Preliminary Design and Thermal Study of the IGOSat Project

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M2 OSAE Internship Report August 2014

Abstract (English)

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by Pedro Lopes

The Ionospheric Gamma Ray Observation Satelllite, also known as IGOSat, was the instigator to start this study. Being a project embracing the knowledge of miscellaneous areas, it represents a very interesting opportunity for many students to discover and develop their knowledge on the field.

The IGOSat project is being developed by many recognized entities in the space field, such as Paris-Diderot University, CNES, JANUS, the Laboratoire d'Excellence UnivEarthS and others.

This study in particular focuses on the design implementation and thermal characterization of a satellite in space, namely a CubeSat.

In order to proceed with this investigation, we had to resort to IDM-CiC and *Systema & Thermica* as working tools, which proved to be very effective. IDM-CiC was used to create a preliminary model and *Systema & Thermica* used this model to simulate the satellite in orbit and calculate its thermal behaviour.

The main conclusion that came to light with this study is that, at the moment, it seems to be too early to determine the exact thermal control requirements of this CubeSat project. However, it was possible to perceive that the sun sensors will require isolation from the structure.

Bearing this in mind, the model established in this paper needs further development in order to achieve its maximum potential.

KEYWORDS: IGOSat, CubeSat, student satellite, design, IDM-CiC, thermal study, Systema & Thermica, thermal control subsystem

Abstract (Français)

Modèle préliminaire et étude thermique du Projet IGOSat

par Pedro Lopes

Le satellite d'observation de la radiation gamma ionosphérique, en anglais Ionospheric Gamma Ray Observation Satellite, donc son acronyme est IGOSat, est le responsable pour le commencement de cette étude. L'IGOSat, dont sa mission est d'observer la Terre – l'ionosphère terrestre pour être plus précis - est une opportunité motivante et pédagogique pour beaucoup d'étudiants de différents champs pour agrandir leurs connaissances sur ce métier.

L'IGOSat est en plein développement par de différentes entités reconnues, comme l'université Paris-Diderot, CNES, JAUNUS, le Laboratoire d'Excellence UnivEarthS et d'autres.

L'étude proposée par ce document se centre particulièrement sur l'implémentation modulaire et sur la caractérisation thermique d'un satellite dans l'espace, notamment d'un CubeSat. Afin de procéder avec cette investigation, nous avons recouru aux logiciels IDM-CiC et *Systema & Thermica*, qui ont prouvé être très efficaces. L'IDM-Cic était utilisé pour la création d'un modèle mécanique préliminaire et *Systema & Thermica* a utilisé ce modèle pour simuler le satellite en orbite et calculer son comportement thermique.

La conclusion principale que nous avons de cette étude c'est que, à ce jour, il est prématuré de déterminer les réquisits exacts de contrôle thermique de ce projet CubeSat. Par contre, il était possible de vérifier qu'il faut isoler les senseurs solaires de la structure principale.

Pour conclure, le modèle développé dans cette étude a besoin des futurs développements pour atteindre son maximum potentiel.

MOTS CLES: IGOSat, CubeSat, satellite étudiant, modèle, IDM-CiC, étude thermique, Systema & Thermica, sous-système de contrôle thermique

Contents

Figure Index

Abreviations (English)

ADCS - Attitude Determination and Control System
AIM - Astrophysique, Instrumentation et Modélisation
AMSAT – Amateur radio Satellite
APC - AstroParticule et Cosmologie
BC – Brillance Scintillator
BOL - Beginning of Life
CDS - CubeSat Design Specifications
CNES - Centre National d'Etudes Spaciales
COG - Centre Of Gravity
COTS - Components Of The Shelf
EASIROC - Extended Analogue SI-pm ReadOut Chip
EOL - End of Life
EPFL - École polytechnique fédérale de Lausanne
GEFL – Groupe d'Études et de Fabrications du LESIA
GPS – Global Positioning System
IDM CiC – Integrated Design Model – Centre d'Ingénierie Concourante
IGOSat - Ionospheric Gamma Ray Observation Satellite
IPGP - Institut de Physique du Globe de Paris
ISIPOD - ISIS Deployment Pod
ISIS – Innovative Solutions In Space
JANUS - Jeunes Apprentis en Nanosatellites des Universités et des écoles de l'enseignement Supérieur
LaBr3 – Lanthanum Bromide
LESIA – Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique
M2 OSAE - Second Year Master "Outils et Systèmes de l'Astronomie et de l'Espace"
MS – Mission Specifications
PCB - Printed Circuit Board
RoHS - Restriction of Certain Hazardous Substances
SiPM - Silicon PhotoMultiplier
SSBV - Satellite Service BV
SSP - Side Shear Panel
STS - STructural Specifications
TCS – Thermal Control Subsystem
TEC - Total Electronic Content
TSP - Top Shear Panel
UI - User Interface

Abréviations (Français)

BC-412 - Brillance Scintillator
CG - Centre de Gravité
M2 - Deuxième année du niveau master
OSAE - Outils et Systèmes de l'Astronomie et de l'Espace
SCAO - Système de Contrôle d'Attitude et d'Orbite
SCT - Sous-système de Contrôle Thermique

1. Introduction

IGOSat, which stands for Ionospheric Gamma Ray Observation Satellite, is a CubeSat project being developed by Paris-Diderot University, with the support of Project JANUS and the Laboratoire d'Excellence UnivEarthS, comprised by the laboratories of the APC, AIM and IPGP.

The project started in September 2012 at the hands of students from many scientific and non-scientific fields lectured at Paris-Diderot University and other partners, giving them the opportunity to get hands-on experience in the several phases of a satellite's development. The project benefits from the technical support from the CNES and the experience from several universities such as Montpellier 2, EPFL de Lausanne, l'École Polytechnique and more.

IGOSat is expected to be a 3U CubeSat (3-unit with 10x10x34cm), carrying an organic scintillator and GPS as payload. The scientific objectives are comprised of measuring the total electronic content (TEC) of the ionosphere using GPS, and gamma ray observations in the inner Van Allen belt, more specifically, the polar cups and the South Atlantic Anomaly. It will have no propulsion and it will be spin stabilized.

The project is divided in several subsystems, each referring to a specific component or set of components that are critical to the success of the mission. Each subsystem has its own requirements and specifications that must be taken into account when designing the satellite and are for the most part, still in development by other students, hence there is no choice in components.

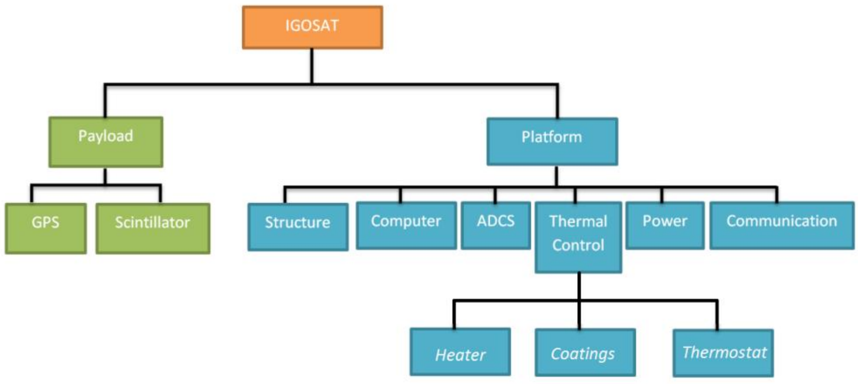

Fig. 1 - List of IGOSat's subsystems

The subsystems are expected to be formed by space ready and tested components that offer a large thermal operational range to survive against the space environment – typically between -40ºC to 80ºC. However, there are subsystems such as the Scintillator that have a much smaller range than the typical one. This could be a problem and it is why the thermal study is so important.

This paper is written as part of the master M2 OSAE from Paris Observatory, namely during a 5 months internship for the APC at the Paris Diderot University Space Campus.

The main objectives of this internship were to perform a preliminary mechanical design and a thermal study of the satellite in order to evaluate the Thermal Control Subsystem requirements.

At the start of this internship there were no complete models available for any of the components of the satellite. As so, I created a list of needed components for each subsystem, so that the mechanical design could be developed.

Each component is designed with IDM-CiC and Google SketchUp, thus enabling the study of different configurations and the identification of possible mechanical constraints.

Once the mechanical design is completed, the thermal design could be created, as it is based on the mechanical one.

The thermal control subsystem is a key element for the stability and longevity of any satellite, as it is responsible for monitoring and controlling the temperatures in the different components. Furthermore, it can make use of both active and passive components to control these temperatures.

Subsequently, this report aims to identify the heat transfer mechanisms that are present in the satellite and in the space environment in order to calculate the exchanged internal and external heat fluxes.

Based on these last steps, a new thermal model is built with *Systema & Thermica*, the software that allows the simulation of a space environment and its effects on a satellite. With the completion of this thermal study, it will be possible to identify which equipments might be subjected to temperatures outside their operational range and possibly, to provide solutions.

At the end of this report, I hope to have provided this project with two, simple working models that might be the ground work on which future students will be able to improve and easily update.

The image below shows the current configuration of the satellite. The components are identified as follows, from top to bottom:

1. Scintillator with shielding
2. Battery
3. Empty Board
4. ISIS Communication Antenna
5. AMSAT Communication Board
6. Magnetorquer Board
7. ISIS Computer
8. Sun Sensors
9. GPS Board
10. Thermal Control
11. GPS Antenna

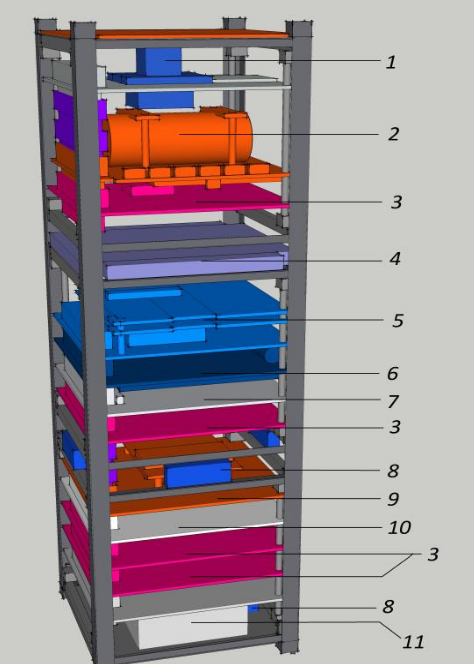

Fig. 2 - Internal View of IGOSat with Google SketchUp

Introduction (Français)

L'IGOSat, désignation pour satellite d'observation de la radiation gamma ionosphérique en anglais, est née au sein du campus spatial de l'université Paris-Diderot, dans le cadre du Laboratoire d' Excellence UnivEarthS, composé par les laboratoires APC, AIM et IPGP, et dans le cadre du projet JANUS.

La volonté de réaliser un nano satellite d'observation de la Terre par des étudiants, a commencé en septembre 2012. C'est pour cela que l'IGOSat représente par les étudiants de différents champs scientifiques et non scientifiques de l'université Paris Diderot et d'autres partenaires l'opportunité de suivre d'une façon plus proche les différentes phases de développement d'un satellite. L'IGOSat s'appuie également sur le soutien technique du CNES et sur l'expérience l'expérience de plusieurs universités, comme Montpellier 2, EPFL de Lausanne, l'École Polytechnique et beaucoup d'autres.

Sous la forme de 3 unités CubeSat, le nano satellite aura la forme et les dimensions standards d'un triple CubeSat (10x10x34cm total), dans lequel seront embarquées deux charges utiles - un scintillateur et un GPS. Les objectifs scientifiques de ce projet sont la mesure du contenu électronique de l'ionosphère capté par le GPS et à l'observation de la radiation gamma dans la ceinture Van Allen – plus précisément les gobelets polaires et l'anomalie magnétique de l'Atlantique Sud.

Le projet est divisé par de nombreux sous-systèmes et chacun représente un component ou un groupe de components spécifiques qui sont essentiels au succès de la mission. Chaque sous-système est encore en train de développement par des étudiants, donc il n'y a pas encore un choix de components définis.

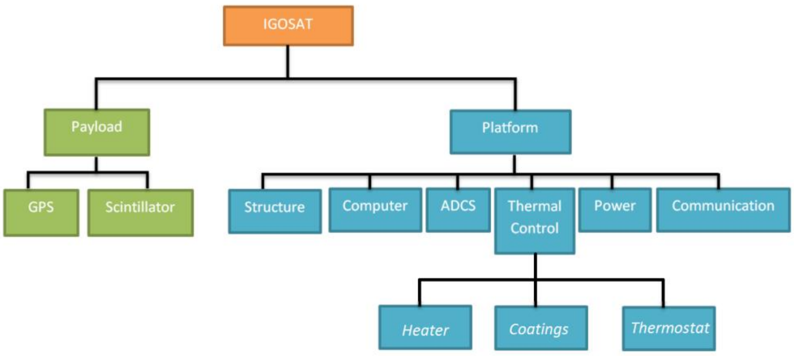

Fig. 3 - Liste des sous-systhèmes de l'IGOSat

Il se suppose que les sous-systèmes seront formés par des éléments testés et aptes à l'espace, en offrant un intervalle thermal opérationnel normalement entre -40ºC et 80ºC. Par contre, certes sous-systèmes, comme le scintillateur, ont une capacité thermale plus réduite, ce que peut poser des problèmes. C'est pour cela qu'une étude thermique est très importante.

Ce document s'est produit dans le cadre du master M2 de l'OSAE de l'observatoire de Paris, notamment sur le stage d'une durée de 5 mois dans le laboratoire APC de l'Université Paris Diderot.

Les objectifs de ce stage sont l'élaboration d'un modèle mécanique préliminaire et d'une étude thermale d'un satellite, pour pouvoir évaluer les réquisits du sous-système de Contrôle Thermique.

