astrea

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Astrea

ANNEX IV: Satellite Design

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1.1 Structure and thermal protection

1.1.1 Structure

There are several types of commercial structures. According to the needs of the project, the structure that Astrea is looking for has to be very flexible regarding the placement of the subsystems. It has to adapt to the needs of the project continuously given that the satellite does not have a typical configuration.

A basic schematics can be found in 1.1.1.

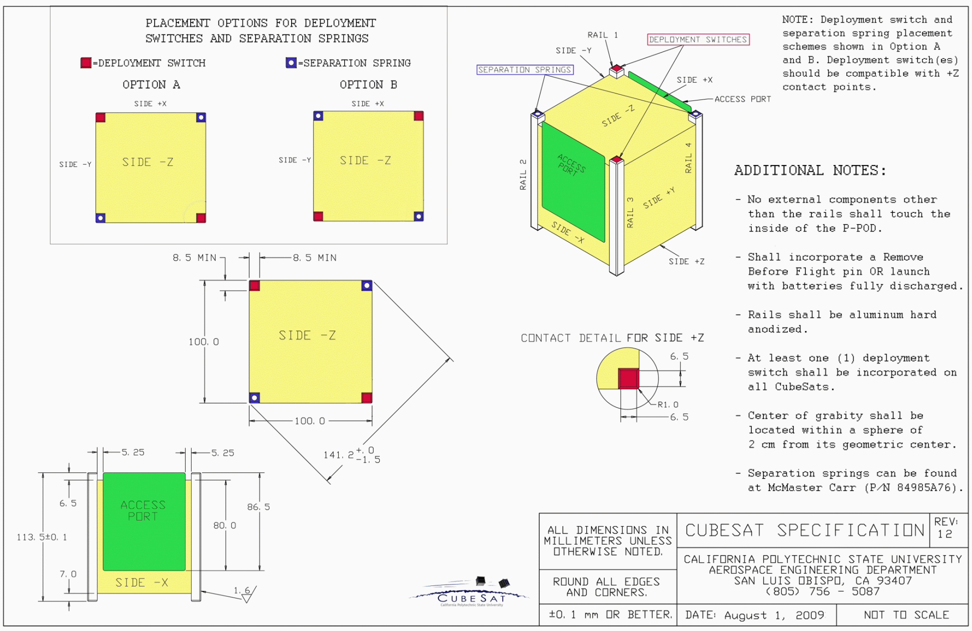

Figure 1.1.1: Dimensions of a 1U CubeSat. Source [1]

Besides this flexibility, several other parameters have to be taken into account. Given that the satellite will work under extreme environmentally conditions, the structure has to withstand space conditions for at least 4 years. Also, the weight should be kept down since there are lots of systems to be placed and the ratio $mass/satellite$ is limited. Finally, the structure should have a way to place all the subsystems (like holes, *trays*, ...).

The two most interesting options that were considered when the structure had to be chosen are presented in 1.1.1.

Brand and model	Features	Total price (€)
Structure		
ISIS 3U structure	Low mass (304.3g) Highly compatible High temperature range	3900
Gomspace GOMX-Platform	High mass (1500g) Comes fully equipped (basic systems) High temperature range	11000

Table 1.1.1: Options studied for the structure

And the option chosen has been the **ISIS 3U structure**, as explained in the report.

1.1.2 Thermal protection

The thermal protection system consists of various insulating materials that aim to protect the CubeSat from heat produced by radiation. Currently, the most used element in the aerospace industry is the MultiLayer Insulation (MLI), a set of multiple thin insulation layers. For the satellite, its main objective is to reduce the heat generated by radiation, given that the heat generated by convection or conduction does not have such a high impact on the on-board systems and is also comparatively small with radiation.

The more layers that the thermal protection has, the more heat is being redressed to the space. An expression for the calculation of the heat flux is presented below:

$$Q = UA\Delta T \tag{1.1.1}$$

- Q stands for the radiative heat flow rate between two parallel surfaces
- U is the global heat transfer coefficient
- T is the temperature difference between two parallel surfaces

The heat transfer coefficient can be derived, theoretically, using the following relation

$$U = 4\sigma T^3 \frac{1}{1/\epsilon_1 + 1/\epsilon_2 - 1} \tag{1.1.2}$$

If the emissivity is decreased or the number of layers is increased, the heat transfer coefficient is reduced. It means that the system is more insulated, more protected to radiation. Thus, the MLI system is a perfect choice for the satellite: the mass is really low and the insulation obtained is really high (NASA is actually using it for the development of their satellites).Furthermore, this kind of system can also be used as a first protection to dust impacts if the layers are big enough.

Finally, a few options were studied when the thermal protection had to be selected. These options are presented in 1.1.2.

