astrea

ESEIAAT

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UNIVERSITAT POLITÈCNICA DE CATALUNYA

Cubesat Constellation
Astrea

Report

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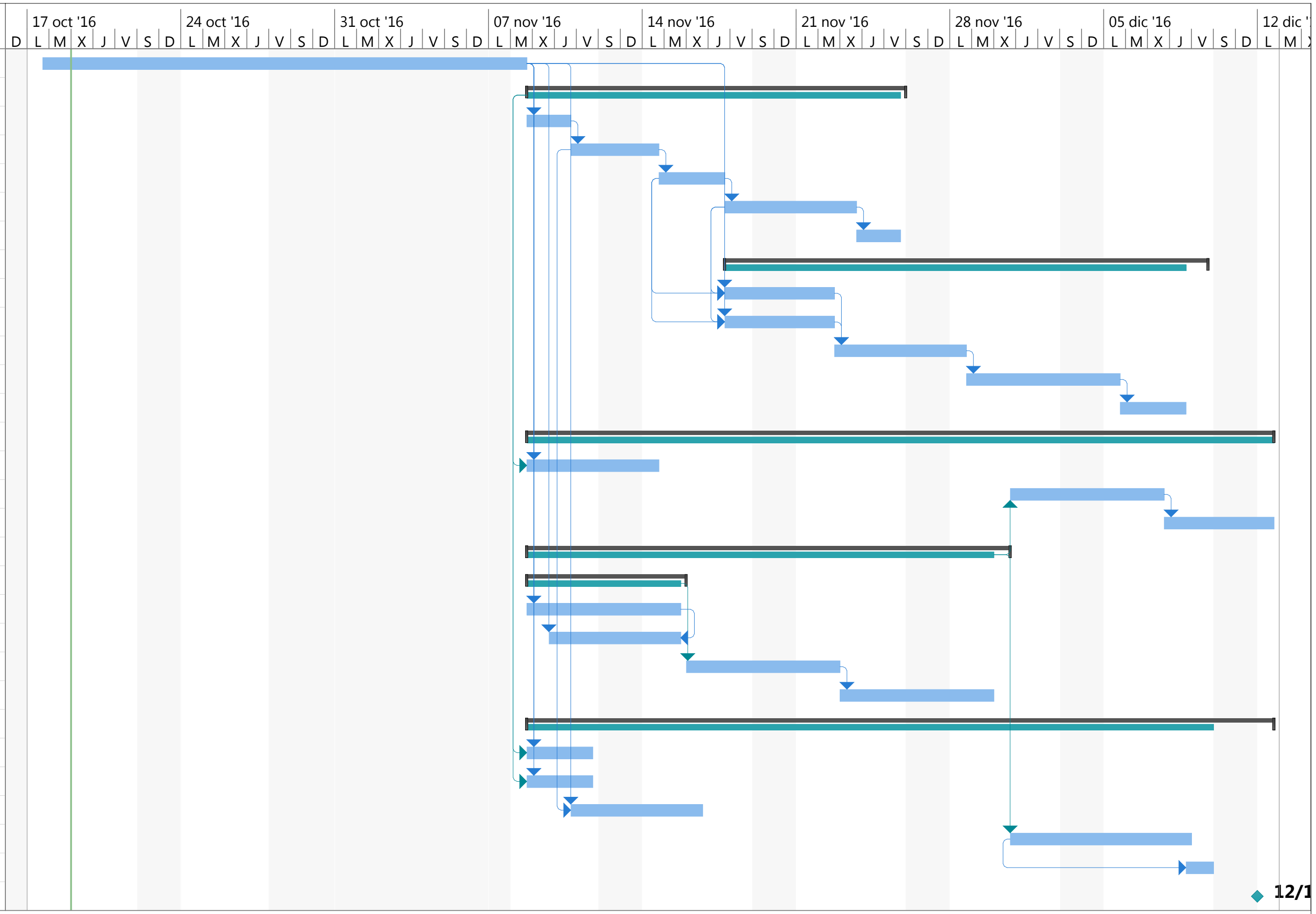
Table 1.1: Prelations and Time

