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Cubesat Constellation
Astrea

ANNEX II: Constellation Deployment

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Contents

List of Tables

List of Figures

1 | Constellation Deployment

1.1 Launching System

The following table displays the first seven candidates.

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

Table 1.1.1: List of Launchers

Figure 1.1.1: Electron Rocket

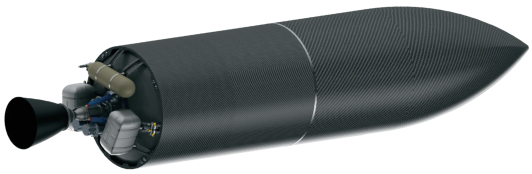

Figure 1.1.2: Second Stage

Figure 1.1.3: Electron Rocket Fairing

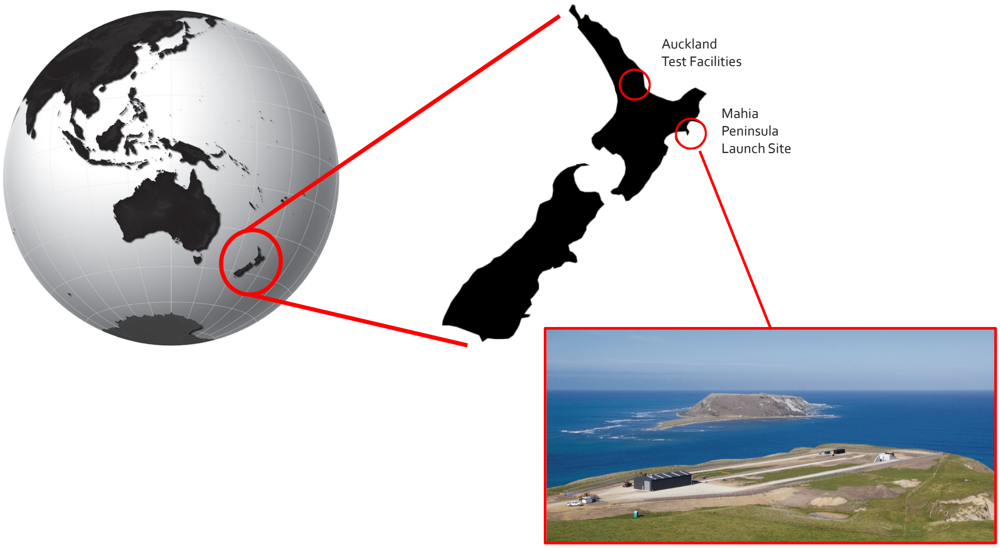

Figure 1.1.4: Rocket Lab Facilities

Characteristics of GPOD and ISIPOD. First, the main ones that both have in common are shown, secondly, the few differences between them are listed:

- Main features
  - Provide deployment status signal.
  - No battery needed nor external power source
  - No pyrotechnics
  - Protect the CubeSat from external environmental impact
  - Mechanically interfaces with the CubeSats by means of guidelines
  - Mechanically interfaces with the launch vehicle by means of standard fasteners
  - Qualified for multiples launch vehicles
- ISIPOD

  - The satellites are fully enclosed inside the deployer, so once the CubeSat is fit in, there is no access to it (see image 1.1.5)
  - Electrically interfaces with launch vehicle for telemetry

- GPOD
  - Accessible panels: all the side panels allow the access to the integrated CubeSat (see image 1.1.6). This means that the entire area between the guide rails over the entire CubeSat length may be freely accessed.
  - The price for a single deployer 3U is 16000 euros.

Figure 1.1.5: ISIPOD

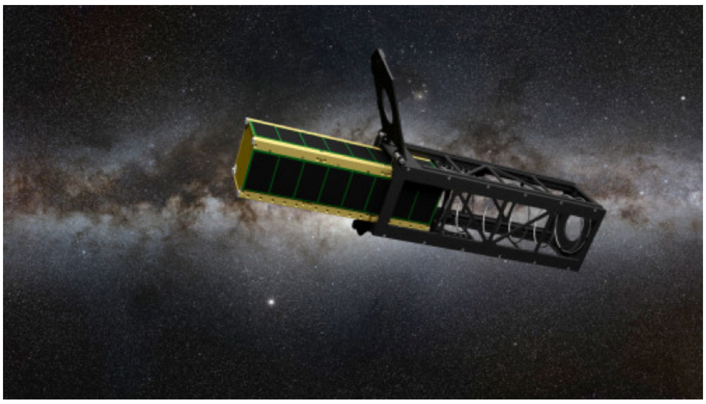

Figure 1.1.6: GPOD

1.2 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, whereas the second one is focused on the maneuver required so as to deploy the satellites into orbit.

