Master thesis : Study of a cooling system for a CubeSat Infrared detector

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Study of a cooling system for a CubeSat infrared detector

Graduation Studies conducted for obtaining the Master’s degree in Aerospace Engineering by:

Pierre REMACLE

Academic advisor: Prof. Jérôme LOICQ

Academic year 2017 - 2018
Abstract

This thesis focuses on the design of different cooling systems for a CubeSat infrared detector.

This work is carried out as a part of the OUFTI-Next satellite project, led by the University of Liège. It highlights the different constraints linked to the use of such detectors is small satellites like CubeSats and analyzes different cooling solutions enabling the detector to work at its recommended operating temperature.

After a definition of the OUFTI-Next mission context and requirements, a description of the different thermal flows and temperatures is done, followed by a preliminary geometrical modeling of the detector and its cooling system inside the CubeSat payload volume.

The first cooling design evaluated consists of only passive systems. This design is analyzed, combined with the thermal model described above. Results obtained by checking detector temperature and heat fluxes allow to draw conclusions that can lead to potential improvements of the passive used in this initial model.

Active systems are then introduced in the initial design to check their influence on the detector temperature, in particular, Peltier and cryocooler devices.

Finally, a transient analysis is performed to find a smart cooling down strategy that will minimize the eventual electrical consumption and decrease the cooling down time.

Keywords: OUFTI-Next, CubeSat, MWIR, Thermal design, Cooling system, Matlab
Acknowledgments

I want to sincerely thank Prof. Jérôme Loicq, for giving me the opportunity to realize my integration internship at the Centre Spatial de Liège and taking part of the amazing OUFTI-Next project, but also for all its fruitful advice and its availability.

I also thank Lucas Salvador for being member of my academic jury, but mostly for all the time he spent to answering carefully my numerous questions during the whole semester.

I express my gratitude to Prof. Gaetan Kerschen and Prof. Serge Habraken for accepting to be members of my academic jury, but also for all their advice given during OUFTI-Next meetings.

More generally, I want to thank all the OUFTI-Next team members. Teamwork is very common during an engineer career, and realize this thesis in collaboration with such a team was a great experience.

I especially thank my dad for all evenings he spent to read my work and for all advice he gave me to improve this report. I also thank the rest of my family and my friends for their strong support and numerous encouragement, but also for all amazing moments I lived with them during these five years of study.

Last but not least, I finally thank you, Carole, for always being my main supporter during these four months, and for all the interest you had for my work.

Liège, June 2018
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**Acronyms**

ADCS  Attitude Determination and Control System  
BOL   Beginning Of Life  
CAD   Computer-Assisted Design  
CCD   Charged Coupled Device  
CIRAS CubeSat Infrared Atmospheric Sounder  
COP   Coefficient Of Performance  
DC    Dark Current  
EFL   Effective Focal Length  
EMS   Electromagnetic spectrum  
EOL   End Of Life  
EPS   Electrical Power System  
ESA   European Space Agency  
FIR   Far-Infrared  
FPA   Focal Plane Array  
GSD   Ground Sample Distance  
HOT   High Operating Temperatures  
IR    Infrared  
ISS   International Space Station  
LEO   Low Earth Orbit  
LWIR  Long-Wave Infrared  
MLI   MultiLayer Insulation  
MTTF  Mean Time To Failure  
MWIR  Mid-Wave Infrared  
NASA  National Aeronautics and Space Administration  
NIR   Near-Infrared  
OBC   On-Board Computer  
OUFTI Orbital Utility For Telecommunication Innovation (OUFTI-1)
OUFTI Orbital Utility For Thermal Imaging (OUFTI-Next)
PCB Printed Circuit Board
P-POD Poly-Picosatellite Orbital Deployer
REF Radiative Exchange Factor
SAMCEF Système pour l’Analyse des Milieux Continus par Elements Finis
SNR Signal to Noise Ratio
SSO Sun Synchronous Orbit
SPF Single Point of Failure
SWIR Short-Wave Infrared
TEC ThermoElectric Cooling
TMM Thermal Mathematical Model
TOP Thermo-Optical Properties
UV UltraViolet
VIS Visible
Chapter 1

Introduction

Since the beginning of space exploration, a large number of missions were devoted to Earth observation to better understand our planet. It is still the case nowadays, and thanks to the CubeSat project, space became accessible at a much lower financial investment, resulting in an increasingly interest of academical institutions, like the University of Liège.

Observations methods are numerous, and depend on the electromagnetic bandwidth considered (Fig. 1.1). One of the most used bandwidth is the Infrared (IR) region, which allows to obtain thermal information of the observed sample. Infrared detectors are designed for these thermal analysis, but needs to be cooled down at cryogenic temperatures to limit the thermal noise on the sensor.

This thesis highlights the constraints that arise with the use of an IR detector for a CubeSat project under development by the University of Liège: OUFTI-Next (Orbital Utility For Thermal Imaging). Using results coming from other members of the OUFTI-Next team, this work reviews all existing cooling solutions that exists and proposes several systems that can be integrated in a CubeSat nanosatellite to bring the IR detector in an acceptable temperature range.
1.1. The OUFTI-Next project

The idea of the OUFTI-Next project came almost naturally at the University of Liège, after the successful launch of its first nanosatellite OUFTI-1 (Orbital Utility For Telecommunication Innovations) in 2016\(^1\). The OUFTI-Next team, composed of Prof. Jérôme Loïcq, Prof. Serge Habraken, Prof. Gaëtan Kerschen and Xavier Werner, decided to start again a CubeSat project but with greater ambitions, gathered academics and industrial partners around a table to define objectives of a new CubeSat project. The idea of hydric stress detection in agricultural fields of arid regions has been chosen as the most promising proposal. The mission would consist in a demonstrator CubeSat which monitors the Earth in the MWIR (Mid-Wave Infrared) bandwidth in order to detect fields that needs to be watered. Since leaves surface temperature changes with plants hydric stress, a thermal monitoring of agricultural fields would directly provide information on plants water needs. Images obtained would thus help to develop a smart irrigation strategy of monitored areas, in a world where 69% of water is used for agriculture, and where 40% of farmlands are irrigated [2].

The first phase of the project began in 2017, with the mission analysis and a payload feasibility study (phase 0), conducted by Enrico Ghidoli [3], Dimitry Schklar [4]. Phase A followed in 2018, gathering six other students, each of them associated to a specific subsystem (Tab. 1.1). The aim of the team is to demonstrate the global mission feasibility and propose first system definitions, so that phase B can take place, based on phase A

---

\(^1\) Contact with OUFTI-1 has been lost several days after the launch
1.2. **THE CUBESAT STANDARD**

Chapter 1. **INTRODUCTION**

At its beginning and until the end of the XX\textsuperscript{th} century, access to space was restricted to governmental and intergovernmental organizations, such as NASA (National Aeronautics and Space Administration) or ESA (European Space Agency), mainly due to the expensive costs of space missions development. However in 1999, two professors, Jordi Puig-Suari (California Polytechnic State University) and Bob Twiggs (Stanford University) proposed a new standardized nanosatellite design, the CubeSat standard. The main goal of this project was to diminish the costs of such space missions, providing the ability for academical institutions to develop and launch their own satellites. The first CubeSat has been launched on June 30, 2003, and since that day the number of launched satellites and planned launches is in constant increase (Fig. 1.2), making of this project a true success. Initially, the term CubeSat refers to the 1U standard (1U for one-unit), which represents a \(10\times10\times10\) [cm] volume, with a maximum weight of 1 [kg] and a maximum power consumption of 1 [W]. These constraints have been chosen to fit with the CubeSat

#### Table 1.1 – Students members of the 2017-2018 OUFTI-Next team

<table>
<thead>
<tr>
<th>Student</th>
<th>Subsystem</th>
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<td>Anna Riera Salvà</td>
<td>Optical refractive design</td>
</tr>
<tr>
<td>Anthony Keelens</td>
<td>Thermal study</td>
</tr>
<tr>
<td>Colin Dandumont</td>
<td>Systems engineering</td>
</tr>
<tr>
<td>Donatien Calozet</td>
<td>Optical reflective design</td>
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<tr>
<td>Lidiia Suleimanova</td>
<td>Optical system using Fresnel lenses</td>
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<tr>
<td>Pierre Remacle</td>
<td>Detector cooling</td>
</tr>
</tbody>
</table>

Table 1.1 – Students members of the 2017-2018 OUFTI-Next team

#### Table 1.2 – Typical lifetime cycle of an ESA mission [5]

<table>
<thead>
<tr>
<th>Phase 0</th>
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<td>Phase A</td>
<td>Feasibility</td>
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<td>Phase B</td>
<td>Preliminary definition</td>
</tr>
<tr>
<td>Phase C</td>
<td>Detailed definition</td>
</tr>
<tr>
<td>Phase D</td>
<td>Qualification and production</td>
</tr>
<tr>
<td>Phase E</td>
<td>Utilization</td>
</tr>
<tr>
<td>Phase F</td>
<td>Disposal</td>
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</tbody>
</table>

Table 1.2 – Typical lifetime cycle of an ESA mission [5]
1.3 THE MWIR BANDWITH

Infrared radiations are part of the electromagnetic spectrum with longer wavelengths than visible light, that are therefore invisible to the human eye. IR wavelengths typically extends from the red edge of the visible spectrum, at around 700 [nm] to 1 [mm]. The IR spectrum itself is divided in five sub parts (Tab. 1.3). All objects with a temperature between -100 and 100 [°C] emit radiations belonging to MWIR and LWIR bandwidths, in an amount depending on the temperature of the object. By sounding and focusing these radiations, it is possible to translate the temperature variations into a grey-scale image, where darker and brighter shades respectively represents cooler and hotter temperatures.
The OUFTI-Next mission plans to sound the Earth using the MWIR bandwidth, especially wavelengths between 3 [µm] and 5 [µm], due to the high Earth atmospheric transmission at these wavelengths (Fig. 1.3), and also because of a lower diffraction limit than LWIR, which allows to use smaller pixels, resulting in smaller optics. A detector, made up of a CCD (Charge Coupled Device) sensor is intended to be used. The incoming photons are collected by a semiconductor material constituting the CCD, and are converted into an electrical signal before being translated. The choice of the semiconductor material depends on the observed bandwidth, but more than only one material can be sensitive at a considered wavelength (Tab. 1.4).

![Figure 1.3 – Earth atmosphere transmission windows [2]](image)

<table>
<thead>
<tr>
<th>Name</th>
<th>Wavelength [µm]</th>
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<tr>
<td>Near-Infrared (NIR)</td>
<td>0.7 - 1.4</td>
</tr>
<tr>
<td>Short-Wave Infrared (SWIR)</td>
<td>1.4 - 3</td>
</tr>
<tr>
<td>Mid-Wave Infrared (MWIR)</td>
<td>3 - 8</td>
</tr>
<tr>
<td>Long-Wave Infrared (LWIR)</td>
<td>8 - 15</td>
</tr>
<tr>
<td>Far infrared (FIR)</td>
<td>15 - 1000</td>
</tr>
</tbody>
</table>

Table 1.3 – The different IR bandwidths
1.4 Cooling necessity

Since IR detectors are electronic devices working at a non zero temperature, they are subject to noise, especially DC (Dark Current) noise, which is related to the detector material properties (bandgap $\Delta E$) and detector temperature ($T_d$). Physically, DC noise corresponds to the random generation of electrons and holes within the depletion region of the sensor. It can be estimated, for some specific materials such as InSb, by using the Richardson equation (Eq. 1.1) [7].

\[
I_{DC} = A_d \cdot C \cdot T_d^2 \cdot e^{\frac{\Delta E \cdot Q}{k \cdot T_d}},
\]

where:

- $I_{DC}$: dark current intensity [A]
- $A_d = ps^2$: pixel area [m$^2$] ($ps$: pixel size)
- $C = 1.2 \cdot 10^6$: constant parameter [A·m$^{-2}$·K$^{-2}$]
- $T_d$: pixel temperature [K]
- $\Delta E$: energy bandgap [eV]
- $Q = -1.6022 \cdot 10^{-19}$: electron charge [J]
- $k = 1,38064852 \cdot 10^{-23}$: the Boltzmann constant [J/K]

Applying this equation for different materials (InSb, InAs) at different temperatures (considering the temperature dependence of the energy bandgap (Eq. 1.2, Eq. 1.3) [8]), and by using a pixel size equal to 15 [$\mu$m],

\[
\Delta E_{\text{InSb}} = \frac{0.24 - 6 \cdot 10^{-4} \cdot T_d^2}{T_d + 500} \quad \text{[eV]} \quad (1.2)
\]
1.4. COOLING NECESSITY

\[ \Delta E_{\text{InAs}} = \frac{0.415 - 2.76 \cdot 10^{-4} \cdot T_d^2}{T_d + 83} \] [eV] \hspace{1cm} (1.3)

It is possible to get the temperature dependency of the DC noise for considered materials.

Due to the form of the Richardson equation, the DC noise exponentially decreases when lowering the temperature (Fig. 1.4), meaning that sensing with a detector at a low temperature will make it able to work with a better accuracy and a higher definition. This is why most of the IR photodetectors are cooled to cryogenic temperatures, going from 70 [K] to 150 [K], depending on the considered detector specifications.

Figure 1.4 – Temperature dependency of the DC noise for InSb and InAs (ps=15 µm)

2. A temperature reduction results in a SNR (Signal To Noise) increase

Remacle Pierre

7

Academic Year 2017-2018
Chapter 2

OUFTI-Next mission specifications

This chapter briefly reviews all mission specifications that have already been defined for the OUFTI-Next demonstrator project, either by the 2016-2017 or the 2017-2018 team. These specifications concern basic points, such as structure configuration or orbit choice, directly or indirectly affecting detector operating conditions.

2.1 Choice of a 3U standard

When integrating an imaging system into a satellite, both optical and detecting systems have to be considered. Inside a CubeSat, space is limited, and the optic itself will certainly need the equivalent of a 1U standard volume. Adding the space required for the detector and its cooling system, but also all other components that are mandatory to control the satellite (ADCS (Attitude Determination and Control System), EPS (Electrical Power System), OBC (On-Board Computer), antennas, batteries), it becomes clear that the space provided by a 1U standard or even a 2U standard will not be enough to place all the required payload into the structure.

Figure 2.1 – OUFTI-Next CubeSat preliminary CAD drawings

(a) Simple (fictive payload) [4]  
(b) Detailed [2]
2.2 ORBIT

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The 3U standard has thus been chosen for the OUFTI-Next demonstration mission, and preliminary CAD (Computer-Assisted Design) drawings have also been realized by the previous team (Fig. 2.1). On these two drawings, it can be seen that an equivalent space of between 1U and 1.5U is available for the payload\(^1\). In this thesis, an available space of 150×100×100 [mm] is considered, representing a little bit less than an 1.5U CubeSat standard\(^2\).

2.2 Orbit

2.2.1 Orbital constraints

The choice of the orbit is a parameter that has to be defined as early as possible in a space mission project, because it affects nearly all systems of the satellite. The main constraint concerning the orbit of OUFTI-Next is that the orbit can not be freely chosen as nanosatellites are considered as secondary payload. Indeed, CubeSats can either be launched by a rocket, using the residual space left by the primary payload, and where the orbit will be the same as the one chosen for the main satellite, or they can also be released by the ISS (International Space Station), where the orbit of the CubeSat will be the one of the ISS. Extensive research on upcoming launches must be done in order to find the best opportunity which would bring the CubeSat on the desired orbit. Furthermore, as the IR sounding mission requires an acceptable resolution to image the ground, OUFTI-Next is intended to fly on a LEO (Low Earth Orbit), and the considered altitude has been set to 600 [km].