2 Gantt of the section

Id	EDT	Nombre de tarea	Duración	Comienzo	Fin
1	1	PRELIMIARY DESIGN	28 horas	lun 17/10/16	mar 08/11/16
2	**2**	**Structure and mechanics**	**5 días**	**mar 08/11/16**	**vie 25/11/16**
3	2.1	Structure	6 horas	mar 08/11/16	jue 10/11/16
4	2.2	Deployments	6 horas	jue 10/11/16	lun 14/11/16
5	2.3	Thermal protection	9 horas	lun 14/11/16	jue 17/11/16
6	2.4	Comercial availability	12 horas	jue 17/11/16	mié 23/11/16
7	2.5	Choose option	6 horas	mié 23/11/16	vie 25/11/16
8	**3**	**Electrical Power System**	**6 días**	**jue 17/11/16**	**vie 09/12/16**
9	3.1	Solar arrays	9 horas	jue 17/11/16	mar 22/11/16
10	3.2	Batteries	9 horas	jue 17/11/16	mar 22/11/16
11	3.3	Power management	12 horas	mar 22/11/16	lun 28/11/16
12	3.4	Comercial availability	15 horas	lun 28/11/16	lun 05/12/16
13	3.5	Choose option	9 horas	lun 05/12/16	jue 08/12/16
14	**4**	**Propulsion Systems**	**9 días**	**mar 08/11/16**	**lun 12/12/16**
15	4.1	Requirements	12 horas	mar 08/11/16	lun 14/11/16
16	4.2	Comercial availability	15 horas	mié 30/11/16	mié 07/12/16
17	4.3	Choose option	9 horas	mié 07/12/16	lun 12/12/16
18	**5**	**Payload**	**6 días**	**mar 08/11/16**	**mié 30/11/16**
19	**5.1**	**Communication systems**	**2 días**	**mar 08/11/16**	**mar 15/11/16**
20	5.1.1	Data Handling Systems	15 horas	mar 08/11/16	mar 15/11/16
21	5.1.2	Antenna	12 horas	mié 09/11/16	mar 15/11/16
22	5.2	Comercial availability	15 horas	mar 15/11/16	mar 22/11/16
23	5.3	Choose option	15 horas	mar 22/11/16	mar 29/11/16
24	**6**	**AOCS**	**9 días**	**mar 08/11/16**	**lun 12/12/16**
25	6.1	Attitude Determination	9 horas	mar 08/11/16	vie 11/11/16
26	6.2	Attitude control	9 horas	mar 08/11/16	vie 11/11/16
27	6.3	Orbital Control	12 horas	jue 10/11/16	mié 16/11/16
28	6.4	Comercial availability	20 horas	mié 30/11/16	jue 08/12/16
29	6.5	Choose option	4 horas	jue 08/12/16	vie 09/12/16
30		FINISH	0 horas	lun 12/12/16	lun 12/12/16



Proyecto: planning
Fecha: mié 19/10/16

Tarea
División
Hito
Resumen
Resumen del proyecto
Tarea inactiva
Hito inactivo
Resumen inactivo
Tarea manual
solo duración
Informe de resumen manual
Resumen manual
solo el comienzo
solo fin
Tareas externas
Hito externo
Fecha límite
Progreso
Progreso manual

3 Satellite design

3.1 Structure and mechanics

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

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

3.1.1 Structure

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

The structure chosen is manufactured by Innovative Solutions In Space (ISIS). Among its features it is worth mentioning that it can withstand the high range of temperature it will face in the space (from -40ºC to 80ºC) and it is highly compatible; almost every physical system used can be placed within the structure or on its faces (such as the antennas or the solar arrays). Finally, the mass of the structure is relatively low, and given that the mass of the other subsystems is not their best feature, it is plus point.

