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Master of Science in Photonics Engineering

Freeform Catoptric Design of Wide-Field-of-View Spectral Imagers for UV Spaceborne Observation of Mars

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Preface

This master's thesis, entitled "Freeform Catoptric Design of Wide-Field-of-View Spectral Imagers for UV Spaceborne Observation of Mars", has been written to fulfill the graduation requirements of the Master of Science in Photonics Engineering at the Vrije Universiteit Brussel, Brussels, Belgium. I worked on the research and writing of this thesis from February to June 2026.

I chose this topic because of my interest in space instrumentation and my desire to expand my knowledge and skills as much as possible. In the past, I have worked with different software tools, designed systems and components, and performed characterization tasks. However, I wanted to gain experience in optical design, particularly because designing manufacturable systems, such as cameras, is something I have always wanted to learn. It brings me great satisfaction to see my creations come to life. Through this thesis, I have gained valuable experience in optical design principles and have become familiar with optical design software such as Ansys Zemax OpticStudio.

I would like to thank my promotor and supervisor, Prof. Dr. Ir. Lien Smeesters and Dr. Ir. Alejandro Madrid Sánchez, for their excellent guidance and support throughout this process. I started learning Zemax and optical design from scratch, and I could not have done it without their support. They were always available to answer my questions and help me whenever I was stuck.

I would also like to note that Artificial Intelligence, specifically Microsoft Copilot, was used as a supporting tool during the writing process. It was used to help correct academic text, proofread theoretical concepts, and provide Python code for generating illustrative figures and data-processing plots.

Finally, I would like to thank my family, friends, and colleagues who supported me throughout the journey of completing this master's thesis. I would also like to thank you, the reader. I hope you enjoy reading this thesis.

Artyom Petrosyan
Brussels, May 25, 2026

Abstract

Wide-field-of-view (WFOV) imaging systems are highly valued for space-based observation. They are particularly challenging to design due to the presence of off-axis aberrations. This thesis presents three novel wide-field-of-view (WFOV) ultraviolet (UV) imaging architectures for the Mars Imager for Dust and Ice clouds Monitoring (MIDIM): a 2D non-scanning multispectral imager, a 2D scanning multispectral imager, and a 1D pushbroom multispectral imager. The UV spectral range is intended and optimized for climate monitoring of Mars, including atmospheric circulation and dynamics, dust cycles and storms, and water cycles, clouds, and atmospheric chemistry.

Our research work tackles the optical design of WFOV UV imagers, exploring different configurations and benefiting from freeform optical design. The key challenges we faced were dealing with the off-axis aberrations due to the wide fields, vignetting, and angle-of-incidence (AOI) reduction, while still keeping the designs manufacturable and within the packaging requirements. Furthermore, the UV operation range further increased the complexity and difficulty of the design as the optical throughput needs to be increased due to low radiometric signals paired with the small Airy disk compared to larger wavelength ranges. Finally, to ensure a manufacturable design, a design-for-manufacturing approach was adopted, taking system tolerances into account.

The 2D scanning multispectral imager showed the most optimal performance despite its increased system complexity, such as the inclusion of a scan mirror, while the 2D non-scanning multispectral imager showed the worst nominal and radiometric performance. The 1D pushbroom multispectral imager showed a comparable nominal performance to the 2D scanning system. However, it lacked the tolerance robustness. The 2D scanning multispectral imager shows an unprecedented performance featuring a WFOV of $48^\circ \times 10^\circ$, spatial resolution of 2.50 km, F/# of 4.63, 80% of the encircled energy confined within a radius of 2.15 μm , distortion of 7.30%, $\text{MTF} \geq 0.91$ at 50 cycles/mm, volume of $170 \times 150 \times 135 \text{ mm}^3$, and smeared spatial resolutions between 5.96 km and 12.06 km for an SNR of 100 at 220 nm on Mars.

This work presents the full optical design methodology and results, adopting a design for manufacturing approach, taking into account the path towards further prototyping of the design. Consequently, with our research, we hope to pave the way towards a novel UV space-based imaging telescope, enhancing space exploration.

Keywords: wide-field-of-view spectroscopy, ultraviolet spectroscopy, freeform optical design, optical design for manufacturing.

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Chapter 1

Introduction

Spaceborne imaging systems are commonly designed either as wide-field-of-view (WFOV) imagers or as scanning instruments. WFOV systems increase the instantaneous spatial coverage of the instrument, allowing large areas to be observed rapidly and making them attractive for monitoring applications that require frequent temporal sampling. Scanning systems instead form an image sequentially, either by sweeping the field-of-view (FOV) across the target or by using the motion of the spacecraft to acquire consecutive image lines. For example, whiskbroom imagers scan across the swath using moving optical elements, whereas pushbroom sensors observe an entire line across the swath at once as the spacecraft moves forward [1, Chapter 6]. Therefore, the choice between WFOV and scanning configurations depends on the required compromise between spatial coverage, spatial resolution, temporal sampling, and instrument complexity.

Importance of studying Mars

Mars exploration has been ongoing since the 1960s, using both orbiters and unmanned surface vehicles such as rovers [2]. Mars is the most Earth-like planet in the Solar System and is therefore a key target for investigating planetary evolution, past habitability, and the conditions required to support life. Although Mars is currently a cold and dry planet with a thin atmosphere, evidence suggests that it may once have had a warmer climate, a thicker atmosphere, and stable liquid water on its surface [3]. Understanding how Mars evolved from these earlier conditions to its present state requires long-term monitoring of its surface and atmosphere over diurnal, seasonal, and interannual timescales. Figure 1.1 shows an illustration of a Martian temperature map, including wind vectors.

Rocks, sediments, and soils on Mars provide information about the planet's formation and surface evolution. Of particular scientific interest is the history of water, since the presence of liquid water is closely linked to the possibility of past habitability [5]. Strong evidence indicates that liquid water once flowed on the Martian surface, as shown by branching channels, river valleys, basins, and deltas. Today, however, Mars has a thin, CO₂-dominated atmosphere [6] and water is mainly present in frozen form, for example, in the polar ice caps and possibly beneath the Martian surface [7].

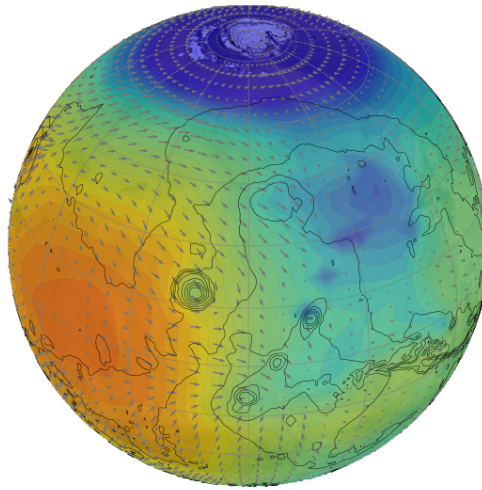


Figure 1.1: Temperature map of Mars with wind vectors, illustrating the type of data relevant for Martian climate monitoring. Figure adapted from [4].

Studying the Martian climate over extended periods can provide insight into the transformation of Mars from a potentially warmer and wetter planet to the cold, dry environment observed today, while also improving our understanding of how climate processes shape the long-term evolution of terrestrial planets [7]. Mars climate monitoring is also important for future exploration, since atmospheric dust, seasonal variations, radiation exposure, and surface-atmosphere interactions can affect visibility, thermal conditions, solar power generation, surface operations, and habitat protection [8].

Imaging remote sensing of Mars

Imaging remote sensing is therefore a key technology for linking the scientific objectives of Mars climate research to practical observation capabilities. From orbit, imaging instruments can provide repeated, spatially resolved measurements of atmospheric and surface phenomena over large areas and over extended timescales [9] [10]. Multispectral imaging acquires images in a limited number of discrete wavelength bands, allowing selected atmospheric or surface features to be isolated based on their spectral response. Hyperspectral imaging extends this principle by recording many narrow and contiguous spectral bands, providing a more detailed spectral signature for each spatial element in the scene.

Multispectral and hyperspectral imaging are particularly relevant in this context, since different wavelength channels can be used to distinguish and monitor atmospheric dust, clouds, ice-related processes, ozone, and surface changes [9] [10]. In this context, the instrument's FOV directly affects the type of climate information that can be retrieved. Wide-FOV imagers enable broad and repeated coverage of large-scale atmospheric phenomena such as clouds and dust activity, while narrower-FOV imagers provide more localized atmospheric information [9] [11].

The scientific objectives are described in Section 1.1.1, followed by a discussion on the related design challenges in Section 1.1.2. Finally, Section 1.2 summarizes the objectives and structure of the Master's thesis.

1.1 Objectives and challenges of this thesis

This thesis investigates three novel WFOV UV spectral imagers for Mars observation, which are designed and optimized to match the Mars Imager for Dust and Ice clouds Monitoring (MIDIM) specifications, targeting the detection of dust at 220 nm, ozone at 260 nm, and ice clouds at 320 nm [12]. However, the underlying optical design approach can potentially be extended to other spaceborne remote-sensing applications requiring compact WFOV imaging in the selected spectral band.

1.1.1 MIDIM scientific objectives

The Mars Imager for Dust and Ice clouds Monitoring (MIDIM) instrument is a scientific mission concept derived from the broader LightShip-1 [13] science goals. Its main objective is to support the monitoring of key Martian atmospheric phenomena relevant to climate studies and future exploration, which can be grouped into four main themes [12].

Atmospheric circulation and dynamics

The Martian thermal budget is strongly influenced by aerosols circulating within the planet's atmosphere. Atmospheric gas circulation, ice-cloud condensation and dissipation, ozone transport, and the lifting of dust particles all contribute to processes ranging from small-scale local phenomena to large-scale atmospheric variability. Therefore, monitoring atmospheric circulation on sub-diurnal to decadal timescales can improve the understanding of how the atmospheric temperature structure evolves and how it influences the general circulation.

Dust cycle and storms

Dust plays a central role in the Martian climate due to the radiative balance of Mars. Although seasonal dust variations have been studied in the past, the mechanisms behind dust lifting, the growth of local events into global storms, and storm decay remain not fully understood. MIDIM can monitor how isolated dust events evolve into regional and global dust storms. Additionally, it can help assess the effects of different physical processes on the formation, maintenance, and dissipation of dust storms.

Water cycle, clouds, and chemistry

Water-ice clouds and atmospheric chemistry play an important role in the Martian climate system. Ice crystals affect the radiative balance by reflecting ultraviolet (UV) and visible (VIS) radiation and absorbing infrared (IR) radiation, while the formation of water-ice clouds depends on the circulation of water vapor and the presence of lifted dust particles. These dust particles can act as condensation nuclei and influence the efficiency of cloud formation. MIDIM can contribute by monitoring the variability of clouds, water-related processes, and ozone, which is closely linked to atmospheric chemistry and can serve as an indicator of moisture variability.

Climate monitoring and prediction

Dust storms and atmospheric variability are major challenges for future Mars exploration, as they can affect landing safety, surface operations, visibility, and the performance of instrumentation. Reliable predictions of winds, temperature, pressure, and dust density require improved atmospheric models supported by regular observations. MIDIM can help by monitoring dust activity and atmospheric conditions, helping to improve early warning of dust storms and supporting safer mission planning and surface operations.

MIDIM optical design requirements

Within the scientific MIDIM mission, a broadband spectral imaging instrument has been proposed as part of the overall payload to contribute to the previously mentioned scientific goals by providing full-disk synoptic imaging of the Martian atmosphere, including the limb. The instrument uses selected ultraviolet (UV), visible (VIS), and near-infrared (NIR) spectral channels to provide complementary information on atmospheric and surface phenomena. These measurements complement the capabilities of other Lightship payload instruments, such as thermal IR observations for atmospheric temperature and aerosol retrievals, sub-millimeter observations for wind and trace-gas measurements, and NIR spectral imaging for water-vapor and CO₂-band information. In the full mission concept, the multispectral imaging instrument covers a spectral range extending from the UV at 220 nm to the NIR at 850 nm [13].

The focus in this thesis is on the UV channels specifically, at 220 nm, 260 nm, and 320 nm. This spectral region is of particular interest for MIDIM because it enables sensitivity to key Martian atmospheric constituents and phenomena, including dust, ozone, and water-ice clouds, which are directly linked to the scientific objectives discussed above. Secondly, a wide-field-of-view (WFOV), $48^\circ \times 48^\circ$ in the non-scanning configuration (discussed in more detail in Section 1.1.2.1), is required to provide broad spatial coverage of the Martian atmosphere and surface from orbit, while allowing pointing errors. Third, sufficient spatial resolution, expressed through the ground sampling distance (GSD), is needed to resolve atmospheric structures and regional variations. The targeted GSD is $2.55 \text{ km} \times 2.55 \text{ km}$. Additionally, the optical system must provide adequate throughput, corresponding to a signal-to-noise ratio (SNR) greater than 100, and sufficient image quality while remaining compatible with the strict volume and mass constraint of $220 \times 200 \times 150 \text{ mm}^3$ (L $\times$ W $\times$ H) and 3.6 kg, respectively. Finally, the suitability for a spaceborne application needs to be ensured.

1.1.2 UV spectral imager design challenges and trade-offs

This thesis focuses exclusively on the optical design challenges and trade-offs associated with the UV spectral band. Guided by the scientific objectives outlined in the previous section, the UV spectral instrument must satisfy several design constraints. These include the selection of an appropriate optical architecture for a broadband spectral imager that complies with strict volume and mass limitations while fulfilling the imaging and performance requirements imposed by the scientific mission.

The UV spectral imager is particularly challenging from an optical design perspective. The radiance at UV wavelengths is several orders of magnitude lower than in the VIS/NIR, resulting in significantly reduced photon budgets. This typically leads to an unwanted increase in the integration time, leading to a degradation of the effective spatial resolution, or GSD, due to image smear. Consequently, the maximization of the optical throughput is critical in the system design.

Furthermore, the spectral bandwidth of each channel must remain sufficiently narrow to avoid spectral contamination between the different wavelength bands. Increasing the spectral bandwidth allows more radiation to reach the detector, thereby improving the signal level, but reducing the spectral selectivity of the measurement. A trade-off must therefore be made between achieving a sufficiently narrow spectral bandwidth and maintaining a sufficiently short integration time.

1.1.2.1 Optical architecture trade-offs

Successful UV imaging systems based on refractive optical architectures have already been demonstrated in the literature (Section 2.1). However, only a limited number of materials are suitable for use within the UV wavelength range (e.g., fused silica, see [14]), resulting in a bulky and expensive design. We favour a reflective architecture since this can be prototyped using less expensive mirror substrates with appropriate coatings (see Section 4.2.1), avoiding the need for multiple UV-transmitting lens elements.

Different reflective design configurations are considered and evaluated, driven by the volume and mass constraints, while being closely linked to the FOV and the need for additional scanning elements. If the single-frame FOV of the optical system is too narrow, a two-axis scanning mechanism would be required to achieve the desired spatial coverage. Such a mechanism would introduce additional components, thereby increasing the size, mass, and mechanical complexity of the instrument. For this reason, architectures providing full coverage in at least one dimension are preferred, as they allow the system to rely on at most a single scanning axis. Within this trade-off, three optical sampling architectures are considered in this thesis: i) a 2D non-scanning multispectral imager ($48^\circ \times 48^\circ$), ii) a 2D scanning multispectral imager ($48^\circ \times 10^\circ$), and iii) a 1D pushbroom multispectral imager ($48^\circ \times 0.03^\circ$).

The principal distinction between the three proposed architectures lies in how the required spatial coverage is acquired while the spacecraft orbits Mars. The 2D non-scanning system captures the full planetary disk without a scanning mechanism and therefore requires a single-frame FOV of $48^\circ \times 48^\circ$. In contrast, the 2D scanning architecture reduces the single-frame FOV to $48^\circ \times 10^\circ$ and relies on a scan mirror to sample the remaining spatial dimension. The 1D pushbroom design acquires the scene line by line over a $48^\circ \times 0.03^\circ$ field, using the spacecraft motion along its orbit to build up the full image over time. These three sampling approaches are illustrated in Figure 1.2.

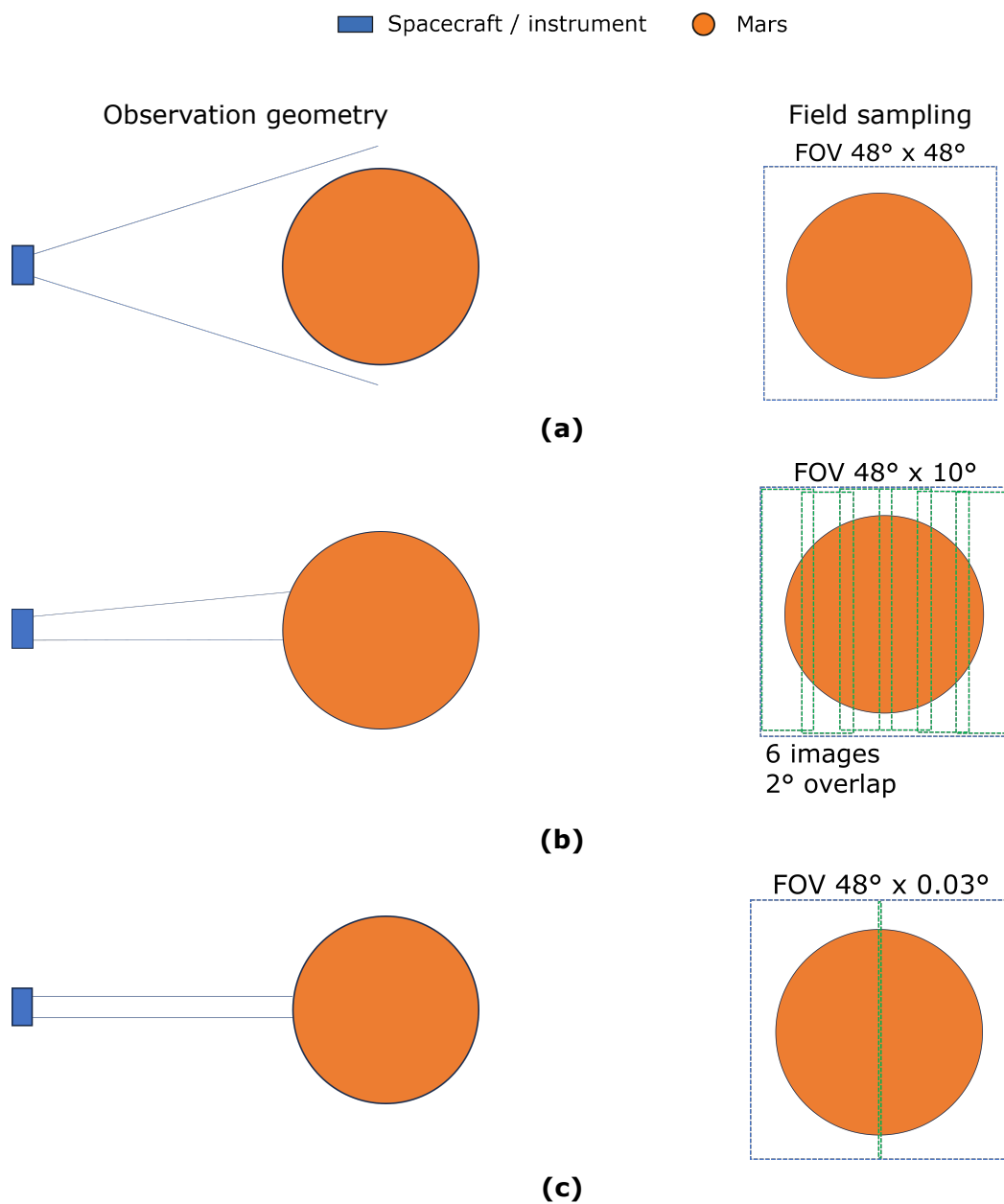


Figure 1.2: Comparison of the observation geometry and field acquisition approach for the three proposed imaging architectures: (a) 2D non-scanning multispectral imager, (b) 2D scanning multispectral imager, (c) 1D pushbroom multispectral imager.

1.1.2.2 System specifications

The required system specifications are extracted from the MIDIM proposal [12] and summarized in Table 1.1. Depending on the imaging concept, the relevant spectral information is obtained either by means of discrete filters, in the case of the 2D non-scanning and 2D scanning multispectral imagers, or by means of a diffraction grating, in the case of the 1D pushbroom multispectral imager. For the 2D spectral imager, three UV wavelengths are considered: 220 nm, 260 nm, and 320 nm, corresponding to the observation of atmospheric dust, ozone, and ice clouds, respectively. The 1D spectral imager considers a broader range of wavelengths: 195 - 345 nm with a spectral bandwidth of 25 nm, resulting in 7 multispectral wavelengths.

Table 1.1: Proposed system specifications of the spectral imaging systems [12].

Parameter	Value
Spectral bands	Filters: 220 nm, 260 nm, 320 nm Grating: 195 - 345 nm
Field of View	2D non-scanning: $48^\circ \times 48^\circ$ 2D scanning: $48^\circ \times 10^\circ$ 1D pushbroom: $48^\circ \times 0.03^\circ$
Altitude	5720 km
Ground Sampling Distance	2.55 km
Spectral bandwidth	25 nm
F/#	$\leq F/8$
Encircled Energy	80% $< 5 \mu\text{m}$
Distortion	$< 10\%$
Modulation Transfer Function	> 0.5 at f_{Nyq}
Volume	$\leq 220 \times 200 \times 150 \text{ mm}^3$
Mass	$\leq 3.6 \text{ kg}$

1.2 Thesis objectives

In the framework of the MIDIM scientific questions, this thesis aims to assess the feasibility of three proposed optical design architectures for the UV spectral band of MIDIM: a 2D non-scanning multispectral imager, a 2D scanning multispectral imager, and a 1D pushbroom multispectral imager. Our study aims to optimize, evaluate, and compare the performance of each of the three proposed optical architectures, as specified within the following specific objectives. For each of the designs, a design for manufacturing approach is adopted, starting from an initial design calculation and the optimization using freeform optics, towards the tolerance analysis and evaluation of the manufacturing constraints.

1.2.1 Specific objectives

1. Optical design of the 2D non-scanning multispectral imager to meet the proposed system requirement.
2. Optical design of the 2D scanning multispectral imager to meet the proposed system requirement.
3. Optical design of the 1D pushbroom multispectral imager to meet the proposed system requirement.
4. Compare the optical performance and design trade-offs of the three architectures.
5. Perform a tolerance analysis for the developed design architectures.
6. Identify suitable off-the-shelf optical components, including bandpass filters and mirror coatings.
7. Estimate the SNR based on the selected components and design parameters.

