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Photonics Engineering

COMPACT SPACE SPECTROMETER BENEFITTING CLIMATE CHANGE MONITORING

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ABSTRACT

Space-based spectrometers are of high importance for Earth observation and greenhouse gas sensing, providing vital information for climate and climate change monitoring. Today, an ongoing trend towards miniaturization and the use of cost-effective small satellites can be observed, while also wide field-of-view (FOV) imaging is considered to offer a huge potential by enabling to capture global data. We present a novel freeform pushbroom imaging spectrometer, covering the near-infrared and thermal wavelength range, and showing a full field-of-view of 120° , while fitting within only 2 CubeSat Units. According to our knowledge, our novel design shows the widest FOV that has ever been realized for space-based telescopes, nearly reaching Earth observation from limb to limb from an altitude of about 700 km, while fitting in a compact design ($100 \times 47 \times 105 \text{ mm}^3$). The design is composed of a freeform telescope, followed by a three-channel freeform spectrometer unit. The freeform telescope comprises 2 off-axis freeform mirrors with an aperture stop at the focal point of the secondary mirror, collecting the light and sending it to a spectrometer slit. Following the spectrometer entrance slit, a collimating mirror is present, after which the light is split to the visible (400 – 1100 nm), the near-infrared (1100 – 1700 nm) and thermal spectrometer channel (8 – 14 μm). Each of the three spectrometer channels comprise of a diffraction grating and 2 freeform mirrors to focus the light on a 2D detector, providing both spatial and spectral information. The design was optimized considering the spot size and Modulation Transfer Function in the merit function. All mirrors are described using XY polynomials, up to the 6th order, enabling a close to diffraction-limited performance. Considering the visible and near-infrared channels, a spatial resolution better than 5 km and a spectral resolution better than 4 nm is achieved. For the thermal channel, the spatial resolution is limited by its Airy disc to 20 km, and the spectral resolution is limited to 150 nm. Starting from the nominal simulated design, an evaluation was made towards to realization of a laboratory demonstrator setup, including the performance of a tolerance and stray light analysis, validating the manufacturability of the design. We believe the proposed design might pave the way towards future space missions enabling an improved Earth observation and climate monitoring.

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TABLE OF CONTENT

Abstract.....	0-3
Acknowledgement.....	0-4
Chapter 1: Introduction.....	1-7
1.1 Climate change and global policy.....	1-7
1.2 State-of-the-art WFOV spectrometer: TROPOMI.....	1-10
1.3 thesis objective: design novel imaging spectrometer.....	1-12
1.4 Starting point: Wide field of view telescope.....	1-13
1.5 Key challenges of this master thesis.....	1-15
1.6 Structure of the thesis.....	1-15
Chapter 2: Physical concepts necessary to build a three-channel spectrometer.....	2-17
2.1 Basic spectrometer architecture.....	2-17
2.2 Novel freeform VIS-NIR-Thermal spectrometer design.....	2-19
2.3 Channels separation.....	2-19
2.4 diffraction gratings for high spectral resolution.....	2-21
2.5 Freeform optics modeled via polynomials for high spatial and spectral resolution.....	2-29
2.5.1 XY Polynomials.....	2-29
2.5.2 Materials and manufacturing.....	2-31
2.6 Summary and conclusion.....	2-33
Chapter 3: Novel freeform spectrometer designs.....	3-34
3.1 Single VIS channel.....	3-37
3.2 Single-channel NIR spectrometer.....	3-44
3.3 Single-channel Thermal spectrometer.....	3-47
3.4 Final three-channel spectrometer.....	3-51
3.4.1 VIS channel.....	3-51
3.4.2 NIR channel.....	3-56
3.4.3 Thermal channel.....	3-60
3.5 Summary and conclusion.....	3-65
Chapter 4: Ways to the physical realization.....	3-65
4.1 Optical sensors.....	4-67
4.1.1 CMOS-based detector for the VIS range.....	4-68
4.1.2 InGaAs detector for the NIR range.....	4-70
4.1.3 Bolometer technology for the Thermal range.....	4-72
4.2 Energy budget.....	4-73
4.3 Tolerancing.....	4-76
4.4 Stray light.....	4-77
4.5 Summary and conclusion.....	4-78
Chapter 5: Conclusion and future perspectives.....	5-79

0-6

5.1	Conclusion	5-79
5.2	Future perspectives	5-81

Chapter 1: INTRODUCTION

1.1 CLIMATE CHANGE AND GLOBAL POLICY

Climate change is one of the biggest threats humanity is facing. According to the World Health Organization (WHO), a perspective of 250 000 deaths due to climate change is expected between 2030 to 2050.[1] Climate change causes an increase in extreme events such as storms, heatwaves, and floods. In addition to the direct harm to people and infrastructures, these extreme weather conditions can also induce the propagation of infectious diseases causing an increase of mortality following the natural disaster. I.e. in 2022, after a flood in Pakistan, stagnant water induced a severe increase amongst mosquitoes, flies, and other infection propagators, causing a severe dengue virus epidemic months after the event. Moreover, post-flooding wound infections, respiratory problems, cholera, diarrheal infections, etc., increasing the death rate amongst extreme events survivors.[2] Another issue caused by climate change consists of a possible global migration over time. The agricultural system is threatened in many countries by floods or desertification. This leads to a lack of subsistence, conflicts for water, or other phenomena contributing to migration as happened in Somalia in 2022 where a drought event displaced 1 million people. In total in 2022, natural disasters were the cause of 33 million displacements, primarily within the country.[3]

In addition to the extreme events caused by climate change that will increase over time, our actual daily lives are impacted by pollution. I.e. pollution leading to poor air quality heavily impacts general health by introducing fine particles, nitrogen dioxide (NO₂), ozone (O₃), and sulfur dioxide (SO₂) into the air we breathe. Short and long-term exposure to those pollutants worsens and can lead to cancers, and lung conditions (as asthma or respiratory infections), while generally impacting all human organs. People are not equally sensitive to bad air quality as old people, children, and people with pre-existing health conditions are more vulnerable to develop complications. The European Environment Agency (EEA)[4] estimates that in 2022, fine particles were linked to the premature death of approximately 238,000 persons within the 27 European states. [4] Therefore, actions have been taken by several countries and organizations to limit global warming and pollution. I.e. the Paris Agreement made during the COP21 aims limiting greenhouse gases (mainly CO₂) such that global warming does not exceed 1.5°C by 2050 (in comparison to the pre-industrial era). Several global warming scenarios are possible in function of the greenhouse gasses emission rate. Following the Paris agreements it is expected that the 197 signatory states reduce their growth to keep global warming below 2°C. [5], [6] However, as shown in Figure 1, the current agreement doesn't lower the warming below 2°C but 2.1°C by 2100. If the current policies continue, it would reach between 2.5° to 2.9°C.

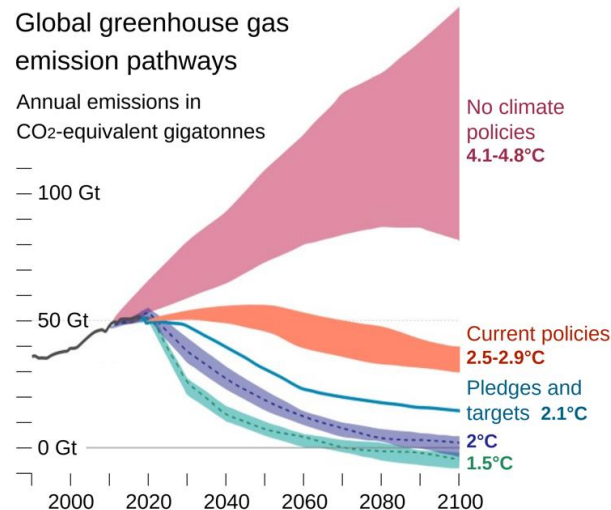


FIGURE 1: GLOBAL WARMING EVOLUTION FOR DIFFERENT GREENHOUSE GAS EMISSION SCENARIOS[7]

On a global scale, large differences in greenhouse emission concentrations can be identified. In 2021, the main emitters of greenhouse gases were China and the USA with a total of 43% of the global emission. Followed by India and Russia with respectively 7.3% and 4.7%. Considering Europe, Germany is the main emitter and in 7th position with 1.8% followed by Italy and Poland in 18th and 19th position with 0.9% of the global emission of CO₂. [8] CO₂ corresponds to 80% of man-made greenhouse gases. Other main greenhouse gases include methane CH₄ that is produced by agricultural activities represents 11%, and NO₂ representing 6%. [9] Those three greenhouse gases are produced and influenced by human activities but if we look at the whole amount of greenhouse gases, water vapor is responsible for 41 to 67% of the greenhouse gases effect. [10] Water vapor is not human-made; however, it currently undergoes positive feedback due to global warming. An increase in temperature amplifies water evaporation which in turn increases back the greenhouse gas effect.

The present greenhouse gases influence global warming and climate change. The global warming phenomena can be explained through the Earth's energy budget, considered as the balance between incoming solar radiation and outgoing terrestrial energy in W/m², which can be measured by satellites at the Top-of-the-Atmosphere (TOA). When solar energy hits the Earth (with an irradiance of approximately 340 W/m² perpendicularly to the Sun-Earth axis at the mean distance between those two [11]), a major part of the light is reflected by Albedo or clouds, while the rest of the incoming solar energy is absorbed. The reflected irradiance equals approximately 101 W/m². The absorbing surfaces emits thermal radiation to space, when heating up, corresponding to approximately 238 W/m². When the incoming energy from the Sun equals the outgoing energy from the Earth, the system is in radiative equilibrium. If the outgoing energy is higher or lower, the temperature at the Earth's surface is respectively decreasing or increasing, and an Earth's energy imbalance occurs. Currently, due to the greenhouse gases effect, Earth tends to store part of the incoming energy (approximately 0.9 W/m²) and heat up i.e. global warming. [12] The special attention to the monitoring of greenhouse gases is therefore highly important to predict, evaluate, and monitor the global warming phenomena and to ensure better air quality for everyone, hence reducing large amounts of premature death.

The monitoring of the five main greenhouse gases (water vapor, carbon dioxide, methane, nitrous oxide, and ozone) requires a broad spectral sensitivity, covering at least the visible and near-infrared spectral range. Additionally, to measure the absorption of both reflected and thermally emitted Earth radiation, it is advantageous to have wide spectral monitoring that covers visible, near-infrared, and thermal wavelength bands.

Two main types of imaging space spectrometer geometries can currently be distinguished to achieve global data; the whiskbroom (Figure 2) and the pushbroom (Figure 3) geometry. A whiskbroom scanner features a small FOV but uses a mechanical rotating mirror to scan along the swath and to allow an extended FOV. The spatial resolution is determined by the scanned area, while the detector, consisting of a linear array of pixels, is responsible for the spectral resolution. Initially, space-spectrometers tended to use a whiskbroom configuration, scanning the Earth perpendicularly to their line of motion, as was the case for the Global Ozone Monitoring Experiment (GOME and GOME2)[13], [14], the Greenhouse Gases Observing Satellite (GOSAT)[15], and the SCanning Imaging Absorption spectroMeter for Atmospheric Cartography (SCIAMACHY).[16] The main drawback of these configurations is the presence of a moving mirror, leading to low signal intensity and efficiency due to the point-by-point imaging method, driving the transition to wide field-of-view (FOV) pushbroom configurations.

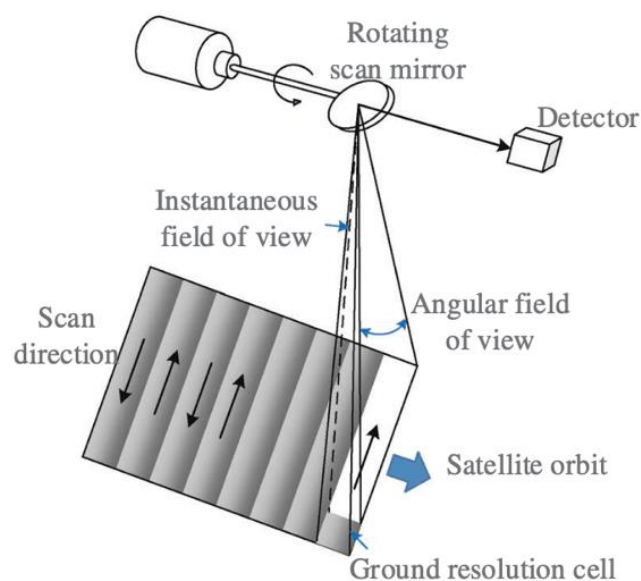


FIGURE 2: WHISKBROOM CONFIGURATION[17]

The pushbroom configuration has a fixed telescope, continuously scanning along the swath. The spatial resolution is determined on one axis by the number of frames per second (FPS) the scanner captures, which is influenced by its speed and altitude. This determines the ground swath resolution (Figure 3). The spatial resolution along the second axis consists of the subdivision of the ground swath and is determined at the detector by the quality of the optical system, the detector size and the number of pixels. To provide additional information on the spectral resolution, the detector must be constituted of a 2D array of pixels, corresponding on one axis to the spatial coordinates, and on the other axis the spectral resolution.

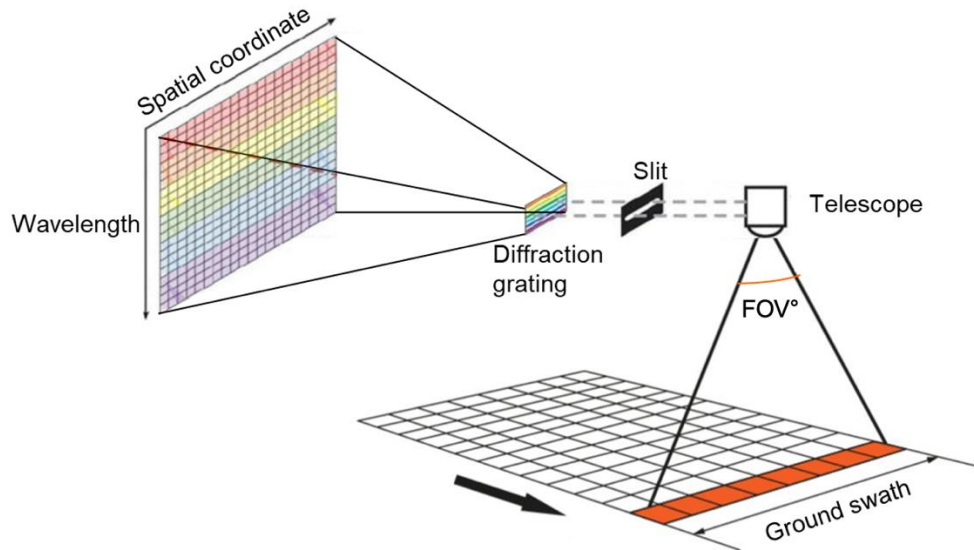
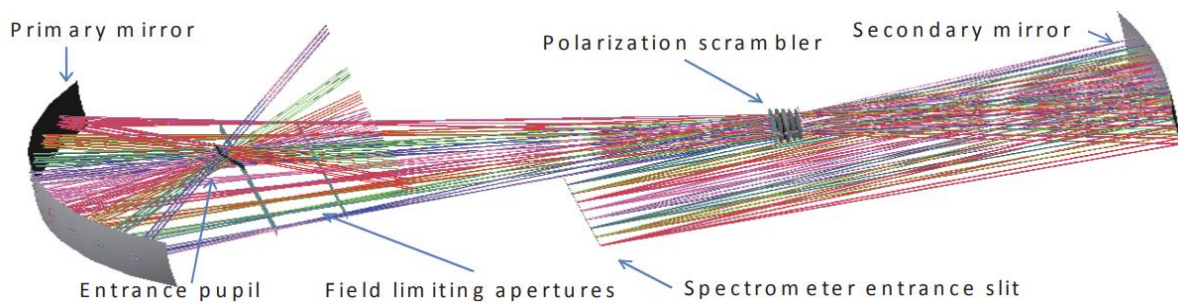


FIGURE 3: PUSHBROOM CONFIGURATION[18]

Pushbroom imaging requires a more challenging optical design to achieve a wide field of view (WFOV) with a qualitative resolution; however, the choice has been made for this thesis's work to make a WFOV spectrometer based on the pushbroom method, avoiding mechanical movements within the setup. Today's state-of-the-art WFOV is embedding pushbroom scanning.

1.2 STATE-OF-THE-ART WFOV SPECTROMETER: TROPOMI

TROPOMI (TROPOspheric Monitoring Instrument) (Figure 4) is part of the European program Copernicus, dedicated to Earth observations. Through this program, a fleet of satellites named "Sentinel" has been launched to monitor the Earth's climate, soil exploitations, and natural resources. The satellite Sentinel-5P, launched in 2017 for a seven-year mission, embeds the most sophisticated multi-spectral spectrometer, TROPOMI, and provides data about the atmospheric composition with an extremely high resolution and wide FOV (108°). TROPOMI particularly aims contributing to climate and air quality monitoring, while providing global cartography of the pollution state and its evolution. TROPOMI reaches a swath width of 2600km while having a resolution of $3,5 \times 7 \text{ km}^2$ at nadir; however, since the 6th of August 2019, the resolution has improved to $3,5 \times 5,5 \text{ km}^2$ at nadir.[19] This spatial resolution allowed for the first time to resolve pollution on a city scale, i.e. Figure 5 compares different resolution performances for previous satellite missions and TROPOMI, showing the good performances and capacities of this instrument.

FIGURE 4: TROPOMI'S WFOV TELESCOPE SHOWING THE WFOV OF 108° ANT THE ENTRY THEN THE FREEFORM MIRRORS FOCUSING THE RAYS AT THE ENTRY OF THE SPECTROMETER[20]

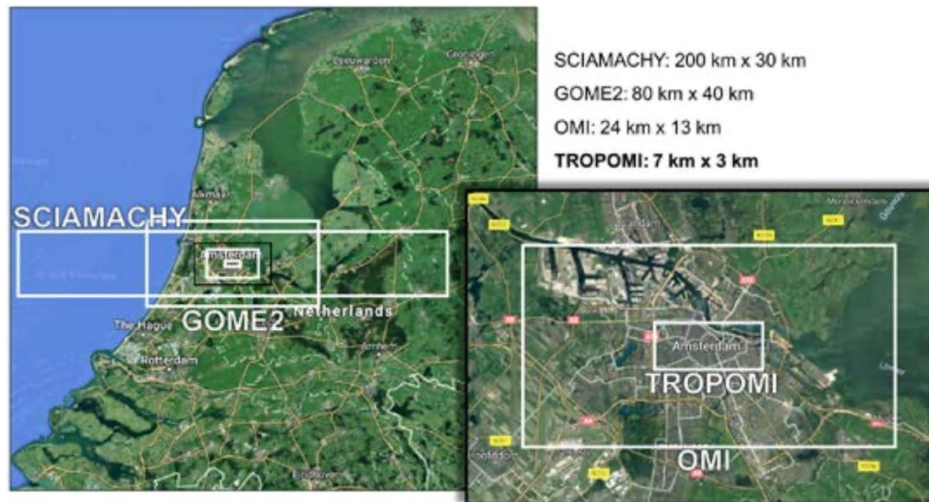


FIGURE 5: TROPOMI'S RESOLUTION IN COMPARISON TO PREVIOUS SATELLITES SHOWING THE POSSIBILITY TO MONITOR GREENHOUSE GASES ON A CITY SCALE[21]

TROPOMI embeds four spectrometers analyzing the spectrum (Table 1) in the UV (270-320nm), the UVIS (320-490nm), the NIR (710-775nm), and the SWIR (2305-2385nm). The spectral resolution for each of the four channels is below 1nm offering a good performance.

TABLE 1: TROPOMI'S FOUR SPECTRAL BANDS WITH THE CORRESPONDING ABSORBING GASES MONITORED, THE SPECTRAL RANGE OF THE SPECTROMETERS, AND THEIR SPECTRAL RESOLUTION [22], [23]

Spectrometer	UV	UVIS	NIR	SWIR
Main gases	O ₃	O ₃ , SO ₂ , CH ₂ O, aerosols, NO ₂ , clouds	Aerosols, clouds	CO, CH ₄
Spectral range (nm)	270 - 320	320 - 490	710 - 775	2305 - 2385
Spectral resolution (nm)	0,45 – 0,5	0,45 – 0,65	0,34 – 0,35	0,225 – 0,227
Dimension (m ³)	0,56 x 0,45 x 0,38			0,45 x 0,3 x 0,2

The optical system of TROPOMI is composed of different 'building blocks' (Figure 6). The first one from the left is the calibration unit that provides different types of light to calibrate the system and is switched on/off via a folding mirror mechanism, but this part of the instrument is out of this thesis's scope. The second component at the bottom left after the calibration unit is the telescope, which collects the light from the Earth with a WFOV of 108° and has an f-number between 9 and 10.[24] The telescope is made out of two concave freeform mirrors. The first one collects the light and forms an intermediate focus while the second one is focusing the light at the spectrometer entrance (Figure 4). The polarization scrambler is added to make the system polarization-independent.[20] After the telescope, at the spectrometer entrance, the light is first separated at the slit. The UVIS and NIR channels are transmitted by the slit while the UV and SWIR channels are reflected. Each of the channels is separated by dichroic mirrors, but the SWIR channel is first relayed to another optical bench before entering its corresponding spectrometer.[22] Due to the differentiation between the UV-UVIS-NIR bench and the SWIR bench, they both require a different volume (Table 1). The size of the UV-UVIS-NIR bench requires a volume of 0,56x0,45x0,38m³ and the SWIR channel has a volume of 0,45x0,3x0,2m³. In comparison with the standard CubeSat size (10x10x10cm³), the UV-UVIS-NIR bench would require 60 CubeSat units and the SWIR would require 30 units for a total of 90 units.[23]

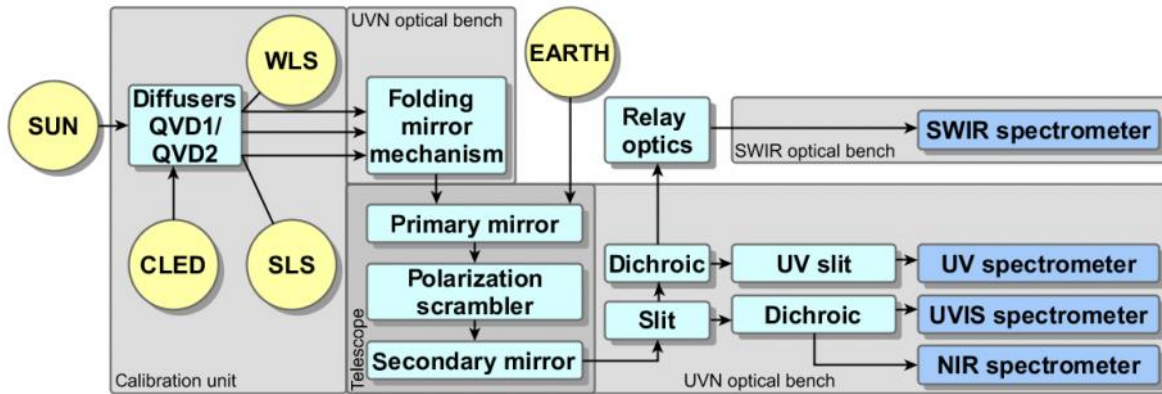


FIGURE 6: TROPOMI'S OPTICAL SYSTEM SHOWING THE DIFFERENT UNITS, THE CALIBRATION, THE TELESCOPE AND THE TWO BENCHES FOR THE UV-UVIS-NIR AND SWIR CHANNELS. [22]

1.3 THESIS OBJECTIVE: DESIGN NOVEL IMAGING SPECTROMETER

This thesis targets the design of a space-based imaging spectrometer, exceeding the state-of-the-art in terms of field-of-view and compactness of the design.

An ongoing trend towards miniaturization and the use of cost-effective small satellites can currently be observed, while also extended wide field-of-view imaging is considered to offer a huge potential by enabling to capture global data. We pursue improving the state-of-the-art space spectrometers by targeting an enlarged FOV enabling Earth observation from limb to limb at an altitude of 700 km, by extending the considered wavelength range and by miniaturizing the design. This thesis therefore presents the work made to model a novel WFOV freeform imaging spectrometer, imaging the Earth with a FOV of 120°, and featuring 3 spectral channels covering the visible, near-infrared, and thermal wavelength range (Figure 7).

We target the following specifications:

- Wide FOV of 120° using pushbroom scanning
- Spatial resolution < 5 km
- Spectral resolution < 20 nm
- Three channels (Figure 9):
 - VIS (400-1100nm)
 - NIR (1100-1700nm)
 - Thermal (8-14μm)
- Fit within a single CubeSat

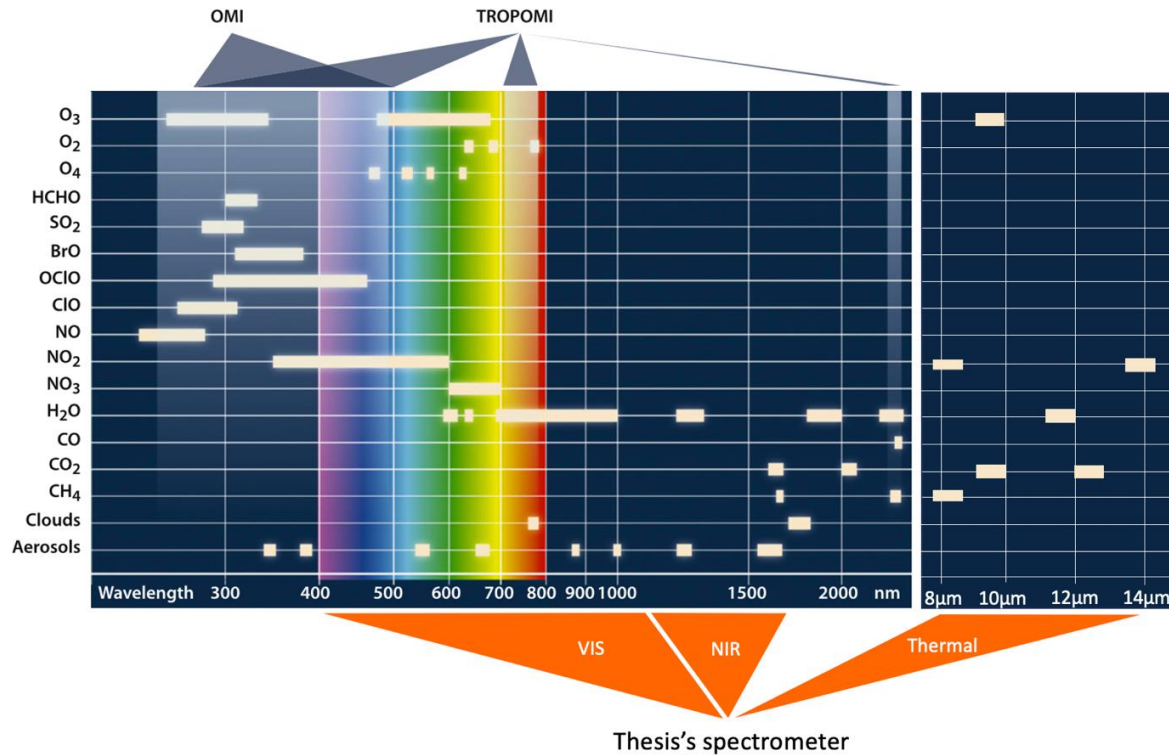


FIGURE 7: GREENHOUSE GASES ABSORPTION WAVELENGTH WITH TROPOMI, OMI, AND THIS THESIS'S SPECTROMETER SPECTRAL RANGE ANALYZED SHOWING THAT OUR SPECTROMETER IS ANALYZING A WIDER SPECTRAL RANGE.[25]

The comparison between the spectral range covered in this thesis with the one of TROPOMI and OMI (Figure 7) indicates the extended wavelength range. Our proposed design includes the 1100nm -1700nm range that is not often studied but offers precious data to study greenhouse gases such as methane. The addition of the thermal channel is beneficial, not only to analyze the five main greenhouse gases but also to monitor their influence on the thermally emitted radiation by the Earth. A broader the spectrum will ease the identification and interpretation during post-processing, benefitting the accuracy of the greenhouse gas measurement. The integration of the three channels within one spectrometer serves two purposes: (1) The miniaturization of the system such that it enters within one CubeSat making it highly competitive in terms of cost and offering extended possibilities to embed the instrument within space missions. (2) The reduction in inter-system alignment errors. When considering separated spectrometer instruments, each of these systems would have an error (tolerancing error, and pointing and alignment error) leading to a lower measurement accuracy.

1.4 STARTING POINT: WIDE FIELD OF VIEW TELESCOPE

Similar to the state-of-the-art designs, our targeted miniaturized imaging spectrometer will comprise a telescope followed by the 3-channel spectrometer unit. Before the start of this thesis, and based on the TROPOMI telescope, a design of the wide-field-of-view telescope was designed by Luca Schifano in his PhD thesis.[26] This compact telescope (X,Y,Z = 96 mm x 15 mm x 95 mm) fits within one CubeSat unit (Figure 8). As for TROPOMI, the telescope is made out of two concave freeform mirrors: one to collect the light, and one to focus the light at the spectrometer entrance. Despite the similarities, this new telescope design improves the FOV to reach 120°, an addition of 12° in comparison to TROPOMI. In addition, at the entrance of the spectrometer, each field is diffraction-limited with an RMS spot radius fitting within the Airy disk (Figure 8).

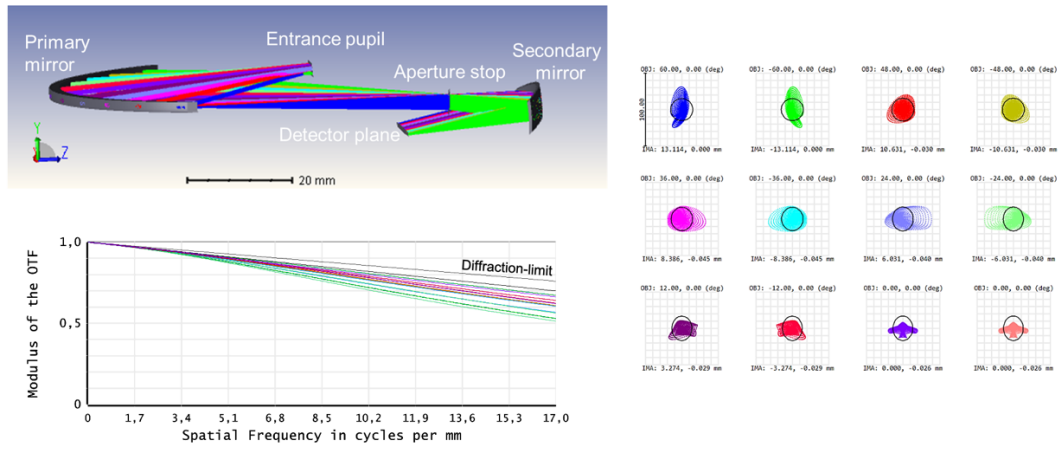


FIGURE 8: WFOV TELESCOPE COMPRISING OF 2 FREEFORM MIRRORS, DESCRIBED USING XY POLYNOMIALS, AND SHOWING A DIFFRACTION LIMITED PERFORMANCE [26]

The WFOV telescope is intended to observe the Earth from the Low Earth Orbit, at an altitude of approximately 700km, resulting in a swath width of 3700km. Since the Earth's diameter is equal to 10 000 km, it would require a spectrometer equipped with this telescope less than three revolutions to scan Earth from limb to limb.

The freeform telescope mirrors were manufactured in-house at the VUB B-PHOT Brussels Photonics Innovation Centre, using ultraprecision diamond tooling. Following, a proof-of-concept laboratory demonstrator was realized showcasing a great performances (Figure 9), and indicating this telescope form a solid basis for the 3-channel spectrometer. Figure 9 shows the system manufactured and tested, both in Zemax and in the laboratory.

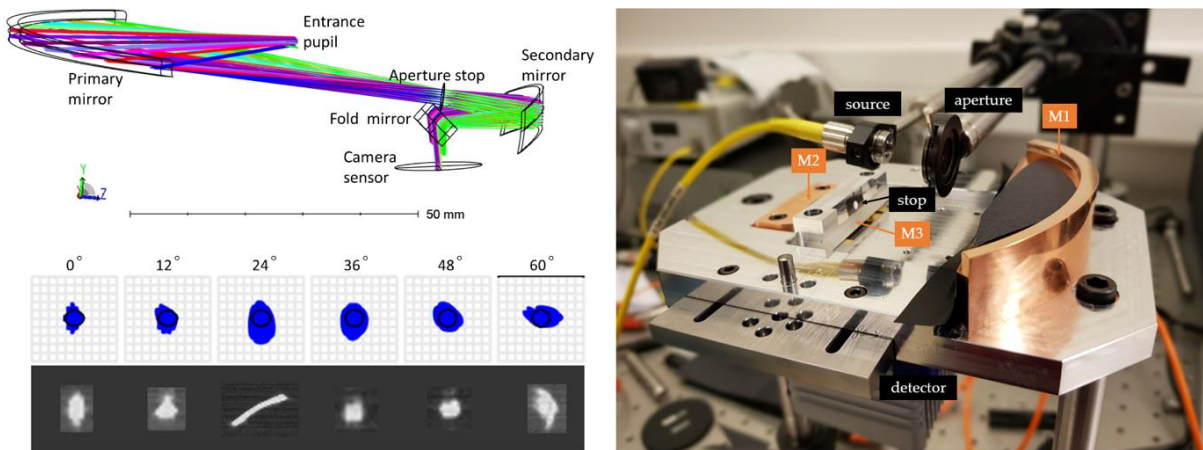


FIGURE 9: WFOV TELESCOPE LABORATORY DEMONSTRATOR. AT THE BOTTOM LEFT, COMPARISON BETWEEN THE SIMULATION AND EXPERIMENT SHOW A MATCHING PERFORMANCE, INDICATING THE DESIGN CAN BE USED WITH CONFIDENCE WITHIN THIS THESIS'S WORK. [26]

1.5 KEY CHALLENGES OF THIS MASTER THESIS

Key challenge of this master thesis is the design of the 3-channel spectrometer, following the previously developed freeform WFOV telescope. The successful design of the spectrometer requires tackling the following 6 key challenges:

- (1) Geometrical design optimization and folding of the design to ensure its fitting within a single CubeSat.
- (2) The parameterization of the freeform components will be extremely important to achieve the targeted spectral and spatial resolution. The freeform terms need to be exploited in view of aberration reduction (including keystone and smile distortion).
- (3) The extended wavelength range imposes challenges with respect to the material and sensor selection. The broad spectrum requires a careful selection of the components (especially the gratings) and used materials.
- (4) Power budget analysis of the design ensuring sufficient light at the detectors, providing an acceptable signal-to-noise ratio.
- (5) Tolerance analysis in view of achieving a manufacturable design. Given that the resulting design is envisioned to comprise 9 freeform mirrors, it is important to have an accurate tolerance analysis ensuring a realizable design.
- (6) Stray light evaluation to minimize light crossing between the different channels.

A multidisciplinary approach is required to tackle these challenges, including an understanding of diffraction optics, freeform lens design, and material science.

1.6 STRUCTURE OF THE THESIS

This thesis is structured into five main chapters, highlighting different aspects of the three-channel spectrometer. Chapter 2 covers the basic physical concepts needed to make our new freeform design. It includes an introduction to different spectrometer designs, how to separate the channels, and how to understand and calculate the diffraction grating parameters. It also discusses how freeform optics are modeled, together with the mirror material requirements. Chapter 3 provides the results (spot diagram, spatial and spectral resolution, MTF, aberrations) of the simulated spectrometer designs, first considering the single-channel designs for the VIS, NIR, and Thermal range, and subsequently evaluating the full three-channel design. Chapter 4 introduces the detector technology required for each channel, like CMOS for VIS, InGaAs for NIR, and bolometer technology for Thermal; and compares commercially available detectors with the performances of the simulated design. Finally, we explore in Chapter 4 practical steps to prototype the spectrometer by studying the integration of commercially available components, the energy budget, the Signal-to-Noise Ratio (SNR) and the tolerance and stray light analysis.