3.1.2 Thermal protection

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

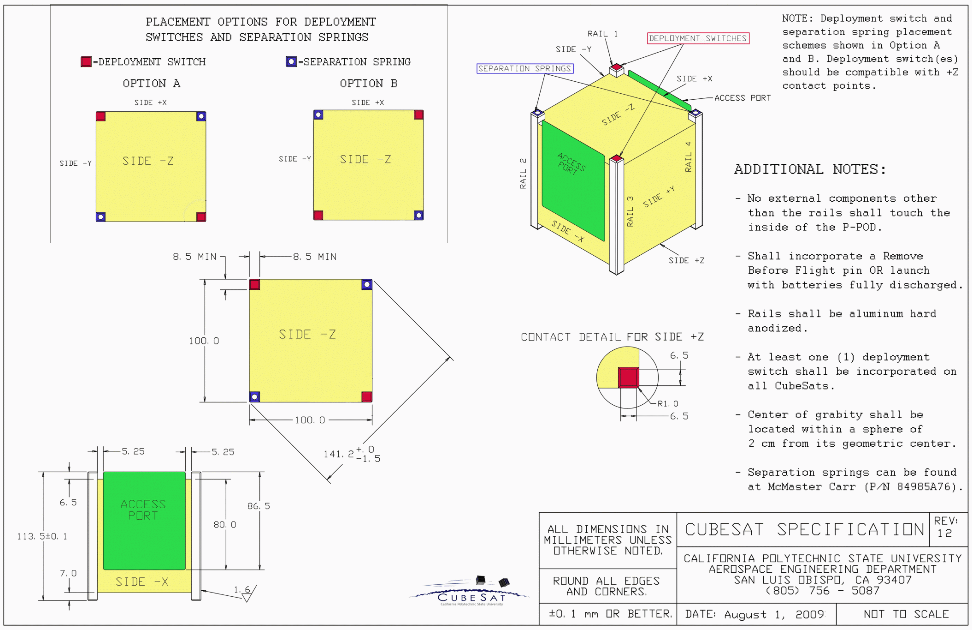


Figure 3.1: Dimensions of a 1U CubeSat

[?]

Operating in space, the CubeSat is vulnerable to suffer extreme temperatures, both below zero and above zero, and thermal protection must guarantee that all subsystems are protected. Furthermore, the thermal protection system should also dissipate the heat produced by the other systems.

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

After a market study, Dunmore Aerospace company has been chosen to provide us its MLI product. Specially, the product is the Dunmore Aerospace Satkit and it is made for small satellites for low earth orbit.

3.1.3 Study of the commercial available options and options chosen

A broad marked study is needed since all the options have to be considered. For this reason, and with the aim to show all the information and features of each system that has been considered in this section, the table 3.1 is presented below.

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

Table 3.1: Options studied

Finally, the options chosen are presented in the table 3.2.

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

Table 3.2: Options chosen

3.2 Electrical Power System

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

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

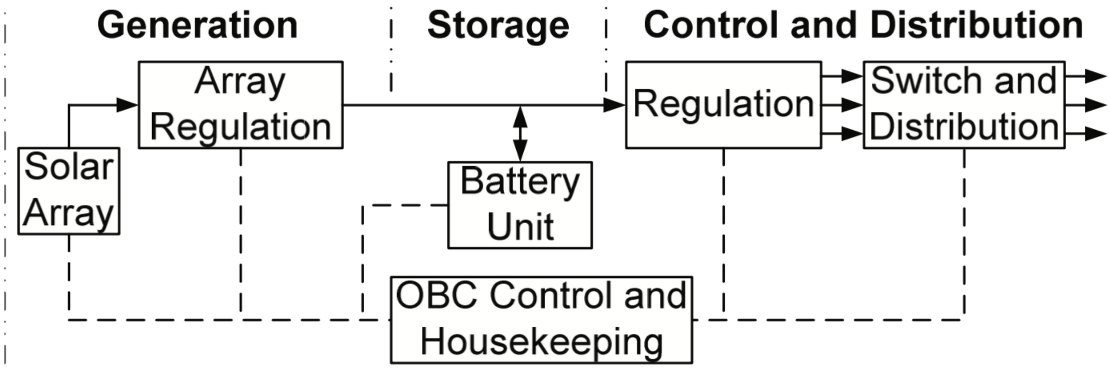


Figure 3.2: Basic schematics of the EPS

[?]

