	-1,20	-1,20	-1,20	-1,20	-1,20	-1,20	-1,20	-1,20
Total Cost	**-107,54**	**-3,71**	**-3,71**	**-3,71**	**-59,92**	**-54,99**	**-3,71**	**-3,71**	**-3,71**	**-59,92**	**-54,99**	**-3,86**	**-3,86**
CASH FLOW	**-111,61**	**40,64**	**43,60**	**46,55**	**-6,71**	**1,19**	**55,42**	**55,42**	**55,42**	**-0,79**	**4,14**	**55,27**	**55,27**
DISC CF	**-111,61**	**38,34**	**38,80**	**39,09**	**-5,31**	**0,89**	**39,07**	**36,86**	**34,77**	**-0,47**	**2,31**	**29,12**	**27,47**
CUM CF	**-111,61**	**-70,97**	**-27,37**	**19,18**	**12,47**	**13,66**	**69,08**	**124,50**	**179,92**	**179,13**	**183,27**	**238,54**	**293,82**
DIS CUM CF	**-111,61**	**-73,27**	**-34,47**	**4,62**	**-0,69**	**0,19**	**39,26**	**76,12**	**110,89**	**110,42**	**112,74**	**141,85**	**169,32**

Table 7.0.1: Feasibility Study

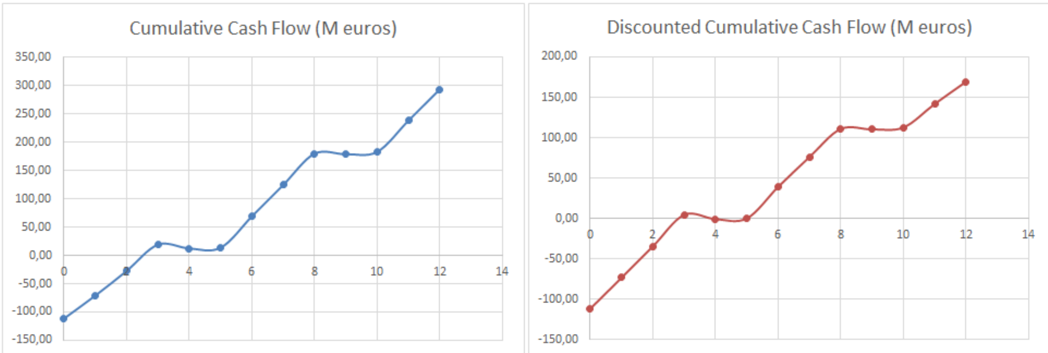


Figure 7.0.1: Cumulative Cash Flows (normal and dicounted, for 12 years, with a discount rate of 6%)

- **Pay Back Time**. The Cumulative Cash Flow is plotted next. It can be seen that the Pay Back Time is between years 2 and 3. Assuming linearly distributed, it will be of **2.59 years**. This 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. In year 4, the satellites that are going to be launched in year 5 are made. This means an increase in the cost, due to the fabrication and assembly. Moreover, in year 5, there is also a increase, because of the re-launching itself of those satellites. This is what causes that interval of time in which the Cumulative Cash Flow does not increase, but even decreases a bit: that year, the income is slighly smaller than the re-launching costs. Despite so, the Cumulative Cash Flow does not get to a negative value this time. Therefore, a second Pay Back Time can't be found, since profit is high enough. In years 9 and 10, the same process takes place again: the fabrication and re-launching of the new satellites, but again, no third Pay Back Time might be found.