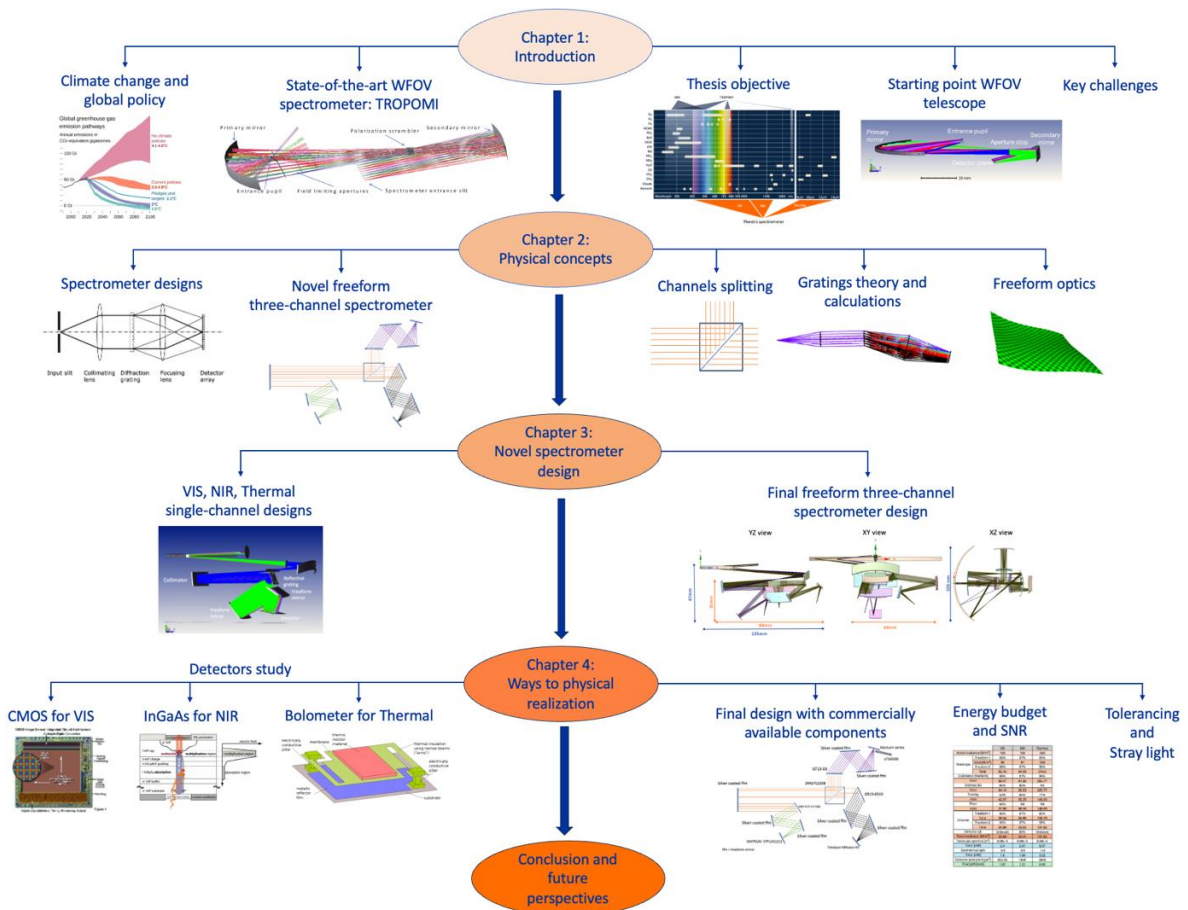


FIGURE 10: THESIS'S WORKFLOW

Chapter 2: PHYSICAL CONCEPTS NECESSARY TO BUILD A THREE-CHANNEL SPECTROMETER

2.1 BASIC SPECTROMETER ARCHITECTURE

The essence of a spectrometer is depicted in Figure 11, indicating the use of a diffractive component to split the light into its wavelength components. First, a collimating element (often a lens or a concave mirror) converts the diverging light rays to parallel rays. This step is of high importance for accurate focusing afterwards in the system. Following the collimating element, a diffraction grating (or possibly a prism) is present. The incoming light is separated with a different angle as a function of the wavelength. From the perspective of a single ray of white light passing through a diffractive element, the output is a continuously diverging set of rays featuring a different angle for the different wavelengths. The diffractive behavior and mechanism are further discussed in section 0. The focusing element (a lens or a concave mirror) focuses the different wavelengths on the detector array. Since each wavelength is diffracted with a specific angle, a given image point will be the focus of a specific wavelength. The detector array must be compatible with the spot size and sensitive to the wavelength analyzed. Further discussion on the detector is given in Section 4.1.

The spectrometer architecture (Figure 11) showcases a system not suitable in the scope of this work due to its large system size. The requirement for a small spectrometer restricts the use of lenses, and the broad spectral range adds extra limitations on suitable materials. Additionally, since lenses can suffer from chromatic aberrations a reflective mirror design is preferred. The choice of the spectrometer's architecture is decided according to the compactness potential and the ease of implementation for a three-channel spectrometer.

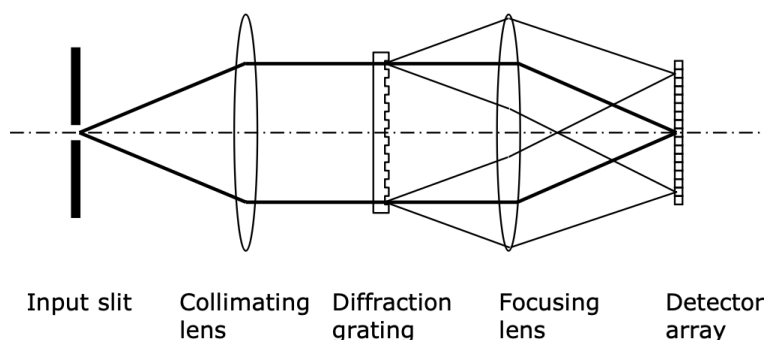


FIGURE 11: BASIC SPECTROMETER ARCHITECTURE[27]

The Czerny-Turner spectrometer is the main type of spectrometer architecture featuring two variants, the crossed and the unfolded one as presented in Figure 12. The Crossed Czerny-Turner spectrometer has the advantage of being highly compact, making this a popular geometry. However, the realization of a three-channel spectrometer complicates the implementation of a crossed system. The risk of stray light and back reflection is high and the complexity of a three-channeled crossed system is too high to be interesting to implement. For those reasons, the unfolded Czerny-Turner spectrometer is preferred for the three-channel spectrometer design. It is planned to separate the channels at the collimator and design for each of them specific gratings and freeform mirrors. Each channel will be separated and independent, thus minimizing the risks of interference between them, while in addition allowing for each channel an independent optimization process (as long as they do not overlap).

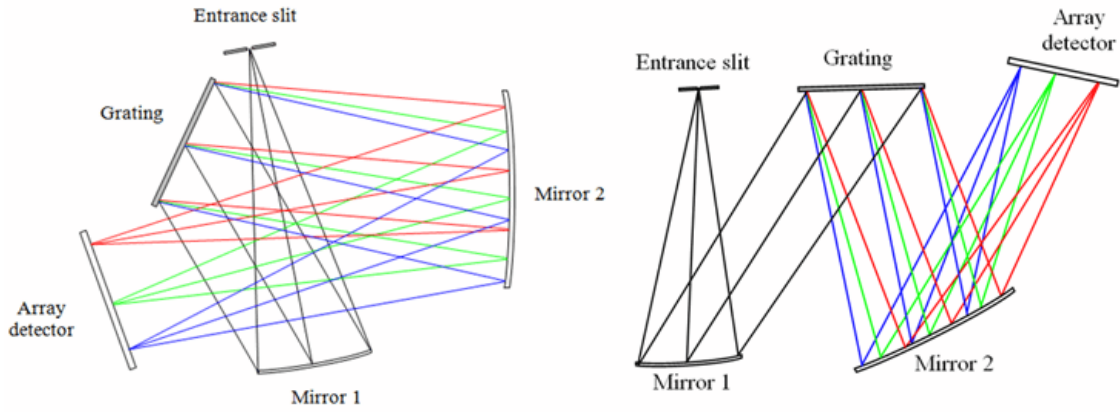


FIGURE 12: CROSSED (LEFT) AND UNFOLDED (RIGHT) CZERNY-TURNER SPECTROMETER[28]

Another interesting configuration considered during the design development stage is the Offner spectrometer (Figure 13). This relatively compact spectrometer is made out of two concave mirrors and one convex grating. In contrast to the previous designs, the light does not require to be collimated, and the grating is curved, in addition to being between the two mirrors. Another important feature of the system is that the object (at the entrance slit) and the image are positioned parallel to each other and on the same plane.

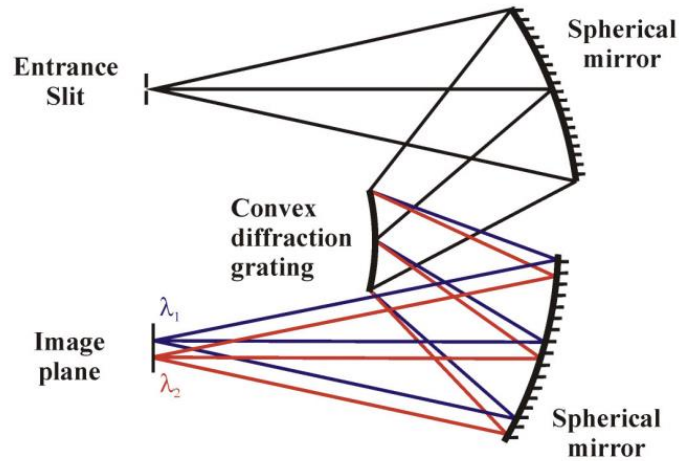


FIGURE 13: OFFNER SPECTROMETER[29]

The convex diffraction grating complicates the calculation of the diffraction angle and is less commercially available (none are sold on the Thorlabs website). However, the Offner design is implemented and tested for a single VIS spectrometer in section 0 because its impact on the smile effect has revealed interesting results.

The summary table comparing the different systems (Table 2) shows that the unfolded Czerny-Turner is preferred, taking the three-channel geometrical integration into account. The Offner design operates without a collimated beam, which complicates channel splitting and makes it unsuitable for final integration. However, its architecture is studied in the context of a single channel.

TABLE 2: COMPARATIVE TABLE BETWEEN THE DIFFERENT DESIGNS TESTED IN THIS THESIS SHOWING THAT THE UNFOLDED CZERNY-TURNER HAS THE BEST CAPABILITY TO INTEGRATE THREE CHANNELS

		Compactness	Optimisation convenience	Manufacturability	3-channel integration
Czerny-Turner	Folded	+++	+++	+++	-
	Unfolded	+	+++	+++	+++
Offner		+	++	+	-

2.2 NOVEL FREEFORM VIS-NIR-THERMAL SPECTROMETER GEOMETRY

Our novel design geometry for the three-channel spectrometer is depicted in Figure 14 (note that this design is flattened and does not correspond to a geometrically accurate model). The collimated light coming from the telescope introduced in section 1.4 is the input of the schematic. The collimated light is separated into three channels via two distinct mechanisms. The first beam splitting occurs between the thermal and the VIS-NIR channel. Due to material requirements (see section 2.3), a “geometrical” splitting is set in place and consists of a grating added along the light path. After the “geometrical” splitting, a second splitting between the VIS channel and the NIR channel is performed using a dichroic beam splitter. Taken separately, each of the three channels uses the Unfolded Czerny-Turner model. A reflective grating is used for the Thermal and NIR channels and a transmissive grating is used for the VIS channel. The choice of a transmissive grating instead of a reflective one has been made to better manage the space between the VIS and the NIR channels. Gratings are discussed in detail in Section 0. After the gratings, free-form mirrors are added to focus the light at the detector plane. Two free-form mirrors are placed at each channel to compensate for the aberrations discussed in the introduction of Chapter 0: Free-form mirrors are designed using the XY polynomials and are further discussed in Section 2.5. Finally, light is focused on the detector. The detector’s technology and requirements are discussed in Section 4.1.

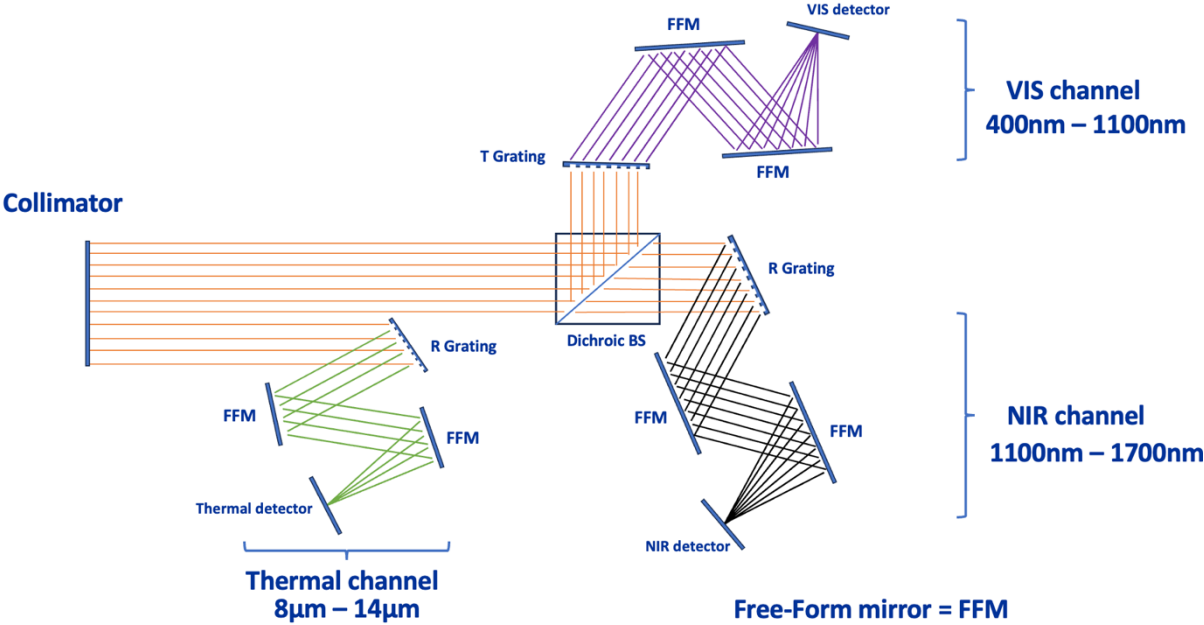


FIGURE 14: NOVEL FREEFORM THREE-CHANNEL SPECTROMETER GEOMETRY SHOWING A FLATTENED POSITIONING OF EACH COMPONENTS

2.3 CHANNELS SEPARATION

Two splitters are necessary to split the light beam into three beams of different wavelengths corresponding to our three different channels. The splitting strategy is to first separate the thermal channel from the incoming beam, followed by a separation between the VIS and NIR channels.

The key difficulty to split the light in the different channels is related to the material properties and the limited wavelength range of each of the typically used materials (Figure 15).

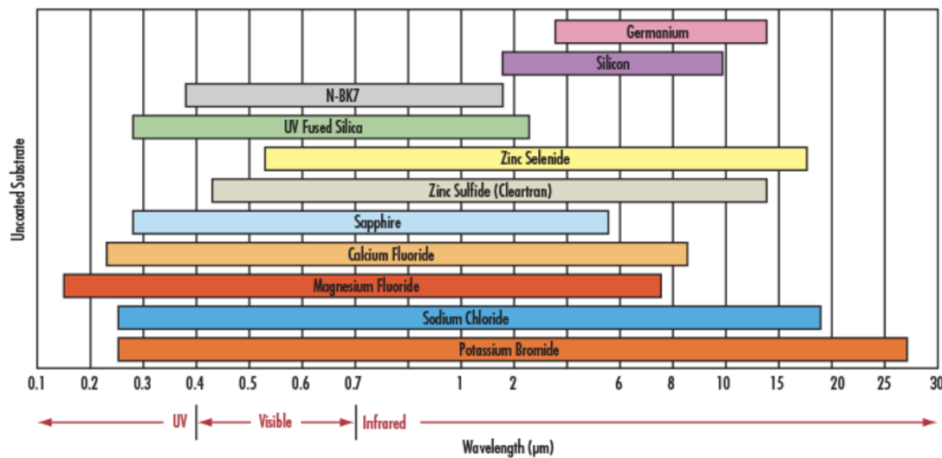


FIGURE 15: MATERIAL ABSORPTION FOR DIFFERENT WAVELENGTHS SHOWING THE REDUCED CHOICE FOR MATERIALS WORKING IN A SPECTRAL RANGE FROM 0,4 μ M (SHORTEST VIS WAVELENGTH ANALYZED) TO 14 μ M (LONGEST THERMAL WAVELENGTH ANALYZED)[30]

Considering the VIS-NIR splitting, a dichroic beam splitter can be used. Such a splitter is expected to reflect the light with a wavelength between 400nm to 1100nm and to transmit the light in 1100nm to 1700nm wavelength range (Figure 16).

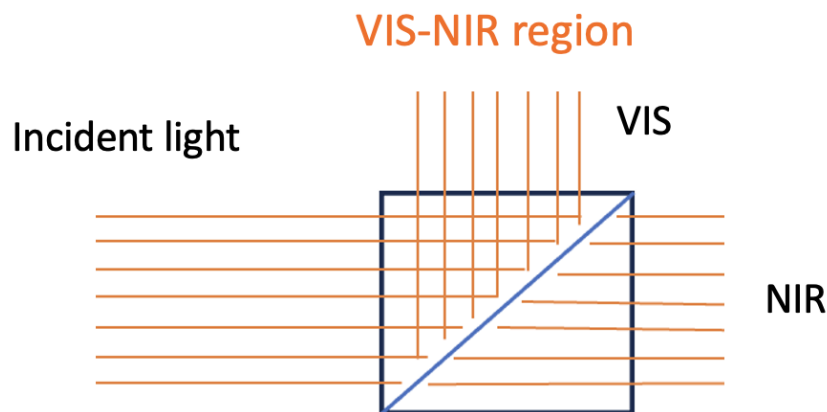


FIGURE 16: CONVENIENT REPRESENTATION OF A DICHOIC BEAM SPLITTER USED TO SEPARATE THE VIS AND THE NIR CHANNELS

Dichroic beam splitters with similar characteristics are commercially available. The DMLP1150B from Thorlabs (Figure 17)[31] constitutes a possible non-custom made dichroic beam splitter. The junction between the VIS and the NIR range is not ideal with a gap of 200nm between 1000nm and 1200nm, however, its good transmission and reflectance with an average efficiency exceeding 95% makes him a good candidate for a first evaluation.

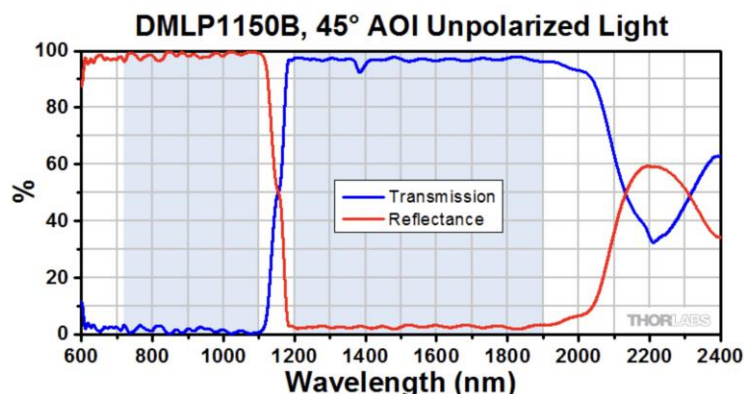


FIGURE 17: COMMERCIALY AVAILABLE DICHOIC BEAM SPLITTER (DMLP1150B) CHARACTERISTICS FROM THORLABS SHOWING PERFORMANCES MATCHING THE SIMULATED REQUIREMENTS BUT WITH A GAP AROUND 1150NM[31]

The splitting of light between the Thermal channel and the VIS-NIR channels is extremely complicated to achieve due to the large gap in the spectrum between those two regions. Most of the regular and efficient materials are not able to perform in such a wide range as depicted in Figure 15. N-BK7, a regular glass used for optical components is showing a strong absorption within the thermal wavelength regions. Alternatively, specific materials such as Sodium Chloride or Potassium Bromide must be used to span the whole range, requiring custom-made coatings. To keep the design convenient and possible to work with commercially available components, a geometrical splitting approach is used. It consists of splitting directly the beam into different parts using the reflective diffractive grating, where one-third of the light is separated from the main beam and corresponds to the thermal channel (Figure 18).

Incident light

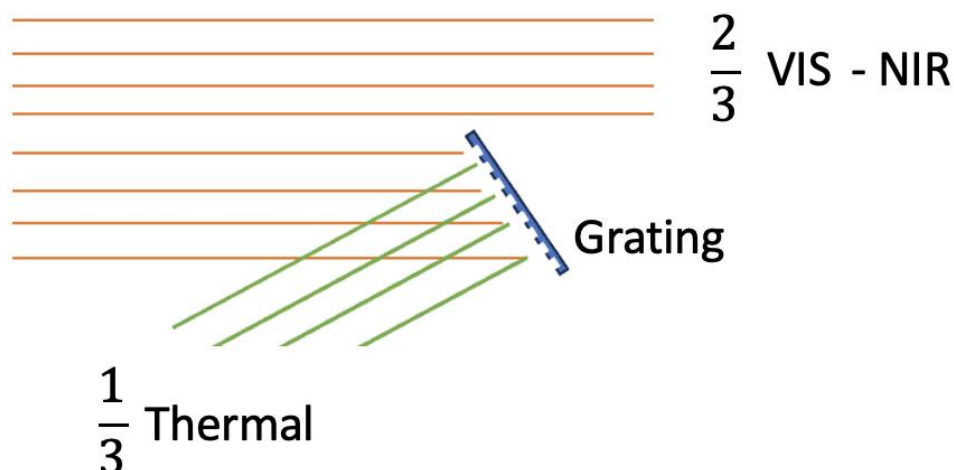


FIGURE 18: "GEOMETRICAL" BEAM SPLITTING METHOD TO SEPARATE THE VIS-NIR AND THE THERMAL CHANNEL. TWO-THIRD OF THE LIGHT GOES TO THE VIS-NIR CHANNELS AND ONE-THIRD TO THE THERMAL CHANNEL.

The geometrical splitting has the advantage of not affecting the channel spectrum; while in contrast an additional dichroic beam splitter would have affected the efficiency of the different channels. However, the geometrical splitting acts as an aperture and comes with a trade-off in the irradiance of each channel. Considering the Earth irradiance (section 1.1) as approximately 100 W/m² for the VIS-NIR range and 240 W/m² for the Thermal range. The ratio of the splitting provides new values for the three channels with approximately 66 W/m² for the VIS-NIR channels and 80 W/m² for the Thermal channel.

The geometrical splitting thus induces a more balanced irradiance along the whole spectrum. The full energy budget at each pixel of the detector is discussed in the energy budget table in Section 4.2.

2.4 DIFFRACTION GRATINGS FOR HIGH SPECTRAL RESOLUTION

This part aims to introduce the mathematical concepts and equations necessary to understand and demonstrate the grating equation and to study the corresponding resolution of the spectrometer. First, the transmission of a surface grating will be studied, leading to the grating equation. Then, a more complex system will be analyzed: the grating with N slits. Finally, the spectral resolution will be discussed based on the Rayleigh criterion and the Free Spectral Range (FSR). Some FSR calculations are applied to the wavelength range in this work. The mathematical derivations are taken from the course notes on Microphotonics.[32]

The transmission function of the light passing between the environment n_1 and n_2 is given by:

$$\psi(x, 0^+) = t(x) \psi(x, 0^-) \quad (1)$$

Where:

- $\psi(x, 0^-)$ is the incident field
- $\psi(x, 0^+)$ is the Transmitted field
- $t(x)$ is the transmission function and describes the local change in amplitude and phase of the field

For a periodic surface structure, the transmission function is the sum of the transmission at each period individually:

$$t(x) = \sum_{n=1}^N t_1(x - x_n) \quad (2)$$

Where:

- $x_n = (n - 1)\Lambda$ is the value of the x coordinate the n^{th} period
- Λ is the period of the grating
- N is the number of periods
- $t_1(x)$ is the transmission function for the interval lying between $x \in [0, \Lambda]$

To consider the value of the transmitted field, one must consider the plane wave decomposition of the incident field passing through the gratings. Intuitively, this phenomenon results from the desired effect of a grating: spatially split the light relatively to the wavelength/frequency.

The notion of frequency or spatial frequency becomes present through the Fourier transform applied to equation (1).

$$F_x\{\psi(x, 0^+)\} = F_x\{t(x)\} * F_x\{\psi(x, 0^-)\} \quad (4)$$

This transform reveals the transfer function $T(f_x)$ of the grating. It is the Fourier transform of the transmission function in equation (2).

$$T(f_x) = F_x\{t(x)\} = F_x\left\{\sum_{n=1}^N t_1(x - x_n)\right\} \quad (4)$$

With the Fourier transform given by:

$$T(f_x) = \int_{-\infty}^{+\infty} e^{-j2\pi f_x x} dx \quad (5)$$

The transfer function is developed as follows:

$$T(f_x) = \int_{-\infty}^{+\infty} \left(\sum_{n=1}^N t_1(x - x_n) \right) e^{-j2\pi f_x x} dx \quad (6)$$

By substituting the integral to fit $dx \rightarrow d(x - x_n)$, it is possible to put the sum outside the integral:

$$T(f_x) = \sum_{n=1}^N e^{-j2\pi f_x x} \int_{-\infty}^{+\infty} t_1(x - x_n) e^{-j2\pi f_x (x - x_n)} d(x - x_n) \quad (7)$$

It gives the transfer function of a local grating period on one side multiplied by the sum of an exponential this is the same sum but with a change of parameter:

$$T(f_x) = T_1(f_x) \cdot \sum_{m=0}^{N-1} e^{jm\delta} \quad (8)$$

With $\delta = -2\pi f_x \Lambda$ and $x_n = m\Lambda$ with $m \in [0, N - 1]$ whereas $x_n \in [1, N]$.
The expansion of the sum term gives:

$$T(f_x) = T_1(f_x) \cdot e^{\frac{j(N-1)\delta}{2}} \frac{\sin \frac{N\delta}{2}}{\sin \frac{\delta}{2}} \quad (9)$$

The $T_1(f_x)$ term corresponds to the effect of the transmission for one grating while the rest of the equation corresponds to the effect of a periodic extension on this effect.

With the dependencies in f_x

$$f_x = \frac{\sin \theta}{\lambda} \Leftrightarrow \sin \theta = f_x \lambda \quad (10)$$

and in δ

$$\delta = -2\pi f_x \Lambda \quad (11)$$

The sinusoidal function in equation (10), if under an incident plan wave in the normal axis ($\theta_{in} = 0$), results in the following values for the different diffraction orders:

- Order zero:

$$\sin \left(\frac{\delta}{2} \right) = 0 \text{ and } \frac{\delta}{2} = 0 \Rightarrow f_x \Lambda = 0 \Rightarrow \sin \theta = 0 \quad (12)$$

- Order -1 or +1:

$$\sin\left(\frac{\delta}{2}\right) = 0 \text{ and } \frac{\delta}{2} = \pm\pi \Rightarrow f_x\Lambda = \pm 1 \Rightarrow \sin\theta = \pm \frac{\lambda}{\Lambda} \quad (13)$$

- Order -2 or +2:

$$\sin\left(\frac{\delta}{2}\right) = 0 \text{ and } \frac{\delta}{2} = \pm 2\pi \Rightarrow f_x\Lambda = \pm 2 \Rightarrow \sin\theta = \pm \frac{2\lambda}{\Lambda} \quad (14)$$

Results in a generalization for the m^{th} order of diffraction as

$$\sin\theta_m = \pm \frac{m\lambda}{\Lambda} \quad (15)$$

Extended to a more general equation named the grating equation in case of oblique incidence:

$$\sin\theta_m - \sin\theta_i = \pm \frac{m\lambda}{\Lambda} \quad (16)$$

The grating equation can be directly derived by using the Bragg condition

$$k'_m = K_m + k_{in} \quad (17)$$

And the k-vector diagram as depicted in Figure 19.

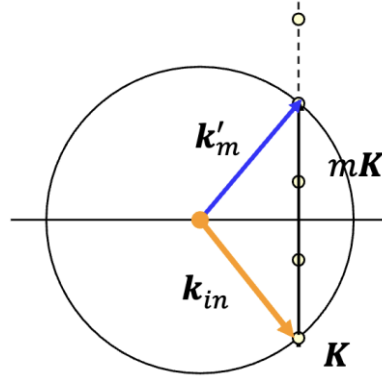


FIGURE 19: K-VECTOR DIAGRAM[33]

With $k'_m = \frac{2\pi}{\lambda_0} n_0 \sin\theta_m$, $k_{in} = \frac{2\pi}{\lambda_0} n_0 \sin\theta_{in}$ and $K_m = \frac{2\pi}{\Lambda}$ the Bragg condition

$$k'_m - k_{in} = mK_m \quad (18)$$

Gives

$$\frac{2\pi}{\lambda_0} n_0 \sin\theta_m - \frac{2\pi}{\lambda_0} n_0 \sin\theta_{in} = m \frac{2\pi}{\Lambda} \quad (19)$$

And finally, the grating equation is

$$\Rightarrow \sin\theta_m - \sin\theta_i = \frac{m\lambda}{n_0\Lambda} \quad (20)$$

Note that in air, $n_0 = 1$ and in the case of a transmissive grating between environments of different refractive index, n_0 becomes Δn .

Based on the above theoretical concepts, the grating parameters are selected. For each of the 3 channels, similar incident and diffraction angles at the 1st order are chosen, reducing the optimization time for the free-form mirrors. The approach is to balance the ratio of the central wavelength and the grating's periodicity in the grating's equation (equation 20) such that the three gratings have the same incident and diffracted angles (Figure 20). The 1st order is privileged because the grating's priority is to provide light with a sufficient intensity at the detectors (already limited by the geometrical splitting) and not to provide an extremely high spectral resolution (required at minimum 20nm). The specific incident and diffraction angles are chosen by considering the system's geometry. A smaller angle means a more compact design; however, with three channels, we must carefully choose a minimal angle such that the channels do not overlap. Since the NIR and Thermal channels have both a reflective grating and are on the same axis, the same angles are chosen such that the channels can be nested with 10° for the incident angle and 20° diffraction angle. The VIS channel is initially reflected by the dichroic beam splitter, resulting in it being oriented orthogonally to the paths of the NIR and Thermal channels (which continue on the original axis). To avoid a channel overlap between the VIS and the NIR channels and to maximize the design's compactness, the VIS channel has a transmissive grating with an incident angle of 2° and a diffracted angle of 10°.

With those input parameters, the periodicities of the gratings calculated from the grating equation are equal to 230[l/mm] for the VIS channel, 120[l/mm] for the NIR channel, and 15[l/mm] for the Thermal channel (Figure 20).

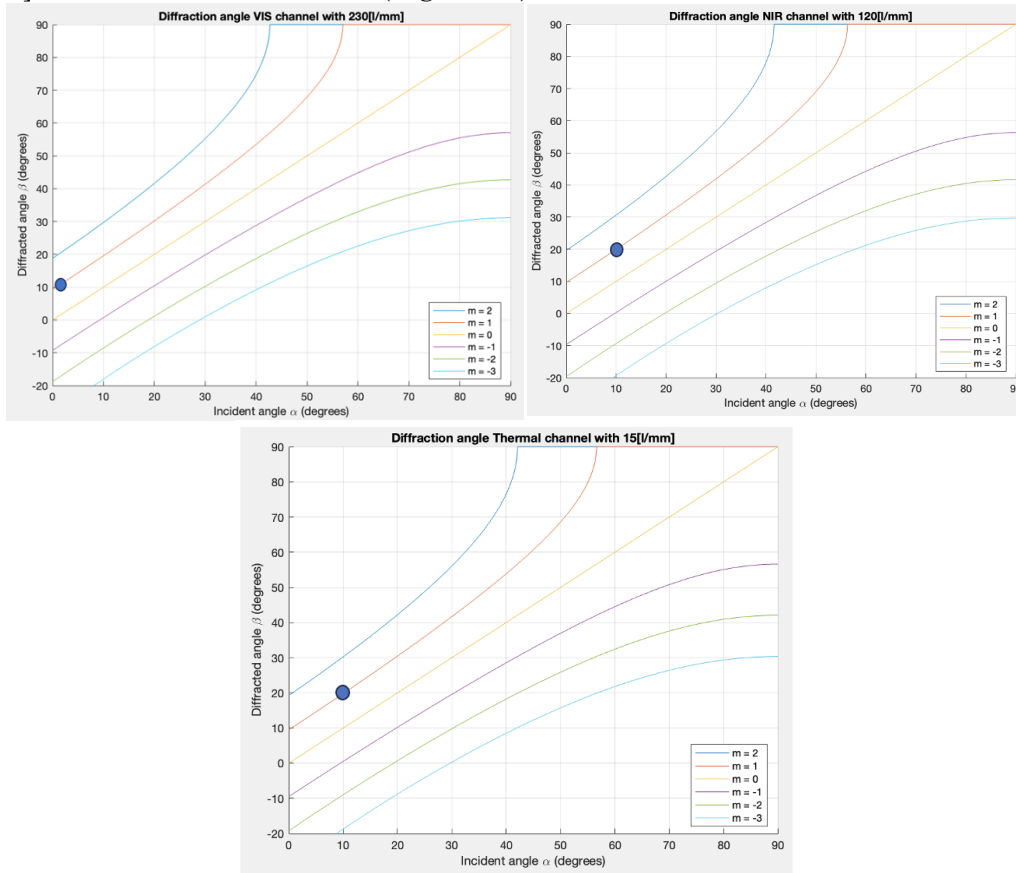


FIGURE 20: GRATING'S EQUATION GRAPH FOR THE VIS CHANNEL WITH 230[L/MM] (TOP-LEFT), THE NIR CHANNEL WITH 120[L/MM] (TOP-RIGHT), AND THE THERMAL CHANNEL WITH 15[L/MM] (BOTTOM), WITH A DOT AT THEIR OPERATING POINT

A mathematical analysis of the Free Spectral Range (FSR) for the three channels shows no overlap between modes for the NIR and the Thermal spectrums (Figure 21) but an overlap is present in the VIS spectrum in Figure 22.

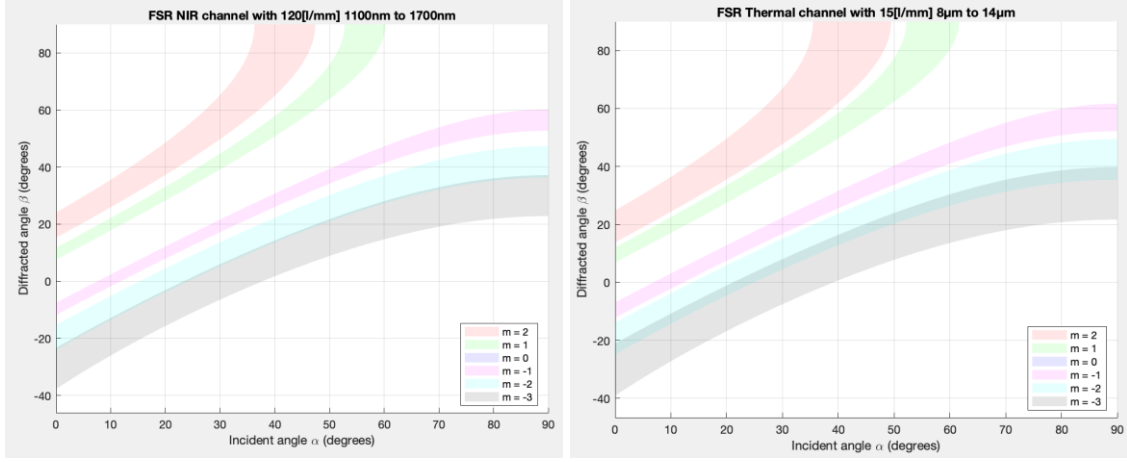


FIGURE 21: FSR FOR NIR CHANNEL (LEFT) AND THERMAL CHANNEL (RIGHT) SHOWING NO OVERLAP BETWEEN THE MODES

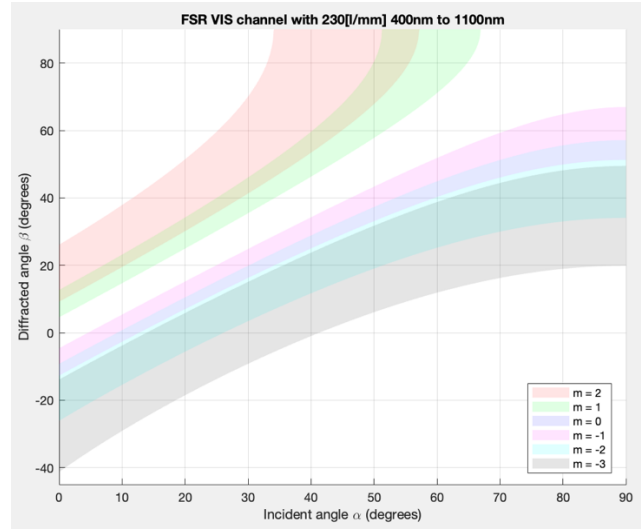


FIGURE 22: FSR FOR THE VIS CHANNEL SHOWING OVERLAPS BETWEEN THE MODES

Through the mathematical development of the grating equation, one can prove that the only parameter to avoid any overlapping is the wavelength and that it is technically impossible to avoid an overlap if one wants to measure a spectral range from 400nm to 1700nm (it requires at least three channels). By assuming that the spectrum lies between two wavelengths λ_1 and λ_2 with $\lambda_1 < \lambda_2$ and that the focus is on the overlap between the first and the second mode, one can zoom in on the overlap in Figure 22 and name for the same incident angle θ_{in} two diffracted angles θ_1, λ_2 and θ_2, λ_1 corresponding respectively to the angle of the first mode on the upper wavelength and the angle of the second mode at the lower wavelength as in Figure 23.