1.2.1 First Placement logistics

Gantt charts provided by Rocketlab USA:

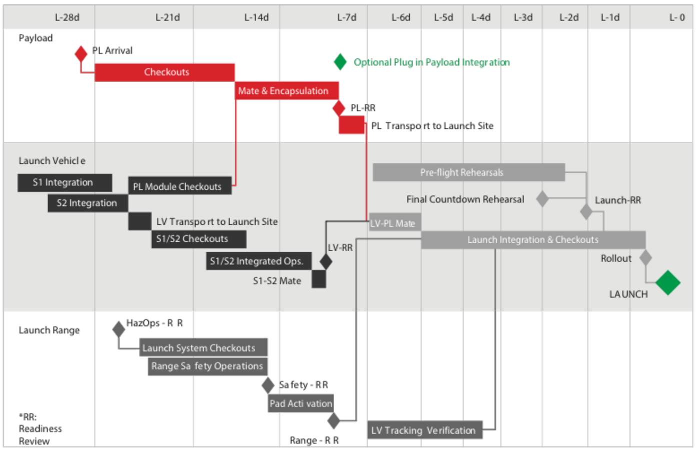

Figure 1.2.1: Launch Range Operations Flow/Schedule

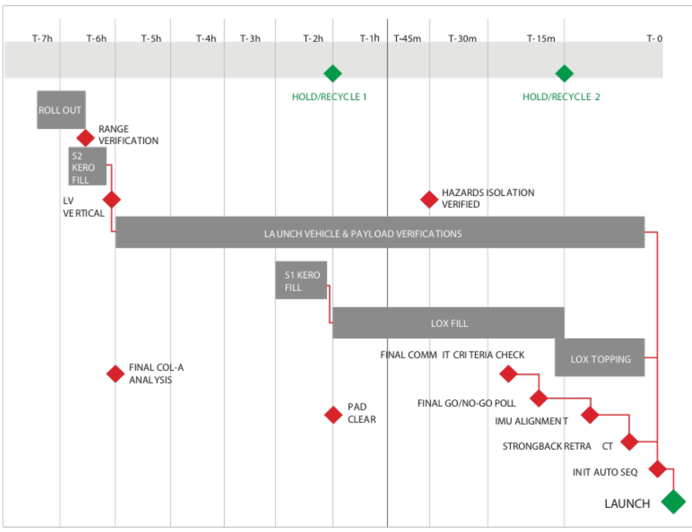

Figure 1.2.2: Countdown Operations Flow

1.2.2 1st Placement In-Orbit Injection Maneuver

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

1. The rocket goes through the procedure designed by Rocketlab USA to get to the destination orbit. The approximate trajectory during this stage is represented in 1.2.3.Right after entering into the destination orbit, the first satellite is deployed into it as seen in 1.2.3 represented with a red dot.
2. Once the latter is completed, the rocket's engine gives it the necessary ΔV in order to get to the elliptical spacing orbit. In 1.2.4 half a revolution of the rocket is represented along with the orbit of the first deployed satellite at the same point in time.
3. After one full revolution of the rocket in the elliptical orbit, the first satellite will have left the right phase spacing with respect to the rocket. At this point the rocket's engine gives the same ΔV as in step 2 but negative. This will cause it to enter again into the circular orbit of the satellites. At this point the rocket deploys the second satellite as shown in 1.2.5. Right after this deployment the rocket enters into the elliptical orbit again.
4. 1.2.6 represents again half a revolution of the rocket in the elliptical orbit along with the deployed satellites so far.
5. Finally, the rocket reduces its velocity again to enter into the circular destination orbit in order to deploy the third satellite (1.2.7).
6. This aforementioned procedure is iterated until the orbital plane is full.