3.2.1 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 batteries, as well as the power management system, an estimation of the power consumed has to be made.

The vast majority of the time the satellite will work under typical operation conditions. However, the estimation of the power consumption provided in the table 3.3 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 (4)	6
Turnstile antenna (2)	6
Payload power consumption	36
Electrical Power System	
NanoPower P60 Power Module (1)	2
Battery (2)	-
Solar arrays (4)	-
EPS power consumption	2
Data Handling Systems	
Transceiver (4)	6
DHS power consumption	X
Propulsion and ACDS	
Thruster (1)	20
Turnstile antenna (2)	6

OACDS power consumption	X
Estimated total power consumption	45

Table 3.3: Estimation of the power consumption under typical working conditions

3.2.2 Solar arrays

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

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

The option selected for the mission is a set of deployable solar panels provided by EXA (Agencia Espacial Civil Ecuatoriana). These solar arrays fulfill all the requirements mentioned above: they are low mass (135g per unit), they have a protective radiation shield (NEMEA Anti Radiation Shield protects the solar panels of EM, High Gamma, X-Ray, Alfa, Beta and low neutron radiation) they can withstand a very high temperature range (from -80 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 4 deployable solar panels providing it with 67.2W of power, approximately, to supply peak demands during the lifetime of the mission. Additionally, it is worth mentioning that these solar arrays are compatible with the hardward used (the structure and the power management system).

3.2.3 Power management system

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

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

The motherboard supports up to 4 ACU and PDU modules and has different regulated outputs (3.3V and 5V). It means that with one single motherboard, several conditioning and distributing units can be connected.

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

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

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

3.2.4 Batteries

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

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

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

3.2.5 Study of the commercial available options and options chosen

A broad marked study is needed since all the options have to be considered. For this reason, and with the aim to show all the information and features of each system that has been considered in this section, the table 3.4 is presented below.

Brand and model	Features	Total price (€)
Solar arrays		
EXA-Agencia Espacial Ecuatoriana	Total power of 67.2W (4units) Mass of 270g (p.unit) Included thermal protection At least 4 years lifetime	17000
ISIS	Total ower of 30W (4units) Mass of 150g (p.unit) No thermal protection At least 2 years lifetime	**TO REQUEST!**
Power management		
Crystalspace P1 Vasik	Mass of 80g Full redundancy Low volume 6x outputs Up to 10W input High temperature range	**TO REQUEST!**
Gomspace NanoPower P60	Mass of 176g 9x configurable outputs 6x inputs per module EMI shielding High temperature range	16000

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

Table 3.4: Options studied

Finally, the options chosen are presented in the table 3.5.

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

Table 3.5: Options studied

3.3 Propulsion Systems

3.3.1 Requirements

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

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

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

3.3.2 Thrusters

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

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

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

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

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

The following table 3.6 shows the main parameters of this thruster.

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

Delta V	146 m/s

Table 3.6: Thruster chosen

3.3.3 Study of the commercial available options

A broad marked study is needed since all the options have to be considered. For this reason, and with the aim to show all the information and features of each system that has been considered in this section, the table 3.7 is presented below.

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

Table 3.7: Options studied

Finally, the option chosen is presented in the table 3.8.

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

Table 3.8: Options chosen

3.4 Attitude and Orbital Control Systems

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

3.4.1 Attitude Determination

EMPTY

3.4.2 Attitude Control

EMPTY

3.4.3 Orbital Control

Thrusters

3.4.4 Study of the commercial available options

Brand and model	Features and description	Money (€)
Solar Panels		
Fabricant 1	EMPTY	2000000
Chuscas 1	EMPTY	20000
Truñaas 1	EMPTY	20000
Cuescas 1	EMPTY	20000

Table 3.9: Options studied

3.5 Payload

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

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

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

The radio frequencies that we can use to establish the previous described links are regulated in [3] by frequency, bandwidth and type of communication . So, for the **Space to Ground link** we can use frequencies from **70MHz** to **240GHz**; for **Inter-satellite Space to Space link** plus data relay type of communication, frequencies are **2-2.4GHz**, **4-4,4GHz** and **22-240GHz**.