Au commencement de ce stage, il n'y avait pas de modèles complets disponibles pour aucun élément du satellite. Par conséquence, j'ai créé une liste de components nécessaires pour chaque sous-système pour que le modèle mécanique pût être conçu.

Chaque component a été créé par IDM-CiC et Google SketchUp, permettant l'étude de différentes configurations et l'identification de possibles limitations mécaniques.

Une fois le modèle mécanique terminé, le modèle thermique peut être crée une fois que celui-ci se base sur le premier.

Le sous-système de contrôle thermique est un élément clé pour la stabilité et longévité de n'importe quel satellite, une fois qu'il est responsable pour monitorer et contrôler les températures des différents components. En plus, il peut utiliser les component actifs et passifs pour contrôler les températures.

Par conséquence, ce rapport a comme objectif d'identifier les mécanismes de transfert thermiques présents sur le satellite et l'environnement spatial pour calculer les échanges de fluxes internes et externes.

Basée sur ces dernières étapes, un nouveau modèle thermale est créé avec *Systema & Thermica*, le logiciel de simulation de l'environnement spatial et de ces effets sur un satellite. Avec la conclusion de l'étude thermale il sera possible d'identifier quels équipements ont un intervalle de température hors de son intervalle opérationnel et, peut-être, suggérer des solutions.

A la fin de ce rapport, j'espère avoir créé deux modèles de travail simples et de facile actualisation qui pourront fonctionner comme base pour l'avenir.

L'image à droite représente la configuration actuelle du satellite. Ses components sont identifiés de la façon suivante :

1. Scintillateur avec bouclier
2. Batterie
3. Plaque vide
4. Antenne de communication ISIS
5. Plaque de communication AMSAT
6. Plaque Magneto coupleur
7. Ordinateur ISIS
8. Senseurs solaires
9. Plaque GPS
10. Contrôle thermique
11. Antenne GPS

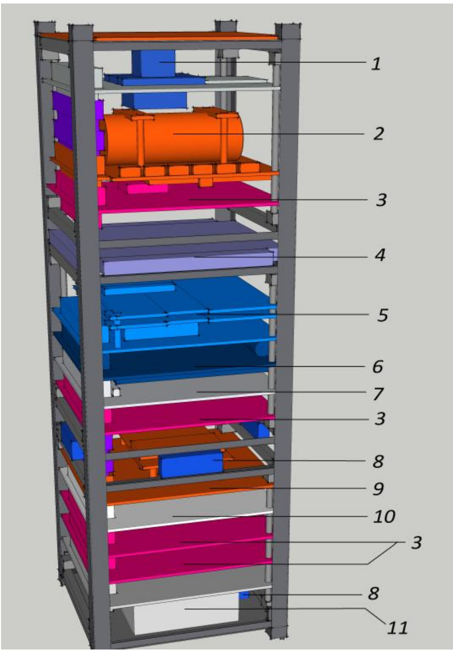

Fig. 4 - Visuel interne de l'IGOSat sur Google SketchUp

2. Preliminary Design

Preliminary design serves an important function as it allows a better visualization of:

1. The satellite layout;
2. The room available;
3. Mechanical constraints that are not easily visible by written specifications alone.

2.1 Introduction to IDM-CiC

The preliminary design was done using a software called IDM-CiC provided by the CNES, which is a macro for Microsoft Excel. It simulates a Concurrent Design Facility by enabling the user to create a project and define each subsystem. The same Excel file can then be used concurrently by several teams, as they define the equipment of their subsystem, with access to only that subsystem.

Using IDM-CiC, each user can define the shape (cylinder, rectangle...), fields of view of sensors, mass, operational temperatures, power modes and more. By adding more than one shape per equipment and managing their relative position, the software allows the creation of more complex equipment's visual representations, which can be used to build a more complete model. The equipment can then be visualized using a plugin for Google SketchUp.

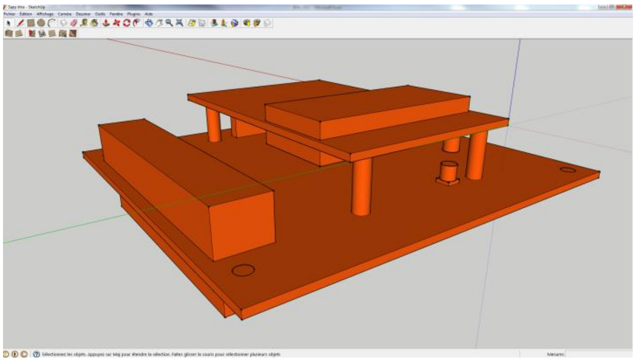

Fig. 5 – CAD view of the Novatel OEM615 designed with IDM

In the image above it is possible to see the GPS receiver board (top) attached to a CubeSat form PCB, with the stack connector on the left and coaxial connectors on both boards. The circles in the corners represent the PCB mounting holes as per PC/104 specifications [RD3], the standard format for CubeSat.

When the model is complete, it can be exported to a widely supported CAD format such as STEP by means of another plugin – in this case the STEP converter.

2.1.1 The System View

IDM also provides several calculations and manager functionalities that are enabled in the System view.

As each subsystem is defined, IDM will track the changes and build a mass and power budget. The System Power Budget allows the creation of several System Modes, which in this case were defined by CHARIET Moufida, another student from the Master M2 OSAE filling the role of System's Engineer.

These Power Modes will define which components will be ON or OFF in any given circumstance and return the total dissipation in each case, which will be useful for the thermal study.

The System view will allow the overall configuration of the satellite (Annex 1), by allowing each equipment position to change through manipulation of an Excel sheet. It will also calculate the current system's Centre of Gravity (COG), a key piece of information for the design as it will be discussed in the next section.

The final result can then be seen using the Google SketchUp plugin.

2.2 Design Constraints

Design constraints can be divided into two categories:

1. The general constraints due to CubeSat rules (CDS Constraints)
2. Mission Specific Constraints, which are particular to each satellite

2.2.1 CDS Constraints

As per [RD4], the CubeSat construction is subject to several limitations and rules. The constraints that have the greatest effect over the design are the dimensions and mass. A CubeSat can exist in a variety of sizes, from the most basic one cube satellite, typically referred to as a 1U satellite to larger 6U satellites.

As per [RD1] and [RD2], IGOSat is expected to be a 3U CubeSat, which means it will have three cubes. These are assembled in a line following the Z direction. The following is a list of the specifications that have the greatest impact on the satellite's design:

CDS 2.2.5.1: The dimensions of a 3U satellite are of 100x100x340.5 mm;

CDS 2.2.6: The components cannot exceed 6.5mm outside the 100mm cube (9mm if using ISIPOD [RD5]);

CDS 2.2.9: The contact rails between deployment pod and satellite must have a minimum width of 8.5mm;

CDS 2.2.16: The mass of a 3U satellite cannot exceed 4.0kg;

CDS 2.2.17: The centre of gravity (COG) must be within a sphere of 20mm from the satellite's geometrical centre.

The best way to comply with most of these and the remaining specifications is to select a tested and flight proven structure readily available on the market, also known as COTS (Components of the Shelf).

The current design uses the ISIS CubeSat structure [RD5]. It was chosen due to its simple design, good documentation and a significant difference in price when compared to the Pumpkin alternative. With this choice the design complies with the better part of these constraints, however, the last two will be design dependent and must be supervised.

2.2.2 Mission Specific Constraints

Besides the aforementioned constraints, there are also the limitations imposed by the mission to consider. For these, one can refer to the Mission Specifications report [RD1] (translated from French):

MS-4.8-9: For the (TEC) measurements, we will prioritize the descending occultations.

MS-4.2-14: To be able to perform any measurements, the (GPS) antenna needs to be pointed to a GPS satellite: therefore an inboard ADCS (Attitude Determination and Control System) is required to stabilize and point the satellite in the desired direction.

MS-4.2-15: The orientation and attitude control will be done in the 3 rotation axis.

MS-4.2-16: The antenna pointing to the GPS satellite must be placed in the back of the satellite, in a way that is facing the direction opposed to the movement of the IGOSat.

These impose one special constraint in the design: the GPS antenna must be placed on the -Z Plane.

As this work progressed, so did the study regarding the second payload: the scintillator. According to [RD6], the performance of the instruments that form this payload will be affected mainly by three factors:

- Temperature - both the SiPM and the scintillator (LaBr3 crystal and plastic) have an optimal operational temperature range between 0 and 40ºC;
- Position - the scintillator needs as few physical obstructions as possible;
- Shielding - the SiPM requires a significant amount of shielding on the lateral and bottom sides to avoid particle detection from directions that do not come from the scintillator.

2.3 Designing IGOSat

2.3.1 Choosing the Components

In addition to the previous constrains, the constraints of the hardware that will be used in the satellite should also be considered. However, since the project is still in early stages, some subsystems have not been fully determined and are, therefore, lacking hardware specifications. For these subsystems, the components used in the design were chosen based on the following priority list:

- Most information available;
- Flight heritage;
- Compatibility with the mission and existing hardware.

The table below, lists each subsystem, their components, status (**D**etermined or **T**o **B**e **D**etermined), problems that arise from their use and possible solutions.

Subsystem	**Component**	**Status**	**Problem**	**Solution**	**Notes**
Structure	ISIS 3U	TBD	---	---	---
Command	ISIS Computer	TBD	---	---	Allows custom daughter board
Power	LFP26650EV Battery Cell	TBD	Requires custom board Low thermal range	---	Might require heater
Power	Gomspace Nano Power P110 series (Solar Panel)	TBD	Lower thermal range	---	Higher efficiency
ADCS	Magnetometer	TBD	Usually placed in a boom far from the satellite	Place it in the cube with less active elements	No boom planned
ADCS	Magnetorquer	TBD	3 coils (one for each axis) will nearly need an entire cube	Use a design similar to ISIS or use solar panel with ADCS	ISIS uses an air core torquer that requires less room
ADCS	Sun Sensors	TBD	Must have a view of the exterior	---	---
COM	AMSAT-F	D	Smaller than CubeSat form; requires special connector	Use custom board	Compatible with ISIS daughter board
COM	ISIS UHF/VHF Antenna	TBD	---	---	Fits between the feet, can take solar panel and ADCS
GPS	Novatel OEM615	D	Smaller than CubeSat form; has two connectors (coaxial and 20 pin)	Use custom board	---
GPS	AeroAntenna AT2775-103	TBD	Dimensions (23mm tall)	Must be attached to a board inside the satellite	Heritage: CANX2
SCI	EASIROC	D	Requires custom board	---	---
SCI	SiPM	D	Connects to EASIROC; requires shielding; efficiency depends on temperature	---	Might need heater
SCI	Scintillator	D	Requires a support to hold it over the SiPM	---	----

Table 1- list of each subsystem and possible problems.

2.4 Assembling IGOSaT

The ISIS Structure is relatively complex to assemble. Each internal cube is formed by four lateral ribs (two on top, and two on the bottom) and four vertical rods where the PCBs are stacked. The structure is enclosed by two aluminium side frames that form the feet, rails and remaining ribs.

Fig. 6 - Disassembled 1U CubeSat (credit: ISIS)

In the above image we can see the components of a cube, from left to right:

Aluminium TSP(2x) and SSP(4x), Side Frames Black Anodised with attached kill switch(2x), Boards, Ribs Blank alodyned (4x), M3 Threaded Rods (4x), several M3 Bus spacers, Hex Nuts and Washers.

Since IGOSat is a 3U CubeSat, each side frame will be 340mm tall and 100mm wide and will enclose the three cubes. As this configuration is simply an extension of the simple 1U configuration, there will be some free space between each stack, which will be equivalent to twice the feet height of the satellite (approximately 14mm between cubes).

There are two stack options available:

- Custom 94x94 boards: vertical clearance between boards of 13mm;
- Standard PC/104 boards: vertical clearance between boards of 14mm.

The stack option chosen was the standard for PC/104 PCB as these are the ones most readily available as COTS, and are approximately 90x96mm. Communication between boards is assured by a 104 pin stack through connector as per PC/104 specifications.

This stack has a maximum distance of 75mm between ribs, which assuming the thickness of the PCB as 1.6mm and the necessary clearance for the stack connectors of 14mm gives a total maximum of five PCBs per stack. Each PCB is usually separated by a 12 mm aluminium spacer and four washers of 0.5mm thickness each.

This internal organization should work fine for regular sized components. However, given some mechanical constraints, some stacks had to be slightly adapted in some cases.

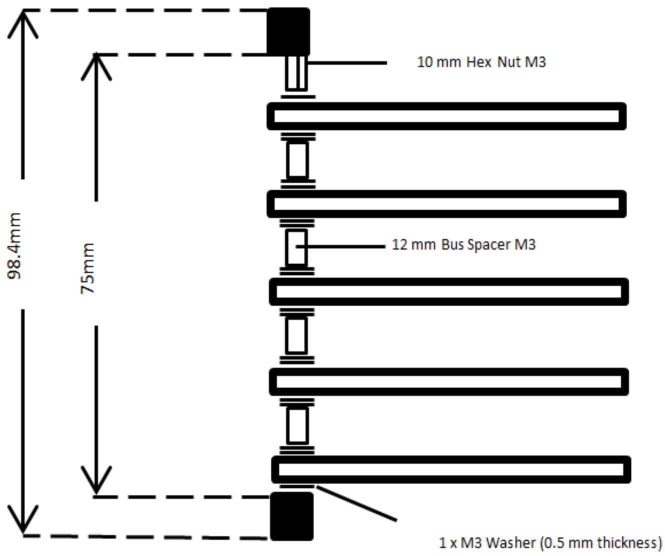

Fig. 7 - General internal organization of a cube as per ISIS.