Brand and model	Features	Total price (€)
Thermal protection		
Dunmore Aerospace Satkit	Lightweight Durability Made for small satellites	1000
Dupont Kapton Aircraft Thermal	Lightweight Durability Non-flammable	1200

Table 1.1.2: Options studied for the thermal protection

1.2 Electrical Power Systems

1.2.1 EPS Scheme

The figure 1.2.1 shows how the different electrical subsystems are related with one another.

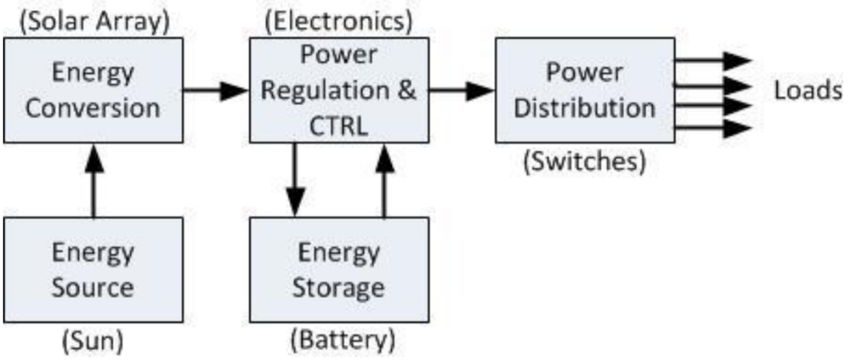

Figure 1.2.1: Basic schematics of the EPS. Source [2]

The need for a system that regulates, manages and distributes the energy to all of the other subsystems is clear. Every system (or load) has its own energy needs and the power distributing system must have several buses in order to maintain all the systems working at the same time. Also, redundant buses and connections should be mounted to ensure the least possible failures in the EPS; a failure of the EPS could compromise the whole satellite.

The electrical power unit should also measure the power consumed in real time and the intensity and voltage of the different buses to communicate possible failures to the on-board computer. If a failure is detected, the system should adapt in order to avoid being *in the dark* (this is: there has to be some power always available).

1.2.2 Estimation of the power required

The vast majority of the time, the subsystems of the satellite will work under typical operation conditions. However, the estimation of the power consumption provided in the table 1.2.1 has been made for typical-high conditions in order to have a power margin and a more reliable estimation.

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

Table 1.2.1: Estimation of the power consumption under typical working conditions

It is worth mentioning that the thrusters are not included in the final estimation of the power. The propulsion system will only be active for shorts periods of time to maintain the orbit, and when it ignites, the other subsystems will not perform under typical working conditions. The CubeSat will manage to send only the essential information to the other satellites and, since it is unlikely that their thruster is ignited at the same time, the communication is ensured during the maneuver. There will not be any loss of communication given the different ground stations placed around the Earth and the capacity of the satellite to communicate the essential information to its constellation neighbours.

1.2.3 Solar arrays

They are an essential part of the mission since they are the main source of energy for the CubeSat. The solar arrays used must have a decent efficiency and capacity to collect the energy from the sun, have to keep their mass relatively low, must have a protective radiation shield to ensure their full efficiency for at least 4 years, a proper deployment system, the ability to withstand space conditions and also must be highly compatible with all the other systems used, especially the power management system.

Two options were considered regarding the solar arrays. These options are presented in 1.2.2.

Brand and model	**Features**	**Total price (€) per unit**
Solar arrays		
EXA-Agencia Espacial Ecuatoriana	Total power of 67.2W (4 units) Mass of 175g (per unit) Included thermal protection At least 4 years lifetime	17000
ISIS	Total power of 30W (4 units) Mass of 150g (per unit) No thermal protection At least 2 years lifetime	9000

Table 1.2.2: Options studied for the solar arrays

The option selected for the mission is a set of deployable solar panels provided by **EXA (Agencia Espacial Civil Ecuatoriana)**. These solar arrays fulfill all the requirements mentioned above: they are low mass (135g per unit + 40g of cable weight), they have a protective radiation shield (NEMEA Anti Radiation Shield protects the solar panels of EM, High Gamma, X-Ray, Alfa, Beta and low neutron radiation) they can withstand a very high temperature range (from -80°C to 130°C) ensuring that they can operate in space, they have a gentle release and deployment system with artificial muscles (developed by EXA) and they provide a power of 16.8W each (19.2V@0.5A).

Every CubeSat will come with at least 4 deployable solar panels providing it with 67.2W of power, approximately. Note that additional panels can be equipped but they have to be also low mass equipment (about 80g per array) and highly compatible with the structure of the CubeSat.

1.2.4 Power management system

From the figure 1.2.1, the need of a system that regulates and distributes the energy to the other systems is more than clear. In fact, the Power Management System (PMS) is mandatory for this CubeSat given that the systems used are manufactured by different companies and they have completely different specifications regarding its energy requirements.

Several options were considered regarding the power management system. These options, with their respective main features, are presented in 1.2.3.