Finally, **Client Space to Space link**, they exist to cases; on the one hand, the client points towards the Earth like a standard satellite, we capture its signal and make the data relay, since it is like a Space to Ground communication and also like a inter-satellite communication, we can combine the two previous restrictions. On the other hand, if the client satellite is below our constellation, we only had inter-satellite communication, therefore **Inter-satellite Space to Space link** rules are applied.

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

3.5.1 Antennas

The antennas are essential in this mission, since their role is to transmit and receive the data from other satellites as well as the ground stations. In order to provide fast and reliable communication, several options have been studied and information about their main parameters is presented below.
It has to be kept in mind that the mass of the antennas should be as low as possible given that there are already a lot of subsystems in the CubeSat and the mass limitation is about 4kg. Additionally, the power consumption has to be kept as low as possible given the limitations regarding to the power supply of the CubeSat. The antennas must be certified to work under space conditions (high temperature range and radiation protection shield).
Preliminary, after a first satellite preliminary design, seems that patch and turnstile antennas will cover the needs of AstreaSAT.

3.5.1.1 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.

3.5.1.2 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 microstrip antenna described by Howell in 1972. [**?**, wikipedia]

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

Table 3.10: Main features of the patch antenna

3.5.1.3 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 3.11: Main features of the turnstile antenna

3.5.2 Antenna selection

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

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

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

3.5.3 Payload Data Handling Systems

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

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

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

3.5.3.1 Transceivers

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

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

Table 3.12: 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	-40ºC to +85ºC	-35ºC to +70ºC
Mass	350 grams	250 grams

Table 3.13: 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.

3.5.3.2 PDHS computers

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

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

Table 3.14: Main PDHS computers features

3.5.3.3 Commercial options

3.5.4 Study of the commercial available options and options chosen

A broad marked study is needed since all the options have to be considered. For this reason, and with the aim to show all the information and features of each system that has been considered in this section, the table 3.15 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)	To request
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		
POSAR!!!	**POSAR!!** **POSAR!!**	17000
POSAR!!!	**POSAR!!** **POSAR!!**	17000

Table 3.15: Options studied

Finally, with the aim to clarify all the information of this section, the chosen systems and components are presented in the table 3.16.

System	Brand and model	Price per unit (€)	N. of units
Antenna	Patch antenna AntDevCo	TO REQUEST!	4
Antenna	Turnstile antenna ANT430 Gomspace	9500	2
TRANSCEIVER	EMPTY	TO REQUEST	1
DHS	EMPTY	20000	1

Table 3.16: Options chosen

3.6 Communication module

Every Astrea satellite (AstreaSAT) of the constellation, needs to communicate to the ground for providing basic telemetry status about its operating status. It could also need to receive commands from the ground to reprogram its software, change attitude or even the orbit. So,

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

The command and control subsystem allows the ground station to control the satellite.

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

3.7 Link Budget

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

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

The link budget calculations are mostly calculated using the following fonts: [1].

3.7.1 Communications Basics

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

1. How much radio frequency (RF) power is available?
2. How much bandwidth is available?
3. What is the required reliability (as defined by Bit Error Rate, or BER)?

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

$$C = Blog_2(1 + S/N) \tag{3.1}$$

where:

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

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

<table>
<tr><td rowspan="12">TRANSMISSION LOSSES</td><td rowspan="9">PROPAGATION LOSSES</td><td colspan="3">FREE SPACE LOSSES</td></tr>
<tr><td rowspan="7">ATMOSPHERIC LOSSES</td><td>Ionospheric effects</td><td>Faraday rotation
Scintillation effects</td></tr>
<tr><td rowspan="5">Tropospheric effects</td><td>Attenuation</td></tr>
<tr><td>Rain attenuation</td></tr>
<tr><td>Gas absorption</td></tr>
<tr><td>Depolarization</td></tr>
<tr><td>Sky noise</td></tr>
<tr><td colspan="2">Local effects</td></tr>
<tr><td colspan="3">POINTING LOSSES</td></tr>
<tr><td rowspan="3">LOCAL LOSSES</td><td rowspan="2">EQUIPMENT LOSSES</td><td>Feeder losses</td><td rowspan="2"></td></tr>
<tr><td>?????</td></tr>
<tr><td>ENVIRONMENT LOSSES</td><td colspan="2"></td></tr>
</table>