Based on the proposed system requirements, the three architectures are designed, analyzed, and compared according to the linear framework illustrated in Figure 1.3.

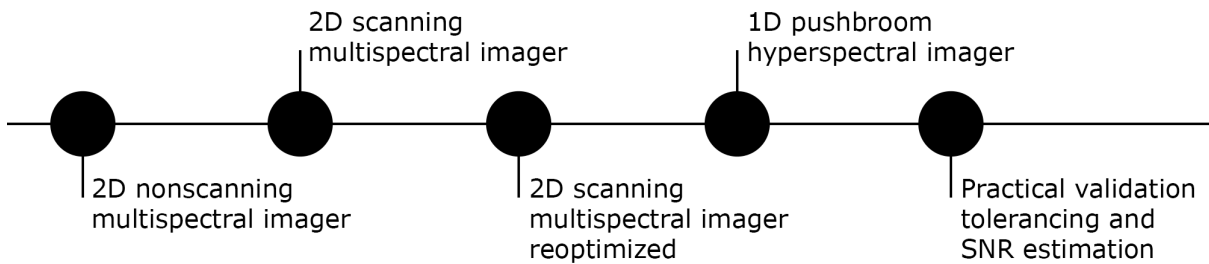


Figure 1.3: Overview of the investigated optical design architectures and the subsequent practical validation through tolerancing and SNR estimation.

1.2.2 Challenges

1. **Ultraviolet operation:** the instrument operates at short UV wavelengths, where material transmission, mirror coatings, filter selection, and detector sensitivity become more restrictive. In addition, the shorter wavelengths impose a stricter diffraction limit, making the optical performance more sensitive to residual aberrations and fabrication errors.
2. **Wide-field-of-view imaging from a compact platform:** the required WFOV must provide broad spatial coverage of the Martian atmosphere and surface while remaining compatible with the strict volume and mass constraints of the payload without vignetting.
3. **Use of freeform optics:** freeform surfaces are investigated to increase the available design freedom, reduce system size, and improve image quality over the full field. Their use also introduces additional challenges related to optimization, manufacturability, alignment, and surface tolerancing.

4. **Design for manufacturing:** the designs are not only optimized for nominal optical performance, but are also evaluated in terms of tolerance sensitivity, manufacturability, component availability, and compatibility with realistic alignment constraints.
5. **Radiometric feasibility:** the optical architectures must also provide sufficient throughput to achieve the required SNR, linking the optical design choices directly to the scientific detectability of dust, ozone, and water-ice clouds.

1.2.3 Structure of this thesis

This thesis is organized as follows. Chapter 2 provides the theoretical foundation for the work by introducing the fundamentals of spaceborne imaging remote sensing systems. This includes a review of the state of the art in remote sensing instruments and presents the essential optical theory required for the design process. Chapter 3 describes the optical design methodology and presents the resulting designs for the three proposed imaging architectures, followed by a comparative assessment of their optical performance. Chapter 4 evaluates the practical feasibility of the designs by addressing tolerance sensitivity, implementation aspects, and SNR estimations. Finally, Chapter 5 concludes the thesis by summarizing the main findings and outlining future perspectives.

Chapter 2

State of the Art and Fundamentals of Spectral Imaging Systems

This chapter first introduces the state of the art in spaceborne remote sensing instruments. Relevant missions are discussed, and their technical objectives and specifications are compared with the MIDIM specifications considered in this thesis work. The chapter then presents the theoretical background required for the optical design of remote sensing instruments, starting from geometrical optics and extending to diffraction theory. Aberrations and image quality metrics are subsequently introduced to describe the optical performance assessment, while providing insight into how the deviations from ideal imaging affect system performance. Finally, freeform optics is introduced, including representative examples of freeform surface descriptions. Together, these concepts provide the basis for evaluating the performance and feasibility of the different optical architectures investigated in this thesis.

2.1 Spectral imager's state of the art

To position the ambitious novel optical design (specifications in Section 1.1.2.2) within the context of Mars UV imaging and spectroscopy, four representative instruments are considered: MRO/MARCI, SPICAM, MAVEN/IUVS, and the ECO spectrometer concept. These reference instruments were selected since they consider WFOV UV imaging of Mars, UV atmospheric spectroscopy, and WFOV pushbroom spectroscopy, respectively. No single existing mission combines all these aspects simultaneously. Therefore, each reference instrument is used to benchmark a specific aspect of the MIDIM specifications, and particularly the UV spectral imaging system that we develop in this thesis.

2.1.1 Mars Reconnaissance Orbiter/Mars Color Imager (MRO/MARCI)

The Mars Reconnaissance Orbiter's Mars Color Imager (MRO/MARCI) is the most directly comparable existing instrument for the present work [9]. MARCI is a wide-angle multispectral Charge Coupled Device (CCD) push-frame camera designed to provide daily synoptic, low-resolution observations of the Martian atmosphere and surface. Its scientific objectives include the monitoring of

weather systems, dust and cloud activity, ozone variability, polar processes, and surface-atmosphere interactions. The instrument employs seven narrowband channels, consisting of five VIS/NIR bands and two UV bands.

Optically, MARCI uses separate UV and VIS optical paths that are combined onto a single focal plane. Since its launch in 2005, MRO has operated far beyond its nominal mission lifetime, and MARCI has provided long-term, continuous global monitoring of Mars. For this reason, MARCI is used here as the primary reference for WFOV UV imaging of Mars. Figure 2.1 shows a picture of the final instrument.

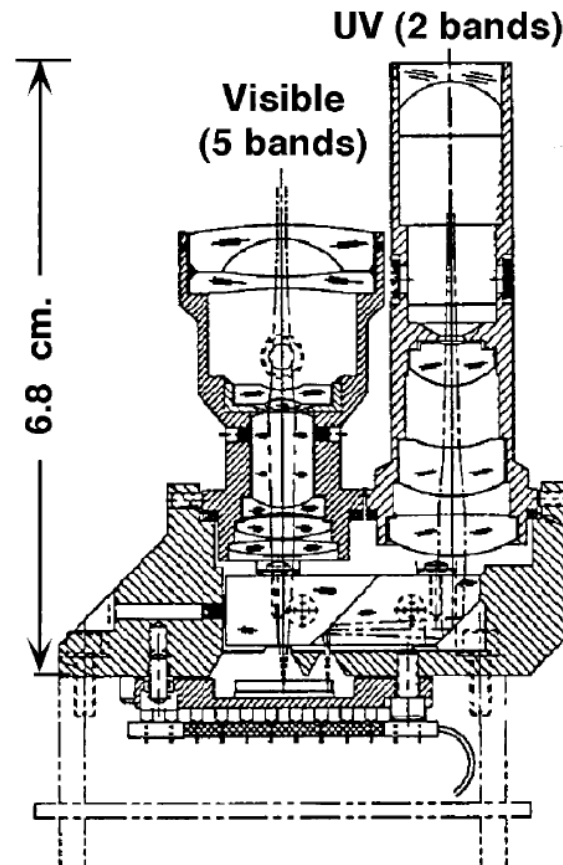


Figure 2.1: Mars Color Imager (MARCI) wide-angle camera optics. Reproduced from [15]

The comparison between MARCI and MIDIM, given in Table 2.1, shows that both instruments target full-disk UV observation, albeit from very different orbital altitudes. MARCI demonstrates that global UV imaging at wavelengths near 260 nm and 320 nm is feasible using a compact optical system. However, the optical architectures differ fundamentally. MARCI relies on a refractive lens-based design with separate optical paths, whereas MIDIM adopts a reflective mirror-based configuration. MARCI uses a compact set of 5 fused silica lenses for the UV channel [9]. The material transmission is not really an issue as fused silica lenses exist with transmissions of >99% at 260 nm and 320 nm [16]. However, fused silica will cause chromatic dispersion and will be expensive. The reflective architecture selected for MIDIM, therefore, avoids these chromatic effects and cost issues, making it more suitable for the broader UV wavelength range and cheaper prototyping and manufacturing.

Table 2.1: Comparison between MIDIM (this thesis) and MRO/MARCI. Specifications taken from [9].

Specification	MIDIM (this thesis)	MRO/MARCI
Altitude	5720 km	300 km
GSD	2.55 km	1 - 10 km
Spectral bandwidth	25 nm	30 nm @ 260 nm 25 nm @ 320 nm
Spectral range	220 nm, 260 nm, 320 nm	260 nm, 320 nm
FOV	2D non-scanning: $48^\circ \times 48^\circ$ 2D scanning: $48^\circ \times 10^\circ$ 1D pushbroom: $48^\circ \times 0.03^\circ$	$180^\circ \times 26^\circ$
Footprint	Full disk coverage	Full disk coverage
F/#	$\leq F/8$	F/7.5 @ 260 nm F/7.8 @ 317 nm
Volume	$\leq 220 \times 200 \times 150 \text{ mm}^3$ (optics)	$92 \times 72 \times 140 \text{ mm}^3$ (optics + electronics)
Mass	$\leq 3.6 \text{ kg}$ (optics + electronics)	0.481 kg (optics + electronics)

2.1.2 Spectroscopy for the Investigation of the Characteristics of the Atmosphere of Mars (SPICAM)

SPICAM, the Spectroscopy for the Investigation of the Characteristics of the Atmosphere of Mars instrument onboard Mars Express, is included as a reference UV spectrometer [11]. Launched in 2003, SPICAM was designed primarily to investigate the vertical structure and composition of the Martian atmosphere. The instrument comprises UV and NIR spectrometer channels, with the UV channel covering the wavelength range from 118 to 320 nm. This range overlaps strongly with the UV wavelengths considered for MIDIM, making SPICAM a relevant reference for UV atmospheric spectroscopy at Mars. Figure 2.2 shows the optical scheme of SPICAM's UV and IR channels.

SPICAM employs grating-based spectroscopic observation modes, including nadir viewing, limb observations, and stellar and solar occultations, enabling detailed vertical profiling of atmospheric constituents. In contrast, the most comparable MIDIM concept targets WFOV UV observations using a 1D pushbroom imaging approach rather than limb or occultation sounding. MIDIM is therefore not intended to provide altitude-resolved atmospheric profiles. Consequently, key system-level parameters such as FOV, GSD, and spectral resolution differ significantly between the two instruments. SPICAM is therefore not used as a direct reference for optical architecture or imaging geometry, but rather as a demonstration of the feasibility and scientific value of UV spectroscopic measurements at Mars, as well as a benchmark for achievable UV wavelength coverage. Table 2.2 compares the specifications of SPICAM with MIDIM.

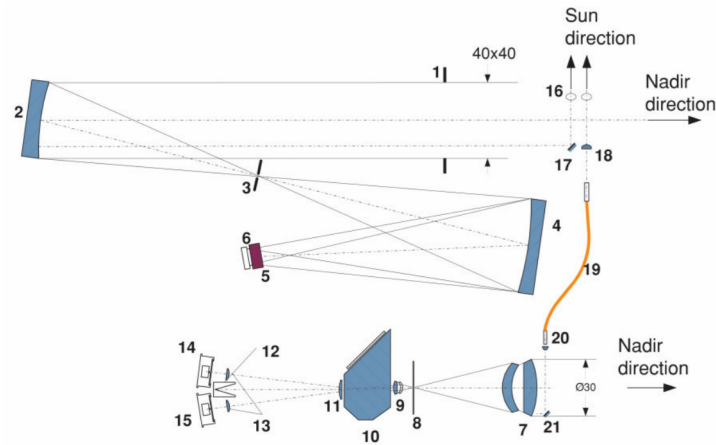


Figure 2.2: Optical scheme of SPICAM's UV and IR channels. 1: aperture blend of the UV channel; 2: off-axis parabolic mirror; 3: slit (can be changed from wide to narrow, by a mechanical actuator, see text); 4: concave UV grating; 5: intensifier; 6: CCD; 7: IR channel objective; 8: IR FOV diaphragm; 9/11: collimating lens; 10: AOTF crystal; 12: light trap for undiffracted light; 13: detector proximity lenses; 14: 'extraordinary' beam detector; 15: 'ordinary' beam detector; 16: solar opening (closed by shutter when not looking at Sun); 17/21: flat mirror; 18: IR solar entry; 19: optical fibre; 20: fibre collimator. Reproduced from [11].

Table 2.2: Comparison between MIDIM (this thesis) and SPICAM. Specifications taken from [17]

Specification	MIDIM (this thesis)	SPICAM
Altitude	5720 km	330 - 10530 km (periapsis - apoapsis)
GSD	2.55 km	4 km
Spectral bandwidth	25 nm	0.51 nm
Spectral range	195 - 345 nm	118 - 320 nm
FOV	2D non-scanning: $48^\circ \times 48^\circ$ 2D scanning: $48^\circ \times 10^\circ$ 1D pushbroom: $48^\circ \times 0.03^\circ$	No slit: $2^\circ \times 3.16^\circ$ (stellar occultation) Slit: $0.24^\circ \times 0.95^\circ$
Footprint	Full disk coverage	No slit: $11.5 \times 18.2 \text{ km}^2$ - $357 \times 581 \text{ km}^2$ (stellar occultation, periapsis - apoapsis) Slit: $1.38 \times 5.48 \text{ km}^2$ - $44 \times 175 \text{ km}^2$ (periapsis - apoapsis)
F/#	$\leq F/8$	F/3
Volume	$\leq 220 \times 200 \times 150 \text{ mm}^3$ (optics)	$565 \times 354 \times 180 \text{ mm}^3$ (optics + electronics)
Mass	$\leq 3.6 \text{ kg}$ (optics)	4.85 kg (optics + electronics)

2.1.3 Mars Atmosphere and Volatile and Evolution/Imaging Ultraviolet Spectrograph (MAVEN/IUVS)

The Mars Atmosphere and Volatile Evolution mission's Imaging Ultraviolet Spectrograph (MAVEN/IUVS) is included as a second reference UV spectrograph [10], similar to the SPICAM spectrograph mentioned in Section 2.1.2. MAVEN was launched in 2013 with the objective of investigating the upper atmosphere, ionosphere, and atmospheric escape processes of Mars. IUVS performs UV measurements using several observing modes, including limb scans, disk mapping, coronal scans, and stellar occultations. Figure 2.3 shows a picture of the IUVS instrument.

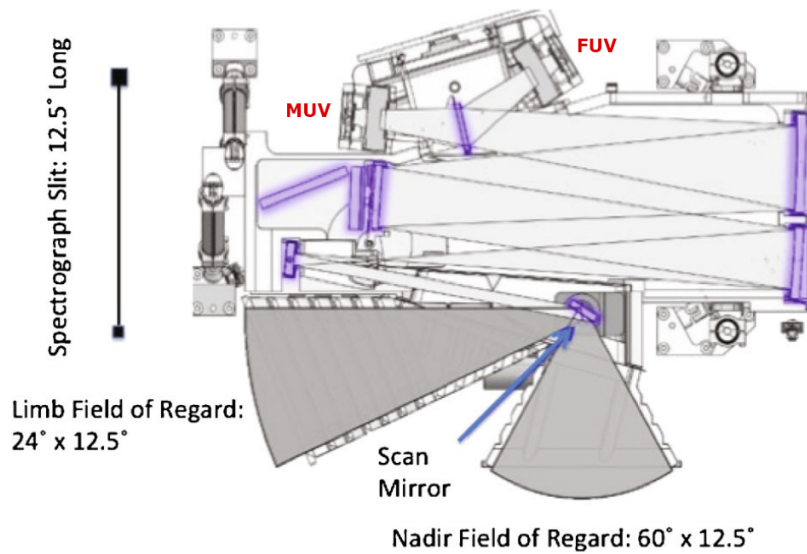


Figure 2.3: MAVEN/IUVS instrument cross section through the instrument case in the dispersion plane shows the optical elements, which are highlighted in purple, and the optical path, which is shaded with light grey. The spectrograph entrance slit, shown on the left side of the figure, contains both a narrow, long region ($0.06^\circ \times 11^\circ$) to measure atmospheric emissions and two wider keyholes used for stellar occultations. Reproduced from [10].

The comparison of the achieved specifications of MAVEN/IUVS with the proposed specification of MIDIM is given in Table 2.3. IUVS operates in the UV wavelength range and achieves spectral resolutions of approximately 0.6 nm in the far UV (FUV) and 1.2 nm in the mid UV (MUV) in its normal-incidence mode. Similar to SPICAM, MAVEN/IUVS is optimized for atmospheric composition and escape studies rather than for global surface or disk imaging. Its relevance to the present work, therefore, lies in its demonstrated UV spectroscopic performance at Mars rather than in its optical architecture. Together, SPICAM and MAVEN/IUVS establish that high-quality UV spectroscopic measurements of the Martian atmosphere are feasible from orbit, albeit using slit-based observing strategies that differ from the WFOV pushbroom approach adopted for MIDIM.

Table 2.3: Comparison between MIDIM (this thesis) and MAVEN/IUVS. Specifications taken from [10]

Specification	MIDIM (this thesis)	MAVEN/IUVS
Altitude	5720 km	160 - 6250 km (periapsis - apoapsis)
GSD	2.55 km	0.3 - 6.3 km (periapsis - apoapsis)
Spectral bandwidth	25 nm	1.2 nm
Spectral range	220 - 320 nm	180 - 340 nm
FOV	1D pushbroom: $48^\circ \times 0.03^\circ$	$0.06^\circ \times 11.3^\circ$
Footprint	Full disk coverage	$0.17 \times 31.5 \text{ km}^2 - 6.5 \times 1230 \text{ km}^2$ (periapsis - apoapsis)
F/#	$\leq F/8$	F/5 - F/8
Volume	$\leq 220 \times 200 \times 150 \text{ mm}^3$ (optics)	$867 \times 861 \times 330 \text{ mm}^3$ (optics + electronics)
Mass	$\leq 3.6 \text{ kg}$ (optics)	26.8 kg (optics + electronics)

2.1.4 Earth Climate Observatory (ECO)

The final reference system is the spectrometer concept proposed for the Earth Climate Observatory (ECO) mission [18], given in Figure 2.4. ECO is designed for Earth climate monitoring, with a focus on atmospheric greenhouse gases such as water vapor, carbon dioxide, and methane. Although the scientific target and wavelength range differ from those of MIDIM, ECO is highly relevant because it adopts a WFOV pushbroom spectrometer configuration.

This configuration makes ECO the closest architectural reference for the 1D pushbroom spectrometer geometry investigated in the present work. ECO is designed to operate from an altitude of approximately 700 km, whereas MIDIM targets observations from a significantly higher Mars orbit. As a result, the ECO optical design cannot be transferred directly to the MIDIM case. Nevertheless, ECO provides an important reference for WFOV pushbroom system geometry, optical layout, and scaling behavior. In this work, ECO is therefore used as an architectural benchmark rather than as a spectral or scientific analogue. Table 2.4 compares the specifications between MIDIM and ECO.

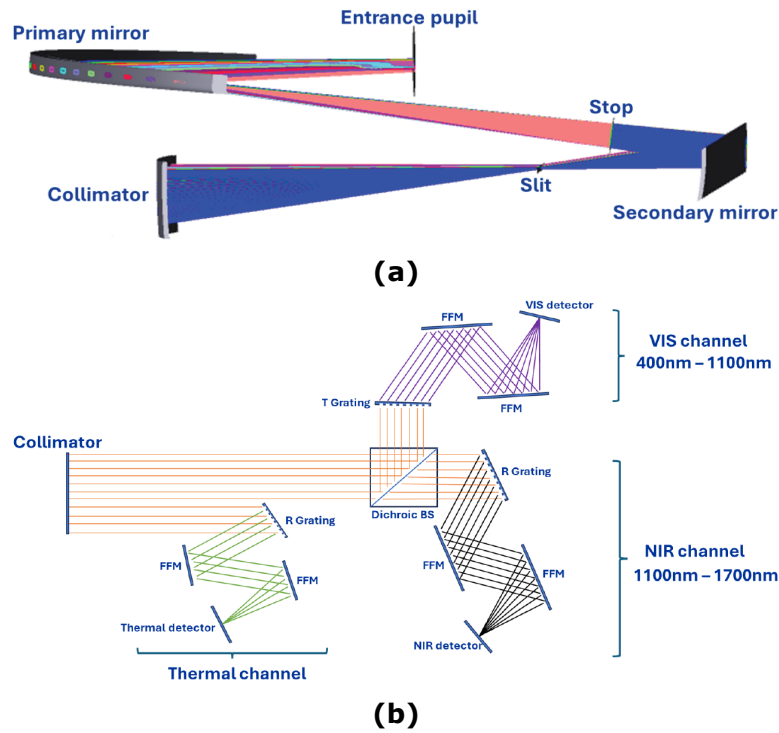


Figure 2.4: (a) ECO telescope consisting of 2 freeform mirrors, a slit, and a collimator. (b) ECO spectrometer channels consisting of a VIS (400 - 1100 nm), NIR (1100 - 1700 nm), and thermal (8 - 14 μm) channels. Reproduced from [19].

Table 2.4: Comparison between MIDIM (this thesis) and ECO. Specifications taken from [18]

Specification	MIDIM (this thesis)	ECO
Altitude	5720 km	700 km
GSD	2.55 km	2.6 km
Spectral bandwidth	25 nm	VIS: 5.18 nm NIR: 2.74 nm Thermal: 48.27 nm
Spectral range	195 - 345 nm	VIS: 400 - 1100 nm NIR: 1100 - 1700 nm Thermal : 8 - 14 μm
FOV	1D pushbroom: $48^\circ \times 0.03^\circ$	1D pushbroom: 120°
Footprint	Full disk coverage	Full disk coverage
F/#	$\leq F/8$	F/7.23
Volume	$\leq 220 \times 200 \times 150 \text{ mm}^3$ (optics)	$< 1 \text{ dm}^3$ (optics + electronics)
Mass	$\leq 3.6 \text{ kg}$ (optics)	/

2.1.5 Comparison between existing instruments

To date, no spaceborne instrument is available matching the required specifications of the MIDIM instrument. The reference instruments considered occupy distinct and complementary regions of the instrument design space. MRO/MARCI provides the closest comparison in terms of WFOV UV imaging of Mars, but operates from a much lower altitude. SPICAM and MAVEN/IUVS demonstrate UV spectroscopic capability at Mars, but employ grating-based observing modes optimised for atmospheric profiling rather than full-disk imaging. ECO demonstrates a WFOV pushbroom spectrometer architecture, but for Earth observation and at larger wavelengths.