2.4.1 Cube 1

The first cube (lower cube) contains for the most part, the GPS system, empty boards and potentially the Thermal Control board and magnetometer.

The magnetometer can be very small - about the size of a 5 cents coin - and it is used to measure the magnetic field in order to make the ADCS able to change the satellite's attitude.

To do this, the device needs to have as little magnetic interference as possible coming from the other electronic devices. This is the reason why the magnetometer is typically deployed outside the satellite. Usually to do this a boom similar to what was done in CanX-2, a student satellite from Canada [OR1], is used.

As for this project there is no boom planned, the magnetometer could benefit from being in the first cube if the GPS is not going to be operational at all times (To be determined).

The current GPS antenna is over 2cm thick, which means it cannot be placed on the surface of the satellite as it would violate **CDS 2.2.6**. Consequently, the antenna was placed on a PCB board that is secured in the internal stack of the lower cube.

For this cube, and in order to be able to follow the internal organization suggested by ISIS, the Hex Nut M3 was placed on the bottom ribs. This small change in placement allows the antenna to have only 2-3 millimetres outside the cube respecting CubeSat Specifications.

After the GPS antenna, the stack is formed by two empty boards - the Thermal Control and finally the Novatel OEM 615 GPS receiver. The latter, being smaller than CubeSat standard, needs to be placed in a CubeSat format PCB that fits the specifications.

The Novatel OEM615 GPS receiver can be attached to the PCB with 12 mm Hex Stands and screws. This extra height and the dimensions of the small board together with its electronic parts are the reason why this receiver was placed on the top of the stack. Overall, this component would need a vertical clearance larger than the typical 14mm allowed between PCBs but in this position it can make use of the free space between cubes.

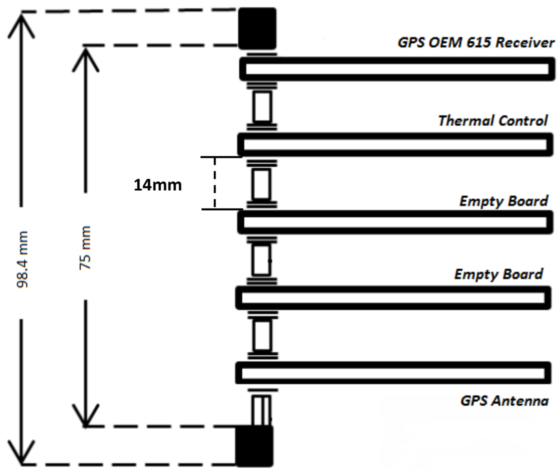

Fig. 8 - Cube 1 Internal Layout

2.4.2 Cube 2

Cube 2 is home to part of the ADCS, computer and communications subsystems. The ADCS is composed of several instruments such as the magnetorquers for attitude control, magnetometer and sun sensors for attitude determination. Due to its complexity, it creates some potential technical problems for the design.

The list presented on Table 1 was compiled based on the information available before the preliminary design was done. However, it became evident upon completion of the first design that, for some subsystems such as the ADCS, the three rod torquers with a length of 70mm being considered were impractical. Such configuration meant that the third torquer (vertical) would require a full cube, otherwise it would intersect any PCB board placed there. This subsystem was then replaced by a similar ISIS Magnetorquer board design that makes use of an air core torquer, of much smaller dimensions than the rods, and it was placed under the PCB to replace the vertical rod.

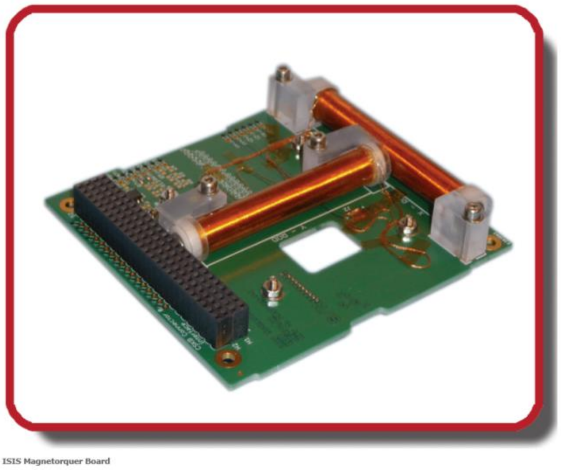

Fig. 9 - ISIS Magnetorquer Board (source: CubeSatShop.com)

One other problem comes from the Sun Sensors. These, as the name suggests, are used to determine the position of the Sun and would require a full coverage of the sky. Four of these sensors are placed on the side panels, in the space between cubes 1 and 2, facing out between the solar panels.

However, the top and bottom sides might prove impractical for Sun Sensors placement. Although the current placeholder allows enough room around the antenna for a sensor to be placed, the bottom is occupied by the GPS antenna, and depending on the final antenna it might not have room for a sun sensor. The top side is completely occupied by a solar panel leaving no room for a sensor. One option however, is to use a solar panel with integrated sun sensor which is available from most sellers.

The choice of the computer will affect mostly how the communication board can be connected, since it is smaller than PC/104 specifications. If the chosen computer accepts a custom daughter board, such as the ISIS option or the Cube Computer, the AMSAT board can be placed on the computer and will require less clearance upwards.

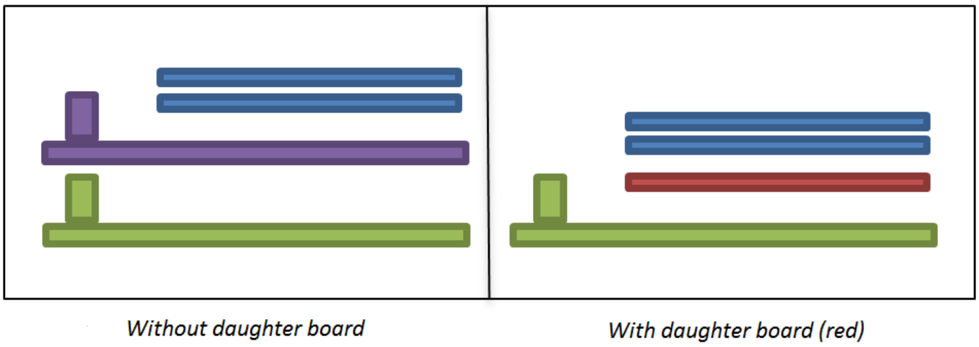

Fig. 10 – Cube computer with and without daughter board

Otherwise, a computer without this option will mean that the AMSAT board will require an extra custom PCB to fit the CubeSat standard format, requiring more vertical clearance since there is a minimum 13-14mm average distance between each PCB due to the stack connectors as seen in Fig. 8. However, this configuration would have the advantage that the communication board and computer would be independent from each other and would not affect their placement. For this study a version without daughter board will be used as it is the most generic option and would be compatible with any computer.

The final layout for this cube is similar to cube 1's distribution but with one less PCB, whose place is occupied by the AMSAT, and with only 13mm between boards. These changes were necessary due to the irregular size of the AMSAT board, which is by default composed by two small PCBs stacked with a separation of 5mm, as seen in the image below. This is then aggravated by the need of this component to be placed in another PCB with at least an 11-12mm clearance to accommodate the SSQ-114-21-G-D connector as per AMSAT specifications [RD7].

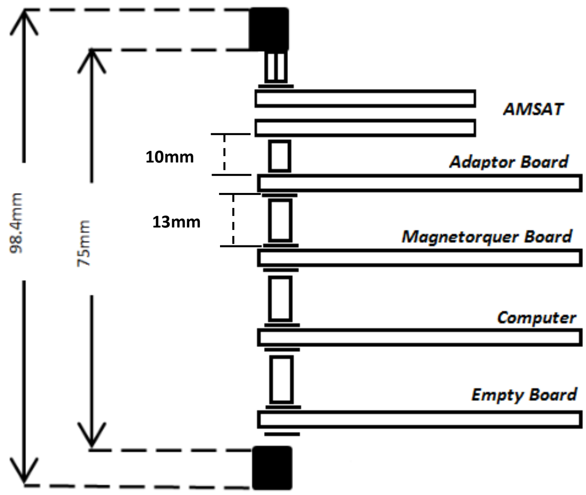

Fig. 11 - Internal Layout of Cube 2

2.4.3 Cube 3

The final cube houses the battery and the second payload, which is a LaBr3 scintillator. Both equipment lower temperature operational limits are shorter than most other components: -20ºC for the battery and 0ºC for the Silicone Photo Multiplier (SiPM - responsible for the detection of events in the LaBr3 crystal). Since both might require a heater, they were placed in close proximity so that both could benefit from the same heat source.

One other reason for these two components to be in the same cube is due to mechanical restrictions. The battery cell is a cylinder with 26.5mm diameter, which means it can't follow the same internal organization that the other cubes follow.

The scintillator payload main components are the crystal with plastic scintillator, the SiPM, a high voltage generator to power the SiPM and the EASIROC (***E**xtended **A**nalogue **SI**-pm **R**ead**O**ut **C**hip* from OMEGA Micro) that is dedicated to read the SiPM.

The crystal is approximately a cube with a height of 1.5cm and sits on the SiPM that is 0.33cm thick, which means this component won't fit between two boards following the typical layout observed so far. This coupled with the fact that the scintillator would benefit from having as little obstructions as possible, makes the top of the third cube the best position for this payload. Here the only obstructions to the scintillator are the aluminium structure and solar panels that are present in the four sides and top face of the satellite.

One additional constraint is the aluminium shielding required so that the SiPM only detects events coming from the scintillator. Thus it needs to be shielded from particles coming from the sides (same thickness as the SiPM) and below (1.1cm thick). This shielding adds to the vertical clearance requirements of the battery and so the battery and scintillator boards are placed 4.1cm apart. The remaining space under the battery is taken with an empty board as is shown in the image below.

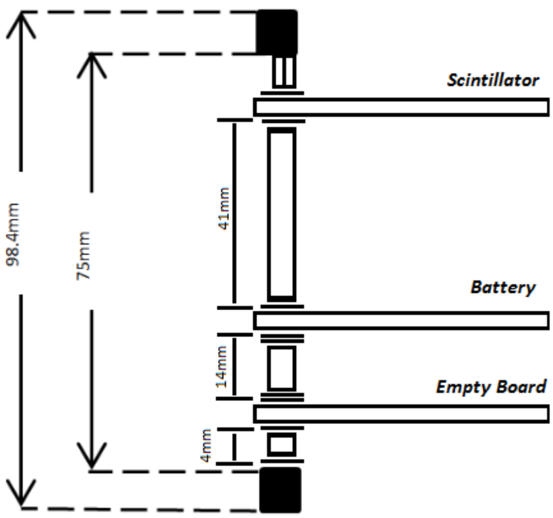

Fig. 12 - Internal Layout of Cube 3

The UHF/VHF communication antenna is based on the ISIS design for the Deployable Antenna System seen below.

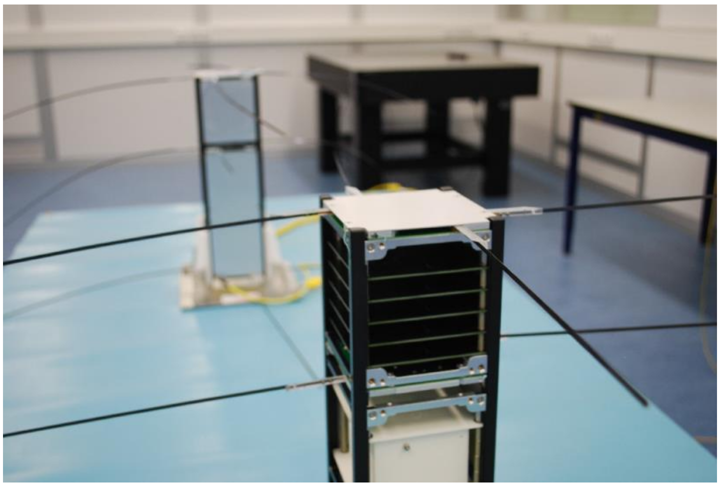

Fig. 13 - ISIS antenna and ISIS structure (credit: CubeSatShop.com)

Figure 12 shows the ISIS structure with the side frames in black and ribs in blank alodyned. At the back it is possible to see another satellite with the SSP.

Typically this device is screwed to the side frames and positioned between the feet of the structure. However since the GPS antenna already occupies one of these faces and in the other face it would obstruct the scintillator, the only place left is between Cube 2 and 3.

This placement is made possible by the antenna model with a 3cm diameter hole for pass-through cables to connect cube 2 to cube 3. Otherwise, the antenna would block the stack connectors that link all the boards together making impossible the communication between them.

2.4.4 Fulfilling Design Specifications

The sole intent of the distribution described above was to fulfil the requirements imposed by the design constraints mentioned in section 2.2. The **MS** constraints are easily respected by placing the GPS antenna in the lower cube attached to a PCB in the internal stack. The **CDS** and mechanical constraints imposed by the components however, require some additional considerations.

The empty boards are present to provide balance and to help follow the correct internal organization of the PCBs, this not only makes it easier to keep the satellite organized and balanced but also helps considerably in the calculation of the thermal links later on.

One important consequence of the decisions taken so far is concerning the solar panels. These components are available in different sizes: 1U, 2U and 3U, each covering the totality of a face corresponding to one, two or three cubes and are screwed to the structure's ribs. However, since the space between cubes is occupied by other instruments such as the Sun Sensors and the communication antenna, the larger configurations are no longer compatible. Therefore, IGOSat is powered by a total of thirteen 1U solar panels that are distributed around the four sides and top face of the satellite.

With this configuration, the satellite has a total mass of 2,8 kg (with 20% mass margin), well within the limit of 4 kg imposed by **CDS 2.2.16** and leaves a margin of 1,2 kg to account for spacers, washers and cables that were not modelled and any other component that might be added in the future.