- **Updated Pay Back Time**. The Discounted Cumulative Cash Flow has already been plotted too. It can be seen that the Updated Pay Back Time is between 2 and 3 years. If again linearly distribution is assumed, the Updated Pay Back time will be of **2.88 years**. This value seems reasonably acceptable, because of the nature of the project, within the space sector, a very demanding and expensive one. This time, because of the significat costs during year 4 (building and assembling of satellites) and especially year 5 (re-launching of satellites), added to the fact that the discount rate is now being taken into account to, it makes the Discounted Cumulative Cash Flow negative again, as can be seen in the graphic. Therefore, there will be another Updated Pay Back Time for the inversion done during years 4 and 5, exactly at year **4.99**. Taking into account that this inversion was made during the year 4, it turns out to be an actual UPBT of 0.99 years. There won't be a third UPBT, bcause in years 9 and 10 there is a big investment again, but by then, the profit is high enough so as to make it possible for the Discounted Cumulative Cash Flow to not become negative any more.

- **Break Even Point**. By changing manually the parameter "Number of Mbits hired" of first year, it is found that the Break Even Point is of **3708000 Mbits** (with this value of Mbits hired the first year, the Cash Flow is approximately 0). This means that under no account there can be less Mbits hired that that, because otherwise the Cash Flow would be negative and the Cumulative Cash Flow, negative at beginning since first year is fully just 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. Thus, the cash flow will be positive and consequently there will be a time in which there is benefit.

- **Net Present Value**. From the table, it can be immediately seen that the Net Present Value (for the period of time studied, of 12 years) is of **+169.32M€**. 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. It is clearly positive, which indicates that the project earnings generated by the investment exceeds the costs. In other words, it will be profitable. The Net Present Value coincides with the value of the Discounted Cumulative Cash Flow of the twelfth year.

- **Internal Rate of Return**. 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. The studied carried on uses a 6% as the discount rate, and this value gives a positive Net Present Value, as has been already explained. By manually changing the discount rate, it can be achieved that the Net Present Value gets to 0, or very closely. This value of the discount rate is the Internal Rate of Return, and is used to evaluate the attractiveness of a project. In this case, it has been found that the IRR is of **29.15%**. The higher the IRR is, the more desirable is to undertake the proeject. In any case, it must be greater than the actual discount ratio. In this case, not only the IRR is greater, but it is actually a very high rate. Therefore, the project is very attractive, feasibly speaking.

The Pay Back Time and the Updated Pay Back Time are of approximately 3 years, quite acceptable in the space sector. The Net Present Value is really great, as well as the Internal Rate of Return. Moreover, the estimation of demand is far higher than the Break Even Point. In conclusion, all the parameters analysed happen to indicate the same thing: the investment is **strongly recommended** and the project is **feasible**.

Nevertheless, it must not be forgotten than this study is done upon some important assumptions, which provide a certain degree of uncertainty. In spite of that, the results of the study have been so positive that a slight variation of the hypothesis done could not lead to an unfeasible situation.

8 | Environmental Impact Study

This chapter 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. The entire study can be seen at the [REF TO ANNEX: Anex V. Section 13], since in this document there are only exposed the conclusions of it. The study is focused in these 3 aspects:

- **Ground stations**. It is concluded that they would not represent any environmental impact if they are in a place where they do not interfere with the normal behaviour of any ecosystem.
- **Satellites**. The study analyses the impact of the fabrication and the performance. The satellites are certificated by all the corresponding regulations and there is no significant environmental impact during the fabrication. On the other hand the satellites are designed to be burned out in the atmosphere in a period of 5 years, and they would not be orbital waste.
- **Launching**. The launching is the most critical part in environmental terms and it is depth analysed. Basing in a Environmental Assessment done by the Ministry for the Environment of New Zealand [17] it is concluded that there is no significant damage in the environment at short term.

In conclusion the project is environmentally viable.

9 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.

This project is based on the design of a satellite constellation dedicated to communication. 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 of great benefit. In these missions highlights the spatial photography and weather control, which allow the following of natural catastrophes, earthquakes and fires. The crop monitoring, the evaluation of natural resources or the research on climate change, through the monitoring of ocean temperatures, the rising and falling sea levels, etc. are other services that Astrea could provide.

Currently, the constellations of CubeSats dedicated to the communication are in development and 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 and with total privacity, avoiding that third people interfering in the communication.