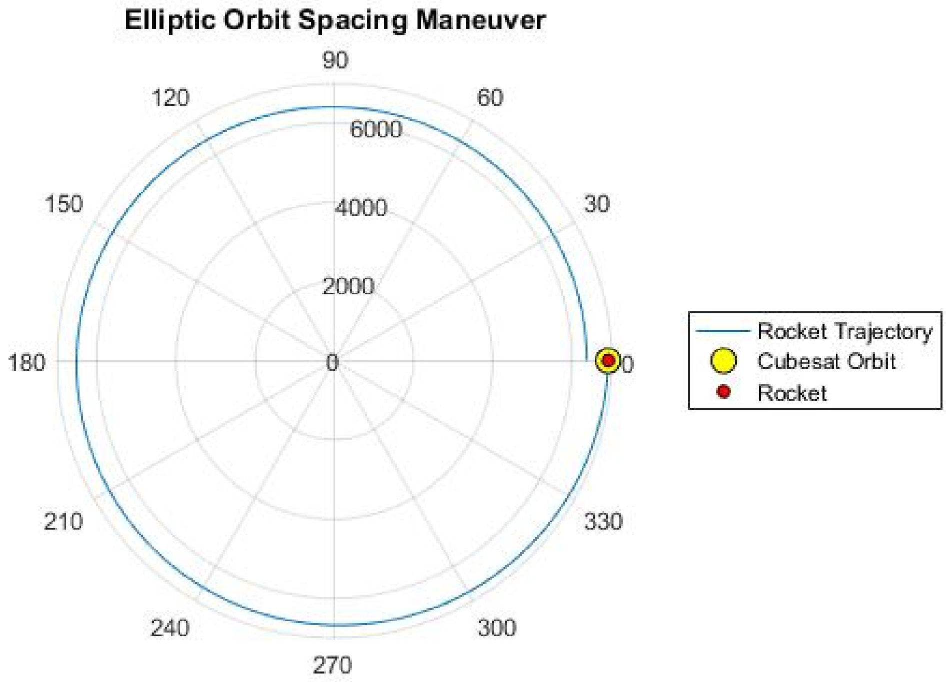

Figure 1.2.3: Rocket's trajectory from lift-off to final orbit.

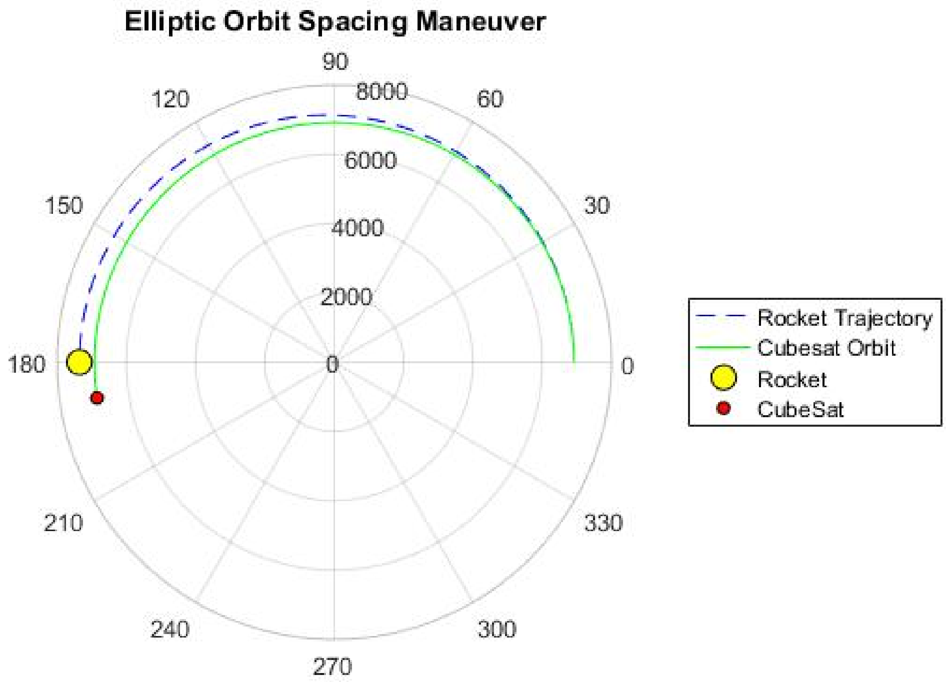

Figure 1.2.4: Half of a revolution of the rocket in the elliptical spacing orbit.

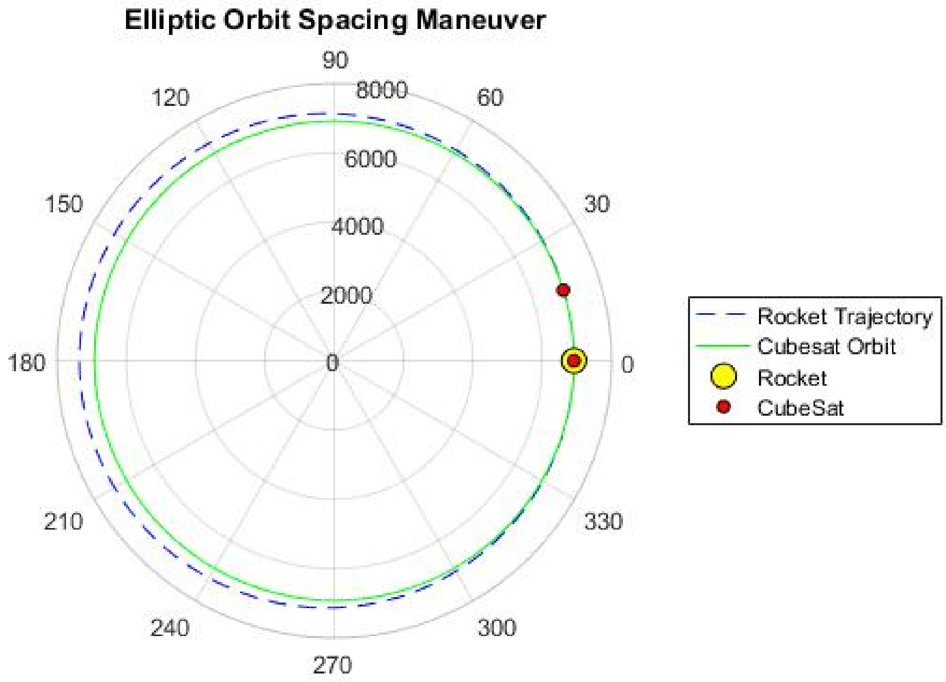

Figure 1.2.5: Deployment of the second satellite.