The centre of gravity reported by IDM-CiC is located at X= -0,29 mm, Y= 2,93 mm and Z= -0,3 mm in relation to the geometrical centre of the satellite, which is well within the expected coordinates imposed by **CDS 2.2.17** and can be further adjusted by adding mass to the empty boards.

3. Heat Transfer Mechanisms: Theoretical Background

There are typically three mechanisms for heat transfer: Conduction, Radiation and Convection. However, since the satellite will be at a rather large altitude (600km), the latter is negligible since there will be little influence from the atmosphere [RD8]. To perform this study, a nodal model was created, where each component is reduced to a single isothermal node and the links between each node are calculated for each type of transfer mechanism. Therefore, the following definitions are done in such context providing the basis for those calculations.

3.1 Conduction

Conduction is ruled by Fourier's Law and occurs when two bodies (gas, liquids or solids) are placed in contact, or between two points in the same body due to the temperature gradient between them, with heat flowing from the hotter to the colder point.

For the purpose of this study, the conduction links are defined by the thermal conductance (**GL** in W/K units), that refers to the quantity of heat passing through a body.

The value of the **GL** can then be easily calculated from Fourier's equation for heat transfer:

$$\frac{dQ}{dt} = \frac{kF\Delta T}{d}$$

$$GL \; in \frac{W}{K} \; units = \frac{\frac{dQ}{dt}}{\Delta T} = \frac{kF}{d} \qquad \text{(Eq.1)}$$

dQ/dt =heat flow (W, J/s)

k = heat conductivity (W/m.K)

F = area of the heat flow (m^2)

ΔT = temperature gradient between the two points (K)

d = distance between the two points (m)

The inverse of this concept is called Thermal Resistance $\mathbf{R_{th}}$ (K/W), which is given by:

$$R_{th} = \frac{d}{kF} \quad \text{(Eq.2)}$$

Given a series of resistances, the total resistance is given by the sum of resistances that form the path. This is particularly useful because as seen in chapter 2, the link between two PCBs is often made of more than one body, and so the thermal conductance is given by:

$$R_{th\ total} = \sum Rth \iff GL = \frac{1}{\sum Rth} \quad \text{(Eq.3)}$$

When the heat flow is parallel, like the case of four parallel spacers that link one PCB to the next or the dual connection between a PCB and a rib, the equivalent conductance is given by the sum of the conductance:

$$\frac{1}{R_{th\ total}} = \frac{1}{R_{th1}} + \frac{1}{R_{th2}} \iff GL_{total} = GL_1 + GL_2 \quad \text{(Eq.4)}$$

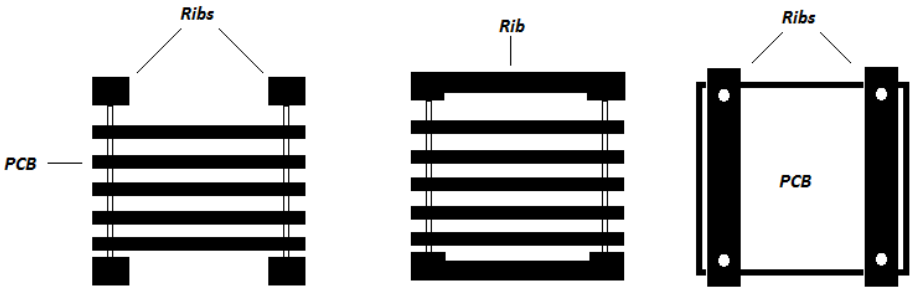

Fig. 14 - Front, side and top view of the internal stacks

Fig 14 represents the internal stacks' views, showing the number and type of connections that are made between PCB/PCB and PCB/Rib.

Since the internal organization of the stacks described in chapter 2 is rather regular for Cubes 1 and 2, most of the links need only to be calculated once, with the sole variation from one cube to the other being that the link PCB/PCB has less two washers in Cube 2.

These links will be fundamental for the satellite's internal heat transfers and will require detailed knowledge of the interfaces for each component. Since *Systema & Thermica*'s conduction module proved too complex and required a very detailed model in order to allow automatic calculation of these links, the calculations were done without the aid of the software and are presented in the next chapter.

3.2 Thermal Radiation

Thermal Radiation is the process by which the heat transfers through electromagnetic waves. It depends on the optical thermal property of the emitting body known as emissivity and its temperature.

The emitted energy is given by:

$$P = \sigma\epsilon F T^4 \quad \text{(Eq.5)}$$

F= surface area

T= temperature

σ = Stefan-Boltzmann constant

ϵ = emissivity

For this study, the value needed is the radiative coupling (**GR**) between two nodes that depends on their emissivity and view factor. *Systema & Thermica* allows for the automatic calculation of these values by using Monte-Carlo Ray-Tracing.

3.3 Space Environment

In-orbit satellites are subjected to a very particular environment that is dependent of their orbit, time of the year and optical thermal properties of the satellite. There are three main sources of heat that should be considered: Solar Flux, Albedo Flux and Planetary Flux.

Solar Flux relates to solar activity and can vary with time. As the planet orbits the Sun, the relative distance between the two will change as well, causing a variation on the amount of solar flux received by the planet and orbiting satellites. There are however, two positions of interest for the thermal study, which are the northern winter and summer Solstices (Hot and Cold Cases). At these dates, the planet will be at the farthest and closest position from the Sun respectively and the Solar Flux will have a maximum and minimum value at these points.

Albedo Flux also relates to Solar Flux, but more precisely to the amount of Solar Flux that is reflected by the Earth (or another celestial body) back to space. Albedo is a reflection coefficient that depends on the surface at which the satellite is looking at. Values can range from 0.05 to 0.6 depending if we are looking at clouds, trees, water, etc... But an average value of 0.3 can be assumed for a spacecraft [RD8]. The Planetary Flux is the heat flux released by the planet in the infrared spectrum due to its surface temperature.

The final element of this environment is Space which acts as a heat sink for all other objects and has a temperature of 3K. As these elements are radiation based, their values will also be determined using *Systema & Thermica*.

4. Thermal Interfaces

Another important factor to be taken into account is the interaction of each component with its surroundings in terms of heat transfer. From the previous section it was observed that the two predominant forms of heat transfer will be conduction and radiation. However, the amount of this transfer will depend on the interface between a component and its surroundings.

4.1 Thermal Properties

The table below provides some information related to the thermal interfaces and requirements for each component.

Component	Thermo Optical Properties		Op. Temperature		Material	Surface Finish	Area (m2)	Mass (kg)	Cp (J/kg K)
	Emissivity	Absorptivity	Min. (C)	Max. (C)					
Rail	0,86	0,4	-40	80	Al6082	hard anodized	5,78E-03	2,06E-02	894
Sideframe rib							5,81E-04	6,70E-03	
Cage rib	0,15	0,08				blank alodyned			
SSP 1U	0,15	0,08			Al5754	blank alodyned	8,80E-03	1,40E-02	897
SSP 2U	0,15	0,08					1,78E-02	2,90E-02	
TSP	0,15	0,08					9,70E-03	1,51E-02	
Solar Cells	0,81	0,91	-40	85	GaAs		8,09E-03	2,50E-02	350
Empty Boards	0,85		-40	85	PCB		8,27E-03	7,00E-02	396
GPS antenna	TBD	TBD	-50	70	TBD		4,18E-03	1,27E-01	900
PCB Board	0,85		-40	85	PCB		8,27E-03	7,00E-02	396
GPS OEM615			-40	85			3,27E-03	2,40E-02	396
PCB Board			-40	85			8,27E-03	7,00E-02	396
COM antenna	TBD	TBD	-30	70	TBD		9,60E-03	1,00E-01	900
Band board	0,85		-20	45	PCB		7,38E-03	3,00E-02	396
TXRX board							7,38E-03	7,00E-02	396
PCB Board (Easiroc)			-40	85			8,27E-03	9,00E-02	396
EMCO High Volt.	TBD		-55	75	TBD		9,68E-04	4,25E-03	TBD
SiPM	0,85		0	40	TBD		2,92E-04	2,00E-03	900
Crystal	TBD	TBD	-20	50	LaBr3		7,29E-05	4,44E-03	270
Plastic	TBD	TBD			BC-412		2,92E-04	3,61E-03	TBD
Computer	0,85		-20	60	PCB		8,27E-03	7,00E-02	396
Daughter Board			-20	60			8,27E-03	2,40E-02	396
Torque Board			-35	75			8,27E-03	2,40E-01	900
Magnetometer			-50	85			1,00E-04	1,50E-02	396
Sun Sensor	TBD	TBD	-25	50			3,63E-04	5,00E-03	900
PCB Board	0,85		-40	85			8,27E-03	7,00E-02	396
Battery Cell	TBD	TBD	-20	60	TBD	TBD	6,53E-03	0,082	900

Table 2 - Thermal interfaces and properties[1]

It is important to note, that the specific heat capacities presented for the electronics are approximations (900 J/ kg.K) taken from the case study of the SPOT satellite provided by *Systema & Thermica*. This value however, is only used for electronic boxes, i.e., for components such as the antennas and SiPM where the exact composition is unknown. The remaining electronic boards use the specific heat capacity of a printed circuit board (396 J/ kg.K) [OR2].

Lacking an exact description of all the thermal properties of these components and pending confirmation from the manufacturers, some approximations were done based on studies from other CubeSat's and other bibliography. The thermo-optical properties for the structure were obtained from [RD9] and [RD10] and are the default coatings of the structure that might be subject to changes depending on the results of this study. The values for the solar cells were obtained from [OR3] and [OR4].

The scintillator is composed of a LaBr3 crystal embedded in a plastic scintillator of BC-412 enclosed in an aluminium cover. Between the crystal and plastic, there is a thermal interface of

[1] The components marked in orange are not modelled due to lack of information.

aluminium. However, the exact specifications of this interface are not known, neither are the thermal properties of the plastic such as specific heat capacity. Without this information, it is not possible to build an accurate thermal study, and as a consequence, this study will be done assuming a full cube of LaBr3 for which the specific heat capacity is known [RD11].

One additional component that was suppressed from this model was the High Voltage Generator that will power the SiPM. According to the manufacturer it consists of two small PCBs and a transformer with a ferrite pot core. The transformer is soldered with RoHS compliant solder to both PCBs and is held with tape and epoxy potting compound inside the case. Since it has a significant amount of dissipation (0,5W) and a rather large operational temperature range (-55 to 75ºC) its dissipation was placed on the EASIROC micro controller card that will support the scintillator payload.

4.2 Conductive Interfaces

The following table lists the thermal interfaces for the conductive links. These can be formed due to contact between surfaces, like SSP to Structure or Solar Panel to SSP, where these components are screwed together or through other interfaces such as adhesives or spacers:

Connection	Type of Interface	Quantity	Area (m2) (per contact)	Material
Side frame / Ribs	Screw M2.5	8	1,59E-5	Stainless Steel
SSP / Structure	Screw M2.5	16	1,59E-5	Stainless Steel
Solar Panel / SSP	Screw M2.5	4	1,59E-5	Stainless Steel
Solar Panel / Battery	Molex PicoBlade Cable	-	-	-
Ribs / Stack Rods	Screw M3	4	2,38E-5	Stainless Steel
GPS antenna/PCB	Screw M3	3	2,38E-5	Stainless Steel
GPS antenna / Receiver	Coaxial Cable	-	-	-
GPS Novatel OEM615 / PCB	M3 Hex Standoff + Stack (28pins)	4	M3: 1,59E-5 Pin: 5,08E-7	Aluminium / Phosphorous Bronze (pins)
COM Antenna/Ribs	Screw M2.5	4	1,59E-5	Stainless Steel
COM Antenna/PCB	Coaxial cable to AMSAT + Power cable to battery	-	-	-
AMSAT/PCB	M3 Spacer + Washer + Stack (28pins)	4	M3: 1,59E-5 Pin: 5,08E-7	Aluminium / Phosphorous Bronze (pins)
LaBr3 / BC-412	Aluminium*	-	TBD	TBD
High Voltage Gen / PCB	Solder*	TBD	TBD	TBD
SiPM/Crystal	Silicone adhesive (0.5um)	1	2,97E-4	Silicone [OR6]*
SiPM/PCB (EASIROC)	Pins	32	1,59E-7	Phosphorous bronze*
Sun Sensor/SSP	Screw M1*	3	3,14E-6	Stainless Steel
Sun Sensor/ADCS	Cable*	-	-	-
Battery Cell/PCB	Surface Contact + support*	-	TBD	TBD
PCB/Rib	Spacer + Washer	varies	varies	Aluminium
PCB/PCB	Spacer + Washer +Stack Connector	varies	varies	Aluminium / Phosphorous Bronze (pins)
Magnetometer / PCB	9 pin micro D connector*	-	1,96E-7	Gold Plated Copper
Kill Switch / Rail	Screw M1.6	2		Stainless Steel

Table 3: Conduction Thermal Interfaces (*to be confirmed)

	Silicon Adhesive	Spacers - Aluminium 1050A H08	Standoff - Aluminium ASTM B211 (7075)	Pins - Phosphorous Bronze	Pins - Gold Plated Copper
k (W/m K)	0.39	229	175	75	314

Table 4: Thermal conductivity for some interfaces *(OR6, 7, 8, 9)*

4.3 Conductive Links

Conductive links will have to be calculated individually and depend on the geometry of the link and thermal properties of the material. These calculations were performed following the technical advices and expertise of Mr. Napoléon Nguyen Tuong (*Responsable du Groupe d'Etudes et de Fabrications du LESIA*) and the EPSILON training courses for thermal control provided by himself.

The conductive link formed in screwed components will be based on the contact quality, which is very difficult to determine exactly. Therefore, these values will be determined following the mentioned training courses where a contact quality value of 5000 W/m^2K is suggested.