This thesis combines aspects of these reference systems by targeting WFOV UV observation of Mars from high altitude while maintaining kilometre-scale GSD. The resulting design occupies a region of the design space that is not covered by existing or flown instruments, as illustrated by the comparative design-space analysis presented in Figure 2.5.

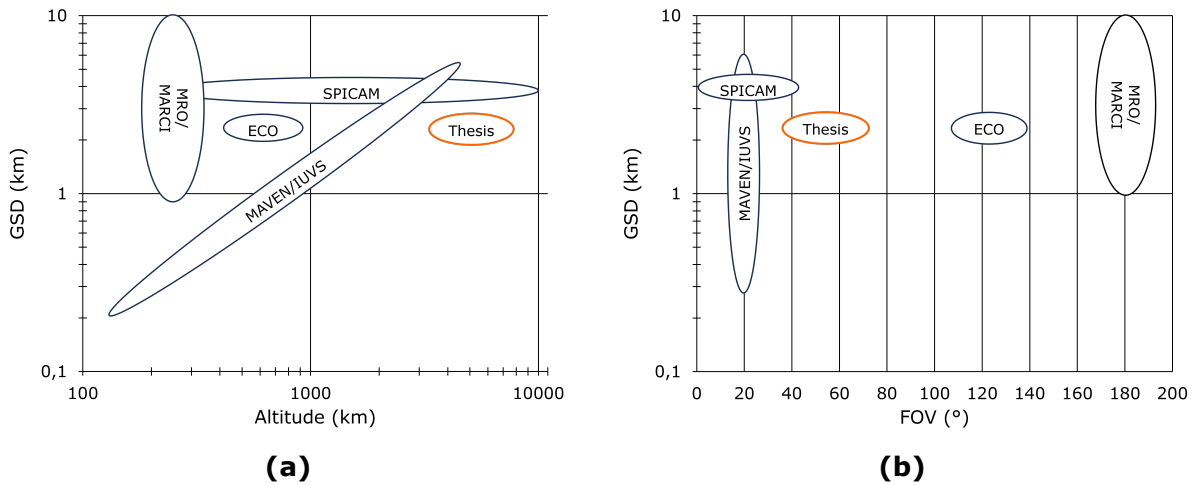


Figure 2.5: Design-space comparison between this thesis and selected reference instruments. (a) GSD in function of orbital altitude. (b) GSD in function of FOV.

2.2 Theoretical Foundation of Imaging Systems

2.2.1 Geometrical Imaging Parameters

The specifications of the imaging system observing Mars from a given altitude are defined using first-order geometrical relations [20, Chapter 1]. These first-order parameters describe the required imaging geometry and provide the basis for the preliminary optical design.

Five parameters are used to define and relate the optical systems in this thesis: i) the ground sampling distance (GSD), ii) the field of view (FOV), iii) the effective focal length (EFL), iv) the orbital altitude, and v) the F-number (F/#). These parameters are geometrically related, such that a change in one parameter affects the others. The following subsection first gives an introduction to first-order geometrical imaging, after which each of the 5 key parameters is described in the subsequent subsections.

2.2.1.1 First-order Imaging Geometry

In geometrical optics, ideal image formation is described in terms of object and image conjugates. Two points are conjugate if light originating from one point is brought to focus at the other point by the optical system. If a point in object space is imaged as a single point in image space, the imaging condition is referred to as stigmatic imaging [21, Chapter 5.1].

In real optical systems, perfect stigmatic imaging cannot be achieved over an extended field due to aberrations and the finite aperture of the system. Even in the absence of aberrations, diffraction imposes a fundamental limit on the achievable image quality [20, Chapter 3]. Therefore, first-order geometrical optics is used here to define the initial system geometry, while diffraction, aberrations, image-quality metrics, and freeform surface representations are treated separately (Section 2.2.2 - Section 2.2.5).

For systems composed of multiple optical surfaces, it is convenient to introduce an equivalent first-order representation. In this approach, the complete optical system is treated as a black-box system characterized by its principal planes and EFL, while the internal complexity is neglected [20, Chapter 1]. In this representation, the principal planes define the locations at which the system can be considered to refract light equivalently to a single optical surface. To determine these planes, one can consider ray tracing through the system. A paraxial ray entering the system from the object side parallel to the optical axis will emerge converging towards the image point. By extending the incident and emerging rays until they intersect, the location of the image-side principal plane is obtained. Similarly, by tracing rays originating from the image side, the object-side principal plane can be determined [20, Chapter 1].

The principal planes, therefore, act as equivalent reference planes for the optical system. The intersections of these planes with the optical axis define the nodal points. A key property of the nodal points is that a ray directed towards the first nodal point at a given angle will emerge from the second nodal point at the same angle with respect to the optical axis. The principal planes are important for the definition of the key design parameters, such as the effective focal length. Consequently, the principal planes provide the reference framework required to define the paraxial specifications of an optical system, including its effective focal length, conjugate distances, and magnification [20, Chapter 1].

2.2.1.2 Ground Sampling Distance and Field of View

The ground sampling distance (GSD) defines the smallest object-space detail that can be resolved by the imaging system. It represents the ground-projected area corresponding to a single detector pixel. For example, a GSD of 2.55 km implies that each pixel corresponds to an area of approximately $2.55 \times 2.55 \text{ km}^2$ on the observed surface. Features smaller than this projected area cannot be individually resolved.

The field of view (FOV) defines the angular extent of object space that can be imaged by the optical system. For an object located at a distance A , the corresponding object-space height is related to the angular field by Eq. 2.1

$$h_o = A \tan \left(\frac{\text{FOV}}{2} \right). \quad (2.1)$$

In the image space, the detector size defines the corresponding image height. Together with the pixel pitch p , the GSD and FOV determine the required focal properties of the system. An illustration of the FOV is shown in Figure 2.6.

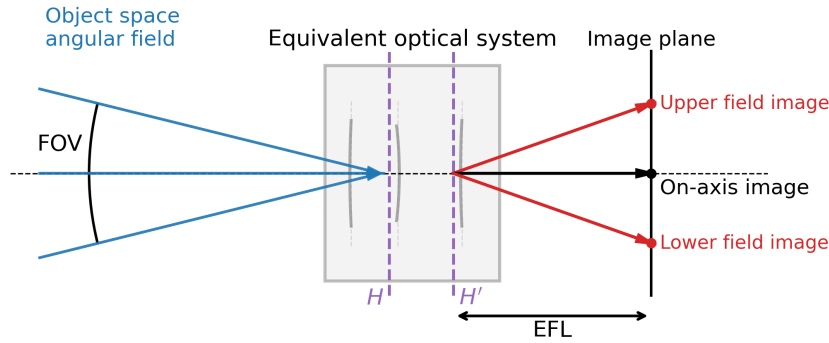


Figure 2.6: Schematic representation of the FOV of an equivalent optical system, where H and H' denote the object-side and image-side principal planes, respectively. The FOV defines the angular extent in object space accepted by the system, while the corresponding image size is determined by the effective focal length measured from H' .

2.2.1.3 Effective Focal Length

The paraxial ray behavior of converging and diverging reflective surfaces is shown in Figure 2.7. For an object at infinity, the effective focal length (EFL) corresponds to the distance from the optical component to the focal point, where parallel incoming rays converge [20, Chapter 1]. The on-axis ray is called the chief ray, and the outer rays are called the marginal rays. Depending on the sign of the optical power, a reflective surface either converges or diverges the incoming light. The equivalent black box system is illustrated in Figure 2.8

Lenses have a certain thickness with a lens-specific refractive index. This means that in the final calculations, this thickness and refractive index have to be considered. As a first-order approximation, most lenses are approximated to be infinitely thin, removing the thickness factor. Mathematically, this is given by Eq. 2.2 and 2.3 [21, Chapter 5.2]:

$$\text{Gaussian lens formula: } \frac{1}{f} = \frac{1}{x_o} + \frac{1}{x_i} \quad (2.2)$$

$$\text{Lensmaker's formula: } \frac{1}{f} = (n_l - 1) \left(\frac{1}{R_1} - \frac{1}{R_2} \right) \quad (2.3)$$

Where x_o and x_i are the object and image distances, respectively, f is the focal length (EFL), and R_1 and R_2 are the curvatures of the front and back of the lens, respectively.

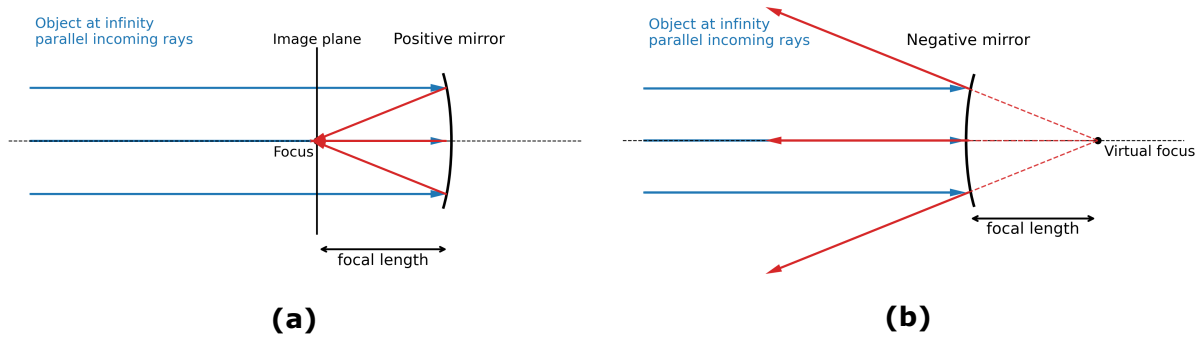


Figure 2.7: Illustration of the focusing behavior of mirrors for an object located at infinity. A positive mirror converges incoming parallel rays to a real focal point, whereas a negative mirror diverges the rays such that they appear to originate from a virtual focal point behind the mirror. (a) Converging mirror with positive optical power. (b) Diverging mirror with negative optical power.

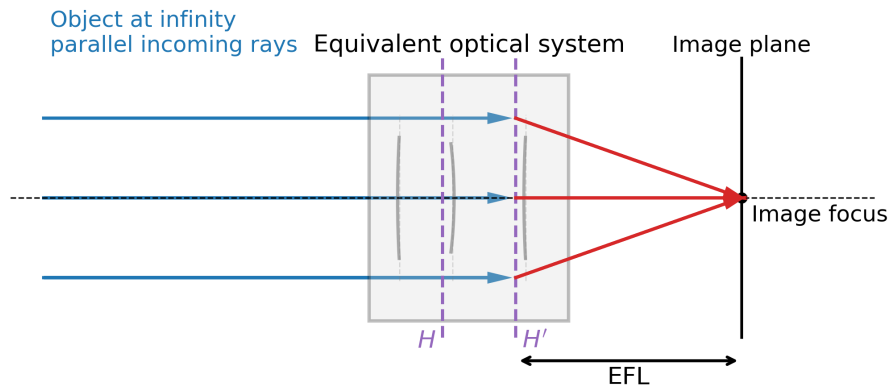


Figure 2.8: Equivalent black-box representation of an optical system for an object located at infinity. The internal optical components are shown schematically, while the principal planes define the equivalent first-order system. The effective focal length is measured from the image-side principal plane H' to the image plane.

For a catoptric system (only mirrors), the optical path does not undergo changes in the refractive index. Additionally, mirrors have only a single relevant surface, which means that Eq. 2.4 can be used for mirrors [21, Chapter 5.4]:

$$\text{Mirror formula: } \frac{1}{f} = \frac{1}{x_o} + \frac{1}{x_i} = -\frac{2}{R} \quad (2.4)$$

Where x_o and x_i are the object and image distances, respectively, f is the EFL, and R is the curvature of the mirror surface. Because the formula is not dependent on two separate surface curvatures, the focal lengths at the object side and the image side are equivalent. Take note that the sign depends on the adopted optical sign convention.

For a finite object distance, the object can no longer be treated as being located at infinity. In that case, the image distance is not exactly equal to the EFL. This situation is illustrated in Figure 2.9.

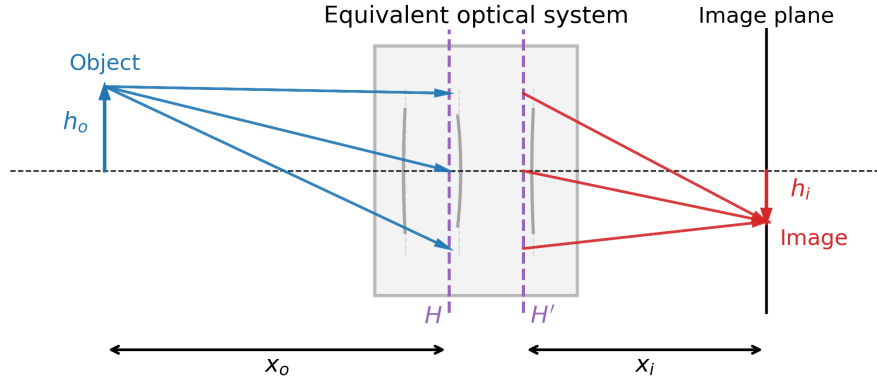


Figure 2.9: Equivalent black-box representation of an optical system imaging a finite object point. Rays originating from the on-axis object point are transformed by the optical system and converge to the corresponding image point on the image plane. The object and image distances are measured from the object-side and image-side principal planes, respectively.

The signed transverse magnification M in a transverse direction is defined by Eq. 2.5 [21, Chapter 5.2]

$$M = \frac{h_i}{h_o} = -\frac{x_i}{x_o} \quad (2.5)$$

where h_o and h_i are the signed object and image heights, respectively, and x_o and x_i are the object and image distances measured from the corresponding principal planes H and H' . The negative sign indicates inversion of a real image formed by a positive optical system when positive object and image distances are used. For remote sensing applications, the ground sampling distance (GSD) is related to the magnitude of the transverse magnification. Therefore, the magnitude of M can be calculated using Eq. 2.6

$$|M| = \frac{p}{\text{GSD}}, \quad (2.6)$$

where p is the pixel pitch, and GSD is the ground sampling distance. For an object at a sufficiently large distance A , such as an orbital altitude, the image distance can be approximated by the effective focal length (EFL), $x_i \approx \text{EFL}$. Under this far-field approximation, the magnification is given by Eq. 2.7

$$|M| = \frac{p}{\text{GSD}} \approx \frac{\text{EFL}}{A}. \quad (2.7)$$

Thus, Eq. 2.5 describes the signed magnification and therefore contains information about image orientation, whereas Eq. 2.7 describes only the positive image scale used for GSD calculations.

The EFL can be determined using two equivalent first-order relations. From geometrical considerations using detector width w_{det} and FOV, given by Eq. 2.8

$$\text{EFL} = \frac{w_{\text{det}}/2}{\tan\left(\frac{\text{FOV}}{2}\right)}. \quad (2.8)$$

Alternatively, using the sampling relation, given by Eq. 2.9

$$\frac{p}{\text{GSD}} = \frac{\text{EFL}}{A}, \quad (2.9)$$

which gives Eq. 2.10

$$\text{EFL} = \frac{p \cdot A}{\text{GSD}}. \quad (2.10)$$

2.2.1.4 Orbital Altitude Dependence

To optimize the communications and navigation functions, the spaceborne telescope is placed in a near-equatorial orbit with an inclination of 20° at an orbital altitude of 5720 km [13]. From an optical design perspective, a higher orbital altitude reduces the FOV required to image the full planetary disk. The EFL and FOV can be estimated using Eq. 2.11 and 2.12

$$\text{EFL} = \frac{p \text{ (m)} \cdot A \text{ (m)}}{\text{GSD (m)}} = \frac{10 \cdot 10^{-6} \text{ m} \cdot 5720 \cdot 10^3 \text{ m}}{2.55 \cdot 10^3 \text{ m}} \approx 22.46 \text{ mm} \quad (2.11)$$

$$\text{FOV} = 2 \cdot \arctan \left(\frac{w_{\text{det}} \text{ (mm)}}{2 \cdot \text{EFL (mm)}} \right) = 2 \cdot \arctan \left(\frac{20 \text{ mm}}{2 \cdot 22.46 \text{ mm}} \right) \approx 48^\circ \quad (2.12)$$

The required FOV for full-disk imaging decreases with increasing orbital altitude. However, this does not come without a trade-off in GSD. For a fixed detector size, the EFL is constrained by the FOV according to Eq. 2.12. An increase in FOV results in a decrease in EFL for the same detector size. Since the GSD is inversely proportional to the EFL, as shown in Eq. 2.11, a larger FOV leads to a coarser GSD. These geometrical and optical relations are visualized in Figure 2.10.

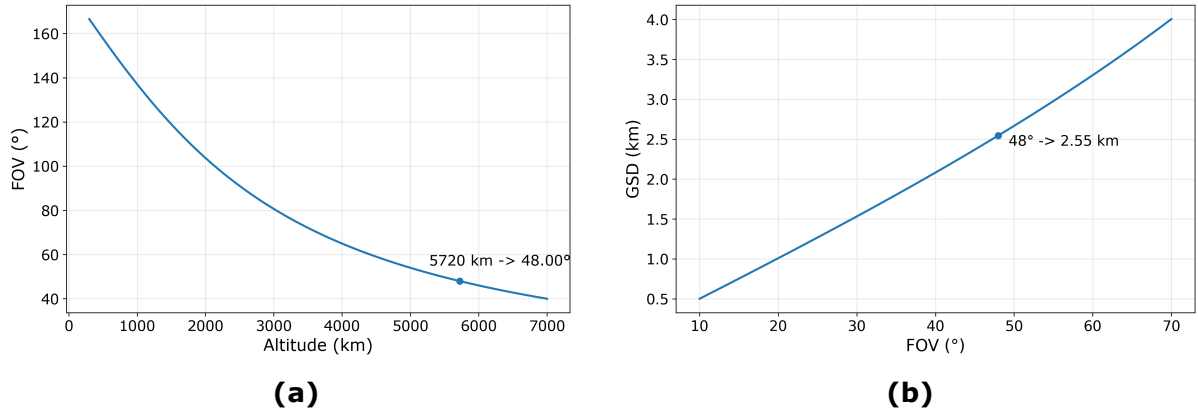


Figure 2.10: Geometrical and optical relations governing full-disk imaging of Mars. (a) Required FOV as a function of orbital altitude, assuming a 150 km margin beyond the planetary limbs. (b) Achievable GSD as a function of FOV for a fixed orbital altitude of 5720 km, where the EFL is constrained by the detector geometry.

2.2.1.5 F-number and Entrance Pupil Diameter

An important concept is the aperture stop. This is a physical diaphragm or the size of a component, such as a lens or a mirror. It essentially controls the amount of light that reaches the image plane. Similarly, the field stop limits the angular breadth of the object. It determines the FOV of the system. All chief rays intersect the aperture stop on the optical axis, while the marginal rays intersect the edges of the stop.

The entrance and exit pupils are the images of the aperture stop, seen from an axial point on the object or image, respectively, looking through the elements preceding the aperture stop. The entrance pupil diameter (EPD) is directly related to the light-collecting capability of the system [21, Chapter 5.3] [20, Chapter 2].

The F-number (F/#) characterizes the optical speed of the system and is directly related to the optical throughput [20, Chapter 1]. It gives the ratio between the EFL and the EPD of the system. An illustration is shown in Figure 2.11. Mathematically, this can be expressed by Eq. 2.13

$$F/\# = \frac{EFL}{EPD} \quad (2.13)$$

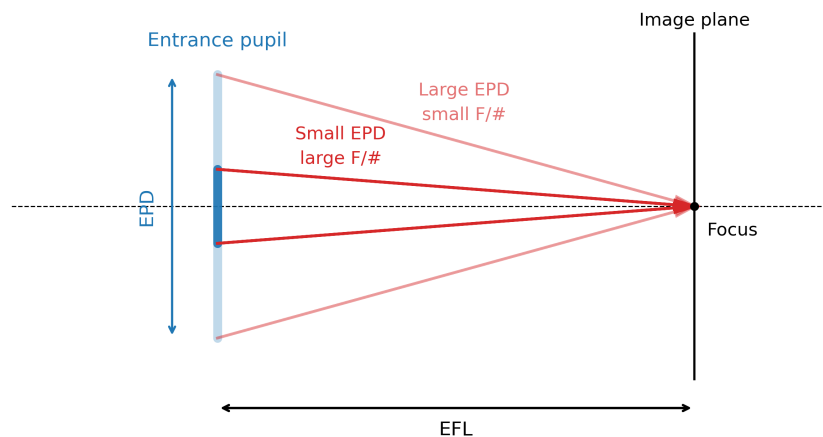


Figure 2.11: Illustration of the F/# for an optical system. For a fixed EFL, a larger EPD produces a wider converging ray cone and therefore a smaller F/#, while a smaller EPD produces a narrower ray cone and therefore a larger F/#.

Smaller F/# values correspond to larger apertures and generally increase the amount of light collected by the system. However, this also makes the optical design more challenging, since aberration control becomes more difficult. For larger F/# values, the opposite is true.

The F/# is especially relevant for the signal-to-noise ratio (SNR), since a smaller F/# generally increases the irradiance at the detector (more light gets in). The exact dependence of SNR on F/# depends on the adopted radiometric and noise model, but reducing the F/# is typically beneficial from a radiometric point of view. This must, however, be balanced against the increased optical complexity required to control aberrations, for example, through the use of additional freeform surfaces or a larger system envelope.

2.2.1.6 Vignetting

Vignetting occurs when part of the ray bundle from a field point is blocked by an aperture, mirror edge, mechanical boundary, or another optical component before reaching the image plane. In an unvignetted system, each field point uses the full entrance pupil. In off-axis reflective systems, however, ray bundles may pass close to mirror edges or neighboring optical surfaces, causing field-dependent clipping. This reduces the transmitted energy, changes the effective pupil, and can influence both throughput and image quality [20, Chapter 2]. In optical system design, vignetting is undesirable and should be minimized to ensure uniform illumination and consistent system performance across the full FOV.