In relation to security, it must be considered different factors, where CubeSats could be in danger. The launch stage is one of the most important, because it is where the mission has more probability to fail. In the **PONER ANEXO** 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.

Once the constellation is in orbit, CubeSats can find dangers how colliding with space debris, whose movement 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*.

10 | Organization and Planning

10.1 Internal Structure

In order to build a work strategy, the project is divided in tasks that will be described later on. As the different tasks are strongly interrelated, the project members have decided to follow a hierarchy. Every task is developed by a small team composed of two to five people depending on the amount of work that the task requires and its complexity.

Each small team has to have a coordinator which has two principal functions. The first one is to manage the group so he / she is responsible for the good organization and progression of the task. The second is that he / she is the voice of the team. That means that the coordinator is the one who represents his / her work team when transferring information to the other group coordinators and the project managers and vice versa.

Over all the teams Boyan Naydenov is the project manager who ensures the project progress and manages people for major decisions. Finally, Silvia González is the secretary in charge to write and delivery the minutes and agendas of each meeting. She is also in charge of the organization and storage of all the documents in BSCW.

The final organization of the team has been:

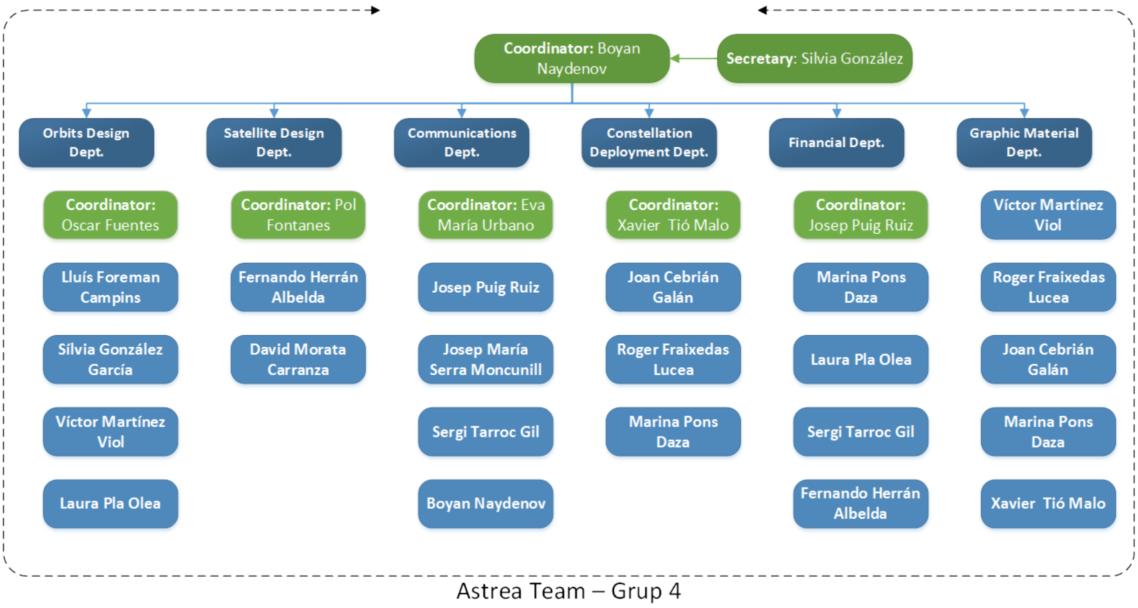


Figure 10.1.1: Roles and Responsabilities

10.2 Documents organisation

The Astrea team has **17 members** so it is essential to define a protocol to organize all the documents and information found to take advantage of resources.

The main internal communication tool used is *Slack* which is a platform specialized in team communication. *Slack* defines itself as a real-time messaging, archiving and searching tool for modern teams which is interesting for us since it allows the group to communicate at all times for punctual doubts and small decisions. For major decisions a meeting date will be specified using doodle. Communication between the customer and project manager will be carried out via e-mail. Weekly meetings with the customer are scheduled every Thursday and will be formalized through the agenda.