4.3.1 Screws and Conductance

Using the contact value mentioned above and knowing the screw geometry, the conductance value of the link formed by two screwed components can be calculated by simply multiplying the contact area of the screw with 5000 W/m^2K. However, there are some considerations to be taken:

1. If the contact area is smaller than twice of the area of the screw head's diameter, then we consider only the real contact area (top image);

2. If the contact area is larger than twice of the area of the screw head's diameter, we consider the contact area corresponding to twice the diameter of the screw head (bottom image).

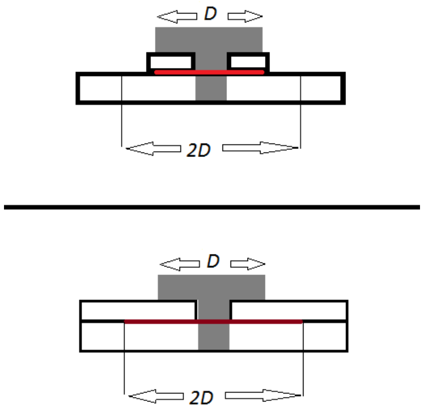

Fig. 15 - Examples of effective conduction area based on the screw size

For this study, case 2 is applied for the connections Solar Panel / SSP. For the remaining connections presented in Table 3 the contact area considered is that of the screw head because the ribs are barely larger than the screw head used. Conduction through the stack rods, washers and screws is negligible due to the low thermal conductivity of stainless steel.

4.3.2 Simple Contact Conductance

To calculate the conductive links between PCBs inside the cubes, one can make use of the thermal resistances as seen in section 3.1.

The values for the conductive links can be calculated by following the geometry of the thermal path as showed in the next figure:

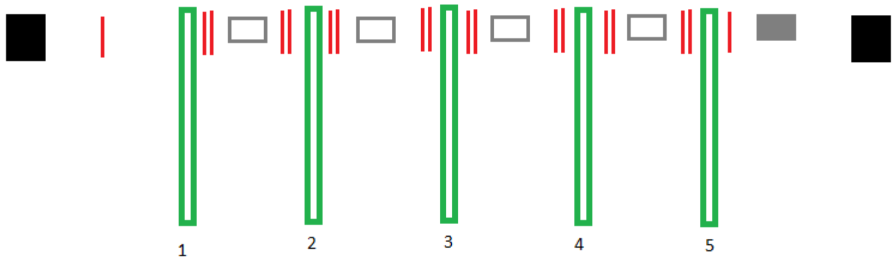

Fig. 16 - Thermal path inside a cube

The black squares represent a rib, each red line one washer, the grey rectangles represent a spacer and hex standoff (hollow: 12mm spacer, full: 10mm hex standoff) and finally, the green rectangles represent the PCBs.

So for this example, the link between the first rib and PCB 1 would be given by the sum of contact resistances between Rib/Washer and Washer/PCB:

$$GL(Rib, PCB1) = \frac{1}{R_{th}(Rib/Washer) + R_{th}(Washer/PCB1)} \quad (Eq.6)$$

Where R_{th} is the inverse of the conductance values from table 5 for an area of 1D (where 1D and 2D refers to the diameter of the contact area) which in this case means using the contact area between Rib/Washer and Washer/PCB: i.e. the area of the washer. Since the PCB will connect twice to the rib, this GL must be multiplied by two.

Interface	Diameter (mm)	Radius (mm)	for 1D area Area (m2)	Conductance (W/K)	for 2D area Area (m2)	Conductance (W/K)
M1 Screw	2	1	3,14E-06	1,57E-02	1,26E-05	6,28E-02
M2 Screw	3,8	1,9	1,13E-05	5,67E-02	4,54E-05	2,27E-01
M2.5 Screw	4,5	2,25	1,59E-05	7,95E-02	6,36E-05	3,18E-01
M3 Screw	5,5	2,75	2,38E-05	1,19E-01	9,50E-05	4,75E-01
Washer	7	3,5	3,85E-05	1,92E-01	1,54E-04	7,70E-01
Spacer	*External(d)*	*Internal(d)*				
M3	5,5	3,3	1,52E-05	7,60E-02	6,08E-05	3,04E-01
Hex Stand	*External(d)*	*Internal(d)*				
M3	5,5	3,3	1,52E-05	7,60E-02	6,08E-05	3,04E-01

Table 5: Contact Conductance

4.3.3 Conductance between PCBs

Following a similar reasoning, the link GL(PCB1,PCB2) can also be calculated with a sum of thermal resistances considering the aluminium spacer geometry and thermal conductivity. In this path it would be as follows:

R_{th} = Contact(PCB1,Washer) + Contact(Washer,Washer) + Contact(Washer,Spacer) + Resistance(Spacer) + Contact(Spacer,Washer) + Contact(Washer,Washer) + Contact(Washer,PCB2) (Eq.7)

Where for PCB/Washer and Washer/Washer the contact area is the area of a washer and for Washer/Spacer is the contact area of the spacer. Finally, the thermal resistance in the spacer is calculated with equation 2 using its length and cross section. This link must then be multiplied by four due to the four connections between PCBs in the stack:

$$\mathrm{GL(PCB1, PCB2)} = \frac{4}{\sum R_{th}} \text{ (Eq.8)}$$

If there is also a stack connector linking two PCBs, then this contribution is added to the previous link. Since the stack connector and the path through the spacers are in parallel, the conductances of the two links are added together instead of the thermal resistances. The pins (104 pins) are phosphorous bronze, as per [RD3] with an area of 5.08E-7 m2.

The link becomes:

$$\mathrm{GL(PCB1, PCB2)} = \frac{4}{\sum R_{th}} + \mathrm{Conductance(Stack)} \quad \text{(Eq.9)}$$

$$\text{With } Conductance(Stack) = N_{pins} * \frac{kF}{d}. \text{ (Eq. 10)}$$

4.3.4 Interface SiPM/Scintillator

This interface is not yet fully determined, but it is assumed that for this connection a silicone pressure sensitive adhesive with a thickness of 0.5 microns will be used. For this simulation, the values used are from [OR6].

The link is calculated using the result of Eq.1 for the full area of the SiPM.

4.3.4 Interface SiPM/PCB

The exact connector is also not determined, but the SiPM uses 32 pins to connect to the PCB. The conductive link can be determined using Eq.10.

4.3.4 Interface Battery Cell/PCB

This subsystem is not fully developed, however it is known that the cell is going to be laying down in the PCB and will require a support to brace the cell to the PCB. Conduction in this case would be done in three parts:

1. Contact Cell/PCB;
2. Contact Cell/Support;
3. Contact Support/PCB;

Since there are too many unknowns, the link is determined by assuming that the battery is screwed to the PCB with four M3 screws.

4.3.5 Interface Magnetometer/PCB

This magnetometer uses a 9 pin micro D connector. The pins are gold plated copper, with an assumed length of 1mm, a diameter of 0,5um and an area of 1,96E-7 m^2.

The link is calculated using Eq.10.

4.3.6 Interface Kill Switch/Side frame

CubeSat also requires a device called kill switch. Its task is to keep the satellite inactive during launch, and activate it short after the CubeSat is deployed.

The kill switch used by the ISIS structure is the Panasonic AV4 micro switch (AV402461) [RD5] that uses a travelling pin at the feet of the structure to activate the switch. The structure makes use of two of these switches, one for each side frame. Each switch has 0.3 grams and an operating temperature range between -25ºC to 80ºC. The switch is screwed with M1.6 screws and an aluminium Al6082 bracket to the rails.

Since the temperature range is large and ISIS thermal cycling testing results did not report any adverse effects to the operation of the switch at temperatures below -25ºC, this device is not modelled in the current version of the satellite's thermal model. Given the high thermal conductivity of aluminium, it is assumed that the switch temperature will be approximately the same as the rails.

Later, depending on the results or for a more detailed model, the switch can be added.

Similarly, the same behaviour is expected to happen to the Sun Sensors that are screwed to the SSPs, however since there is no information regarding their capacity to operate outside their thermal ranges, they were modelled and will be studied later on.

4.4 Test Cases: Cold and Hot Case

As mentioned before, the satellite will have several operating modes. These will define which equipment will be ON or OFF during these modes and how much dissipation will occur.

These values are shown in the table below:

Mode	1	2	3	4	5	6	7	8	9	10
Total Dissipation (W)	0,956	4,546	2,596	3,731	3,731	4,676	3,731	6,646	3,731	2,596

Table 6: Total dissipation with 30% margin.

With this table it is possible to identify which modes will be important for this study in order to define the Hot and Cold Case. These test cases represent the two extreme situations the satellite will be subject to during its life and if it fails in one of these tests, then the model will need to be adjusted to keep the temperatures in the appropriate ranges using other coatings, placing heaters, etc...

The coatings' properties used for these simulations were the default coatings for the structure, as shown in Table 2. However, some components don't have their thermo-optical properties determined and, as such need to be defined.

Typically, these test cases should also consider the ageing of the thermal coatings. As the satellite is irradiated in orbit and bombarded by atomic oxygen, the properties of the coatings will change; mainly the absorptance value will tend to increase over time [RD9]. The Cold Case would then be considering the absorptance for BOL, as it would be the lowest. Finally, the Hot Case would use the EOL values.

However, since the EOL values have not been determined (pending more information from ISIS) and given the short life period of one year that the satellite is expected to operate, this study will not take in consideration the EOL values. The GPS and Communications antennas were given a coating of Chemglaze A276 white paint for BOL [RD12]:

- $\epsilon_{BOL} = 0.88$;
- $\alpha_{BOL} = 0.28$.

And the sun sensors were given a coating of gold paint [RD8]:

- $\epsilon_{BOL} = 0.02$;
- $\alpha_{BOL} = 0.19$

4.4.1 Cold Case

This test case consists of the scenario where the satellite will have the lowest amount of internal dissipation and external fluxes. For the external fluxes, this will be in the Summer Solstice when the Earth is in the aphelion and will affect mostly the Solar Flux and Albedo.

The internal dissipation that fits the requirements is mode 1. To better approximate to the worst cold case scenario, the 30% margin is removed which gives a total dissipation of 0,72 W.

The equipment active on this mode will be:

Equipment	Dissipation (W)
Battery	0,128
Computer	0,4
Communication (AMSAT)	0,195
Com. Antenna	<0,02*

Table 7: Internal dissipation in the Cold Case

4.4.2 Hot Case

The Hot case consists on the opposite scenario, where the satellite will have the highest amount of internal dissipation and external fluxes. This happens in the Winter Solstice, which means in the perihelion.

The mode chosen is mode 8 with a total dissipation of 6,56W, this time accounting for the extra 30% dissipation to really represent the worst case scenario. The equipment active on this mode will be:

Equipment	Dissipation (W)
Battery	0,162
Computer	0,52
Communication (AMSAT -RX)	0,254
Com. Antenna	<0,02*
Torquer Board	0,815
Sun Sensor (x5)	0,065
Magnetometer	0,52
GPS Receiver	1,43
GPS Antenna	0,65
EASIROC (SCI)	1,95**

Table 8: Internal dissipation in the Hot Case

Notes:

- **AMSAT -RX stands for reception mode;**
- ***nominal dissipation as per supplier specifications : we use 0,02 W for the simulations;**
- ****it includes the dissipation from the EMCO High Voltage Generator that powers the SiPM and the dissipation from EASIROC.**

5. Thermal Study

This Thermal Study is performed using the *Systema & Thermica* 4.6.1 software, provided by *Airbus Defence and Space* and recommended by the CNES. The software provides an all-in one interface that allows the creation of the spacecraft geometry and defines its orbit, kinematics and mission scenario. This information can then be used to compute the fluxes and calculate the temperature variation for each component of the model. The next sections will provide a short introduction on how the software works.

5.1 Systema & Thermica

5.1.1 Modeler and Mesh

The modeller allows the creation of the geometry by assembling basic geometries (rectangles, boxes, etc..). It is possible to import CAD models which would have allowed us to import the geometry built with IDM-CiC or even use the STEP files provided by the manufacturers. However, it was decided to create a new geometry using *Systema & Thermica*.

Here is also where material properties are defined, such as coatings (absorptance and emissivity), density, etc... That will be used for the computation later on.

The mesh, which is a collection of nodes, is created from the geometry. By default, each face of a box or of a rectangle is a different node, but the numbering of the nodes can be changed to fit our purposes. Below the list of nodes and corresponding component is shown:

Subsystem	Node	Equipment	Shapes
	1-28	Rails and ribs	Rail: Rectangles ; Rib: Box
STRUCTURE	29-38	Side Shear Panels	Rectangles
	40, 50, 60, 70	Empty PCB	Rectangles
TC	80	Thermal Control Board	Rectangles
GPS	100-101	GPS antenna and support board	Antenna: Box ; Board: Rectangle
	200-201	GPS OEM615 and support board	Rectangles
COM	300	Antenna	Box
	400-401-402	AMSAT (RX-TX + Pass Band)	Rectangles
	500	EASIROC and PCB	Rectangles
SCI	600	SiPM	Box
	700-800*	LaBr3 crystal and BC-412 plastic scintillator	Box
CPU	900-901	Computer and daughter board	Rectangles
	1000	Torquer Board	Rectangles
ADCS	1100	Magnetometer	Box
	1200-1500,1501	Sun Sensors	Internal: Rectangle ; External: Circle
	1600-1601	Battery board and cell	Board: Rectangle ; Cell: Cylinder
	1700, 1800,…, 2900	Solar Panels	Rectangles
Total	**79 nodes**		

Table 9: Identification of the Model's Nodes (*not used in the model)

For simplicity, the internal components were designed as one node per equipment and use simple individual shapes, or as in the case of the structure, a collection of different shapes with individual nodes.