Figure 3.3: Principal losses in the received signal [1]

3.7.2 Propagation losses

3.7.2.1 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 [2]:

$$L = 20log_{10}(4\pi D/\lambda) \tag{3.2}$$

where:

$D =$ the distance between receiver and transmitter

$\lambda =$ free space wavelength = c/f

$c =$ speed of light$(3\text{x}10^8 m/s)$

$f =$ frequency (Hz)

3.7.2.2 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 weatherrelated, while absorption comes in clear-sky conditions. Likewise, these losses can be due to ionospheric, tropospheric and other local effects. [1]

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. [1]

Tropospheric Effects [1] 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: Once these values depend on atmosphere thickness, it becomes necessary to perform

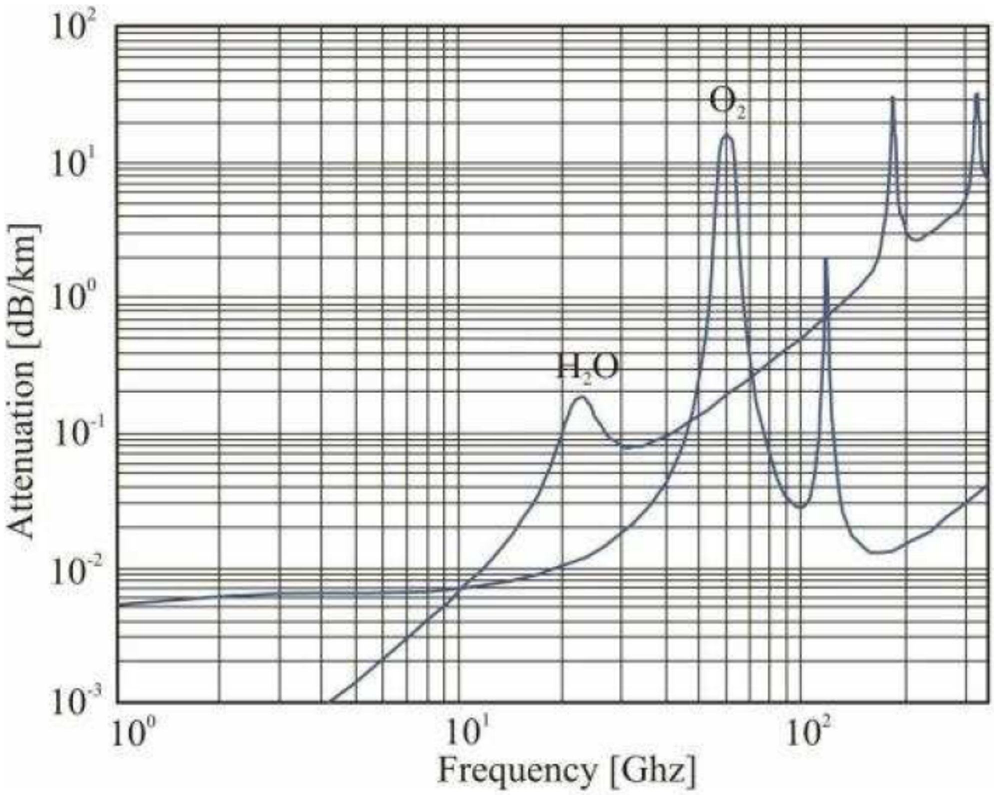


Figure 3.4: Specific attenuation for different frequencies [1]

all calculations taking into account troposphere's thickest layer (T_trop), which has 20 km.