Moreover, to share documents two platforms are used: *Slack* and *BSCW*. Slack is used just for some discussion while *BSCW* is the main information storage because information and documents are stocked and organized in folders. Hence, it is really helpful for keeping track of the proper progress of the work.

Besides, the text editor used to develop the project is the *Latex* text processor which combined with *Git* allows the team to work remotely on a same document without overriding other's work. Git is just on of the many available *Version Control System* out there. It keeps track of the changes done to the documents, so it is very easy to go back in case something goes wrong. Also, it avoids overwriting other's work. This features seem to be essential if a smooth workflow is to be assured in such a big team.

Finally, Git is combined with Slack and with Latex. The work-flow achieved doing this is the following:

- Someone is about to write some conclusions in the report. He/she checks if their local folder (repository) is synced with the online repositroy. That is done through a simple terminal command. If there is new text, it will be added to their local folder.
- The user works on the document with *Latex* and applies some changes.
- The user finishes and wants to upload the new changes to the online repository so he/she just writes a command on the terminal and then, his or her local repository is synced with the on-line one. In the case that someone has done some changes before the user finishes, then *Git* will inform the user that he or she has to take actions in order to merge the files safely.
- Once the updates have been applied to the on-line repository, *Slack* notifies automatically all the team that the current user has made some changes.
- Finally, the user also publish the document on BSCW so that files arrive to the costumer as well.

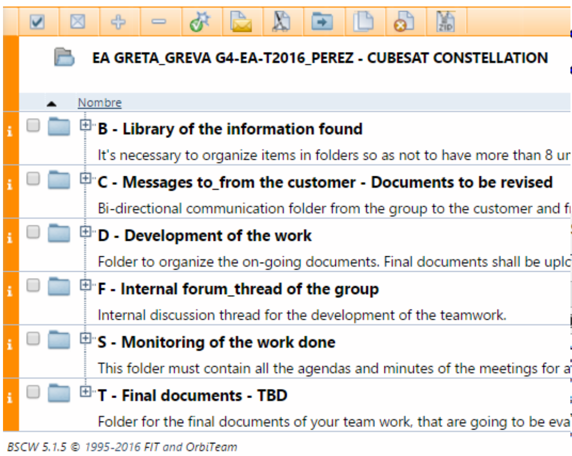


Figure 10.2.1: BSCW

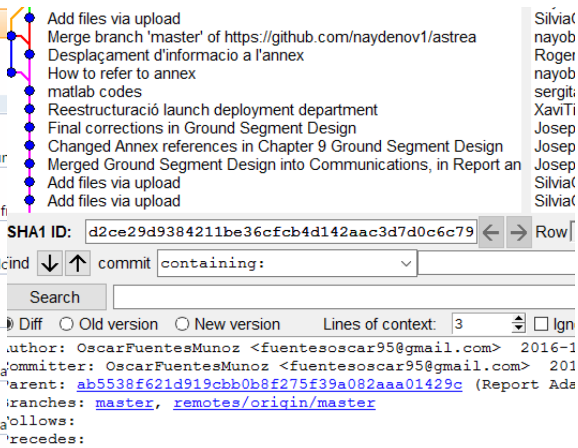


Figure 10.2.2: Git commits, viewed with Gitk

Figure 10.2.3: Texmaker, Latex.