Each side frame is a single element that includes two rails and six ribs and where each rail forms a corner. Since there is no natural shape that looks like this, each rail was modelled with two rectangles that were condensed into one node. The ribs were then modelled as boxes and linked conductively to the rails to form the side frame.

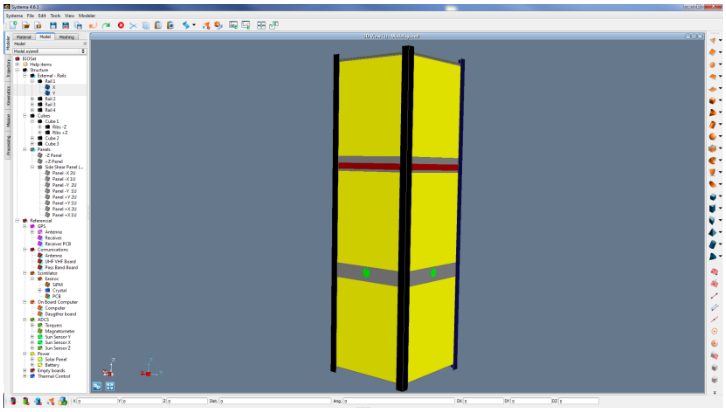

Fig. 17 – IGOSat model built in *Systema & Thermica*

According to Mr. Soriano (*Software, Numerical Analysis & Thermal Modelling Specialist from Airbus*), this would reduce the error if there is a large temperature gradient between the rail and the ribs. Otherwise they can be condensed into one node.

Regarding the Sun Sensors, these are placed inside the satellite but they face outside. So to emulate this behaviour, they were modelled in two parts:

- Internal: rectangle with the size of the sun sensor;
- External: circle with the approximate size of the sensor hole.

This will allow approximating the area of the sensor that will receive external fluxes.

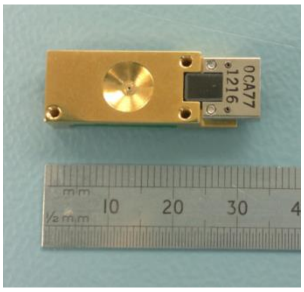

Fig. 18 - CubeSat's Sun Sensor (credit: SSBV datasheet)

5.1.2 Trajectory

In this section we define the orbit parameters:

- Type of orbit: Sun Synchronous orbit;
- Altitude: 600 km;
- Date: Summer Solstice/Winter Solstice;
- Start and End parameters.

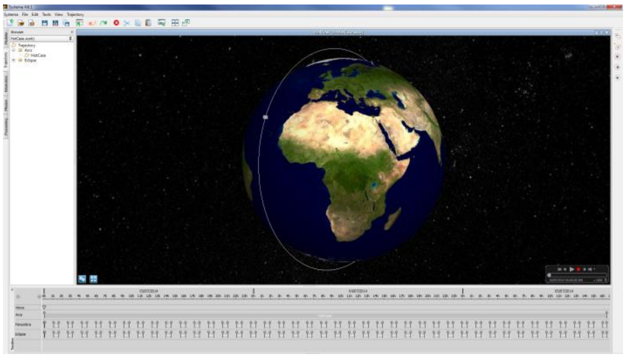

Fig. 19 - *Systema & Thermica*'s Trajectory Interface

Each orbit takes approximately 1h30m, where 34 minutes are spent in full eclipse. Each simulation is computed for 40 revolutions.

5.1.3 Kinematics

Here is where the attitude of the satellite is defined, such as rotation axis, rotation speed, etc. For our study, the X axis points to the planet and Z points to the orbital velocity vector. The rotation around the Z axis is defined to 10 rotations per hour.

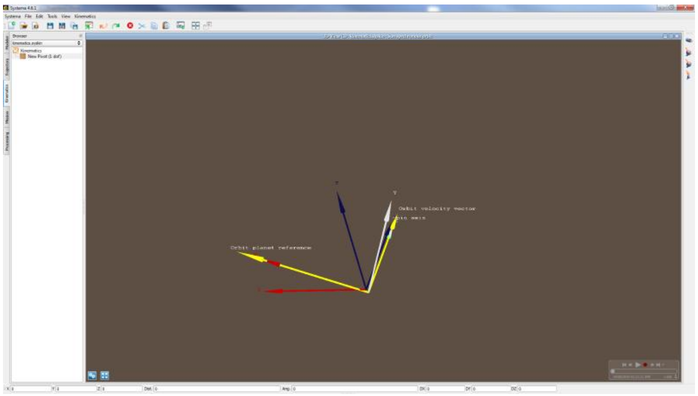

Fig. 20 -*Systema & Thermica's* Kinematics Interface

5.1.4 Mission

This part is where all the previous files are selected and compiled into a single mission file.

It allows the user to visualize if the satellite is spinning in the correct way and pointed in the right direction. It also allows animated sequences to be created, for example, to point the satellite to a specific direction when it reaches a given position to simulate a specific behaviour.

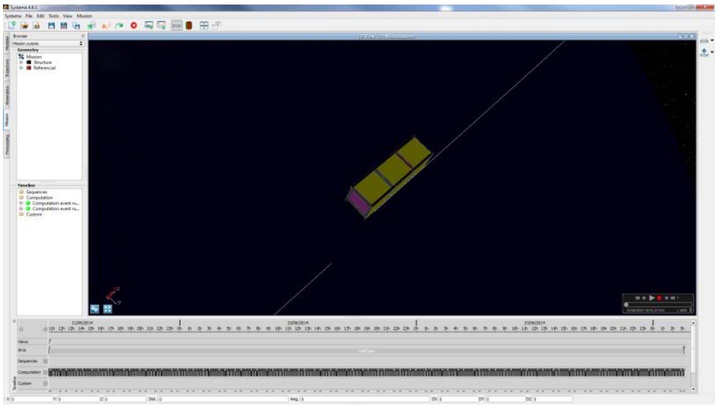

Fig. 21 - *Systema & Thermica*'s Mission view

This last part was not used in this study but could be developed in the future.

5.1.5 Processing

This is where the simulations are launched after the required toolboxes from Thermica and Thermisol are configured. When each toolbox is activated they need to be connected accordingly - this will ensure that each toolbox will send the correct information forward to be used on the next calculation.

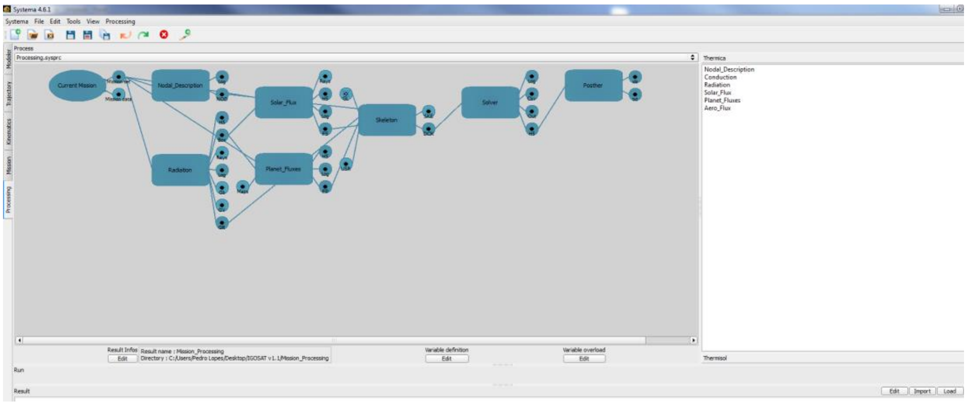

Fig. 22 - ***Systema & Thermica's*** **Processing Interface**

The modules used from Thermica are:

- **Nodal Description:** builds the Thermal Mathematical Model from the geometry;
- **Radiation:** performs the radiative calculations, view factors, etc...;
- **Solar/Planet Flux:** calculates the incoming fluxes from the planet and Sun.

From Thermisol:

- **Skeleton:** receives all the previous information. Its where the type of analysis is defined and their parameters. This is also where the user file is declared.
    - The user file is a text file that requires a specific syntax to declare the values that are going to be used; these are then translated to FORTRAN by Thermica. For this study the values declared are:
        - Conductive links (GL in units W/K);
        - Capacitance (C in units J/K);
        - Internal Dissipation (QI in units W).

      Other values, such as heaters consumptions and area/flux corrections can also be declared here.

- **Solver:** performs the calculations with Skeleton's output;
- **Posther:** exports the results to one of the available structures for all nodes, or specific individual nodes:
    - **All data**: outputs all the values obtained for fluxes, temperatures and dissipations at each time step;
    - **Min/Max/Mean by nodes**: outputs a smaller table with only the minimum, maximum and mean values for temperature, fluxes and dissipation with the corresponding time at which they occurred.

  There are other formats available but these were the ones used for this study.

5.2 Results

After applying the data calculated in chapter 4 to the working model developed throughout this project, *Systema & Thermica* yielded some encouraging results which will be discussed in this section.

5.2.1 Cold Case

Table 10 reports the values obtained for a Transient State analysis for a period of 40 orbits and compares them to the specifications temperatures.

Cold Case		Simulation Temperature (°C)			Specification Temp. (°C)	
Node	*Subsystem*	*Min.*	*Max.*	*Mean*	*Min.*	*Max.*
1 to 28	Structure	-28	27	-3	-40	80
29 to 38	SSP	-31	37	-3	-40	80
40 to 70	Empty PCB	-23	20	-2	-40	85
80	Thermal Control	-23	19	-4	-40	85
100	GPS Antenna	-23	17	-6	-50	70
200	GPS OEM615	-24	21	-3	-40	85
300	Com. Antenna	-27	24	-3	-30	70
400 to 401	AMSAT	-26	24	-3	-20	45
500	EASIROC (PCB)	-20	19	-3	-40	85
600	SiPM	-20	19	-2	0	40
700	Scintillator	-20	19	-2	-20	50
900	Computer	-16	18	-1	-20	60
1000	Torquer Board	-15	17	-1	-35	75
1100	Magnetometer	-23	18	-5	-50	85
1200 to 1501	Sun Sensors	-30	34	-3	-25	50
1601	Battery Cell	-18	19	-2	-20	60
1700 to 2900	Solar Panel	-32	40	-3	-40	85

Table 10: Minimum and maximum temperatures reached by each node, or inside a group of nodes for the Cold Case

For the most part, equipment temperatures stay inside their operational ranges and follow a periodical pattern, as seen in Fig. 23. This behaviour is due to successive eclipse and solar exposure. However, some cases that do not meet the requirements are expected to be found.

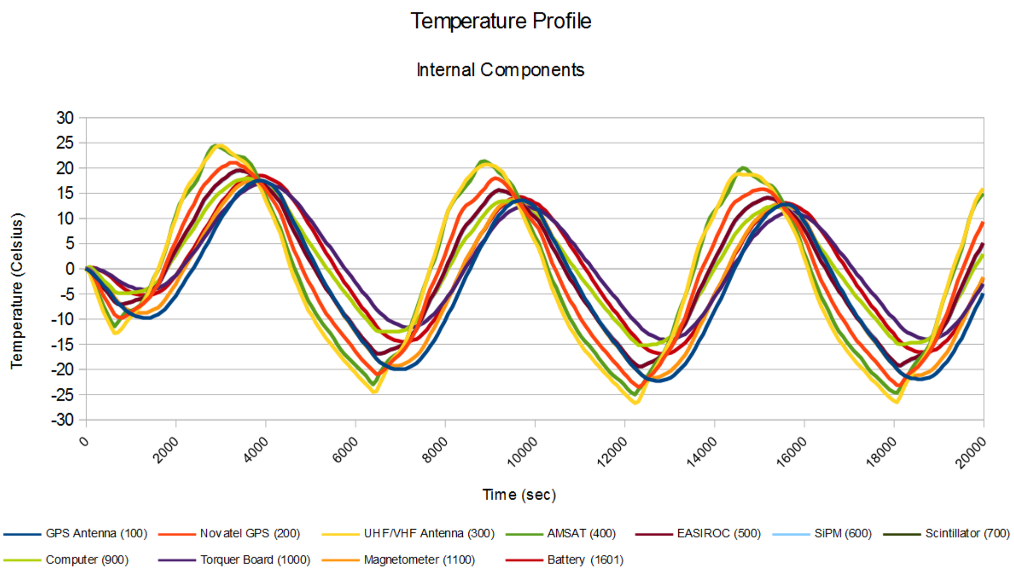

Fig. 23 - Internal Component's Temperature profile in the Cold Case

There are some equipment that also have a shorter thermal range such as the Computer, Scintillator, Communications Antenna and Battery, that can reach temperatures very close to their operational limits.

The worst case is the SiPM that falls 20ºC under its lower limit due to its very small operational range (0-40ºC) and it is likely to require heating. However, since the remaining components of the Scintillator Payload are not fully developed, these results are likely to change in the future as the design evolves.

The AMSAT is one the few components dissipating heat in this test case, but considering that its lower temperature range is shorter than most electronic boards it wasn't completely unexpected. Taking a closer look to the internal arrangement of the components in Cube 2 it might be possible to see why this happens:

This component is made of two boards: nodes 400 and 401 (the node with the dissipation), and they are attached to a secondary board, node 402 to fit CubeSat Standards. At the same point in time when node 400 reaches the -26ºC, node 401 is at -24ºC and the secondary PCB (node 402) is at -22ºC. Node 400 connects to one rib (node 19) while the secondary board connects to the opposite rib (node 17) - the temperature of these ribs at this point is -27ºC.

What seems to be happen in this case is that the thermal path between node 400 and node 19 might allow too much heat to pass compared to the path between nodes 402 and 17. Observing the values for the thermal resistance calculated for these links in chapter 4, it is possible to see that this is true:

- $R_{th}(400,19) = 1.71$ K/W
- $R_{th}(402,17) = 2.88$ K/W

The reason why one link offers 1.68 times the resistance of the other is simply due to the geometry of the link:

- $R_{th}(400,19)$ connects to the rib with only one washer and the Hex Nut;
- $R_{th}(402,17)$ uses two washers, one 17mm Bus Spacer and the Hex Nut, which results in additional contact resistances causing increased thermal resistance.