It is also mandatory to refer that this graph represents the absorption for a satellite in the zenith, in other words, for an elevation angle of 90° ($\theta = 90°$). For lower angles, the atmospheric absorption (L_{abs}) is given by [1]:

$$L_{abs}(dB) = L_{abs|90^o}(dB/km)\ cosec(\theta)\ T_{trop}(km) \tag{3.3}$$

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)[1]. To overcome this attenuation problems a circular polarization is the best option.

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.

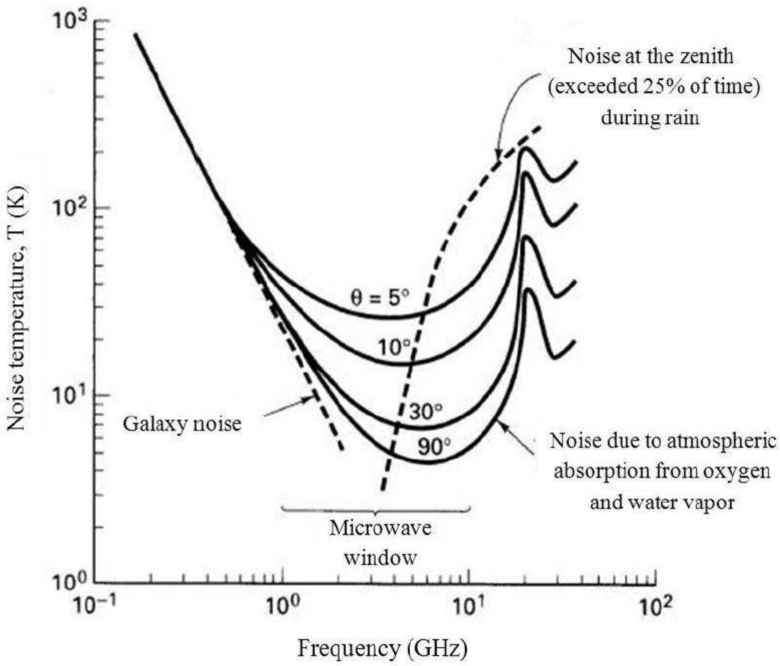


Figure 3.5: Galaxy noise influence in noise temperature [1]

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.

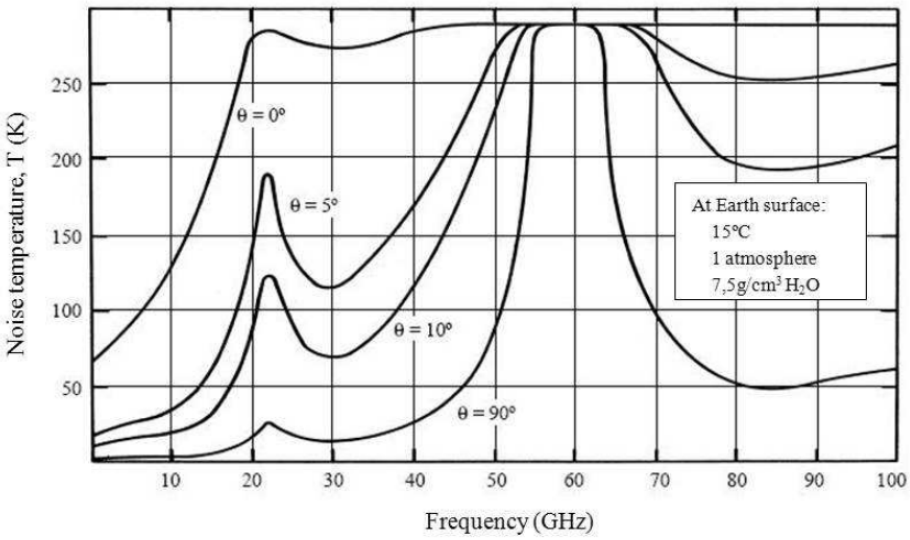


Figure 3.6: Noise temperature variation with frequency [1]

3.7.2.3 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.[1]

3.7.2.4 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.