2.2.2 The SSO (Sun Synchronous Orbit)

A SSO is a nearly polar orbit chosen in such a way that it precesses through one complete revolution each year (Fig. 2.2). In this configuration, the orbit plane maintains a constant angle with the Sun, which means that the sunlight coming onto a satellite do not vary over a year, as well as the sunlight coming on the observed area. The main advantage of the SSO is that both thermal and power control are easier to manage, since the sunlight only depends on the position along the orbit. It also have the advantage that a lot of missions plans to use this orbit, making the SSO a frequent destination for main payloads. The launch opportunities are thus more numerous, and this provides a larger choice of available orbits.

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1. The payload consists in the optical system, the detector and its cooling system
2. A 1.5 unit has dimensions equal to 170.2×100×100 [mm]
2.3 Optics

The aim of the optical system is to focus the light coming from the sounded area so that it reaches the detector with an acceptable resolution. Three possibilities are proposed for the mission, and are currently under investigation (a reflective design, a refractive design and a design based on Fresnel lenses). The different bandwidths that will reach the sensor represent an incoming thermal flux that needs to be cleared out, and directly depends on the chosen system (some refractive lenses are able to transmit IR radiations, but are opaque to visible wavelengths). Since the optical system remains to be selected by the team, this project takes into account both VIS (visible) and IR thermal contributions in the design to represent a worst case during the analysis.

Even if the type of optical system has not been chosen yet, it must satisfy some mission requirements. One of them which will be taken into account in this thesis is the GSD (Ground Sample Distance), which represents the equivalent size of a pixel on the ground. The SWATH is obtained by multiplying the number of pixels in one direction of the detector by the GSD, and corresponds to the total effective ground area sounded by the satellite. This value is important since it is linked with the amount of radiation coming from the ground that directly reach the detector through the optic (Fig. 2.3).
2.4 Power

The electrical power needed by all subsystems will be produced by solar panels. The produced power will be stored in batteries, and the EPS (Electrical Power System) will distribute it to all different subsystems when needed. Position of solar panels has not been chosen yet, but three configurations exist (body-mounted, cross and table configurations) (Fig 2.4). It is also possible to combine these configurations to increase the number of solar panels on the structure if more electrical power is needed by the different subsystems.

For the OUFTI-Next mission, the cross configuration, combined with body-mounted panels seems to be the best design, since it provide less constraints on the payload and on the satellite orientation than the table configuration.
2.5 Detector

The choice of the detector is crucial, since it will represent a large part of the satellite financial budget. Thus, it should be carefully selected to fit best all requirements. Many types of detectors are available on the market, depending on the manufacturer. They can stand out by their size, their FPA (Focal Plane Array) constituting material, or their operating temperature. Tab. 2.1 presents three different sensors provided by three different manufacturers.

<table>
<thead>
<tr>
<th>Pixel size [µm]</th>
<th>FLIR Neutrino</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor size [pixels]</td>
<td>SCD Kinglet 640</td>
<td>640×512</td>
</tr>
<tr>
<td>FPA Material</td>
<td>Sofradir LEO-LP MW</td>
<td></td>
</tr>
<tr>
<td>InSb</td>
<td>640×512</td>
<td></td>
</tr>
<tr>
<td>XBi (InAsSb)</td>
<td>HgCdTe</td>
<td></td>
</tr>
<tr>
<td>Spectral band [µm]</td>
<td>3.4 - 5.1</td>
<td>3.6 - 4.2</td>
</tr>
<tr>
<td>Recommended temperature [K]</td>
<td>80</td>
<td>150</td>
</tr>
</tbody>
</table>

Table 2.1 – Properties of MWIR detectors from different manufacturers [12][13][14]

These three detectors all have very low operating temperature, which confirms results presented in section 1.4. Most of manufacturers associate their detector with a dedicated cryocooler (Fig. 2.5), which often consists in a Stirling refrigerator. The disadvantage of that type of cooler is the presence of small moving parts inside the mechanism, that are subject to wear, and which create vibrations that spread in the CubeSat can disrupt the other subsystems (pointing accuracy, detector resolution, ...). Moreover, Stirling coolers require high amounts of electrical power, which can cause problems in the power management of the satellite. That is mainly why the idea of an alternative cooling system must be investigated, with no moving parts and a reduced power consumption. The Stirling option will be considered as the last available option, and related constraints will be deeply analyzed at the end of this thesis.

Figure 2.5 – the FLIR Neutrino MWIR detector, with its cryocooler
2.6 Pointing

The satellite orientation will depend on the task to be fulfilled in orbit. Three main orientations are considered for this mission, each related to a specific task: acquisition, communication and battery charging. These orientations are briefly described hereafter.

2.6.1 Acquisition

Since the optical system is supposed to point the Earth and is oriented along the length of the CubeSat (same configuration than Fig. 2.6a, representing the DOVE-1 satellite, where the optical system is also oriented along the length of the 3U CubeSat), a nadir pointing is required during the acquisition of thermal images. This configuration consists in having the \(-z\)-axis of the CubeSat pointing towards the Earth (Fig. 2.6b), such as the optical system is perfectly positioned. This is when the detector has to be at its operating temperature\(^3\). However, the satellite will only have to be in this configuration for several minutes, when it passes over areas specified by the mission.

![DOVE-1 nanosatellite](a) DOVE-1 nanosatellite [15]

![Nadir pointing configuration](b) Nadir pointing configuration [16]

Figure 2.6 – Optical system positioning and sounding pointing configuration

2.6.2 Communication

Once the thermal images have been acquired during the acquisition phase, they have to be sent to Earth. This is done by using the S-band antenna installed on one of the CubeSat faces. Data transmission is supposed to be done when the satellite passes over the ground station, and the antenna, placed on a lateral CubeSat face, must thus points the Earth surface to insure the transmission (Fig. 2.7). The detector at this moment does not work, and thus do not need to be cooled down.

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3. I.e. needs to be cooled down
2.6. POINTING  
CHAPTER 2. OUFTI-NEXT MISSION SPECIFICATIONS

2.6.3 Battery charging

To ensure a sufficient electrical production, the satellite must orient itself in order to have the most important incoming solar flux on the solar panels. This orientation corresponds to a sun pointing (Fig. 2.8), and will take place most of the time, when acquisition or communication processes are not in progress. In this configuration also, the detector is not in use, and the cooling system does not need to work.

These three configurations have different impacts on the detector cooling. As it will be explained further in this thesis, the use of a radiator is mandatory to clear out heat fluxes arriving on the detector, and its direct exposition to sunlight can have huge impacts on the detector temperature. Therefore, satellite orientations have to take into account the radiator position, in order to prevent it from a too high solar flux. In a first step, only the acquisition configuration will be taken into account (nadir pointing), since it is the crucial moment when the detector needs to be cooled down as much as possible.
2.7 Summary

<table>
<thead>
<tr>
<th>Structure</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chosen CubeSat standard</td>
<td>3U</td>
</tr>
<tr>
<td>Available space for payload</td>
<td>$10 \times 10 \times 15$ [cm$^3$]</td>
</tr>
<tr>
<td>Solar panels configuration</td>
<td>Cross - Body mounted</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>SSO</td>
</tr>
<tr>
<td>Mean altitude</td>
<td>600 [km]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Detector</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>640 x 512 [px]</td>
</tr>
<tr>
<td>Pixel size</td>
<td>15 [$\mu$m]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Optics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSD</td>
<td>100 [m]</td>
</tr>
<tr>
<td>Pixel size</td>
<td>15 [$\mu$m]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pointing</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>Nadir pointing</td>
</tr>
</tbody>
</table>

Table 2.2 – Summary of mission requirements

Tab. 2.2 summarizes all different features defined by OUFTI-Next team members. All along this thesis, these parameters will be supposed to be constant. Other data, such as the solar panels configuration, the satellite orientation or the optical system chosen will each be analyzed in order to see their impact on the cooling system. The aim is to obtain a system that has the biggest cooling capacity, regardless of the operating detector temperature. If the operating temperature provided by the detector manufacturer can not be reached, an additional trade-off study between detector SNR and temperature will have to be done, in order to determine if the required resolution can still be obtained at an higher temperature.
Chapter 3
Thermal control

This chapter will first recall some theoretical laws concerning heat exchanges happening in space that will be used in the thermal model. A description of heat sources in LEO will thus be done, followed by a listing of existing thermal control devices used in space.

3.1 Heat exchanges in space

In space, convective heat transfer is negligible, due to the low pressure value encountered in space ($\sim 10^{-6}$ [mmHg] [17]). Heat transfer in space is thus occurring by conduction and radiation exchanges.

3.1.1 Conduction

Thermal conduction into a solid is related to phonons interaction inside matter. These interactions depend on medium, and characterize the thermal diffusion. Macroscopically, conduction occurs when two regions of a medium are not at the same temperature, resulting in a heat transfer from the warmest region to the coldest. This transfer mode thus need a medium to occur (i.e. no conduction in vacuum), and the thermal power transmitted can be determined using the Fourier law:

$$Q_{\text{cond}} = \frac{k \cdot A}{l} \cdot \Delta T,$$

(3.1)

where $Q_{\text{cond}}$ is the transmitted power [W], $\Delta T$ is the temperature difference between cold and hot side [K], $k$ is the medium thermal conductivity [W·m$^{-1}$·K$^{-1}$], $A$ and $l$ are respectively the cross-section [$m^2$] and the length [m] of the heat path inside the medium.

If Eq. 3.1 is well adapted for geometries where cross section and lengths can easily be calculated, it becomes more complicated in the case where complex geometries are studied. To get rid of this problem, electrical analogy can be used, and the concept of
thermal conductance is introduced. In the case of a simple geometry (cross section \( A \) and length \( l \)), the analogy gives:

- \( I \): current [A] \( \rightarrow \) \( Q_{\text{cond}} \): power [W]
- \( \Delta V \): voltage [V] \( \rightarrow \) \( \Delta T \): temperature difference [K]
- \( G_{\text{elec}} \): electrical conductance [\( \sigma \cdot \text{A} \cdot \text{m}^{-1} \)] \( \rightarrow \) \( G_L \): thermal conductance [\( k \cdot \text{A} \cdot \text{m}^{-1} \)]

And the Fourier equation can now be written as follows:

\[
Q_{\text{cond}} = G_L \cdot \Delta T,
\]  
(3.2)

where \( G_L \) depends on material properties (\( k \)) and geometry. The thermal conductance is the only parameter that can be modified in order to change the conductive transfer inside a material or a part. A high value of \( G_L \) will result in a large amount of heat transferred by conduction, whereas a low value of \( G_L \) will make the conductive heat transfer smaller. Depending on the needs, it is thus possible to play on the geometry as well as on the material choice in order to create a conductive or an insulating part.

Fourier laws well describes the conductive heat transfer when only one medium is taken into account, but most thermal models, including incoming OUFTI-Next models consist in many parts made of different materials, with different geometries tied together. Therefore, conductive transfer at each interface between each part must also be calculated, and can not be neglected, since it can represents up to tenths of percents of the assembly total final conductance. However, solutions exists to improve or diminish the contact conductance when needed, such as filler materials or high and low conductivity glues. Even if it can be estimated by mathematical models, interface conductance remains the main source of uncertainties when analyzing a thermal conductive path.

### 3.1.2 Radiation

Radiative heat transfer is the only mode able to transmit heat through vacuum for distant devices, and it is thus the only way for a spacecraft to exchange energy with its environment. Physically, the energy is transferred from a medium to another using electromagnetic waves, and the amount of radiative power emitted by a black body\(^1\) can be related to its temperature using the Stefan-Boltzmann law:

\[
Q_{\text{rad},BB} = \sigma \cdot A \cdot T^4,
\]  
(3.3)

where \( Q_{\text{rad},BB} \) is the emitted flux [W/m\(^2\)], \( T \) is the object temperature [K], \( \sigma \) is the Stefan-Boltzmann constant (\( = 5.67 \cdot 10^{-8} \) [W·m\(^{-2}\)·K\(^{-4}\)]) and \( A \) is the area of the considered object [m\(^2\)]. However, the concept of black body is only theoretical, and most existing

\(^1\) A black body is an idealized object with an emissivity value equal to 1

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**Remacle Pierre**  
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**Academic Year 2017-2018**
objects emit less radiations than predicted by the Stefan-Boltzmann law. Actually, all bodies emits radiation which is comprised between 0% and 100% of the energy emitted by the analogous blackbody. This fraction is given by the emissivity ($\epsilon$) coefficient of the surface material. Most of the body thus follow a law slightly different from the one predicted by Stefan-Boltzmann,

$$Q_{\text{rad}} = \sigma \cdot \epsilon \cdot A \cdot T^4. \tag{3.4}$$

By the same way, absorptivity, transmissivity and reflectivity can respectively be defined as the amount of power effectively absorbed, transmitted and reflected by the surface of the considered body. These three parameters have to follow the energy conservation rule (Fig. 3.1):

$$\alpha + \rho + \tau = 1, \tag{3.5}$$

![Figure 3.1 – Absorption, reflection and transmission processes](image_url)

Coefficients $\epsilon$, $\alpha$, $\rho$ and $\tau$ generally depends on the wavelength considered, but this spectral dependency can be simplified with the grey surface assumption. The grey surface assumes that values of absorptivity and emissivity are independent of the considered wavelengths over spectral regions, such as the visible and the IR region.

The *Kirchhoff law* also states that at equilibrium, for a specific temperature and diffuse grey surfaces, emissivity is equal to absorptivity over spectral regions [18].

$$\epsilon = \alpha, \tag{3.6}$$

Since the Sun principally emits radiations in the UV (UltraViolet) and the VIS spectrum² (Fig. 3.2), and on the other hand, most other bodies with a temperature between -100 and 100 [°C] like Earth principally emit radiations in the IR spectrum, both VIS and

---

² The Sun also emits some IR radiations, but in a much smaller amount
IR spectral bands will be considered to define what is called *Thermo-Optical Properties* (TOP) of a surface: the *absorptivity* is defined as the emissivity/absorptivity of a surface in the VIS spectral band, while the *emissivity* is defined as the emissivity/absorptivity of a surface in the IR spectral band:

\[ \alpha = \alpha_{\text{vis}} = \epsilon_{\text{vis}}, \]  

\[ \epsilon = \alpha_{\text{ir}} = \epsilon_{\text{ir}}, \]  

(3.7)

(3.8)

![Figure 3.2 – Irradiance distribution for Sun and Earth [19]](image)

IR radiative exchanges between surfaces is a complex equilibrium which involves geometries, thermo-optical properties and temperatures of all considered surfaces. Many methods can be used to determine these exchanges, but the Gebhart factors method will be used in this thesis, since it takes into account the case of multiple reflections. As in the case of conduction, the electrical analogy can also be used in the case of thermal radiation, which leads to the following equation for a radiative exchange between two surfaces:

\[ Q_{\text{rad},1\rightarrow2} = \sigma \cdot G_{R,12} \cdot (T_1^4 - T_2^4), \]  

(3.9)

where \( Q_{\text{rad},1\rightarrow2} \) corresponds to the transmitted power from surface 1 to surface 2 [W], \( T_1 \) and \( T_2 \) are respectively the temperatures of the first and second surfaces [K], and \( G_{R,12} \) is the REF (Radiative Exchange Factor) between the two surfaces, which is calculated using the following formula [20]:

\[ G_{R,12} = \epsilon_1 \cdot A_1 \cdot B_{12}, \]  

(3.10)

With \( \epsilon_1 \) the emissivity of the first surface, \( A_1 \) the area of the first surface and \( B_{12} \) the Gebhart factor (calculated within the IR bandwidth) corresponding to radiation leav-
ing surface 1 that reaches surface 2. By using the following relation based on energy conservation,

\[ Q_{\text{rad},2 \rightarrow 1} = \sigma \cdot G_{R,21} \cdot (T_2^4 - T_1^4) = -Q_{\text{rad},1 \rightarrow 2}, \tag{3.11} \]

the equivalence between the two REF is easily demonstrated, meaning that

\[ G_{R,12} = \epsilon_1 \cdot A_1 \cdot B_{12} = \epsilon_2 \cdot A_2 \cdot B_{21} = G_{R,21}. \tag{3.12} \]

### 3.1.3 Thermal equilibrium

Radiative and conductive heat transfer equations, combined with the concept of thermal network allow to define a thermal equilibrium for each thermal node, which can thus be used to calculate the different temperatures of the considered model. This equilibrium is based on the energy conservation principle:

\[ Q_{\text{in}} = Q_{\text{out}}, \tag{3.13} \]

which states that the amount of incoming thermal energy for a considered physical system must be equal to the amount of leaving thermal energy. A physical system is however a general notion, and can represent various devices, like solar panels or batteries. When building a thermal model, several connected subsystems can be considered, and the concept of thermal node is introduced. Each subsystem constituting the global model is thus divided in multiple nodes, depending on the geometry. Writing Eq. 3.13 for each node composing the model, and solving the resulting system provide a set of nodal temperatures. Since most of the time, the energy conservation equation consists of a non linear expression\(^3\), the thermal equilibrium presented in the following of this work will be solved using the Matlab software, and the `fsolve` command, especially dedicated to calculations of non linear systems \[21\].