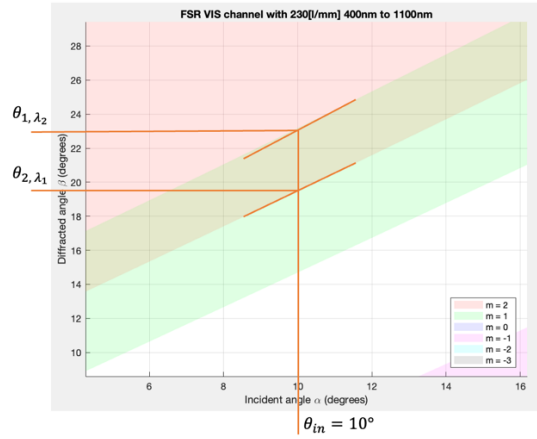


FIGURE 23: ZOOM ON THE FSR OF THE VIS RANGE FROM FIGURE 22 WITH ANNOTATIONS SHOWING THE OVERLAP'S DIFFERENCE BETWEEN THE FIRST AND THE SECOND MODES

If:

- $\theta_{2, \lambda_1} - \theta_{1, \lambda_2} < 0 \Rightarrow \text{Overlap}$
- $\theta_{2, \lambda_1} - \theta_{1, \lambda_2} = 0 \Rightarrow \text{Perfect match}$
- $\theta_{2, \lambda_1} - \theta_{1, \lambda_2} > 0 \Rightarrow \text{No overlap}$

According to the grating equation:

$$\begin{cases} \sin(\theta_{2, \lambda_1}) = \frac{2\lambda_1}{\Lambda} - \sin\theta_{in} \\ \sin(\theta_{1, \lambda_2}) = \frac{\lambda_2}{\Lambda} - \sin\theta_{in} \end{cases} \quad (21)$$

And by subtracting those two equations:

$$\sin(\theta_{2, \lambda_1}) - \sin(\theta_{1, \lambda_2}) = \frac{1}{\Lambda}(2\lambda_1 - \lambda_2) \quad (22)$$

To have no overlapping FSR, one must satisfy the condition $\lambda_2 \leq 2\lambda_1$ and the periodicity term Λ acts solely as a scaling factor and does not influence the overlapping. For a wavelength range from $\lambda_1 = 400\text{nm}$ to $\lambda_2 = 1700\text{nm}$, it is impossible to satisfy the overlap condition with one channel or two channels. With two channels, the only possibilities of arrangement are as follows:

TABLE 3: SPECTRUM ARRANGEMENTS FOR A TWO-CHANNELED SYSTEM WITH A SPECTRUM BETWEEN 400NM TO 1700NM WITHOUT OVERLAPPING IN THE FSR

First channel		Second channel		
λ_1 [nm]	λ_2 [nm]	λ_1 [nm]	λ_2 [nm]	$\Delta\lambda_{loss}$ [nm]
400	800	800	1600	100
400	800	850	1700	50
425	850	850	1700	25

The solution proposed in the third line of Table 3 is the best option with the lowest difference in wavelength $\Delta\lambda_{loss} = 25nm$ according to the initial spectrum from 400nm to 1700nm. The spectrums of the VIS and NIR channels must then be rearranged as follows:

- VIS: [400nm to 1100nm] becomes [425nm to 850nm]
- NIR: [1100nm to 1700nm] becomes [850nm to 1700nm]

A graph of the FSR according to these new ranges for the VIS and NIR ranges is shown in Figure 24. The matching condition between the first and the second order is perfectly depicted in this figure and confirms the development of the condition $\lambda_2 \leq 2\lambda_1$ defined above.

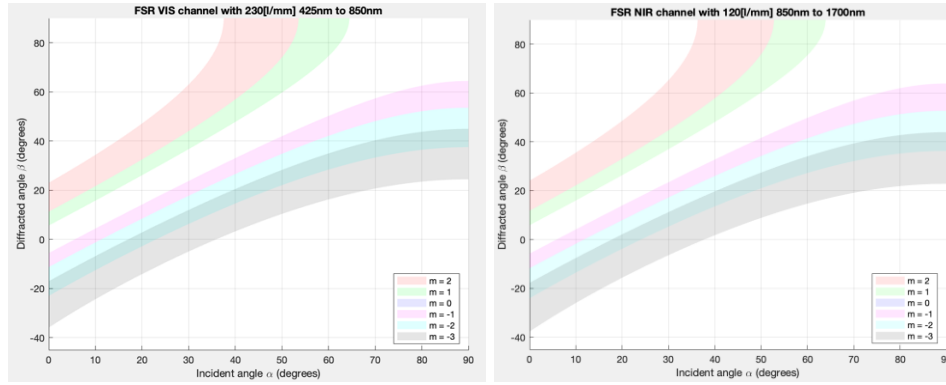


FIGURE 24: ADAPTED FSR FOR VIS AND NIR CHANNELS TO AVOID A SPECTRAL OVERLAP BY MATCHING THE EQUATION 22

The hypothetical solution proposed for which the channel's spectrum is changed is not in accordance with the initial requirements but is interesting to explore for future research. In addition, commercially available gratings with a wide diffractive spectrum can be found, i.e. the Transmissive VIS grating GT13-03 from Thorlabs[34] has an adequate spectrum as shown in Figure 25 and has a number of 300 grooves/mm which is relatively close to the 230 grooves/mm simulated and an efficiency of 50% for the first order along the VIS channel's spectrum. Note that this grating and most commercially available gratings are blazed. This characteristic has an incidence on the order strength, i.e. blazed gratings will contribute to a maximum efficiency along one order and minimize the power along other orders. The disadvantage is that the blazed shape suffers from periodic defects causing ghosting and scattered light. This can be remediated with holographic gratings but with a reduced efficiency. Whatever the shape of the grating, it has no influence on the grating equation, and calculations made above are valid for any gratings while it respects the number of grooves/mm.[35]

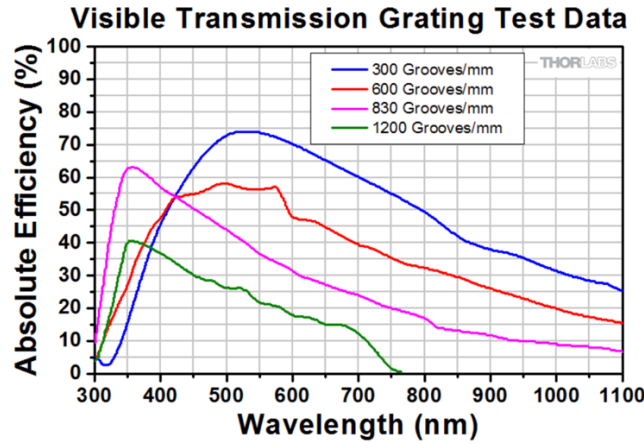


FIGURE 25: THORLABS TRANSMISSIVE GRATINGS FOR SEVERAL GROOVES/MM (GT13-03 PERFORMANCES GIVEN AT THE BLUE CURVE)[36]

After contacting Thorlabs, they confirmed that the graph provided in the datasheet and shown in Figure 25 only contains the first order and that no filters are added to avoid an overlap in the FSR. To avoid the presence of higher orders, an additional filter can be implemented, such as one from Delta Optical Thin Films.[37] The LF104200[38] is added after the focusing mirrors, close to the detector array, and filters the modes higher than one with an efficiency of 90%. Specifications from the LF104200's datasheet are given in Figure 26.

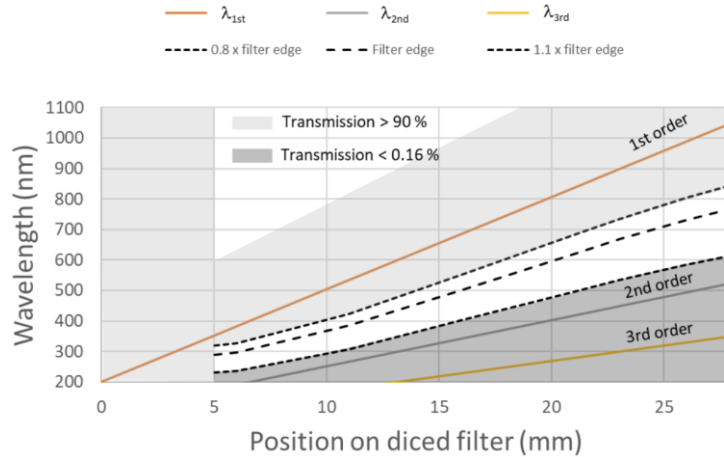


FIGURE 26: EXAMPLE IN THE DATASHEET OF A 200-1050NM SPECTROMETER ON A 28MM DETECTOR WITH A LF104200 FILTER[38]

The position of the detector relative to the incident ray with a specific wavelength is important for filtering. Indeed, when looking back at the grating studied in Figure 22, by considering that at the detector the lowest wavelength of the first order is at the bottom of the pixel's array and that the highest wavelength is at the top, the overlap will occur at the top of the detector array between the high wavelengths of the first order and the low wavelengths of the second order. The filtering technique proposed by Delta Optical Thin Films is to put at the top of the detector a high-pass filter. Therefore, at the overlapping region, only the high wavelengths from the first order will pass the filter and be incident on the detector.

2.5 FREEFORM OPTICS OPTIMIZATION USING XY POLYNOMIALS

Freeform optics are used in the system to focus the light in the image plane while minimizing the system's volume and aberrations. Two freeform mirrors are placed within each spectral channel. Freeform optics are modeled using polynomial descriptions. The

choice of polynomials depends on the surface's shape. For a circular aperture, Zernike polynomials are preferred due to their model in polar coordinates. On the other hand, in the case of a rectangular aperture, Chebyshev or XY polynomials are often preferred. We consider XY polynomials within this thesis work, enabling separate optimization of the X and Y curvatures.

2.5.1 XY POLYNOMIALS

XY polynomials are defined according to the following equation:

$$z = \frac{cr^2}{1 + \sqrt{1 - (1 + k)c^2r^2}} + \sum_{n=1}^N A_n E_n(x, y) \quad (23)$$

Where z describes the surface sag of the component. The first term of the equation corresponds to the shape of a standard conic asphere (e.g. Parabolic, Elliptical,.. Surface) while the second term corresponds to a series of high order polynomials increasing to the N^{th} term.

The first nine polynomials are $X, Y, X^2, XY, Y^2, X^3, X^2Y, XY^2, Y^3$ and the X terms are illustrated in Figure 27.

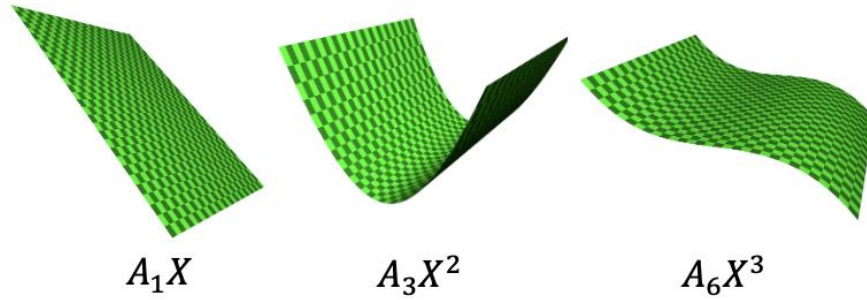
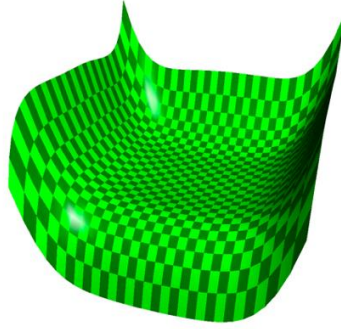


FIGURE 27: X TERMS FOR THE FIRST, SECOND, AND THIRD ORDER FOR A = 1

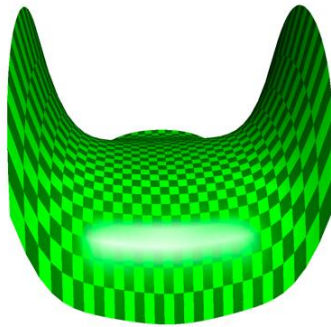
The A_n coefficient indicates the function's speed of variation (a kind of slope term) and the rule of thumb for manufacturing is that the absolute value of the order of this term must be higher than the order of the polynomial.

The configuration of the custom mirrors is optimized by adjusting first the radius of the conic's curvature, and then the XY polynomials across the FOV for each wavelength.[26] Specifically, the optimization focuses on the following parameters: X^2Y^0 , X^0Y^2 , X^0Y^3 , X^4Y^0 , X^2Y^2 , X^0Y^4 , X^2Y^3 , X^0Y^5 , X^6Y^0 , and X^4Y^2 . Given the orthogonal symmetry along the optical axis, we prioritize even orders in X^0 , X^2 , X^4 , and X^6 , omitting odd orders like X^1 , X^3 , and X^5 . The parameters for the first and the second freeform mirrors used in the NIR channel are given in Figure 28 and Figure 29. The optimization strategy for the three channels was to locally optimize parameters by parameters (meaning the distance between mirrors, their tilts, their centering, and each term of the polynomial separately) and look at the spot diagram and the Modulation Transfer Function (MTF) to distinguish which parameters have the best/worst effects.



$$z = 2,123e^{-3x^2} + 1,456e^{-3y^2} - 4,383e^{-5y^3} - 1,910e^{-8x^4} + 3,208e^{-7x^2y^2} - 7,749e^{-8y^4} \\ - 2,917e^{-9x^2y^3} + 2,115e^{-8y^5} + 2,191e^{-10x^6} + 2,144e^{-9x^4y^2}$$

FIGURE 28: FIRST MIRROR FREEFORM SURFACE XY POLYNOMIAL



$$z = 4,667e^{-3x^2} - 5,339e^{-3y^2} - 3,137e^{-5y^3} - 4,107e^{-6x^4} - 1,170e^{-6x^2y^2} - 4,297e^{-6y^4} \\ - 1,666e^{-7x^2y^3} + 1,574e^{-7y^5} + 1,192e^{-8x^6} - 6,140e^{-9x^4y^2}$$

FIGURE 29: SECOND MIRROR FREEFORM SURFACE XY POLYNOMIAL

The shape of the surfaces in the two previous figures is willingly zoomed out to increase the perception of the freeform optics. The final freeform mirror is a projected rectangle cut at the center of the figures above and the saddle shape is then less visible.

2.5.2 MATERIALS AND MANUFACTURING

The freeform mirrors in the telescope presented in Figure 9 have been manufactured with oxygen-free high thermal conductivity (OFHC) copper, which is a material used for broadband IR reflection. The manufacturing is done in three steps, starting from a polishing step to give the material a general shape to the surface, then (2) the 2 mirror surfaces are added together to make a monolithic system, and finally (3) ultraprecision diamond tooling machine is used to manufacture the final freeform shapes of the monolithic system.[26]

The material used in the previous description is not usable within the scope of this thesis since copper does not cover a sufficiently wide wavelength region. The best materials for such broadband applications are found within the metal family. A comparative graph considering the main reflective metallic surface is given in Figure 30.

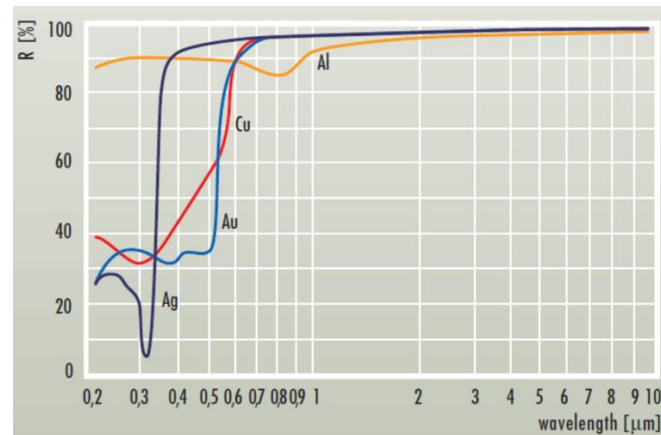


FIGURE 30: COMPARATIVE REFLECTANCE AS A FUNCTION OF THE WAVELENGTH OF SEVERAL METALLIC COATINGS SHOWING THAT ONLY ALUMINUM AND SILVER ARE MATCHING WITH THE SPECTRAL RANGE ANALYZED BY OUR SPECTROMETER (0,4-14 μ m) [39]

In Figure 30, one clearly sees that copper is extremely performing well within the IR range but lacks the visible spectrum. The two materials working within the whole spectrum analyzed in this thesis are aluminum and silver. Silver coatings are extremely sensitive to their external environments, especially to humidity from which silver can tarnish, but is showing slightly better performances. According to Thorlabs, their protected silver coatings (Figure 31) are achieving a reflection of 97% for the spectrum between 450nm to 2 μ m and 95% for the range between 2 μ m to 20 μ m. Those results are really good except that the reflectance decreases from 98.7% at 450nm to 90.7% at 400nm. Despite this reflectance's loss at 400nm, the efficiency remains extremely good, and the average efficiency of the coating for the VIS, NIR and Thermal channels is respectively of 95%, 97%, and 96%. [40]

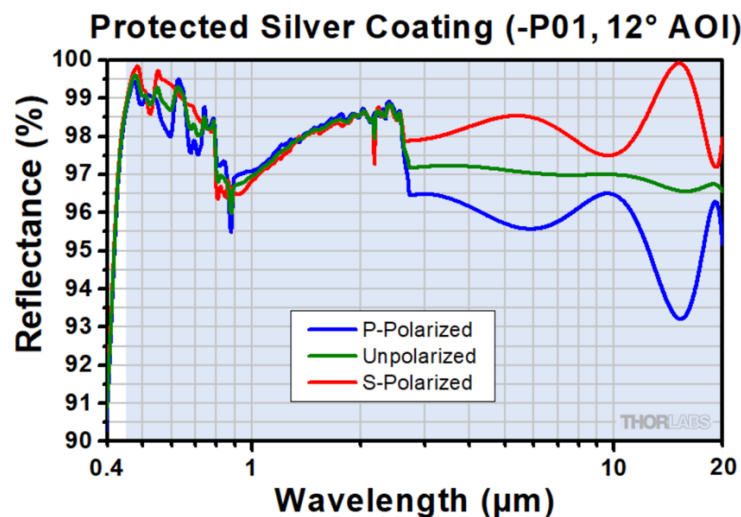


FIGURE 31: PROTECTED SILVER COATING FOR A 12° INCIDENT ANGLE SHOWING FOR THE UNPOLARIZED LIGHT (GREEN) A REFLECTANCE OF APPROXIMATELY 97% ALONG THE WHOLE SPECTRUM CONSIDERED BY OUR SPECTROMETER (0,4 μ m - 14 μ m)[40]

An alternative to Silver is Aluminum; it offers a less expensive material but with lower performance. From Thorlabs, the average efficiency is higher than 90% for the VIS-NIR channels and higher than 95% for the Thermal channel. However, the efficiency curve (Figure 32) undergoes a massive decrease in efficiency from 500nm to 1050nm with a minimal efficiency of 77% at 800nm giving an average efficiency of 86% for the VIS range. It corresponds to an approximative drop in efficiency of 10% in comparison to the silver

coated mirror but is certainly acceptable for prototyping.[41] The telescope of TROPOMI has been manufactured in aluminum by diamond tooling. [20]

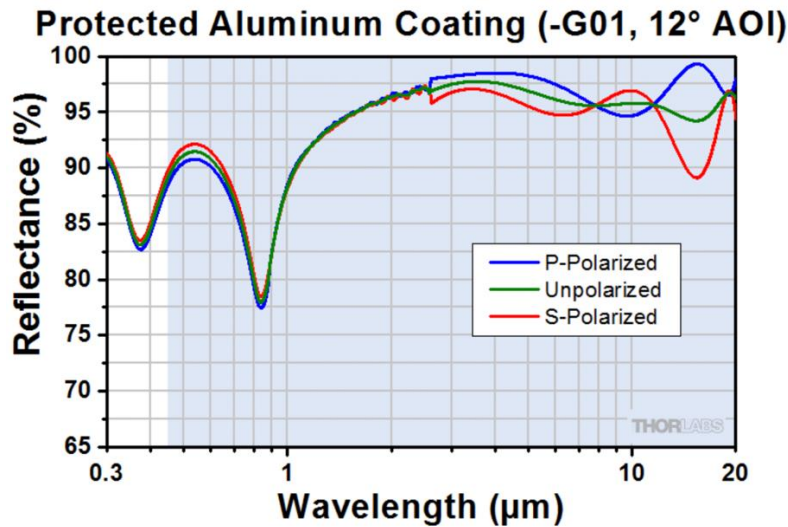


FIGURE 32: PROTECTED SILVER COATING FOR A 12° INCIDENT ANGLE SHOWING FOR THE UNPOLARIZED LIGHT (GREEN) A REFLECTANCE OF APPROXIMATELY 94,5% ALONG THE WHOLE SPECTRUM CONSIDERED BY OUR SPECTROMETER ($0,4\mu\text{m}$ - $14\mu\text{m}$) BUT WITH A DECREASE PERFORMANCE IN THE VIS RANGE.[41]

The energy budget presented in section 4.2 considers silver coated mirrors because this material, even if expensive, is commercially available and shows the best performances. Nevertheless, aluminum could also be used in our system but would come with a decrease in efficiency, especially in the VIS range.

2.6 SUMMARY AND CONCLUSION

This chapter discusses the physical concepts and components necessary to build a freeform multi-channel spectrometer. We first compared several spectrometer architectures and decided to choose the unfolded Czerny-Turner to develop our three channel spectrometer. From this structure, we proposed a novel design (Figure 14) able to separate our three channels, diffract the light via gratings and focus the light at the image plane via freeform mirrors. The thermal channel is achieved using “geometrical splitting” directly splitting one-third of the light beam to the Thermal channel and two-third to the VIS-NIR channels, while a dichroic beam splitter is used for the VIS-NIR channels. The grating’s physics has been reviewed and calculations have been made to carefully choose the good gratings periodicity for each channels: $230[\text{l/mm}]$ for the VIS channel, $120[\text{l/mm}]$ for the NIR channel, and $15[\text{l/mm}]$ for the Thermal channel. The Free Spectral Range of the VIS channel was overlapping between the first and second modes and the addition of a filter at the detector’s plane was proposed. Ultimately, the freeform mirrors and the mathematics behind the XY polynomials has been presented. The latter also includes a discussion about the best material suited for manufacturing, indicating aluminum and silver as the material of choice.

Chapter 3: NOVEL FREEFORM SPECTROMETER DESIGN

This chapter focuses on the design and evaluation of the novel miniature spectrometer, starting from single channel designs for the VIS, NIR and thermal wavelength range, towards the integrated 3-channel system. All designs were simulated using Ansys Zemax OpticsStudio, and are designed in the sequential mode for a source located at an infinite distance, covering fields from 0° to 60° (due to the system's symmetry, the full field of view of 120° is covered). Each of the spectrometer channels comprises of 2 freeform mirrors, described using XY polynomials. The following key parameters were considered to specify and evaluate the design.

- **RMS spot radius [μm] for the different fields**

The spot diagram is provided for each field, visualizing the RMS spot radius, a key metric for assessing image quality. This radius is determined by calculating the square root of the sum of the squared distances of each point from the centroid (the center of gravity of all rays). A smaller RMS spot radius indicates better resolution. When the system is not diffraction-limited, four RMS spot radii are recorded: the RMS spot at nadir, the best and worst RMS spots, and the average RMS spot value across all fields. These data will determine the resolution in the spatial and spectral axes at the detector for the nadir, best, worst, and average cases.[42]

- **Aperture specifications and f-number**

The aperture diameter provides insights into the amount of light collected by the system and impacts its resolution limit. For systems with a distant object (infinite distance), the aperture specification is typically given by the f-number (f/#), defined as the ratio between the focal length of the system and its entrance pupil diameter.

- **Resolution and Airy disc**

With the f-number, it is possible from the Rayleigh criterion to derive the Airy radius as [42]:

$$r_a = 1,22\lambda \left(\frac{f}{\#} \right) \quad (24)$$

The Airy radius represents the best achievable resolution, where the resolution is defined as the shortest distance between two points where they can still be distinguished from each other. A system is considered diffraction-limited if it is focused entirely within the Airy disk.[42]

- **Footprint diagram**

The footprint diagram simulates the field positions on the detector surface, and is given for the HFOV and the whole spectrum of the designated channel. The colors (X-axis) correspond to the various field angles, and the rows (Y-axis) to the wavelengths. This diagram gives information about the size that the detector requires to collect light of the whole FOV and spectral range, while also indicating the magnitude of the smile effect. The smile effect is a key aberration occurring in pushbroom spectral imaging systems, inducing that the fields are not imaged on a flat line but on a curved one (looking like a smile). Correction of this aberration can be managed via post-processing but impact the detector size upon which the resolution is calculated. Smile effect tends to increase the detector size along the spectral axis and decrease the size along the spatial axis. The effect on the spatial resolution is minor, and therefore ignored during calculations, however, its influence on the spectral resolution must be considered when calculating the spectral resolution. Note that the footprint diagram of the final three-channel design is given in the next chapter where it is used to define the detectors requirements.

- **Point Spread Function (PSF)**

The Point Spread Function visualizes the intensity distribution on the image plane for an array or a grid of spots at nadir. The objective of this diagram is first to check if the

resolution calculated via the RMS spot radius allows spots to be resolved on the detector's plane, and secondly to calculate the maximum resolution at which two points can be resolved. This latter value provides the best approximation of the spatial resolution, accounting for the smile effect.

- **Modulation Transfer Function (MTF)**

The MTF quantifies a system's ability to resolve spatial frequencies in the image relative to the object. In a typical MTF graph, such as Figure 33, the function is plotted for various spatial frequencies (in cycles/mm) along the sagittal and tangential plane. At low spatial frequencies, the MTF is close to one, indicating that the object and the image are equally resolved. At high spatial frequencies, the MTF approaches zero, showing a loss of detail resolution. Ultimately, the MTF drops to zero at the optical cut-off frequency. It is influenced by the Airy disc and is defined by $f_{\text{cutoff}} = 1/\lambda(f/\#)$, indicating that the system cannot image details beyond this point.

By considering the RMS spot radius as half the pixel pitch, it is possible to determine the Nyquist limit—the maximum spatial frequency at which features can be sampled. This limit is calculated as the reciprocal of twice the pixel pitch. From this, the corresponding MTF value can also be determined.[42]

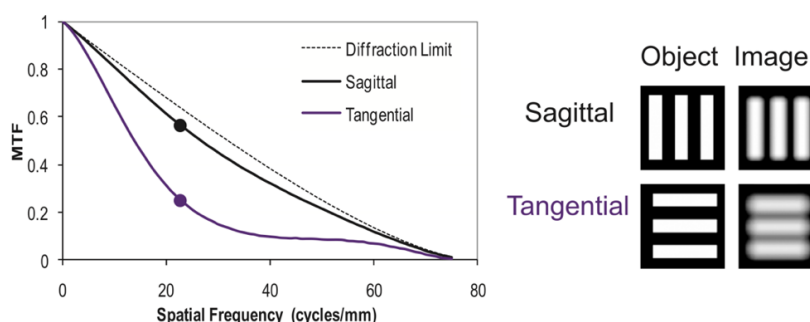


FIGURE 33: MTF TYPICAL GRAPH[42]

- **Seidel diagram and aberrations**

The Seidel diagram provides surface-by-surface information about aberrations present in the optical system. The Seidel diagram includes third-order aberrations, namely: Spherical aberration, Coma, Astigmatism, Field curvature, and Distortion. For each of those aberrations, compensators can be included to reduce the effect (this is the reason why there are always two freeform mirrors in each design).[42] Note that since our system is fully reflective, no chromatic aberrations are present.[26]

Spherical aberration (Figure 34) is caused by a difference of focus between rays passing at the center of the lens (with small angles included) and the rays passing at the edges of the lens. It causes a blur effect at the image plane. In comparison with the other types of aberrations, the spherical is the only one appearing at an angle of incidence of 0° . It has the same magnitude for every angle of incidence.

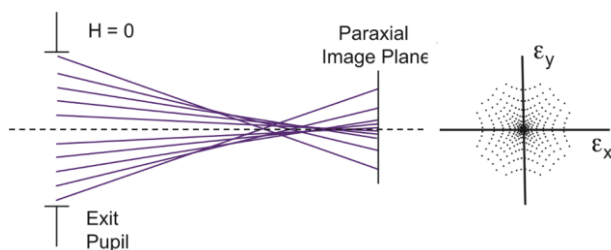


FIGURE 34: SPHERICAL ABERRATION[42]

Coma (Figure 35) is an off-axis aberration causing a comet-like shape of the spot at the image plane. This aberration is due to imperfections in the lens magnification, or in the case of this thesis, different magnifications along the freeform surface of the mirrors. Because of this high sensibility, Coma is the first aberration to appear in tolerancing analysis. In addition, Coma increases linearly with the field angle.

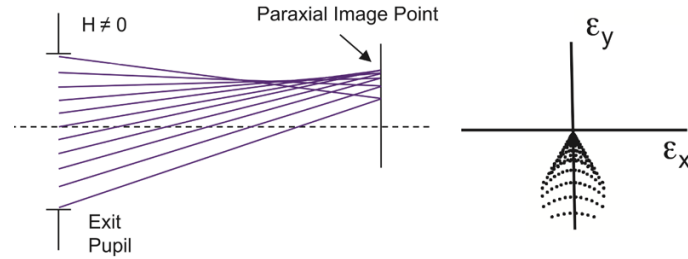


FIGURE 35: COMA[42]

Field curvature (Figure 36) describes the aberration causing the image to focus from a flat surface to a curved surface. The spot can be perfectly focused at the curved focal surface but will be out of focus at the flat image plane. This off-axis aberration's magnitude increases with the field angle. [42]

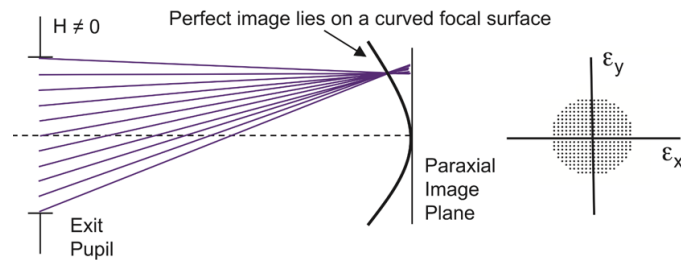


FIGURE 36: FIELD CURVATURE[42]

Astigmatism (Figure 37) looks fundamentally like field curvature, but in addition, sagittal and tangential rays are focused at different points in the image plane. This phenomenon gives an oval shape to the spot and increases with the field's angle. [42]

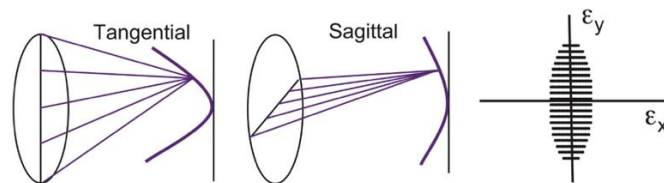


FIGURE 37: ASTIGMATISM[42]

Barrel distortion (Figure 38) causes a variation of magnification along the image plane. At the edges of the image plane, lines will tend to bend and straight lines become curved. This effect does not influence in terms of focusing (it doesn't make the image blurry) and can be corrected through post-processing. Therefore, this aberration is only minimally considered in the optimization. [42]

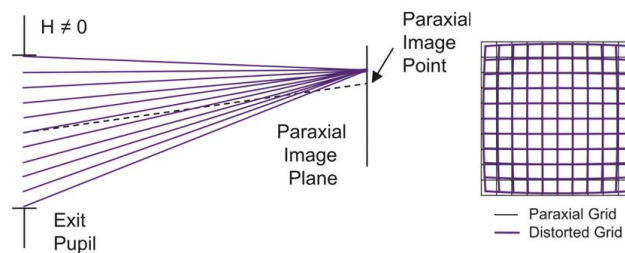


FIGURE 38: BARREL DISTORTION[42]

The optimization of the design targeted minimizing the present optical aberrations. A merit function was first defined, considering the RMS spot radius or MTF. Following the optimization was performed targeting minimization of the merit function. The mirror surface parameters and freeform terms were set as variables during the optimization. Since adapting the freeform mirrors for each of the channels would complicate the design in terms of optimization, the same freeform mirrors at each channel were used. The XY polynomials for the first and the second freeform mirrors is given in **Error! Not a valid bookmark self-reference..**

TABLE 4: 6TH ORDER XY POLYNOMIAL VALUES FOR THE TWO FREEFORM MIRRORS

	Radius [mm]	X2Y0	X0Y2	X0Y3	X4Y0	X2Y2	X0Y4	X2Y3	X0Y5	X6Y0	X4Y2
First	0,83	2,123E-03	1,456E-03	-4,383E-05	-1,910E-08	3,208E-07	-7,749E-08	-2,917E-09	2,115E-08	2,191E-10	2,174E-09
Second	0,83	4,667E-03	-5,339E-03	-3,137E-05	-4,107E-06	-1,170E-06	-4,297E-06	-1,666E-07	-1,574E-07	1,192E-08	-6,140E-09

Once the freeform optics were integrated to the configuration, the merit function focused on the geometry of the design. Optimization of the merit function was performed considering the distances and angles between surfaces as variables. Dedicated operands were added to limit aberrations, focal lengths and to correctly position the spots on the image plane. This latter was particularly required in view of minimizing the smile distortion. Additionally, the tilt angles were kept minimal to improve compactness and to minimize aberrations. Additional operands were included to limit the size of the detector such that the different spots are confined in a limited area, namely the image plane.

3.1 SINGLE VIS CHANNEL

The single VIS channel spectrometer (Figure 39) diffracts the light after the collimator with a diffraction grating featuring 230[l/mm]. The diffracted light is focused through two freeform mirrors, modeled with XY polynomials up to the 6th order. The first mirror is concave while the second one is convex. Light is focused at the detector after the second convex freeform mirror. The system fits within a CubeSat unit (1U) and the performances at the image plane match the initial requirements.

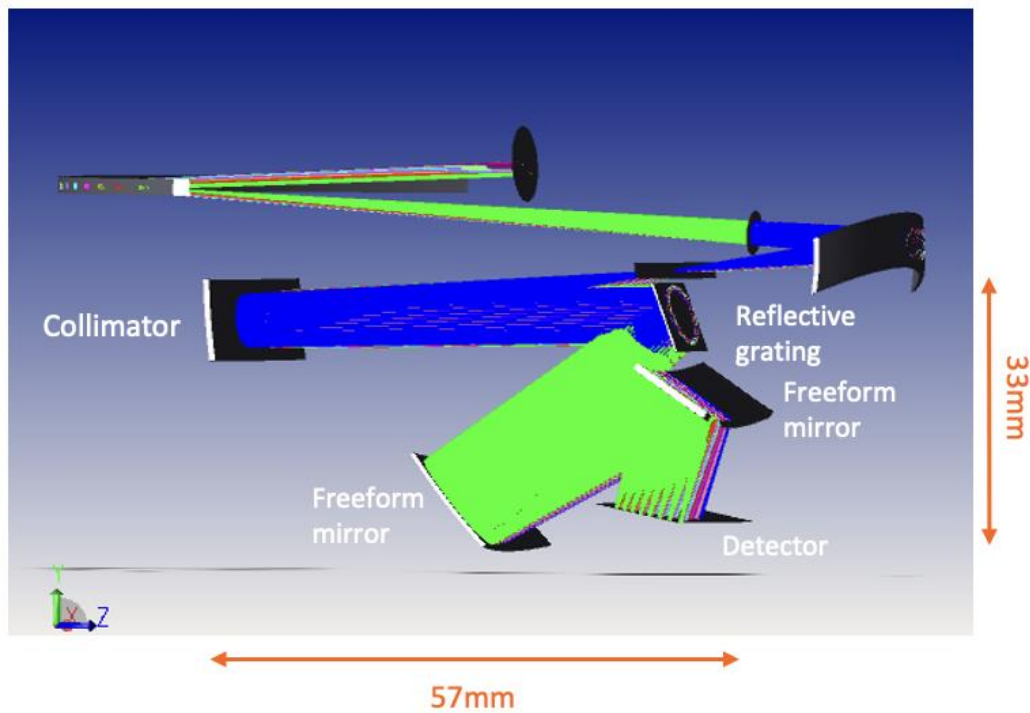


FIGURE 39: SINGLE VIS CHANNEL SHOWING THE DIFFERENT PARTS OF THE SYSTEM AND ITS SIZE FITTING IN ONE CUBESAT UNIT

The RMS spot radius (Figure 40) for different fields from 0° to 60° at 700nm (the central wavelength of the VIS channel) shows an increasing spot from nadir to 60° respectively with a value of $12,69\mu\text{m}$ and $27,08\mu\text{m}$, nearly doubling the size. The spot radius tends to increase between 0° and $21,82^\circ$ FOV then decreases to reach its best performance with $12,05\mu\text{m}$ at $43,64^\circ$. At the outer angles of the FOV, the RMS spots increases significantly. At $54,55^\circ$ the RMS spot is still in the same order as the previous RMS spots, however between the $54,55^\circ$ to 60° FOV the spot increases from $17,87\mu\text{m}$ to $27,08\mu\text{m}$.