Brand and model	Features	Total price (€) per unit
Power management		
Crystalspace P1 Vasik	Mass of 80g Full redundancy Low volume 6x outputs Up to 10W input High temperature range	5400
Gomspace NanoPower P60	Mass of 176g 9x configurable outputs 6x inputs per module EMI shielding High temperature range	16000

Table 1.2.3: Options studied for the power management system

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

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

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

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

All these features make the **NanoPower P60** a very efficient and configurable power management unit that fulfills the mission requirements. Furthermore, given this capacity to configure each input and output channel and the high number of channels that it has, the compatibility between all the systems used in the satellite is ensured. Additionally, the communication between this system and the on board computer in order to detect potential

failures is a really adequate feature, mentioned previously.
With the NanoPower P60, the PMS aims to distribute the energy to all of the subsystems of the CubeSat.

1.2.5 Batteries

The batteries have to provide the energy that the system requires when the solar arrays are not operational. Therefore, it is a very important system due to an energy loss could mean a mission failure (although it would be unlikely since more CubeSats would be ready to handle the information of the CubeSat that failed). The following options (1.2.4) were considered.

Brand and model	Features	Total price (€) per unit
Batteries		
Gomspace NanoPower BP4	Total capacity of 77Wh (2u) Automatic heat regulation Highly stackable Mass of 270g (p.unit)	3250
EXA-Agencia Espacial Ecuatoriana	Total capacity of 106.4Wh (2u) Automatic heat regulation Highly stackable Total mass of 155g	6300

Table 1.2.4: Options studied for the batteries

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

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

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

1.3 Propulsion

There is a big risk of a collision with space debris while a spacecraft is operating in Low Earth Orbits. The Inter-Agency Space Debris Coordination Committee recommended to the United Nations (section 5.3.2 'Objects Passing Through the LEO Region'): "Whenever possible space systems that are terminating their operational phases in orbits that pass through the LEO region, or have the potential to interfere with the LEO region, should be de-orbited (direct re-entry is preferred) or where appropriate manoeuvred into an orbit with a reduced lifetime. Retrieval is also a disposal option." and "A space system should be left in an orbit in which, using an accepted nominal projection for solar activity, atmospheric drag will limit the orbital lifetime after completion of operations. A study on the effect of post- mission orbital lifetime limitation on collision rate and debris population growth has been performed by the IADC. This IADC and some other studies and a number of existing national guidelines have found 25 years to be a reasonable and appropriate lifetime limit." [3]

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

The two most interesting options that were considered when the thruster had to be chosen are presented below.These two thruster are among the most used in the aerospace industry for small satellites. The main difference between both are the thrust and the specific impulse. On the one hand, the BIT-1 thruster provides a lower thrust but with a high specific impulse. On the other hand, BGT-X5 thruster provides a high thrust, around 0.5 N but with a lower specific impulse.

Brand and model	Features	Total price (€)
Propulsion		
Busek ion thruster BIT-1	Volume 1/2 U High Isp (2150 s) Low thrust (100 uN)	58000
Busek BGT-X5	Volume 1 U High thrust (0.5 N) High delta V (146 m/s)	50000

Table 1.3.1: Options studied for the propulsion system

The following table 1.3.2 shows the main parameters of the thruster chosen.

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

Table 1.3.2: Main features of BGT-X5

1.4 AOCS

Given that the AOCS involve so many systems working together, a fully assembled module has been considered in order to avoid compatibility issues.

The two most interesting options that have been considered when the AOCS has been chosen are presented in 1.4.1.

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

Table 1.4.1: Main ADACS features

The options presented in 1.4.1 are the unique systems that fulfill the requirements stated above. Therefore, a decision has been made taking into account only these two systems. Finally, **CUBE ADCS** has been chosen.

1.5 Payload

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

1.5.1 Antennas

The antennas are essential in this mission, since their role is to transmit and receive the data from other satellites as well as the ground stations.

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

Preliminary, after a first satellite preliminary design, seems that patch and turnstile antennas will cover the needs of AstreaSAT.

1.5.1.1 Basic parameters

The **frequency range** is one of the most important parameters, since it is related to an effective satellite-satellite and satellite-ground station communication. The frequency range should be between 1GHz and 10GHz, which is a very demanding condition given that the CubeSat has a limited space and power supply. Those frequencies, assure the desired data rates an negligible atmosphere attenuations.

For an effective communication, the signal has to be able to trespass the atmosphere without a high number of losses and interference. The high frequency range allows the signal to go through this barrier and reach the ground stations.

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

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

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

1.5.1.2 Patch antenna

A **patch antenna** is a type of radio antenna with a low profile, which can be mounted on a flat surface, It consists of a flat rectangular sheet or "patch" of metal, mounted over a larger sheet of metal called a ground plane. They are the original type of micro strip antenna described by Howell in 1972. [4]

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

Table 1.5.1: Main features of the patch antenna

1.5.1.3 Turnstile antenna

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

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

Table 1.5.2: Main features of the turnstile antenna

Although this antenna was considered in the first approximation to the problem, it was finally discarded since it did not fulfill the mission requirements at the same level that the patch antenna did.