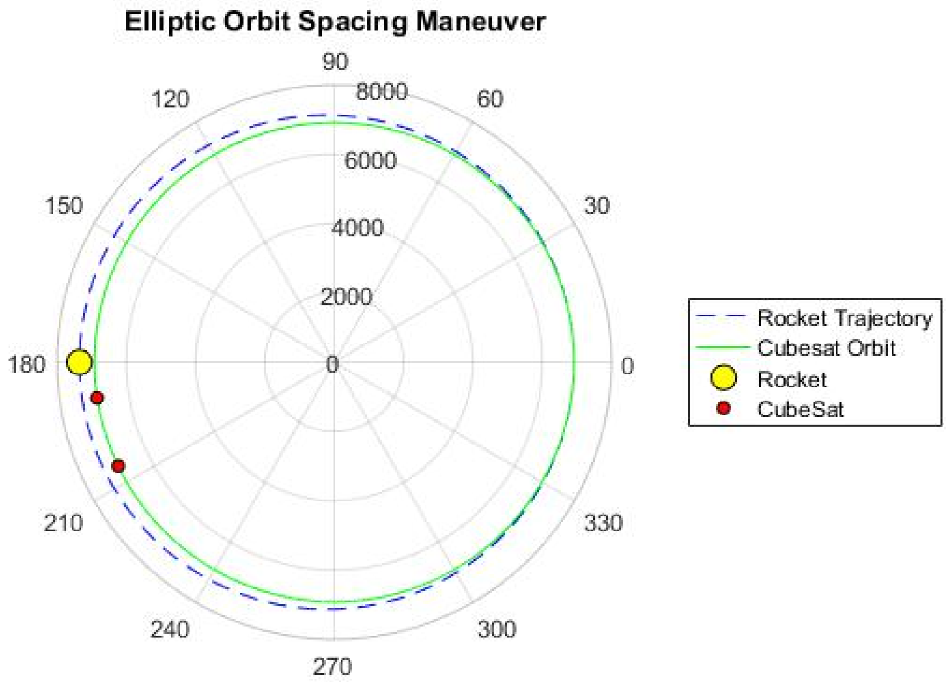

Figure 1.2.6: Half of a revolution of the rocket after the deployment of the second satellite.

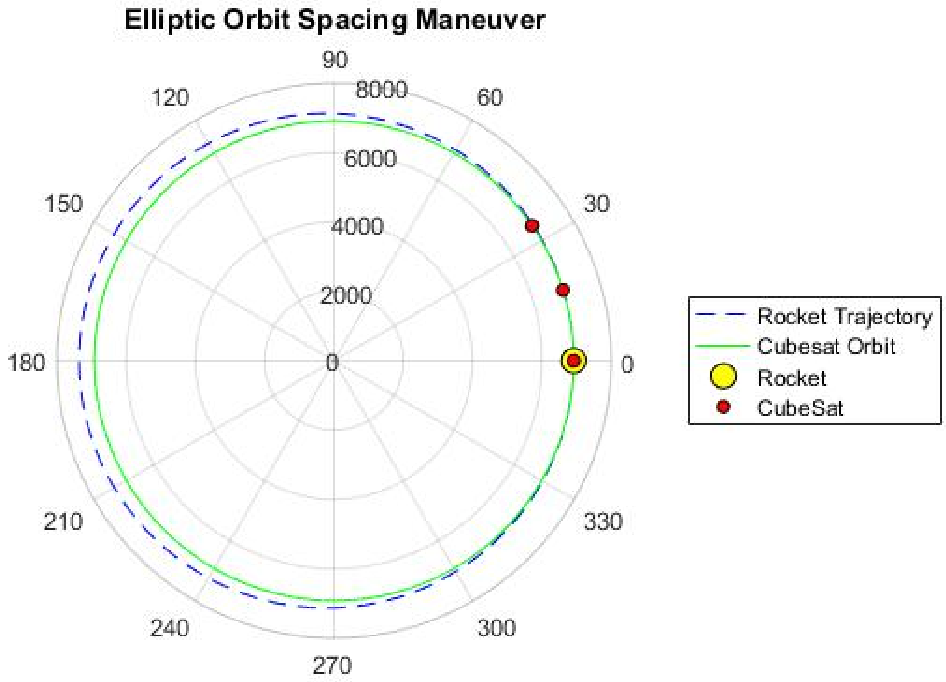

Figure 1.2.7: Deployment of the third satellite.