### 3.2 Space environment

There are three main thermal sources when considering a satellite in LEO: firstly, the Sun, that principally emits in the VIS, and with a value of heat flux varying between 1322 and 1414 [W/m\(^2\)] \[22\]. Secondly, the albedo, characterized by a value between 0 and 1, which represent the fraction of solar flux reflected by the Earth, which is thus in the VIS range. Albedo depends on the illuminated surface (0.8 for snow, 0.05 for oceans), but the

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3. Non linearity is due to the fourth powers appearing in the radiative heat transfer equation
4. Variation of solar flux is due to the eccentricity of the Earth orbit around the Sun
mean value for Earth is 0.33. Finally, the Earth itself, which emits in the IR range due to its mean temperature, which vary from 250 (summer solstice) to 260 (winter solstice) [K].

Even if some of these heat loads will not be directly taken into account during the modeling of the cooling system (the detector is located inside the CubeSat structure, and is not directly reached by these heat fluxes), they will play a significant indirect role by heating the satellite structure and its internal components, changing their temperatures and therefore their amount of emitted radiation. Anthony Keelens, who works on the thermal management of the entire satellite, calculated faces and subsystems temperatures that will be used for the enclosure modeling and the radiation exchanges calculations.

### 3.3 Thermal control systems

The role of a thermal control system is to regulate the temperature of specific part of the satellite to make sure that it works into its ideal temperature range. They can be separated in two classes: passive and active systems.

#### 3.3.1 Passive systems

This category is composed of systems that do not need any external power to operate. Since they consist in reliable, cheap and lightweight solutions, they are often implemented in first when designing a thermal control system. Some well-known passive systems are presented hereafter:

- Radiator: consists in a high-emissivity surface, designed to reject a heat load by using radiative transfer (heat loads are usually rejected to deep space).
- Coatings: can consist in paints, thin films of filters placed on object surfaces, designed to modify their surface properties (high emissivity, low absorptivity,...).
- Thermal straps: high conductivity material designed to conduct a conductive heat load through two objects (usually made of copper, which is thermally very conductive).
- Filler materials: used to modify the interface conductivity between two parts of a thermal control system.
- MLI (MultiLayer Insulation): a common used material, consisting in multiple layers of thin sheets. The resulting sheets assembly is characterized by a very low value of emissivity, and is mainly used to reduce heat losses by thermal radiation.
3.3. THERMAL CONTROL SYSTEMS

3.3.2 Active systems

Active systems sometimes require external power (electrical power) to operate. These systems allow to have a more precise regulation of the temperatures, thereby offering more possibilities to operate in different thermal configurations. They are also able to manage with higher heat load values, and can be associated with passive methods if a passive system alone is not powerful enough to control a given thermal load. Some active systems are gathered by the list below:

- **TEC (ThermoElectric Cooling):** Solid-state heat pump able to provide localized cooling by using the Peltier effect [26]
- **Louvers:** often placed over radiators, louvers consist in mobile metallic blades which allow to control the amount of rejected heat to space [27].
- **Heat pipes:** use a closed two-phases liquid-flow cycle with an evaporator and a condenser to transport relatively large quantities of heat from one location to another without electrical power [28].

Figure 3.3 – Passive thermal control systems [23] [24] [25]

(a) ISS radiators  (b) Copper thermal strap

(c) Layers of a MLI sheet
3.3. THERMAL CONTROL SYSTEMS

(a) Louvers on Rosetta spacecraft

(b) TEC module

Figure 3.4 – Active thermal control systems [29] [30]
Chapter 4

Thermal model

This chapter describes the different detector cooling systems designed for the OUFTI-Next mission, and the different heat fluxes reaching the detector and the radiator. In order to keep the simplest possible configuration (KIS - Keep It Simple), first cooling devices will only consist in fully passive systems. Based on results given by these designs, improvements will be done in order to reach the coldest detector temperature.

4.1 Designs definition

After an analysis of the temperature range reached by the detector when no cooling system is considered, the first design will simply consist of a radiator exposed to deep space, conductively linked to the sensor by a high conductivity heat path. The methodology is similar to that followed by the ASPIICS instrument used by the PROBA 3 mission [31], with the FPA glued to a coldfinger - thermal strap - radiator system to clear out the incoming heat on the detector.

Results coming from this first design will be analyzed and passive improvements will be proposed to increase the thermal system performances. Two configurations are thus presented, and based on the first design, one of them radiatively insulating the detector by using MLI, the other implementing a heat shield to protect the radiator from Earth thermal fluxes.

Last systems introduce some active systems to increase the cooling capacity of the fully passive system. The idea of Peltier and cryocooler devices are especially investigated. Fig 4.1 gathers all different systems that are going to be studied in this thesis.
4.2 Model definition

This section presents the methodology followed to implement the thermal system used for different presented designs. Radiative and conductive links are detailed, and some preliminary geometries are defined to quantify these links. The global geometry is presented by Fig. 4.2 and Fig. 4.3, and consists in a detector placed inside the CubeSat, and bounded by four rods to the basis plate. A conductive link connecting the sensor and the radiator is placed between the basis plate and the detector. Insulators are used when the value of the thermal needs to be lowered. Their geometries will be detailed later during the conductances calculations.

Figure 4.2 – Detector enclosure global geometry (front CubeSat face hidden)
Thermal exchanges between the detector and its environment can be separated in four contributions:

- Radiative exchanges between detector and sounded area, optics and CubeSat faces.
- A conductive exchange between the detector and its holding structure (basis plate).
- Electrical dissipation of the detector itself.
- Conductive exchange between the detector and the radiator.

The electrical dissipation is given by the chosen detector datasheet, and remains unchanged. However, solutions exist to diminish the amount of radiative and conductive fluxes, by choosing appropriate surfaces coatings and thermal insulating materials. These two contributions can vary in time, since they depend on surfaces temperatures.

By the same way, an equilibrium is reached between the radiator and its environment, and fluxes contributing to this balance can also be separated:

- Radiative exchanges between radiator and Earth, satellite panels and deep space.
- A conductive exchange between the detector and the radiator.
- A parasitic conductive link due to radiator bindings

All these different fluxes will modify both detector and radiator temperature to reach a thermal equilibrium. They will be calculated in the following of this section. Fig. 4.4 gives an overview of all different thermal fluxes arriving on the detector and the radiator.
An IR flux leaving the detector is added, since the detector is at a non-zero temperature and radiates heat towards its environment.

The thermal equilibrium can finally be expressed based on previous scheme, and leads to a non-linear system composed of two equations, given by Eq. 4.1 for the detector equilibrium, and Eq. 4.2 for the radiator equilibrium. VIS corresponds to power directly or indirectly coming from the Sun, with visible wavelengths, while IR correspond to all other fluxes (satellite, Earth,...) where wavelengths belong to the IR domain:

\[
Q_{\text{cond,struct-det}} + Q_{\text{IR, det in}} + Q_{\text{VIS, det in}} + Q_{\text{diss}} = Q_{\text{cond,rad-det}} + Q_{\text{IR, det out}},
\]

\[
Q_{\text{cond,rad-det}} + Q_{\text{VIS, rad in}} + Q_{\text{IR, rad in}} + Q_{\text{cond,sat-rad}} = Q_{\text{IR, DS}},
\]

where

- \(Q_{\text{cond,struct-det}}\): conductive power from the structure [W]
- \(Q_{\text{IR, det in}}\): total IR incoming power on detector [W]
- \(Q_{\text{VIS, det in}}\): total VIS incoming power on detector [W]
- \(Q_{\text{diss}}\): detector dissipated power [W]
- \(Q_{\text{cond,rad-det}}\): power sent to the radiator [W]
- \(Q_{\text{IR, det out}}\): IR radiated power from the detector [W]
- \(Q_{\text{VIS, rad in}}\): total VIS incoming power on radiator [W]
- \(Q_{\text{IR, rad in}}\): total IR incoming power on radiator [W]
- \(Q_{\text{cond,sat-rad}}\): parasitic power coming from the satellite face [W]
- \(Q_{\text{IR, DS}}\): IR power sent from radiator to deep space [W]
4.3 Thermal cases definition

The space environment is not constant over time. Unsteady solar activity, Earth orbit eccentricity\(^1\) and inhomogeneous Earth surface results in variable IR and VIS fluxes reaching the spacecraft that can modify satellite temperature.

To take these changes into account, some cold and hot thermal cases are defined, each related to an extreme thermal environment. Model variables affected by those cases are gathered by Tab. 4.1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cold case</th>
<th>Hot case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar constant ( C_S ) ([\text{W/m}^2])</td>
<td>1322</td>
<td>1414</td>
</tr>
<tr>
<td>Albedo coefficient ( a ) ([-]</td>
<td>0.25</td>
<td>0.35</td>
</tr>
<tr>
<td>Earth temperature ( T_{\text{Earth}} ) ([\text{K}])</td>
<td>250</td>
<td>260</td>
</tr>
<tr>
<td>Deep space temperature ( T_{\text{DS}} ) ([\text{K}])</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1 – Hot and cold cases definition

As presented during previous sections, these variables directly influence the amount of power directly reaching the detector through the optical system, but also modify the radiator thermal equilibrium. Moreover, those cases have a global influence on the satellite components, such as lateral faces and internal systems, which are considered for detector temperature determination. Faces, solar panels and ADCS temperature evolutions have been calculated by the thermal engineer for a 600 \([\text{km}]\) SSO orbit, and relative results are presented by Fig. 4.5 for both cold and hot cases [32]. These temperatures correspond to a specific faces disposition presented by Fig. 4.6, where the radiator is thus considered to be placed on the +\( y \) CubeSat face. This implies that the parasitic conductive flux is linked to the radiator and +\( y \) face temperatures. Since temperature of the basis plate (Fig. 4.3) is not already known, the ADCS temperature will be considered for this plate, since it is the subsystem located just behind inside the CubeSat.

---

1. Earth orbit eccentricity is different from zero, and thus results in a variable Sun-Earth distance.
4.3. THERMAL CASES DEFINITION

CHAPTER 4. THERMAL MODEL

(a) Cold case

(b) Hot case

Figure 4.5 – Faces, solar panels and ADCS temperature evolutions [32]

Figure 4.6 – CubeSat faces layout (radiator in green)

In a first step, only the acquisition mode will be considered, since this is when the detector needs to be cooled down. The acquisition mode temperatures correspond to green zones on Fig. 4.5, and eclipse/acquisition beginning and ending times are illustrated in Tab. 4.2, and a detailed temperature evolution during acquisition is given by Fig. 4.7.

<table>
<thead>
<tr>
<th></th>
<th>Start [min]</th>
<th>End [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eclipse</td>
<td>20</td>
<td>55</td>
</tr>
<tr>
<td>Acquisition</td>
<td>75.5952</td>
<td>81.1948</td>
</tr>
</tbody>
</table>

Table 4.2 – Beginning and ending times for eclipse/acquisition phases
4.4 Thermo-optical properties

Tab. 4.3 and Tab. 4.4 gather all TOP that will be used for the implementation of the thermal model. Since some components have still not been clearly defined for the mission such as the detector or the optics, their TOP have been roughly estimated, based on similar devices properties [32].

<table>
<thead>
<tr>
<th>Device</th>
<th>Material</th>
<th>$\epsilon$</th>
<th>$\alpha$</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>CubeSat faces</td>
<td>Black anodized Al</td>
<td>0.86</td>
<td>0.92</td>
<td>[33]</td>
</tr>
<tr>
<td>Detector</td>
<td>CCD array</td>
<td>0.8</td>
<td>0.8</td>
<td>[33]</td>
</tr>
<tr>
<td>Solar panels</td>
<td>Solar cells</td>
<td>0.85</td>
<td>0.72</td>
<td>[32]</td>
</tr>
<tr>
<td>ADCS</td>
<td>Various</td>
<td>0.86</td>
<td>0.65</td>
<td>[32]</td>
</tr>
<tr>
<td>Earth</td>
<td>black body</td>
<td>1</td>
<td>1</td>
<td>[20]</td>
</tr>
<tr>
<td>Deep space</td>
<td>black body</td>
<td>1</td>
<td>1</td>
<td>[20]</td>
</tr>
</tbody>
</table>

Table 4.3 – Thermo-optical properties of surfaces used in the thermal model

The radiator is directly exposed to space environment (located on an external face of the spacecraft) and will thus have its TOP modified during the mission. That is why both BOL (Beginning Of Life) and EOL (End Of Life) properties are taken into account.

<table>
<thead>
<tr>
<th>Device</th>
<th>Material</th>
<th>$\epsilon$ BOL</th>
<th>$\alpha$ BOL</th>
<th>$\epsilon$ EOL</th>
<th>$\alpha$ EOL</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiator</td>
<td>MAP PBCE (white paint)</td>
<td>0.88</td>
<td>0.27</td>
<td>0.088</td>
<td>0.42</td>
<td>[17]</td>
</tr>
</tbody>
</table>

Table 4.4 – Thermo-optical properties for the radiator
4.5 Fluxes modeling

This section models and calculates different thermal fluxes introduced in section 4.2 that will be used in the following chapters, during the analyses of the considered thermal designs (section 4.1).

4.5.1 Radiative flux from Earth

The portion of Earth area sounded by the CubeSat will generate an amount of thermal energy passing through the optical system and reaching the detector (Fig. 4.8). Since the acquisition phase will be made during the day\(^2\), IR and albedo (VIS) contributions will be taken into account\(^3\). However, depending on the optical design chosen, some wavelengths can either be reflected or absorbed by lenses or mirrors constituting the optical system, especially in the refractive case\(^4\). In the case of a reflective optical design, both IR and VIS contributions reach the detector, but the transmission coefficient of the mirrors have to be taken into account.