1.5.1.4 Antenna selection

After a market study, the antenna that has been chosen and will be equipped in the CubeSat is the patch antenna manufactured by AntDevCov. The satellite will come with 8 of this type of antenna; 4-6 of them will be placed on each side face of the CubeSat and they will occupy a 1U face and the other 2-4 of them will be placed on the top and the bottom.

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

1.5.2 Payload Data Handling Systems

1.5.2.1 Transceivers

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

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

Table 1.5.3: Main inter-satellite communication transceivers features

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

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

Table 1.5.4: Main space to ground communication transceivers features

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

1.5.2.2 PDHS computers

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

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

Table 1.5.5: Main PDHS computers features

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

1.5.3 Study of the commercial available options and options chosen

A broad marked study is needed since all the options have to be considered. For this reason, and with the aim to show all the information and features of each system that has been considered in this section, the table 1.5.6 is presented below.

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

Table 1.5.6: Options studied for the payload

Finally, with the aim to clarify all the information of this section, the chosen systems and components are presented in the table 1.5.7.

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

Table 1.5.7: Options chosen for the payload

1.6 Link Budget

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

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

1.6.1 Communications Basics

When evaluating a wireless link, the three most important questions to be answered are: [5]

1. **How much radio frequency (RF) power is available?**
   Up to 2W for S band or up to 12W for Xband.
2. **How much bandwidth is available?**
   Available 400MHz with 28 channels of 14MHz or 228 channels of 1.75MHz for inter-satellite communication at S band. For X band, there's more than 4GHz available [6]. In fact is limited by the TR-600 transceiver at 56MHz for S band and to 100MHz by SWIFT - XTS at X band.
3. **What is the required reliability (as defined by Bit Error Rate, or BER)?**
   Required reliability for space systems$E_b/N_o \geq 10$, so $BER = 5.5x10^{-6}$ for a MSK, PSK (worst case) modulation as shown in Fig.1.6.5.

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

$$C = B \cdot log_2(1 + S/N) \tag{1.6.1}$$

where:

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

With all data known, the minimum required sensitivity of a receiver using the Eq. 1.6.1 will be stated in the Link Budget calculation.

Transmission Losses

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

TRANSMISSION LOSSES	PROPAGATION LOSSES	FREE SPACE LOSSES		
		ATMOSPHERIC LOSSES	Ionospheric effects	Faraday rotation
				Scintillation effects
			Tropospheric effects	Attenuation
				Rain attenuation
				Gas absorption
				Depolarization
				Sky noise
			Local effects	
		POINTING LOSSES		
	LOCAL LOSSES	EQUIPMENT LOSSES	Feeder losses	
			?????	
		ENVIRONMENT LOSSES		

Figure 1.6.1: Principal losses in the received signal [7]

1.6.2 Propagation losses

1.6.2.1 Free Space Losses

Range and Path Loss

Another key consideration is the issue of range. As radio waves propagate in free space, power falls off as the square of range. For a doubling of range, power reaching a receiver antenna is reduced by a factor of four. This effect is due to the spreading of the radio waves as they propagate, and can be calculated by [5]:

$$L = 20log_{10}(4\pi D/\lambda) \tag{1.6.2}$$

where:

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

1.6.2.2 Atmospheric Losses

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

- Atmospheric attenuation.
- Atmospheric absorption.

The major distinguishing factor between them is their origin. Attenuation is weather related, while absorption comes in clear-sky conditions. Likewise, these losses can be due to ionospheric, tropospheric and other local effects. [7]

Ionospheric Effects

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

- **Polarization rotation**: When a radio wave passes through the ionosphere, it contacts the layers of ionized electrons that move according to the Earth's magnetic field. The direction these electrons move will no longer be parallel to the electric field of the wave and therefore the polarization is shifted, in what is called Faraday rotation (θ_F). ;

- **Scintillation effects**: Differences in the atmospheric refractive index may cause scattering and multipath effect, due to the different directions rays may take through the atmosphere. They are detected as variations in amplitude, phase, polarization and angle of arrival of the radio waves. It is often recommended the introduction of a fade margin so atmospheric scintillation can be a tolerated phenomenon.;
- Absorption
- Variation in the direction of arrival
- Propagation delay
- Dispersion
- Frequency change

These effects decrease usually with the increase of the square of the frequency and most serious ones in satellite communications are the polarization rotation and the scintillation effects, and those are the ones that will be treated in this dissertation. [7]

Tropospheric Effects [7]

Troposphere is composed by a miscellany of molecules of different compounds, such as hail, raindrops or other atmospheric gases. Radio waves that pass by troposphere will suffer their effects and will be scattered, depolarized, absorbed and therefore attenuated.