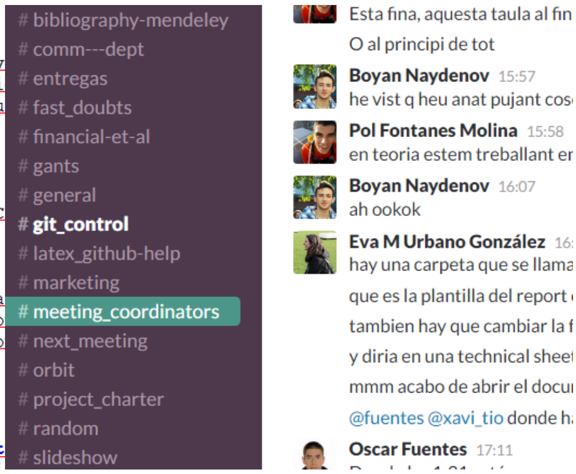
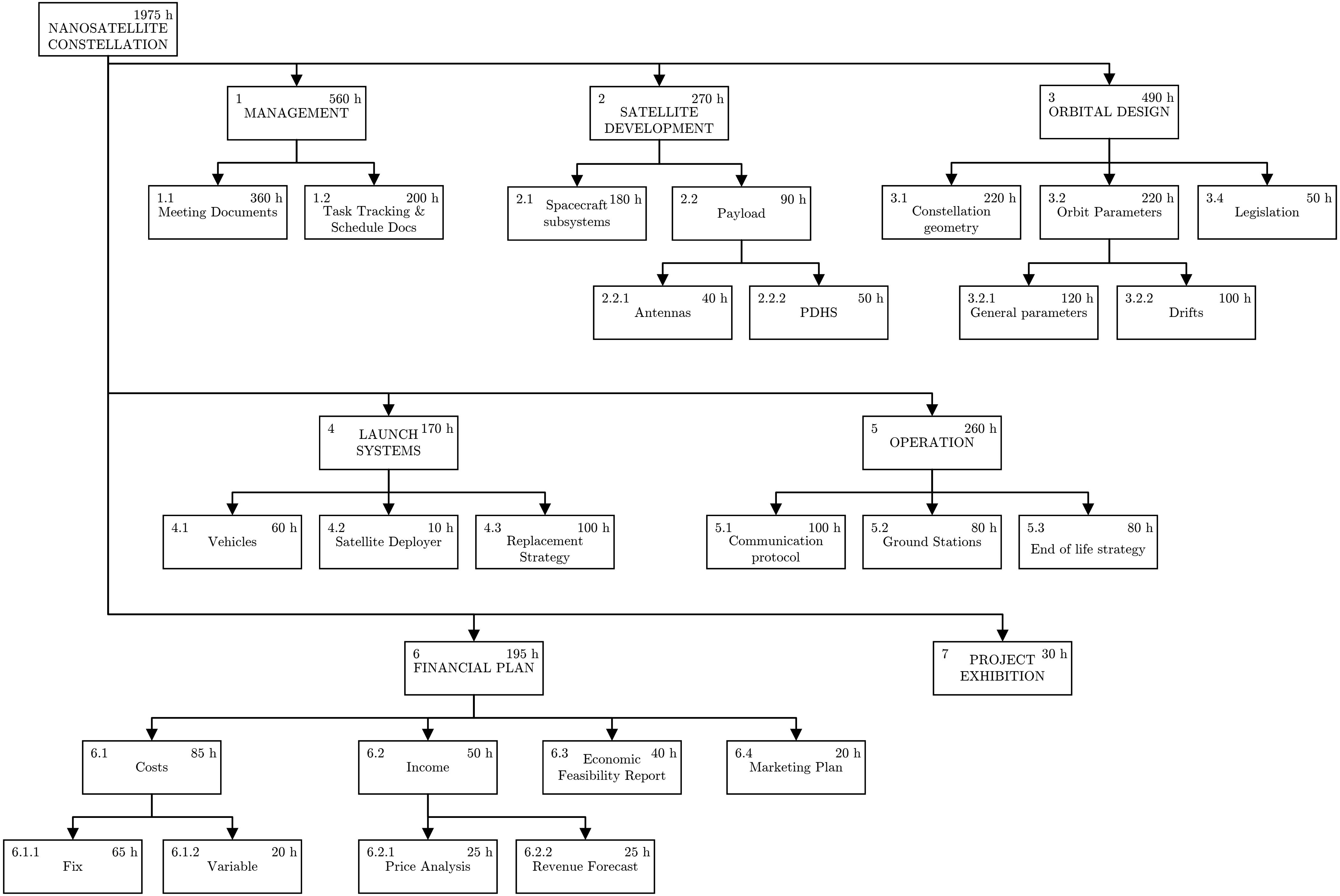


Figure 10.2.4: Slack

The applied system has helped in achieving high modularity and has saved the team many hours of unimportant work.