2.2.1.7 Telecentricity

Telecentricity describes the orientation of the chief rays in object space or image space. In an object-space telecentric system, the chief rays are parallel to the optical axis in object space, whereas in an image-space telecentric system, the chief rays are parallel to the optical axis in image space and therefore reach the image plane at approximately normal incidence. The deviation from this ideal normal-incidence condition is referred to as the telecentricity angle. Image-space telecentricity is important because the angle at which light reaches the detector can influence the detected signal. In particular, detector response and coating performance can depend on the angle of incidence, for example, due to the angle-dependent behavior of an anti-reflection coating or microlens array on the detector. A non-telecentric image-space geometry can therefore lead to field-dependent variations in detector response, throughput, and radiometric uniformity. [20, Chapter 23].

2.2.2 Diffraction Fundamentals

Diffraction is a fundamental phenomenon found in optical systems. When light passes through a finite aperture or interacts with small structures, the wavefront is no longer perfectly confined to its geometrical path and begins to spread. The resulting diffraction pattern depends on the propagation distance between the aperture and the observation plane. Two commonly distinguished regimes are Fresnel (or near-field) diffraction and Fraunhofer (or far-field) diffraction [22, Chapter 4].

2.2.2.1 Fresnel and Fraunhofer Diffraction

In the Fresnel regime, the diffraction pattern depends explicitly on the propagation distance from the aperture. At sufficiently large distances, the Fraunhofer approximation becomes valid, provided that the condition in Eq. 2.14 is satisfied [22, Chapter 4.3].

$$z \gg \frac{k (x_1^2 + y_1^2)_{max}}{2} = \frac{2\pi (x_1^2 + y_1^2)_{max}}{2\lambda} \quad (2.14)$$

Here, z is the propagation distance, k the wavenumber, λ the wavelength, and $(x_1^2 + y_1^2)_{max}$ corresponds to the squared radial distance of the furthest point from the center of the entrance aperture. Due to the wavelength dependence of Eq. 2.14, shorter wavelengths, such as UV, require a larger propagation distance.

Since the relevant propagation distances in this work are large compared to the aperture dimensions, only Fraunhofer diffraction is considered in the following analysis. A schematic representation of the transition from Fresnel to Fraunhofer diffraction is shown in Figure 2.12.

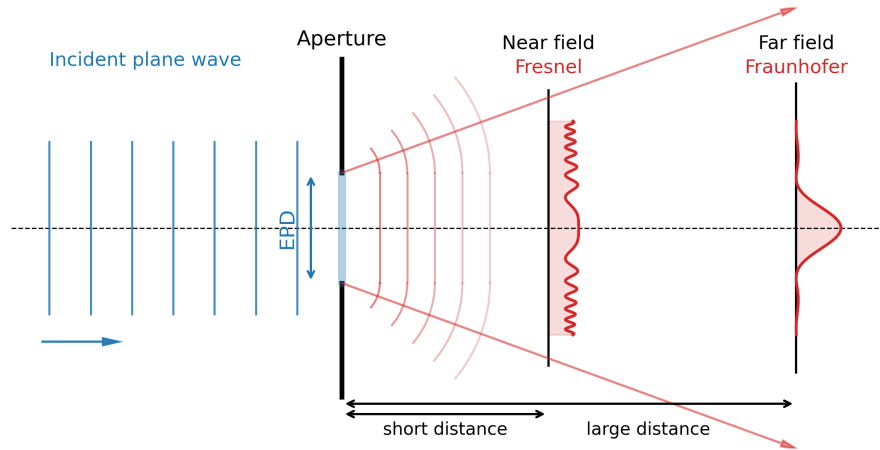


Figure 2.12: Schematic representation of diffraction by a finite aperture. An incident plane wave is clipped by the entrance pupil, causing the transmitted wavefront to spread after the aperture. The near-field region corresponds to Fresnel diffraction, where the diffraction pattern still depends strongly on the propagation distance. At larger distances, the far-field Fraunhofer pattern is formed, characterized by a central maximum and surrounding side lobes.

Diffraction limits the performance of an optical system by spreading the image of an object point over a finite area. This intensity distribution is described by the point spread function (PSF). For a diffraction-limited circular aperture, the PSF takes the form of an Airy pattern, illustrated in 2.13.

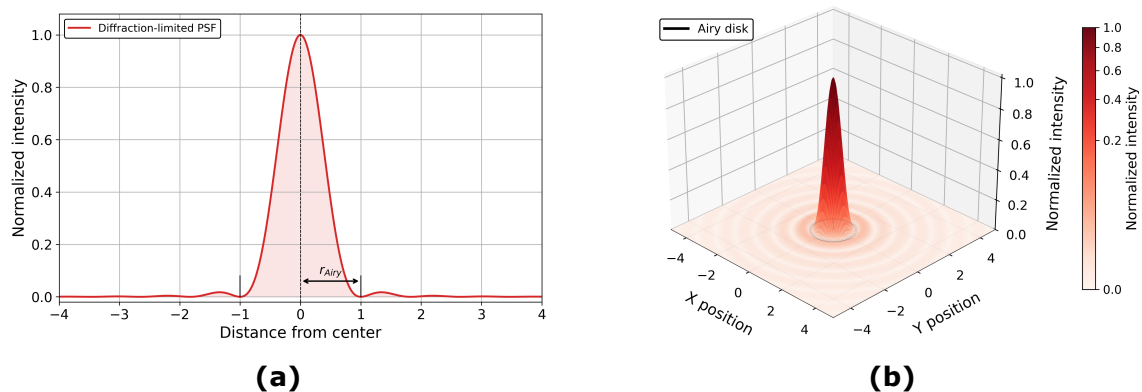


Figure 2.13: Normalized Airy pattern intensity for a diffraction-limited circular aperture, showing the central Airy disk and surrounding diffraction rings; the disk radius is the distance to the first intensity minimum. (a) Radial intensity profile. (b) Three-dimensional intensity distribution.

For a circular aperture, the smallest achievable spot size is determined by the Airy disk radius, defined as the distance from the central maximum to the first intensity minimum [22, Chapter 4.4]. The Airy disk radius r_{airy} is given mathematically by Eq. 2.15 [22, Chapter 4.4]

$$r_{\text{airy}} = 1.22 \cdot \lambda \cdot F/\#, \quad (2.15)$$

For a rectangular aperture or slit, the ideal diffraction-limited line-spread function is sinc²-like, since it follows from the Fourier transform of a rectangular pupil function [22, Chapter 4.4]. However, rectangular apertures are not considered in this thesis.

2.2.2.2 Resolution

Consider two adjacent point sources imaged through a perfect imaging system with an EPD, and an image focused with a given $F/\#$. Each point source will have a corresponding PSF or Airy pattern. If the maximums of the peaks of both point sources are separated by a distance equal to the Airy disk radius, then the intersection point will have an intensity value of 0.74, which is needed for two adjacent points to be resolvable. This is called the Rayleigh criterion [20, Chapter 10].

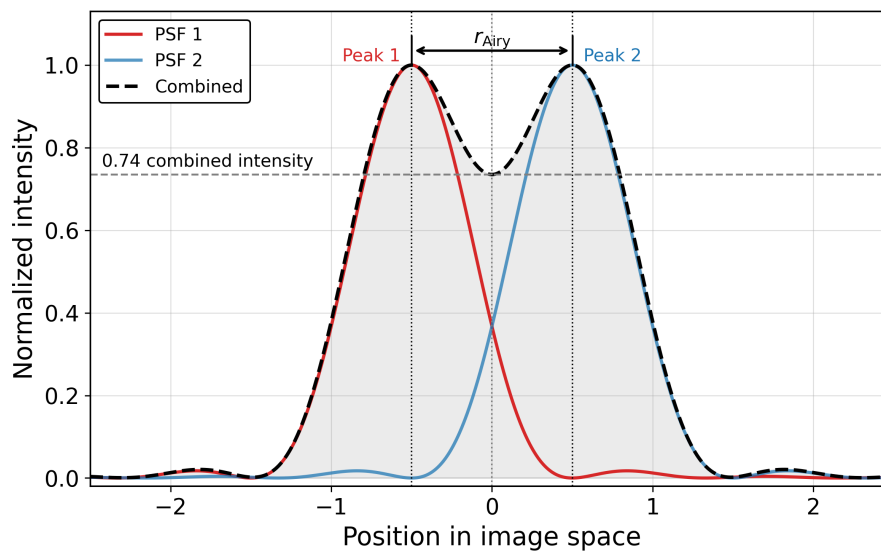


Figure 2.14: Illustration of the Rayleigh criterion for two diffraction-limited point-spread functions. The sources are just resolved when the peak of one Airy pattern coincides with the first minimum of the other, resulting in a combined intensity minimum of approximately 74% between the peaks. Adapted from [20, Chapter 10]

2.2.2.3 Diffraction grating

A controlled use of diffraction is found in diffraction gratings. A diffraction grating is a periodic optical structure that directs incident light into discrete diffraction orders, within which the light is angularly dispersed according to wavelength. The diffraction order therefore influences key spectroscopic properties such as spectral resolution and free spectral range [23, Chapter 2.7]. Gratings can be transmissive or reflective, but in both cases, each wavelength component is diffracted by the periodic groove structure into discrete orders. For a given wavelength, the allowed

diffraction angles correspond to directions in which the fields diffracted by adjacent grooves add in phase, while different wavelengths satisfy this condition at different angles. This condition is called the grating equation and is given by Eq. 2.16 [23, Chapter 2.1]

$$\sin(\theta_m(\lambda)) - \sin(\theta_{in}) = \pm m \frac{\lambda}{\Lambda}, \quad (2.16)$$

where m is the diffraction order (integer), Λ is the groove spacing (or pitch), θ_{in} is the angle of incidence, and $\theta_m(\lambda)$ is the diffraction angle for order m and wavelength (λ). Positive and negative values of m denote diffraction orders on opposite sides of the zeroth order, according to the adopted angle convention. The groove spacing Λ determines the angular positions of the diffraction orders, while the groove profile affects the relative diffraction efficiency of the different orders.

A blazed grating is a diffraction grating whose groove profile is designed to favor a desired diffraction order over a given wavelength range, while reducing the contribution of other diffraction orders. This is commonly achieved using an asymmetric sawtooth groove profile with a specific blaze angle [23, Chapter 9], illustrated in Figure 2.15. In this thesis, the grating is simulated as an ideal grating, while the detailed optimization of the groove profile and blaze angle is outside the scope of the work.

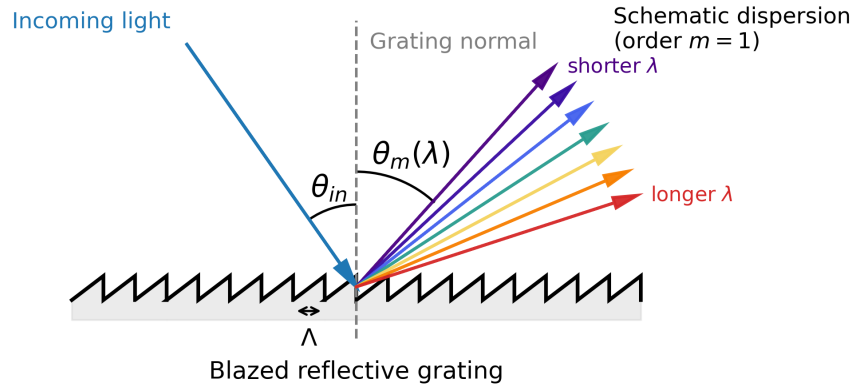


Figure 2.15: Schematic representation of a blazed reflective diffraction grating with a smooth sawtooth groove profile. The incident beam is diffracted into different angular directions according to wavelength, illustrating the dispersive behavior of the grating. The groove spacing is denoted by Λ , while θ_{in} and $\theta_m(\lambda)$ represent the angle of incidence and the diffraction angle of order m , respectively.

Simulating an ideal grating only requires the groove density σ , which is the inverse of the groove spacing Λ , and the diffraction order. To calculate the groove density, the angular dispersion in Eq. 2.17 needs to be derived by differentiating Eq. 2.16 [23, Chapter 2]

$$\text{Angular dispersion: } \frac{d\theta_m(\lambda)}{d\lambda} = \frac{m}{\Lambda \cdot \cos(\theta_m(\lambda))} \quad (2.17)$$

This relation describes the wavelength-dependent angular separation introduced by the grating. As the diffracted beams propagate through the optical system, this grating-induced angular dispersion produces a wavelength-dependent linear separation at the image plane, where different wavelengths are focused onto different detector positions. If the diffracted beam is focused by an optical system with focal length f , the image coordinate can be written as Eq. 2.18

$$x = f \tan(\theta_m(\lambda)). \quad (2.18)$$

Differentiating this expression gives Eq. 2.19 [23, Chapter 2]

$$dx = \frac{f d\theta_m(\lambda)}{\cos^2(\theta_m(\lambda))} \quad (2.19)$$

If we combine this expression with the angular dispersion expression in Eq. 2.17, then the linear dispersion is given by 2.20:

$$\frac{d\lambda}{dx} = \frac{\Lambda \cos^3(\theta_m(\lambda))}{mf} \quad (2.20)$$

Rearranging gives the required groove spacing in Eq. 2.21:

$$\Lambda = \frac{d\lambda}{dx} \frac{mf}{\cos^3(\theta_m(\lambda))} \quad (2.21)$$

The groove density is then given by Eq. 2.22

$$\sigma = \frac{1}{\Lambda} \quad (2.22)$$

where σ is expressed in lines/mm when Λ is expressed in mm.

The diffraction order of $m = 1$ is selected because smaller orders have a higher intensity, and we only require a moderate spectral resolution (25 nm). For spectrometers that need a higher spectral resolution, higher diffraction orders are considered [23, Chapter 2.4].

In addition, the diffraction angle $\theta_m(\lambda)$ is approximated to be small, such that $\cos(\theta_m(\lambda)) \approx 1$. To verify the validity of this approximation, the exact grating (Eq. 2.16) and linear dispersion (Eq. 2.20) relations are combined in Eq. 2.23

$$\frac{d\lambda}{dx} = \frac{\lambda \cos^3(\theta_m(\lambda))}{f \sin(\theta_m(\lambda))} \quad (2.23)$$

For normal incidence ($\theta_{in} = 0^\circ$) and first-order diffraction ($m = 1$), solving this equation numerically for the largest wavelength considered (320 nm), gives $\theta_1(320 \text{ nm}) \approx 1^\circ$. At this angle, $\cos^3(\theta_1(320 \text{ nm})) \approx 0.9996$, so the correction introduced by the angular term is below 0.1%. Therefore, the small-angle approximation is justified for this first-order groove-density estimate.

For a wavelength separation of 25 nm, a detector pixel pitch of 10 μm , and a spectrometer focal length of 22.46 mm, the groove spacing becomes

$$\Lambda = \frac{d\lambda}{dx} \cdot \frac{mf}{\cos^3(\theta_m(\lambda))} = \frac{25 \text{ nm}}{10 \text{ mm}} \cdot \frac{1 \cdot 22.46 \text{ mm}}{1} \approx 0.056 \text{ mm} \quad (2.24)$$

The groove density then becomes:

$$\sigma = \frac{1}{\Lambda} = \frac{1}{0.056 \text{ mm}} \approx 17.81 \text{ lines/mm} \quad (2.25)$$

It should be noted that this calculation provides only a first-order approximation of the required groove density. In the final optical design (see Section 3.5), a slightly higher groove density is required due to non-ideal system effects.

2.2.2.4 Spectral resolution

A spectral bandwidth of 25 nm is proposed for this thesis. For the 2D non-scanning and 2D scanning multispectral imagers, this implies the use of discrete filters with a bandwidth of 25 nm. For the 1D pushbroom multispectral imager, however, angular and linear dispersion must be considered to ensure that different wavelengths can be distinguished on the detector.

The ability of the system to separate adjacent wavelengths is characterized by its spectral resolving power, defined as $R = \lambda/\Delta\lambda$, where $\Delta\lambda$ is the minimum wavelength difference that can be resolved. Two wavelengths are considered distinguishable when their corresponding spectral PSFs are sufficiently separated, such that the intensity maximum of one coincides with the first intensity minimum of the other, in accordance with the Rayleigh criterion [23, Chapter 2.4]. An illustration of the multispectral wavelength distribution is shown in Figure 2.16.

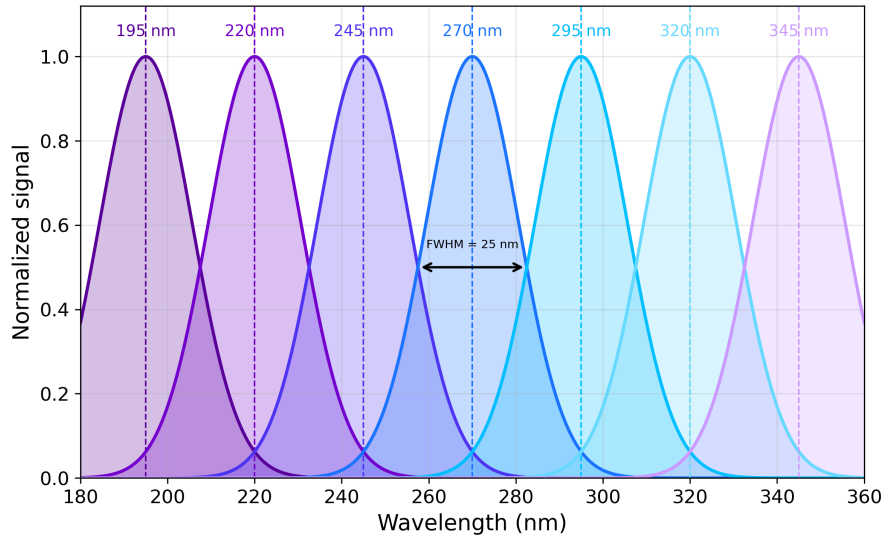


Figure 2.16: Idealized spectral response of the 1D pushbroom multispectral imager with a nominal spectral resolution of 25 nm. The Gaussian-shaped spectral bands (approximating the instrument spectral response) are centered at wavelengths from 195 nm to 345 nm with 25 nm spacing. The full width at half maximum (FWHM) is shown for the band at 270 nm, indicating the wavelength range over which the signal exceeds half of the peak value.

2.2.3 Aberration theory

We present a concise overview of geometrical aberrations, enabling an interpretation of residual field-dependent image degradation. Since the optimized systems are close to diffraction-limited performance, the aberration discussion is limited to the dominant residual effects observed in the final designs.

2.2.3.1 Wave and ray aberration

In an ideal optical system, rays emerging from the exit pupil converge to the Gaussian image point, and the corresponding wavefront coincides with a Gaussian reference sphere centered on that image point. If a ray deviates from its ideal path between the exit pupil plane and the image plane, the resulting displacement at the image plane is referred to as ray aberration. Similarly, if the actual wavefront deviates from the Gaussian reference sphere, this deviation is referred to as wave aberration. A schematic representation of wave and ray aberrations is shown in Figure 2.17 [24, Chapter 5.1].

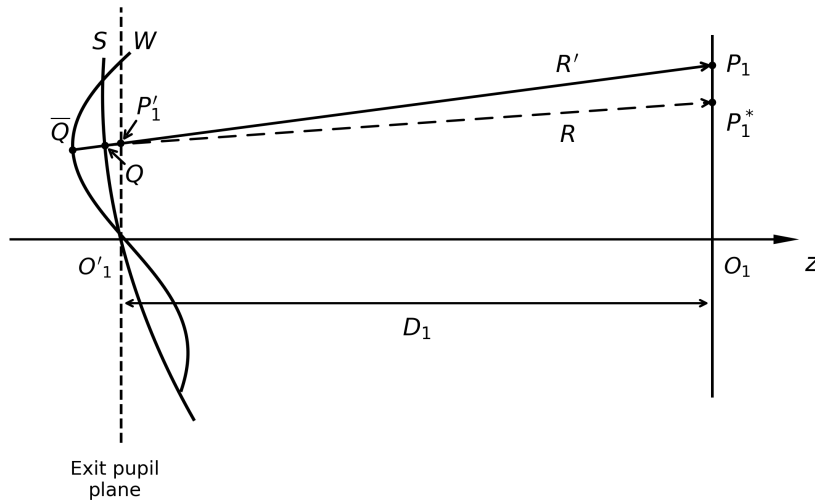


Figure 2.17: Illustration of wave and ray aberrations. The distance $[QQ]$ represents the wave aberration, expressed as the optical path difference between the actual wavefront and the Gaussian reference sphere. The distance $[P_1P_1^*]$ represents the ray aberration at the image plane. Adapted from [24, Chapter 5.1].

The wave aberration is quantified by the optical path difference (OPD), which describes the optical path length difference between the actual aberrated wavefront and the ideal Gaussian reference sphere. In this sense, the OPD provides a wavefront-based measure of the aberration. For well-corrected imaging optics, the OPD is typically on the order of one wavelength or smaller [24, Chapter 5.1].

2.2.3.2 Primary (Seidel) aberrations

Perturbations of the Gaussian reference sphere are described using third-order Seidel aberrations. These aberrations provide a low-order description of the wavefront and ray deviations introduced by an optical system. They do not fully describe the behavior of complex WFOV freeform systems, but they still provide

a qualitative framework for understanding the dominant residual aberrations. The third-order transverse ray aberrations are given by Eq. 2.26 [24, Chapter 5.3]

$$\begin{cases} \Delta^{(3)}x = B\rho^3 \sin(\theta) - 2Fy_0\rho^2 \sin(\theta) \cos(\theta) + Dy_0^2\rho \sin(\theta) \\ \Delta^{(3)}y = B\rho^3 \cos(\theta) - Fy_0\rho^2 (1 + 2\cos^2(\theta)) + (2C + D)y_0^2\rho \cos(\theta) - Ey_0^3 \end{cases} \quad (2.26)$$

Here, B , C , D , E , and F are aberration coefficients, ρ is the normalized pupil radius, θ is the pupil angle, and y_0 is the object height in the object plane. Each coefficient corresponds to a different third-order aberration contribution.

Spherical aberration

Spherical aberration is obtained when $B \neq 0$ and the other coefficients are zero. In that case, Eq. 2.26 reduces to Eq. 2.27

$$\begin{cases} \Delta^{(3)}x = B\rho^3 \sin(\theta) \\ \Delta^{(3)}y = B\rho^3 \cos(\theta) \end{cases} \quad (2.27)$$

Spherical aberration occurs when rays passing through different pupil zones focus at different axial positions. As a result, the rays do not converge to a single point, and the smallest transverse blur along the optical axis is referred to as the circle of least confusion. A normalized spot-pattern representation of spherical aberration is shown in Figure 2.18.