1.2.3 Orbit Parameters Calculation

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

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

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

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

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

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

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

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

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

1.2.3.1 Plane Order

The aim of this section is to describe the order in which all of the 9 planes are put into orbit. The fact that establishes one path or another is the fact that satellites can only communicate with neighbours, that is, one satellite can only communicate with its neighbours from the same plane and the neighbours from the neighbour planes.

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

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

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

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

1.3 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 placed into the same position than the old ones. A rapid replacement is also interesting regarding the need of providing full service to the customers without interruption. The solution adopted consists on placing the new planes between the old ones consecutively, following the order of the first placement. In order to clarify the process, a detailed explanation is shown below:

First of all, since different orbital planes are going to be taken into account in this explanation a nomenclature is set: old planes are the ones that have to be replaced, the new ones are the planes that will substitute them. If a plane is named with the number 1, it means that is the first one to be placed (old or new) and so on (2,3,..,21).

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

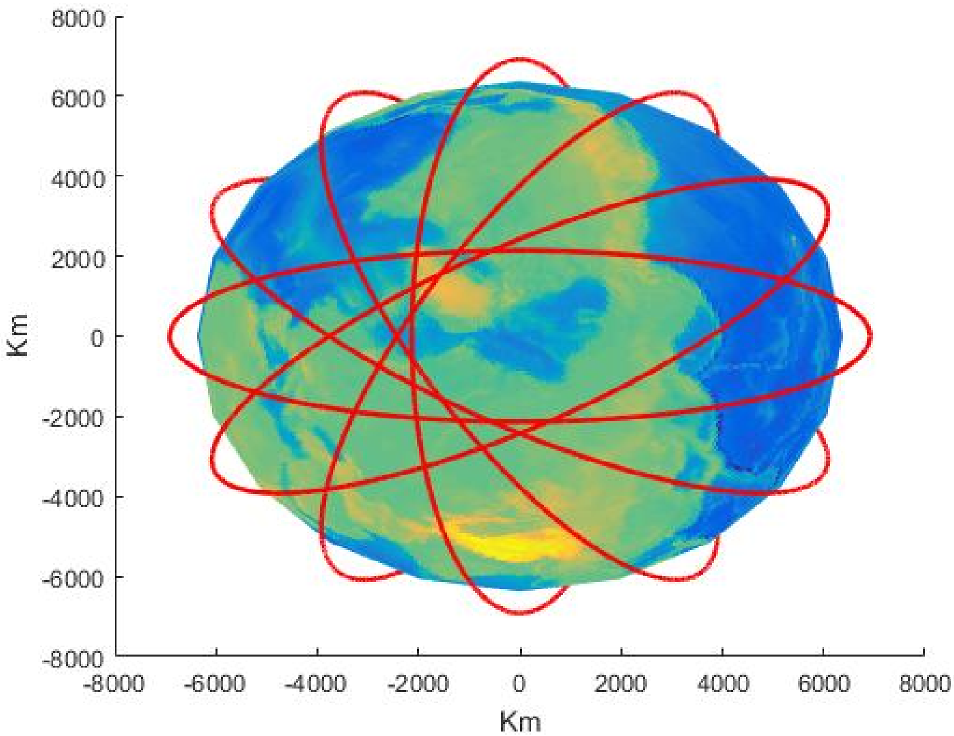

Figure 1.3.1: Old Constellation

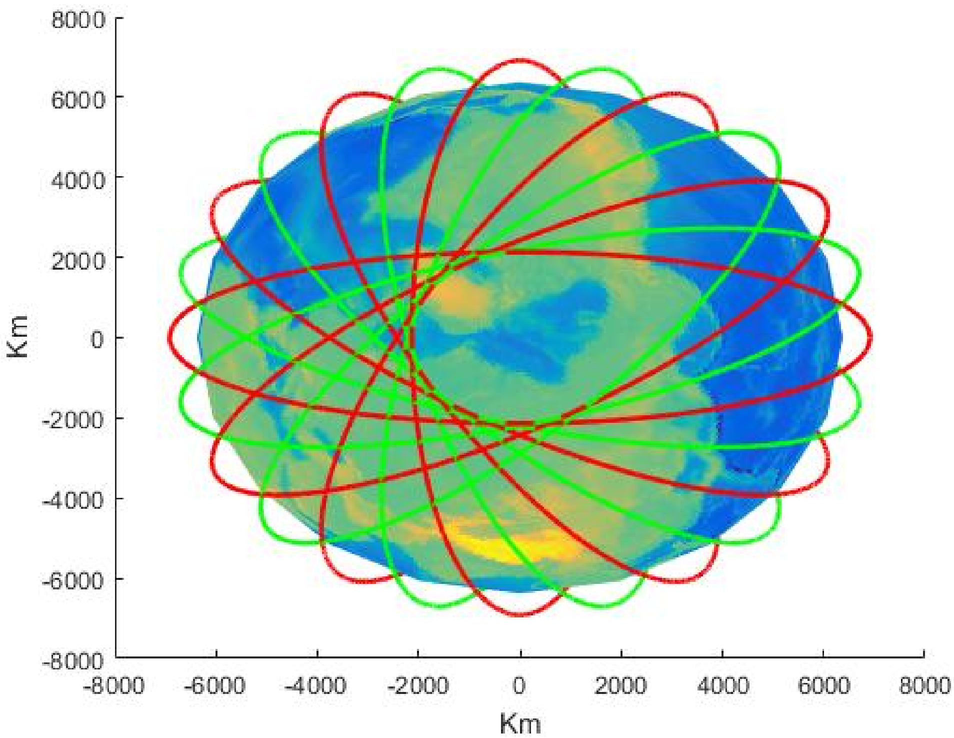