![Image of Earth and CubeSat](image)

Figure 4.8 – Incoming radiative flux through the optical system [34]

The detection area is represented by the SWATH, and thus depends on the GSD and the pixel size. Using data coming from section 2.7, it is possible to calculate the amount

---

2. The best moment for leaves temperature detection is in the early afternoon
3. Even if the sensor is only sensible to a given IR spectral band, both IR and VIS bandwidth will contribute to heat the FPA, and thus must be considered
4. Some lenses are transparent to IR, but opaque to VIS
of collected power:

$$A_{\text{sounded}} = (Nb^x_{\text{px}} \cdot GSD) \times (Nb^y_{\text{px}} \cdot GSD)$$  \hspace{1cm} (4.3)

Knowing the pixel size and the pixel number in each detector direction, is it also possible to determine the FPA area:

$$A_{\text{det}} = (Nb^x_{\text{px}} \cdot px_{\text{size}}) \times (Nb^y_{\text{px}} \cdot px_{\text{size}})$$  \hspace{1cm} (4.4)

Since the detection area is very small compared to the whole planet surface, Earth curvature can be neglected. Thereby, the sounded area can be considered as a plane surface. Eq. 4.3 thus gives $A_{\text{sounded}} = 3 \times 123 \times 200 \times 000 \text{ [m}^2\text{]} = 3123.2 \text{ [km}^2\text{]}$

Usually, when considering a space thermal equilibrium, Earth is neglected, because the IR power sent from the satellite to the planet is negligible and not able to modify the planet temperature. Moreover, the view factor from planet to satellite is very small, and can lead to numerical problems during simulations. Thus, to respect the energy conservation on the system, an IR backload coming from Earth and reaching the detector is calculated.

The incoming thermal load on the FPA is calculated by first determining the power coming on one pixel, and by multiplying the obtained value by the total number of pixel. IR and albedo contributions coming from the Earth on one pixel are respectively calculated using Eq 4.5. and Eq. 4.6:

$$Q_{\text{Earth,IR}} = \sigma \cdot T^4_{\text{Earth}} \cdot A_{\text{sounded}} \cdot \Omega_{\text{OS}} \cdot \tau_{\text{ir}},$$  \hspace{1cm} (4.5)

$$Q_{\text{Earth,VIS}} = a \cdot P_{\text{Sun}} \cdot A_{\text{sounded}} \cdot \Omega_{\text{OS}} \cdot \tau_{\text{vis}},$$  \hspace{1cm} (4.6)

where $a$ is the Earth albedo coefficient, $P_{\text{Sun}}$ the solar flux [W/m$^2$], $\Omega_{\text{OS}}$ is the solid angle leaving the source that reaches the pupil (Fig.4.9), $\tau_{\text{ir}}$ and $\tau_{\text{vis}}$ respectively represent the transmissivity coefficient in the IR and the VIS region. Since optical systems are composed of circular mirrors or circular lenses, the solid angle $\Omega_{\text{OS}}$ can be determined using Eq. 4.7,

$$\Omega_{\text{OS}} = \frac{A_{\text{pupil}}}{H^2} = \frac{\pi \cdot D^2_{\text{pupil}}}{4 \cdot H^2}$$  \hspace{1cm} (4.7)

Where $A_{\text{pupil}}$ is the pupil area and $H$ is the orbit altitude.
In Fig. 4.9, $\Omega_{SO}$ corresponds to the solid angle exiting the pupil that reaches the source, $\Omega_{OD}$ is the solid angle exiting the pixel that reaches the pupil and $\Omega_{DO}$ is the solid angle exiting the pupil that reaches the pixel.

The etendue $T$ is defined as the product of the solid angle leaving the surface and reaching the observer and the emitting surface area:

$$T = A \cdot \Omega$$  \hspace{1cm} (4.8)

Thanks to the etendue invariance law, it is possible to associate different couples of solid angles and surfaces from Fig. 4.9 [7]:

$$T = A_s \cdot \Omega_{OS} = A_o \cdot \Omega_{SO} = A_o \cdot \Omega_{DO} = A_d \cdot \Omega_{OD}$$  \hspace{1cm} (4.9)

The last member of the equation $A_d \cdot \Omega_{OD}$ is the easiest to calculate, but involves some optical parameters. The area $A_d$ corresponds to the pixel area ($px^2_{size}$), while the solid angle $\Omega_{OD}$ can be calculated using the $f/#$ parameter of the optical system:

$$\Omega_{OD} = \frac{\pi \cdot D_{pupil}^2}{4 \cdot EFL^2} = \frac{\pi}{4 \cdot f/#^2},$$  \hspace{1cm} (4.10)

where EFL corresponds to the Effective Focal Length [m] of the optical system. Eq. 4.5 and Eq. 4.6 can now be modified using the etendue invariance law:

$$Q_{Earth,IR} = \sigma \cdot T_{Earth}^4 \cdot A_{pixel} \cdot \Omega_{OD} \cdot N_{px} \cdot N_{py} \cdot \tau_{ir},$$  \hspace{1cm} (4.11)

$$Q_{Earth,VIS} = a \cdot P_{Sun} \cdot A_{pixel} \cdot \Omega_{OD} \cdot N_{px} \cdot N_{py} \cdot \tau_{vis},$$  \hspace{1cm} (4.12)
The total amount of incoming power from Earth is finally obtained by adding up the two contributions:

\[ Q_{\text{Earth,TOT}} = Q_{\text{Earth,IR}} + Q_{\text{Earth,VIS}} \]  

(4.13)

Results

Since some optical parameters are not yet defined in the mission requirements, a parametric study, involving the effective focal length \( EFL \) and the optical system transmissivity \( \tau \) is performed.

Reflective optical system

The case of a reflective optical system involves the use of mirrors, that reflect both IR and VIS wavelengths. As a first approximation, an optical system composed of two mirrors will be considered (Fig. 4.10), each mirror having a transmissivity equals to 0.9 for both IR and VIS bandwidth.

Fig. 4.11 gives the evolution of the absorbed\(^5\) Earth incoming radiative power with a \( f/\# \) going from 0.5 to 5. These values of \( f/\# \) correspond to preliminary results given by mission optical engineers [35].

![Figure 4.10 – Scheme of a reflective optical design involving two mirrors (Cassegrain telescope) [35]](image)

---

5. The detector thermo-optical properties are taken into account
The decrease of the power when increasing \( f/\# \) is in agreement with Eq. 4.10, stating that the solid angle is inversely proportional to the square of the \( f/\# \). For the mission, an estimated value of 1.5 for the \( f/\# \) is intended to be used [35], and Fig. 4.12 gives the evolution of the incoming radiative IR and VIS power when changing the transmission coefficient \( \tau \) of a mirror for both visible and IR region.

Figure 4.12 – Evolution of the incoming radiative power with \( \tau \) (two reflective mirrors, reflective case)

Its observed that the incoming power logically goes down when decreasing the mirrors transmissivity. The quadratic evolution is due to the presence of two mirrors in the system (graphs abscissa represents the transmissivity for a single mirror).
Refractive optical system

The refractive case involves the use of lenses instead of reflective mirrors, and the choice of materials constituting the lenses have a direct impact on the system transmissivity, since some materials are opaque in the visible range but transparent for IR bandwidths (Fig. 4.13). An example of a simple refractive system is given by Fig. 4.14. The refractive optical system designer plans to use at least one lens made of germanium, which is totally opaque in the visible ($\tau_{\text{vis}} = 0$). The analysis presented here will thus only take the IR bandwidth into account for the incoming power. Fig. 4.15 gives the evolution of the incoming power when changing the $f/\#$ with a IR transmissivity equals to 0.9, while Fig. 4.16 shows the power evolution when modifying the IR transmissivity value.

![Figure 4.13 – Transmissivity evolution with wavelength for a germanium lens [36]](image1)

![Figure 4.14 – Scheme of a refractive optical design involving three lenses (Si-Ge doublet with a GaAs third lens) [37]](image2)
Figure 4.15 – Evolution of the incoming radiative power with $f/#$ (refractive case)

Figure 4.16 – Evolution of the incoming radiative power with $\tau$ (refractive case)

Now that each optical system has been separately analyzed, the thermal model will use the highest amount of collected power in order to simulate a thermal equilibrium corresponding to a worst case\(^6\). Values of incoming power corresponding to each optical system with the considered parameters are listed in Tab. 4.5.

<table>
<thead>
<tr>
<th>Optical system</th>
<th>Cold case [W]</th>
<th>Hot case [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflective</td>
<td>$9.21 \cdot 10^{-3}$</td>
<td>$12.57 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>Refractive</td>
<td>$3.65 \cdot 10^{-3}$</td>
<td>$4.27 \cdot 10^{-3}$</td>
</tr>
</tbody>
</table>

Table 4.5 – Summary of incoming power for each optical system type

---

\(^6\) The worst case will correspond to the highest possible equilibrium temperature
It can be seen that in both cold and hot cases, the choice of a reflective system results in a higher amount of incoming power on the sensor. For the subsequent developments of this project, only the reflective optical system will be considered. It will be seen later than these values are relatively small compared to others power amounts coming from the detector electrical dissipation or the structure conductive heat flow.

### 4.5.2 Radiative flux from satellite

Since the detector is placed inside the CubeSat structure, it is not only reached by fluxes coming from the external environment, but also by radiative power coming from satellite parts located inside the spacecraft, such as CubeSat faces and optical system. Even if a precise disposition of the payload is not available yet (optical system shape, structure,...), a first assumption would be to consider a geometry detailed above in Fig. 4.2, with the detector placed at the bottom of the box representing the payload dedicated volume (Fig. 4.17).

![Figure 4.17 – Simplified geometry of the detector position inside the CubeSat payload volume](image)

The sensor is centered on the bottom face, and thus sees the four lateral faces of the satellite. In a first approximation, the optical system will be represented by the face located in front of the detector, which correspond to the CubeSat face directly looking at the Earth surface. The main idea of this first model is to have an estimation of the order of magnitude for radiative fluxes coming from the spacecraft to the sensor. The view factor is calculated between each face and the detector, and to take into account multiple reflections, Gebhart factors method is intended to be used. Due to small areas of considered surfaces, corresponding radiative fluxes will be much smaller than the detector electrical dissipation. The resulting system is a radiative balance between each face and the detector FPA, which depends both on faces and detector temperatures. Since the detector will have a very low temperature when cooled down, global equilibrium will consist in heat flux leaving each face and optics and arriving on the sensor, resulting in an additional heat flux to clear out. These fluxes will be more deeply analyzed when considering each system defined in section 4.1 separately.
Given thermo-optical properties and dimensions of all faces detector and optics, Gebhart factors can be calculated, and using faces temperatures given by Anthony Keelens (thermal management), a radiative equilibrium between the sensor and its environment can be implemented, based on equations from sections 3.1.2 and 3.1.3. The corresponding electrical analogy is given by Fig. 4.18, where the four lateral faces are gathered in one variable (Lateral faces). However, during calculations, each lateral face has a different temperature, and is treated separately for the balance determination.

### 4.5.3 Electrical dissipation

The amount of heat coming from the electrical dissipation depends on the chosen detector, and can not be easily found on datasheets. However, members of the OUFTI-Next team contacted a detector manufacturer, which accepted to provide the electrical dissipation of its detector, equals to 80 [mW]. The following of this report will thus use a value equal to 100 [mW] for all considered cases.

### 4.5.4 Conductive flux from the holding structure

The determination of the conductive heat transfer that reaches the sensor can only be calculated by determining the total thermal conductance between the detector and the basis of the holding structure, which is supposed to be at a determined temperature. This thermal conductance thus needs to be based on a preliminary design of the holding structure using the CATIA V5R20 software (Fig. 4.19). The different parts constituting this...
structure will be separately analyzed in order to determine their thermal conductance. A simple hand-made calculation will be done for simple geometries, whereas the SAMCEF (Système pour l’Analyse des Milieux Continus par Elements Finis) software and its thermal module, will be used if the geometries are more complex. The conductance using SAMCEF is calculated as follows:

- The part is imported in the software, and material properties, such as thermal conductivity, are defined
- An arbitrary temperature difference $\Delta T$ is placed at the two boundaries of the part, taking into account the path followed by the heat power in this part
- The mesh is generated
- Computations are started, and once results are obtained, heat loads at the boundaries are summed up to obtain the total power entering or leaving the part considering the imposed $\Delta T$
- The conductance is obtained by dividing this heat load by $\Delta T$: $G_L = Q/\Delta T$

![Figure 4.19 – Preliminary CAD drawing of the detector holding structure](image)

The structure is made of the detector itself and its PCB (Printed Circuit Board). Four titanium rods (in red on Fig. 4.19) bond the detector - PCB assembly on the basis plate, with the use of eight M2 screws. Some low conductivity plastic rulers are placed between the PCB and the rods to diminish the value of the total thermal conductance of the structure.

**Titanium rods**

Titanium rods simply consist in some cylinders with a screw thread on the internal surface, made for the M2 screws. Titanium has been chosen due to its low thermal conductivity combined with an high Young modulus. As the aim is to diminish the thermal conductance, a long shape combined with a small cross section is chosen.
Characteristics of those rods are calculated and given in Tab. 4.6 hereafter, using equations presented in section 3.1.1:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length $l$ [m]</td>
<td>0.02</td>
</tr>
<tr>
<td>Thermal conductivity $k$ [W·m$^{-1}$·K$^{-1}$]</td>
<td>6.6$^1$</td>
</tr>
<tr>
<td>Inner radius [m]</td>
<td>7.84$^4$</td>
</tr>
<tr>
<td>Outer radius [m]</td>
<td>0.003</td>
</tr>
<tr>
<td>Cross section area $A$ [m$^2$]</td>
<td>2.63$^5$</td>
</tr>
<tr>
<td>Thermal conductance (one rod) [W/K]</td>
<td>8.69$^3$</td>
</tr>
<tr>
<td>Total thermal conductance (four rods) [W/K]</td>
<td>3.48$^2$</td>
</tr>
</tbody>
</table>

Table 4.6 – Titanium rods characteristics

**Screws**

The screws conductance is difficult to estimate due to large interfaces between the screw thread and the structure. However, conductance can be obtained from first guess values coming from tables [20]. These values will play the role of interface conductance between the basis plate and the titanium rods, the titanium rods and the plastic rulers, and finally the plastic rulers and the PCB.

<table>
<thead>
<tr>
<th>Screw type</th>
<th>M2</th>
<th>Thermal conductance [W/K]</th>
<th>Total thermal conductance (four screws) [W/K]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.7 – M2 screw characteristics

**Plastic rulers**

Plastic rulers are placed between the PCB and the titanium rods. They are made of Ultem 2300, a 30% glass-filled grade with a low thermal conductivity and a low thermal expansion coefficient [31]. The role of these rulers is to diminish the heat flow between titanium rods and detector PCB.