The spot diagram indicates that rays fall outside the Airy disk; therefore, the system is not diffraction-limited. The Airy disk is linearly dependent on the wavelength making it more challenging to reach the diffraction limit in the lower part of the spectrum. At a wavelength of 700nm and a f-number of 6,69, the Airy radius equals $5,96\mu\text{m}$, corresponding to half of the value of the best RMS spot radius. In addition to the small Airy radius, we can notice that the f-number is lower than the $f/\#$ of TROPOMI, which is between 9 and 10.[24] The reason behind this difference lies in a smaller focal length or/and a larger EPD for TROPOMI (single VIS, NIR, and Thermal channels share the same EPD).

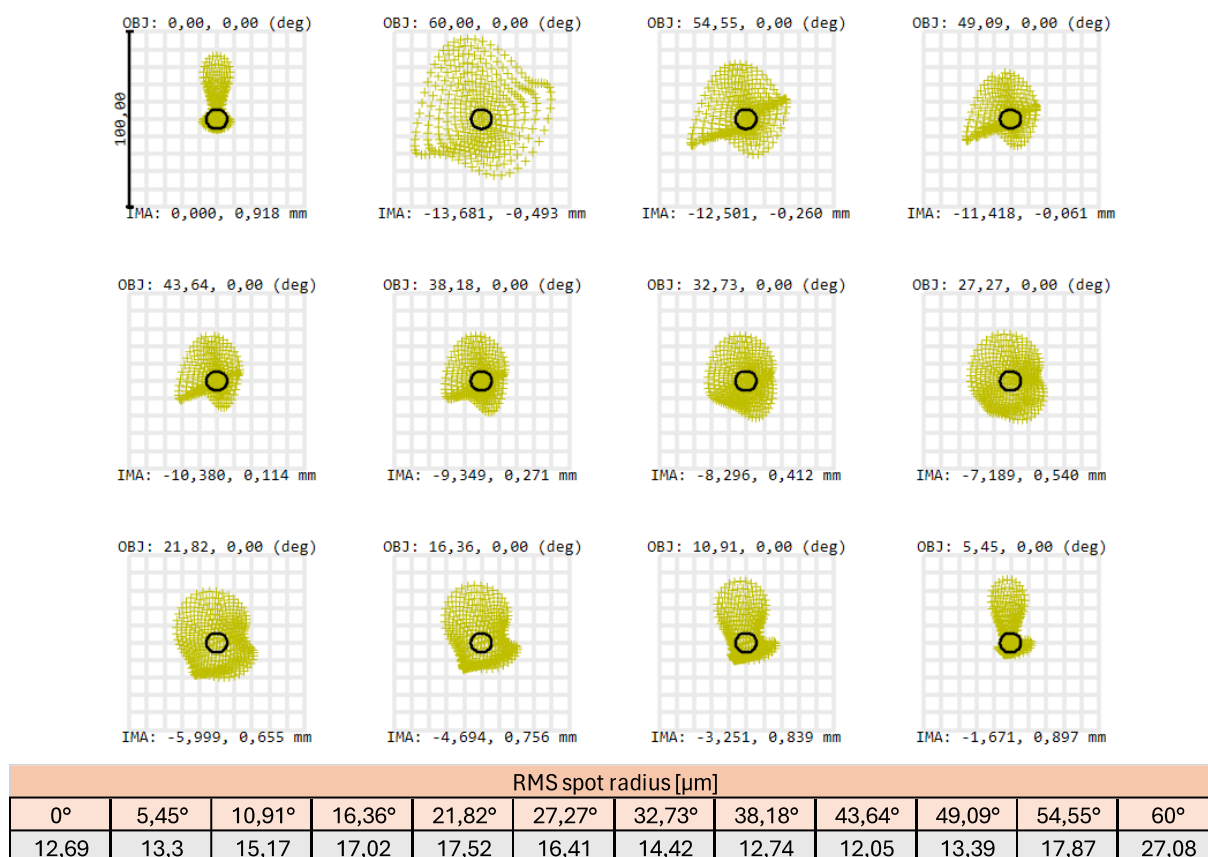


FIGURE 40: SPOT DIAGRAM AT THE CENTRAL WAVELENGTHS (700nm) FOR THE SINGLE CHANNEL VIS SPECTROMETER SHOWING A MINIMUM SPOT AT NADIR AND A MAXIMUM AT 60°

The tendency of the RMS spot radius to increase with wider field of view becomes more present with larger wavelengths (**Error! Not a valid bookmark self-reference.**). At 400nm, the spot size remains almost the same between 0° and 60° while at 1100nm, the spot size at 60° is more than twice the size of the one at 0°. The spot radius evolution across the wavelength range is consistent but the 12μm spot radius at 0° for the central wavelength shows that a possible optimization improvement is still possible.

TABLE 5: SPOT DIAGRAM FOR THE 0° AND 60° FIELD AT THE SHORTEST, CENTRAL AND LONGEST WAVELENGTHS OF THE SINGLE CHANNEL VIS SPECTROMETER RANGE, SHOWING A TENDENCY OF THE SPOT TO INCREASE WITH THE FIELD AT LARGE WAVELENGTHS

	0°	60°	0°	60°	0°	60°
	OBJ: 0,00, 0,00 (deg)	OBJ: 60,00, 0,00 (deg)	OBJ: 0,00, 0,00 (deg)	OBJ: 60,00, 0,00 (deg)	OBJ: 0,00, 0,00 (deg)	OBJ: 60,00, 0,00 (deg)
	IMA: 0,000, 3,410 mm	IMA: -13,832, 2,269 mm	IMA: 0,000, 0,918 mm	IMA: -13,681, -0,493 mm	IMA: 0,000, -3,120 mm	IMA: -13,579, -5,161 mm
Wavelength	400nm		700nm		1100nm	
Airy radius	3,41μm		5,96μm		9,37μm	
RMS spot radius	19,47μm	19,38μm	12,69μm	27,08μm	20,15μm	54,64μm

Resolution (**Error! Not a valid bookmark self-reference.**) is calculated at nadir, and when considering the best, worst, and average spot radius. The best and worst spots are respectively found at the fields of 43,64° and 60° while the average spot equals 15,81μm. The resolution determines the performance quality both in the spatial and spectral axis. Considering the average resolution, the 4km x 2,41nm resolution is better than the initial requirements of 5km x 20nm. The spectral resolution is one order of magnitude better

than what was targeted while the spatial resolution is almost a fifth better. Although the best spatial resolution at nadir equals less than 3,4km, the resolution at 60° demonstrates reduced performance with a spatial resolution of 7,16km. Nevertheless, this resolution is comparable to TROPOMI's performance and only concerns the FOV higher than what TROPOMI is capable of capturing.

TABLE 6: SPATIAL AND SPECTRAL RESOLUTION AT THE DETECTOR'S PLANE FOR THE SINGLE CHANNEL VIS SPECTROMETER (AT 700NM), CALCULATED CONSIDERING THE NADIR, BEST, AVERAGE AND WORST SPOT RADIUS.

Resolution nadir		Resolution best spot		Resolution average spot		Resolution worst spot	
Spatial [km]	Spectral [nm]	Spatial [km]	Spectral [nm]	Spatial [km]	Spectral [nm]	Spatial [km]	Spectral [nm]
3,35	1,93	3,18	1,83	4,18	2,41	7,16	4,12

The footprint diagram (Figure 41) shows that the shape of the detector is highly horizontal with a dimension of approximately 28mm by 9,2mm. This is due to the demand for a high spatial resolution requiring stretching the spots on the spatial axis to resolve them more easily. We also notice that smile effect is present on the footprint diagram.

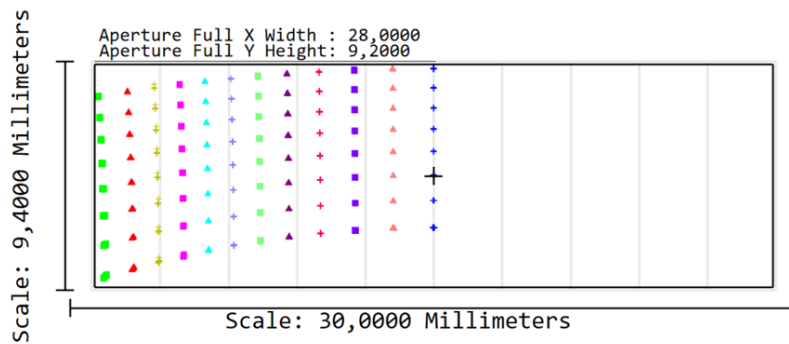


FIGURE 41: FOOTPRINT DIAGRAM ON THE DETECTOR FOR THE SINGLE CHANNEL VIS SPECTROMETER WITH THE FIELDS BETWEEN 0° TO 60° SHOWING THE PRESENCE OF SMILE AND THE SIZE OF THE AREA OF THE DETECTOR. THE SPATIAL AND SPECTRAL AXES ARE X (COLORS) AND Y (ROWS), RESPECTIVELY.

The PSF diagram validated the resolving power of the system for three neighboring spots at nadir when considering the calculated resolution of 3,35km. To push the system to its limit and to consider the smile effect in the resolution, the distance between the three neighboring spots has been reduced until the resolution limit. The best spatial resolution found based on the PSF (Figure 42) shows that a distance of 1,85km between two spots can still be resolved at nadir. This excellent resolution is close to the Airy disk resolution of 1,58km. This value is consistent when observing the spot radius shape at nadir. The elongated shape of the spot indicates an almost diffraction-limited spatial axis, but the tail on the spectral axis increases the RMS value, resulting worse resolution value.

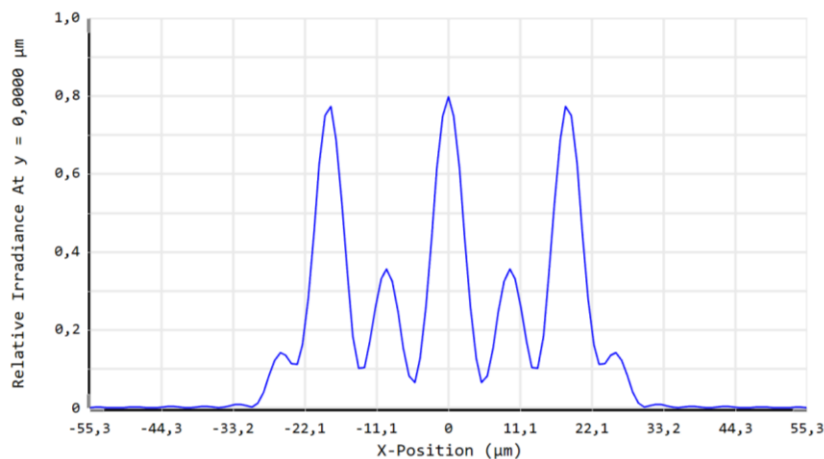


FIGURE 42: PSF OF THREE NEIGHBORING SPOTS AT NADIR FOR THE SINGLE CHANNEL VIS SPECTROMETER (AT 700NM)
SHOWING THE BEST RESOLVABLE DISTANCE BETWEEN THE SPOTS

The MTF (Figure 43) shows that the system is not entirely diffraction-limited (the diffraction limit for the tangential and sagittal rays are the black curves at the top). Indeed, some fields, especially the one at 60° in green, have some issues to provide a good resolution. However, the Nyquist frequency for the system, calculated with the average RMS spot radius as half the pixel pitch, yields a value of 15.81 cycles/mm. At this value, the overall Modulation Transfer Function (MTF) exceeds 0.5, which means that the resolution of our optical system is able to resolve 50% of the initial contrast.

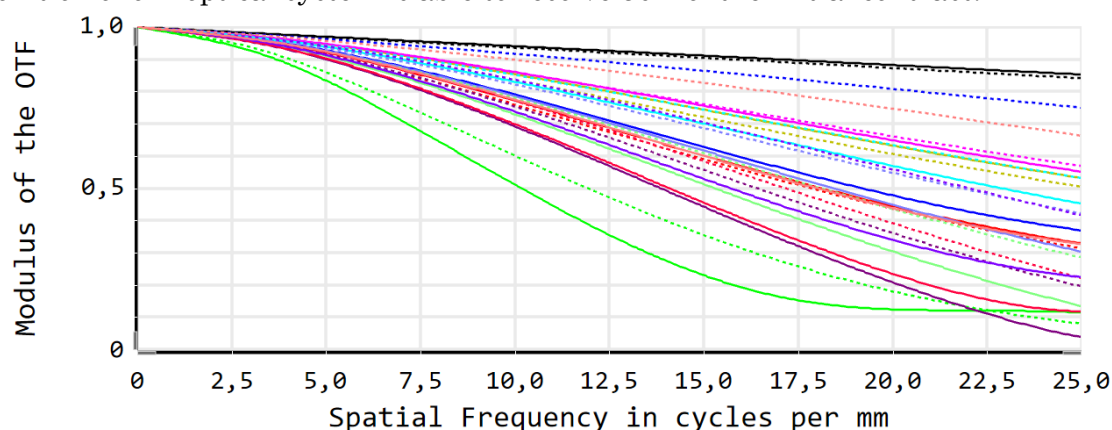


FIGURE 43: MTF FOR THE SINGLE CHANNEL VIS SPECTROMETER (AT 700NM)

The system for the single-channel VIS spectrometer only suffers from spherical aberration (Figure 44). This result wasn't expected especially since distortion is meant to be present for WFOV systems. However, due to the complexity of the freeform terms, a trade-off often occurs between the compensation and minimization of the aberrations.

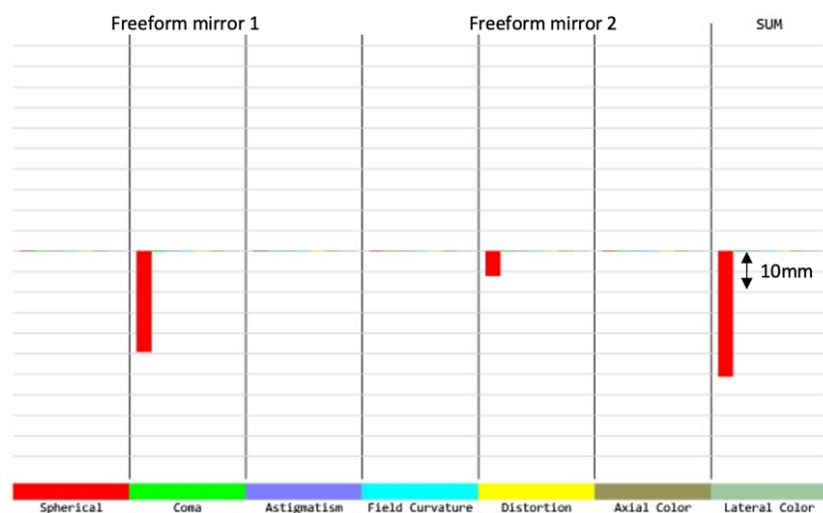


FIGURE 44: SEIDEL DIAGRAM FOR THE SINGLE VIS CHANNEL SPECTROMETER SHOWING THE PRESENCE OF ONLY SPHERICAL ABERRATION

A second design for the VIS channel is proposed and evaluated. This design is based upon the Offner relay which consists, for a spectrometer, of two concentric spherical mirrors with a grating between them (considering the optical path). This design is one of the most used configurations, showing excellent performances in previous research, making it an interesting candidate to explore.[43] In our design, the mirrors share the same radius but are freeform with independent XY polynomials, since only spherical mirrors did not offer a sufficient amount of degrees of freedom to optimize the design.

The geometry of this design requires the rays to diverge from the object, therefore, no collimator is present in the system, making this geometry hard to integrate into a full three-channel spectrometer. The aim of this design is therefore not to be integrated into our final three-channel spectrometer, but to see the effects of an alternative design on the performances at the image plane.

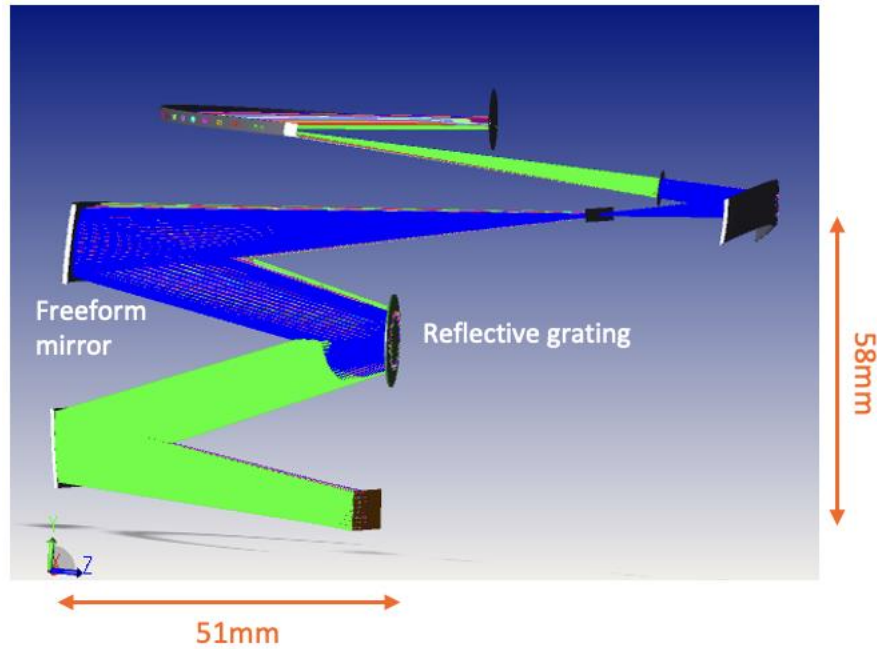


FIGURE 45: SINGLE VIS CHANNEL SPECTROMETER WITH THE OFFNER ARCHITECTURE

The system still requires an extended optimization to reach the diffraction limit. The RMS spot diagram (Figure 46) shows that rays have an RMS spot radius between $62,05\mu\text{m}$ at nadir to $87,15\mu\text{m}$ at 60° , with an average spot of $68,24\mu\text{m}$. In comparison with the previous single-channel VIS spectrometer, the radius is 3,2 to 5,4 times larger.

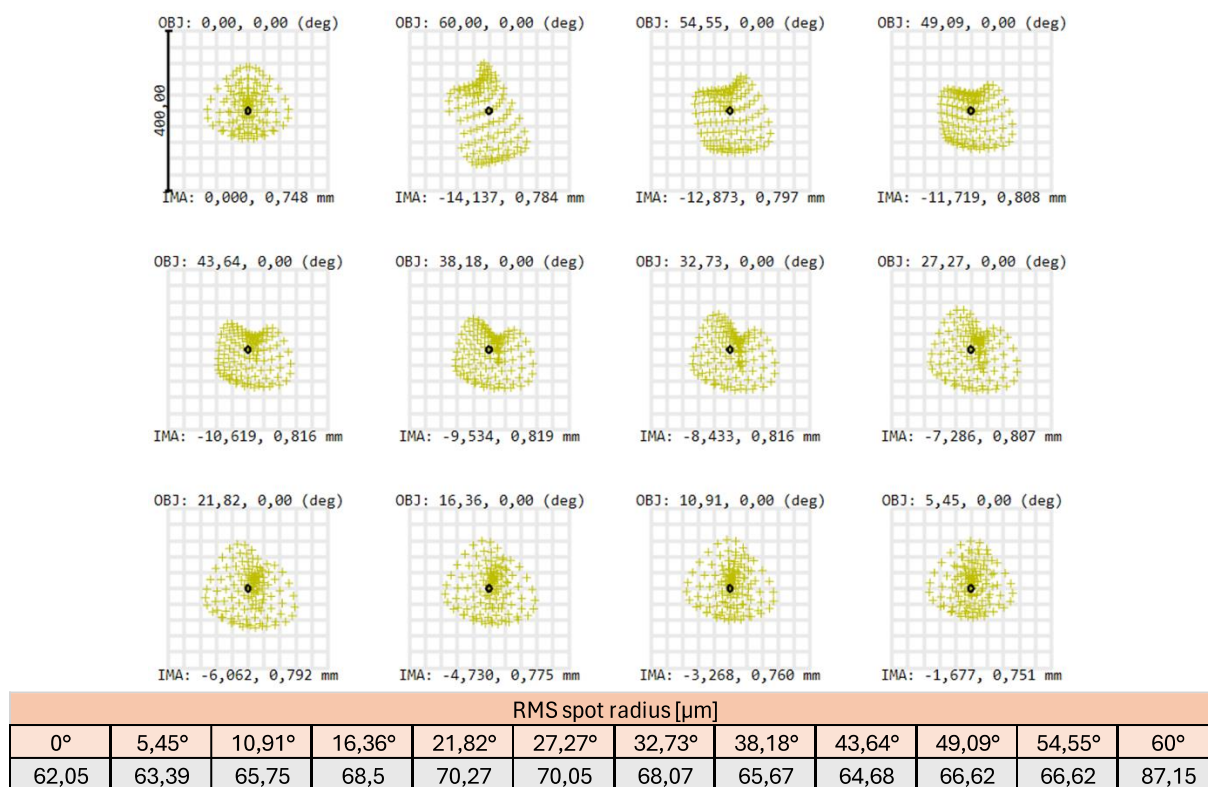


FIGURE 46: SPOT DIAGRAM AT 700NM FOR THE SINGLE CHANNEL VIS OFFNER SPECTROMETER SHOWING A SPOT SIZE LARGER THAN THE PREVIOUS SINGLE CHANNEL DESIGN

The large spot radius is negatively impacting the resolution both on the spatial and spectral axis. The spectral resolution remains below or equal to the required 20nm, but the spatial resolution is three to four times larger than the required 5km.

TABLE 7: SPATIAL AND SPECTRAL RESOLUTION AT THE DETECTOR'S PLANE FOR THE SINGLE CHANNEL VIS OFFNER SPECTROMETER (AT 700NM), CALCULATED CONSIDERING THE NADIR, BEST, AVERAGE AND WORST SPOT RADIUS.

Resolution nadir		Resolution best spot		Resolution average spot		Resolution worst spot	
Spatial [km]	Spectral [nm]	Spatial [km]	Spectral [nm]	Spatial [km]	Spectral [nm]	Spatial [km]	Spectral [nm]
15,83	14,48	16,50	15,09	17,56	16,05	22,24	20,34

With an Airy radius of 6,75 μm and an average spot radius ten times larger, equal to 68,24 μm , the design is far from the diffraction limit. This has an effect on the resolution, but also on the MTF that is showing a bad performance. The MTF drops below 0,5 at 3,5 cycles/mm for every tangential ray, and 6 cycles/mm for every sagittal ray. In addition, due to the large spot radius, the Nyquist frequency for the detector limits the optical system's resolution at 3,6 cycles/mm.

The optical system needs improvements and further optimization to achieve acceptable resolution levels. Despite the current poor resolution, the results shown in the footprint diagram (Figure 47) are promising for the future exploitation of this design. Particularly, this system has been able to reach an imaging without smile effect. Each spot on the footprint diagram is perfectly aligned, indicating that the detector's plane accurately matches the edges of spatial and spectral coordinates. The absence of the smile is thanks to the symmetrical design featuring identical radii of the two mirrors, together with the parallel orientation of the object and image planes. Care should however be taken when optimizing towards higher resolution, since this might still induce an enlarged smile effect.

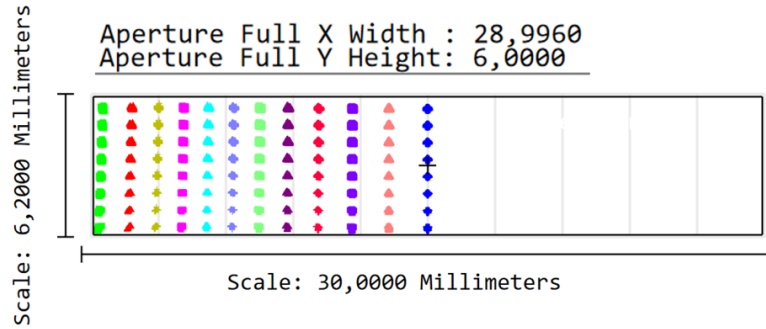


FIGURE 47: FOOTPRINT DIAGRAM OF THE SINGLE CHANNEL VIS OFFNER ARCHITECTURE SHOWING THE ABSENCE OF SMILE EFFECT IN THE SYSTEM. THE SPATIAL AND SPECTRAL AXES ARE X (COLORS) AND Y (ROWS), RESPECTIVELY.

3.2 SINGLE-CHANNEL NIR SPECTROMETER

The design of the single-channel NIR spectrometer (Figure 48) followed the same methodology as the single-channel VIS spectrometer. A collimator provides parallel rays to the 120[l/mm] diffraction grating; light is then focused via two freeform mirrors, the first concave, and the second convex.

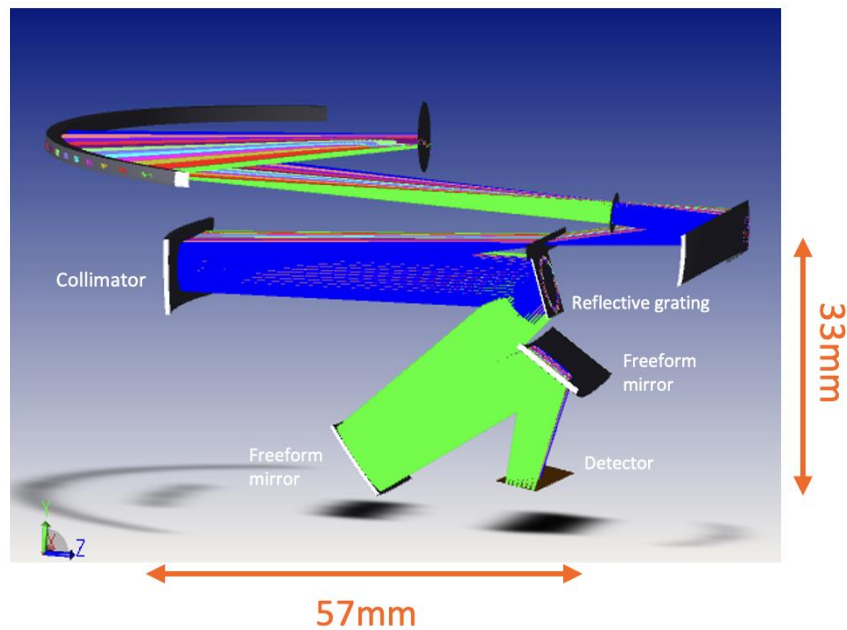


FIGURE 48: SINGLE CHANNEL NIR SPECTROMETER

The RMS spot radius at 1400nm (Figure 49) shows great performances with a range of values for the spot radius between $4,61\mu\text{m}$ at $38,18^\circ$ and $11,39\mu\text{m}$ at 60° . The average spot is equal to $6,28\mu\text{m}$ and the spot radius at nadir is $7,21\mu\text{m}$. The evolution of the spot through the increasing FOV does not exhibit a constant variation; there are two minima at $5,06^\circ$ and $3,18^\circ$, and three maxima at nadir, $21,82^\circ$, and 60° . The variation at the largest FOV angles is significant, with the spot size doubling in the last 5° . Specifically, between $54,55^\circ$ and 60° , the RMS spot radius increases from $6,08\mu\text{m}$ to $11,39\mu\text{m}$.

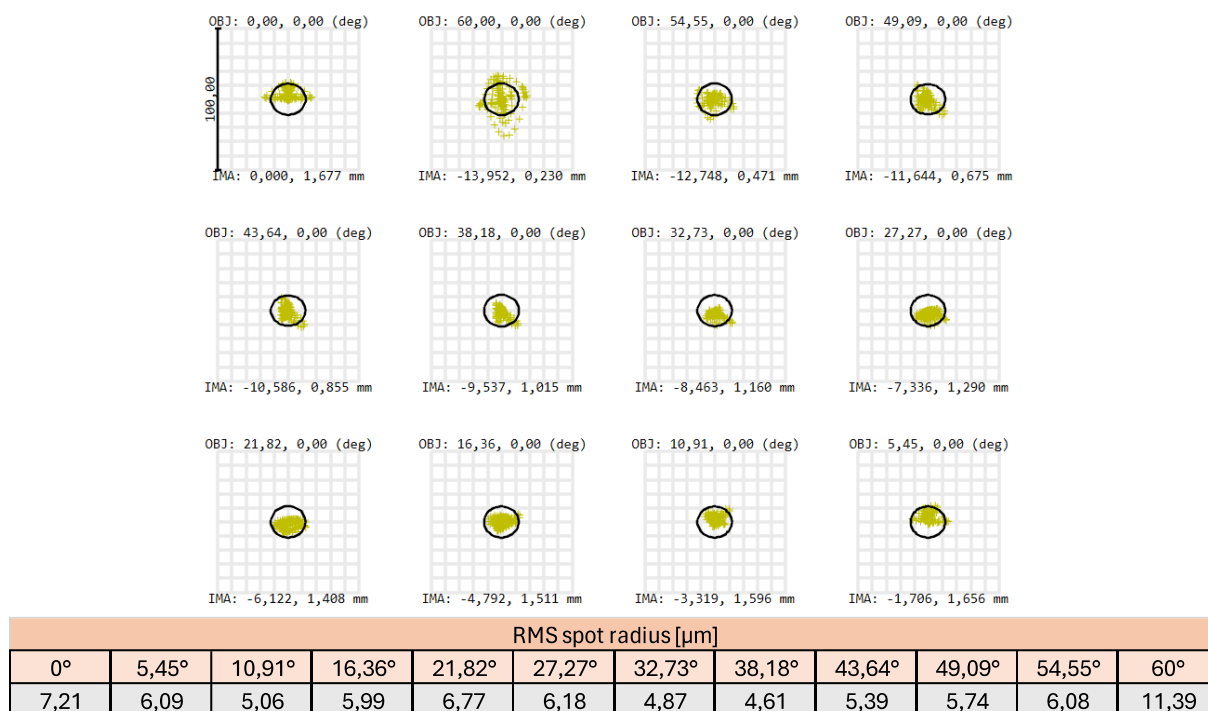


FIGURE 49: SPOT DIAGRAM OF THE SINGLE CHANNEL NIR SPECTROMETER AT 1400NM SHOWING DIFFRACTION-LIMITED SPOTS AT EACH FIELDS

Along several wavelengths of the single channel NIR spectrometer (Table 8), we notice that the spot radius is nearly diffraction limited. The spot does not systematically increases its radius along the fields since the spot radius at 1100nm decreases at 60°.

TABLE 8: SPOT DIAGRAM FOR THE 0° AND 60° FIELD AT THE SHORTEST, CENTRAL AND LONGEST WAVELENGTHS OF THE SINGLE CHANNEL NIR SPECTROMETER RANGE, SHOWING AN APPROXIMATIVELY CONSTANT VARIATION ACROSS THE SPECTRUM AND THE FIELDS.

	0°		60°		0°		60°		0°		60°	
	OBJ: 0,00, 0,00 (deg)		OBJ: 60,00, 0,00 (deg)		OBJ: 0,00, 0,00 (deg)		OBJ: 60,00, 0,00 (deg)		OBJ: 0,00, 0,00 (deg)		OBJ: 60,00, 0,00 (deg)	
	IMA: 0,000, 3,195 mm		IMA: -14,045, 1,926 mm		IMA: 0,000, 1,677 mm		IMA: -13,952, 0,230 mm		IMA: 0,000, 0,000 mm		IMA: -13,882, -1,684 mm	
Wavelength	1100nm		1400nm		1400nm		1700nm		1700nm		1700nm	
Airy radius	9,69μm		12,34μm		12,34μm		14,98μm		14,98μm		14,98μm	
RMS spot radius	10,77μm	6,82μm	7,21μm	11,39μm	7,21μm	11,39μm	9,71μm	16,65μm	9,71μm	16,65μm	9,71μm	16,65μm

The $f/\#$ of the system is 7.2, corresponding to an Airy radius of 12.36μm. As each spot radius is smaller than the Airy radius, the system is considered as being diffraction-limited. The calculation of the resolution based on the RMS spot radius (Table 9) shows outstanding results with an average resolution of 1,64km by 1,35nm; however, due to the diffraction-limited nature of the system, the resolution is limited by the Airy disk at nadir at 3,22km by 4,49nm. This outstanding, spatial resolution is 4,2 times better than the one of TROPOMI and a third of the targeted resolution of 5km.

TABLE 9: SPATIAL AND SPECTRAL RESOLUTION AT THE DETECTOR'S PLANE FOR THE SINGLE CHANNEL NIR SPECTROMETER (AT 1100NM) CALCULATED CONSIDERING THE NADIR, BEST, AVERAGE AND WORST SPOT RADII

Resolution nadir		Resolution best spot		Resolution average spot		Resolution worst spot	
Spatial [km]	Spectral [nm]	Spatial [km]	Spectral [nm]	Spatial [km]	Spectral [nm]	Spatial [km]	Spectral [nm]
1,88	1,55	1,41	1,16	1,64	1,35	2,97	2,44

The footprint diagram (Figure 50) shows that a smile effect is present in the system. The final area of the detector is 28,36x5,6mm². The colors (X-axis) correspond to the various field angles, and the rows (Y-axis) to the wavelengths.

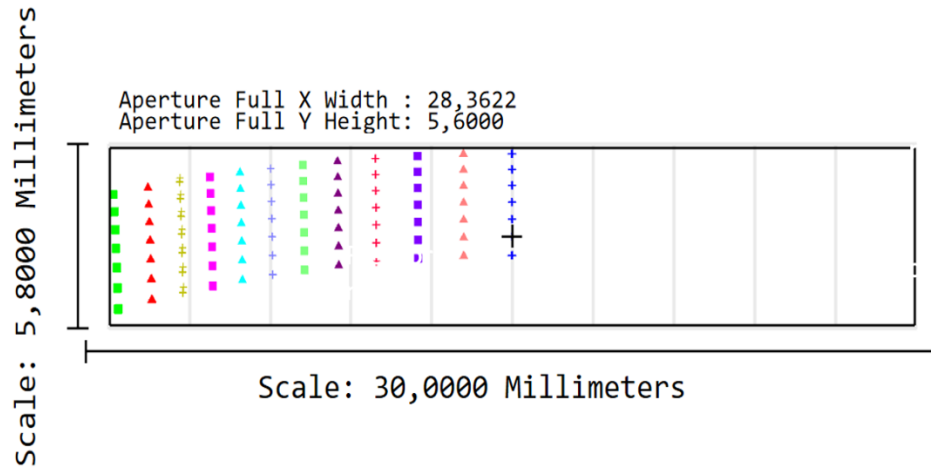


FIGURE 50: FOOTPRINT DIAGRAM OF THE SINGLE CHANNEL NIR SPECTROMETER SHOWING SMILE EFFECT AND THE SIZE OF THE DETECTOR. THE SPATIAL AND SPECTRAL AXES ARE X (COLORS) AND Y (ROWS), RESPECTIVELY.

The spectrometer is well able to resolve three neighboring spots along the spatial axis when considering the Airy disk resolution of 3,22km. We evaluated the spatial resolution by reducing the distance between those three spots at nadir. This calculated resolution does not take the smile effect into account in its calculation. The best resolvable spatial resolution found through the PSF diagram (Figure 51) is equal to 2,77km at nadir. This resolution is approximately 2,5 times better than TROPOMI's resolution. Nevertheless, this resolution considers the system pushed at its limit and in absence of the smile effect.