Figure 1.3.2: Old and New Constellations

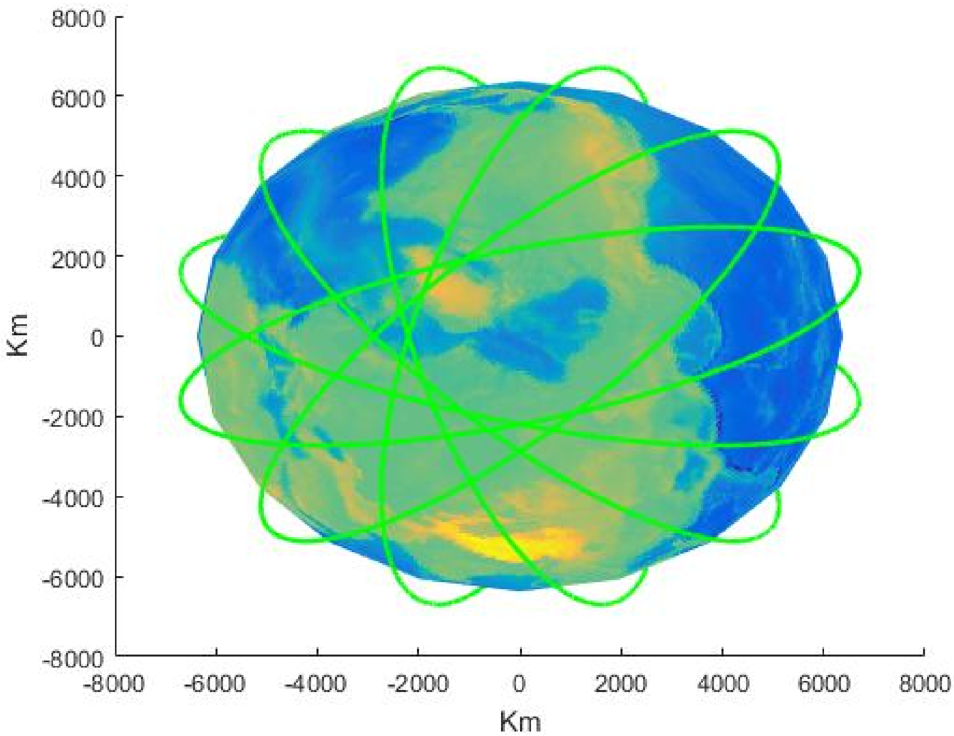

Figure 1.3.3: New Constellation

1.4 Spare Strategy

1.4.1 Spare Strategy Alternatives

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

- One extra Satellite:
  By adding an extra satellite to the primary design of the orbital plane configuration, one satellite failure is covered with little time delay to recover the plan. In this way, the constellation continues to work at maximum capacity after a short interruption and at a suitable cost.
- Two extra Satellites:
  Usually, by adding two extra satellites per orbital plane the reliability of the service achieves values around the 99.99%. This configuration increases considerably the cost of the project and it is mainly neccessary in cases where the availability of the satellite is essential for the proper operation of the constellation.

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

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

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

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

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

1.4.2 Major failure deffinition

In Project Charter, it has been stated that a major failure can be defined as the loss of a client's satellite coverage because of a failure in the network. However, this deffinition is not enough precise. For example, during a communication, it can happen that a data packet is lost, or has an error and it is discarded. This means that, for that packet, the communication was lost, but it does not mean that the communication with the client was lost. Another aspect to take into account is that a satellite may fail, but an alternative path can still exist and therefore the communication can continue. Moreover, if the client satellite loses all communication with all satellites in range, due to the different orbital velocities of the client satellite and the network satellites, the client satellite will eventually be in range of a functional network satellite.