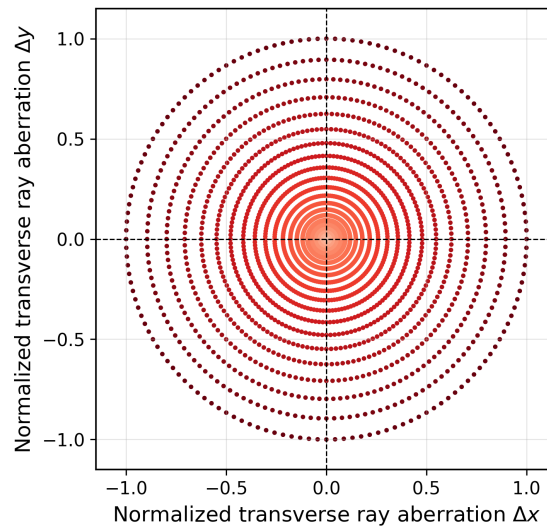


Figure 2.18: Normalized spot-pattern representation of spherical aberration obtained from the third-order Seidel ray-aberration expression.

Coma

Coma is obtained when $F \neq 0$. In this case, Eq. 2.26 reduces to Eq. 2.28

$$\begin{cases} \Delta^{(3)}x = -2Fy_0\rho^2 \sin(\theta) \cos(\theta) = -Fy_0\rho^2 \sin(2\theta) \\ \Delta^{(3)}y = -Fy_0\rho^2 (1 + 2\cos^2(\theta)) = -Fy_0\rho^2 (2 + \cos(2\theta)) \end{cases} \quad (2.28)$$

Unlike spherical aberration, coma depends on the field height y_0 and therefore increases for off-axis field points. It produces an asymmetric spot pattern with a characteristic comet-like shape, as shown in Figure 2.19.

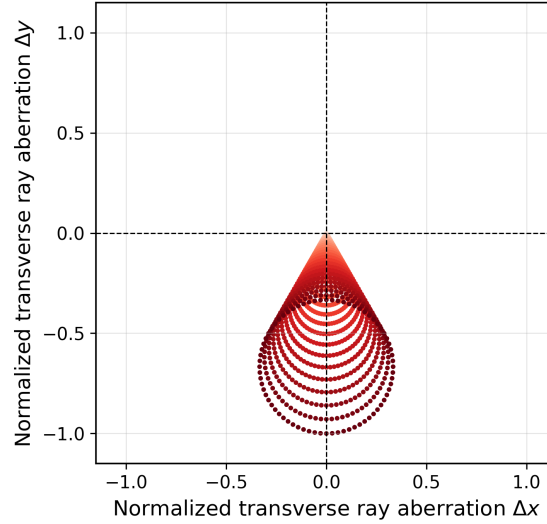


Figure 2.19: Normalized spot-pattern representation of coma obtained from the third-order Seidel ray-aberration expression.

Astigmatism and field curvature

Astigmatism and field curvature are closely related field-dependent aberrations and are therefore discussed together. When the terms associated with C and D are considered, Eq. 2.26 reduces to Eq. 2.29

$$\begin{cases} \Delta^{(3)}x = Dy_0^2\rho \sin(\theta) \\ \Delta^{(3)}y = (2C + D)y_0^2\rho \cos(\theta) \end{cases} \quad (2.29)$$

For an off-axis field point, the tangential and sagittal ray bundles focus at different axial positions. The separation between the tangential and sagittal focal surfaces is referred to as astigmatism. Field curvature, on the other hand, describes the curvature of the best-focus surface relative to a flat image plane. In field-curve plots, the separation between the tangential and sagittal curves indicates astigmatism, while the departure of these curves from a flat image plane indicates field curvature. The tangential and sagittal field curvatures are expressed using Eq. 2.30 and 2.31

$$\frac{1}{R_t} = 2n_1(2C + D) \quad (2.30)$$

$$\frac{1}{R_s} = 2n_1D \quad (2.31)$$

where R_t and R_s are the tangential and sagittal radii of curvature, respectively. The astigmatic contribution is proportional to the difference between these two curvatures:

$$\frac{1}{2} \left(\frac{1}{R_t} - \frac{1}{R_s} \right) = 2n_1C \quad (2.32)$$

Here, $n_1 = \sqrt{n_0^2 - p_0^2 - q_0^2}$ is the longitudinal component of the optical direction vector. n_0 is the refractive index of the object-side medium, the quantities p_0 and q_0 are the transverse direction-cosine-related quantities associated with the propagation between the object plane and the entrance pupil plane, following the notation in [24, Chapter 4.1 and 5.3]. A normalized representation of the combined astigmatism and field-curvature contribution is shown in Figure 2.20.

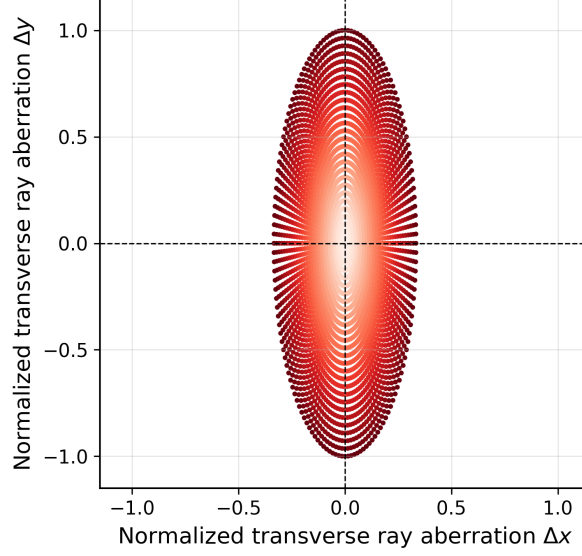


Figure 2.20: Normalized spot-pattern representation of the combined astigmatism and field-curvature obtained from the third-order Seidel ray-aberration.

Distortion

The final primary Seidel aberration is distortion, which is obtained when $E \neq 0$. In that case, Eq. 2.26 reduces to

$$\begin{cases} \Delta^{(3)}x = 0 \\ \Delta^{(3)}y = -Ey_0^3 \end{cases} \quad (2.33)$$

Since this term is independent of the pupil coordinates ρ and θ , distortion does not primarily blur the image of an individual field point. Instead, it changes the geometrical mapping between object and image coordinates. From an optical-design perspective, distortion corresponds to a field-dependent transverse magnification: chief rays from different field points are imaged with slightly different magnifications and therefore intercept the detector at positions that deviate from the ideal linear image mapping. Therefore, the image remains locally sharp while the relative positions of the image points are geometrically deformed.

Different types of image distortion arise depending on how the magnification varies across the field. Common examples include keystone and smile distortions [25], as well as barrel and pincushion distortions [20, Chapter 5], which are illustrated in Figure 2.21. In pushbroom multispectral architectures, additional spectral-spatial distortions may occur. In this context, smile refers to the curvature of constant-wavelength lines on the detector, whereas keystone describes wavelength-dependent spatial displacement or magnification of the slit image [25].

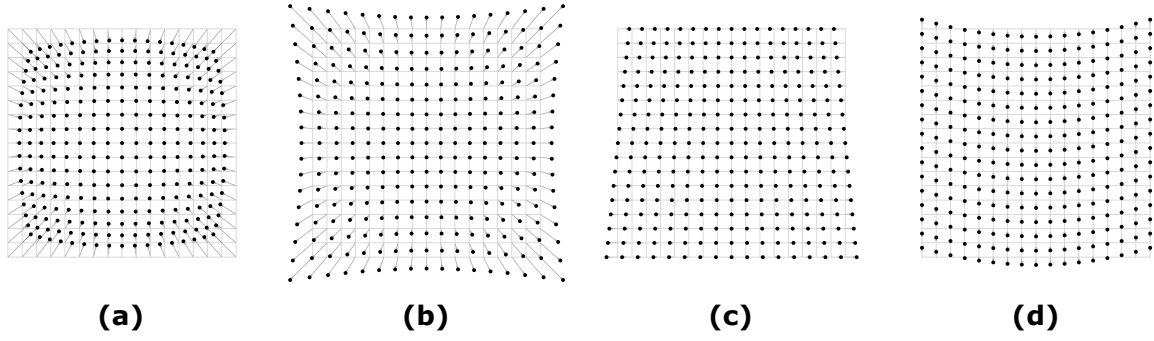


Figure 2.21: Theoretical representation of common optical distortion types. The grey grid represents the ideal undistorted image geometry, while the black points indicate the displaced grid positions after distortion. (a) Barrel. (b) Pincushion. (c) Keystone. (d) Smile.

Ideally, an optical system maps object points to image points without geometric deformation. In practice, however, distortion is unavoidable in WFOV systems. In off-axis freeform systems, the distortion pattern does not necessarily correspond to a purely radial barrel or pincushion form. Therefore, distortion is evaluated more generally using the maximal radial grid distortion. This metric is defined as the largest relative radial deviation between the real chief-ray intercept and the ideal, linearly predicted image position over all sampled grid points. It is given by Eq. 2.34 [20, Chapter 5]

$$D_{\text{grid,max}} = \max_i \left| \frac{R_{\text{distorted}}}{R_{\text{predicted}}} \right| \times 100\% \quad (2.34)$$

where Eq. 2.35, Eq. 2.36, and Eq. 2.37 represent the real, predicted and distortion radial grid positions, respectively

$$R_{\text{real}} = \sqrt{x_r^2 + y_r^2} \quad (2.35)$$

$$R_{\text{predicted}} = \sqrt{x_p^2 + y_p^2} \quad (2.36)$$

$$R_{\text{distorted}} = \sqrt{(x_p - x_r)^2 + (y_p - y_r)^2} \quad (2.37)$$

where (x_r, y_r) are the real chief-ray intercept coordinates on the image plane, and (x_p, y_p) are the corresponding ideal coordinates predicted by the local linear, undistorted image model around the reference field.

Chromatic aberration

Although chromatic aberration is not one of the Seidel aberrations, it is an important consideration in broadband refractive optical systems. Chromatic aberration arises from material dispersion, where the refractive index depends on wavelength, causing different wavelengths to focus at different axial positions or to be imaged with different magnifications. In the present design, however, the optical system is fully reflective. Since reflection from mirrors is essentially independent of wavelength in terms of geometrical focusing, the system does not introduce chromatic aberration in the same way as a refractive lens system [24, Chapter 5.7].

Summary

In summary, spherical aberration, coma, and astigmatism mainly reduce image sharpness by spreading ray intercepts in the image plane. Field curvature and distortion are primarily related to the location and geometrical mapping of the image. Field curvature shifts the best-focus surface away from a flat detector plane. Distortion arises from a field-dependent magnification, meaning that points at different field positions are imaged with different transverse magnifications. This changes the relative positions of image points and leads to geometrical deformation of the image, without necessarily reducing the local sharpness. Chromatic aberration is normally important in broadband refractive systems, but is not introduced by the fully reflective optical system considered in this thesis.

2.2.4 Image Quality Metrics

The performance of the designed optical system must be evaluated using several image quality metrics. In this work, the relevant metrics include the root mean square (RMS) spot size, the encircled energy (EE), the Strehl ratio, and the modulation transfer function (MTF).

2.2.4.1 RMS Spot Size

The RMS spot size provides a geometrical measure of the spatial spread of ray intercepts at the image plane. The RMS spot diameter contains approximately 68% of the energy [20, Chapter 10]. It is commonly used as a practical verification of the focusing performance of an optical system and can be compared with both the Airy disk and the detector pixel size. The RMS spot size is given by Eq. 2.38 [26]

$$r_{\text{RMS}} = \sqrt{\frac{1}{N} \sum_i^N \left((x_i - \bar{x})^2 + (y_i - \bar{y})^2 \right)} \quad (2.38)$$

Here, (x_i, y_i) is the image-plane intercept position of the i^{th} ray, $(\bar{x}, \bar{y})$ is the centroid of the ray intercept distribution, and N is the total number of rays used in the calculation.

2.2.4.2 Encircled Energy

The encircled energy (EE) describes the fraction of the energy that falls within a given radius or area around the centroid of the spot on the image plane. Unlike the RMS spot size, which gives a single measure of the spatial spread of the ray intercepts, the EE directly indicates how much of the energy is concentrated within a specified detector area. This makes it particularly relevant for detector-limited imaging systems. A reliable rule of thumb is that 80% of the energy should fall within one pixel to meet the optical performance requirement [20, Chapter 10]. The same evaluation criterion is considered for this thesis work.

2.2.4.3 Strehl Ratio

The Strehl ratio quantifies how close the actual point spread function (PSF) is to the diffraction-limited PSF by comparing their peak intensities. It is defined by Eq. 2.39

$$S = \frac{I_{\text{peak,actual}}}{I_{\text{peak,diffraction-limited}}} \quad (2.39)$$

The Maréchal criterion dictates that an optical system can be considered diffraction-limited when the Strehl ratio is larger than 0.8. Following the criterion, the RMS wavefront error shall not exceed $\lambda/14$ for a diffraction-limited system (or field) [24, Chapter 9.3]. This concept is illustrated in Figure 2.22.

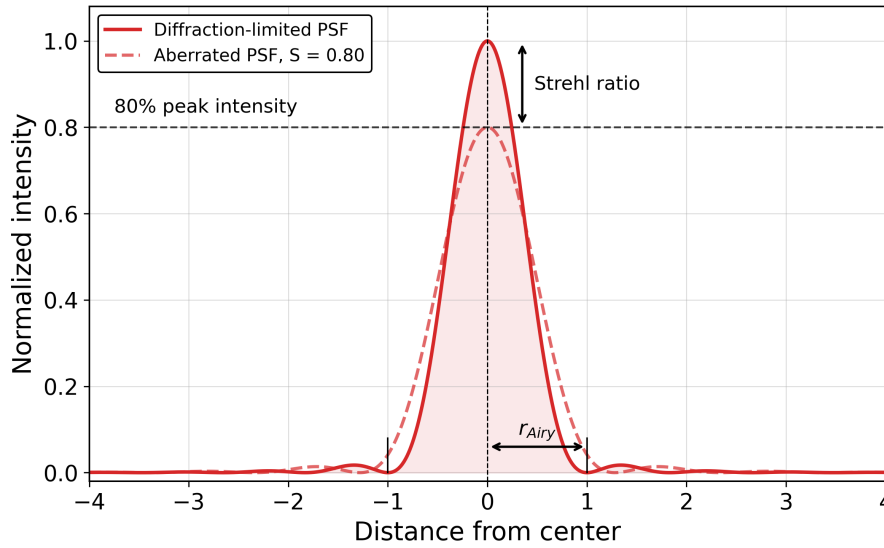


Figure 2.22: Illustration of the Strehl ratio using normalized point spread functions. The diffraction-limited PSF has a peak intensity normalized to unity, while the aberrated PSF exhibits a reduced peak intensity. A Strehl ratio of 0.8 corresponds to a peak intensity equal to 80% of the diffraction-limited value.

2.2.4.4 Modulation Transfer Function

The modulation transfer function (MTF) quantifies the ability of an optical system to transfer object contrast to the image plane as a function of spatial frequency. The MTF allows for evaluating the imaging quality of all images. It considers the contrast as function of object frequency. Spatial frequency describes variations in image intensity rather than the physical size of the object itself. Slowly varying structures, such as broad uniform regions, correspond to low spatial frequencies, whereas rapidly varying structures, such as sharp edges, fine texture, or closely spaced line pairs, correspond to high spatial frequencies. Following diffraction theory and Fourier optics, the MTF is defined as the magnitude of the optical transfer function (OTF) [22, Chapter 7.3].

An important concept in the diffraction-limited MTF is the cut-off frequency f_c . The cut-off frequency is the highest spatial frequency that the optical system can transfer to the image plane. Spatial frequency components above this frequency are not transmitted by the system and therefore cannot be resolved. For an

incoherent diffraction-limited optical system with a circular aperture, the cut-off frequency is defined by Eq. 2.40 [22, Chapter 7.3]:

$$f_{c,\text{incoh}} = \frac{w}{\lambda z_i} \quad (2.40)$$

Where w is the diameter of the exit pupil, λ is the wavelength, and z_i is the distance between the exit pupil and the image plane.

For an aberration-free diffraction-limited system, the MTF is determined by the finite aperture of the optical system and decreases with increasing spatial frequency. In the optical designs considered in this thesis, the aperture stop is circular and is assumed to define a circular entrance pupil. Therefore, the diffraction-limited incoherent MTF is given by 2.41 for a circular aperture [22, Chapter 7.3]:

$$\text{MTF}(f) = \begin{cases} \frac{2}{\pi} \left[\arccos\left(\frac{f}{f_{c,\text{incoh}}}\right) - \frac{f}{f_{c,\text{incoh}}} \sqrt{1 - \left(\frac{f}{f_{c,\text{incoh}}}\right)^2} \right], & f \leq f_{c,\text{incoh}}, \\ 0, & f > f_{c,\text{incoh}}. \end{cases} \quad (2.41)$$

Here, f is the spatial frequency. Aberrations reduce the MTF compared to the diffraction-limited case, especially at higher spatial frequencies. Therefore, the MTF provides a useful image quality metric for evaluating how well fine spatial details and contrast are preserved by the optical system. An illustration of the MTF is shown in Figure 2.23.

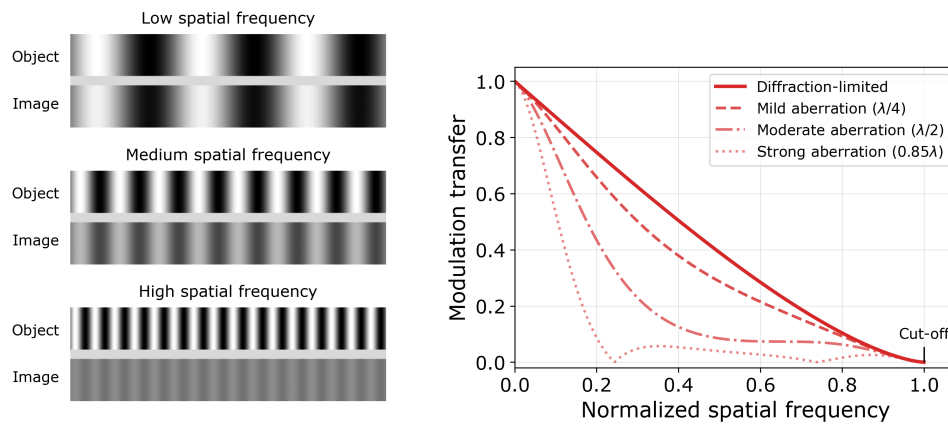


Figure 2.23: Illustration of the Modulation Transfer Function (MTF) for a circular aperture. The left side shows the imaging of sinusoidal object patterns with increasing spatial frequency, demonstrating the loss of contrast at higher frequencies. The right side shows the diffraction-limited and aberrated MTF curves, illustrating the reduction of contrast transfer and the cut-off frequency beyond which spatial information is no longer transmitted.

In addition to the optical cut-off frequency, the detector sampling imposes an additional constraint on the spatial frequencies. For a detector with pixel pitch p , the highest spatial frequency that can be sampled without aliasing is the Nyquist frequency, given by Eq. 2.42 [20, Chapter 23]

$$f_{\text{Nyq}} = \frac{1}{2p} \quad (2.42)$$

We evaluated the MTF at the Nyquist frequency to determine whether sufficient contrast is preserved at the highest spatial frequency that can be sampled by the detector. The effective system resolution is therefore determined by both the optical cut-off frequency and the detector Nyquist frequency.

For a detector with pixel size $10\text{ }\mu\text{m}$, the Nyquist frequency $f_{\text{Nyq}} = 50\text{ cycles/mm}$. For this thesis, a minimum MTF of 0.5 at f_{Nyq} is considered [27]. It should be noted that this definition assumes a monochrome detector with uniform sampling. For detectors employing color filter arrays, such as Bayer patterns, the effective sampling frequency differs between color channels, resulting in direction-dependent and channel-dependent Nyquist frequencies [20, Chapter 23].

2.2.5 Freeform Optical Surfaces

Complex optical systems often have very tight volume requirements or an ambition for a reduction in the number of considered surfaces. Therefore, they benefit from optical components with a large number of degrees of freedom. Rotationally symmetric surfaces, such as spherical and aspherical surfaces, are mainly defined by the radius of curvature, conic constant, aspheric coefficients, and the relative distances between the mirrors.

A way to introduce additional design freedom is to use freeform surfaces. Freeform surfaces allow the surface sag to vary as a function of both transverse coordinates, making it possible to describe asymmetric surface shapes that are no longer rotationally symmetric and that cannot be obtained with classical spherical and aspheric surface descriptions [28].

Freeform surface representations can be divided into multiple categories, including point clouds, basic splines, and polynomial descriptions. Considering the latter polynomials, both orthogonal and non-orthogonal functions have been explored, depending on the aperture shape and design specifications. Some examples of orthogonal surface representations include Zernike polynomials, Q-type polynomials, 2D Chebyshev polynomials, and 2D Legendre polynomials [28]. Examples of non-orthogonal representations include XY-type polynomials, spline-based descriptions, and radial basis functions [28]. Each surface description starts from a base function. This can be a rotationally symmetric conic or aspheric surface, or it can be a non-rotationally symmetric representation.

In this thesis, the freeform catoptric mirrors are described by an off-axis conic base surface with an additional XY polynomial freeform departure. The off-axis conic representation follows the XY polynomial description, with an additional offset Y_0 . The offset Y_0 defines the displacement between the parent conic coordinate system and the local coordinate system of the off-axis surface section. An illustration of this offset is given in Figure 2.24. More detailed calculations are given in [29].

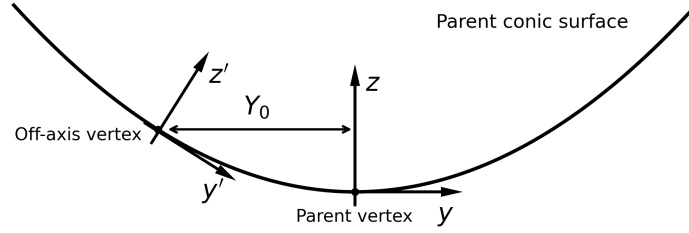


Figure 2.24: Geometrical representation of the global (y, z) and local (y', z') coordinate systems used to describe the off-axis conic surface. The local coordinate system is shifted from the parent conic vertex by the offset Y_0 . Adapted from [29].