Attenuation As radio waves cross troposphere, radio frequency energy will be converted into thermal energy and that attenuates signal.

Rain attenuation Ground stations had been chosen in order that the attenuation caused by rainfall will be very punctual. Also, the fact that there are three ground stations makes really difficult that a satellite can not communicate to the ground in all the orbit period.

Gas absorption Under normal conditions, only oxygen and water vapour have a significant contribution in absorption. Other atmospheric gases only become a problem in very dry air conditions above 70 GHz.

Thereby, losses caused by atmospheric absorption vary with frequency and the collection of data already received allows the elaboration of the graphic that follows:

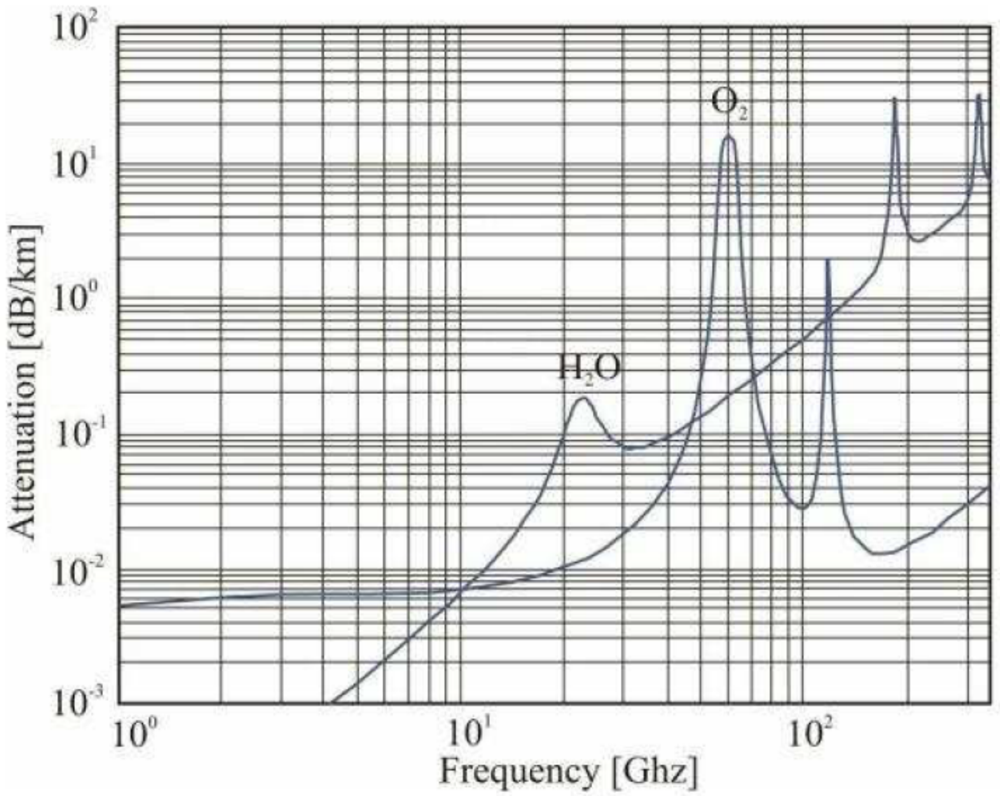

Figure 1.6.2: Specific attenuation for different frequencies [7]

Once these values depend on atmosphere thickness, it becomes necessary to perform all calculations taking into account troposphere's thickest layer (T_{trop}), which has 20 km.
It is also mandatory to refer that this graph represents the absorption for a satellite in the zenith, in other words, for an elevation angle of 90º ($\theta = 90º$). For lower angles, the atmospheric absorption (L_{abs}) is given by [7]:

$$L_{abs}(dB) = L_{abs|90^{o}}(dB/km)\ cosec(\theta)\ T_{trop}(km) \tag{1.6.3}$$

For AstreaSAT, $5\text{x}10^{-3} dB/km$ attenuation factor is considered for S band due to the O_2 specific attenuation. On the other hand, $4\text{x}10^{-3} dB/km$ attenuation factor is considered for X band due to the H_2O and to the O_2 specific attenuations. An study of the critical elevation angle will lately be performed.

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

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

Polarization Satellite communications use linear and circular polarization, but undesirable effects may transform it into an elliptical polarization. Depolarization may occur when an orthogonal component is created due to the passing of the signal through the ionosphere. There are two ways to measure its effect, cross polarization discrimination (XPD) and polarization isolation (I) [7]. To overcome this attenuation problems a circular polarization is the best option. AstreaSAT patch antennas will mitigate this problem, therefore this loses are considered negligible.