10.3 Planning

10.3.1 Tasks identification from work breakdown structure (WBS)



1975 h NANOSATELLITE CONSTELLATION
1 560 h MANAGEMENT
1.1 360 h Meeting Documents
1.2 200 h Task Tracking & Schedule Docs
2 270 h SATELLITE DEVELOPMENT
2.1 180 h Spacecraft subsystems
2.2 90 h Payload
2.2.1 40 h Antennas
2.2.2 50 h PDHS
3 490 h ORBITAL DESIGN
3.1 220 h Constellation geometry
3.2 220 h Orbit Parameters
3.4 50 h Legislation
3.2.1 120 h General parameters
3.2.2 100 h Drifts
4 170 h LAUNCH SYSTEMS
4.1 60 h Vehicles
4.2 10 h Satellite Deployer
4.3 100 h Replacement Strategy
5 260 h OPERATION
5.1 100 h Communication protocol
5.2 80 h Ground Stations
5.3 80 h End of life strategy
6 195 h FINANCIAL PLAN
7 30 h PROJECT EXHIBITION
6.1 85 h Costs
6.2 50 h Income
6.3 40 h Economic Feasibility Report
6.4 20 h Marketing Plan
6.1.1 65 h Fix
6.1.2 20 h Variable
6.2.1 25 h Price Analysis
6.2.2 25 h Revenue Forecast

10.3.2 Interdepency relationships, human resources and level of effort

ID	Work Package	Time (h)	Prelations
	1.Management		
1.1	Meetings Documents	360	
1.2	Tasks tracking and scheduling	200	BB - 1.1
	2.Satellite		
2.1	Spacecraft Subsystems	180	BB - 1
2.2.1	Payload antenna	40	BB - 2.1
2.2.2	PDHS	50	BB - 2.1
	3. Orbital Design		
3.1	Constellation geometry	220	BB - 1
3.2.1	General parameters	120	BF - 3.1
3.2.2	Drifts	100	BB - 3.2.1
3.3	Legislation	50	BB - 1, 2, 3.1
	4. Launch Systems		
4.1	Vehicle	60	BF - 4.3
4.2	Satellite Deployer	10	BF - 4.3
4.3	Replacement Strategy	100	BB - 1
	5. Operations		
5.1	Communication protocol	100	BB - 1
5.2	Ground station	80	BF - 5.1
5.3	End of life Strategy	80	BF - 5.2
	6. Financial Plan		
6.1.1.1	Maintenance Cost Analysis	10	BF - 3,4,5; BB - 2
6.1.1.2	Insurance Cost Analysis	15	BF - 3,4,5; BB - 2
6.1.1.3	Administration Cost Analysis	15	BF - 3,4,5; BB - 2
6.1.1.4	Taxes Cost Analysis	25	BF - 3,4,5; BB - 2
6.1.2.1	Manufacturing Cost Report	10	BF - 3,4,5; BB - 2
6.1.2.2	Launching Cost Report	10	BF - 3,4,5; BB - 2
6.2.1	Price Analysis	25	BF - 3,4,5; BB - 2
6.2.2	Revenue Forecast	25	BF - 3,4,5; BB - 2
6.3	Economic Feasibility Report	40	BF - 3,4,5; BB - 2
6.4	Marketing Plan	20	BF - 6.2.1,6.2.2
	7. Project Exhibition		
7	Project Exhibition	30	BF - 3