The surface sag (Eq. 2.43) can be written as a base rotationally symmetric conic surface with an additional freeform XY polynomial departure [28]:

$$z(r) = \frac{cr^2}{1 + \sqrt{1 - (1+k)c^2r^2}} + \sum_{i=1}^N A_i E_i(x, y) \quad (2.43)$$

where z is the surface sag, c is the curvature of the base conic surface, $r = \sqrt{x^2 + y^2}$ is the radial distance from the surface vertex, and k is the conic constant. The second term represents the freeform departure from the base conic, where N is the number of polynomial terms, A_i is the coefficient of the i^{th} polynomial term, and $E_i(x, y)$ is the corresponding XY polynomial basis function.

For the off-axis conic freeform representation, the rotationally symmetric conic base is replaced by a coordinate-shifted off-axis conic base, denoted by $w(r)$. The more general formulation of the surface sag is then given by Eq. 2.44 [29]:

$$z_f(r) = w(r) + \sum_{i=1}^N A_i E_i(x, y) \quad (2.44)$$

In this expression, $z_f(r)$ represents the total freeform sag, $w(r)$ represents the off-axis conic base surface, and the summation term represents the additional XY polynomial freeform departure, centered at the off-axis vertex at a distance Y_0 from the parent vertex.

In an XY polynomial description, the freeform departure is written as a sum of monomial terms of the form $x^p y^q$, where p and q are non-negative integers. The total order of each term is given by $p + q$. Increasing the number of included terms, therefore, increases the maximum polynomial order and adds additional degrees of freedom to the surface description. Some terms depend only on x , some only on y , and mixed terms depend on both transverse coordinates. The first terms of the polynomial expansion are given by Eq. 2.45 [29]

$$\begin{aligned} z_f(r) = w(r) &+ A_1 x + A_2 y \\ &+ A_3 x^2 + A_4 xy + A_5 y^2 \\ &+ A_6 x^3 + A_7 x^2 y + A_8 xy^2 + A_9 y^3 + \dots \end{aligned} \quad (2.45)$$

The first line contains first-order terms, the second line contains second-order terms, and the third line contains third-order terms. Higher-order terms are added in the same way. Depending on the powers of x and y , individual terms may be

even or odd in one or both transverse directions. This is important because the symmetry of the optical system will be used to reduce the number of polynomial terms. If the surface is symmetric with respect to one coordinate direction, all terms that are odd in that coordinate can be omitted, since they would break that symmetry.

For the designs considered in this thesis, the optical system retains symmetry in the x -direction. Therefore, only terms with even powers of x are used in the freeform departure. The reduced polynomial expansion is given in Eq. 2.46

$$\begin{aligned}
 z_f(r) = & w(r) + B_1y \\
 & + B_2x^2 + B_3y^2 \\
 & + B_4x^2y + B_5y^3 \\
 & + B_6x^4 + B_7x^2y^2 + B_8y^4 \\
 & + B_9x^4y + B_{10}x^2y^3 + B_{11}y^5 + \dots
 \end{aligned} \tag{2.46}$$

where B_i are the remaining freeform coefficients after applying the symmetry constraint. Terms such as x , xy , x^3 , and xy^2 are omitted because they contain odd powers of x and would introduce an antisymmetric contribution in the x -direction. In this work, the optimized coefficient amplitudes depend on the specific design (2D non-scanning, 2D scanning, and 1 pushbroom multispectral imager). Examples of individual XY polynomial terms are shown in Figure 2.25.

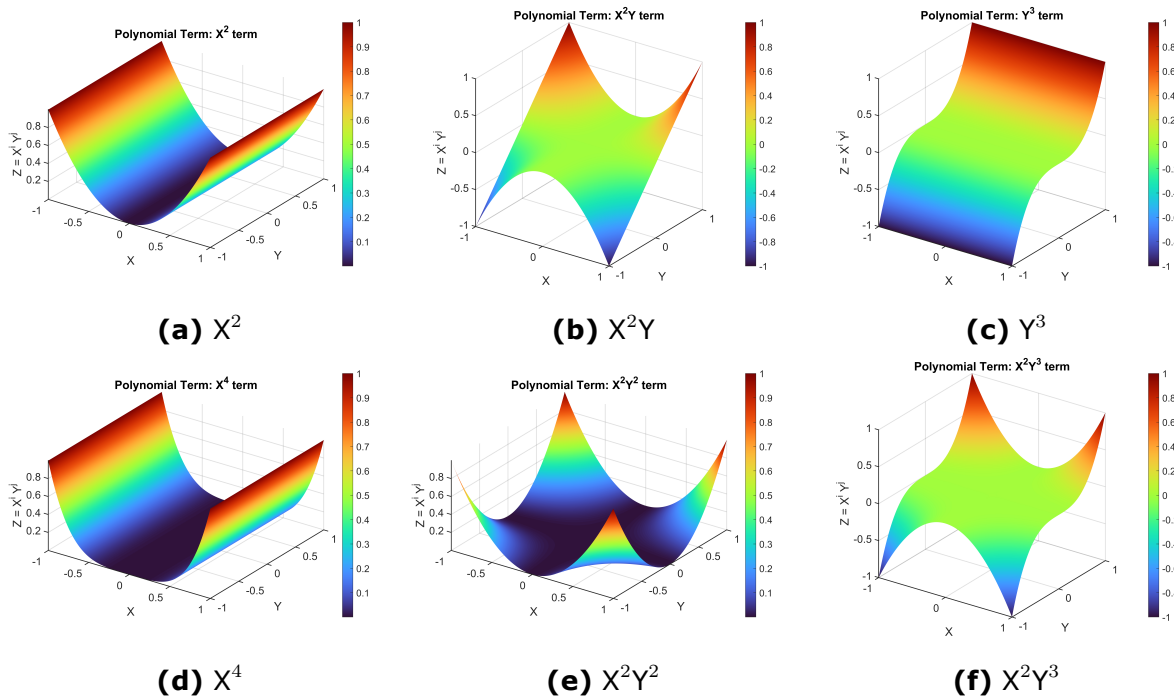


Figure 2.25: Examples of individual XY polynomial basis terms used to describe freeform surface departures. Each term represents a different contribution to the total surface sag and can be weighted by its corresponding polynomial coefficient during optimization.

2.3 Summary

The optical architectures investigated in this thesis, namely the 2D non-scanning, 2D scanning, and 1D pushbroom multispectral imagers, target a design space that is not covered by the selected state-of-the-art instruments. Existing systems such as MRO/MARCI, SPICAM, MAVEN/IUVS, and ECO demonstrate individual capabilities that are relevant to this work, including WFOV UV imaging using a refractive design, UV spectroscopy, and catoptric pushbroom spectral imaging. However, none of these instruments simultaneously combines the specific requirements considered here: WFOV UV spectral imaging of Mars from high altitude, kilometer-scale GSD, and a compact instrument volume and mass.

This combination of requirements is challenging from an optical-design perspective. WFOV imaging strongly increases field-dependent aberrations, while operation in the UV restricts the use of refractive optics because of material transmission limitations, chromatic aberration, and prototyping cost. A fully reflective architecture is therefore pursued in this thesis. By avoiding refractive optical power, the designs inherently avoid refractive chromatic aberration and remain suitable for broadband UV operation. This makes the reflective approach particularly attractive for a spectral imaging system in which multiple UV wavelengths must be handled within a compact optical envelope.

A key enabling technology in the proposed designs is the use of freeform reflective optics. Compared to rotationally symmetric spherical or aspherical mirrors, freeform surfaces provide additional degrees of freedom by allowing the surface sag to vary independently as a function of both transverse coordinates. This is especially valuable in compact off-axis systems, where asymmetric and field-dependent aberrations cannot be corrected efficiently using conventional rotationally symmetric surfaces alone. Freeform optics, therefore, provide a direct path toward miniaturization, since they allow aberration correction over a WFOV using a limited number of optical surfaces and within a reduced system volume.

The novelty of the work lies in the combination of three design choices: a fully reflective UV-compatible architecture, a WFOV spectral imaging requirement, and freeform surfaces for compact aberration control. This combination differentiates the investigated optical systems from the selected state-of-the-art instruments.

Chapter 3

Design and comparison of three spectral imager architectures

3.1 General design procedure

Due to the different wavelength selection principles (discrete filters versus diffraction grating), the 2D non-scanning and scanning multispectral imagers differ in system architecture compared to the 1D pushbroom multispectral imager. The 2D systems are based on a three-mirror anastigmat (TMA) architecture consisting of three off-axis freeform mirrors. The TMA configuration is a well-established reflective imaging architecture that provides strong aberration correction while maintaining a compact system layout [30]. In contrast, the 1D pushbroom multispectral imager consists of a two-mirror telescope, a collimator, and a three-mirror spectrograph, and is based on the freeform spectrometer concept developed for the ECO mission [18], introduced in Section 2.1.4.

The optical design is performed in the Sequential Mode of Ansys Zemax OpticStudio [31]. The design methodology follows the off-axis design approach described by Reshidko et al. [29]. An overview of the general design workflow is shown in Figure 3.1. The optimization process starts from an on-axis configuration with flat mirrors, while obscuration effects are initially neglected. The number of mirrors depends on the selected system architecture, as was mentioned in the previous paragraph.

The initial inter-mirror distances are set based on the required $F/\#$ and EFL from the proposed specifications in Table 1.1, while keeping the system within the predefined volume constraint of $220 \times 200 \times 150 \text{ mm}^3$. In the first optimization stage, only the main geometrical parameters are optimized, including radii of curvature, conic constants, inter-surface distances, tilts, and decenters. Once no further performance improvement can be obtained with these parameters, additional degrees of freedom are introduced by sequentially adding freeform terms up to the 8th order. Introducing complexity in small, controlled steps improves the stability of the optimization process and reduces the risk of convergence toward non-physical or poorly constrained solutions. The optical performance is evaluated using RMS spot size, encircled energy, and MTF as figures of merit, as described in Section 2.2.4. A similar design methodology is applied to all proposed architectures, of which a representative example is shown in detail in Figure 3.2.

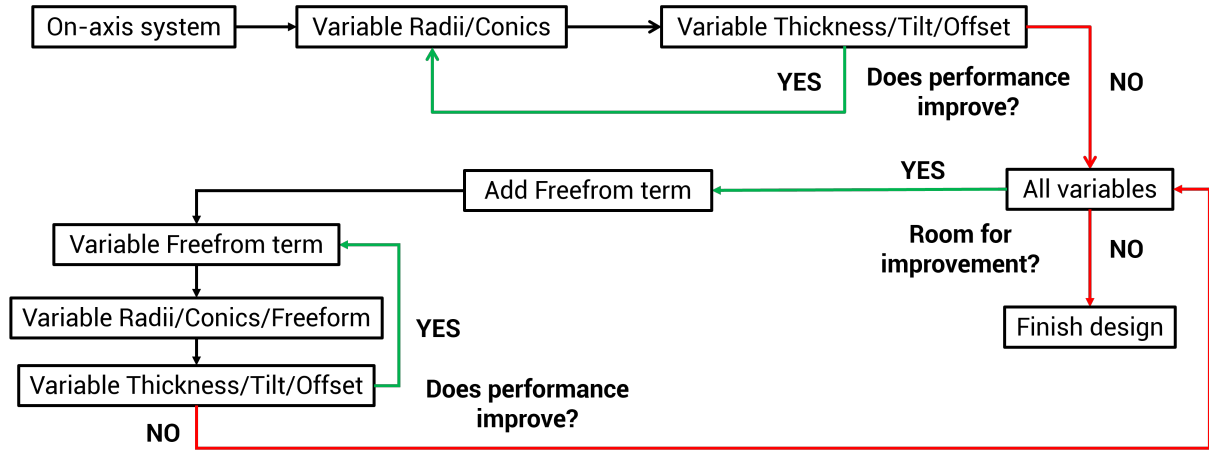


Figure 3.1: Overview of the general optical design methodology adopted in this work. The workflow starts from an on-axis configuration and proceeds through successive optimization loops, first using first-order geometrical parameters and subsequently introducing freeform terms when additional performance improvement is required.

In addition to the general optimization procedure, the design of the pushbroom multispectral imager includes the diffraction grating as an explicit design parameter. The initial groove density, calculated in Section 2.2.2.3 ($\sigma \approx 17.8$ lines/mm), represents a first-order approximation and is therefore used as a starting point rather than a fixed value. After the system is optimized using this initial estimate, the groove density is adjusted slightly, and the system is reoptimized to achieve the required spectral and imaging performance. This will be explained in more detail in Section 3.5.

The pupil, image, ray, and grid sampling used for the different quality metrics, including MTF, PSF, EE, RMS wavefront error, and distortion, were selected based on the requirements of each metric. The pupil and ray sampling were determined by gradually increasing the sampling density until the corresponding quality metric changed by less than 5%. The image sampling was either matched to the pupil sampling or selected such that the relevant plot limits remained within the desired range, for example, in the PSF evaluation. This approach ensures that the reported results are not dominated by numerical sampling effects, while avoiding unnecessary computation time. For the distortion evaluation, increasing the grid size did not lead to a noticeable change in the maximum distortion value, indicating that the maximum error occurs near the corners of the image field. Therefore, in this case, the grid size was selected primarily for visual clarity rather than numerical convergence.

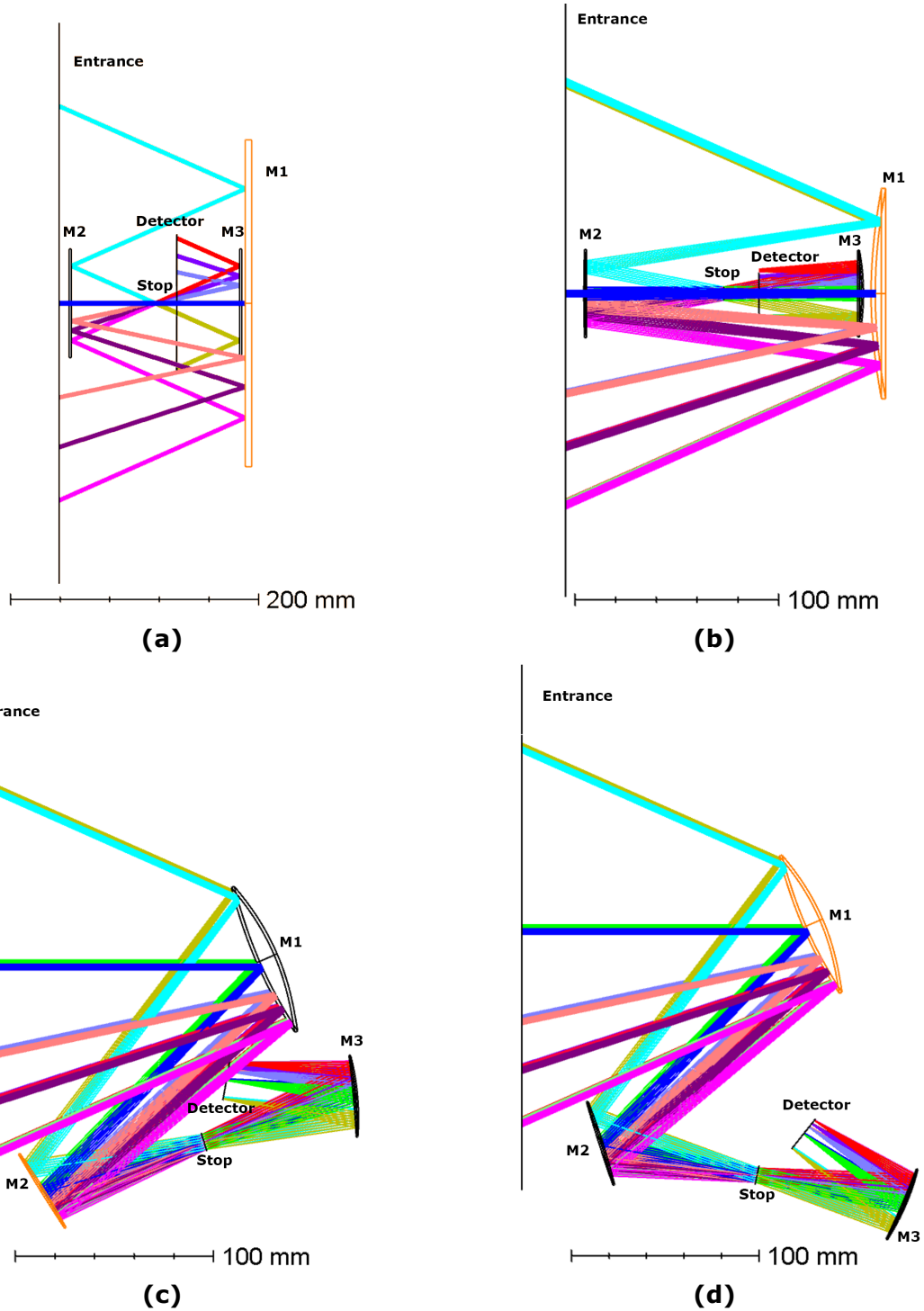


Figure 3.2: Sequential optimization of the 2D non-scanning multispectral imager, starting from an on-axis three-mirror geometry and progressively adding additional design degrees of freedom. (a) On-axis starting geometry. (b) Optimization of radii, conic constants, and inter-surface distances. (c) Additional optimization of tilts and decenters. (d) Final optimization including freeform surface terms.

3.2 Design optimization constraints

During the optimization, the standard image-quality metrics are supplemented with several practical constraints, ensuring the optimized systems remain physically meaningful and compatible with realistic optical components. These latter constraints include the angle-of-incidence (AOI) at the bandpass filters, the mirror coatings, the chief-ray angle at the detector, the clear-aperture margins, and vignetting. A large AOI causes a shift of the filter transmission band towards shorter wavelengths [32, Chapter 8.2.4]. To preserve the intended spectral response of each channel, the AOI through the filters must therefore be limited. This imposes an additional constraint on the optical architecture and must be considered during the design process. The detector has an angle-dependent anti-reflective (AR) coating. Therefore, the chief-ray angle is controlled to maintain a near-telecentric image-space configuration.

In addition to AOI constraints, obscuration effects or vignetting play an important role, especially in off-axis reflective systems. During the final optimization stages, vignetting must be controlled to ensure that the relevant ray bundles remain unobstructed. We achieved this using ray-intersection calculations, which check whether selected rays remain within the allowed optical path between successive surfaces. These calculations are applied only to the multispectral imaging systems, since they are formulated for the TMA architecture. The corresponding geometries are shown schematically in Figure 3.3.

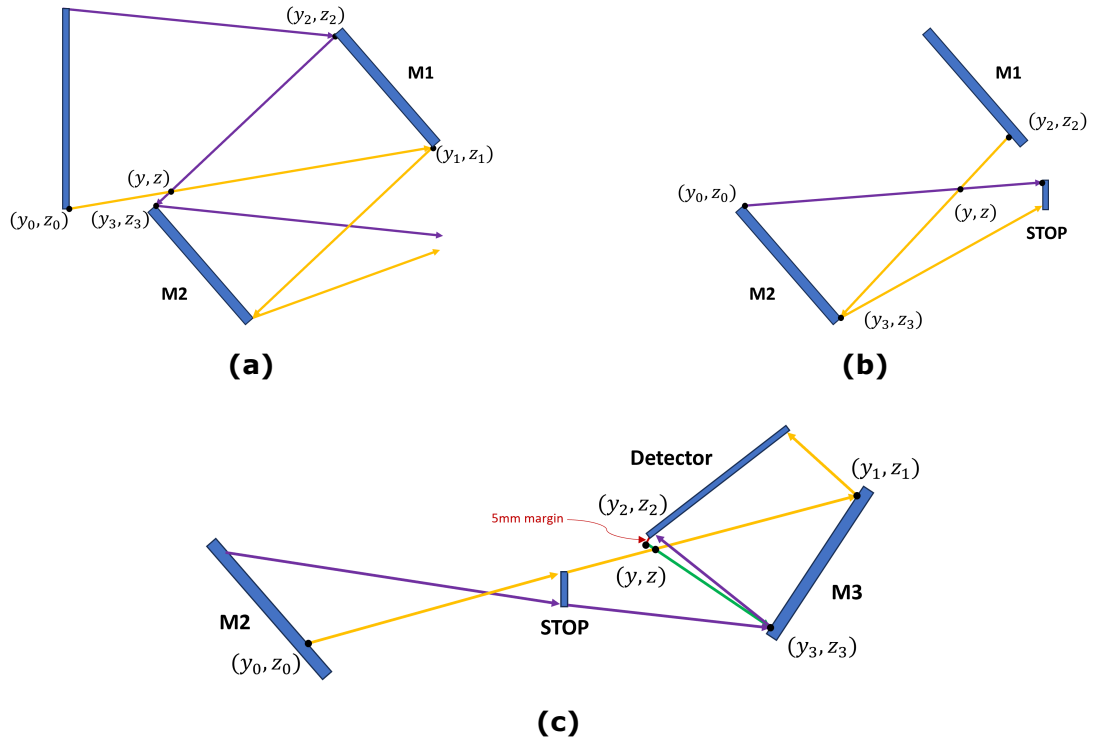


Figure 3.3: Ray-intersection geometries used to evaluate possible vignetting locations during optimization. The intersection point (y, z) is calculated and checked against the corresponding reflected marginal-ray segment to verify whether the ray remains within the allowed optical path between the relevant surfaces. (a) Vignetting check at M2. (b) Vignetting check at the stop. (c) Vignetting check at the detector, including a 5 mm margin.

The intersection condition is evaluated using the global ray coordinates on the mirrors by considering the straight-line paths between successive ray positions. The resulting intersection coordinate is given by Eq. 3.1

$$z = \frac{\frac{y_2 - y_3}{z_2 - z_3} z_3 - \frac{y_1 - y_0}{z_1 - z_0} z_0 + y_0 - y_3}{\frac{y_2 - y_3}{z_2 - z_3} - \frac{y_1 - y_0}{z_1 - z_0}} \in [z_3, z_2] \quad (3.1)$$

In the final design optimizations, only the vignetting constraint at the M2 mirror was used, as shown in Figure 3.3a. The other vignetting checks were not included in the final merit function because they significantly slowed down the optimization and could be controlled more efficiently by manually constraining the tilts of the optical components.

It should be noted that the vignetting calculation is only applied from the third optimization step onward, as shown in Figure 3.2c. Prior to this, the system geometry is still too close to the initial on-axis configuration. Therefore, an initial off-axis tilt must first be introduced before the vignetting calculation can be applied correctly.