The results regarding the Sun Sensors are as expected. Their temperatures appear to be dominated by the SSPs to which they are attached, similarly to what is expected to happen to the kill switches as stated in 4.3.6. This comparison can be seen in the next table where the minimum and maximum temperatures for each pair *"SSP-Sun Sensor"* are compared and their difference calculated.

SSP	Temperature (°C)		Sun Sensor	Temperature (°C)		SSP – Sun Sensor	Temperature Variation (°C)	
Node	*Min.*	*Max.*	*Node*	*Min.*	*Max.*		*Min.*	*Max.*
35	-30.35	33.63	1200	-29.56	31.54	35 – 1200	-0.80	2.09
33	-30.41	32.54	1300	-29.51	30.32	33 – 1300	-0.90	2.22
31	-30.71	37.03	1400	-30.18	34.19	31 – 1400	-0.53	2.84
37	-31.24	33.65	1500	-30.10	30.91	37 – 1500	-1.14	2.74
29	-27.42	23.22	1501	-27.11	23.57	29 – 1501	-0.31	-0.35

Table 11: SSP temperature vs Sun Sensors

The temperature profiles for some of these pairs can also be seen below. The plot in Fig.24 refers to the pair *"SSP-Sun Sensor"* in the bottom of the satellite that has the most unique profile of the group while the Fig.25 plot refers to one of the pairs of the side faces.

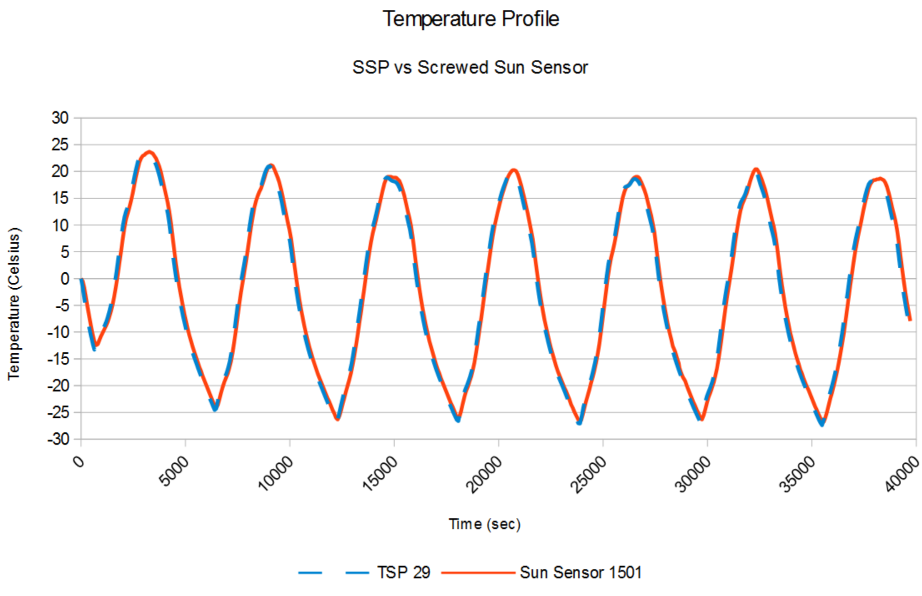

Fig. 24 – Paired TSP vs Sun Sensor Temperature Profile

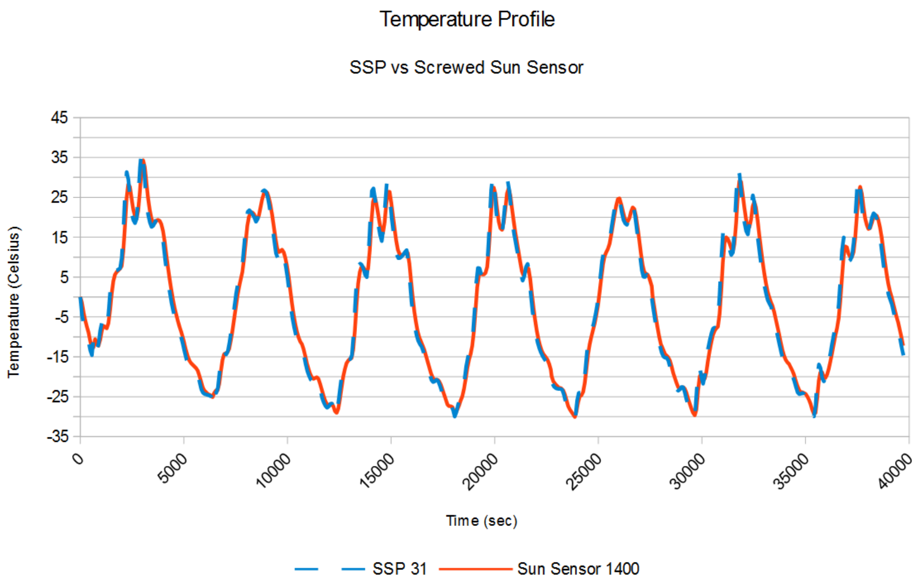

Fig. 25 - Paired SSP vs Sun Sensor Temperature Profile

The odd shape of the temperature curve seen for the side faces (SSP 31 - Sun Sensor 1400) can be explained with the change of incoming fluxes due to the satellite's spin and its orbit around the planet that can cause a quick succession of eclipses in the satellite's face. This behaviour can be better seen in the next plot in a close-up of the temperature profile for a solar panel when compared to the incoming fluxes.

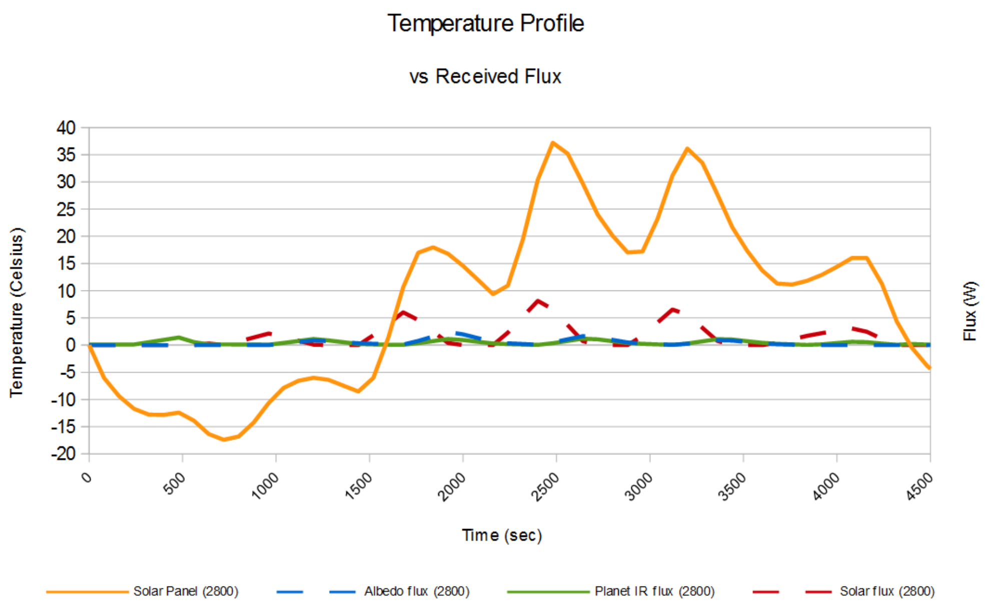

Fig. 26 - Temperature profile vs Flux for node 2800 (solar panel)

5.2.2 Hot Case

The following table shows the temperature ranges obtained for the Hot Case, where the satellite is exposed to higher solar fluxes and has nearly 7 times the internal dissipation of before.

Hot Case		Simulation Temperature (°C)			Specification Temp. (°C)	
Node	*Subsystem*	*Min.*	*Max.*	*Mean*	*Min.*	*Max.*
1 to 28	Structure	-16	36	8	-40	80
29 to 38	SSP	-20	46	8	-40	80
40 to 70	Empty PCB	-6	31	12	-40	85
80	Thermal Control	-7	30	12	-40	85
100	GPS Antenna	-6	30	11	-50	70
200	GPS OEM615	-1	38	19	-40	85
300	Com. Antenna	-15	31	8	-30	70
400 to 401	AMSAT	-14	32	10	-20	45
500	EASIROC (PCB)	0	36	19	-40	85
600	SiPM	0	36	18	0	40
700	Scintillator	0	36	18	-20	50
900	Computer	0	29	14	-20	60
1000	Torquer Board	0	29	16	-35	75
1100	Magnetometer	-4	31	13	-50	85
1200 to 1501	Sun Sensors	-17	42	9	-25	50
1601	Battery Cell	0	32	16	-20	60
1700 to 2900	Solar Panel	-21	49	8	-40	85

Table12: Minimum and maximum temperatures for the Hot Case

This time all components stay within operational ranges but some familiar behaviour can still be observed:

- The SSP-Sun Sensors pairing is still noticeable and this time causes the temperature of the Sun Sensors to go close to its upper operational limit;

SSP – Sun Sensor	Temperature Variation (ºC)	
	Min.	*Max.*
35 – 1200	-2.07	1.0554
33 – 1300	-2.14	1.6255
31 – 1400	-1.82	1.703
37 – 1500	-2.14	1.5058
29 – 1501	-1.78	-1.5008

Table 13: Temperature difference between pair SSP - Sun Sensors in the Hot Case

- The AMSAT is still being dominated by the Structure's temperature due to its close link; the same is observed for the Communication Antenna since it is directly screwed to the ribs of the side frame right next to the AMSAT.

The overall temperature profile for the internal equipment can be seen in the next plot, where the same periodic behaviour is observable again. It is also possible to see that some lower limits reported in Table 12 are not real and are caused by the initial conditions of the simulation where the starting temperature for every node is set to 0ºC.

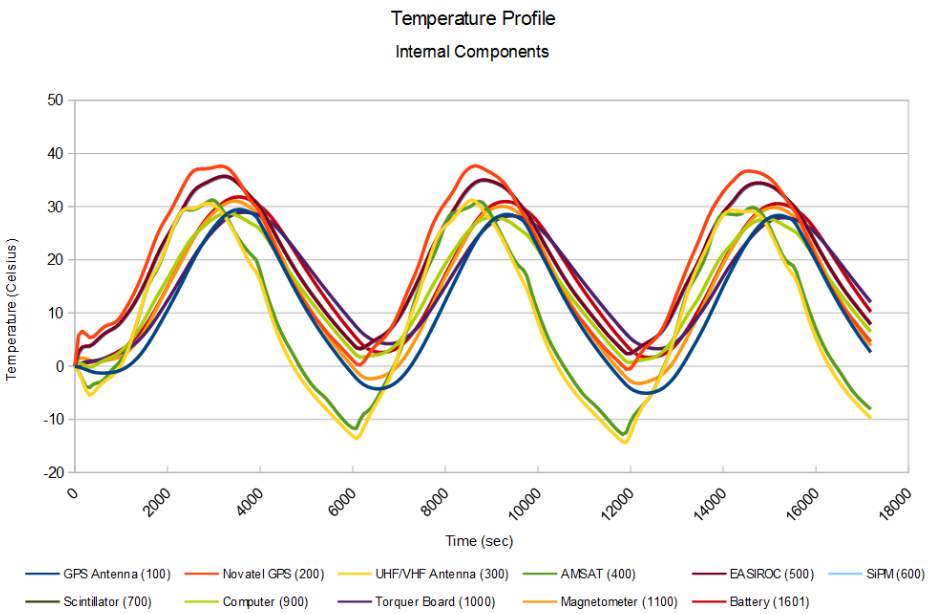

Fig. 27 - Hot Case Temperature Profile for Internal Components

Looking at the Solar Flux and one of solar panel's temperature profile and comparing to the previous plot, it is possible to see the influence that the solar flux and eclipses have in the satellite temperature.

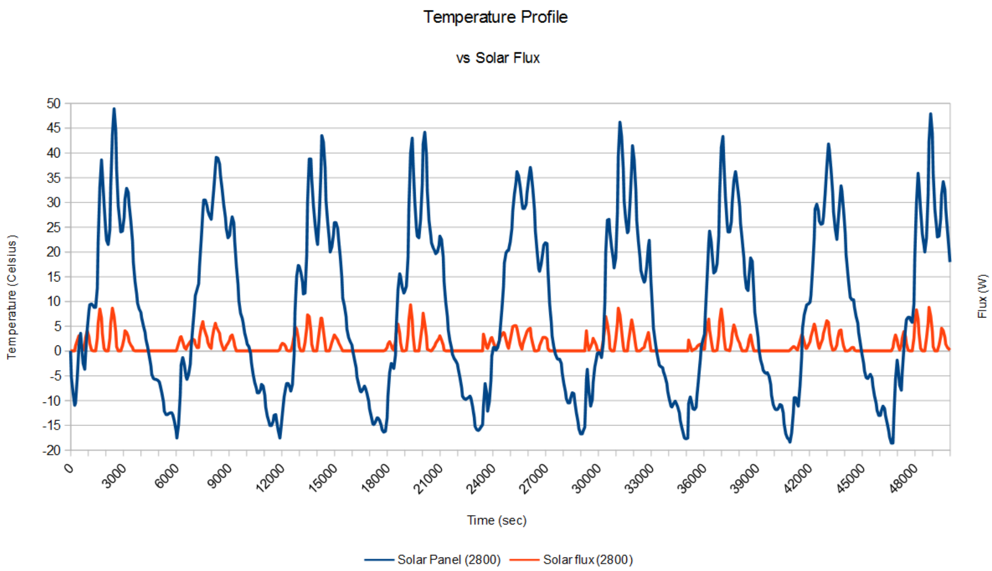

Fig. 28 - Solar Panel temperature vs received solar flux

6. Conclusion

As previously explained, this study is the result of the OSAE master's internship and it was a great opportunity to broaden my knowledge in the field. The biggest challenge for me was to create something with so little information available since, as stated before, many components are yet to be defined. Consequently, this had a great impact in the thermal study I had to perform, since the thermal model is based on several assumptions.