Table 10.3.1: Prelations and Time

10.4 Scheduling

Along the past four months, the costumer has been periodically informed, on a weekly basis, about the project situation regarding the scheduling. This has been done using *Microsoft Project* with which a *Gant* was done. This Gant has been updated by the team coordinators in a modular way since every department managed their own Gant, while the project manager kept track of all of them together.Samples of this documents can be found at [ANEEXO X SECTION Y]. It can be seen in red the critical path, among many other indicators. Furthermore, Microsoft Project was also used for generating weekly reports, showing a very short and clear summary regarding the overall situation. It showed the late tasks, the percentage of completion of the departments and the finished tasks during the last few days.

11 | Bibliography

[1] Patch antenna - Wikipedia.

[2] The Wireless Telegraphy (Licence Charges) Regulations 2011, 2011.

[3] Kepler Communications, 2016.

[4] Canada Government. RSP-101: Licence Application Submission Procedure for Planned Radio Stations Below 960 MHZ, 2008.

[5] Canada Government. RIC-42: Guide for Calculating Radio Licence Fees, 2014.

[6] CCSDS. *Report Concerning Space Data System Standards - Overview of Space Communications Protocols*. Number CCSDS 130.0-G-3. 2014.

[7] Vladimir A Chobotov. *Orbital Mechanics*. 2002.

[8] Howard D.. Curtis. *Orbital Mechanics for Engineering Students*, volume 3rd editio. Elsevier, Burlington, 2 edition, 2014.

[9] Dartcom. X-band EOS System, 2014.

[10] E. Buchen and D. DePasquale. Nano/Microsatellite Market Assessment 2014. pages 1–18, 2014.

[11] United Kingdom Government. The wireless telegraphy (Recognised Spectrum Access Charges), 2015.

[12] Satellites Iridium. The Iridium System.

[13] ISISpace. Full Ground Station Kit for S-band.

[14] Erik Kulu. Nanosatellite and CubeSat Database, 2016.

[15] Kyushu Institute of Technology. BIRDS project., 2017.

[16] Malcolm Macdonald and Viorel Badescu. *The International Handbook of Space Technology*. 2014.

[17] Ministry for the Environment of New Zealand. *Proposed regulation of jettisoned material from space launch vehicles under the Exclusive Economic Zone and Continental Shelf (Envionmental Effects)*. 2016.

[18] NASA. Small Spacecraft Technology State of the Art. (August):1–197, 2016.

[19] Ofcom. UK Frequency Allocations for Satellite Earth Stations, 2013.

[20] Ofcom. Application form OfQ564: Application for the Issue of Variation of a Satellite (Non-Geostationary Earth Station Licence), 2016.

[21] Radhika Radhakrishnan, William Edmonson, Fatemeh Afghah, Ramon Rodriguez-Osorio, Frank Pinto, and Scott Burleigh. Survey of Inter-satellite Communication for Small Satellite Systems: An OSI Framework Approach. *IEEE Communications Surveys & Tutorials*, (c):1–51, 2016.

[22] Secretaría de Estado de telecomunicaciones y para la sociedad de la información. Cuadro Nacional de Atribución de Frecuencias (CNAF) revisado 2015. pages 3–110, 2015.

[23] CCSDS Secretariat. Overview of Space Communications Protocols. (CCSDS 130.0-G-3):43, 2014.

[24] D.A. Vallado. *Fundamentals of Astrodynamics and Applications*. Springer-Verlag New York, 3 edition, 2007.

[25] J.G. Walker. Some Circular Orbit Pattern Providing Continuous Whole Earth Coverage. *Journal of the British Interplanetary Society*, 24:369–384, 1971.

[26] J.G. Walker. Continuous whole-Earth coverage by circular-orbit satellite patterns. *Royal Aircraft Establishment. Technical report 77044*, 1977.

[27] IQ wireless. S Band Transceiver for Small Satellites., 2015.