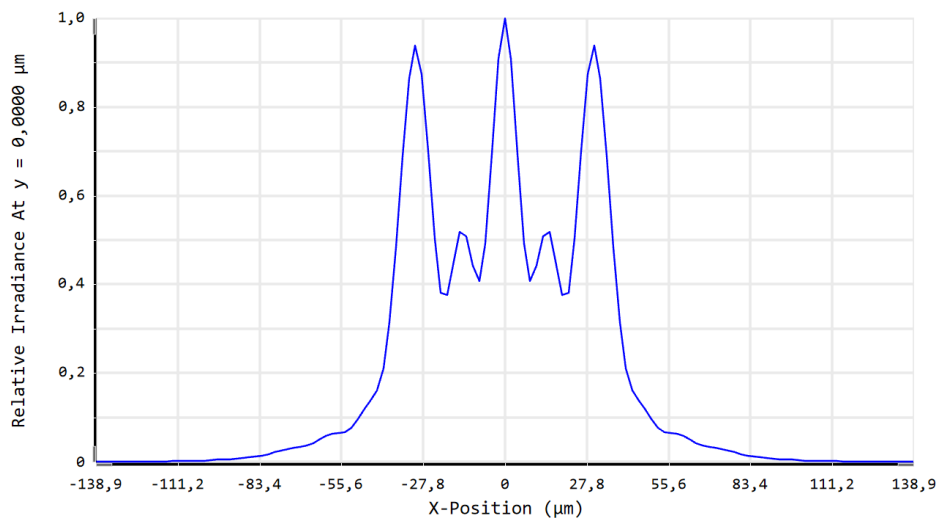


FIGURE 51: PSF OF THREE NEIGHBORING SPOTS AT NADIR FOR THE SINGLE CHANNEL NIR SPECTROMETER (AT 1100NM) SHOWING THE BEST RESOLVABLE DISTANCE BETWEEN THE SPOTS

The MTF (Figure 52) shows that the system is well diffraction limited even if the 60° field in green is a bit lower. The Nyquist value, calculated from the Airy disc radius, limits the MTF at 20 cycles/mm. All fields at this spatial frequency have an MTF between 0,65 and 0,77 except for the tangential field at 60° which shows a value around 0,55.

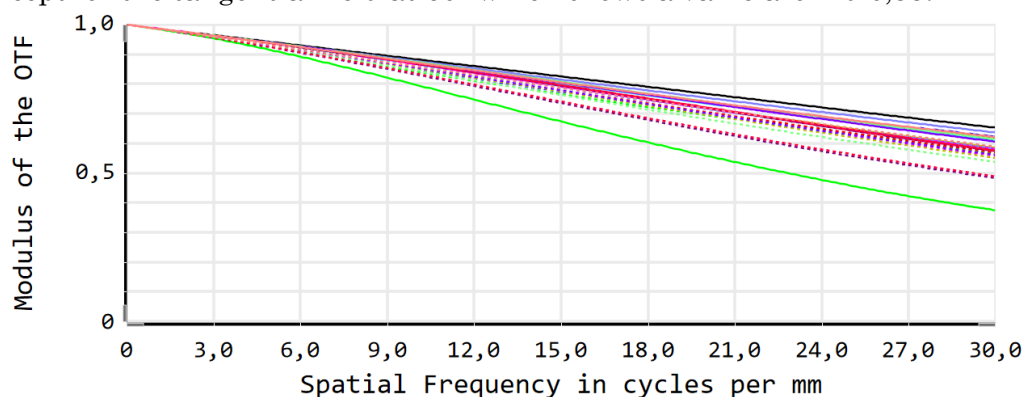


FIGURE 52: MTF OF THE FULL FOV AT 1100NM FOR THE SINGLE CHANNEL NIR SPECTROMETER

The Seidel diagram (Figure 53) shows an even presence of each type of aberration in the system (except field curvature) but the aberrations in the system are relatively minor and do not significantly impact the final resolution of the system.



FIGURE 53: SEIDEL DIAGRAM OF THE SINGLE-CHANNEL NIR SPECTROMETER

3.3 SINGLE-CHANNEL THERMAL SPECTROMETER

The single-channel thermal spectrometer fits inside one CubeSat unit and has a diffractive grating of 0,015 lines per millimeter. It has the same structure as the single VIS and NIR channel made of one reflective grating with two 6th order XY polynomial freeform mirrors to focus the light at the detector's plane (Figure 54).

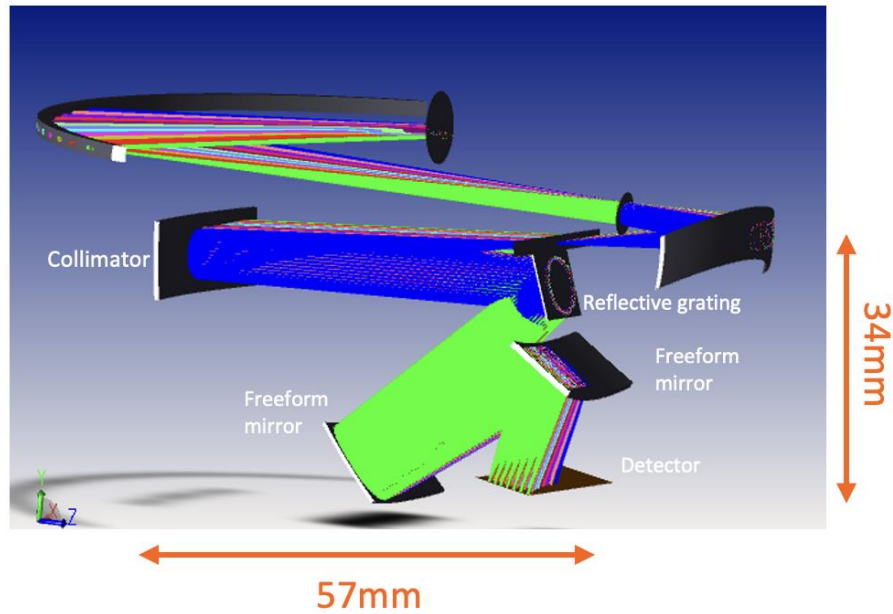
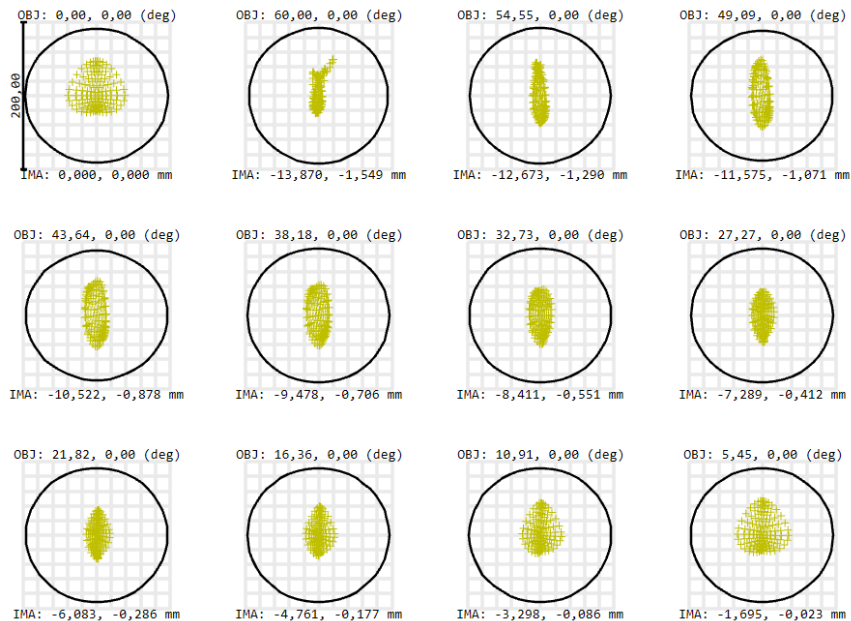


FIGURE 54: SINGLE THERMAL CHANNEL SHOWING THE DIFFERENT PARTS OF THE SYSTEM AND ITS SIZE FITTING IN ONE CUBESAT UNIT

The RMS spot radius diagram (Figure 55) shows a fully diffraction-limited system. Reaching the diffraction limit eases with increased wavelength, since the Airy disk is linearly proportional to the wavelength. Since the system is operational on a spectrum between $8\mu\text{m}$ to $14\mu\text{m}$, the central wavelength ($11\mu\text{m}$) at which the RMS spot radius is simulated showcases an Airy radius of $94,18\mu\text{m}$. At this central wavelength, the spot radius goes from $20\mu\text{m}$ at $21,82^\circ$ to $27,93\mu\text{m}$ at $43,64^\circ$ field angles.

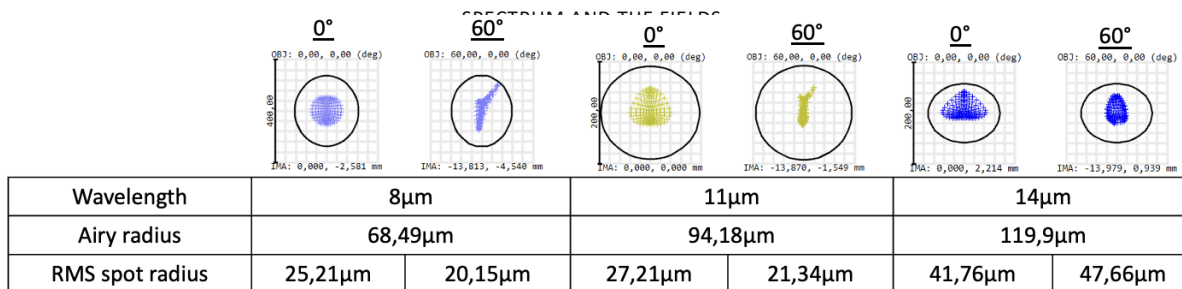


RMS spot radius [μm]												
0°	5,45°	10,91°	16,36°	21,82°	27,27°	32,73°	38,18°	43,64°	49,09°	54,55°	60°	
27,2	25,81	22,92	20,59	20,03	21,25	23,51	25,96	27,68	27,93	27,73	21,34	

FIGURE 55: SPOT DIAGRAM OF THE SINGLE THERMAL CHANNEL AT THE CENTRAL WAVELENGTH ($11\mu\text{m}$) SHOWING THAT THE SPOTS ARE DIFFRACTION-LIMITED AT EACH FIELDS

Table 10 shows that the spots are diffraction limited at each wavelengths of the Thermal channel.

TABLE 10: SPOT DIAGRAM FOR THE 0° AND 60° FIELD AT THE SHORTEST, CENTRAL AND LONGEST WAVELENGTHS OF THE SINGLE CHANNEL THERMAL SPECTROMETER RANGE, SHOWING THAT THE SPOTS ARE DIFFRACTION LIMITED ACROSS THE



The calculated resolution (**Error! Not a valid bookmark self-reference.**) based on the RMS spot radius yields an average value for the spectral resolution that is twice the requirement of 20nm. This is due to the broadness of the spectrum rather than the quality of the focus (a better resolution is achievable by increasing the grating's periodicity/diffraction angle but requires then a wider detector). The spatial resolution is between 5km and 7km. The 5km resolution matches the requirements, while the 7km resolution is in the same order of magnitude as TROPOMI. Considering the system being fully diffraction limited, the Airy disc size needs to be considered during the resolution calculations. The shorter distance at which two spots can be resolved in the simulations equals 94,18μm, corresponding to a resolution of 24,4km by 230nm. This physical limitation on the resolution influences the average spatial resolution calculated via the spot radius being reduced by a factor of four and the required spectral resolution by a factor of five. The spectral resolution induced by the Airy radius is eleven times higher than the 20nm required.

TABLE 11: SPATIAL AND SPECTRAL RESOLUTION AT THE DETECTOR'S PLANE FOR THE SINGLE CHANNEL THERMAL SPECTROMETER (AT 11μm), CALCULATED CONSIDERING THE NADIR, BEST, AVERAGE AND WORST SPOT RADIUS.

Resolution nadir		Resolution best spot		Resolution average spot		Resolution worst spot	
Spatial [km]	Spectral [nm]	Spatial [km]	Spectral [nm]	Spatial [km]	Spectral [nm]	Spatial [km]	Spectral [nm]
7,10	42,95	5,23	31,63	6,35	38,41	7,29	44,10

As expected by the Rayleigh criterion, it is not possible to resolve three neighboring spots on the PSF by considering the RMS spot radius resolution. In this case, the PSF merges with the neighboring spots. By considering the resolution measured via the Airy radius, it is possible to draw a PSF plot in which the three neighboring beams are resolved. The maximum resolvable spatial resolution on the PSF diagram (Figure 56) showed that it is possible to reach a 16,95km resolution at nadir. This resolution features a net improvement of 7,5km from what has been calculated and is now only 3,5 times higher than the spatial resolution required. The improvement from the calculation is partially due to the smile effect that is not considered in the resolution calculation but also to the enclosed energy that shows the percentage of light present as function of the distance from centroid (Figure 57). At 95μm (the Airy radius), the encircled energy of each field is positioned on a plateau (where 83% of the light is encircled) that begins around 75μm from the centroid. . It means that between 75μm and 95μm the same amount of light is encircled and the resolution can possibly be improved.

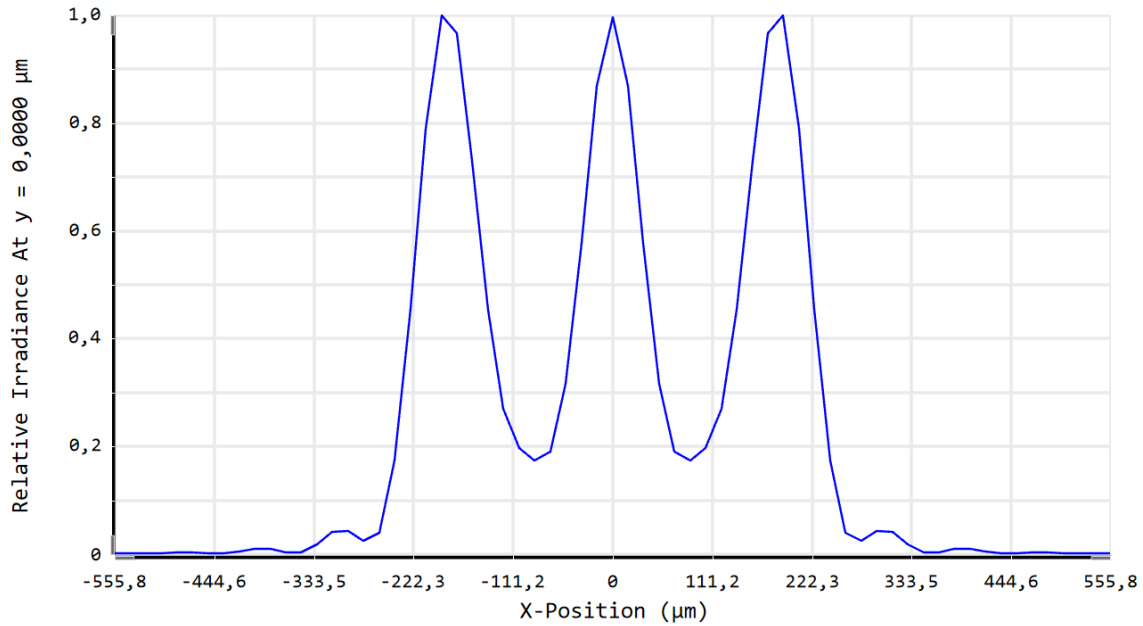


FIGURE 56: PSF OF THREE NEIGHBORING SPOTS AT NADIR FOR THE SINGLE CHANNEL THERMAL SPECTROMETER (AT 700NM) SHOWING THE BEST RESOLVABLE DISTANCE BETWEEN THE SPOTS

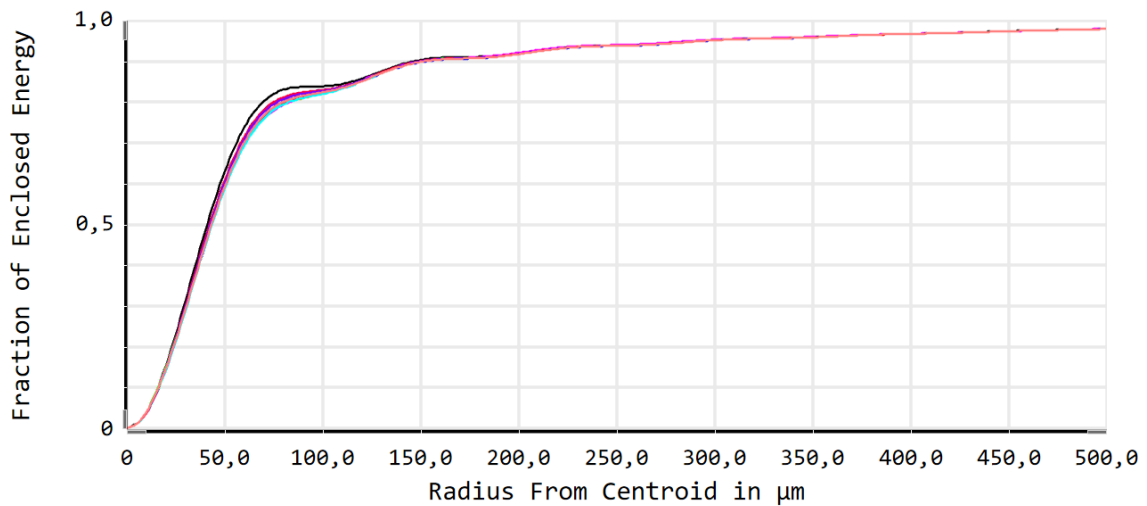


FIGURE 57: ENCLOSED ENERGY FOR EACH FIELD AT 11 μ m FOR THE SINGLE THERMAL CHANNEL SPECTROMETER

The MTF (Figure 58) shows a diffraction-limited system in which each field perfectly matches the diffraction limit despite a small difference between the sagittal and tangential rays at higher frequencies, certainly due to astigmatism. The Nyquist frequency for a pixel pitch defined as twice the Airy radius limits the optical system at 2,65 cycles/mm, corresponding to an MTF of 0,7. The low value of this limiting spatial frequency significantly restricts the system's resolution in terms of spatial frequencies.

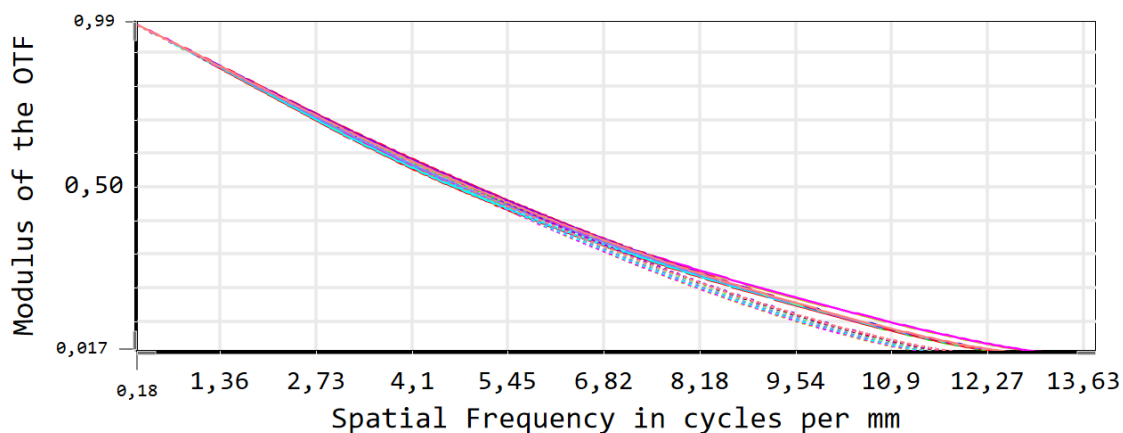


FIGURE 58: MTF AT THE CENTRAL WAVELENGTH ($11\mu\text{m}$) OF THE SINGLE-CHANNEL THERMAL SPECTROMETER

The Seidel diagram shows a moderate presence of each type of aberration. Some of them, such as astigmatism leading to an oval shape of the spot or spherical causing a blurry focus at small angles, can easily be distinguished on the spot diagram (Figure 55).

The main possible improvement of this system lies in the reduction of the Airy radius size. The current Airy radius is too large and has a huge effect on the spatial and spectral resolution. Techniques for improvements should focus on reducing the f-number by increasing the focal length or increasing the entrance pupil diameter.

3.4 FINAL THREE-CHANNEL SPECTROMETER

The final design of the freeform three-channel spectrometer (Figure 59) features 9 freeform mirrors: two are dedicated to the telescope to collect the light and then focus it to the spectrometer's entrance, one is for the collimator, and two are required at each channel of the spectrometer to focus the light on the detector's plane. Channels are separated "geometrically" between the Thermal and the VIS-NIR channels, the two latter are separated via a dichroic beam splitter. Each channel has its proper diffraction gratings. Additionally, the spectrometer is fitting inside one CubeSat unit (1U) which is a requirement's achievement.

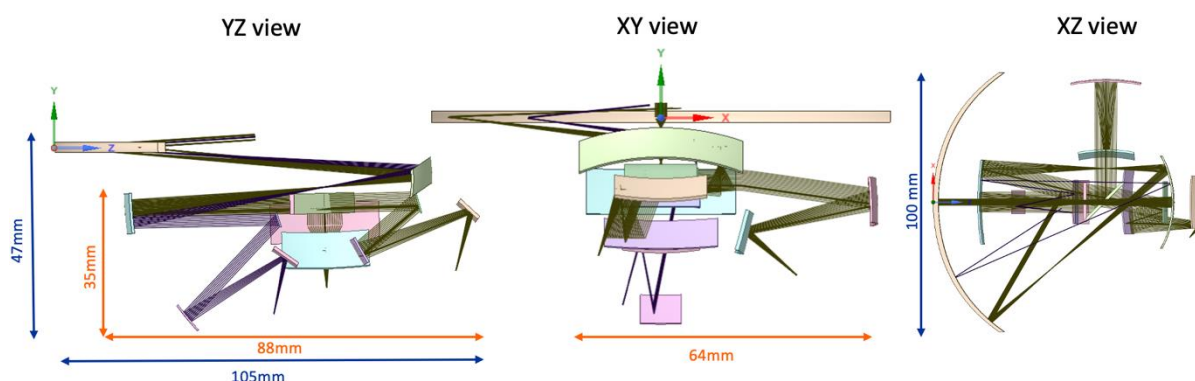


FIGURE 59: FULL VIEW OF THE FINAL THREE CHANNEL SPECTROMETER INCLUDING THREE FIELDS (0° , 32.73° , 60°) AND THE MEASURES OF THE SPECTROMETER (ORANGE) AND SPECTROMETER + TELESCOPE (BLUE) SHOWING THAT THE SPECTROMETER IS FITTING IN ONE CUBE SAT UNIT

Each of the channels is discussed separately in the next sections. They all feature extremely good performances and all match the requirements (given in section 1.3), except for the thermal channel which limited by the Airy radius.

3.4.1 VIS CHANNEL

The three-channel freeform spectrometer's VIS channel, covering the 400 nm – 1100 nm wavelength range (Figure 60), collects two-third of the collimated light at the dichroic beam splitter. The splitter divides the light between the VIS and the NIR channel. The light for the VIS channel is reflected and then passes through a transmissive grating with a periodicity of 230 l/mm. The choice of a transmissive grating is driven by geometrical reasons to make the system as compact as possible and avoid an overlap between the mirrors of the VIS and NIR channels. After the grating, the diffracted light is focused on the image plane by two freeform mirrors modelled with XY polynomial coefficients up to 6th order (The optimization of the design targeted minimizing the present optical aberrations. A merit function was first defined, considering the RMS spot radius or MTF. Following the optimization was performed targeting minimization of the merit function. The mirror surface parameters and freeform terms were set as variables during the optimization. Since adapting the freeform mirrors for each of the channels would complicate the design in terms of optimization, the same freeform mirrors at each channel were used. The XY polynomials for the first and the second freeform mirrors is given in **Error! Not a valid bookmark self-reference..**

Table 4).

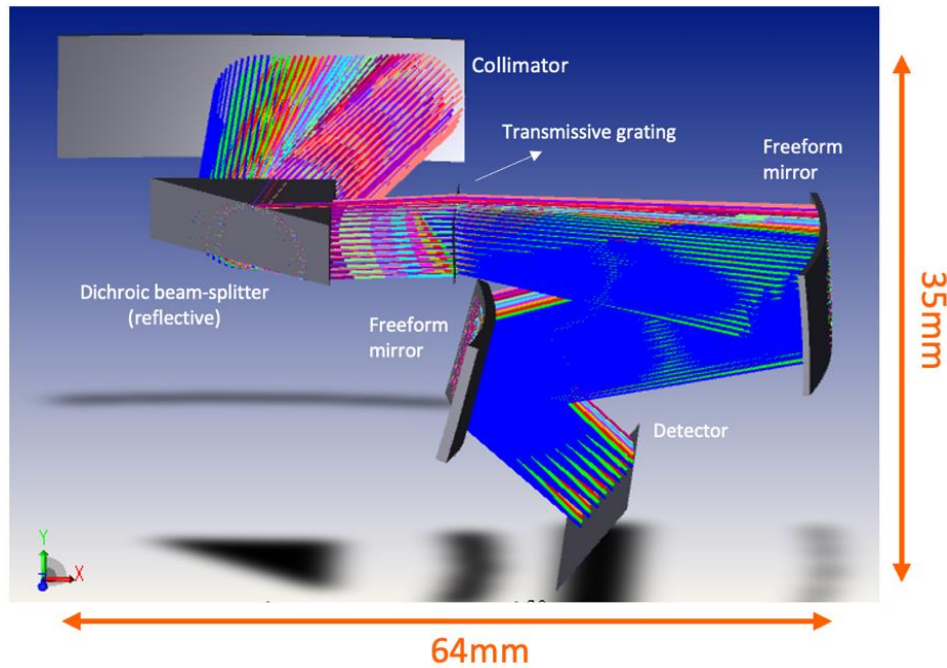
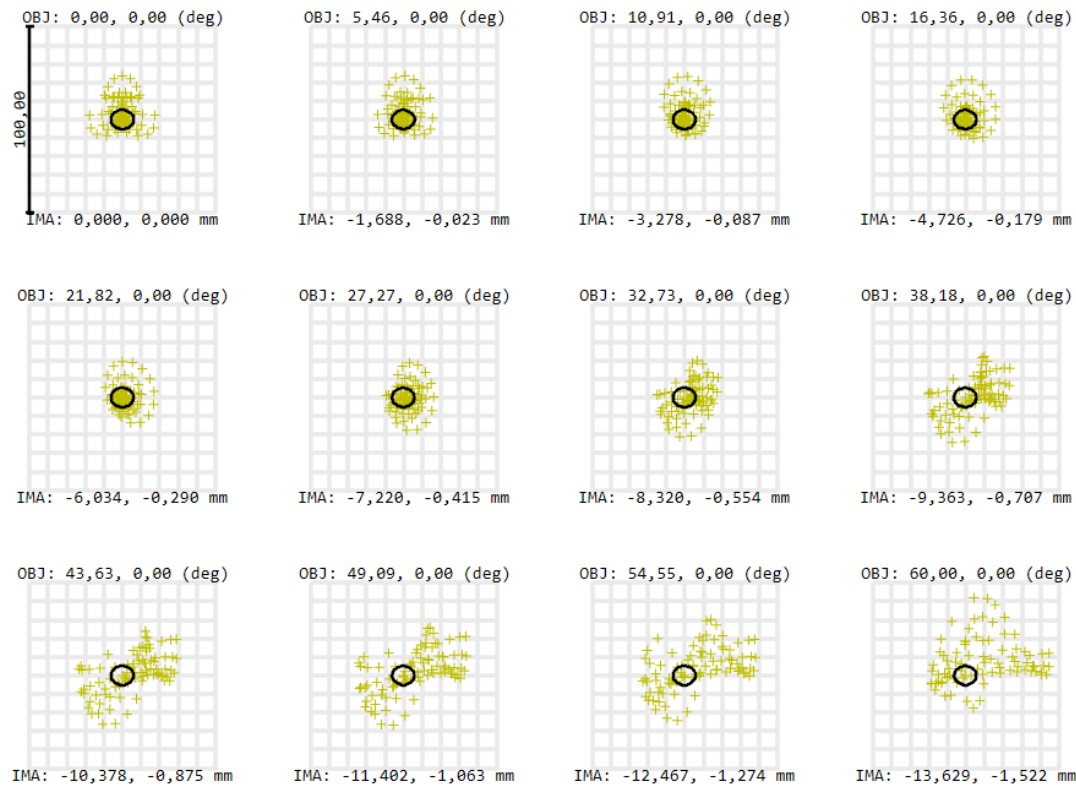


FIGURE 60: VIS CHANNEL OF THE FINAL THREE-CHANNEL SPECTROMETER'S DESIGN, SHOWING EACH COMPONENTS PRESENTS IN THE SYSTEM AND A FINAL SIZE FITTING IN ONE CUBE\$AT UNIT.

The RMS spot radius diagram at 700nm (Figure 61) showcases values between 9,85 μ m at nadir to 25,1 μ m at 60°. The variation of the spot radius is constant (with a small decrease around 20°) along the FOV. The current design has better performances at 700nm in comparison with the single-channel VIS spectrometer; the smallest spot (8,3 μ m) radius is 4 μ m smaller, and the average spot (14,05 μ m) is 2 μ m smaller, as for the largest spot (25,1 μ m).



RMS spot radius [μm]											
0°	5,45°	10,91°	16,36°	21,82°	27,27°	32,73°	38,18°	43,64°	49,09°	54,55°	60°
9,85	9,42	8,83	8,55	8,3	9,24	11,96	15,54	18,23	21,11	22,47	25,1

FIGURE 61: SPOT DIAGRAM OF THE VIS CHANNEL OF THE FINAL DESIGN AT THE CENTRAL WAVELENGTH (700NM) SHOWING THAT THE SPOTS HAVE THE TENDENCY TO INCREASE WITH THE FIELD

The spot radius, in comparison with the single-channel VIS spectrometer, is not uniformly improved across the spectral range and the field (**Error! Not a valid bookmark self-reference.**). The spot radius shows outstanding results at small and medium angles but the spot radius tends to increase at large angles. I.e. the 400nm spots is $12\mu\text{m}$ smaller at 0° than its relative single-channel spectrometer but the spot at 60° is $10\mu\text{m}$ larger. Considering the 1100nm wavelength, the field at 0° is $10\mu\text{m}$ larger and the field at 60° is $2\mu\text{m}$ larger. This difference is due to a merit function focusing too much on the central wavelength. Nevertheless, those results are quite positive considering the challenging design.

TABLE 12: SPOT DIAGRAM FOR THE 0° AND 60° FIELD AT THE SHORTEST, CENTRAL AND LONGEST WAVELENGTHS OF THE FINAL DESIGN'S VIS CHANNEL

Wavelength	400nm		700nm		1100nm	
Airy radius	3,15μm		5,51μm		8,66μm	
RMS spot radius	7,19μm	30,75μm	9,85μm	25,10μm	30,57μm	56,16μm

At 700nm, the f-number of 6,45 is a bit smaller but is still close to the f-number of the single channel spectrometers (6,97). For the central wavelength of the VIS channel, this

corresponds to an Airy radius of $5,51\mu\text{m}$. In comparison with the RMS spot radius values present in Figure 61, this Airy radius is half of the RMS spot radius at nadir. Nevertheless, the resolution (**Error! Reference source not found.**) still matches the requirements with an average spatial and spectral resolution of $3,71\text{km}$ and $3,03\text{nm}$ respectively. The worst resolution (at 60°) yields a spectral resolution that is a fourth smaller than what is required (20 nm), while the spatial resolution at this field is $6,63\text{km}$, slightly exceeding the 5km required. However, the larger spot radius at larger wavelengths induces a loss in resolution (The spot radius, in comparison with the single-channel VIS spectrometer, is not uniformly improved across the spectral range and the field (**Error! Not a valid bookmark self-reference.**)). The spot radius shows outstanding results at small and medium angles but the spot radius tends to increase at large angles. I.e. the 400nm spots is $12\mu\text{m}$ smaller at 0° than its relative single-channel spectrometer but the spot at 60° is $10\mu\text{m}$ larger. Considering the 1100nm wavelength, the field at 0° is $10\mu\text{m}$ larger and the field at 60° is $2\mu\text{m}$ larger. This difference is due to a merit function focusing too much on the central wavelength. Nevertheless, those results are quite positive considering the challenging design.

Table 12) i.e., the spatial resolution at 0° and 60° for the longest wavelength (1100nm) is respectively $7,9\text{km}$ and $14,8\text{km}$. The spectral resolution remains below the required limit (20nm).

TABLE 13: SPATIAL AND SPECTRAL RESOLUTION AT THE DETECTOR'S PLANE FOR VIS CHANNEL OF THE FINAL SPECTROMETER'S DESIGN (AT 700nm), CALCULATED CONSIDERING THE NADIR, BEST, AVERAGE AND WORST SPOT RADIUS

Resolution nadir		Resolution best spot		Resolution average spot		Resolution worst spot	
Spatial [km]	Spectral [nm]	Spatial [km]	Spectral [nm]	Spatial [km]	Spectral [nm]	Spatial [km]	Spectral [nm]
2,60	2,12	2,60	2,12	3,71	3,03	6,63	5,41

The normalized PSF diagram for a 5×5 grid of spots around nadir and the central wavelength (700nm) shows that the spots can be resolved with the resolution defined at nadir; however, it is possible to tighten the spot's distance on a PSF diagram until the resolution limit (Figure 62), thereby improving the spatial and spectral resolution until $1,54\text{km}$ by 2nm . This spatial resolution represents an improvement of 1km compared to the calculated resolution at nadir. However, in practice these values will not be reached, since a system is never perfect and this includes really pushing the boundaries. The improvement of 1km can be explained via the presence of smile affecting the calculations but also by looking at the enclosed energy diagram (Figure 63). Small angles have the best encircled energy, (the closest to the full black line) and the RMS spot radius at nadir ($9,85\mu\text{m}$) shows an encircled energy of 80% . However it is still possible to decrease the radius from centroid, thus improve the resolution on the PSF diagram, and keep a large encircled energy.

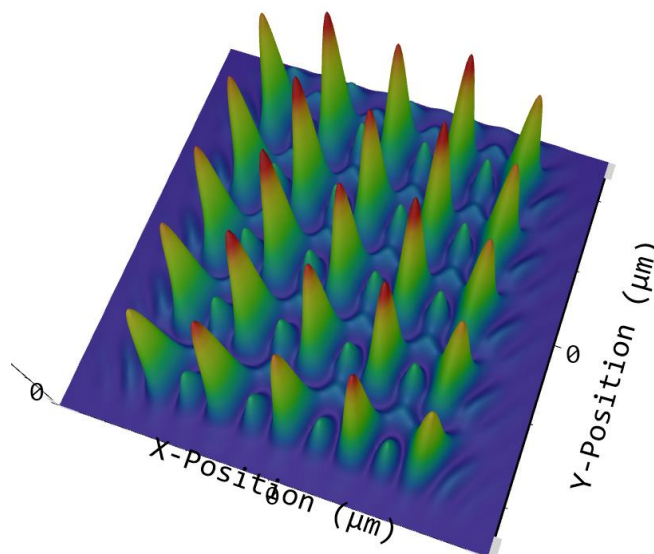


FIGURE 62: NORMALIZED PSF OF 5X5 NEIGHBORING SPOTS AROUND NADIR AND 700NM FOR VIS CHANNEL OF THE FINAL DESIGN, SHOWING THAT THE SPOTS CAN BE RESOLVED. THE SPATIAL AND SPECTRAL AXES ARE X AND Y, RESPECTIVELY.