The AOI on the mirror coatings is not directly constrained during the optical optimization. At larger AOI values, only a limited reduction in mirror reflectivity is expected. However, this loss in reflectivity can be significant for the overall system throughput, particularly in the UV wavelength range. This is explained in more detail in Section 4.2.

Priority is given to optical performance and system compactness rather than explicitly minimizing the AOI on the mirror surfaces. Nevertheless, care is taken to keep the mirror tilts as small as possible within the constraints imposed by vignetting and volume limitations, and mirror tilts are ensured to remain well below extreme values (max 30°, i.e., far from grazing incidence of 90°). Table 3.1 gives an overview of the optimization variables and design constraints considered in this thesis.

Table 3.1: Overview of optimization variables and design constraints used in the optical design process.

Category	Parameter	Description
Variable	Radius of curvature	Surface curvature of components
	Conic constant	Aspheric base shape
	Surface distances	Axial distance between optical components
	Surface tilt	Component orientation
Variable	Surface decenter	Position shift of the mirror surface within the optical layout
	Surface offset	Parent-conic offset Y_0 used to define the off-axis conic section, measured along the y -axis of the parent coordinate system (see Figure 2.24)
	Freeform coefficients	Higher-order surface terms (X even): $X^2, Y^2, X^2Y^1, Y^3, X^4, X^2Y^2, Y^4, X^2Y^3, X^4Y^1, Y^5, X^6, X^2Y^4, X^4Y^2, Y^6, X^2Y^5, X^4Y^3, X^6Y^1, Y^7, X^8, X^2Y^6, X^4Y^4, X^6Y^2, Y^8$ (see Section 2.2.5)
Constraint	Field position	Image plane field distribution
	AOI at filters	Incidence angle on bandpass filters
	Telecentricity	Image-space telecentricity
	Vignetting	Obscuration control between surfaces
	Clear-aperture	Physical realizability
	Volume envelope	Maximum allowed system size

3.3 Architecture 1: 2D non-scanning multispectral imager

3.3.1 Design layout and challenges

The first design that is considered is the 2D non-scanning multispectral imager. This architecture features a WFOV ($48^\circ \times 48^\circ$) in two dimensions. Therefore, it eliminates the need for a scanning mechanism and temporal image reconstruction.

Due to the WFOV requirement and the UV wavelength range, more degrees of freedom are required to fully optimize the system. A conventional two-mirror reflective system can generally correct only two aberrations, typically spherical aberration and coma, while a three-mirror anastigmat system can correct four aberrations: spherical aberration, coma, astigmatism, and field curvature [30]. An additional fourth mirror will not be necessary because the three-mirror system already corrects the required aberrations and provides the required performance (see Section 3.3.2). Therefore, the 2D non-scanning spectral imager consists of three freeform mirrors, a detector, and a filter wheel with its associated electronics. The data acquisition electronics located behind the detector are not included in this design. Figure 3.4 shows a conceptual design of the architecture.

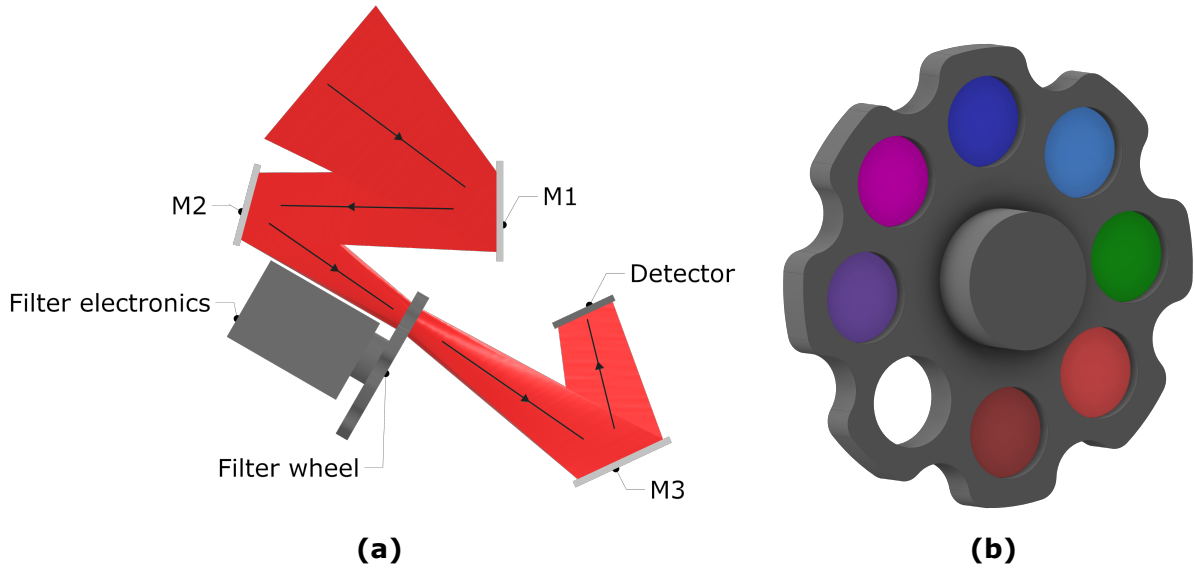


Figure 3.4: Conceptual layout of the 2D non-scanning multispectral imager, illustrating the three-mirror optical architecture (M1 - M3), beam propagation, and the placement of the detector, filter wheel, and associated filter wheel electronics. The colors on the filter wheel are not representative of the wavelengths used in the thesis, they are meant for illustrative purposes. (a) Conceptual layout. (b) Filter wheel concept.

The primary challenge of the design was controlling the mapping of the wide-angle fields onto the finite detector area while simultaneously reducing distortion. The detector has dimensions of 20.48×20.48 mm, and the objective was to ensure that all field points remain within the active detector region. Owing to the large FOV ($48^\circ \times 48^\circ$), this requirement proved difficult to satisfy. In particular, the extreme corner field at position $24^\circ \times -24^\circ$ frequently extended beyond the detector boundaries during intermediate optimization stages, necessitating careful balancing of optical power distribution and system geometry.

Distortion control represents a second major challenge for this architecture. In strongly off-axis, WFOV reflective systems, distortion is inherently difficult to control due to the non-paraxial nature of the ray propagation [29]. Furthermore, many classical distortion correction strategies and distortion-related merit-function operands are based on paraxial field assumptions. These operands were therefore not considered directly applicable to the present strongly non-paraxial WFOV configuration and were not used as optimization constraints in the merit function [31]. For a significant portion of the optimization process, the maximum radial distortion exceeded the proposed requirement of 10%. The distortion was reduced in two ways: i) reoptimizing from scratch, but constraining the mirror tilts to smaller angles in the second optimization loop (see Section 3.1) and ii) Changing the geometry from an initial design exploration of a zigzag TMA towards a triangular TMA (see Figure 3.4), reducing the distortion further.

Constraining the system within the prescribed volume envelope posed an additional challenge. The large field angles require sufficient inter-mirror clearance to avoid vignetting, which naturally increases the overall system size. Moreover, the requirement to maintain a small angle of incidence at the bandpass filter further constrained the optical layout, leading to an increase in system volume. The final design, therefore, represents a compromise between optical performance, distortion control, volume constraints, and filter AOI requirements.

In addition to the optical design challenges, numerical issues were encountered during the optimization process. At certain stages, the optimization became unstable and failed to converge, resulting in non-physical system configurations and divergent merit function values. These numerical instabilities were typically associated with extreme surface parameters or geometries outside the valid domain of the applied ray-tracing model. An example of such a non-converging configuration is shown in Figure 3.5.

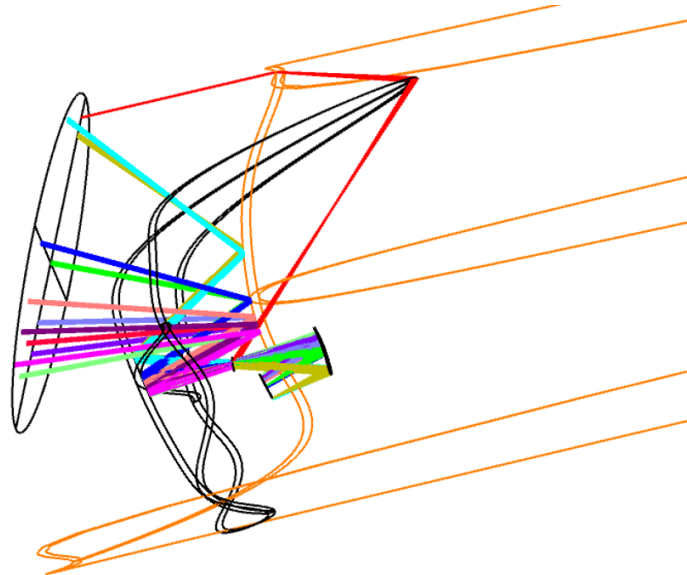


Figure 3.5: Non-converging numerical optimization. Merit function value became infinity.

To address these numerical instabilities, two solutions are considered. i) Using gradual optimization steps before optimizing for a larger set of variables. In other words, following the workflow shown in Fig. 3.1 reduced the occurrence of numerical instabilities. However, this approach did not remove them completely. ii) Using the robust ray tracing option in Zemax [31]. This option uses a slower but more reliable algorithm to perform the ray tracing calculations. Combining both approaches fully resolved the numerical instabilities.

3.3.2 Optical performance

The final design of the 2D non-scanning multispectral imager adopts a compact off-axis TMA layout, as discussed in Section 3.3.1, with dimensions of $220 \times 200 \times 150 \text{ mm}^2$, which is the maximal allowed system envelope (see Section 1.1.2.2). It has no vignetting (smallest clearance $\approx 5 \text{ mm}$) and is near-telecentric ($\theta_{\text{chief}} \leq 8^\circ$) at the detector. The stop position is considered

because its location provides more available space for practical implementation and avoids further constraining the sensitive distance between the last mirror and the detector. In addition, the beam is less strongly focused at the stop than near the detector, which helps limit the incidence angles on the filters and is therefore beneficial for reducing angle-dependent spectral shifts. This section discusses the resulting optical layout and evaluates the main performance metrics of the optimized design. The optimized 2D non-scanning multispectral imager is shown in Figure 3.6.

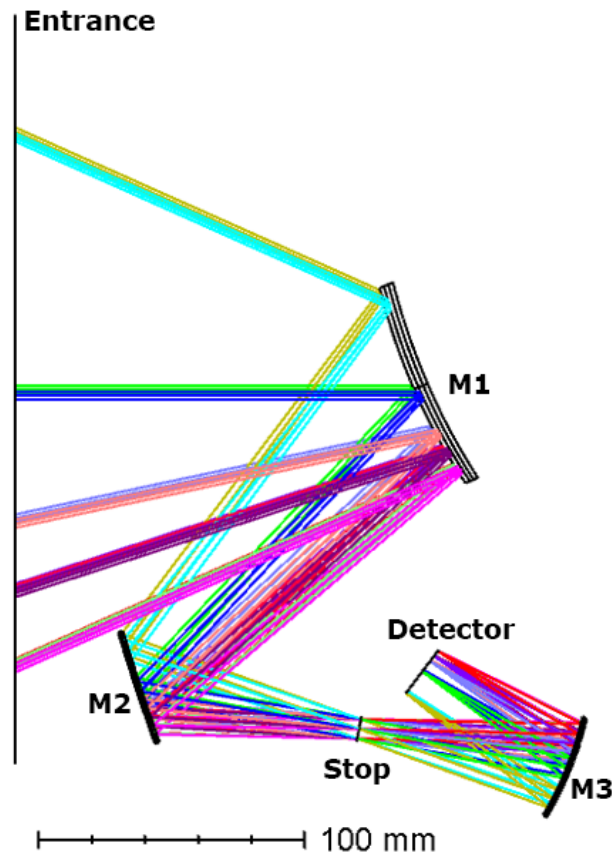


Figure 3.6: Final 3D layout of the 2D non-scanning multispectral imager. M denotes a mirror.

The design is symmetric in the X direction, so only half of the full FOV ($0^\circ \rightarrow 24^\circ$) is considered in this dimension. In contrast, an increased sampling is used in the Y dimension since this dimension is the most sensitive to change due to the off-axis nature of the design. Figure 3.7 shows the final footprint on the image plane of the real positions from the considered field sampling ($0^\circ \rightarrow 24^\circ$ in X and $-24^\circ \rightarrow 24^\circ$ in Y). In Chapter 2, it was assumed that we only deal with circular apertures. The field distribution is rectangular due to the WFOV requirement. Nevertheless, this does not define the aperture shape. This is determined by the stop and not the field distribution.

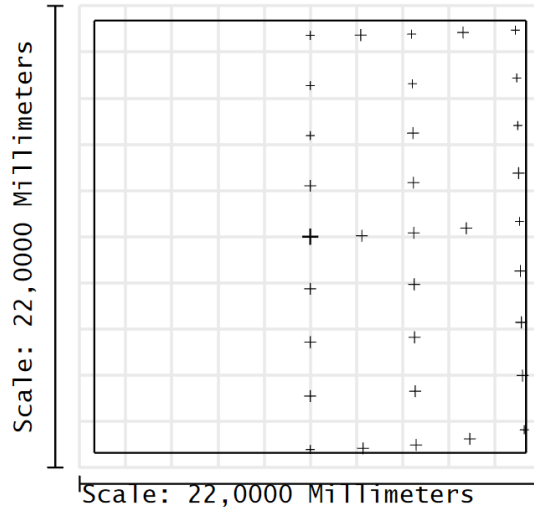


Figure 3.7: Footprint diagram at the image plane (detector) of the 2D non-scanning multispectral imager. The black crosses represent the real positions of the field sampling used during optimization.

The radial distortion is shown in Figure 3.8. The central field is used as the reference point to define the image-plane origin and nominal field mapping. The distortion values, therefore, represent the radial deviation of each off-axis field point from its ideal image position relative to this central reference. The maximum radial distortion occurs at the outer field points and reaches 9.09%, which remains below the proposed requirement of 10%. The distortion pattern is predominantly barrel-like, although it is not purely rotationally symmetric due to the off-axis freeform geometry. The distortion sampling does not affect the maximum radial grid distortion, indicating that the largest deviation occurs at the field corners. Increasing the sampling density, therefore, only adds interior points. Consequently, the sampling density is selected for visual clarity rather than computational accuracy.

The RMS wavefront error map is a good metric to visualize field performance. The RMS wavefront error should not exceed 0.0714 waves ($\lambda/14$) to be considered diffraction-limited (Section 2.2.4.3). Figure 3.9 shows the RMS wavefront error of the full field centered around the on-axis center field. The yellow-red regions exceed the diffraction-limited threshold of 0.0714 waves and are therefore not strictly diffraction-limited. Based on the RMS wavefront error map, a subset of best and worst performing fields, including the absolute best and worst fields, is selected (see Table 3.2). Due to the off-axis geometry and asymmetric optimization, the best-performing fields are not necessarily located at the geometrical field center.

Table 3.2: Subset of the best and worst performing fields of the 2D non-scanning multispectral imager. The absolute best and worst fields are highlighted in bold.

Best-performing	Worst-performing
$12^\circ \times 18^\circ$	$24^\circ \times -12^\circ$
$0^\circ \times 18^\circ$	$24^\circ \times -18^\circ$
$0^\circ \times 24^\circ$	$24^\circ \times -6^\circ$

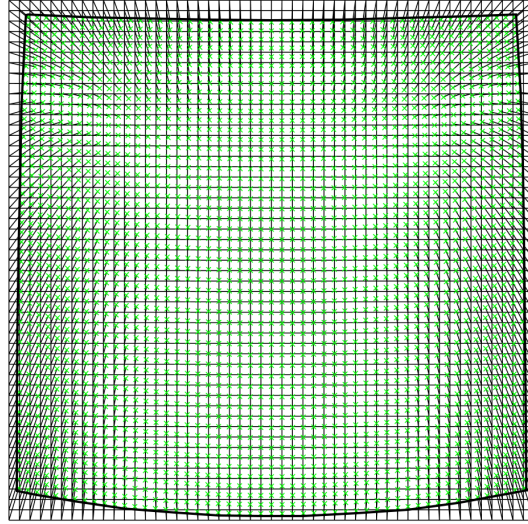


Figure 3.8: Grid distortion of the 2D non-scanning multispectral imager for the on-axis field. Green crosses inside black contour represent the real grid points, and the black lines represent the vectors connecting the real with the ideal grid points. The grid size is 50×50 . Field width is 48° . Aspect ratio is 1.

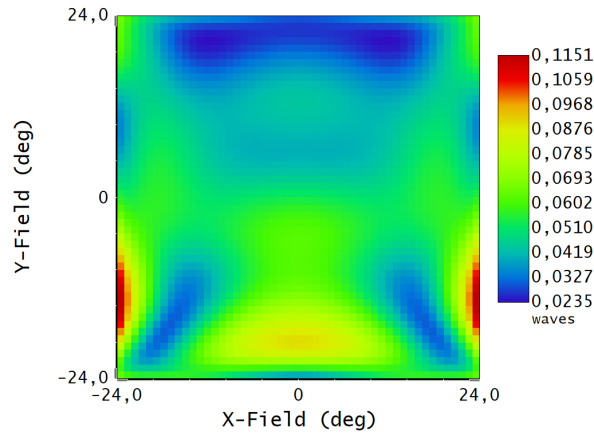


Figure 3.9: RMS wavefront error of the 2D non-scanning multispectral imager. The RMS wavefront error map shows variation across the field relative to the diffraction limit, with edge regions slightly exceeding it. The RMS wavefront error is evaluated using a ray density of 64×64 and a field sampling of 50×50 .

The spot diagram is used as a first-order visual confirmation of the performance of the optical system, given in Figure 3.10. The spot diameters are close to diffraction-limited ($d_{\text{airy}} \approx 4.3 \mu\text{m}$ for 220 nm and F/8). It should be noted that only a wavelength of 220 nm is used during the design of this architecture. If the system is diffraction-limited at 220 nm, it remains diffraction-limited at 260 nm and 320 nm, because mirrors have a wavelength-independent performance and the Airy disk increases towards longer wavelengths (see Eq. 2.15).

The low-performing fields still have geometric spots that are larger than the Airy disk. This is due to residual aberrations that are still present within those fields. To not go into too much detail about all the aberrations, only the worst field will be discussed ($24^\circ \times -12^\circ$). The spot diagram of the worst-performing field shows

an elongated spot that is slightly shifted from the best focus. The increase in spot size is therefore mainly caused by a combination of residual defocus and astigmatism. The defocus contribution indicates that the best-focus position for this field does not coincide exactly with the fixed image plane. The elongated shape of the spot indicates astigmatism, where the ray bundle focuses differently in orthogonal directions. In this case, numerical aberration decomposition shows that the dominant contribution is associated with defocus and astigmatism in the X direction. Note that distortion is not included in this spot-shape interpretation, since it mainly describes a field-mapping error rather than a broadening of the spot for a single field point. It is therefore evaluated separately (see further).

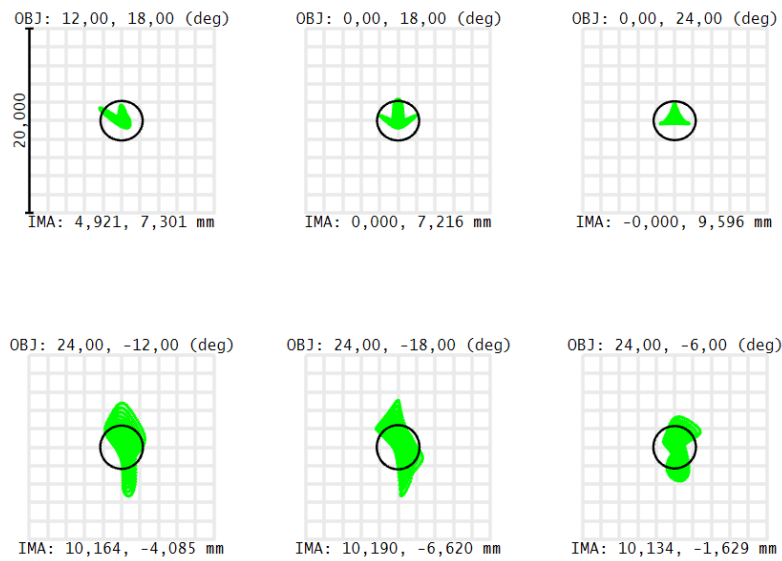


Figure 3.10: Spot diagram of the 2D non-scanning multispectral imager for the subset of field points. The black circle indicates the Airy disk diameter, and thus diffraction-limited spot size. For a wavelength of 220 nm, the Airy disk diameter is 4.3 μm .

As the next evaluation metric, we consider the encircled energy (EE). It shows the cumulative energy at a certain radial distance from the centroid position of the field. A requirement is set that 80% of the energy must fall within a radius of 5 μm from the centroid (half of the 10 μm pixel pitch). The EE is shown in Figure 3.11, indicating 80% of the energy is concentrated at a radius of 3.2 μm from the centroid, which is within the proposed requirement. Therefore, this does not pose an issue for the final performance as 80% of the energy is still confined within a single pixel.

In Section 2.2.2, it was explained that the PSF can also be used to determine if a system is diffraction-limited ($S \geq 0.8$). The PSF of the best field ($12^\circ \times 18^\circ$, shown in Figure 3.12) shows a Strehl ratio ≥ 0.8 , meaning that the field is diffraction-limited. In contrast, the PSF of the worst field ($24^\circ \times -12^\circ$, shown in Figure 3.13) has a Strehl ratio < 0.8 . This confirms that the system is not diffraction-limited over the full field. However, since the EE criterion is still satisfied, the image quality remains limited by the detector sampling.