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

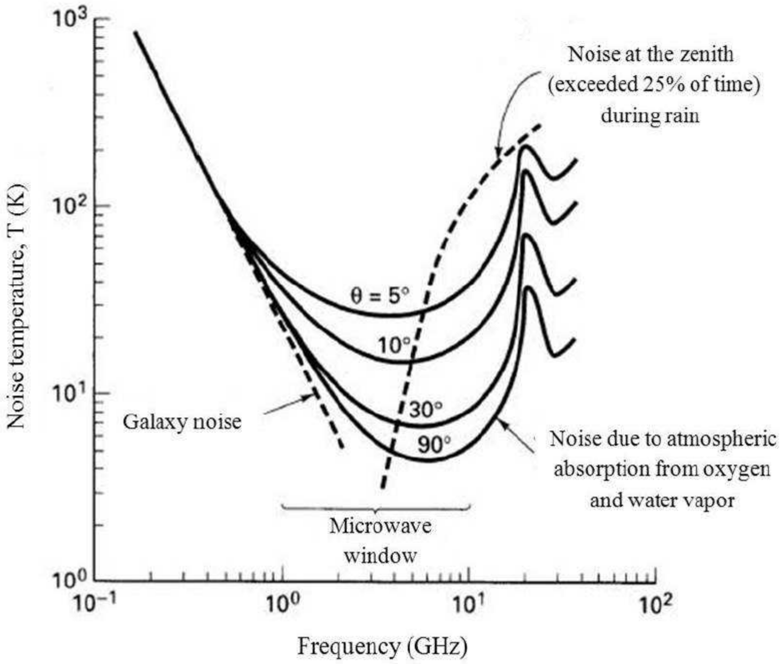

Figure 1.6.3: Galaxy noise influence in noise temperature [7]

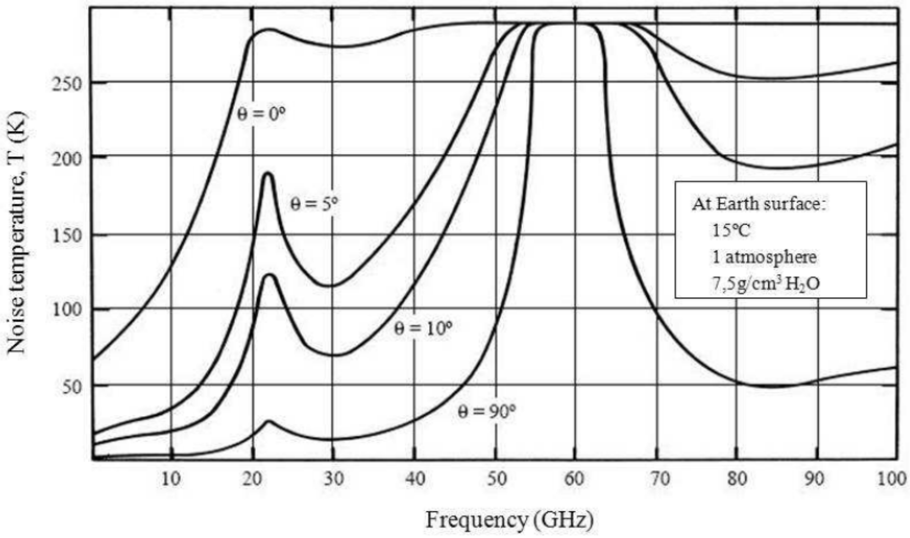

Figure 1.6.4: Noise temperature variation with frequency [7]

AstreaSAT noise temperature A good approximation based on Fig.1.6.3 is that Galaxy noise is 3K for S band and almost 1K for X band. Furthermore, for the previous worst case scenario stated before $\theta = 10$, noise temperature due to atmospheric absorption is 19K for both bands (S and X).

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

1.6.2.3 Pointing Losses

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

Antenna misalignment losses (L_{aml}) are calculated using statistical data, so these values are an approximation based on real data observed in several GS. Ergo, these values are not calculated, but estimated. [7]

Based on a estimation from [8] a $L_{aml} = 1dB$ is a good approximation.

1.6.2.4 Multipath and Fade Margin

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

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

1.6.3 Local Losses

1.6.3.1 Equipment Losses

The receiving and emitting equipments also introduces some losses to the signal.