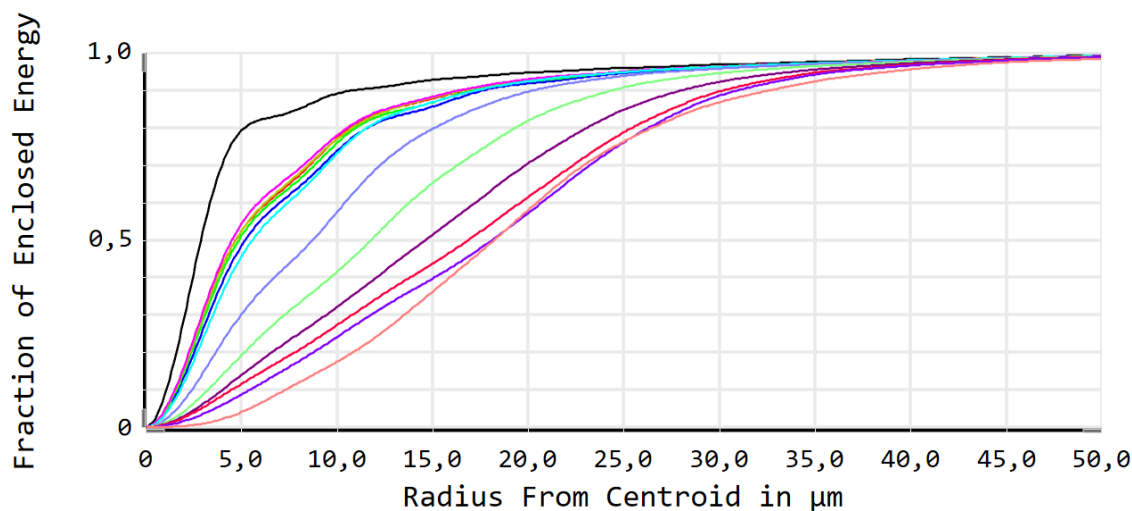


FIGURE 63: ENCLOSED ENERGY FOR EACH FIELD AT 700NM FOR THE VIS CHANNEL OF THE FINAL THREE-CHANNEL SPECTROMETER DESIGN, SHOWING GOOD PERFORMANCES FOR SMALL FIELDS AND A DECAY FROM THE 38° FIELD (GREEN)

The MTF (Figure 64) shows that the resolution does not reach the diffraction limit. At higher frequencies, an imbalance between sagittal (dotted line) and tangential (full lines) orientations becomes apparent, with a tendency for the sagittal fields to decrease more rapidly. Nevertheless, a Nyquist limit (calculated as the reciprocal of twice the pixel pitch) of 17 cycles/mm represents the maximum spatial frequency at which features can be sampled. Almost every field at this spatial frequency has an MTF exceeding 0,5 meaning that our system is able to resolve half of the object's contrast.

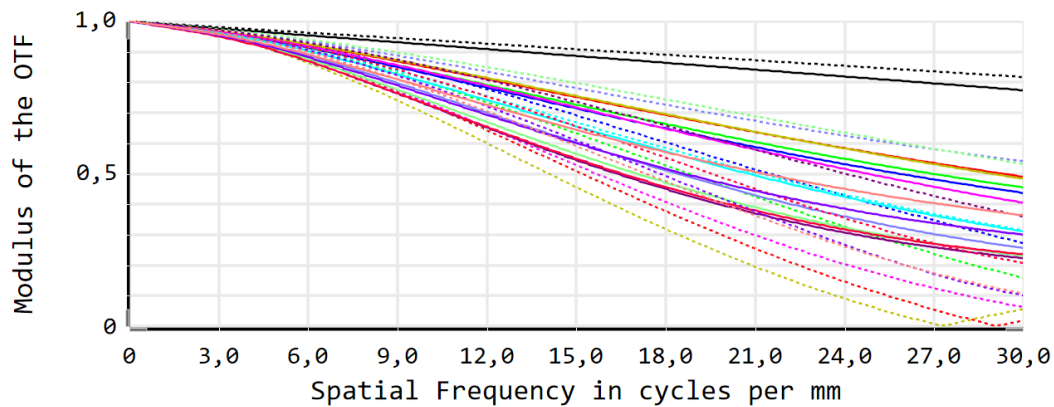


FIGURE 64: MTF OF THE FINAL SPECTROMETER'S DESIGN VIS CHANNEL, INDICATING AN AVERAGE MTF HIGHER THAN 0,5 AT 17 CYCLES/MM (THE NYQUIST LIMIT)

A particular optimization effort has been given to the aberrations control. The Seidel diagram (Figure 65) shows small aberrations except for distortion. Distortion is induced by the wide FOV and can be managed via post-processing. On a smaller scale, also astigmatism and coma are present. Astigmatism can be noticed in the spot diagram (Figure 61) with the oval shape appearing at higher angles (above 38°).



FIGURE 65: SEIDEL DIAGRAM FOR THE FINAL SPECTROMETER'S DESIGN VIS CHANNEL, INDICATING DISTORTION AS THE MAIN ABERRATION

The footprint diagram at the detector's plane (Figure 66) shows the presence of smile effect. This has the effect to increase the size of the detector along the Y-axis. The area of the detector is $28 \times 9 \text{ mm}^2$ and suitable commercially available detectors are discussed in the next chapter.

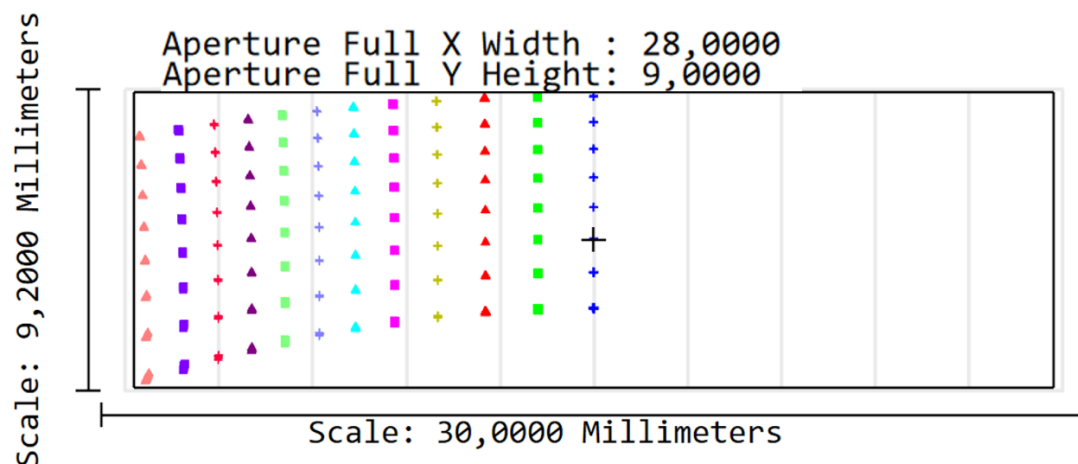


FIGURE 66: FOOTPRINT DIAGRAM OF THE VIS CHANNEL OF THE FINAL THREE CHANNEL DESIGN, SHOWING SMILE EFFECT AND PROVIDING THE AREA REQUIRED FOR THE DETECTOR. THE SPATIAL AND SPECTRAL AXES ARE X (COLORS) AND Y (ROWS), RESPECTIVELY.

3.4.2 NIR CHANNEL

The final spectrometer's design NIR channel, covering the 1000 nm – 1700 nm wavelength range (Figure 67), collects two-thirds of the light through the dichroic beam splitter, where the latter also operates as an aperture stop. The beam splitter transmits light to the reflective grating (0,12 lines/mm), and the diffracted light is ultimately focused by the two freeform mirrors at the image plane. The geometrical characteristics of the system are mainly dictated by compactness and positioning with the VIS channel. The second VIS mirror and the first NIR mirror are positioned closely to each other, showing a separation of 3,86mm. In Figure 60 and Figure 67, we can see at the bottom left the XYZ axis, showing the VIS channel propagating along the X direction and the NIR channel along the Z direction. The dichroic beam splitter is positioned 40,12mm from the collimator to avoid masking the rays at the entrance slit of the spectrometer (Figure 59). To limit the Z dimension, a reflection grating is used for the NIR channel.

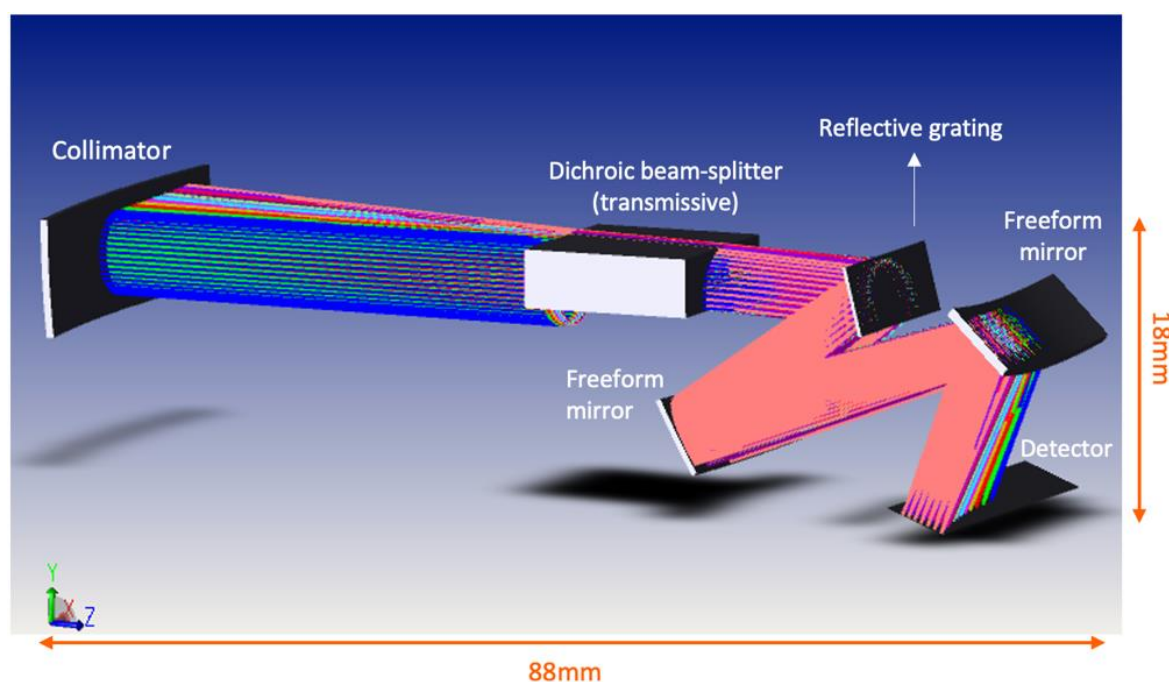


FIGURE 67: NIR CHANNEL PART OF THE THREE-CHANNEL FREEFORM SPECTROMETER'S FINAL DESIGN, SHOWING THE COMPONENTS PRESENTS IN THE DESIGN AND THE SIZE OF THE CHANNEL THAT IS FITTING INSIDE ONE CUBESAT UNIT.

The RMS spot radius diagram (Figure 68) at 1400nm showcases spots that are close to the diffraction limit. The spot radius has values between 11,91 μm at 16,36° and 20,69 μm at 49,09° with an average spot radius of 16,31 μm . The spot radius at nadir and 60° lies between those two values with radii of respectively 16,37 μm and 14,38 μm . The spot radius decreases from nadir to 16,36°, then increases until 49,09° to decrease for the rest of the fields. The inconstancy between the spots variation suggests that a possible amelioration is possible for the fields between 0° and 60°. The shortest field angles show the presence of spherical aberrations. However, optimization using the freeform terms does not enables a straightforward solution, since the reduction of one aberration type induces other aberrations. Consequently, the presented spots and performance offered the best trade-off between the different design parameters.

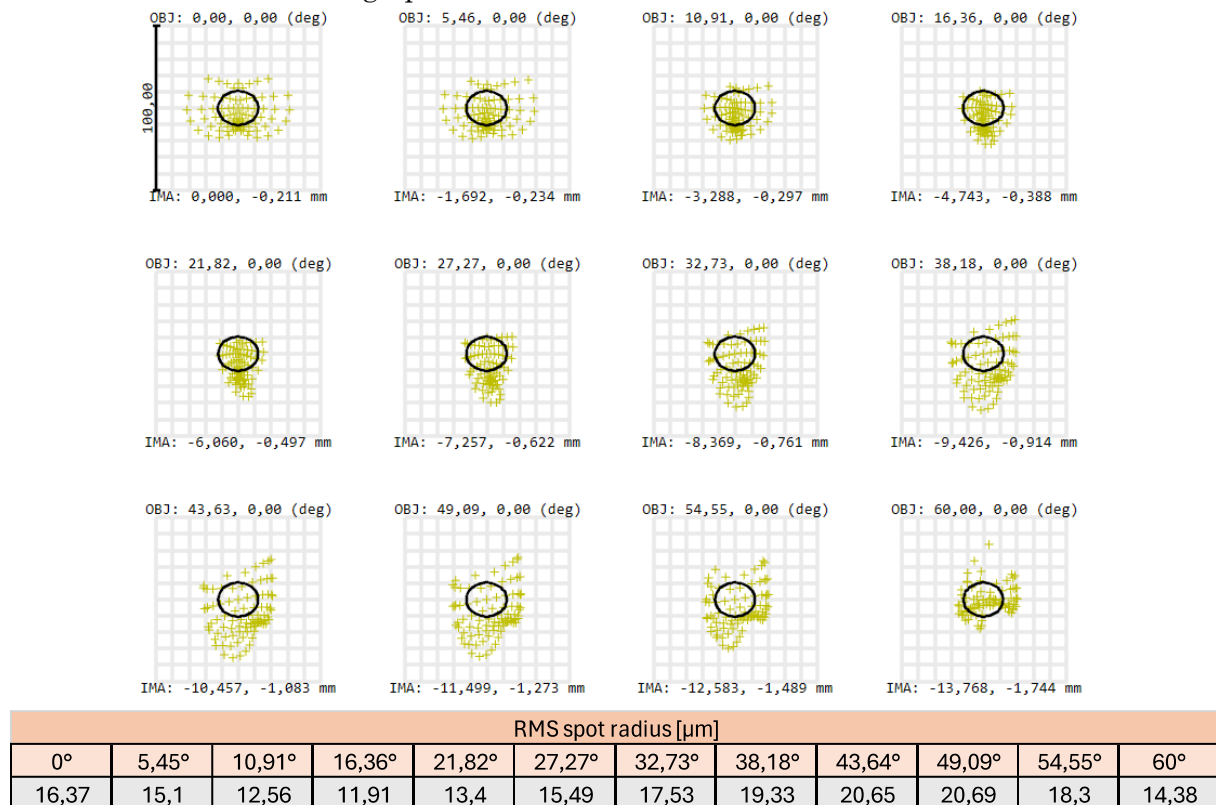
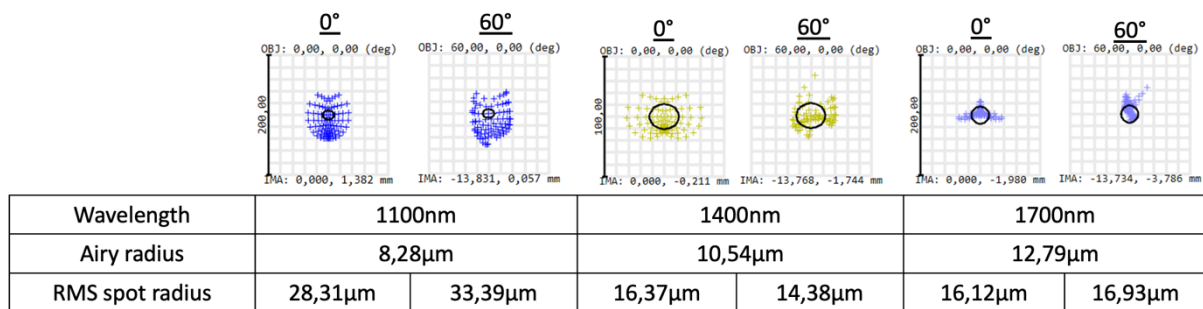


FIGURE 68: SPOT DIAGRAM OF THE NIR CHANNEL OF THE FINAL DESIGN AT THE CENTRAL WAVELENGTH (1100NM) SHOWING THAT THE SPOTS RADII VARY BETWEEN 11,91 μm AND 20,69 μm ALONG THE FIELDS

The spot radius at the shortest, central and longest wavelengths of the NIR range (Table 14) are showing good performances in the medium-large range but the spot radius tends to increase at the shortest wavelength. The RMS spot radius at 60° for 1100nm shows a size twice as large as the same field for other wavelengths.

TABLE 14: SPOT DIAGRAM FOR THE 0° AND 60° FIELD AT THE SHORTEST, CENTRAL AND LONGEST WAVELENGTHS OF THE FINAL DESIGN'S NIR CHANNEL, SHOWING A SMALL AND CONSTANT SPOT RADIUS AT MEDIUM-LARGE WAVELENGTH BUT WITH A TENDENCY TO INCREASE AT SMALL WAVELENGTHS



With an average spot radius at 1400nm of 16.31μm, we are close to the diffraction limit, considering the Airy radius is 10.54μm. The $f/\#$ equals 6.17, which is 1 unit lower than the single-channel NIR spectrometer and the lowest f -number of all systems presented in this thesis. The resolution calculated upon the RMS spot radius (Table 15) equals on average 4,31km spatially and 3,62nm spectrally. The spectral resolution does not vary much along the field angles and remains below the requirements (20nm), but the spatial resolution varies between 3,15km and 5,47km for the best and worst spot radii respectively. At the central wavelength, this channel successfully indicated a resolution fitting in the resolution's requirements of 5km by 20nm. However, the large spot radius at 1100nm (Table 14) induces a spatial resolution of 7,4km at 0° and 10,3km at 60° meaning that the requirement is not verified across the whole spectrum for the spatial resolution (the spectral resolution equals 6,2nm at 0° and 8,6 at 60°); nevertheless, the majority of the NIR spectral range (medium-long range) has a resolution below the 5km by 20nm required.

TABLE 15: SPATIAL AND SPECTRAL RESOLUTION AT THE DETECTOR'S PLANE FOR NIR CHANNEL OF THE FINAL SPECTROMETER'S DESIGN (AT 1100NM), CALCULATED CONSIDERING THE NADIR, BEST, AVERAGE AND WORST SPOT RADIUS.

Resolution nadir		Resolution best spot		Resolution average spot		Resolution worst spot	
Spatial [km]	Spectral [nm]	Spatial [km]	Spectral [nm]	Spatial [km]	Spectral [nm]	Spatial [km]	Spectral [nm]
4,33	3,64	3,15	2,65	4,31	3,62	5,47	4,60

The PSF diagram (Figure 69), is given for a 5x5 spot grid at nadir with a resolution of 4,1km by 3nm, which is approximately the same value as the calculated nadir resolution. It is interesting to notice that at each field, a three-beam shape is present along the spatial axis, indicating an influence by the neighboring spots. This broadening along the spatial axis causes the resolution to be uneven between the spatial and spectral axis. Due to the higher resolution on the spectral axis, it is easier to tighten the grid in this direction, giving a rectangular shape to the detector.

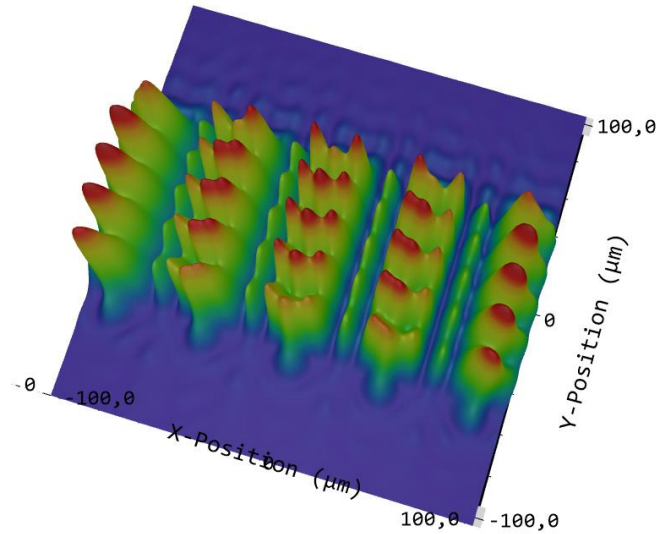


FIGURE 69: NORMALIZED PSF OF 5X5 NEIGHBORING SPOTS AROUND NADIR AND 1100NM FOR THE NIR CHANNEL OF THE FINAL DESIGN, SHOWING THAT THE SPOTS CAN BE RESOLVED. THE SPATIAL AND SPECTRAL AXES ARE X AND Y, RESPECTIVELY.

On the MTF diagram of the system (Figure 70), it is clear that the general tendency of each field is to follow the diffraction limit (black full and dotted lines). With a Nyquist limit calculated at 15 cycles/mm (considering the average spot radius), almost every field shows an MTF value of at least 0,5. However, performances are dropping for sagittal resolution at fields exceeding 43°, which show an MTF around 0,4 at 15 cycles/mm and 0,5 at 12 cycles/mm.

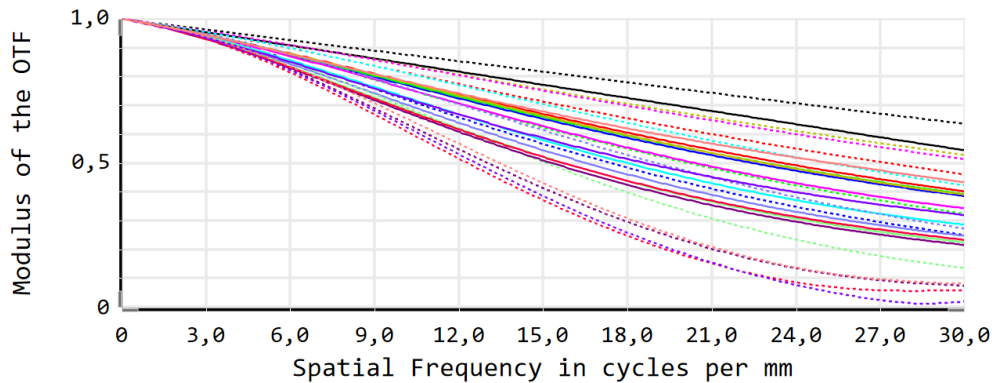


FIGURE 70: MTF FOR THE HFOV AT THE CENTRAL WAVELENGTH FOR THE FINAL DESIGN'S NIR CHANNEL

The Seidel diagram is similar to the Seidel diagram of the VIS channel (Figure 65), both showing a high distortion value, with decrescendo astigmatism, coma, and finally spherical aberrations. The magnitude of astigmatism and coma is featuring values of 20mm and 3mm, respectively. By looking at the spot diagram (Figure 68), spherical aberrations seem the most obvious at small angles. Coma can be seen at the center of the spot, especially between 16° to 27°, but astigmatism is the more underlying aberration, providing an elongated shape of the spots at fields higher than 21°.

Smile effect is present at the detector's plane and the detector's area is 28x5,4mm² (Figure 71). A discussion about commercially available detectors fitting the resolution and the area of the detector is proposed in the next chapter.

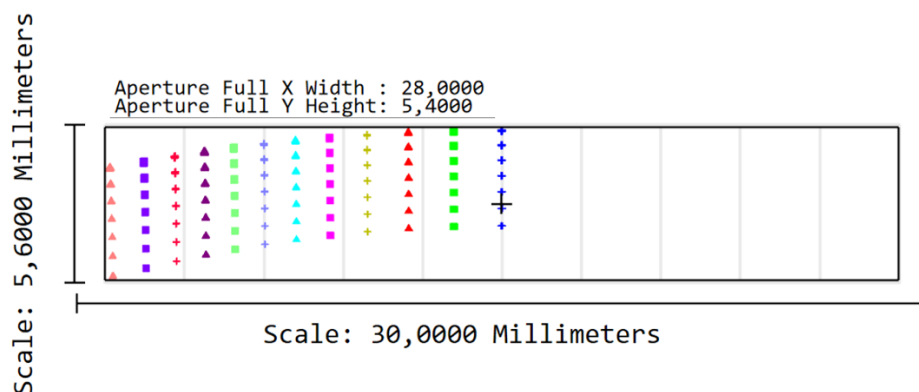


FIGURE 71: FOOTPRINT DIAGRAM AT THE DETECTOR PLANE OF THE NIR CHANNEL OF THE FINAL THREE-CHANNEL SPECTROMETER DESIGN, SHOWING THE PRESENCE OF SMILE EFFECT AND GIVING THE DETECTOR'S AREA. THE SPATIAL AND SPECTRAL AXES ARE X (COLORS) AND Y (ROWS), RESPECTIVELY.

3.4.3 THERMAL CHANNEL

The Thermal channel, covering the $8\mu\text{m} - 14\mu\text{m}$ wavelength range (Figure 72), of the final spectrometer design is not separated from the two other channels via a beam splitter, but rather directly takes the light from the collimated beam. One-third of the light is taken by the reflective grating (Figure 73) and two freeform mirrors are focusing the light to the image plane. The grating [15 l/mm], has been chosen reflective to maximize the compactness of the system.

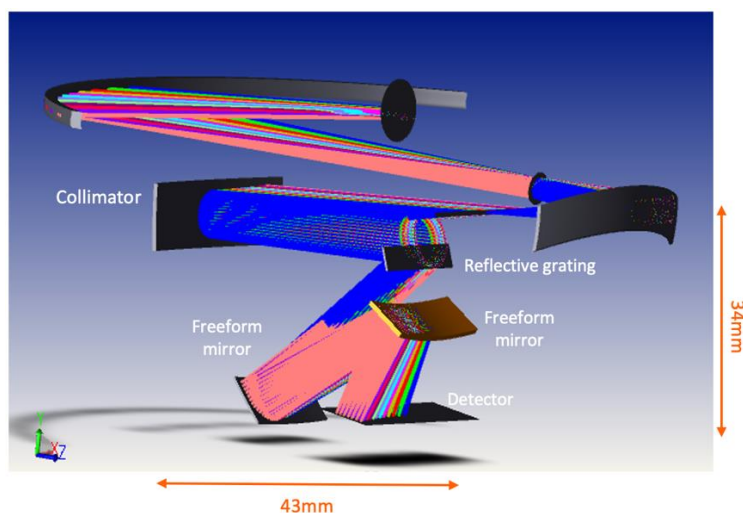


FIGURE 72: THERMAL CHANNEL PART (WITH THE TELESCOPE) OF THE THREE-CHANNEL FREEFORM SPECTROMETER 'S FINAL DESIGN, SHOWING THE COMPONENTS PRESENTS IN THE DESIGN AND THE SIZE OF THE CHANNEL THAT IS FITTING INSIDE ONE CUBESAT UNIT.

The reflective grating plays the geometrical splitting's role in the system. Placed in front of the dichroic beam splitter, the grating must reflect precisely one-third of the light, and leave the remaining two-thirds for the VIS-NIR channels. The positioning of the Thermal reflective grating is hence the main important part of the beam splitting. The portion of rays reflected through the thermal channel (Figure 73) equals 33% of the light, confirming the correct positioning of the grating. The 66% remaining are transmitted to the VIS-NIR channels.

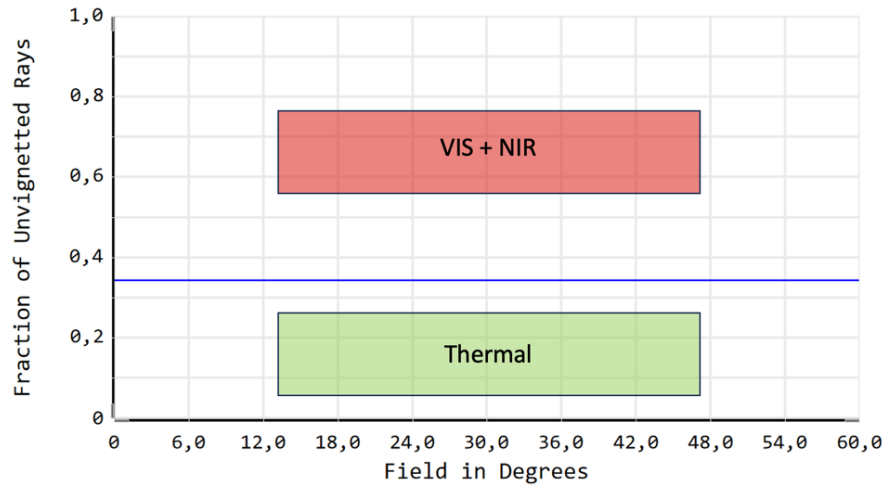


FIGURE 73: PORTION OF RAYS FROM THE COLLIMATED BEAM THAT IS REFLECTED BY THE GRATING OF THE THERMAL CHANNEL SHOWING THAT WELL TWO-THIRD OF THE LIGHT IS SEPARATED TO THE VIS-NIR CHANNELS AND ONE-THIRD TO THE THERMAL CHANNEL.

The RMS spot diagram (Figure 74) shows that the spots all fit inside the Airy radius, making this channel fully diffraction-limited. Spots radii vary in size with two maximums at nadir and 60°, corresponding to 36,2 μm and 43,5 μm , respectively, and one minimum at 49,09° with a spot radius of 25,64 μm .

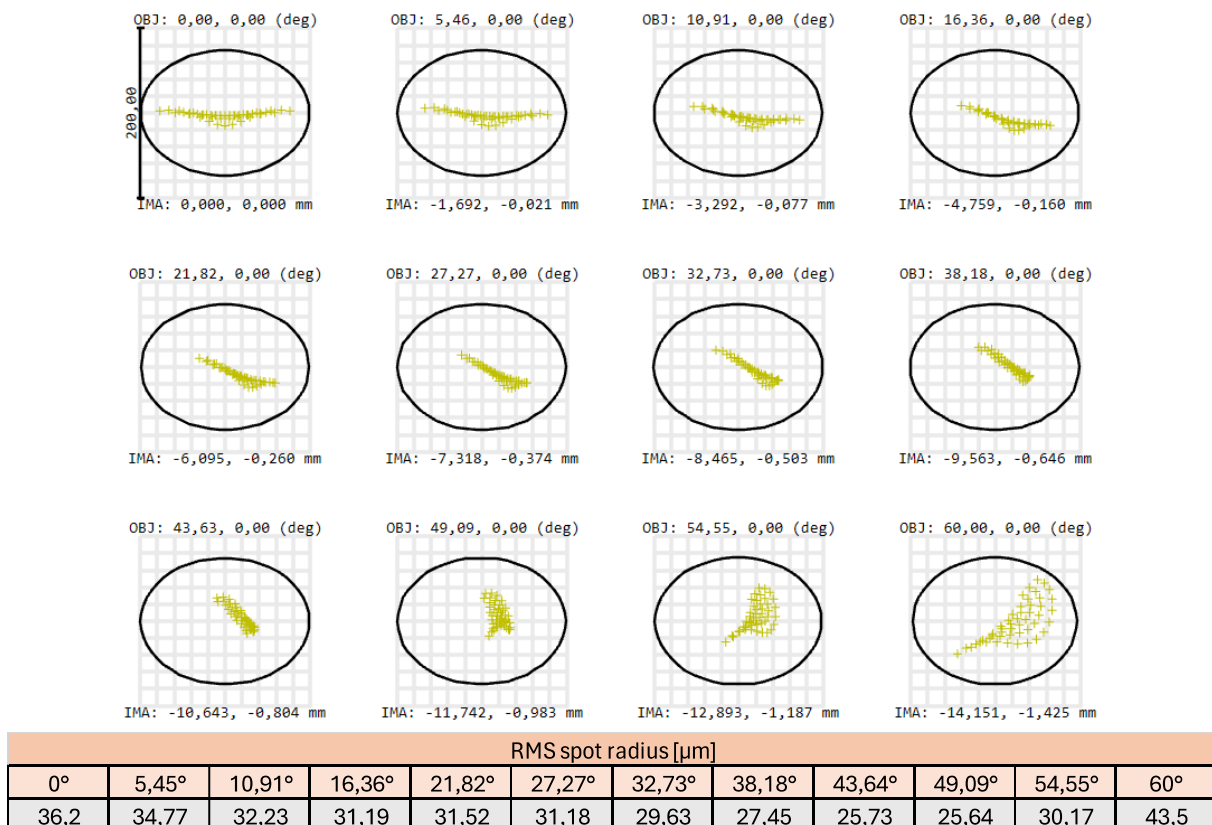
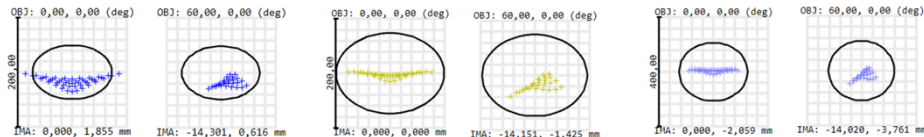


FIGURE 74: SPOT DIAGRAM OF THE THERMAL CHANNEL OF THE FINAL DESIGN AT THE CENTRAL WAVELENGTH (11 μm) SHOWING THAT THE SPOTS ARE DIFFRACTION-LIMITED AT EACH FIELDS

The spot radius at 0° and 60° for the shortest, central and longest wavelength (Table 16) feature the same shape and approximately the same size across the spectral range of the Thermal channel. This result shows a good optimization of the channel and even at the

shortest wavelength, the spot size remains inside the Airy disc proving a fully diffraction-limited system along the fields and the spectrum.

TABLE 16: SPOT DIAGRAM FOR THE 0° AND 60° FIELD AT THE SHORTEST, CENTRAL AND LONGEST WAVELENGTHS OF THE FINAL DESIGN'S THERMAL CHANNEL, SHOWING FULLY DIFFRACTION-LIMITED SPOTS ACROSS ALL WAVELENGTHS



Wavelength	8μm		11μm		14μm	
Airy radius	61,02μm		83,91μm		106,8μm	
RMS spot radius	43,60μm	29,27μm	36,20μm	31,37μm	44,27μm	33,89μm

The fully diffracted system means that the resolution is limited by the Rayleigh criterion defining the smallest pixel pitch as the Airy disk value. With this pitch, the resolution was calculated at the central wavelength (11μm) as 21,54km by 251nm. Even if this resolution is higher than the requirements (5km by 20nm), the physical limitations are making this resolution difficult to improve. However, in comparison to the single-channel Thermal spectrometer, the Airy disk decreased from 94,18μm to 83,9μm for the final three-channel design. This improvement finds its roots in the f-number that decreased from 7,01 to 6,25. Since the grating reduces the aperture of the Thermal channel, it is expected to have a higher f/#, but the increased focal length has a stronger impact on the f-number and reduces it to 6,25.

Plotting the PSF (Figure 75) with the minimal spatial resolution possible (such that fields can still be resolved) showed that it is possible to achieve a spatial resolution of 18,5km. This resolution is 3km better than the Airy disc resolution, which can only be attributed to the smile effect. And as for the single-channel Thermal spectrometer, an evaluation of the enclosed energy is required.

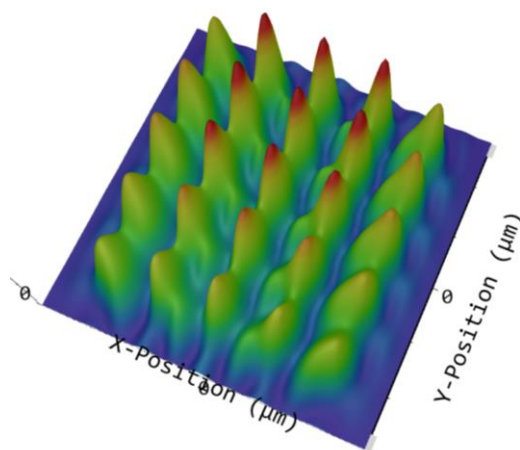


FIGURE 75: NORMALIZED PSF OF 5X5 NEIGHBORING SPOTS AROUND NADIR AND 11μm FOR THE THERMAL CHANNEL OF THE FINAL DESIGN, SHOWING THAT THE SPOTS CAN BE RESOLVED. THE SPATIAL AND SPECTRAL AXES ARE X AND Y, RESPECTIVELY.

The enclosed energy diagram (Figure 76) shows that at 83μm (the Airy radius) the fraction of enclosed energy is equal to approximately 65%. A possible improvement of 3km (as shown in the PSF diagram) corresponds to a spot radius of 73μm which approximates 60% of the encircled energy. This small difference in the fraction of enclosed energy, in addition to the smile effect, induces the possibility to improve slightly the resolution.