7. Corresponds to a titanium alloy: Ti-5Al-6Sn-2Zr-1Mo [26]
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Figure 4.21 – CAD drawing of a plastic ruler

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length $l$ [m]</td>
<td>0.002</td>
</tr>
<tr>
<td>Thermal conductivity $k$ [W·m$^{-1}$·K$^{-1}$]</td>
<td>0.22</td>
</tr>
<tr>
<td>Inner radius [m]</td>
<td>7.84·10$^{-4}$</td>
</tr>
<tr>
<td>Outer radius [m]</td>
<td>0.003</td>
</tr>
<tr>
<td>Cross section area $A$ [m$^2$]</td>
<td>2.63·10$^{-6}$</td>
</tr>
<tr>
<td>Thermal conductance (one ruler) [W/K]</td>
<td>2.9·10$^{-3}$</td>
</tr>
<tr>
<td>Total thermal conductance (four rulers) [W/K]</td>
<td>1.16·10$^{-2}$</td>
</tr>
</tbody>
</table>

Table 4.8 – Plastic rulers characteristics

PCB

The printed circuit board considered for the mission is a composite material composed of an FR-4 epoxy matrix and copper layers [17]. Thermal properties of the composite are thus anisotropic, since they depend on the layers configuration. In this case, the main thermal path follows an in-plane direction, and thermal conductivity in this direction is given by Eq. 4.14 [17].

$$k_{PCB} = k_{Cu} \cdot \frac{n_{Cu} \cdot t_{Cu}}{n_{Cu} \cdot t_{Cu} + n_{FR4} \cdot t_{FR4}} + k_{FR4} \cdot \frac{n_{FR4} \cdot t_{FR4}}{n_{Cu} \cdot t_{Cu} + n_{FR4} \cdot t_{FR4}},$$ (4.14)

Figure 4.22 – CAD drawing of the PCB
By considering as a first approximation a PCB made of two copper layers with a 37 [\mu m] thickness [38], combined with a unique layer of FP-4 with a 2 [mm] thickness, and by using values of thermal conductivity equal to 391 for copper and 0.9345 for FP-4 [W-m^{-1}K^{-1}] [17], Eq.4.14 gives a value of thermal conductivity equals to $k_{\text{PCB}} = 14.852$ [W-m^{-1}K^{-1}]. Since the PCB geometry is complex, SAMCEF thermal is used to determine the conductance. A temperature difference of 100 [K] is imposed between the four holes at the corner of the PCB and the 18 holes used to pin the detector. Tab. 4.9 shows the results of the computation.

<table>
<thead>
<tr>
<th>Temperature difference [K]</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat power [W]</td>
<td>12.89</td>
</tr>
<tr>
<td>Thermal conductance [W/K]</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Table 4.9 – PCB conductance

Detector

The detector is made of the FPA (in green on Fig. 4.23a) which effectively collects the photons, and its structure that connects the FPA to its PCB. As a detailed detector datasheet is not available yet, this structure is supposed to be clipped by 18 copper pins (Fig. 4.23b). Thermal conductance is given by Tab. 4.10.

<table>
<thead>
<tr>
<th>Length $l$ [m]</th>
<th>0.002</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity $k$ [W-m^{-1}K^{-1}]</td>
<td>391</td>
</tr>
<tr>
<td>Radius [m]</td>
<td>4·10^{-4}</td>
</tr>
<tr>
<td>Cross section area $A$ [m^2]</td>
<td>5.03·10^{-7}</td>
</tr>
<tr>
<td>Thermal conductance (one pin) [W/K]</td>
<td>0.098</td>
</tr>
<tr>
<td>Total thermal conductance (18 pins) [W/K]</td>
<td>1.77</td>
</tr>
</tbody>
</table>

Table 4.10 – Copper pins characteristics

---

8. The mesh generated for the computation used a 0.4 [mm] element length
The detector is also bonded to the PCB with glue points, to ensure its stability. This link is made by using a low-conductivity glue\(^9\). This glue is applied at 8 different points, as showed by Fig 4.24.
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Holding structure total conductance

Now that thermal conductances have been calculated for each element, the calculation of the total structure thermal conductance can be computed, by considering appropriated associations (series or parallel). Fig. 4.25 gives an overview of these associations.

\[ \frac{1}{G_{L,\text{tot,series}}} = \frac{1}{G_{L,1}} + \frac{1}{G_{L,2}} + \frac{1}{G_{L,3}} + \ldots + \frac{1}{G_{L,n-1}} + \frac{1}{G_{L,n}} \]  \hspace{1cm} (4.15)

The final conductance for the total structure is thus given in Tab. 4.12. Because of the uncertainties appearing during the calculations, a margin will be considered, such that the value of the total conductance is decreased by 10%.

| Total thermal conductance [W/K] | 7.88 \cdot 10^{-3} |
| 10% margin [W/K] | 7.09 \cdot 10^{-3} |

Table 4.12 – Total thermal conductance for the structure

4.5.5 Conductive evacuation path

Since the aim of this path is to clear out the heat arriving on the detector and transfer it to the radiator, its total thermal conductance must be maximized. High conductivity materials will be considered, as well as high conductivity fillers and glues to improve the interface conductances between each part of the system.

The methodology used in this section is similar to the one followed in section 4.5.4. A preliminary CAD drawing has thus been implemented, with all calculations based on this CAD (Fig. 4.26).
Coldfinger

The coldfinger makes the link between the FPA and thermal straps. It is made of copper, and is directly glued to the detector with a high conductivity glue. Fig. 4.27 gives an overview of the part geometry.

The SAMCEF analysis gives results presented by Tab. 4.13. The temperature difference has been imposed between front and back detector faces.

| Thermal conductivity $k$ [W·m$^{-1}$·K$^{-1}$] | 391 |
| Temperature difference [K] | 100 |
| Heat power [W] | 415.67 |
| Thermal conductance [W/K] | 4.16 |

Table 4.13 – Coldfinger conductance
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Thermal straps

Thermal straps connects the coldfinger to the radiator. It is also made of copper, and results are also calculated using SAMCEF\(^1\).

| Thermal conductivity \(k\) [W·m\(^{-1}\)·K\(^{-1}\)] | 391 |
| Temperature difference [K] | 100 |
| Heat power [W] | 139.45 |
| Thermal conductance [W/K] | 1.39 |

Table 4.14 – Thermal straps conductance

![Figure 4.28 – CAD drawing of thermal straps](image)

Interface conductances

The first interface considered is the one between the detector and the coldfinger. This link must be maximized, using a high conductivity glue\(^2\). The characteristics of this link are gathered in Tab. 4.15.

| Thermal conductivity \(k\) [W·m\(^{-1}\)·K\(^{-1}\)] | 3.61 |
| Thickness [m] | \(5 \cdot 10^{-5}\) |
| Glued area [m\(^2\)] | \(7.37 \cdot 10^{-5}\) |
| Thermal conductance [W/K] | 5.32 |

Table 4.15 – Interface conductance detector - coldfinger

The link between the coldfinger and copper straps and between copper straps and radiator are made by using a sets of M2 screws. Results are given by Tab. 4.16.

---

11. The mesh generated for the computation used a 0.5 [mm] element length
12. The considered adhesive is the EP30AN-1, from MasterBond [31]
4.5. FLUXES MODELING

CHAPTER 4. THERMAL MODEL

<table>
<thead>
<tr>
<th>Link between</th>
<th>By means of</th>
<th>Thermal conductivity</th>
<th>Total conductance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coldfinger - Straps</td>
<td>$4 \times M2$</td>
<td>0.21 [W·m$^{-1}$·K$^{-1}$]</td>
<td>0.84 [W/K]</td>
</tr>
<tr>
<td>Copper straps - Radiator</td>
<td>$2 \times M2$</td>
<td>0.21 [W·m$^{-1}$·K$^{-1}$]</td>
<td>0.42 [W/K]</td>
</tr>
</tbody>
</table>

Table 4.16 – Interface conductances

Total thermal conductance

Fig 4.29 shows the associations of conductances constituting the thermal network from the sensor to the radiator. The calculations are similar to those done in section 4.5.4, and the total thermal conductance is thus given by Tab. 4.17.

![Thermal Network Diagram](image)

Figure 4.29 – Thermal network for the cooling conductive path

<table>
<thead>
<tr>
<th>Total thermal conductance</th>
<th>[W/K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.21</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>10% margin</th>
<th>[W/K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.19</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.17 – Total thermal conductance for the cooling conductive path

It can be seen, by comparing these values with those coming from section 4.5.4 that the total conductance for the conductive evacuation path is much more higher than the one from the holding structure, meaning that geometries and material choices revealed judicious.

4.5.6 Radiator heat exchanges

The role of the radiator is to evacuate the incoming heat flow through a radiative transfer. As total thermal conductance calculated in section 4.5.5 is very high, the radiator temperature will be very close to that of the detector. For this reason, the radiator must be maintained at the coldest possible temperature.

Radiative exchanges

The radiator is considered to be placed on one of the CubeSat lateral faces. In this case, the satellite is supposed to be in acquisition mode (Fig.2.6(b)). The radiator thus have an interaction with the Earth and the satellite solar panel. Since the temperature must be minimized, a direct exposition with solar flux must be avoided. This can be
easily done by modifying the CubeSat orientation, thanks to the ADCS. The different fluxes reaching the radiator are represented by Fig. 4.30.

An IR flux comes directly from the CubeSat solar panel. This panel also reflects VIS and IR radiations directly coming from the Earth, and a part of these reflected fluxes reach the radiator, with an amount depending on the value of the associated Gebhart factor. Finally, the radiator is directly reached by IR and VIS fluxes coming from Earth. This configuration leads to a thermal equilibrium for the radiator, when taking into account the conductive flux coming from the detector (Fig. 4.31). Radiative balance is calculated similarly to the detector - CubeSat faces equilibrium, considering appropriated view factors [20].
Parasitic radiator conduction

Since the radiator is fixed to the CubeSat, a parasitic conductive heat flux coming from one of the satellite faces reaches directly the radiator. To minimize this potential energy transfer, radiator is physically insulated by the use of four titanium flexures, shaped to obtain the lowest possible conductance. The design of these titanium flexures is inspired from the insulators used for the ASPIICS instrument [31], modified to respect constrains imposed by the 3U CubeSat standard 13, with a thickness of 3.5 [mm] (Fig. 4.32). Results of the SAMCEF simulation are given by Tab. 4.18.

![Figure 4.32 – CAD drawing of a titanium flexure](image)

| Thermal conductivity \( k \) \([\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}]\) | 6.6 |
| Temperature difference \([\text{K}]\) | 100 |
| Heat power \([\text{W}]\) | 0.745 |
| Thermal conductance \([\text{W} / \text{K}]\) | \(7.45 \cdot 10^{-3}\) |

Table 4.18 – Titanium flexure conductance

The low conductance value is due to the folded shape of the structure, resulting in a long path followed by heat, combined with a small cross-sectional area and the low thermal conductivity of titanium.

Each flexure is bolted to the panel thanks to 4 M2 screws, and only one additional M2 screw bolts the flexure to the radiator. Equivalent thermal conductance is given by Tab. 4.19.

---

13. The standard allows a maximum protrusion thickness equals to 6.5 [mm] [39]
### 4.5. FLUXES MODELING

#### CHAPTER 4. THERMAL MODEL

<table>
<thead>
<tr>
<th>Link</th>
<th>By means of</th>
<th>Thermal conductance [W/K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel - flexure</td>
<td>4 × M2 screws</td>
<td>0.84</td>
</tr>
<tr>
<td>Flexure</td>
<td>Geometry</td>
<td>7.45·10⁻³</td>
</tr>
<tr>
<td>Flexure - radiator</td>
<td>1 × M2 screw</td>
<td>0.21</td>
</tr>
<tr>
<td>Equivalent conductance</td>
<td></td>
<td>7.13·10⁻³</td>
</tr>
<tr>
<td>Equivalent conductance (4 flexures)</td>
<td></td>
<td>2.85·10⁻²</td>
</tr>
<tr>
<td>10% margin</td>
<td></td>
<td>2.57·10⁻²</td>
</tr>
</tbody>
</table>

Table 4.19 – Equivalent parasitic conductance
Chapter 5

Cooling devices analysis

Now that all thermal fluxes have been investigated and mathematically described, the Matlab software can be used to analyze each configuration presented in Fig. 4.1.

5.1 No cooling device

A first interesting simulation would be to analyze the detector temperature if it is not thermally connected to any radiator. That would be useful to determine if a cooling system is mandatory or not. This can be simulated by setting the conductance between the detector and the radiator to zero. The results are given by Fig. 5.1 for the cold case and by Fig. 5.2 for the hot case. Only the acquisition time has been considered for this analysis. Each figure gives the detector temperature evolution and the balance of different incoming thermal fluxes. A positive value in these graphs means that the corresponding heat flow arrives on the considered node, while a negative value means that the flow leaves the node.

In these figures, $Q_{\text{diss}}$ represents the power dissipated by the detector, $Q_{\text{Earth-det}}$ represents the incoming power from Earth, $Q_{\text{det-sat}}$ represents the sum of all radiative exchanges between the detector and its environment (CubeSat faces, optical system and bottom face) and $Q_{\text{det-struct}}$ represents the conductive exchange between the detector and the holding structure.
5.1. Cold case

Figure 5.1 – Detector temperature and thermal fluxes evolutions - Cold case, no radiator

The cold case evolution shows that the detector temperature increases from -28.2 [°C] at the beginning of the acquisition to -27.45 [°C] at the end, resulting in a temperature increase of less than one degree in more than 5 minutes. This increase is very low, and that explains the almost constant evolution of thermal fluxes during the acquisition. Indeed, since $Q_{\text{diss}}$ and the incoming earth flux are supposed to be constant, the only fluxes that evolve along the acquisition phase are $Q_{\text{det-sat}}$ and $Q_{\text{det-struct}}$. The radiative exchange between the detector and the CubeSat is globally negative, meaning that the detector radiatively sends some power to its environment, which is logical because the detector temperature is globally higher than CubeSat faces.

5.1.2 Hot case

The hot case provides logically higher values of detector temperatures, going from 12.3 [°C] at the beginning of the acquisition to 13.5 [°C] at the end. Once again, the low temperature changing rate explains the constancy of thermal fluxes during the acquisition.
5.2. BASIC DESIGN

5.2.1 Conclusion

This analysis shows clearly that the use of a cooling system for the sensor is mandatory, because temperatures obtained without any cooling system are really too high, and makes the detector unusable for thermal imaging.

5.2. Basic design

This section analyzes both temperatures and thermal fluxes in the detector and the radiator when the passive system described in chapter 4 is at equilibrium. This analysis takes into account the steady state configuration, to have a first idea of the temperature ranges that can be reached. A summary CAD drawing of the basic design is given by Fig. 5.3.

Figure 5.2 – Detector temperature and thermal fluxes evolutions - Hot case, no cooling
The main parameter being analyzed is the radiator area, because it is the variable that will have the greatest influence on the total system thermal equilibrium. Since its width is supposed to be constant, and equals to the CubeSat face width (10 [cm]), the model will only modify the radiator length, going from 0 to the CubeSat face length (32.75 [cm]), and will plot the corresponding detector temperature. Due to a radiative exchange with the CubeSat solar panel, the radiator must be placed at the bottom of the CubeSat lateral face, in order to minimize the corresponding view factor. The analysis will consist in a radiator with a fixed width, growing from the bottom to the top of one CubeSat lateral face (Fig 5.4).
For the next simulation phase, the design of the cooling system will take into account the calculated value for the conductive link detector - radiator.

The thermal environment during the acquisition phase is variable (Fig. 4.6). These variations affect the optimal radiator area at equilibrium. Three cases will be considered and compared: thermal equilibrium at the beginning, at the middle and at the end of the acquisition phase. Corresponding acquisition times are given in Tab. 5.1, and can be related to temperatures from Fig. 4.7.

<table>
<thead>
<tr>
<th>Acquisition moment</th>
<th>Corresponding acquisition time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beginning</td>
<td>75.60</td>
</tr>
<tr>
<td>Middle</td>
<td>78.33</td>
</tr>
<tr>
<td>End</td>
<td>81.19</td>
</tr>
</tbody>
</table>

Table 5.1 – Acquisition times considered for thermal balances

### 5.2.1 Cold case

Fig. 5.5 shows the evolution of the detector/radiator temperature for the three different acquisition moments considered. The radiator absorptivity has been set to the BOL value for cold cases, and the EOL value for hot cases.