For all this reasons, a more specific criteria is needed. In Project Charter it has also been stated that the network will provide communication between a client satellite and a ground station with a latency lower than 5 minutes (300 seconds, or 300,0000 miliseconds). A major failure will consist on a failure in the network that causes a message to arrive from a client satellite to a client ground station with more that 5 minutes of delay, or not arrive at all. Derived from this definition, a minor failure can also be deffined. It can be defined as a delay of more that 5 minutes in a communication between a client satellite and a ground station without any failure in the network.

1.4.3 Major failure

Because of the different height of the client satellite and the network satellites, if all the network satellites in range of the client satellite fail, the client satellite may come in range of a working network satellite if enough time passes. In some cases, this can happen in less than 5 minutes and, therefore, it will not be considered as a major failure. For this reason, a more critical situation will be considered. It will be considered that the client satellite moves at the same speed as the network satellites, in the same orbital plane. In this situation, a major failure can happen because of three reasons: all network satellites in range of the client satellite fail, all ground stations fail, or some satellites fail but the alternative path takes more that 5 minutes to transmit the information.

1.4.3.1 Satellite in range failure

The first reason will be evaluated in the following lines. Depending on the location of the satellite and the distribution of the satellites in the constellation, the number of adjacent satellites may vary. A satellite over the ecuator can have up to six adjacent satellites. If a client satellite only communicates with this network satellite, a major failure will be the failure of this satellite, as it can be seen in Figure 1.4.1. It can also be the failure of a group of satellites surrounding the transmitting satellite, but this number is larger and, therefore, it would not be considered since the failure of the transmitting satellite is more restrictive.

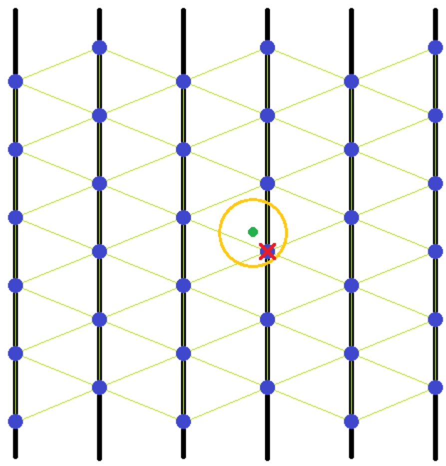

Figure 1.4.1: Failure due to the loss of the only satellite in range of the client satellite.

For antennas with almost half-spherical patterns (an angle of 10º over their horizontal plane has been considered as the minimum angle capable of recieving and transmitting), the minimum height over the satellite network orbit in order to always see more than one satellite is, aproximately, 400 km, considering that our constellation is at 550 km height over the Earth's surface. This means that a significant portion of clients would be in that zone.

For clients that have more than one network satellite in range, the critical failure would be similar as the ones in Figure 1.4.2 and Figure 1.4.3.

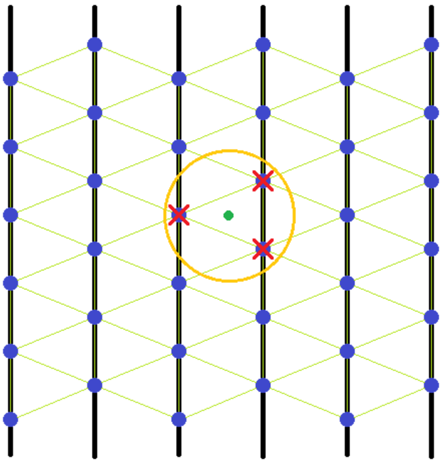

Figure 1.4.2: Failure due to the loss of all possible communication satellites if the client can communicate to three network satellites.

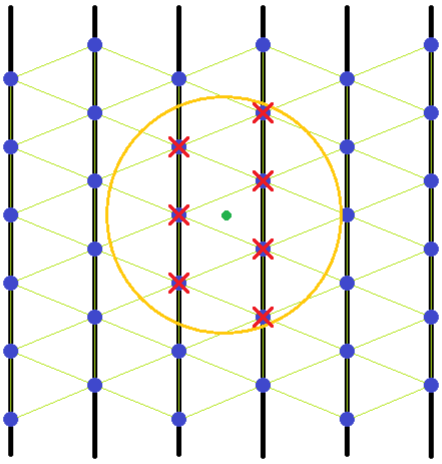

Figure 1.4.3: Failure due to the loss of all possible communication satellites if the client can communicate to seven network satellites.

As it can be seen, the critical failure depends on the communication range of the client satellite. Taking the more restrictive one would mean considering the failure of only one satellite. As this affects a significant amount of potential clients, it can not be neglected.

1.4.3.2 Ground station failure

Since any satellite in the network is able to communicate with any ground station, in order to have a critical failure due to a ground station failure, all ground stations must fail. It will not be considered a failure the loss of connection to a ground station caused by bad weather conditions or radio-fequency interference, since it is not a failure in the network but an anomaly in the medium.