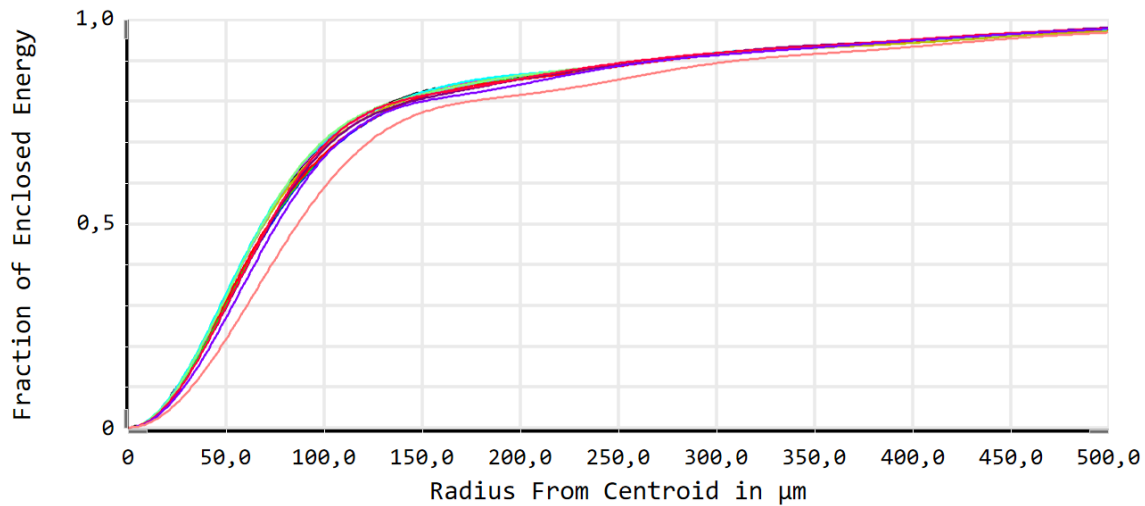


FIGURE 76: ENCLOSED ENERGY FOR EACH FIELD AT 11 μ m FOR THE THERMAL CHANNEL OF THE FINAL THREE-CHANNEL SPECTROMETER DESIGN, SHOWING A FULLY DIFFRACTION LIMITED SYSTEM WITH A SMALL DECAY AT 60°

In comparison with the enclosed energy of the single-channel Thermal spectrometer (Figure 57), the enclosed energy at the Airy radius from centroid of Figure 76 is not located on a plateau. The resolution's improvement is then more complicated. This reasoning is confirmed in Table 10 where the PSF resolution in comparison to the calculated resolution is improved by 7,5km for the single-channel spectrometer while it is improved by 3km for the three-channel spectrometer.

TABLE 17: COMPARISON BETWEEN THE SPATIAL RESOLUTION OF THE SINGLE CHANNEL THERMAL SPECTROMETER AND THE FINAL DESIGN THERMAL SPECTROMETER

	Thermal design	
	Single-channel	Three-channel
Nadir spot radius	27,2 μ m	36,2 μ m
Airy radius	94,18 μ m	83,9 μ m
Calculated resolution	24,57 km	21,41 km
PSF resolution	16,95 km	18,5 km

The MTF of the system confirms that the system is diffraction-limited on the tangential axis and close to the diffraction limit line on the sagittal axis. This difference between the two axes is not problematic since the Nyquist limit (based upon a pixel pitch equal to the Airy disk) gives a spatial frequency limiting the system at 2,97 cycles/mm. At this frequency, the MTF is a bit lower than 0,5 along the tangential axis and around 0,6 for the sagittal axis.

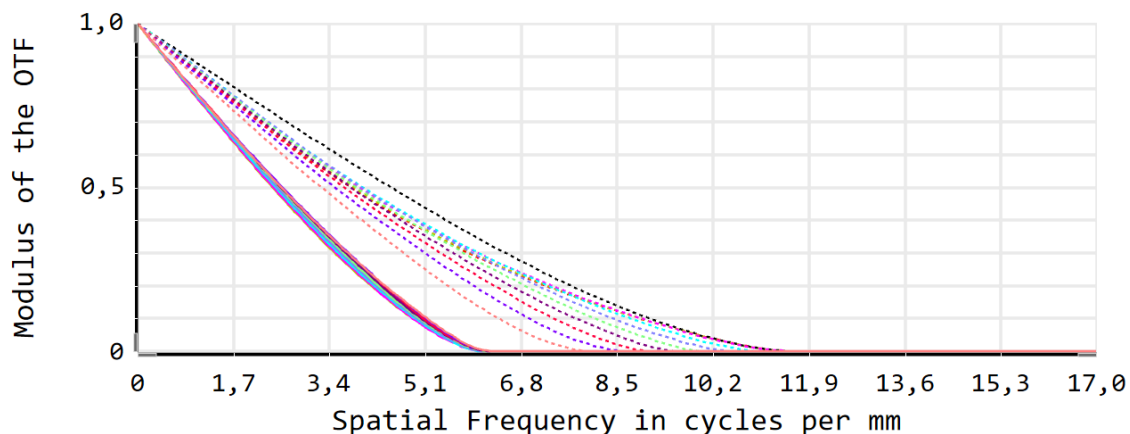


FIGURE 77: MTF OF THE FINAL DESIGN'S SPECTROMETER THERMAL CHANNEL

The Seidel diagram is visually similar to the VIS-NIR Seidel diagrams but with values twice as large. Astigmatism shows the largest effect, and is certainly the reason why the elongated beam along the sagittal axis gets squeezed and becomes oval along the tangential axis for higher fields. The footprint diagram at the detector's plane features smile effect and a detector's area of $29 \times 6,4 \text{ mm}^2$ (Figure 78). Discussion about commercially available detectors fitting the performances of the design is given in the next chapter.

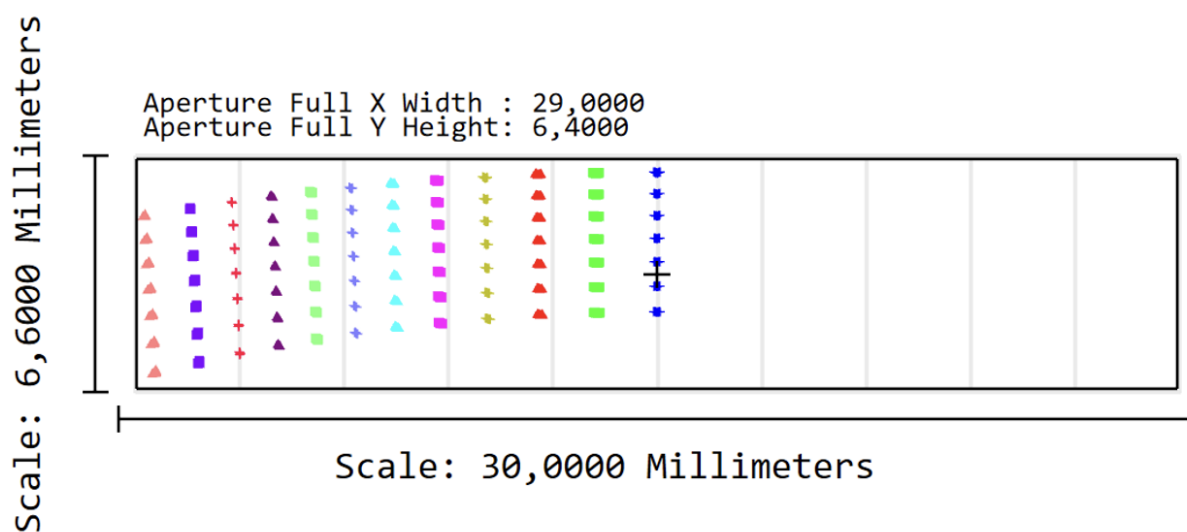


FIGURE 78: FOOTPRINT DIAGRAM AT THE DETECTOR PLANE OF THE NIR CHANNEL OF THE FINAL THREE-CHANNEL SPECTROMETER DESIGN, SHOWING THE PRESENCE OF SMILE EFFECT AND GIVING THE DETECTOR'S AREA. THE SPATIAL AND SPECTRAL AXES ARE X (COLORS) AND Y (ROWS), RESPECTIVELY.

3.5 SUMMARY AND CONCLUSION

This chapter presents our novel spectrometer design, starting from the individual visible, near-infrared and thermal spectrometer channels, towards the combined three-channel system. Considering the visible channel, two design configurations are explored and compared, including an Offner structure. The Offner spectrometer showcased a worse resolution than the single VIS spectrometer, but without the presence of the smile effect. Considering the VIS and NIR single channels, we achieved a better resolution than the targeted one (5 km by 20 nm), while the Thermal channel showed to be limited by its spot radius limiting the resolution to 25 km by 230 nm . The three channel spectrometer is showing an excellent performance while fitting inside one CubeSat unit.

TABLE 18: CALCULATED RESOLUTION AT NADIR AT THE CENTRAL WAVELENGTH (700NM FOR VIS, 1400NM FOR NIR, AND 11 μ M FOR THERMAL) FOR EACH DESIGN PRESENTED IN THIS CHAPTER

		Single channel				Three channel		
Resolution		VIS	VIS Offner	NIR	Thermal	VIS	NIR	Thermal
Calculated	spatial [km]	3,35	15,83	3,22	24,57	2,60	4,33	21,41
at nadir	spectral [nm]	2,73	16,71	4,49	230,64	1,53	3,64	157,31

The variation of the resolution across the respective spectral range of each channel and across the FOV is relatively constant, however, both the VIS and NIR channels could be further optimized around 1100nm (longest wavelength of the VIS range, shortest of the NIR) since the resolution at this wavelength is exceeding the requirement. In addition, each design showed minimal presence of aberrations and an close to diffraction-limited modulation transfer function.

Chapter 4: PATH TOWARDS PHYSICAL REALIZATION

An evaluation is made towards the realization of the three channel demonstrator (Figure 79), which will be discussed within this chapter.

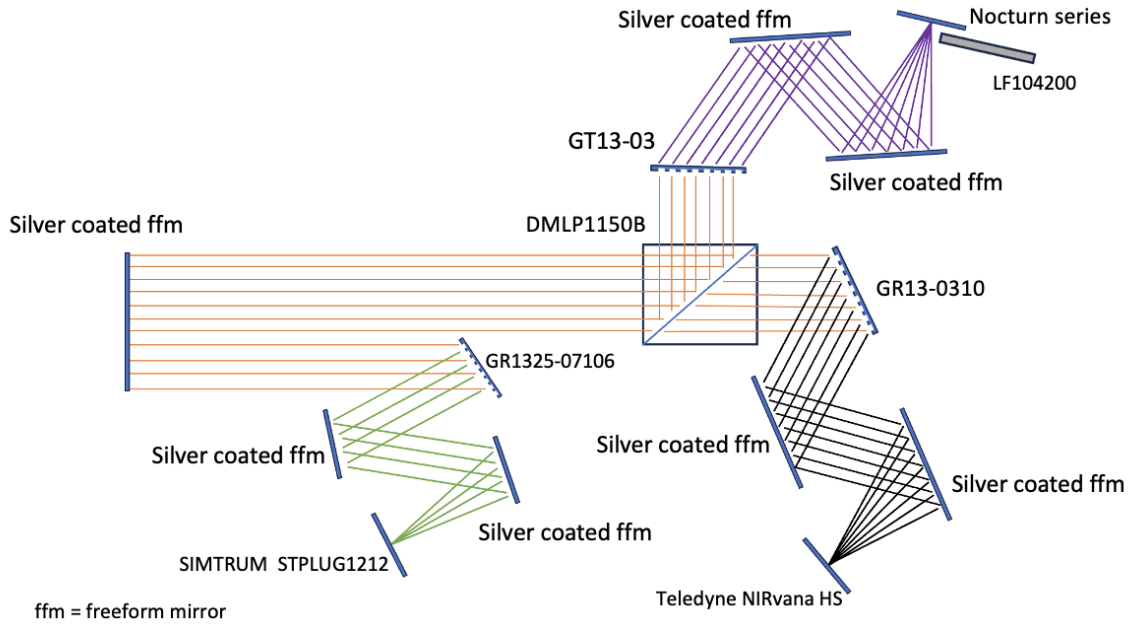


FIGURE 79: FINAL DESIGN SUMMARY WITH EVERY COMMERCIALY AVAILABLE COMPONENTS DISCUSSED IN CHAPTER 2:

Considering the required optical components, the following elements will be included:

- Dichroic beam splitter: DMLP1150B[31] from Thorlabs (section 2.3)
- Diffraction gratings (section 0)
 - VIS channel: GT13-03[34] from Thorlabs
 - NIR channel: GR13-0310[44] from Thorlabs (presented in the next paragraph)
 - Thermal channel: GR1325-07106[45] from Thorlabs (next paragraph)
- Silver freeform mirrors (section 2.5)
- Filter at the VIS channel: LF104200[38] (section 0)
- Optical sensors (section 4.1)
 - VIS detector: Nocturn series[46]
 - NIR detector: Teledyne NIRvana HS[47]
 - Thermal detector: SIMTRUM STPLUG1212[48]

Considering the gratings for the NIR and Thermal channels we select respectively the GR13-0310[44] and the GR1325-07106[45], both available at Thorlabs. The GR13-0310 for the NIR channel is a blazed grating with 300 grooves/mm. This grating periodicity is more than twice the value simulated in this thesis, however, it is difficult to find commercially available gratings matching this thesis's specifications. The high periodicity will increase the diffraction angle and possibly require slight grating adjustments when calibrating the incident angle. The efficiency of the grating at the NIR range (Figure 80 left) shows an average value of 65%. The GR1325-07106, designed for the Thermal range, is a blazed grating with 75 grooves/mm. This value, however, significantly deviates from the simulated value. Consequently, custom-made gratings will be necessary at a later stage of the development process, involving the production of gratings with the appropriate number of grooves/mm and dimensions. The efficiency of this grating, for the first order, shows an average value of 71% between the 8 μ m to 14 μ m wavelengths (Figure 80 right).

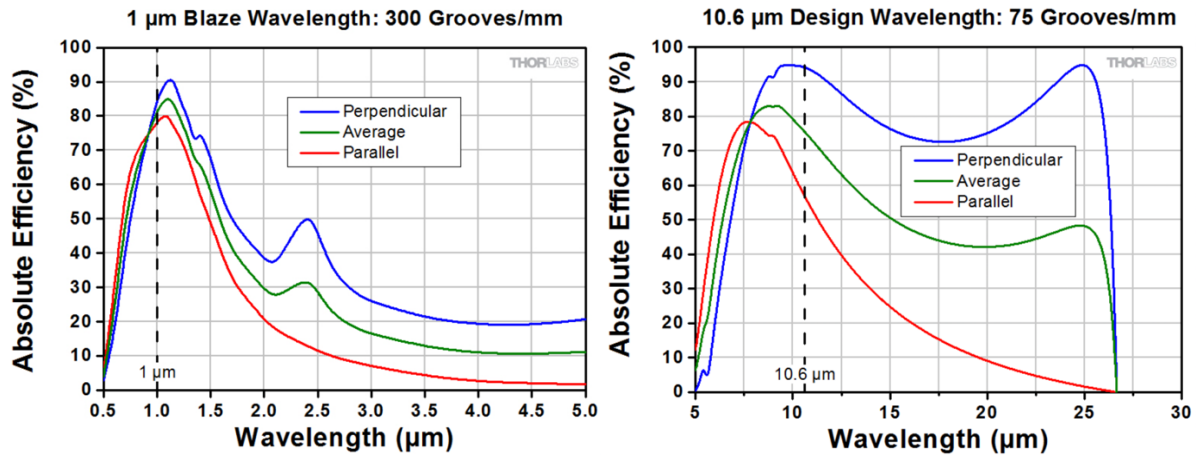


FIGURE 80: GRATING EFFICIENCY CURVE AS A FUNCTION OF THE SPECTRUM FOR (LEFT) THE GR13-0310[44] AT THE NIR CHANNEL AND (RIGHT) THE GR1325-07106[45] AT THE THERMAL CHANNEL

Within the next parts of this chapter, an evaluation will be made on the proposed detectors (Section 4.1), followed by a calculation of the energy budget taking into account the efficiency of all individual components (Section 4.2), a tolerance analysis taking into account the optical and mechanical design errors (Section 4.3) and a stray-light analysis (Section 4.4).

4.1 OPTICAL SENSORS

Considering the final design presented in Section 3.4, performances at the detector plane for the three channels are given in Table 19. The spot radius given is the one calculated from the RMS spot radius diagram (for the central wavelength) and in the Thermal case, is equal to the Airy radius since the spots are diffraction-limited. The number of pixels is calculated by dividing the detector size by the spot radius. Additionally, the number of frames per second (FPS) is given for a resolution of 5km with pushbroom scanning, considering that the telescope moves in space at a speed of 7km/s and approximating that for small displacements, the Earth's surface and the telescope orbits are considered as parallel planes. Note that it is possible to reach a resolution smaller than 1km, since this only requires a FPS of 7Hz.

TABLE 19: PERFORMANCES AND DETECTOR CHARACTERISTICS FOR THE CENTRAL WAVELENGTH OF EACH CHANNELS FROM THE FINAL THREE-CHANNEL DESIGN

Channels	RMS spot radius [μm]			Detector size Full FOV° (x° x λ [mm])	# pixels x° (X-axis)			# pixels λ (Y-axis)			FPS [Hz] 5km
	Best	Avg	Worst		Best	Avg	Worst	Best	Avg	Worst	
VIS (at λ = 0,7μm)	8,3	14	25,1	28 x 9	1687	996	558	542	320	179	1,42
NIR (at λ = 1,4μm)	11,9	16.3	20.7	28 x 5,4	1176	858	677	227	166	130	
Thermal (at λ = 11μm)	83,9			29 x 6,4	173			38			

Considering those values, a technology study has been made to indicate commercially available detectors that could suit the application of this thesis. The outcome of this study is given in Table 20 whereas the choice's criteria are based upon the Table 19 characteristics and the channel's wavelength.

TABLE 20: COMMERCIALY AVAILABLE DETECTORS

Brand	Material	Active area [mm]	# pixels	Pixel size [$\mu\text{m} \times \mu\text{m}$]	Min. Wavelength	Max. Wavelength	FPS [Hz]
S16101 Hamamatsu	CMOS	9.472 x 7.578	1280 x 1024	7.4 x 7.4	200 nm	1000 nm	146
Nocturn Series	CMOS	12.416 x 9.932	1280 x 1024	9.7 μm	350 nm	1100 nm	100
Teledyne NIRvana HS	InGaAs	12.8 x 10.24	640 x 512	20 X 20 μm	900 nm	1700 nm	250
G13393 of Hamamatsu	InGaAs	12.8 x 10.24	640 x 512	20 X 20 μm	950 nm	1700 nm	62
Xenics Dione 1024	Micro-bolometer	12.28 x 9.432	1024 x 786	12 μm	8 μm	14 μm	80
SIMTRUM STPLUG1212R	Micro-bolometer	15.36 x 12.28	1280 x 1024	12 μm	8 μm	14 μm	25

It is clear that the dimensions of the simulated detectors are not matching the ones in Table 20, therefore, the solution is to make a row of detectors such that it matches the number of pixels and the size along the spatial direction. Following the detectors presented, it is required to have a row of three detectors along the spatial direction for the VIS and NIR channels and two detectors along the thermal channel. It is interesting to note that there is a common ground in terms of technologies for each channel. The VIS channel is based on CMOS detectors, the NIR on InGaAs, and the Thermal on the Micro-bolometer technology. To have a more in-depth understanding of those technologies, a small introduction to their operation principles is given in sections 0, 0, and 4.1.3. For each sections, after the introduction to the technology, a discussion is given about the integration of the detectors in Table 20 to the system. We particularly discuss the size of the detector, is pixel pitch and how to manage to get the best possible resolution.

4.1.1 CMOS-BASED DETECTOR FOR THE VIS RANGE

Complementary Metal Oxide Semiconductor (CMOS) has been driving the performance in visible imaging since the 1990s, enabling chips with a smaller pixel size, reduced noise, larger imaging arrays, and better image processing. CMOS sensors are chips constituted of different parts, mainly the sensing one (brown part in Figure 81) constituted of photodiodes and NMOS/PMOS, and processing parts including a clock, signal converters, logic gates, etc.

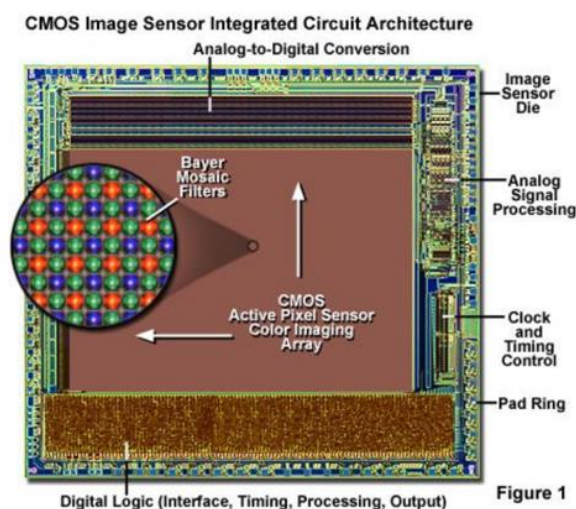


FIGURE 81: CMOS IMAGE SENSOR INTEGRATED CIRCUIT ARCHITECTURE [49]

CMOS chips are integrated on Silicon, using the photoelectric effect to sense the incoming light and image it. When light from the visible spectrum interacts with doped silicon semiconductor materials, the photoelectric effect causes a release of electrons proportional to the intensity and the wavelength of the incident light. Those electrons are trapped in the potential well of the semiconductor until they are released at the end of the illumination where they are converted into a signal. This process occurs at each pixel of the CMOS array and at each frame. The amount of electrons that can be accumulated in the potential well in addition to the conversion efficiency gives insights about the sensitivity of the detector. The sensitivity is also ruled by the geometry of the pixel, its size, and the ratio between the photodiode and the NMOS/PMOS components. Figure 82 depicts four pixels, the photodiode part is represented by a P and the transistor part is represented by a T. It is clear that the majority of the pixel's area is occupied by the transistor causing a loss in conversion efficiency since only the photosensitive part (approximately 25% of the pixel in Figure 82) is used for detection. The fill factor of the CMOS chip represents between 30% to 80% of the pixel area in CMOS sensors. This leads to a reduction in sensitivity that lowers the SNR and the dynamic range. A possible technique to overcome this sensitivity problem with a given CMOS sensor lies in increasing the exposition time of the photodiode. An additional parameter related to the photosensitivity of a sensor device is the Quantum Efficiency (QE). It corresponds to the ratio between the quantity of charge carriers (electrons) created by a quantity of incident photons with a given energy. Two variants of the quantum efficiency are possible, the External and the Internal Quantum Efficiency (EQE & IQE) respectively indicating if the photon flux is considered incident on the whole sensor or if the photon flux is only considered incident on the active, photodiode part of the sensor. Since IQE only considers the number of absorbed photons, its value is larger than EQE, and additionally, a low value of IQE reveals a poor detector not able to convert efficiently light into electricity.[50] Not all manufacturers do specify the quantum efficiency of their product, but it is expected for the three channels to have detectors with a QE constant on the spectral range with a value as high as possible. [49]

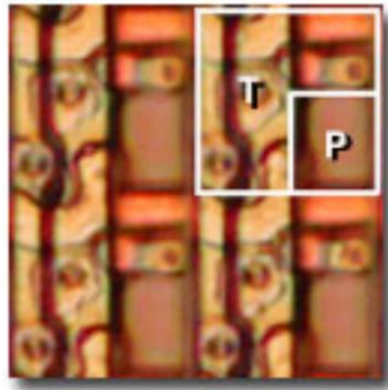


FIGURE 82: CMOS PHOTODIODES ZOOMED[49]

Detectors fitting the design: the Nocturn series and the S16101 from Hamamatsu

The footprints at the detector presented in Figure 66 show the presence of a smile effect increasing the size of the detector along the Y-axis. Nevertheless, the final size of the detector is manageable. The final detector requires an active area of 28mm x 9mm which is not commercially available but possible to make with a row of three or four detectors. Considering the dimensions, a row of three Nocturn series sensors[46] (Table 20) makes a final sensor of 29,7x12,4mm² for a total of 3072 pixels along the spatial axis and 1280 along the spectral axis. The sensor features a 9,7μm pixel pitch, giving the right amount of pixels required to match the values presented in Table 19. The RMS spot radius for the VIS channel, shows that the spot at the detector will have an area (approximating a

square) of $28 \times 28 \mu\text{m}^2$ for the average spot radius and fills 996 pixels on the X direction (spatial) and 320 pixels on the Y direction (spectral). If we consider the Nocturn series with its $9.7 \mu\text{m}$ pitch, we need to merge 3 pixels on the X and 3 pixels in the Y direction to make final pixels with an area of $29.1 \times 29.1 \mu\text{m}^2$ which is almost identical to the simulated value. In addition, the final amount of pixels will be 1024 in the X direction and 426 in the Y direction which is close to the average number of pixels calculated (996×320 in Table 19). Even though the specifications assure good performances from a range between 350nm to 1100nm, the quantum efficiency is not specified and should be asked to the manufacturer.

The other detector, the S16101 from Hamamatsu[51], requires a row of four times the detector to cover an area of $30.3 \times 9.4 \text{mm}^2$, matching the specifications. The number of pixels along the spatial direction matches the different RMS spot radii presented in Table 19. With a pixel pitch of $7.4 \mu\text{m}$, it requires to merge 4×4 pixels to make a final area of $29.6 \times 29.6 \mu\text{m}^2$ which is slightly larger than the spot radius simulated. The final amount of pixels is a bit below 1024 on the X direction and below 320 on the Y direction. The quantum efficiency of this detector is low; it drops below 25% after 950nm and almost at zero at 1100nm. This detector might be useful for first tests but is not advised for the final instrument.

Calculating the possible resolution of those two detectors, we achieve 3.86km by 2.27nm for the Nocturn series and 3.91km by 2.3nm for the Hamamatsu one.

4.1.2 INGAAS DETECTOR FOR THE NIR RANGE

Indium Gallium Arsenide (InGaAs) is from the family of III-V semiconductors and widely used in photonics due to their direct bandgap. Detectors made from this material are photosensitive in the NIR-SWIR region. In comparison, the Silicon platform with its indirect bandgap, used for CMOS detectors, is only sensitive to wavelengths smaller than 1100nm.

The sensitivity of the InGaAs detector can be tuned by changing the doping, allowing the detector to fit the specific requirements of the application. Due to the high sensitivity of the InGaAs detector to temperature, cooling the detector by 10° has as effect to shift by -8nm the long-wavelength cutoff. This cooling parameter is extremely important since it has a positive effect on the dark current more present in InGaAs technology due to its low bandgap. State-of-the-art InGaAs cameras are cooled down to a temperature between -85° to -65°C as it is the case for the two cameras presented in this section that are both cooled thermo-electrically. [47]

The fabrication of InGaAs detectors is done by growing InGaAs on an InP substrate matching the lattice and followed by a readout of integrated circuits as shown in Figure 83. The different layers made of InGaAs and InP have different purposes linked to their charge and their bandgap. In addition, an anti-reflective coating is added at the substrate's entry to transmit all the light into the detector.

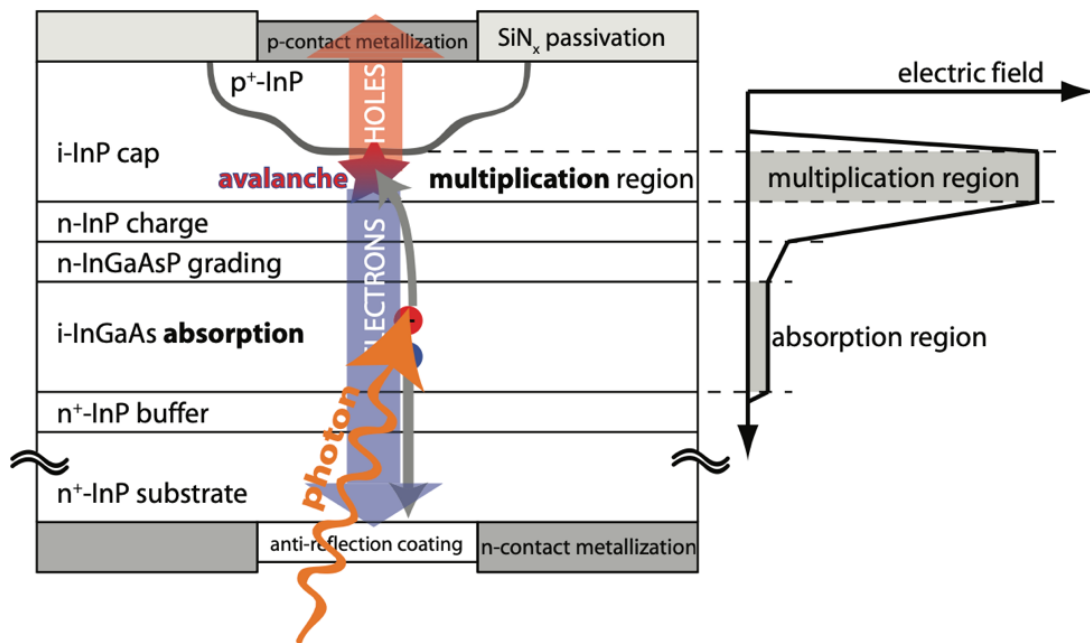


FIGURE 83: InGaAs/InP STRUCTURE AND ELECTRIC FIELD PROFILE[52]

The incoming photon first passes the InP substrate layer. InP is transparent for wavelengths longer than 900nm and the photon continues through the structure until it gets absorbed by the InGaAs layer. At the absorption, an electron-hole pair is generated. The electric field applied on both sides of the detector (in Figure 83 the anode is at the top at the “p-contact metallization” and the cathode is at the bottom at the “n-contact metallization”) drives the electron towards the substrate while the hole is drifted towards the InP-cap layer, called the multiplication region, where the InP lattice ionizes due to collisions. A high electric field may trigger an avalanche current drifting a high amount of holes to the p⁺-InP region triggering the detection.

Dark carriers might drift in the multiplication region and trigger avalanche and false counts even in absence of photons. In addition, the complexity of the manufacturing process tend to result in a small percentage of invalid pixels. Those pixels are sorted into three categories, being non-uniform, dark, and bright. The non-uniform pixels respond differently than their neighboring ones due to a difference in sensibility, dark pixels simply always appear dark whereas the bright ones are always saturated and appear white at the image. In addition to the pixel manufacturability issues, the presence of amplification at each pixel creates a fixed pattern noise at each variation of the gain or the response. To resolve those problems a post-processing specific to InGaAs detectors is required.[53], [54]

Detectors fitting the design: the Teledyne NIRvana HS and the G13393 from Hamamatsu

Considering the final design’s footprint presented in Figure 71, we can see that smile effect is present and that the detector area is 28mm by 5.4mm. Considering the proposed detector in Table 20, the Teledyne NIRvana HS[47] and the Hamamatsu G13393[55]; a row of three detectors is necessary to achieve an active area of 30.72mm by 12.8mm, featuring a total of 1536 pixels for the spatial axis and 640 for the spectral axis with 20μm pixel pitch. The comparison to the results of Table 19 show that this setup works with the average RMS radius of the optical system under the condition to have 2x2 merged pixels for a final pixel area of 40x40μm² matching a simulated area of 32.6x32.6μm² for the average pixel pitch. However, as a consequence of this increase in pixel area, a decrease

in resolution will be faced. The resolution achieved by those two detectors will be 5.28km by 4.44nm. The two detectors feature the same characteristics in terms of size and pixels but the QE is only given for the Teledyne. The strength of the Teledyne QE (Figure 84) is its broad linear efficiency exceeding 80%. For the Hamamatsu detector, an inconstant spectral response is given with a photosensitivity of 0,5 at 1100nm and 0,8 at 1600nm, decreasing to 0,1 at 1700nm.

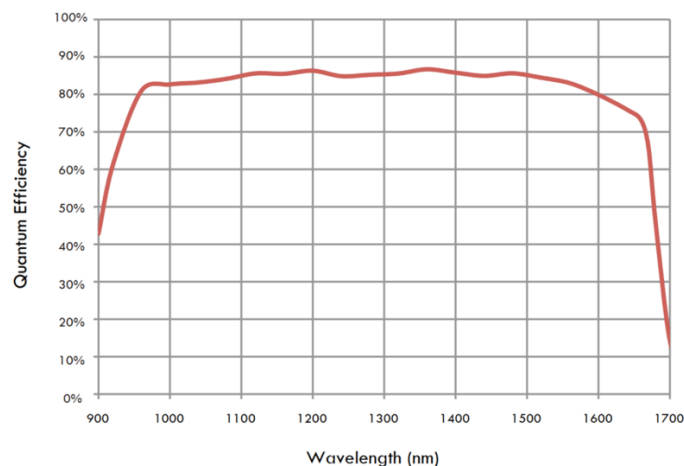


FIGURE 84: TELEDYNE NIR CAMERA QUANTUM EFFICIENCY[47]

4.1.3 BOLOMETER TECHNOLOGY FOR THE THERMAL RANGE

Bolometer's technology is based on the absorption of IR waves to generate heat that is then transformed into a current or a voltage; two measurable quantities. Therefore, a bolometer requires a component capable of absorbing light efficiently, and another component, a thermometer, highly sensitive to heat variations and capable of transforming the information into electricity. Finally, the system can be mounted on a read-out integrated circuit (with a thermal insulator between the thermometer and the readout integrated circuit (ROIC)), to directly process the signal.

The structure of the pixel is one of the key parameters to improve the performance of the detector. I.e. temperature losses and the component's heat capacitance are detrimental to the detector. To avoid such a phenomenon, the absorber and the thermometer are suspended as in Figure 85. This structure allows avoidance of conduction from the thermal parts to the substrate and reduces the heat capacitance of the system. This suspended system is the key to a highly efficient thermal detector, however, it must be consistent in terms of mechanical support, thermal conduction, and electrical conduction.

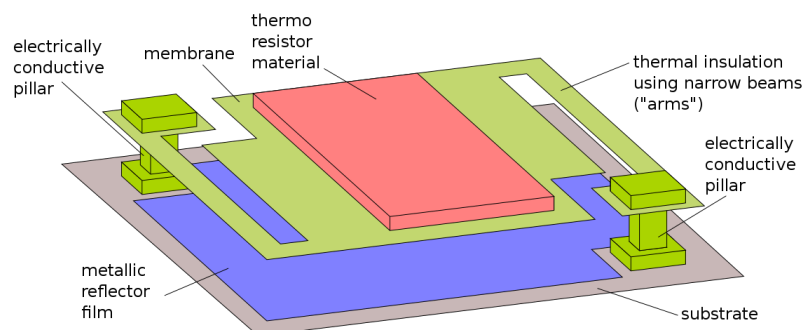


FIGURE 85: BOLOMETER'S PLATFORM[56]

Electricity is added to the system via the pillars to create a bias current. The circuit works as a closed system with a bias current, a load resistor, and a resistor in series corresponding to the membrane's resistance. The membrane's rise of temperature induces

a change in its resistivity; due to this phenomenon, the voltage across the resistance varies subsequently and is amplified through the bias voltage. A wide range of materials can be used for this technology but the principal requirement is the responsivity of the material. It means the ability of the material to convert the received heat into an electrical signal.[57]

Detectors fitting the design: The Xenics Dione 1024 and the SIMTRUM STPLUG1212R

Considering the footprint at the detector's thermal channel as shown in Figure 78, we observe a constant in size and smile effect between the three channels. The two microbolometers in Table 20, the Dione 1024[58] and the STPLUG1212R[48], are both working with a $12\mu\text{m}$ pitch which means that to match the Airy disc of the thermal channel (Table 19), at least 14 pixels are needed. Therefore, to match the simulated pitch of the Airy disc of $167,8 \times 167,8\mu\text{m}^2$, a merge of 14×14 pixels is needed. In the latter case, the final resolution would be $21,6\text{km}$ by 251nm . The size of the detector (Figure 78) is $29 \times 6,4\text{mm}^2$ meaning that a row of two detectors for the SIMTRUM and three detectors for the Xenics is required. The one maximizing the space best is the SIMTRUM STPLUG1212R with a cumulated active area of $30,72 \times 12,28\text{mm}^2$. With this length along the Y-axis being twice the size of the detector's area ($6,4\text{mm}$), it would be interesting as a future improvement to slightly adjust the spot's focusing of the Thermal channel such that it covers a longer Y-axis. This would allow to increase the spectral resolution that is currently limited by the Airy disc. I.e. increasing the detector's height by a factor of two would improve the spectral resolution by a factor of two.