![Figure 5.5 – Detector/radiator temperature evolution with radiator length at different acquisition times (cold case)](image_url)

Fig. 5.5 – Detector/radiator temperature evolution with radiator length at different acquisition times (cold case)
Higher temperatures are observed for both radiator and detector at the end of the acquisition phase. The optimal radiator area, corresponding to the lowest detector temperature, depends also on the acquisition moment. Next, in order to consider a worst thermal case, only the end of the acquisition time will be taken into account (at 81.19 [min]), as it corresponds to highest detector temperatures. Fig. 5.6 shows the evolution of thermal fluxes on the detector and the radiator with the radiator length.

The detector temperature diminishes from its initial value of -28 [°C] to a minimum temperature of -50 [°C]. The minimum temperature corresponds to a radiator length approximately equals to 24 [cm] (green curve on Fig. 5.5). For higher radiator lengths, the temperature rises again, mainly due to increasing incoming radiative thermal flux on the radiator, coming from both Earth and solar panel (Fig. 5.6b). The minimum detector temperature value corresponds on Fig. 5.6a to a maximum value of conductive flux leaving the detector through the coldfinger and the thermal strap ($Q_{det-rad}$). Tab. 5.2 gives a precise value of the minimum temperature and its corresponding radiator temperature and length.

<table>
<thead>
<tr>
<th>Minimum detector temperature [°C]</th>
<th>-49.85</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum radiator temperature [°C]</td>
<td>-50.70</td>
</tr>
<tr>
<td>Corresponding radiator length [cm]</td>
<td>24</td>
</tr>
<tr>
<td>Corresponding radiator area [cm²]</td>
<td>240</td>
</tr>
</tbody>
</table>

Table 5.2 – Minimum detector temperature and its corresponding radiator area for the cold case (end of acquisition)

It is now possible to compute the detector temperature evolution during the acquisition time (Fig. 5.7), when considering the optimal radiator area given by Tab. 5.2. Fluxes evolution for both detector and radiator is given by Fig. 5.8.
Figure 5.7 – Detector temperature evolution during acquisition time (cold case)

The detector temperature is clearly related to the radiator one, since they are conductively linked together. This link makes the detector very sensitive to temperature changes, and this explains why its temperature goes from -53 [°C] at the beginning of the acquisition to -50 [°C] at the end. This temperature increase can be related to the global increase of all CubeSat faces temperature (Fig. 4.5a) during the acquisition phase. This influences the parasitic conductive link existing between one CubeSat face and the radiator. This is confirmed on Fig 5.8b by the increase of $Q_{\text{rad-sat}}$, representing the parasitic conductive heat flow. To clear out this additional parasitic heat power, the radiator must increase its temperature to radiate a higher power amount to deep space (orange curve on Fig. 5.8b), resulting in an increase of the detector temperature.

Figure 5.8 – Thermal flows evolution during acquisition time (cold case)
5.2.2 Hot case

The evolutions of temperatures for acquisition times specified by Tab. 5.1 are shown by Fig. 5.9. Obtained temperatures are logically higher than the cold case, but it can be seen that the curve shapes are similar, with higher temperatures at the end of the acquisition phase.

![Figure 5.9 – Detector/radiator temperature evolution with radiator length at different acquisition times (hot case)](image)

The balance of detector and radiator thermal fluxes are both given by Fig. 5.10, considering the end of acquisition. It can be seen that exchanged amounts of heat power are higher than in the cold case consideration, mainly due to the higher equilibrium temperatures. Tab. 5.3 gives the minimum temperature and its corresponding radiator area.

![Figure 5.10 – Detector/radiator thermal fluxes evolution with radiator length (hot case)](image)
Minimum detector temperature [$^\circ$C] -22.16
Minimum radiator temperature [$^\circ$C] -23.54
Corresponding radiator length [cm] 24.1
Corresponding radiator area [cm$^2$] 241

Table 5.3 – Minimum detector temperature and its corresponding radiator area for the hot case (end of acquisition)

The temperature evolution during the whole acquisition phase, considering results from Tab 5.3 are finally computed, and given by Fig. 5.11 and Fig. 5.12.

Figure 5.11 – Detector temperature evolution during acquisition time (hot case)

Figure 5.12 – Thermal flows evolution during acquisition time (hot case)
5.2.3 Conclusion

The analysis of both hot and cold cases for this first model demonstrates that it is impossible to reach working temperatures defined in section 2.5, since even the cold case assumption provides temperatures more than 100 [K] above the requirements. Another problem is the temperature variations during acquisition, is that this passive system proposed does not allow to control the variations of the temperatures occurring during acquisition. Therefore, some improvements must be made on this first model. This is the aim of the next presented designs.

5.3 MLI insulation

5.3.1 Theoretical aspects

A first step to lower the detector temperature would be to decrease the amount of power received during radiative exchanges occurring between the sensor and CubeSat faces, but also exchanges between the radiator and the solar panel. This can be done by covering CubeSat faces and the bottom of the solar panel by an MLI sheet. Indeed, due to its low emissivity value, the MLI will greatly diminish radiative exchanges. Emissivity of MLI sheets depends on the number of layers constituting the sheet and on the sheet temperature. This dependency is given by Fig. 5.13

![Figure 5.13 – Evolution of MLI emissivity with constituting layers [26]](image)

In this case, 12 constituting layers will be considered [40], resulting in an effective emissivity value between 0.01 and 0.015. An estimated value of 0.0125 is considered for calculations. The absorptivity depends on the outer layer constituting the MLI. In this case, backed Teflon is considered, due to its low absorptivity value and its high
environmental compatibility. The corresponding $\alpha$ value for backed Teflon is equal to 0.1 [26].

MLI sheets are placed on each CubeSat lateral face and on the bottom of the solar panel. This consideration results in a modification of the relative TOP for the covered surfaces. The analysis that will be carried out is similar to the one followed for the basic design, with an evolution of the radiator length, considering the same acquisition times (Tab. 5.1).

5.3.2 Cold case

Fig. 5.14 gives the detector temperature evolution with the radiator length. Curves have similar shapes than in the case of the basic design, but obtained temperatures are lower, meaning that the MLI plays its role well. Fig. 5.15a and Fig. 5.15b give fluxes evolutions on the detector and the radiator at the end of the acquisition times, and it can be seen that fluxes coming from the solar panel on the radiator is very low. The value of $Q_{\text{det-sat}}$ is also very low but it must be noticed that this value includes the flux coming from the optical system itself, which is not covered by MLI.

![Figure 5.14 – Detector/radiator temperature evolution with radiator length at different acquisition times, with MLI consideration (cold case)](image-url)

Tab. 5.4 gives the minimum value obtained by the detector and the corresponding radiator length. The minimum temperature obtained using MLI is effectively lower than in the basic design (Tab. 5.2), but the difference is quite low (only a couple of degrees).
5.3. MLI INSULATION

CHAPTER 5. COOLING DEVICES ANALYSIS

Figure 5.15 – Detector/radiator thermal fluxes evolution with radiator length, with MLI consideration (cold case)

Table 5.4 – Minimum detector temperature and its corresponding radiator area for the cold case (end of acquisition, MLI consideration)

Minimum detector temperature [°C] -52.85
Minimum radiator temperature [°C] -53.82
Corresponding radiator length [cm] 25.7
Corresponding radiator area [cm²] 257

Figure 5.16 – Detector/radiator temperature evolutions during acquisition time (cold case, MLI)
The detector and radiator temperature and fluxes evolutions are finally computed, considering results coming from Tab. 5.4. This is given by Fig. 5.16 and Fig 5.17.

![Diagram of thermal fluxes](image1)

**Figure 5.17 – Thermal flows evolution during acquisition time (cold case, MLI)**

### 5.3.3 Hot case

![Diagram of detector/radiator temperature evolution](image2)

**Figure 5.18 – Detector/radiator temperature evolution with radiator length at different acquisition times (hot case)**

Once again in this hot case, considered temperatures are logically higher than in the cold case, with detector temperatures going from $30 \, ^\circ C$ to $-25 \, ^\circ C$. When compared to the basic design, temperatures are lower, meaning that in this case also, the use of MLI helps to reduce detector temperature. The drop is however rather small, and limited to a few degrees.
5.3. MLI INSULATION  

CHAPTER 5. COOLING DEVICES ANALYSIS

Figure 5.19 – Detector/radiator thermal fluxes evolution with radiator length (hot case)

Table 5.5 – Minimum detector temperature and its corresponding radiator area for the hot case (end of acquisition)

| Minimum detector temperature [°C] | -26.49 |
| Minimum radiator temperature [°C] | -28.03 |
| Corresponding radiator length [cm] | 26.1 |
| Corresponding radiator area [cm²] | 261 |

Figure 5.20 – Detector temperature evolution during acquisition time (hot case)
5.4. HEAT SHIELD

5.4.1 Basic model modifications

The two previous sections showed that the detector temperature clearly depends on the radiator thermal equilibrium. This equilibrium is greatly influenced by VIS and IR fluxes coming from Earth, since they represent a non negligible amount of incoming power. The first idea of passive improvement would be to block this incoming Earth flux, by shadowing the radiator. This can be made by using the principle of the heat shield, consisting in the deployment of a low-emissivity material below the radiator to protect it from Earth radiations. NASA uses this principle for the development of the CryoCube-1 nanosatellite [41], which is designed to perform on-orbit experiments on cryogenic fluids. Artist representations of this satellite are given by Fig. 5.22.

However, the use of an heat shield requires a dedicated deployment mechanism once in orbit, because CubeSat standards restrict the satellite dimensions during launch. An idea would be to take advantage of the solar panels deployment to open the shield at the same time. This idea implies to modify a bit the initial CubeSat design, by moving the solar panels from the top to the bottom of the CubeSat (configuration similar to...
the one shown by Fig. 2.1b). The shield would thus be deployed between each solar panel, and the resulting model would consist in a radiator seeing one solar panel and the radiative shield. To simplify the calculations during simulations, four triangular shields are considered between each panel, as shown by Fig. 5.23.

![Figure 5.22 – Artist representations of CryoCube-1](image1)

![Figure 5.23 – CAD of the modified CubeSat model (radiator in white)](image2)

The shield must be made of a low emissivity material, to diminish its emitted radiations as much as possible. Tab. 5.6 gathers thermo optical properties of the chosen material. Kapton has been considered, due to its low emissivity value that will limit radiative exchanges with the radiator. But even with this small emissivity values, the shield emits a non negligible amount of IR radiation, and the solar panel, which is still present, also radiates a part of IR power (Fig. 5.24).
Table 5.6 – Heat shield thermo-optical properties

<table>
<thead>
<tr>
<th>Material used</th>
<th>Kapton, aluminized, 0.08 mil [26]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissivity $\epsilon$</td>
<td>0.24</td>
</tr>
<tr>
<td>Absorptivity $\alpha$</td>
<td>0.23</td>
</tr>
</tbody>
</table>

To ensure that no part of the radiator will be exposed to the Earth flux during the acquisition phase, the Earth horizon angle must be calculated. This angle will determine the amount of shadow effectively created by the shield on CubeSat faces. It can simply be obtained by considering the geometrical problem described below (Fig. 5.25), where the Earth horizon angle is represented by $\gamma$.

Figure 5.24 – Incoming radiative thermal fluxes on radiator when protected by the heat shield

Figure 5.25 – Schematic view of the Earth horizon angle
The $\gamma$ angle can be calculated using the trigonometric relation:

$$\gamma = \arcsin \left( \frac{R_{\text{Earth}}}{R_{\text{Earth}} + H_{\text{orbit}}} \right), \quad (5.1)$$

where $R_{\text{Earth}}$ represents the Earth radius $^1$, and $H_{\text{orbit}}$ is the orbit altitude. This relation gives a value for $\gamma$ equals to 1.1529 [rad] ($= 66.05 \, [\degree]$). The shadowed length of a CubeSat face can thus be obtained by using Eq. 5.2:

$$L_{\text{shadow}} = \frac{L_{\text{shield}}}{\tan(\gamma)}, \quad (5.2)$$

with $L_{\text{shadow}}$ the length of the shadowed zone and $L_{\text{shield}}$ the length of the smallest distance between a face and the shield. Since the shield consists in four triangular sheets, $L_{\text{shield}}$ is simply equals to the triangle height corresponding to the longest base. This length is represented on Fig. 5.26 by a red line.

$$L_{\text{shield}} = \frac{L_{\text{panel}} \cdot \sqrt{2}}{2} \cdot \tan \left( \frac{\pi}{4} \right), \quad (5.3)$$

Figure 5.26 – Visualization of $L_{\text{shield}}$ (red line)

It is now possible to calculate the value of $L_{\text{shadow}}$:

$$L_{\text{shadow}} = 0.1068 \, [\text{m}],$$

---

1. The mean Earth radius is equal to 6371.0088 [km]
The radiator length must thus not be higher than $L_{\text{shadow}}$ to ensure that no direct Earth thermal flux reaches its surface.

The analysis is performed in the same way than in the previous chapter, where temperatures and heat fluxes are calculated for different values of radiator length. The evolution of this length is given by Fig. 5.27, with a radiator area initially beginning at the shadow line and growing until the intersection with the CubeSat solar panel. The interaction with the solar panel and the heat shield will thus be more important for high radiator areas, resulting in a higher incoming radiative flux on the radiator.

![Figure 5.27 – Scheme of the radiator extension process with the heat shield consideration](image)

5.4.2 Thermal cases updates

The presence of the heat shield does not only shadow the radiator surface, but also all other lateral CubeSat faces. This decrease of Earth direct fluxes has to be taken into account by the CubeSat thermal manager when calculating faces temperatures. Thermal cases have been modified considering this configuration and new temperature evolutions are given in Fig. 5.28. It is assumed that the heat shield and solar panels have the same temperature, since they are exposed to the same external fluxes. The faces layout and the beginning and ending times of the acquisition phases are not changed compared to the first analysis.
Figure 5.28 – Faces, solar panels and ADCS temperature evolutions with the heat shield consideration [32]

5.4.3 Cold case

The temperature evolution at different acquisition times from Tab. 5.1 is given by Fig. 5.29. It can be seen that a minimum temperature appears for radiator length between 7 and 9 [cm], depending on the considered case. As in the previous model, the end of acquisition phase also results in the highest detector temperature, but the range of temperature is globally lower than the first cold case model. Thermal fluxes for the end of acquisition phase are given by Fig. 5.30, and Tab. 5.7 gives the minimum corresponding temperature and the corresponding radiator area.
Figure 5.29 – Detector/radiator temperature evolution with radiator length at different acquisition times, with heat shield consideration (cold case)

Figure 5.30 – Detector/radiator thermal fluxes evolution with radiator length, with heat shield consideration (cold case)

Table 5.7 – Minimum detector temperature and its corresponding radiator area for the cold case (end of acquisition, heat shield consideration)
Considering these optimal values, the thermal equilibrium during the whole acquisition phase can be computed, and results are given by Fig. 5.31 and Fig. 5.32.

Figure 5.31 – Detector/radiator temperature evolutions during acquisition time (cold case, heat shield)

Figure 5.32 – Thermal flows evolution during acquisition time (cold case, heat shield)

5.4.4 Hot case

Temperature evolution for the three acquisition times, and incoming fluxes on both detector and radiator are respectively given by Fig. 5.33 and Fig. 5.34.
Figure 5.33 – Detector/radiator temperature evolution with radiator length at different acquisition times, with heat shield consideration (hot case)

Figure 5.34 – Detector/radiator thermal fluxes evolution with radiator length, with heat shield consideration (hot case)

Tab. 5.8 gathers information on the minimum detector temperature reached at the end of the acquisition phase and the corresponding radiator area.
Minimum detector temperature \[\degree C\] -37.48
Minimum radiator temperature \[\degree C\] -38.29
Corresponding radiator length [cm] 9
Corresponding radiator area [cm\(^2\)] 90

Table 5.8 – Minimum detector temperature and its corresponding radiator area for the hot case (end of acquisition, heat shield consideration)

Fig. 5.35 and Fig. 5.36 shows the evolution of detector and radiator temperatures during the whole acquisition time, considering optimal values for the radiator area (Tab. 5.8).