Therefore, for a critical failure caused by ground station failures, all ground stations must fail. Since at least three ground stations will be used, the three of them must fail. As the previous case, the time of failure does not matter, but the fact that they remain unoperative at a given time.

1.4.3.3 Transmitting time failure

In the following lines, a major failure due to a delay superior to 5 minutes originated by a failure will be evaluated. First of all, it is needed to evaluate the transmission time. The minimum data rate that will handle the satellites is 25 Mbit/s. Therefore, it will be considered 25 Mbit/s as the data rate of the satellites, since it is the most restrictive. The protocols chosen, by deffault, cannot handle data units of more than 62,500 bytes, aproximately. This is 500.000 bits. With the data rate chosen, the time to transmit this information is 0.02 seconds. For a path of 20 nodes, and considering that a satellites recives the entire packet before sending it again, the transmission time will be 0.4 seconds. The transmission is done using electromagnetic waves, which move at the speed of light. For this short distances, it can be considered to be instantaneously. The time used to process each data packet has to be taken into account. If each node needs 1 second to process the packet, the total processing time will be 20 seconds.

Finally, the time to recognize a fallen satellite and the time to compute an alternative route is required. By deffault, OSPF protocol requires 40 seconds of no response to label an adjacent node as dead. When this time expires, the fallen link state will be transmitted. When a node recieves this update, it will wait 5 seconds and then it will calculate new routes. If the process requires 100 seconds, the total time until a failure happens and a new route is calculated is 145 seconds. With the processing time of 20.4 seconds, if one node fails, the time to deliver the message is 165.4 seconds. But if another node fails while the message is still being delivered, the total time to deliver the message would be 310.4 seconds, which is superior to 5 minutes.

Therefore, for a critical failure to happen because of a delay of more than 5 minutes in the communication due to a failure in the network, two satellites must fail in less than 160 seconds, and both of them must be in a communication path between a client and a ground station.

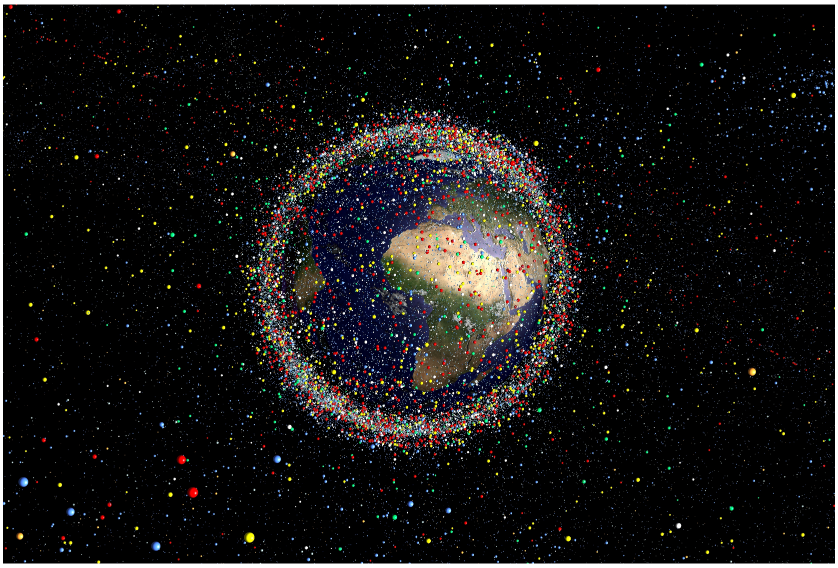

Figure 1.4.4: View of the Space Debris around the Earth

1.4.4 Space Debris

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

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

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

Therefore, by increasing the number of uncontrolled *"dead"* satellites the probability of collision between working satellites and space debris increases at LEO as it is overcrowded. Space debris is small usually and its location can be followed from earth but is impossible to control it. Meanwhile, it is essential for space assets to be free of any impact because avoidance maneuvers are too complicated to have real success. Thereby, the increasing risk of collision becomes the big threat everyone is fighting against.

1.4.5 End-of-Life Types and Analysis

As it has been found in [1], End-of-life strategies were implemented taking into account three factors: the time the satellite can orbit, the technical feasibility of active de-orbiting in terms of propellant and sub-systems enhancements, and the altitude of its nominal orbital plane.

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

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

- Controlled de-orbit:

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

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

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

$$a = \frac{r_1+r_2}{2} = 6672km$$

The speed at apogee of the elliptical orbit is:

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

Finally, the ΔV is computed:

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

- Uncontrolled de-orbit:

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

2 | Bibliography

[1] Stefania Cornara, Theresa W Beech, Miguel Belló-mora, Antonio Martinez De Aragon, and S A Gmv. SSC99-X-1. page 19.