4.2 ENERGY BUDGET

The energy budget for each of the final three spectrometer channels is presented in Table 21, and aims to calculate the amount of light reaching to each of the image sensors. This table is comprising three parts, the orange lines consider the elements impacting the irradiance, particularly those that have an efficiency given in their datasheet, the blue parts considers the elements acting as an aperture, and the green parts looks at the pixel pitch to find the final power at the pixel level. It considers how the Earth irradiance (total Earth irradiance equals 100W/m^2 for VIS-NIR and 240W/m^2 for Thermal) for a surface of 3700km by 500km (surface of one scan with the pushbroom scanning) decreases by interacting with each component of the final design. The energy budget is calculated for each channel separately from the efficiency of each commercially available component. I.e. the silver-coated freeform mirrors lose one percent of efficiency within the VIS range because the efficiency drops from 97% at 450nm to 88% at 400nm while it is given that the efficiency is 97% for the NIR channel and 95% for the Thermal channel. The VIS channel embeds a filter to avoid an overlap in the FSR as discussed in section 0, which transmits 90% of the light. For every component in the orange section, the considered efficiency's corresponds to the average or the lowest performance. An exception is the grating where the efficiency is not the direct given value from the datasheet but is recalculated upon the spectral response given in the datasheet. The detectors chosen for the energy budget are the Nocturn Series[46] for the VIS, the Teledyne[47] for the NIR. No choice has been made for the Thermal channel since both detectors, the Xenics[58] and the SIMTRUM[48], have the same performances. The inconvenience for the VIS and Thermal channel detectors is that the Quantum Efficiency is not given in the datasheet and hence cannot be counted in the energy budget. We assume that the final value for those channels will be less than what is given.

The telescope aperture and the geometrical split (blue lines in Table 21) are separated from the irradiance (orange lines) because they don't affect directly the irradiance, they just have an aperture effect but the ratio of the power by the area will remain unchanged.

At the geometrical splitting, the power undergoes a ratio of 66% at the VIS-NIR channels and 33% at the Thermal channel.

TABLE 21: FINAL DESIGN'S ENERGY BUDGET

		VIS	NIR	Thermal
Irradiance scan [W/m ²]		0,00363	0,00363	0,00871
Telescope	Freeform 1	0,96	0,97	0,95
	Total [W/m ²]	0,00348	0,00352	0,00828
	Freeform 2	0,96	0,97	0,95
	Total [W/m ²]	0,00335	0,00342	0,00786
Collimator		0,96	0,97	0,95
Total [W/m ²]		0,00321	0,00331	0,00747
Dichroic BS		0,95	0,95	NA
Total [W/m ²]		0,00305	0,00315	0,00747
Grating		0,50	0,65	0,71
Total [W/m ²]		0,00153	0,00205	0,00530
Filter		0,90	NA	NA
Total [W/m ²]		0,00137	0,00205	0,00530
Channel	Freeform 1	0,96	0,97	0,95
	Total [W/m ²]	0,00132	0,00198	0,00504
	Freeform 2	0,96	0,97	0,95
	Total [W/m ²]	0,00127	0,00192	0,00479
Detector QE		Unknown	0,80	Unknown
Total [W/m ²]		0,00127	0,00154	0,00479
Telescope aperture [m ²]		6.88e-5	6.88e-5	6.88e-5
Total [μW]		0,087	0,105	0,329
Geometrical split		0,66	0,66	0,33
Total [μW]		0,0576	0,0693	0,109
Detector pixel pitch [μm ²]		852.26	1600	3600
Final [nW/pixel]		0,0673	0,0433	0,0302

The green part of the energy budget (last line in Table 21) represents the final energy received by one pixel at the detector. This calculation is based on the pixel size of the detectors mentioned above and is done by dividing the final power reaching the detector by the area of one pixel. This calculation assumes a full and homogeneous illumination of the detector.

It is possible to calculate the SNR at the NIR channel since the Teledyne detector provides all the information necessary for the calculation of this ratio. The SNR's calculation is based upon the values provided in Table 21 and by the Teledyne[47] datasheet. The SNR is defined as the ratio between the signal acquired by a detector and the noise received. The noise can be due to dark current or background irradiance. Every parameter acting in this ratio is present within the SNR equation presented below in equation 25. As a ratio, the SNR indicates that the signal can be read if its value is exceeding one, but if the final SNR value is lower or equal to one, the signal is drowned out by noise and cannot be distinguished.

The equation of the SNR is as follow[47]:

$$SNR = \frac{Signal}{Total\ Noise} = \frac{I_s \times t_{exp} \times A_{pixel} \times QE}{\sqrt{\left((I_s + I_b) \times t_{exp} \times A_{pixel} \times QE\right) + (\sigma_d \times t_{exp}) + \sigma_r^2}} \quad (25)$$

For which:

- I_s = Irradiance of the incoming signal [photons/second/ μm^2]
- t_{exp} = Exposure time [seconds]
- A_{pixel} = Pixel size [μm^2]
- QE = Quantum Efficiency
- I_b = Background irradiance [photons/second/ μm^2]
- σ_d = Dark current [e-/pixel/second]
- σ_r = Read noise [e-]

I_s is calculated upon the irradiance given in Table 21 and equal to 0,00154 [W/m²]. The conversion of the power in Watt into a unit of photons per second is easily derived via Planck's equation:

$$E = h \times \nu \quad (26)$$

$$\frac{Photons}{second} = \frac{P \times \lambda}{h \times c} \quad (27)$$

This equation must also take into account that the Power is not only given in Watts, but requires considering the irradiance given in W/m² in Table 21. The final unit for I_s is given in photons/second/ μm^2 . The final calculation for I_s is:

$$I_s = \frac{0,00154e^{-12} \left[\frac{W}{\mu\text{m}^2} \right] \times 1400e^{-9} [m]}{6,62607e^{-34} \left[\frac{m^2 kg}{s} \right] \times 2,99792e^8 \left[\frac{m}{s} \right]} = 10853 \left[\frac{\text{photons}}{\text{second} \mu\text{m}^2} \right] \quad (28)$$

The exposure time is based on the amount of FPS required to have a 5km resolution. Since it requires 1.4 FPS, the exposure time equals 0.7 seconds. The pixel size and the QE are given in Table 21. Since the stray light analysis (section 4.4) showed no unwanted rays at the detector's plane, the background irradiance will be supposed equal to zero for the rest of the calculation. The dark current and the read noise are both given within the Teledyne datasheet and equal to respectively 500 [e-/pixel/second] and 60 [e-].

Given all those parameters, we are able to achieve a value of the SNR as:

$$SNR = 2934$$

This value gives confidence in the achievable SNR. In comparison, the TROPOMI satellite features a SNR > 100 for his SWIR range (2300-2389nm) and a SNR $\geq$ 1500 for his UVIS range (305-499nm).[23] Our telescope is expected to provide a SNR of the same order of magnitude when taking all effects into account.

4.3 TOLERANCING

Tolerance analysis is performed on the three spectrometer systems consisting each time of the telescope and one of the three channels, independently from each other. The test is made at the central wavelength of each channel, considering the preset High Precision tolerance values as shown in Table 22. The tolerance analysis evaluates the average RMS spot size of each field for a thousand Monte Carlo runs on the optical system. Similar tolerances were set for the telescope, resulting in a good demonstrator setup, ensuring these tolerances are feasible to consider for the spectrometer manufacturing.

TABLE 22: SURFACE AND ELEMENT TOLERANCES FOR THE HIGH PRECISION TOLERANCE VALUES PRESET

High Precision tolerance values			
Surface tolerances		Element tolerances	
Radius	0.1%	Decenter X	0.01mm
Thickness	0.01mm	Decenter Y	0.01mm
Decenter X	0.01mm	Tilt X	0.01°
Decenter Y	0.01mm	Tilt Y	0.01°
Tilt X	0.0167°		
Tilt Y	0.0167°		
Irregularity	0.2 fringes		

At the spectrometer, tolerancing shows favorable results for the three channels even though the average RMS spot radius is evaluated larger in comparison to the average spot radius calculated in Chapter 3:

Results show that in 98% of the traceable Monte Carlo files, the average RMS spot radius equals 28,81 μm for the VIS channel, 26,87 μm for the NIR, and 54,97 μm for the Thermal channel. Due to the diffraction-limited nature of the Thermal channel, it is not necessary to push the RMS spot radius smaller than what the PSF can resolve, or at least the Airy disc radius. Nevertheless, results for the VIS and NIR channels can be improved by increasing the manufacturing quality. I.e., 2% of the generated files show that the spot radius reaches 25,44 μm for the VIS and 19,28 μm for the NIR channel. Tolerancing results are showing a spatial resolution that is slightly above the requirement (5km) and further studies should investigate how to improve the tolerancing.

TABLE 23: COMPARISON BETWEEN THE SPOT RADIUS AND THE SUBSEQUENT RESOLUTION OBTAINED WITH THE HIGH PRECISION TOLERANCING VALUES AND THE SIMULATED VALUES FROM CHAPTER 3:

		VIS	NIR	Thermal
High Precision RMS spot radius [μm]	98%	28,81	26,87	54,97
	2%	25,44	19,28	39,22
Resolution 98%	Spatial [km]	7,61	7,10	21,41
	Spectral [nm]	4,48	5,97	157,31
Resolution 2%	Spatial [km]	6,72	5,1	21,41
	Spectral [nm]	3,96	4,28	157,31
Average RMS spot radius [μm] (Chapter 3)		14,05	16,31	31,60
Resolution	Spatial [km]	3,71	4,31	21,41
	Spectral [nm]	2,19	3,62	157,31

4.4 STRAY LIGHT

Stray light analysis is made on the final three channel design to indicate whether unwanted light can be scattered and contribute to unwanted effects on the image plane, including cross-channel interference and ghost imaging. This analysis was performed in the non-sequential mode of Ansys Zemax OpticsStudio. First, the full three-channel design was converted from the sequential to the non-sequential mode. The system (Figure 86) is simulated with fields at 0° and 60° with wavelengths of 700nm, 1400nm, and $11\mu\text{m}$ represented in blue, green and red, respectively. The source is described using Source Ellipse with a power of $2.49\text{e-}7$ Watts (calculated power entering the spectrometer) and 5000 rays (at each field). The dichroic beam splitter is implemented such that it reflects wavelengths from 400nm to 1100nm and transmits from 1100nm to 1700nm. The gratings are defined with the periodicity calculated in Section 2.4 (230[l/mm] for the VIS channel, 120[l/mm] for the NIR channel, and 15[l/mm] for the Thermal channel). The image sensors are described using Detector Rectangle, featuring at each channel the average number of pixels in the spatial and spectral direction presented in Table 19. The system correctly split the three channels wavelengths via the geometrical splitting and the dichroic beam splitter in addition to correctly diffract the light at the gratings. The NIR reflective grating, facing the Thermal channel, a mask (labelled 2nd mask in Figure 86) is added to prevent any leaks between the channels. Another mask is necessary at the telescope's first spectrometer (labelled 1st mask) to avoid scattered light entering the spectrometer. A total of two masks is consequently necessary for the system to operate without (or with no significant) stray light.

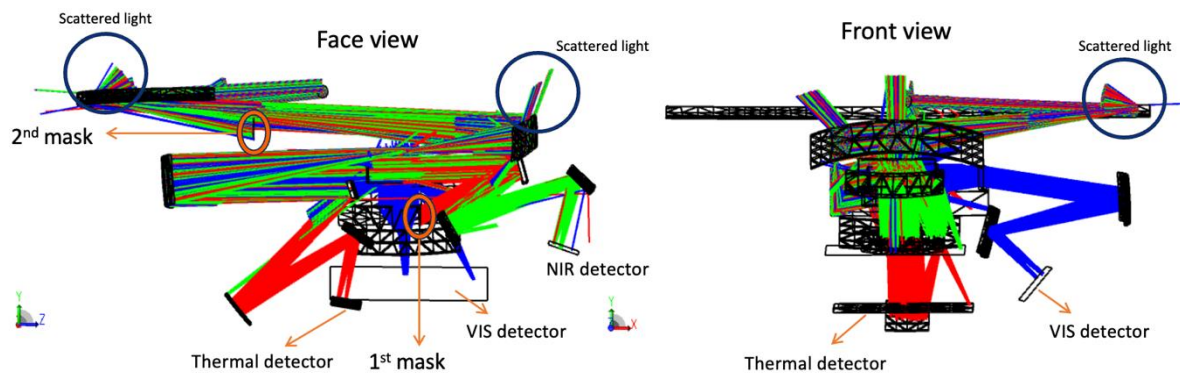


FIGURE 86: FINAL DESIGN IN NON-SEQUENTIAL MODE FOR STRAY LIGHT ANALYSIS

By plotting the image at the detector plane for each channel at their shortest, central and longest wavelengths, we show that no stray light is present when plotting the linear incoherent irradiance (Figure 87). The spot size at the detector's plane is larger than what has been measured in sequential mode because the transition from sequential to non-sequential is complex and caused an approximative resolution of the surface's shape and possible alignment errors.

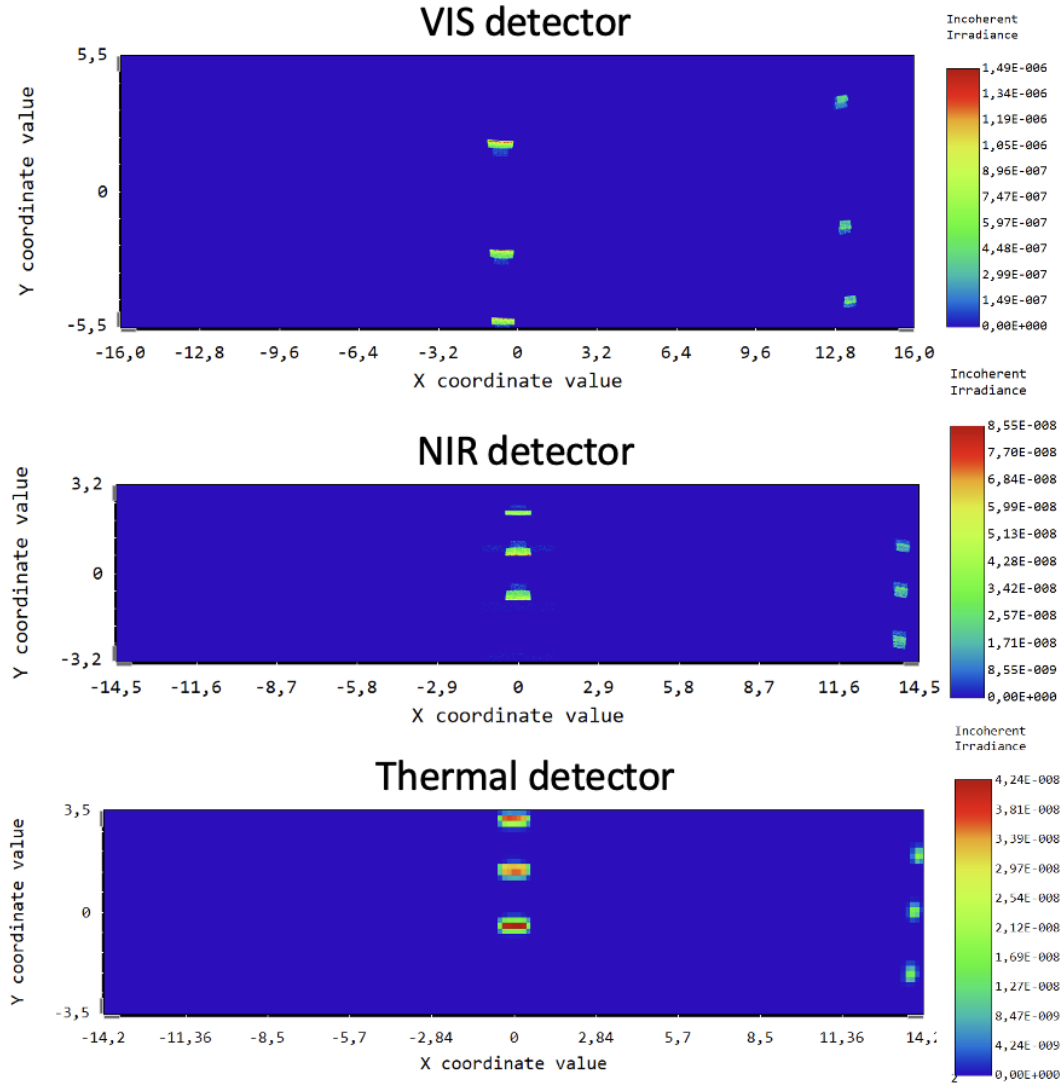


FIGURE 87: INCOHERENT IRRADIANCE AT THE DETECTOR'S IMAGE PLANE FOR THE THREE CHANNEL CONSIDERING FIELDS OF 0° AND 60° AND A WAVELENGTH RANGE INCLUDING THE SHORTEST, CENTRAL AND LONGEST WAVELENGTHS OF EACH CHANNEL (400NM, 700NM, 1100NM, 1400NM, 1700NM, $8\mu\text{M}$, $11\mu\text{M}$, AND $14\mu\text{M}$).

4.5 SUMMARY AND CONCLUSION

This chapter paves the way towards the realization of a laboratory demonstrator of the 3-channel spectrometer design. First, suitable commercially available detectors were identified for each of the 3 spectrometer channels, being the Nocturn series[46] for the VIS channel, the Teledyne NIRvana HS[47] for the NIR channel, and the SIMTRUM STPLUG1212[48] for the Thermal channel. In addition to the detectors, commercially available gratings and beam splitters are proposed for each of the channels. In general, custom components would be preferred for final integration, to fully exploit the most optimal performances. The energy budget for the design is calculated, indicating the average value of energy per pixels as 0,067nW/pixel for the VIS, 0,043nW/pixel for the NIR and 0,03nW/pixel for the Thermal channel. The Signal-to-Noise ratio for the NIR channel is estimated to equal 2934, which is of the same order of magnitude as TROPOMI. A tolerance analysis provided insights in the manufacturing of the design, indicating a decrease of approximately $10\mu\text{m}$ in 98% of the Monte Carlo runs for the VIS-NIR channels and a diffraction-limited Thermal channel. A stray light analysis indicated the necessity to add two masks in the system, after which only minimal stray light is reaching to the detectors.

Chapter 5: CONCLUSION AND FUTURE PERSPECTIVES

5.1 CONCLUSION

In this thesis, we aimed to design a compact spectrometer enhancing greenhouse gases monitoring. Our objectives targeted a wide field of view of 120° , a spatial resolution below 5 km, and a spectral resolution under 20 nm across three distinct channels: visible (VIS: 400-1100nm), near-infrared (NIR: 1100-1700nm), and thermal (8-14 μ m). Moreover, our system was intended to fit within a single CubeSat, and optimized for pushbroom scanning. A comprehensive study combining optical imaging design, diffraction theory and spectrometer design led to our novel optical design. The final presented three channel freeform spectrometer design has successfully been optimized using Ansys Zemax OpticsStudio featuring a 120° FOV and a resolution beyond the requirements for the VIS and NIR channels. Considering the Thermal channel, a fully-diffraction limited design was achieved, of which the performance is limited by the Airy disk radius. (Starting from the nominal design, a technology scouting was performed towards the realization of a laboratory demonstrator. This included the identification of commercially available sensors, and the evaluation of the power budget. A tolerance and stray light analysis was performed. The tolerancing showcased a high sensibility of the system and hence the need of extremely high-precision manufacturing. The stray-light analysis showed indicated the necessity for two absorbing masks, which after implementation would isolate the detectors from disturbing stray-light.

Table 24). The final spectrometer is able to separate the three channels while fitting in volume of 64x35x88mm³ (Figure 88).

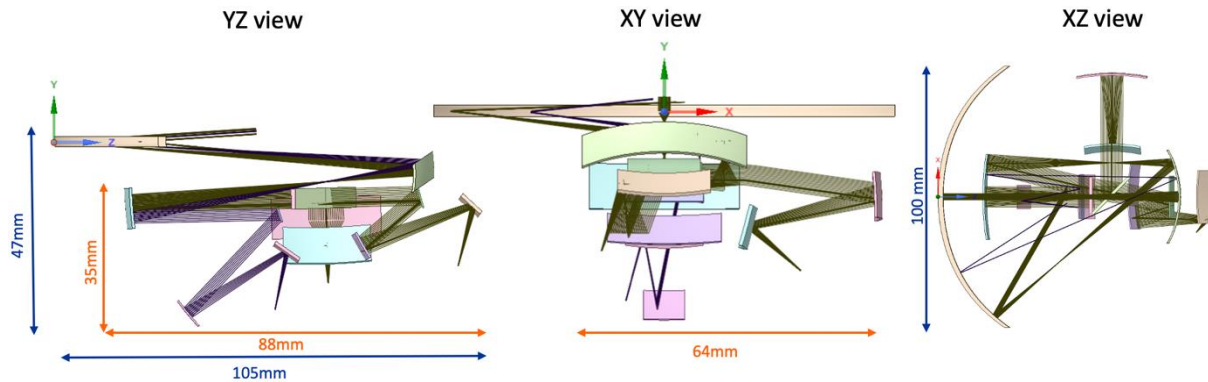


FIGURE 88: FULL VIEW OF THE FINAL THREE CHANNEL SPECTROMETER INCLUDING THREE FIELDS (0° , 32.73° , 60°) AND THE MEASURES OF THE SPECTROMETER (ORANGE) AND SPECTROMETER + TELESCOPE (BLUE) SHOWING THAT THE SPECTROMETER IS FITTING IN ONE CUBE SAT UNIT

Starting from the nominal design, a technology scouting was performed towards the realization of a laboratory demonstrator. This included the identification of commercially available sensors, and the evaluation of the power budget. A tolerance and stray light analysis was performed. The tolerancing showcased a high sensibility of the system and hence the need of extremely high-precision manufacturing. The stray-light analysis showed indicated the necessity for two absorbing masks, which after implementation would isolate the detectors from disturbing stray-light.

TABLE 24: COMPARISON BETWEEN PERFORMANCES OF OUR THREE CHANNEL SPECTROMETER AND THE STATE-OF-THE-ART TROPOMI, SHOWING THAT OUR PERFORMANCES ARE BETTER IN EVERY DOMAINS EXCEPT FOR THE SPECTRAL RESOLUTION[23], [59]

Channels	Three channel spectrometer			TROPOMI			
	VIS	NIR	Thermal	UV	UVIS	NIR	SWIR
FOV	120°			108°			
Swath width [km]	3700			2600			
Dimension [m ³]	0,064 x 0,035 x 0,088			0,56 x 0,45 x 0,38			
Spectral range [nm]	400-1100	1100-1700	8000-14000	267-332	305-499	661-786	2300-2389
Spectral resolution (nadir) [nm]	1,53	3,64	157,31	0,5	0,65	0,35	0,227
Spatial resolution (nadir) [km]	2,6	4,33	21,41	5,5			
Signal-to-Noise Ratio	TBC	2934	TBC	≥ 1000	≥ 1500	≥ 100-500	≥ 100

The design presented in this thesis features unprecedented results for a WFOV pushbroom spectrometer. In comparison with the state-of-the-art TROPOMI (Table 24) the field of view is 12° larger and the spatial resolution for the VIS-NIR channels is respectively 3km and 1,2km better than the TROPOMI's resolution after his last update[19] According to our knowledge, our instrument is the first one to provide a limb-to-limb observation from an altitude of 700 km. Additionally, our spectrometer features a broader spectrum allowing to study and discriminate greenhouse gases more efficiently with only a single instrument. Our spectrometer is expected to significantly improve the greenhouse gases sensing, not only because of its high spatial resolution that could benefit cities for air pollution monitoring, but also because both the Earth reflected and thermally emitted radiation are considered. With a detector enabling a number of FPS of 7Hz, it is possible to acquire an area in average half the size of Ixelles/Elsene (6,3km²) for the VIS-NIR channel, while the Thermal channel can acquire almost eight times the area of Bruxelles/Brussels with its 162km². [60], [61] Ultimately, our compact spectrometer shows to be almost ten times smaller than TROPOMI, enabling its use in a CubeSat platform. Its compact design, together with its higher spatial resolution, FOV, and spectral range could perfectly fit as a future space mission, following the current trend to optimize the size, the weight, and the efficiency of the system. A first iteration of the spectrometer has already been presented in the SPIE Europe 2024 conference and received interest from the scientific community. [18]

As a conclusion, we can say that this thesis contributes to the development of novel wide field-of-view space spectrometers, exceeding the state-of-the-art in terms of spectral wavelength range, field-of-view and compactness of the design. We successfully optimized a novel three-channel imaging spectrometer design covering the visible, near-infrared and thermal wavelength bands, while featuring an extreme field-of-view of 120° enabling limb-to-limb observation. We verified the manufacturability and realizability of the design by evaluating the power budget, tolerances and stray light. This research, and our proposed design, paves the way towards the development of novel space instrumentation, paving the way towards an improved climate and climate change monitoring, benefiting all of us.

5.2 FUTURE PERSPECTIVES

Future investigations could be made on the improvement of the optical design, and towards the realization of a laboratory demonstrator.

5.2.1 OPTICAL DESIGN OPTIMIZATION ITERATION

We identified through this thesis four main design's improvements for the three-channel spectrometer. These enhancements aim to address current limitations and further refine the system's performance and reliability. By implementing these advancements, the spectrometer can achieve greater precision and efficiency:

- (1) The performance of the Thermal channel is currently limited by the Airy disc size. An hypothetical solution to overcome this problem is to increase the focal length of the system, however, at the expense of a loss in compactness.
- (2) A main design improvement lies in the inconstant spot radius within the channels that could be overcome to have a more regular spot radius across all fields and wavelengths.
- (3) Reducing the smile distortion would enhance the resolution of each channel and allow the footprint to better fit the detector's area.
- (4) Exploration of the adaptation of the design using a single beam splitting component immediately creating the 3 channels.

Despite the possible minor improvements, our compact freeform three-channel spectrometer has shown high performances and features specifications unique for this kind of system. It is optimized in terms of resolution and compactness and could have an impact on greenhouse gases monitoring.

5.2.2 REALIZATION OF A LABORATORY DEMONSTRATOR SETUP

This thesis proposed commercially available components, but to achieve performances as good as with the simulated design, tailor-made components are necessary. The design being fully optimized, the main limitation is the manufacturing quality as shown with the tolerancing analysis. The freeform mirrors can be manufactured using ultraprecision diamond tooling, and subsequently characterized using metrology tools (white light interferometer for surface roughness and Coordinate Measurement Machine for the evaluation of the surface shape). Key challenge is envisioned within the alignment of the different components, requiring the inclusion of alignment features in the mechanical design. We propose a stepwise approach to build the spectrometer. First, the freeform components should be manufactured and characterized. Following this, an initial design consisting of separated channels can be developed and characterized in terms of spot radius and power budget. Finally, the complete three-channel system could be integrated.

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List of Figures

Figure 1: Global warming evolution for different greenhouse gas emission scenarios[7]. 1-8	
Figure 2: Whiskbroom configuration[17]	1-9
Figure 3: Pushbroom configuration[18].....	1-10
Figure 4: TROPOMI's WFOV telescope showing the WFOV of 108° and the entry then the freeform mirrors focusing the rays at the entry of the spectrometer[20]	1-10
Figure 5: TROPOMI's resolution in comparison to previous satellites showing the possibility to monitor greenhouse gases on a city scale[21].....	1-11
Figure 6: TROPOMI's optical system showing the different units, the calibration, the telescope and the two benches for the UV-UVIS-NIR and SWIR channels. [22].....	1-12
Figure 7: Greenhouse gases absorption wavelength with TROPOMI, OMI, and this thesis's spectrometer spectral range analyzed showing that our spectrometer is analyzing a wider spectral range.[25]	1-13
Figure 8: WFOV telescope simulation, freeform mirrors have been modeled via 4 th order XY polynomials, the spots at the spectrometer's entrance are close to the diffraction limit[12].....	1-14
Figure 9: WFOV telescope experimental tests[12]	1-14
Figure 10: Thesis's workflow	1-16
Figure 11: Basic spectrometer architecture[26]	2-17
Figure 12: Crossed (left) and Unfolded (right) Czerny-Turner Spectrometer[27].....	2-18
Figure 13: Offner spectrometer[28]	2-18
Figure 14: Novel freeform three-channel spectrometer design showing the positioning of each components	2-19
Figure 15: Material absorption for different wavelengths showing the reduced choice for materials working in a spectral range from 0,4μm (shortest VIS wavelength analyzed) to 14μm (longest thermal wavelength analyzed)[29]	2-20
Figure 16: Convenient representation of a Dichroic Beam Splitter used to separate the VIS and the NIR channels	2-20
Figure 17: Commercially available Dichroic beam splitter (DMLP1150B) characteristics from Thorlabs showing performances matching the simulated requirements but with a gap around 1150nm[30]	2-21
Figure 18: "Geometrical" beam splitting method to separate the VIS-NIR and the Thermal Channel. two-third of the light goes to the VIS-NIR channels and one-third to the Thermal channel.	2-21
Figure 19: k-vector diagram[32]	2-24
Figure 20: The same angle of incidence and diffraction is calculated for the VIS channel with 230[l/mm] (top-left), the NIR channel with 120[l/mm] (top-right), and the Thermal channel with 15[l/mm] (bottom)	2-25
Figure 21: FSR for NIR channel (left) and Thermal channel (right) showing no overlap between the modes.....	2-26
Figure 22: FSR for the VIS channel showing overlaps between the modes	2-26
Figure 23: Zoom on the FSR of the VIS range from Figure 22 with annotations showing the overlap's difference between the first and the second modes	2-27
Figure 24: Adapted FSR for VIS and NIR channels to avoid a spectral overlap by matching the equation 22	2-28
Figure 25: Thorlabs transmissive gratings for several grooves/mm (GT13-03 performances given at the blue curve)[35]	2-29
Figure 26: Example in the datasheet of a 200-1050nm spectrometer on a 28mm detector with a LF104200 filter[37].....	2-29
Figure 27: X terms for the first, second, and third order for A = 1	2-30

Figure 28: First mirror freeform surface XY polynomial.....	2-31
Figure 29: Second mirror freeform surface XY polynomial	2-31
Figure 30: Comparative reflectance as a function of the wavelength of several metallic coatings showing that only aluminum and silver are matching with the spectral range analyzed by our spectrometer (0,4-14 μ m) [39]	2-32
Figure 31: Protected silver coating for a 12° incident angle showing for the unpolarized light (green) a reflectance of approximately 97% along the whole spectrum considered by our spectrometer (0,4 μ m - 14 μ m)[40]	2-32
Figure 32: Protected silver coating for a 12° incident angle showing for the unpolarized light (green) a reflectance of approximately 94,5% along the whole spectrum considered by our spectrometer (0,4 μ m - 14 μ m) but with a decrease performance in the VIS range.[41]	2-33
Figure 33: MTF typical graph[44]	3-35
Figure 34: Spherical aberration[44]	3-35
Figure 35: Coma[44]	3-36
Figure 36: Field curvature[44].....	3-36
Figure 37: Astigmatism[44].....	3-36
Figure 38: Distortion[44]	3-37
Figure 39: Single VIS channel showing the different parts of the system and its size fitting in one CubeSat unit	3-38
Figure 40: Spot diagram at the central wavelengths (700nm) for the single channel VIS spectrometer showing a minimum spot at nadir and a maximum at 60°	3-39
Figure 41: Footprint diagram on the detector for the single channel VIS spectrometer with fields between 0° to 60° showing the presence of smile and the size of the area of the detector.....	3-40
Figure 42: PSF of three neighboring spots at nadir for the single channel VIS spectrometer (at 700nm) showing the best resolvable distance between the spots	3-41
Figure 43: MTF for the single channel VIS spectrometer (at 700nm).....	3-41
Figure 44: Seidel diagram for the single VIS channel spectrometer showing the presence of only spherical aberration.....	3-41
Figure 45: Single VIS channel spectrometer with the Offner architecture	3-42
Figure 46: Spot diagram at 700nm for the single channel VIS Offner spectrometer showing a spot size larger than the previous single channel design	3-43
Figure 47:Footprint diagram of the single channel VIS Offner architecture showing the absence of smile effect in the system.....	3-44
Figure 48: Single channel NIR spectrometer showing the components of the system and his size fitting in one CubeSat unit.....	3-44
Figure 49: Spot diagram of the single channel NIR spectrometer at 1400nm showing diffraction-limited spots at each fields	3-45
Figure 50: Footprint diagram of the single channel NIR spectrometer showing smile effect and the size of the detector	3-46
Figure 51: PSF of three neighboring spots at nadir for the single channel NIR spectrometer (at 1100nm) showing the best resolvable distance between the spots	3-46
Figure 52: MTF of the full FOV at 1100nm for the single channel NIR spectrometer .	3-47
Figure 53: Seidel diagram of the single-channel NIR spectrometer.....	3-47
Figure 54: Single Thermal channel showing the different parts of the system and its size fitting in one CubeSat unit.....	3-48
Figure 55: Spot diagram of the single Thermal channel at the central wavelength (11 μ m) showing that the spots are diffraction-limited at each fields	3-48
Figure 56: PSF of three neighboring spots at nadir for the single channel Thermal spectrometer (at 700nm) showing the best resolvable distance between the spots	3-50

Figure 57: Enclosed energy for each field at 11 μ m for the single Thermal channel spectrometer, showing a fully diffraction limited system.....	3-50
Figure 58: MTF at the central wavelength (11 μ m) of the single-channel thermal spectrometer.....	3-51
Figure 59: Full view of the final three channel spectrometer including three fields (0°, 32,73°, 60°) and the measures of the spectrometer (orange) and spectrometer + telescope (blue) showing that the spectrometer is fitting in one CubeSat unit	3-51
Figure 60: VIS channel of the final three-channel spectrometer's design, showing each components presents in the system and a final size fitting in one CubeSat unit.	3-52
Figure 61: Spot diagram of the VIS channel of the final design at the central wavelength (700nm) showing that the spots have the tendency to increase with the field	3-53
Figure 62: Normalized PSF of 5x5 neighboring spots around nadir and 700nm for VIS channel of the final design, showing that the spots can be resolved.	3-54
Figure 63: Enclosed energy for each field at 700nm for the VIS channel of the final three-channel spectrometer design, showing good performances for small fields and a decay from the 38° field (green).....	3-55
Figure 64: MTF of the final spectrometer's design VIS channel, indicating an average MTF higher than 0,5 at 17 cycles/mm (the Nyquist limit)	3-55
Figure 65: Seidel diagram for the final spectrometer's design VIS channel, indicating distortion as the main aberration.....	3-56
Figure 66: Footprint diagram of the VIS channel of the final three channel design, showing smile effect and providing the area required for the detector	3-56
Figure 67: NIR channel part of the three-channel freeform spectrometer's final design, showing the components presents in the design and the size of the channel that is fitting inside one CubeSat unit.....	3-57
Figure 68: Spot diagram of the NIR channel of the final design at the central wavelength (1100nm) showing that the spots radii vary between 11,91 μ m and 20,69 μ m along the fields	3-58
Figure 69: Normalized PSF of 5x5 neighboring spots around nadir and 1100nm for the NIR channel of the final design, showing that the spots can be resolved.	3-59
Figure 70: MTF for the HFOV at the central wavelength for the final design's NIR channel	3-60
Figure 71: Footprint diagram at the detector plane of the NIR channel of the final three-channel spectrometer design, showing the presence of smile effect and giving the detector's area.....	3-60
Figure 72: Thermal channel part (with the telescope) of the three-channel freeform spectrometer 's final design, showing the components presents in the design and the size of the channel that is fitting inside one CubeSat unit.	3-61
Figure 73: Portion of rays from the collimated beam that is reflected by the grating of the Thermal channel showing that well two-third of the light is separated to the VIS-NIR channels and one-third to the Thermal channel.	3-61
Figure 74: Spot diagram of the Thermal channel of the final design at the central wavelength (11 μ m) showing that the spots are diffraction-limited at each fields	3-62
Figure 75: Normalized PSF of 5x5 neighboring spots around nadir and 11 μ m for the Thermal channel of the final design, showing that the spots can be resolved.	3-63
Figure 76: Enclosed energy for each field at 11 μ m for the Thermal channel of the final three-channel spectrometer design, showing a fully diffraction limited system with a small decay at 60°	3-63
Figure 77: MTF of the final design's spectrometer Thermal channel	3-64
Figure 78: Footprint diagram at the detector plane of the NIR channel of the final three-channel spectrometer design, showing the presence of smile effect and giving the detector's area.....	3-65

Figure 79: Final design summary with every commercially available components discussed in 0	4-66
Figure 80: Grating efficiency curve as a function of the spectrum for (left) the GR13-0310[45] at the NIR channel and (right) the GR1325-07106[46] at the Thermal channel4-67	67
Figure 81: CMOS image sensor integrated circuit architecture[50]	4-68
Figure 82: CMOS photodiodes zoomed[50].....	4-69
Figure 83:InGaAs/InP structure and electric field profile[53]	4-71
Figure 84: Teledyne NIR camera quantum efficiency[48]	4-72
Figure 85: Bolometer's platform[57].....	4-72
Figure 86: Final design in non-sequential mode for stray light analysis.....	4-77
Figure 87: Full view of the final three channel spectrometer including three fields (0°, 32,73°, 60°) and the measures of the spectrometer (orange) and spectrometer + telescope (blue) showing that the spectrometer is fitting in one CubeSat unit	5-79