3.7.3 Local Losses

3.7.3.1 Equipament Losses

The receiving and emitting equipments also introduces some losses to the signal.
Feeder Losses: Feeder losses occur in the several components between the receiving antenna and the receiver device, such as filters, couplers and waveguides. These losses are similar to the ones which occur also in the emission, between the emitting antenna and the output of the high power amplifier (HPA).[1]

3.7.3.2 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. [1]

3.7.4 Modulation Technique

Modulation technique is a key consideration. This is the method by which the analogue or digital information is converted to signals at RF frequencies suitable for transmission. Selection of modulation method determines system bandwidth, power efficiency, sensitivity, and complexity. Most of us are familiar with Amplitude Modulation (AM) and Frequency Modulation (FM) because of their widespread use in commercial radio. Phase Modulation is another important technique. It is used in applications such as Global Position System (GPS) receivers and some cellular telephone networks. [2]

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.

A graph of Eb/No vs BER is shown in Figure 3.7. 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:

$$SNR = (E_b/N_o)(R/B_T) \tag{3.4}$$

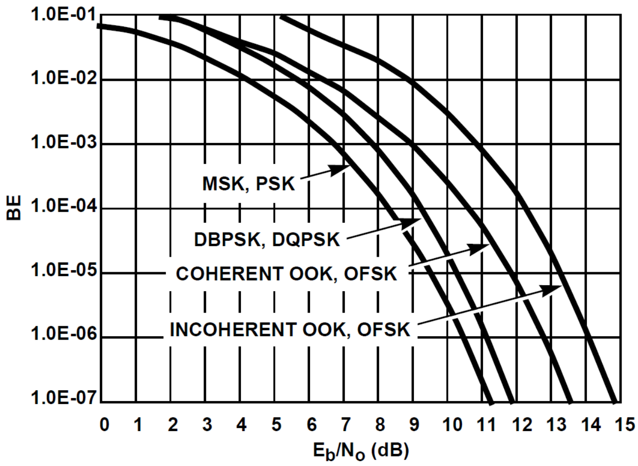


Figure 3.7: Probability of bit error for common modulation methods [2]

where:

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

3.7.5 System Noise

The system noise temperature (T_S) is the sum of the antenna noise temperature (T_A) and the composite temperature of other components (T_{comp}), according to: [1]

$$T_S = T_A + T_{comp} \tag{3.5}$$

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:

$$T_A = T_m\ (1 - 10^{-A/10}) + T_C\ 10^{-A/10} \tag{3.6}$$

Usually, for clouds it is considered $T_m = 280K$ and for the rain $T_m = 260K$. The sky noise tends to be $T_C = 10K$.

According to [1] a good components temperature approximation for a typical ground station is $T_{comp} = 65.5K$.

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 [2]:

$$N = kTB \tag{3.7}$$

where:

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

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 3.1 and 3.7 demonstrate that RF power and bandwidth can be traded off to achieve a given performance level (as defined by BER). [2]

3.7.6 Link Budget Calculation

Methodology From the expected requirements fixed on the Project Charter, general radio systems parameters will computed, in order to have a reference to look for the best communications system on board the Astrea satellites.

$EIRP = P_T - L_T - G_T$

3.8 Budget

System	Weight/unit (g)	Cost/unit (€)	N. of units
STRUCTURE AND MECHANICS			
Structure	304.3	3900	1
Thermal protection			1
Total	304.3	3900	
ELECTRIC POWER SYSTEM			
Solar arrays	270	17000	4
Batteries	155	6300	2
Power management	176	16000	1
Total	1566	96600	
PAYLOAD			
Patch antenna	120		4

Turnstile antenna	30	9500	2
Transceiver			
Data handling system			
Total	540	19000	
AOCDS			
Thruster	1500	50000	1
CubeSpace ACDS			1
Total	1500	50000	
TOTAL ESTIMATION			

3.9 Astrea satellite Final Configuration

4 References

[1] Carlos Jorge and Rodrigues Capela. Protocol of Communications for VORSAT Satellite - Link Budget. (April), 2012.

[2] Application Note. Tutorial on Basic Link Budget Analysis. *Intersil*, (June 1998):1–8, 1998.

[3] 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.