Feeder Losses Feeder losses occur in the several components between the receiving antenna and the receiver device, such as filters, couplers and wave guides. These losses are similar to the ones which occur also in the emission, between the emitting antenna and the output of the high power amplifier (HPA). [7]

1.6.3.2 Environment Losses

This item is related to the specific region of the globe where the ground station is placed (equatorial, tropical, polar…). Depending on its latitude, each region has its own characteristics (e.g. temperature, moisture, thickness of atmospheric ice layer), which may provoke variation in signal reception. [7]

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

1.6.4 Modulation Technique

Modulation technique is a key consideration. This is the method by which the analogue or digital information is converted to signals at RF frequencies suitable for transmission. Selection of modulation method determines system bandwidth, power efficiency, sensitivity, and complexity. Most of us are familiar with Amplitude Modulation (AM) and Frequency Modulation (FM) because of their widespread use in commercial radio. Phase Modulation is another important technique. It is used in applications such as Global Position System (GPS) receivers and some cellular telephone networks. [5]

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

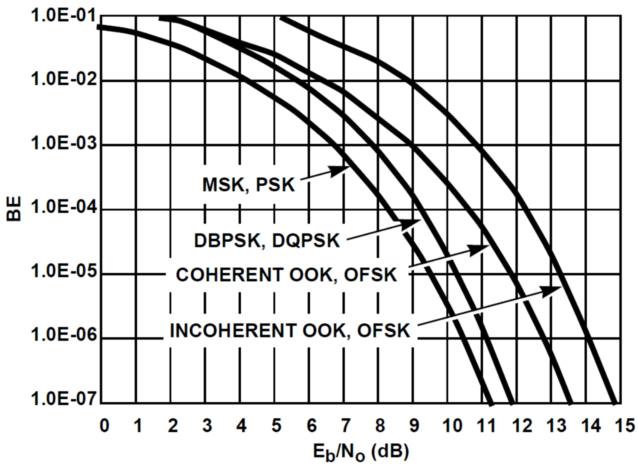

Figure 1.6.5: Probability of bit error for common modulation methods [5]

A graph of E_b/N_o vs BER is shown in Figure 1.6.5. E_b/N_o is a measure of the required energy per bit relative to the noise power. Note that E_b/N_o is independent of the system data rate. In order to convert from E_b/N_o to SNR, the data rate and system bandwidth must be taken into account as shown below:

$$SNR = (E_b/N_o)(R/B_T) \tag{1.6.4}$$

where:

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

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

1.6.5 System Noise

The system noise temperature (T_S) is the sum of the antenna noise temperature (T_A) and the composite temperature of other components (T_{comp}), according to: [7]

$$T_S = T_A + T_{comp} \tag{1.6.5}$$

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

$$T_A = T_m\ (1 - 10^{-A/10}) + T_C\ 10^{-A/10} \tag{1.6.6}$$

Usually, for clouds it is considered $T_m = 280K$ and for the rain $T_m = 260K$. The sky noise tends to be $T_C = 10K$. Taking into account the values from Fig.1.6.3 and Fig.1.6.2 the following estimation can be made:

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

According to [7] a good components temperature approximation for a typical ground station is $T_{comp} = 65.5K$.

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

Channel Noise All objects which have heat emit RF energy in the form of random (Gaussian) noise. The amount of radiation emitted can be calculated by [5]:

$$N = kTB \tag{1.6.7}$$

where:

$$N = \text{noise power (watts)}$$
$$k = \text{Boltzman's constant}(1.38\text{x}10^{-23} J/K)$$
$$T = \text{system temperature, usually assumed to be 290K}$$
$$B = \text{channel bandwidth (Hz)}$$

This is the lowest possible noise level for a system with a given physical temperature. For most applications, temperature is typically assumed to be room temperature (290K). Equations 1.6.1 and 1.6.7 demonstrate that RF power and bandwidth can be traded off to achieve a given performance level (as defined by BER). [5]

1.6.6 Link Budget Calculation

1.6.6.1 Methodology

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

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

To verify communication system chosen options, let's start calculating the minimum required sensitivity for receiving strong enough signal. With this value, it is possible to know how far the satellite can listen to information. Applying equation 1.6.1 and equation 1.6.7 on a simple Matlab routine:

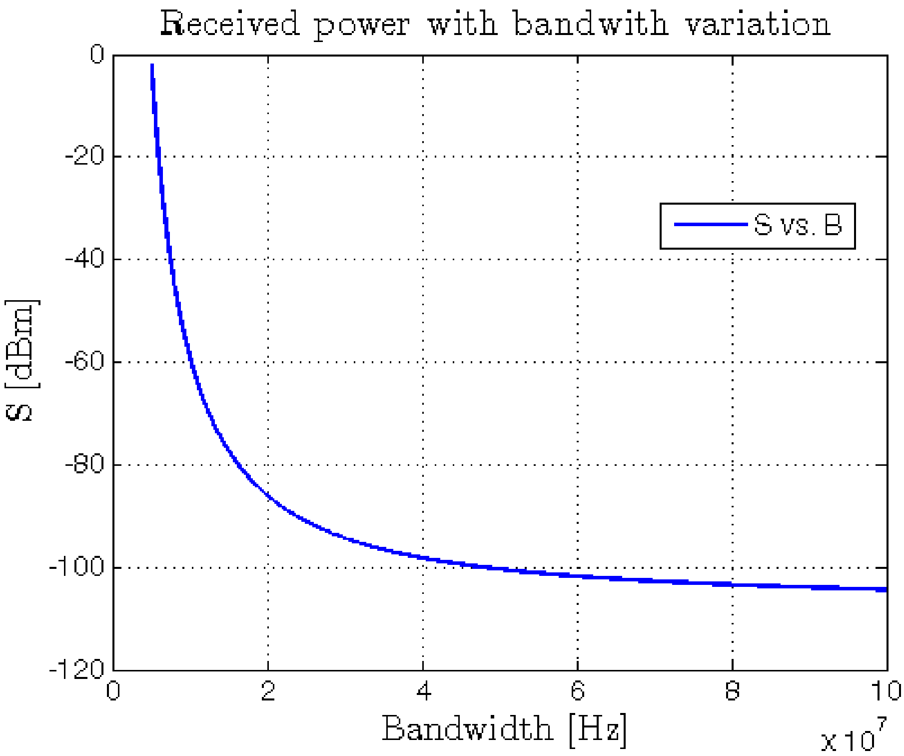

Figure 1.6.6: Sensibility change along Bandwidth variation

As bandwidth increments, Sensitivity decrements, meaning that we need higher powered receivers in order to sense high bandwidth communications.

1.6.6.2 Range calculation

To know how far the satellite can be received or listen to, Friis equation 1.6.8 will be applied.

$$P_r = P_t + G_t + G_r - FSL - L_{abs} - L_{aml} - L_{point} \tag{1.6.8}$$

P_r : Received power

P_t : Transmitted power

G_t : Transmitter antenna gain

G_r : Receiver antenna gain

L_{prop} : All kind of losses

$$L_{prop} = FSL - L_{abs} - L_{aml} - L_{point}$$

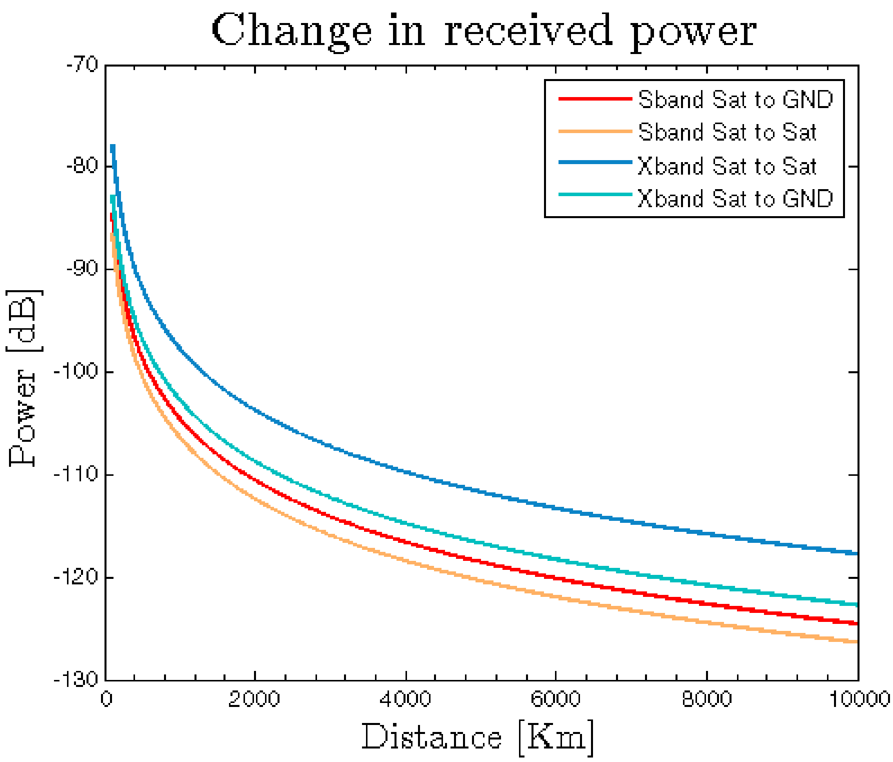

Figure 1.6.7: Received power with distance variation

S band range

On Fig.1.6.7 earth atmosphere and multiple losses (described previously) affect to the received power on ground. Despite all, ground station have powerful antennas that mitigate the losses effect. Therefore, because of the low gain of the antennas between satellites, the link is weaker.

X band range

In this case, X band, because its high frequency is more affected by atmospheric losses. Is it possible to appreciate it on Fig.1.6.7. Link between satellites is stronger that the one with the ground. Finally remark a fact, despite higher frequencies should have weaker links, in this case, the high antenna gains for X band, confer stronger links to the X band.

In order to use satellite communications, will be necessary to use Fig.1.6.6 and 1.6.7. From 1.6.7, given a determinate altitude a power sensibility can be extract. Then, on 1.6.6, taking the previous sensibility calculated, a Bandwidth for operation can be stated. The procedure works on both sites.

1.7 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.

2 | Bibliography

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