Figure 5.35 – Detector/radiator temperature evolutions during acquisition time (hot case, heat shield)

Figure 5.36 – Thermal flows evolution during acquisition time (hot case, heat shield)
5.4.5 Conclusion

From a purely theoretical point of view, the use of a heat shield is proven to be effective, as the obtained temperatures for both the detector and the radiator are much lower than the first passive model. Even if constraints on the radiator size appeared, due to Earth horizon consideration, the absence of incident Earth flow on the radiator allows to obtain lower temperatures even with a smaller radiator area.

However, in the OUFTI-Next mission context, the use of such a system appears to be insufficient to reach the optimal temperature for the good functioning of the IR sensor. Moreover, such a system clearly complicates the whole satellite preliminary design, due to high induced mechanical constraints, and the appearance of a SPF (Single Point of Failure). Indeed, any problem occurring during the shield deployment would result in a failure of the mission since the detector would become unusable.

More generally, these three analyses showed that using only passive cooling systems is not sufficient to bring the detector to its best operating temperature. The next steps of this study will be to introduce some active cooling systems in the thermal model in order to analyze their effects on the system equilibrium.

5.5 Peltier device

Already presented in section 3.3.2, the peltier element, also called thermoelectric cooler (TEC), is a miniature solid-state heat pump able to provide a localized cooling. Its working principle is based on the peltier effect, which is a cooling generation resulting from the passage of an electric current through a junction formed by two different conductive plates [26]. A scheme of the peltier effect is given by Fig. 5.37.

![Figure 5.37 – Thermoelectric couple [26]](image)

Such a system presents the advantage of not having moving parts, which make it more reliable and not subject to wear. Another key point is that using a TEC will allow to uncouple detector and radiator temperatures. Indeed, in the three previous analyses, the
detector was constrained to stay nearly at the radiator temperature, resulting in a strong dependency on the radiator thermal balance. The addition of a TEC in the system will provide a higher temperature difference between the detector and the radiator, enabling the radiator to clear out a higher amount of power. However, the main disadvantage of TEC modules is their relatively low COP (Coefficient Of Performance), which results in a high amount of rejected power by the Peltier hot side. Another disadvantage is the decrease of TEC performances, especially the value of its maximum provided $\Delta T$, when lowering their hot side temperature.

5.5.1 Theoretical aspects

In this section, the following notations are used:

- $I$: electric current passing through the Peltier [A]
- $Q_c$: absorbed power on the Peltier cold side [W]
- $Q_h$: power rejected by the Peltier hot side [W]
- $\Pi_{ab}$: Peltier effect module coefficient [-]
- $S_m$: Seebeck effect module coefficient [-]
- $K_m$: module thermal conductance [W/K]
- $R_m$: module electric resistance [Ω]
- $T_c$: cold side temperature [K]
- $T_h$: hot side temperature [K]
- $\Delta T = T_h - T_c$: temperature difference [K]

Thermal transfers occurring inside a TEC can be modelled by considering three contributions:

Heat transferred by the Peltier effect:

$$Q_c = S_m \cdot T_c \cdot I \quad \text{(pumped at cold side)} \tag{5.4}$$

$$Q_h = S_m \cdot T_h \cdot I \quad \text{(injected at hot side)} \tag{5.5}$$

Heat coming from TEC electrical dissipation (Joule effect):

$$Q_J = \frac{1}{2} \cdot R_m \cdot I^2 \quad \text{(injected on both sides)} \tag{5.6}$$

Thermal conduction, that opposes the desired effect (added on cold side, subtracted on hot side):

$$Q_{\text{cond}} = K_m \cdot \Delta T \tag{5.7}$$
The heat pumped at the cold side can thus be expressed as:

\[ Q_c = S_m \cdot T_c \cdot I - \frac{1}{2} \cdot R_m \cdot I^2 - K_m \cdot \Delta T, \quad (5.8) \]

And the heat rejected by the hot side is expressed as:

\[ Q_h = Q_c + V \cdot I, \quad (5.9) \]

where \( V = S_m \cdot \Delta T + I \cdot R_m \) is the voltage at the module poles².

All these formulas are however difficult to exploit, since \( S_m, K_m \), and \( R_m \) vary with temperature. Instead of using these equations, manufacturers provide TEC datasheets, giving all information about their modules.

Manufacturers propose also Peltier devices that consist of multi-stage modules, providing higher temperature differences than single stages TEC, that are mainly dedicated for small devices cooling. This section will consider TEC coming from Rnt Ltd [42], which is a Russian company providing a wide range of space-qualified Peltier modules. This company also provides a powerful software, TECcad Lite, which gathers information relative to all its TEC [43].

### 5.5.2 Implementation

To maximize its efficiency, the Peltier element must be placed just behind the detector, with the cold side glued to the sensor and the hot side glued to the coldfinger. The hot side of the Peltier will be conductively coupled to the radiator, and its temperature will directly depend on the radiator one.

The temperature difference reached with a TEC depends on the amount of the total thermal flux pumped at the cold side, but this flux itself depends on the detector temperature. This dependency is depicted by Fig 5.39. Moreover, the TEC \( \Delta T \) also depends on the hot side temperature, directly related to the radiator thermal balance. Fig. 5.38 shows the evolution of the radiator and Peltier hot side temperature with the amount of dissipated power by the TEC. In a first step, the radiator area is set to 340 [cm²].

The drop appearing between both temperatures when increasing the rejected flux is due to the presence of the conductive link and its thermal conductance existing between the Peltier and the radiator.

The main problem with this configuration is to find a TEC able to bring a sufficient temperature difference by pumping enough power from the cold side, without rejecting to much power at the hot side, since the amount of rejected power directly influence the Peltier hot and cold sides temperature.

². Both Joule and Seebeck effects are taken into account
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Figure 5.38 – Evolution of the Peltier/radiator temperatures with the heat rejected by the Peltier (radiator area: 340 [cm²])

(a) Cold case

(b) Hot case

Figure 5.39 – Evolution of the detector temperature with the heat pumped by the Peltier

Peltier devices are characterized by values of $I_{\text{max}}$, $Q_{\text{max}}$, and $\Delta T_{\text{max}}$. These three parameters are detailed hereafter:

- $I_{\text{max}}$: electric current providing the maximum $\Delta T$ when no heat load is applied at the cold side.
- $U_{\text{max}}$: voltage providing the maximum $\Delta T$ when no heat load is applied at the cold side.
- $Q_{\text{max}}$: maximum heat load that can be pumped by the TEC, providing a $0^\circ$ temperature difference.
5.5. PELTIER DEVICE

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- $\Delta T_{\text{max}}$: maximum temperature difference that can be reached, when no heat load is applied at the cold side.

Based on these parameters, three Peltier elements have been chosen for the analysis, and are presented hereafter. All of them consist in three-stage modules, chosen because they are the most adapted for the considered case (due to higher temperature differences). Their main properties for a 300 [K] hot side are given by Tab. 5.9.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T_{\text{max}}$ [K]</td>
<td>107.88</td>
<td>108.46</td>
<td>107.53</td>
</tr>
<tr>
<td>$I_{\text{max}}$ [A]</td>
<td>0.77</td>
<td>0.78</td>
<td>0.35</td>
</tr>
<tr>
<td>$Q_{\text{max}}$ [W]</td>
<td>1.65</td>
<td>1.15</td>
<td>0.75</td>
</tr>
<tr>
<td>$U_{\text{max}}$ [V]</td>
<td>11.57</td>
<td>8.54</td>
<td>11.64</td>
</tr>
<tr>
<td>$\tau$ [sec]</td>
<td>25.76</td>
<td>27.35</td>
<td>32.91</td>
</tr>
</tbody>
</table>

Table 5.9 – Characteristics of chosen Peltier devices for a 300 [K] hot side

Figure 5.40 – Evolution of the three TEC performances with temperature

Figure 5.41 – Picture of the 3MDC06-155-15 Peltier device [44]
The resulting system is thus a complex equilibrium between fluxes rejected to the radiator and fluxes coming on the sensor. The evolution of $\Delta T_{\text{max}}$ and $Q_{\text{max}}$ with the hot side temperature, for the three considered TEC can be obtained thanks to TECad, and results are given by Fig. 5.40.

The values of $\Delta T_{\text{max}}$ and $Q_{\text{max}}$ diminish when the hot side temperature decreases. This means that the three considered Peltier can not provide more than a 20 \textdegree C temperature and a pumped heat of 0.3 [W] if the hot side is at 150 [K]. However, since the hot side is related to the radiator temperature, it can be expected that the Peltier hot side temperature will not be lower than 220 [K], which roughly corresponds to the radiator temperature when no heat flux is generated by the Peltier in the cold case (Fig. 5.38a). The main difficulty to determine an accurate value for the TEC power supply is the variable temperature of the hot side due to the radiator thermal balance modified by the heat generated by the Peltier. Peltier elements, due to their low COP, reject heat amounts between 3 and 6 [W], resulting in a hot side temperature able to reach until 45 \textdegree C in the hot case (30 \textdegree C in the cold case). The $\Delta T_{\text{max}}$ at this hot side temperature for the hot thermal case is equal to 110 [K].

In all cases, the minimal temperature reached on the detector stay above 200 [K], which is still to high for efficient use of TEC in the mission case. The main problem comes from too high radiator temperature changes, mainly due to its small size (this analysis considered a radiator area equals to one CubeSat lateral face). An higher radiator area would result in a more stable thermal equilibrium and a more stable Peltier hot side temperature. However, the small size of the 3U CubeSat restricts the amount of available radiator area, taking into account that other subsystems also need some place on CubeSat faces. Moreover, the detector working temperature can not be reached anyway, since the incoming load on the cold face become really high at low temperatures, and the $\Delta T_{\text{max}}$ provided are limited with high heat loads.

## 5.6 Cryocooler

### 5.6.1 Introduction

A cryocooler consists in a substation cooler, used for particular applications requiring cryogenic temperatures. First space-dedicated cryocoolers appeared during the seventies, consisting in heavy and bulky systems able to provide temperatures from 100 to 120 [K] with some heat load up to 100 [mW]. Nowadays, thanks to cryocoolers miniaturization and technical improvements, manufacturers are able to provide high efficiency and vibrationless micro cryocoolers, well adapted for the use in nanosatellites, such as CubeSats.

Several CubeSat missions already chose to use a micro cryocooler device to cool down their IR detector, two examples of which are presented hereafter:

- The Arkyd-6 mission, from Planetary Ressources [45], consists in a demonstration
nanosatellite carrying a MWIR imager, and testing systems planned to be implemented on the *Arkyd-100* satellite [46]. The 6U CubeSat has been launched in January 2018. Fig. 5.42 gives a picture of the whole satellite and an overview of the IR camera with its cryocooler. All the payload takes a 1.5 CubeSat units and uses a 200 [mm] focal length imager, coupled with a $640 \times 512$ InSb cooled at 77 [K] by the Stirling cryocooler.

- The CubeSat Infrared Atmospheric Sounder (CIRAS) is an instrument under development by the NASA Jet Propulsion Laboratory (JPL). The aim of this project is to develop an instrument to measure upwelling IR radiations from Earth in the MWIR region, and able to enter in a 6U CubeSat standard. The used detector would use a Ricor³ cryocooler to cool down its FPA to 120 [K] [47].

Planetary Ressources announced in April 2018 the success of its *Arkyd-6* mission, proving the reliability of micro cryocoolers when used in space missions in CubeSat nanosatellites.

![Figure 5.42 – The Arkyd-6 CubeSat and its IR-cryocooler system [45]](image)

3. Ricor is a manufacturer of space-qualified cryocoolers
5.6.2 Theoretical aspects

A large majority of micro cryocoolers are based on the Stirling thermodynamic cycle, consisting in two isothermal and two isochoric processes. The detailed cycle is presented by Fig. 5.43.

![Thermodynamic processes for an idealized Stirling cycle](image)

**Figure 5.43 – Thermodynamic processes for an idealized Stirling cycle [48]**

The four thermodynamic processes are described below:

- 1 - Isothermal heat addition (volume expansion).
- 2 - Isochoric heat removal, (pressure decrease, constant volume).
- 3 - Isothermal heat removal, (volume compression).
- 4 - Isochoric heat addition,(pressure increase, constant volume).

Heat is thus removed from the cold source during phase 2 and 3, providing the wanted cooling capacity. Three different mountings realizing this cycle have been developed, and are presented hereafter:
5.6. CRYOCOOLER

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Most micro cryocoolers are based on a beta mounting, resulting in long coldfingers with the cooled device at the end (Fig. 5.45).

Figure 5.45 – CAD drawing of a typical micro cryocooler [50]
5.6. CRYOCOOLER

5.6.3 Cryocooler choice

The use of a cryocooler in the OUFTI-Next context implies important modifications on previously presented cooling systems. Indeed, the sensor holding structure will not be considered anymore, since the detector will be glued directly to the cryocooler coldfinger. However, to take into account the heat coming from PCB and electrical connectors, a parasitic heat flux equal to 50 [mW] is considered. The evolution of the heat load to be cleared out by the cryocooler for both hot and cold cases is given by Fig. 5.46. As in previous sections, the end of acquisition time is taken into account.

![Figure 5.46](image)

Figure 5.46 – Detector temperature evolution with the pumped heat load (cryocooler case)

The small peak appearing in Fig. 5.46a simply results from numerical errors, and should not be taken into account. The sensor temperature logically decreases when more heat is pumped, and stops decreasing when reaching the absolute zero (0 [K] / -273.15 [°C]). The following of this analysis will consider a 200 [mW] heat load, representing a mission worst case.

Manufacturers propose several types of cryocoolers, with various sizes and performances. Due to a small on available volume in the CubeSat, the smallest types of cryocoolers will be chosen. A special attention must also be done on the cryocooler electrical consumption, to ensure that no power lacks will appears during the cooling operation.

As in the case of the Peltier system, the cryocooler produces also a waste heat load, and thus needs to be connected to a radiator that radiatively removes this heat. The size of the radiator will depend on the chosen cooler, since their rejected power vary from one to another. Such systems also present the advantage that they can work in different conditions, as their cooling capacity depends on the input power. If additional heat needs to be cleared out, a simple increase of the current will make the Stirling cycle more efficient and the cryocooler able to pump this excess heat.
5.6. CRYOCOOLER

Ricor K562S

The first cryocooler presented is the K562S, specially developed by Ricor to support miniature IR systems where the IR detector operates at temperatures of 95 [K] and above. Its main properties are presented in Tab. 5.10 and Fig. 5.48.