As pointed out before, the main objectives of this internship were to:

1. Create a preliminary mechanical design
2. Create a thermal model to calculate a satellite's thermal behaviour
3. Provide two simple working models for future improvement

The advantage of creating a mechanical design is to identify mechanical constraints and test configurations to find which is the most effective. During this study, several constraints were identified but the main were:

1. Electronic boards (GPS receiver and AMSAT) smaller than the CubeSat standard
2. The use of three magnetorquer rods for ADCS
3. Possible lack of space for the sun sensors on the satellite's tops

The first constraint means that the smaller boards need an adaptor board resulting in more space occupied. The second point suggests the need of a less intrusive design for the magnetorquer board, as the vertical rod would make it impossible to place more boards in the cube. Finally, the last constraint is self-explanatory – on the GPS top the antenna may prevent the placement of a sensor on one face, and on the opposite end, the solar panel also occupies the entire face.

In short, the present state of the mechanical model features a total mass of 2,8 kg out of the 4 kg limit. In order to obtain a constant inertia matrix, which is needed for the ADCS calculations, the 1,2 kg margin is to be distributed by the empty boards. This way it is possible to obtain a COG that satisfies the specifications – currently located at X= -0,29 mm, Y= 2,93 mm and Z= -0,3 mm and well within the limits.

To maintain this type of COG, the empty boards have already a "dummy mass" object that can be shaped and positioned as needed. The empty board's purpose is threefold:

1. Provide balance, giving a place to distribute mass;
2. Provide flexibility, allowing equipment that meet the CubeSat standard format to swap places with them without having to change the internal organization;
3. Provide uniformity to facilitate thermal calculations, since all cubes follow a similar internal structure.

As for the thermal study, the second objective referred above, my results suggest that:

- The structure's temperature profile seems to dominate the behaviour of any equipment attached to it. This was seen for the Sun Sensors and Communication Subsystem and should be possible to improve by isolating them further from the structure with a low thermal conductivity interface, such as Teflon;
- Even though the battery temperature stays inside the operational range, it needs a more detailed model and accurate thermal interfaces;

- It is necessary to improve the Scintillator Subsystem model due to the missing technical data at the time of this study about the BC-412 and its aluminium enclosure. This information was requested to the manufacturer of the scintillator, Saint Gobain, but unfortunately their answer came too late to be integrated in this study.

Another important conclusion related with the thermal behaviour is that the TCS must have the following features:

TCS-1: The TCS must be able to supervise all electronic components temperature by means of temperature sensors;

TCS-2: If an instrument's temperature reaches the specified operational limit, the TCS must be able to either engage heaters if available or shut down the component in question;

TCS-3: If the TCS detects that the satellite is running too hot due to excessive internal dissipation, the TCS must also be capable of changing the satellite's operating mode to survival mode.

By the end of this project, the main objectives presented in previous chapters were achieved, namely the creation of mechanical and thermal models and the presentation of a preliminary thermal study. These models were created with a view for the future as well – in a way to ease future changes and improvements. Namely, some empty boards were left in order to add new components if need be.

Future work should include not only an update of these models with more accurate information, but also the verification of degraded paints' effects and variable spin rates in the temperature profile.

Having in mind the features the TCS should have, if the satellite's spinning rate turns out to have a meaningful effect over the satellite's temperature, the TCS must be able to influence this parameter through a connection to the ADCS in order to control the temperature. This would be one aspect to develop in the future.

Lastly, according to Saint Gobain, there is no accurate data related to the thermal properties of BC-412 but they suggest that it can be approximated to cast polystyrene. They also provided design information about the aluminium enclosure, which was uploaded to the scintillator technical data folder and can be taken into account for the next model.

Conclusion (Français)

Cette étude est le résultat du stage pour le master OSAE, niveau M2, et c'était un vrai plaisir d'avoir l'opportunité d'agrandir mes connaissances sur le ce thème. Le plus grand défi que j'ai eu était la création de quelque chose sans voir beaucoup d'information disponible, une fois que beaucoup de components ne sont pas encore définis. Cela a eu un grand impact sur l'étude thermique que je devais faire, lorsque le modèle thermique s'est basé sur beaucoup d'assomptions.

Comme indiqué précédemment, les objectifs principaux de ce stage étaient de :

1. Créer un modèle mécanique préliminaire
2. Créer un modèle thermale pour calculer le comportement thermique d'un satellite
3. Donner deux modèles de travails simples pour développement futur

L'avantage de créer un modèle mécanique est de pouvoir identifier des limitations mécaniques et de tester configurations pour pouvoir identifier la plus effective. Pendant cette étude, beaucoup de limitations ont été identifiés, mais les principales étaient :

1. Les plaques électriques (récepteur GPS et AMSAT) – elles sont plus petites que le standard CubeSat
2. L'usage de trois magneto coupleur pour les SCAO
3. Possible manque de place pour les panneaux solaires sur les extrémités du satellite

La première limitation signifie que les plaques plus petites ont besoin d'un adaptateur, occupant plus de place. Le deuxième point suggère la nécessité d'un modèle moins intrusive pour le magneto coupleur, une fois que celui-ci pose l'impossibilité de mettre plus de plaques sur le cube. Finalement, le troisième point est bien explicite – la taille de l'antenne GPS peut empêcher l'installation d'un senseur solaire d'une côte, et sur l'autre côté le panel solaire occupe aussi toute la place.

Bref, l'état actuel du modèle mécanique présente une masse totale de 2,8 kg, dont les 4 kg considérés limitent. Pour obtenir une matrix d'inertie constante, qui est essentielle pour les calculs des SCAO, la marge d'un 1,20kg doit être distribuée par les plaques vides. De cette façon, c'est possible d'obtenir un centre de gravité (CG) qui répond aux spécifications : actuellement localisé à X= -0,29 mm, Y= 2,93 mm et Z= - 0,3 mm, ce qui c'est bien dans les limites.

Pour maintenir ce type de CG, les plaques vides ont déjà un « objet faux » qui peut être modifié et positionnée conforme les besoins. Ces plaques vides ont un objectif triple :

1. Donner de l'équilibre, en donnant de la place pour distribuer le poids
2. Concéder flexibilité - les équipements conformes aux réquisits du CubeSat standard peuvent être mouvementés sans changer l'organisation interne du satellite
3. Donner de l'uniformité pour faciliter les calculs thermiques, une fois que tous les cubes ont une structure interne similaire

Concernant l'étude thermique, le deuxième objectif de ce rapport comme mentionné précédemment, mes résultats suggèrent :

1. Le profil de la structure thermique apparait comme dominant, indépendamment des équipements rattachés. Ce comportement été visible pour les senseurs solaires et pour le sous-Système de Communication. Il se suppose que des améliorations sont possibles si ces

components sont plus isolés de la structure avec une interface de baisse conductivité, comme Teflon.
2. Bien que la batterie de la température est bien sur l'intervalle opérationnel, il faut un modèle plus détaillé et des interfaces thermiques plus précises.
3. Il faut développer le modèle du scintillateur par suite d'un manque d'information à l'époque de cette étude en ce qui concerne le BC-412 et la capsule d'aluminium. L'information a été demandée au fournisseur du scintillateur, Saint Gobain, mais elle est arrivée trop tard pour être considérée pour cette étude.

Un autre aspect important concernant le comportement thermique ce sont les propriétés que le SCT (sous-système de contrôle thermique) doit avoir :

SCT-1 : le SCT doit être capable de superviser la température de tous les components électroniques, à travers des senseurs de température

SCT-2 : si la température d'un instrument attendre le limite opérationnel, le SCT aura besoin de soit allumer le chauffage si existant, soit couper l'instrument en question

SCT-3 : si le SCT détecte que le satellite travaille avec une température haute grâce à la dissipation excessive interne, le SCT doit être capable de changer le mode opérationnel du satellite pour le model de survie

A la fin de ce projet, les objectifs présentés précédemment ont été largement réussis – un modèle mécanique et thermal ont été créés et une étude thermique préliminaire a été présenté. Ces modèles ont été créés de manière à être facile à adapter et modifier dans l'avenir. Notamment, les plaques vides existent pour ajouter des éléments dans le futur, si besoin.

Par la suite, ces modèles doivent être actualisés tenant en compte des informations plus précises, mais aussi vérifier les effets de l'usure de la peinture et la variation de rotation sur le profile thermique.

Tenant en compte les caractéristiques que le SCT doit tenir, si la vitesse de rotation du satellite a un effet dominant sur sa température, le SCT doit être capable d'influencer ce paramètre à travers d'une connections avec le SCAO pour contrôler la température. Ce c'est un aspect à développer pour le future.

Pour finaliser, Saint Gobain indique qu'il n'y a pas d'information précise concernant les propriétés thermiques du BC-412, mais il suggère qu'il peut être similaire au polystyrène. L'entreprise a pourvu information sur la capsule d'aluminium, qui a été rajouté au dossier d'information du scintillateur et doit aussi être considérée pour le futur.

7. Annex

Annex 1- IDM-CiC System View

V Configuration of unit instances:

Element	Sub-system	Unit	Unit Type	Instance	Coordinate system definition	Origin in coordinate system			Rotation in coordinate system [°]			
						x	y	z	Order	R1	R2	R3
V **Platform**	V Structure	External Structure Rails	Equipment V									
				1	Platform	100	0	0	Rx - Ry - Rz	0	0	90
				2	Platform	0	100	0	Rx - Ry - Rz	0	0	270
		Shear Panel Sides	Equipment V									
				1	Platform	0	8,5	7	Rx - Ry - Rz	0	0	0
				2	Platform	91,5	0	7	Rx - Ry - Rz	0	0	90
				3	Platform	100	91,5	7	Rx - Ry - Rz	0	0	180
				4	Platform	8,5	100	7	Rx - Ry - Rz	0	0	270
		Shear Panel Tops	Equipment V									
				1	Platform	8,5	0	7	Rx - Ry - Rz	0	0	0
				2	Platform	8,5	0	333,1	Rx - Ry - Rz	0	0	0
		Stack	Equipment V									
				1	Platform	4,93	2,055	7,8	Rx - Ry - Rz	0	0	0
				2	Platform	4,93	2,055	121	Rx - Ry - Rz	0	0	0
				3	Platform	4,93	2,055	234,2	Rx - Ry - Rz	0	0	0
	V Power	Nano PowerP31U	Equipment V									
				1	Platform	5,42	3,62	145	Rx - Ry - Rz	270	0	270
		Solar Panel Side	Equipment V									
				1	Platform	0	8,5	7,4	Rx - Ry - Rz	0	-90	0
				2	Platform	100	91,5	7,4	Rx - Ry - Rz	90	90	90
				3	Platform	91,5	0	7,4	Rx - Ry - Rz	90	0	90
				4	Platform	8,5	100	7,4	Rx - Ry - Rz	90	180	90
				5	Platform	0	8,5	121	Rx - Ry - Rz	0	-90	0
				6	Platform	100	91,5	121	Rx - Ry - Rz	90	90	90
				7	Platform	91,5	0	121	Rx - Ry - Rz	90	0	90
				8	Platform	8,5	100	121	Rx - Ry - Rz	90	180	90
				9	Platform	0	8,5	235	Rx - Ry - Rz	0	-90	0
				10	Platform	100	91,5	235	Rx - Ry - Rz	90	90	90
				11	Platform	91,5	0	235	Rx - Ry - Rz	90	0	90
				12	Platform	8,5	100	235	Rx - Ry - Rz	90	180	90
		Solar Panel Top	Equipment V									
				1	Platform	1	1	333	Rx - Ry - Rz	0	0	0
	V Avionics	ISIS Computer	Equipment V									
				1	Platform	4,95	2,05	180	Rx - Ry - Rz	0	0	0
	V Atitude Control System	Torquer Board	Equipment V									
				1	Platform	4,95	2,05	85	Rx - Ry - Rz	0	0	0
		Sun Sensor	Equipment V									
				1	Platform	5	35	108	Rx - Ry - Rz	0	-90	0
				2	Platform	95	35	119	Rx - Ry - Rz	0	90	0
				3	Platform	65	5	108	Rx - Ry - Rz	90	0	90
				4	Platform	35	95	108	Rx - Ry - Rz	-90	0	-90
		Magnetometer	Equipment V									
				1	Platform	0	6	134	Rx - Ry - Rz	0	0	0
	V Communications	AMSAT-F	Equipment V									
				1	Platform	4,93	4,495	204,4	Rx - Ry - Rz	0	0	0
		ISIS UHF/VHF antenna	Equipment V									
				1	Platform	1	1	220	Rx - Ry - Rz	0	0	0
	V Thermal Control	Thermal Control	Equipment V									
				1	Platform	4,95	2,05	285	Rx - Ry - Rz	0	0	0
V **Payload**	V Subsystem GPS	GPS Receiver OEM615	Equipment V									
				1	Payload	16,95	24,05	54,67	Rx - Ry - Rz	0	0	0
		Antenna AT2775	Equipment V									
				1	Payload	4,95	2,05	25,5	Rx - Ry - Rz	0	0	0
	V Scintilator	Easiroc	Equipment V									
				1	Payload	4,95	2,05	300	Rx - Ry - Rz	0	0	0
		Scintillator	Equipment V									
				1	Payload	42,45	45	301,6	Rx - Ry - Rz	0	0	0

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