<table>
<thead>
<tr>
<th>Weight (without controller)</th>
<th>185 [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
<td>12 [V]</td>
</tr>
<tr>
<td>Cooling capacity @95 [K] @ 71 [°C]</td>
<td>200 [mW]</td>
</tr>
<tr>
<td>Cooling capacity @110 [K] @ 71 [°C]</td>
<td>300 [mW]</td>
</tr>
<tr>
<td>Steady state input power (200 [mW] @ 95 [K] @ 23 [°C])</td>
<td>&lt; 4.5 [WDC]</td>
</tr>
<tr>
<td>Steady state input power (150 [mW] @ 110 [K] @ 23 [°C])</td>
<td>&lt; 3 [WDC]</td>
</tr>
<tr>
<td>Maximum input power</td>
<td>14 [WDC]</td>
</tr>
<tr>
<td>MTTF (Mean Time To Failure)</td>
<td>&gt; 10000 [h]</td>
</tr>
<tr>
<td>Cooldown time (160 [J] @ 110 [K] @ 23 [°C])</td>
<td>&lt; 4 [min]</td>
</tr>
<tr>
<td>Ambient temperature range</td>
<td>-40 - +71 [°C]</td>
</tr>
<tr>
<td>Maximum dimensions</td>
<td>$38.5 \times 59.5 \times 79.2$ [mm$^3$]</td>
</tr>
</tbody>
</table>

Table 5.10 – Ricor K562S properties [51]
It is observed that keeping the detector temperature at 95 [K] (case of a steady-state) requires a maximum input power of 4.5 [W] with a 200 [mW] heat load, if the ambient temperature, that corresponds to the radiator temperature is 23 [°C]. By looking at the radiator temperature evolution with incoming flux (Fig. 5.38), it can be deduced that 4.5 [W] of heat power results in a radiator temperature equals to -10 [°C] in the cold case and 10 [°C] in the hot case. This means that the cryocooler will actually need less power than expected, and fulfills the requirements. Based on graphs from Fig. 5.48, it is possible to determine the amount of power requested to maintain the detector at a constant temperature, whatever the radiator temperature.

The cool down time depends on the material mass and specific heat $C_p(T)$. These two values are difficult to estimate, since the detector is made of many different materials. The datasheet of the *Kinglet* detector [13] informs that a configuration using this cryocooler exists, with a corresponding cool down time between 4 and 5 [min] at 23 [°C]. However, this cool down time should be related to its corresponding input power. Indeed, considering too high power amounts would result in a too high radiator temperature, exceeding the cryocooler limit operating temperature range. A lower power must thus be applied during the cooling down phase, resulting in a lower radiator temperature and a longer cooling time.

**Ricor K561**

The second cooler studied in this section is the K561, also coming from the *Ricor* manufacturer. This model was specially developed to fit hand held thermal imagers applications where low input power and bulk are the most important parameters, but can also be used for space applications. Over 10000 units have been sold since its introduction in 2005. Its properties are given by Tab. 5.11 and Fig. 5.50.
5.6. CRYOCOOLER

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Figure 5.49 – The Ricor K561 micro cryocooler [52]

| Weight (with controller and hardness) | 290 [g] |
| Input voltage | 6, 12 [V] |
| Cooling capacity @ 80 [K] @ 65 [°C] | 250 [mW] |
| Steady state input power (170 [mW] @ 80 [K]) | 4.5 [W_{DC}] |
| Maximum input power | 16 [W_{DC}] |
| MTTF | > 8000 [h] |
| Cooldown time (190 [J] @ 80 [K] @ 23 [°C]) | < 7 [min] |
| Ambient temperature range | -40 - +71 [°C] |
| Maximum dimensions | $66.2 \times 95.5 \times 46.5$ [mm$^3$] |

Table 5.11 – Ricor K561 properties [52]

Figure 5.50 – Performances evolutions of the Ricor K561 [52]

This cooler have more or less same properties than the first one, with input power varying between 3 and 5 [W] for temperatures going from -40 to 80 [°C]. It presents an higher cooling capacity at a lower temperature, and a higher maximum input power. The
main disadvantage of this model is its bigger size, with a maximum dimension 9.5 [cm] in the coldfinger direction, and its greater weight. It also presents a lower MTTF than the K562S model, and a longer cooling time. In this case also, a particular attention must be made concerning the cooling time, since it is given for the maximum applied power.

**AIM SX020**

The last presented cooler is the SX020 model, produced by AIM. It consists in a single piston linear cooler, combining small outline dimensions and high performances and reliability. The data relating to this model are given by Tab. 5.12 and Fig. 5.52.

![The AIM SX020 micro cryocooler](image)

Figure 5.51 – The AIM SX020 micro cryocooler [53]

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor weight</td>
<td>180 [g]</td>
</tr>
<tr>
<td>Input voltage</td>
<td>5 - 15 [V_{AC}]</td>
</tr>
<tr>
<td>Cooling capacity @160 [K] @ 23 [°C]</td>
<td>500 [mW]</td>
</tr>
<tr>
<td>Steady state input power (200 [mW] @ 140 [K])</td>
<td>4 [W_{AC}]</td>
</tr>
<tr>
<td>MTTF</td>
<td>&gt; 30000 [h]</td>
</tr>
<tr>
<td>Ambient temperature range</td>
<td>-54 - +71 [°C]</td>
</tr>
<tr>
<td>Compressor length</td>
<td>58 [mm]</td>
</tr>
<tr>
<td>Compressor diameter</td>
<td>26.5 [mm^2]</td>
</tr>
</tbody>
</table>

Table 5.12 – AIM SX020 properties [53]
5.6. CRYOCOOLER

5.6.4 Conclusion

This cooler is designed to work at higher temperatures than the two previous ones, and thus give its best performances with High Operating Temperature (HOT) sensors. The Kinglet detector is proposed coupled with that cooler [13], making this option usable for detector operating at 150 [K] temperatures (Fig. 2.1). The main advantage of this model is its high MTTF, more than three times greater than the two others. Its small dimensions are also an advantage, due to the small payload available space.

A problem that can arise with the use of a cryocooler is the lack of place inside the CubeSat payload volume. Indeed, cryocoolers dimensions are not negligible, and sufficient place must be available to integrate the optical system. Fortunately, an extension can be added at the bottom of the 3U CubeSat to increase the length of the payload volume. A common analysis with optical designers must be done to determine the exact length of the whole IR system.
Chapter 6

Transient analysis

The analyses done so far were performed under steady state conditions, since the aim was to check if the considered cooling system was able to reach the required operating temperatures. Those analyses showed that only cryocoolers can fulfill these requirements.

The acquisition phase lasts several minutes during each orbit, and the detector must be switched on and be at its operating temperature from the beginning to the end of this phase. However, it is useless to keep the sensor at its operating temperature since it will be switched off during all other phases. A cooling system bringing the detector at its optimal operating temperature just a few minutes before the acquisition phase will be sufficient and will allow saving a non negligible amount of electrical power. This is the topic of this chapter.

6.1 Thermal constraints

As explained in previous chapter, the main constraint appearing in the mission context is the small radiator area, resulting in limitations on the rejected heat power. Since most cryocoolers can not operate at a temperature higher than 71 °C, the input electrical power must be limited, to avoid too high temperatures reached by the radiator and consequently the cryocooler. This analysis will consider the cooler linked to the radiator by the help of a copper thermal strap, with the same thermal conductance as previously defined in section 4.5.5 ($G_{\text{L,strap}} = 1.39 \text{ W/K}$). The heat load considered is the same than the one already defined in the previous chapter ($Q_{\text{in}} = 200 \text{ mW}$), and the radiator thermal balance related to the first passive model is used (no heat shield, no Peltier). The radiator length is set to 0.3 [m].

6.2 Acquisition phase

Considering the thermal constraints defined above, and by using the graphs on Fig. 5.48, it is possible to estimate the input power to apply in the cryocooler to keep the detector at its operating temperature. In this configuration, the detector is supposed to be
switched on. The end of the acquisition phase, corresponding to the highest components temperature, is used for the computation. Fig. 6.1 shows the evolution of the cryocooler temperature with its dissipated power.

![Cryocooler/radiator temperature evolution with cryocooler dissipated power](image)

Figure 6.1 – Cryocooler/radiator temperature evolution with cryocooler dissipated power

It is observed that to reach a temperature of 71 [°C], the cooler must reject more than 14 [W] of heat power, which is much more than the amount rejected during the steady state cooled detector phase. By comparing the K563 cooler performances and temperature (Fig. 5.48 and Fig. 6.1), it is possible to determine a rough value of the power needed to reach a detector temperature equals to 95 [K].

<table>
<thead>
<tr>
<th>Cryocooler temperature [°C]</th>
<th>Cold case</th>
<th>Hot case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input power [W]</td>
<td>≈ -20</td>
<td>≈ 0</td>
</tr>
<tr>
<td></td>
<td>≈ 2.5</td>
<td>≈ 3</td>
</tr>
</tbody>
</table>

Table 6.1 – Cryocooler input power at steady state, during acquisition time

These results show that a maximum of 3 [W] of input power are needed to keep the detector at its operating temperature. The cryocooler stays well below its maximal temperature. The radiator maximum temperature is equal to ≈ -5 [°C], which remains is the CubeSat temperature range requirements.

### 6.3 Non-operating phases

The main goal of this section is to determine the steady state temperature value of the detector and the cryocooler when the satellite is not in the acquisition configuration. The

---

1. CubeSat lateral panels must stay in the [-40 - +80] [°C] temperature range
6.3. NON-OPERATING PHASES

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detector is thus supposed to be switched off, only resulting in a 0.1 [W] heat load on the cooler coldfinger. The problem appearing is the Cubesat orientation modification, since it is supposed to point the Sun when it is not in acquisition mode. The incoming Earth thermal flux on the radiator is thus modified, resulting in other equilibrium temperatures. Fig. 6.2 Shows the radiator temperature evolution with incoming thermal fluxes.

![Temperature Evolution Graph](image)

Figure 6.2 – Cryocooler/radiator temperature evolution with incoming thermal fluxes (cryocooler switched off)

As in the last case, it can be seen that at least 3 [W] of external incoming power are required to keep the radiator in the temperature requirements. The maximum incoming external heat flux on radiator being equal to 10 [W]$^2$, the maximum value reached by the radiator would not be higher than 25 [$^{°}$C]. However, a good orientation of the radiator during the sun pointing phase will allow it to collect enough external power to maintain its minimum temperature. A worst case would be to consider a non sufficient amount of external power, making the use of an heater mandatory. New cold cases will be considered accounting this constraint. The cold case will correspond to the minimum radiator temperature (-40 [$^{°}$C], blue line on Fig. 6.2), and the hot case will correspond to the radiator temperature when reached by the highest external flux (25 [$^{°}$C], yellow line on Fig. 6.2).

It can be seen that in both cases, the cryocooler stays inside its temperature range. Since the detector is supposed to be at the same temperature than the cryocooler, this analyses shows that neither heating nor cooling is required during the non observation phases, since detector operating ranges are similar to cryocooler ones [12].

---

2. This value corresponds to a radiator pointing the Earth during the hot case
6.4 Cooling down phase

The last step to consider is the cooling down process, where the detector is brought from its initial temperature reached during the sun pointing phase to its operating temperature. This process must be done before the satellite enters in its acquisition phase, and the time needed by the system to reach the operating temperature is important to know. Two cooling scenarios are possible and described below:

- **1** - The detector is cooled down when it is switched off, resulting in a lower input power in the cryocooler. Once at its operating temperature, the detector is switched on, and the cooler input power is increased to keep the thermal balance on the coldfinger.
- **2** - The detector is switched on at the same time than the cooler, resulting in a higher amount of input power, and a longer cooling down time.

The second scenario requires a higher power amount compared to the first, but avoids some temperature instabilities when the detector is switched on. Indeed, the thermal inertia of the system can result in a temperature drop, which then disappears after several seconds when the cooler is fully operational. The cooling time also depends on the input power in the cryocooler, the heat capacity of the cooled object and the initial temperature difference. A smaller initial temperature or a more important input power will logically result in a smaller cooling time. Due to constraints on cryocooler temperature, the input power is limited, and will probably increase the cooling down time.

Unfortunately, some parameters are still not known at this time of the mission (detector heat capacity, chosen cryocooler). Develop a consistent transient model to determine the cooling time needed is complicated, but some values can anyway be estimated, by looking at existing detector/cryocooler couplings. For example, the Sofradir sensor [14] proposes a coupling with the K563 cooler, resulting in the following cooling properties:

<table>
<thead>
<tr>
<th>Detector</th>
<th>Sofradir LEO-LP MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Associated cooler</td>
<td>Ricor K563</td>
</tr>
<tr>
<td>Final temperature</td>
<td>110 [K]</td>
</tr>
<tr>
<td>Cooldown input power</td>
<td>11.8 [W DC]</td>
</tr>
<tr>
<td>Cooldown time</td>
<td>200 [sec]</td>
</tr>
</tbody>
</table>

Table 6.2 – Cooldown time of the LEO-LP MW sensor coupled with the Ricor K563 cooler [14]

The main parameters influencing the cooling time is the cryocooler input power. By looking at Fig.6.1, it can be deduced that the Sofradir/K563 assembly, with its 11.8 [W] of input power fulfills the requirements, and can be therefore used for the mission from a thermal point of view. However, the input power can even be diminished if
necessary, resulting in a longer cooling down time. Test should be foreseen to determine experimentally the cooling down time value, and its evolution with the input power.
Chapter 7

Conclusion

This thesis introduced the concept of the cooling system for an infrared detector and its implementation inside a CubeSat standard nanosatellite. Within the context of the OUFTI-Next mission, different systems have been proposed and analyzed, and conclusions were drawn, in order to validate, or invalidate each system.

After a preliminary definition of the thermal model and incoming heat loads on the IR sensor, the case of a fully passive system was first analyzed. This system consists simply in a conductive link connecting the detector to a radiator placed on a lateral CubeSat face. It was shown that such a configuration was unable to bring the sensor to a recommended operating temperature, taken into account environmental heat loads and temperatures.

The idea of using an heat shield to deflect the incoming Earth thermal flows was then proposed, implying structure modifications and bringing mechanical constraints on the thermal model. Once again, it was shown that even if the shield partially fulfilled its role, by bringing the detector to lower temperatures, it is still not enough to allow optimal use of the sensor.

Since cooling capacities of fully passive system were too weak, some active systems were introduced, beginning by the thermo electric cooler device. Unfortunately, due to their low COP values, Peltier elements are also not able to provide the required cooling capacity, due to their too high amount of rejected power.

The last system investigated was the Stirling micro cryocooler. This time, analyses proved that such systems allow to reach detectors operating temperature range, without consuming too high power amounts (higher COP than a Peltier device). However, particular care must be given to the operating temperature of such devices, since the conductive connection with the small radiator area can lead to excessive temperatures if the rejected heat amounts are too high.

This thesis demonstrated that the only IR detector cooling device meeting all requirements is the cryocooler device. The main problems with other systems is their incapacity in lowering sufficiently the sensor temperature, and their unstable thermal balance on the
radiator, mainly due to the small radiator area compared to the considered heat fluxes.

Even so the cryocooler was demonstrated to be the best system, further analyses will be needed to choose the best one that will fulfill all requirements, and this before developing a smart cooling strategy that results in the lowest power consumption. This will be the aim of the next student generations taking part in the OUFTI-Next project, during the B and C phase mission definition.
Appendix A: 3U CubeSat specifications

Figure A1 – Dimensional constraints of a 3U CubeSat [39]
Appendix B: SAMCEF results for complex geometries simulation

PCB

(a) Temperature distribution (hot zones in red, cold zones in blue)

(b) Heat path

Figure B1 – Results of the SAMCEF analysis for the PCB
Coldfinger

(a) Temperature distribution (hot zones in red, cold zones in blue)  
(b) Heat path

Figure B2 – Results of the SAMCEF analysis for the coldfinger
Thermal straps

(a) Temperature distribution (hot zones in red, cold zones in blue)

(b) Heat path

Figure B3 – Results of the SAMCEF analysis for thermal straps
Titanium flexure

Figure B4 – Flexure temperature distribution (hot zones in red, cold zones in blue)
References


[5] ESA. *How a mission is chosen*. URL: [https://www.esa.int/Our_Activities/Space_Science/How_a_mission_is_chosen](https://www.esa.int/Our_Activities/Space_Science/How_a_mission_is_chosen). (accessed: May 4, 2018).