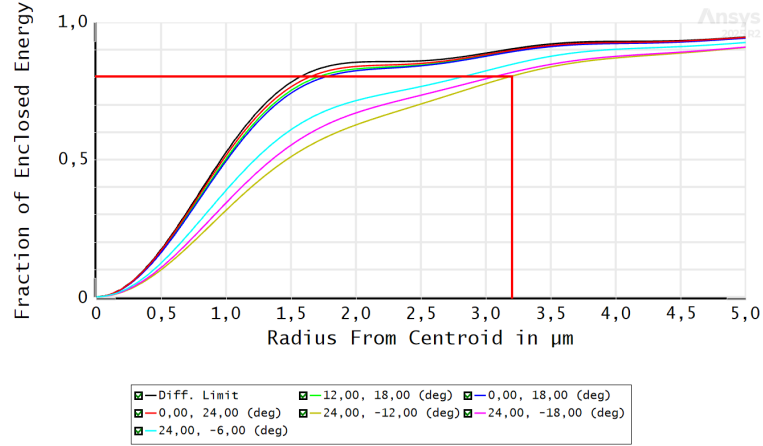
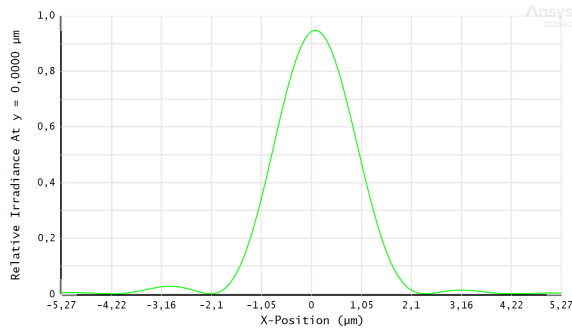
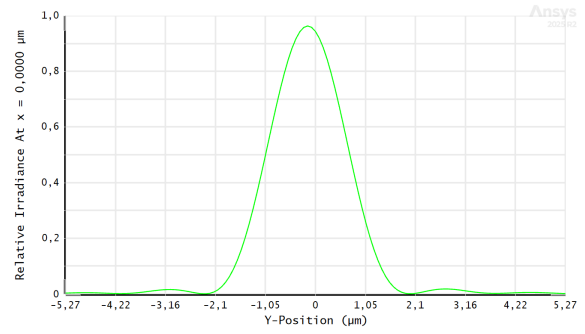


Figure 3.11: Diffraction Encircled Energy of the 2D non-scanning multispectral imager for the subset of field points. The EE of all the other fields will be between the two extremes. The red marking shows a performance requirement of 80% of the EE. Pupil sampling: 256×256 . Image sampling: 256×256 .

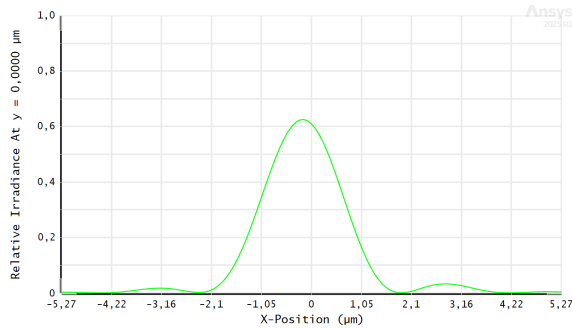


(a)

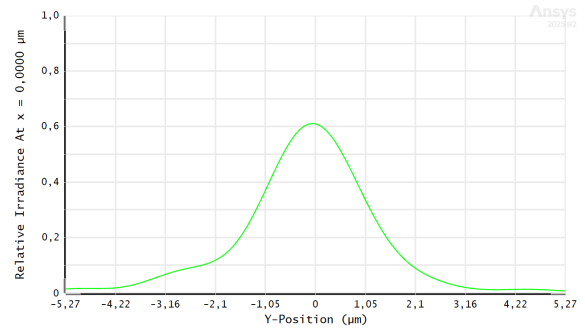


(b)

Figure 3.12: Huygens PSF of the best field ($12^\circ \times 18^\circ$). The achieved Strehl ratio is ≥ 0.8 for both dimensions. Pupil sampling: 512×512 . Image sampling: 128×128 . (a) X dimension. (b) Y dimension.



(a)



(b)

Figure 3.13: Huygens PSF of the worst field ($24^\circ \times -12^\circ$). The achieved Strehl ratio is ≤ 0.8 for both dimensions. Pupil sampling: 512×512 . Image sampling: 128×128 . (a) X dimension. (b) Y dimension.

The modulation transfer function (MTF) is used to evaluate the spatial performance of the imaging system at the detector sampling limit. Particular attention is given to the Nyquist frequency $f_{\text{Nyq}} = 50 \text{ cycles/mm}$, calculated in Section 2.2.4.4 for a detector pitch of $10 \mu\text{m}$. At this frequency, the MTF remains ≥ 0.85 for all selected fields, exceeding the required value of 0.5. This confirms that sufficient contrast is preserved at the detector sampling limit. Therefore, although not all fields satisfy the Maréchal diffraction-limited criterion [24, Chapter 9.3] (Section 2.2.4.3), the system still meets the proposed contrast requirement.

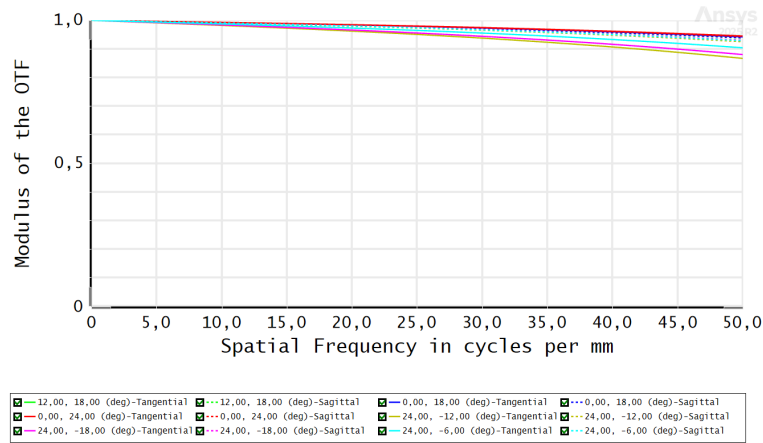


Figure 3.14: MTF of the 2D non-scanning multispectral imager for the subset of field points. $\text{MTF} \geq 0.85$ @ 50 cycles/mm (Nyquist frequency). Pupil sampling: 512×512 . Image sampling: 128×128 .

3.3.3 Performance summary

Most key MIDIM target specifications are met by the final design. This is summarized in Table 3.3. The achieved GSD deviates by less than 2.5% from the target value, while the $F/\#$ has a deviation of about 6%. From an optical design perspective, this deviation is acceptable and does not significantly impact the imaging performance. From a radiometric standpoint, the slightly larger $F/\#$ results in an 11% reduced SNR, which requires an increased integration time and leads to increased resolution smear (see Section 4.3).

This design uses all considered freeform terms up to 8th order, including even powers in X and both even and odd powers in Y, as defined in Table 3.1. Four main trends can be observed from the coefficient magnitudes. i) The magnitudes generally decrease towards higher orders, indicating that the dominant surface departure is captured by the lower-order terms. ii) M3 shows the largest coefficient magnitudes among the three mirrors and therefore provides the strongest freeform correction. iii) The single-axis X terms are generally larger than the corresponding Y terms, despite the system being folded in the Y direction, indicating that the dominant residual correction is more strongly associated with the transverse field direction than with the fold direction. iv) The mixed XY terms are of similar order of magnitude but do not show a single dominant trend, suggesting that they mainly provide coupling between both transverse directions.

Table 3.3: Comparison between the MIDIM requirements and the achieved performance of the 2D non-scanning multispectral imager design.

Parameter	MIDIM requirements	2D non-scanning design
FOV	$48^\circ \times 48^\circ$	$48^\circ \times 48^\circ$
EFL	22.46 mm	21.93 mm
GSD	2.55 km	2.61 km
F/#	$\leq F/8$	F/8.47
EE	$80\% < 5 \mu\text{m}$	80% at $3.2 \mu\text{m}$
Distortion	$< 10\%$	9.09%
MTF	> 0.5	≥ 0.85
Volume	$\leq 220 \times 200 \times 150 \text{ mm}^3$	$220 \times 200 \times 150 \text{ mm}^3$

The residual aberrations could potentially be reduced by adding additional freeform components or by optimizing the system with a stronger weighting on defocus and astigmatism. However, given that the overall system performance is already limited by the detector sampling rather than by the optical diffraction limit, no further complexity was added to the system.

Overall, the design represents a balanced solution that satisfies the required FOV, image quality, distortion, and volume constraints. Any further improvement of individual performance metrics would likely require relaxation of other system constraints, such as volume limitations, AOI requirements, or optical complexity.

3.4 Architecture 2: 2D scanning multispectral imager

3.4.1 Design layout and challenges

The second architecture considered is the 2D scanning multispectral imager. In contrast to the 2D non-scanning architecture, this design includes a scan mirror placed in front of the primary mirror M1. As a result, the single-frame FOV is reduced to $48^\circ \times 10^\circ$. The scan mirror is then used to sample the full surface of Mars using six consecutive images with a 2° overlap, resulting in a final reconstructed FOV of $48^\circ \times 50^\circ$. Figure 3.15 shows the conceptual design. The system consists of one flat scanning mirror, three freeform mirrors, a detector, and a filter wheel with its associated electronics. Again, the data acquisition electronics are not included in the conceptual design.

As an initial approach, the FOV of the previously optimized 2D non-scanning multispectral imager (Section 3.3) was reduced to $48^\circ \times 10^\circ$, and the system was reoptimized. However, this did not provide the best achievable performance. Therefore, the design was restarted from scratch using a similar TMA-based architecture. Compared to the 2D non-scanning multispectral imager, the reduced FOV in one axis relaxes most of the optical design constraints, which reduces the optimization difficulty and manufacturing complexity. However, the same general design challenges remain relevant.

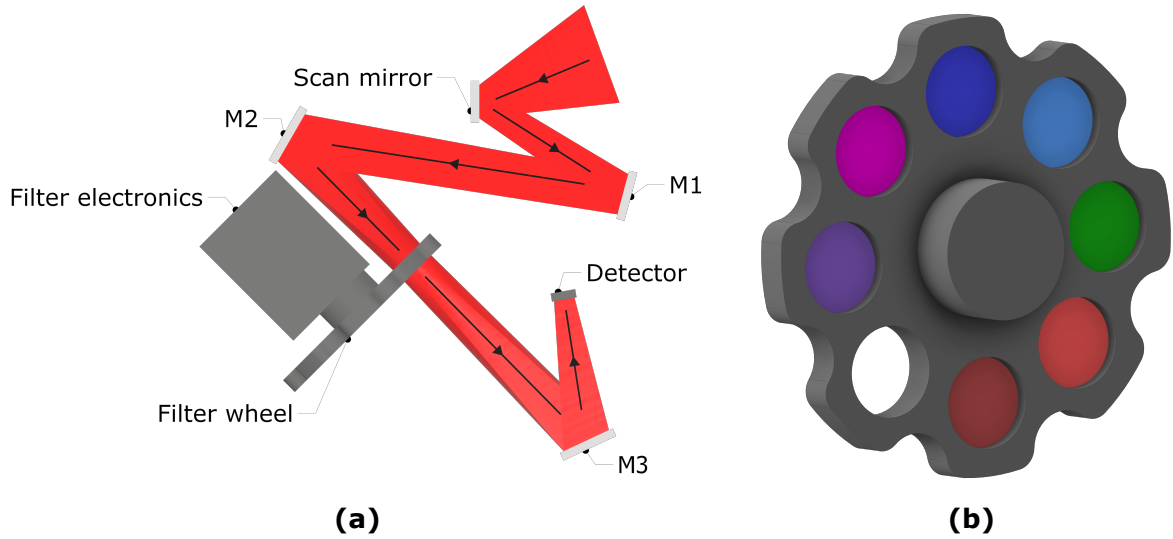


Figure 3.15: Conceptual layout of the 2D scanning multispectral imager, illustrating the flat scan mirror, three-mirror optical architecture (M1 - M3), beam propagation, and the placement of the detector, filter wheel, and associated filter wheel electronics. The colors on the filter wheel are not representative of the wavelengths used in the thesis, they are meant for illustrative purposes. (a) Conceptual layout. (b) Filter wheel.

An additional constraint is related to the mechanical positioning and sizing of the scan mirror. Due to the large FOV in the X direction, the required scan mirror size increases significantly with its axial distance from M1. The scan mirror must therefore be placed far enough from M1 to avoid vignetting, while remaining close enough to keep the mirror size within the imposed volume constraints. This introduces a trade-off between clear aperture, packaging, and mechanical feasibility.

For this second architecture, two final designs are proposed. The first design uses an F/8 configuration, based on the previous 2D non-scanning design and the MIDIM proposed value, providing a conservative optical design with a large performance margin. The second design uses a faster F/4.5 configuration, increasing the optical throughput to improve the SNR and reduce detector smear (see Section 4.3). Both designs are presented and compared in this section.

3.4.2 Optical performance

The optimized slow (F/8) and fast (F/4.5) designs for the 2D scanning multispectral imager are shown in Figure 3.16. The final optical design dimensions remain within $150 \times 130 \times 120 \text{ mm}^3$ for the F/8 design and $170 \times 150 \times 135 \text{ mm}^3$ for the F/4.5 design. Both designs therefore remain within the maximum allowed system envelope of $220 \times 200 \times 150 \text{ mm}^3$ (see Section 1.1.2.2). In addition, both systems maintain vignetting margins larger than 5 mm. The marginal-ray AOI on the filter is constrained to 12° for the F/8 design, while this constraint is further reduced to 8.5° for the reoptimized F/4.5 design. This section discusses the resulting optical layouts and evaluates the main performance metrics of both optimized designs.

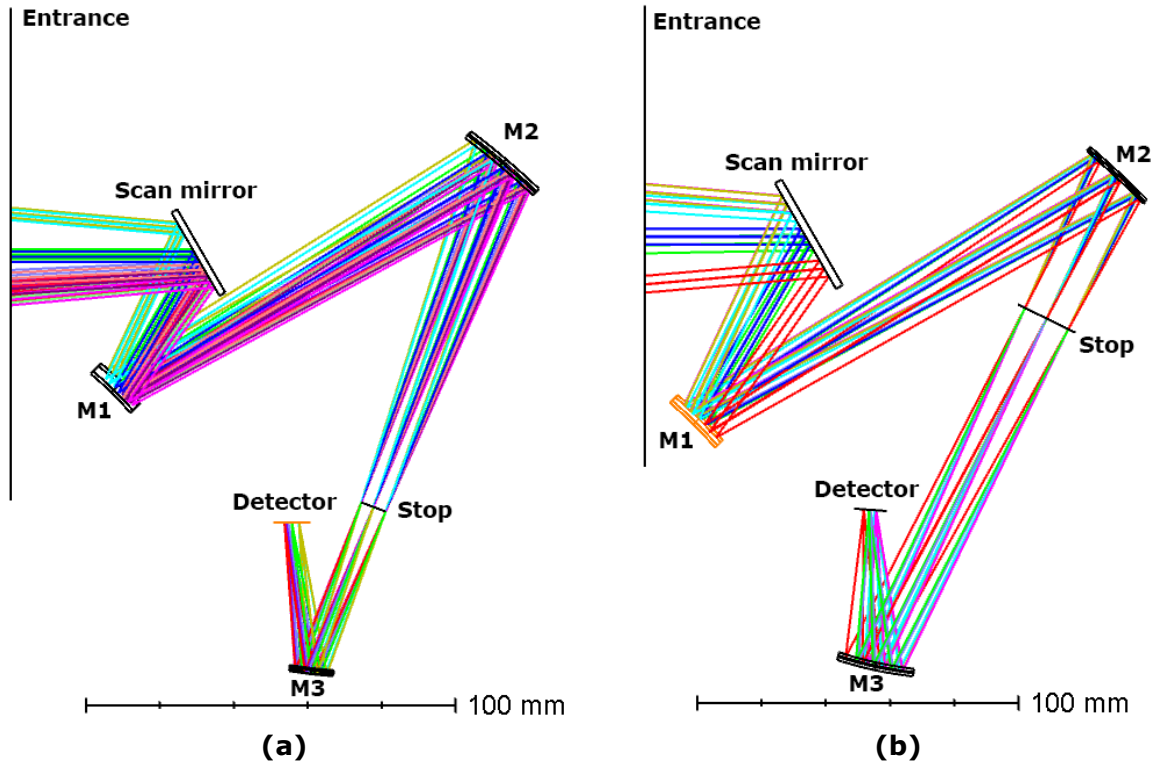


Figure 3.16: Final 3D layout of the 2D scanning multispectral imager. (a) Initial and slower design, featuring an F/8. (b) Final and faster design, featuring an F/4.5. The main difference is the increased optical throughput paired with a faster system, resulting in better radiometric performance. M denotes a mirror.

3.4.2.1 Initial design (F/8)

Similar to the 2D non-scanning multispectral imager, a symmetric sampling in X ($0^\circ \rightarrow 24^\circ$) and an increased sampling in Y ($-5^\circ \rightarrow 5^\circ$) is considered. Figure 3.17 shows the image plane footprint of the used field sampling. A smaller detector area can be considered, in comparison to the 2D non-scanning design. Therefore, a smaller active detector size will be used, while the other detector characteristics will remain the same.

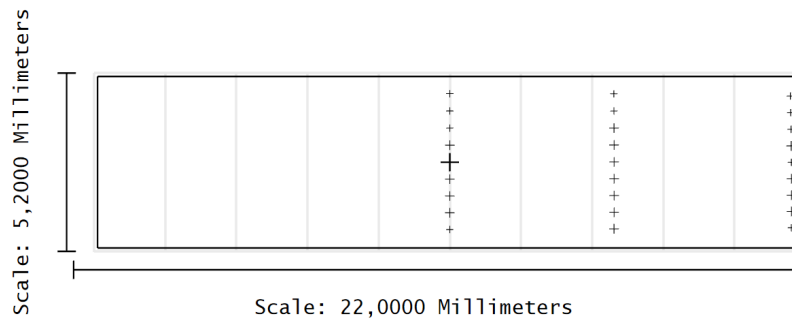


Figure 3.17: Footprint diagram at the image plane (detector) of the 2D scanning multispectral imager. The black crosses represent the real field positions imaged at the image plane.

The distortion, similarly to that of the 2D non-scanning multispectral imager, did not change with increasing grid sampling. This means that the largest distortion is in the corner and that an increase in sampling in between does not change the maximal radial distortion. A 50×50 grid size is selected for visual clarity rather than performance. The maximal radial distortion remains small at 1.29%. It has a large performance margin for the proposed threshold of 10%. The grid distortion is shown in Figure 3.18.

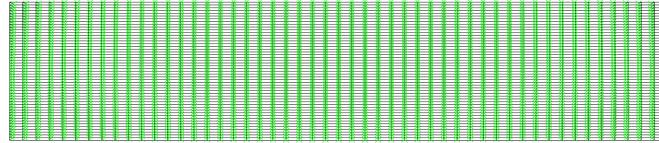


Figure 3.18: Grid distortion of the 2D scanning multispectral imager with F/8 for the on-axis field. Green crosses represent the real grid points, and the black lines represent the vectors connecting the real with the ideal grid points. The grid size is 50×50 . Field width is 48° . Aspect ratio is 0.208.

The RMS wavefront error map, shown in Figure 3.19, can again be used to evaluate the field performance of this design. It uses the on-axis field as a reference. The selected subset of the best- and worst-performing fields is justified using the RMS wavefront error field map, given in Table 3.4. None of the evaluated fields exceeds the diffraction-limited criterion of RMS wavefront error ≥ 0.0714 waves. The maximum wavefront error across the field is 0.0355 waves, leaving a margin of 0.0359 waves relative to the diffraction-limited threshold.

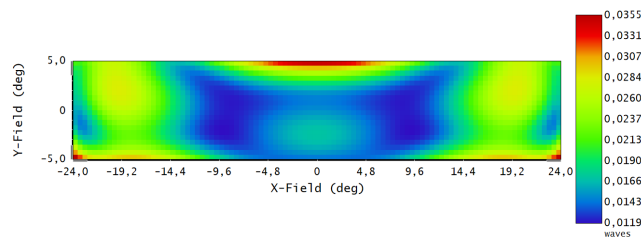


Figure 3.19: Optical performance of the 2D scanning multispectral imager with F/8. The RMS wavefront error map shows the variation of wavefront error across the field of view relative to the diffraction-limited criterion. All fields remain well below the diffraction limit. The RMS wavefront error is evaluated using a ray density of 64×64 and a field sampling of 100×20 .

Table 3.4: Three best-performing and three worst-performing fields of the 2D scanning multispectral imager with F/8. The absolute best and worst fields are highlighted in bold.

Best-performing	Worst-performing
$10^\circ \times -2^\circ$	$24^\circ \times -5^\circ$
$10^\circ \times 2^\circ$	$0^\circ \times 5^\circ$
$0^\circ \times 0^\circ$	$6^\circ \times 5^\circ$

The RMS spot sizes in Figure 3.20 show that the selected field subset remains within the diffraction-limited Airy disk. Residual geometrical aberrations are therefore negligible compared to diffraction.

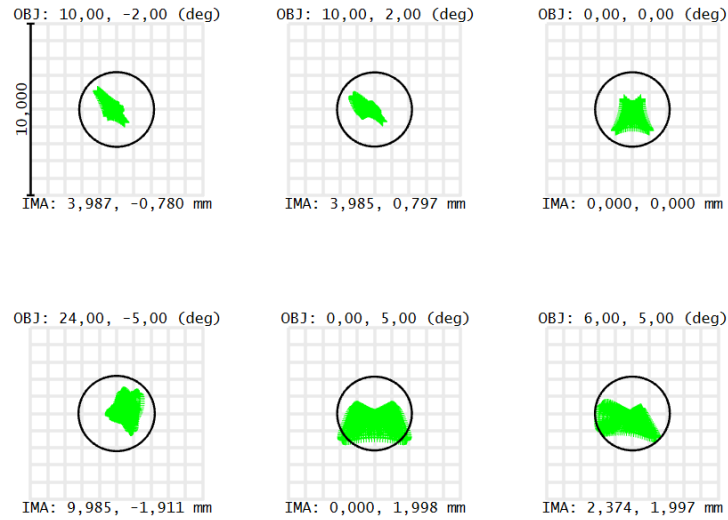


Figure 3.20: Spot diagram of the 2D scanning multispectral imager with F/8 for the selected subset of field points. The black circle indicates the Airy disk diameter for comparison with the diffraction-limited spot size. For a wavelength of 220 nm, the Airy disk diameter is 4.3 μm .

Using the encircled energy (EE) metric, the diffraction limit can be verified in terms of energy rather than geometrical ray intersections. 80% of the encircled energy is concentrated within a radius of 1.75 μm from the centroid. The requirement that 80% of the energy must fall within a radius of 5 μm from the centroid (half of the 10 μm pixel pitch) is still valid here. The EE is illustrated in Figure 3.21.

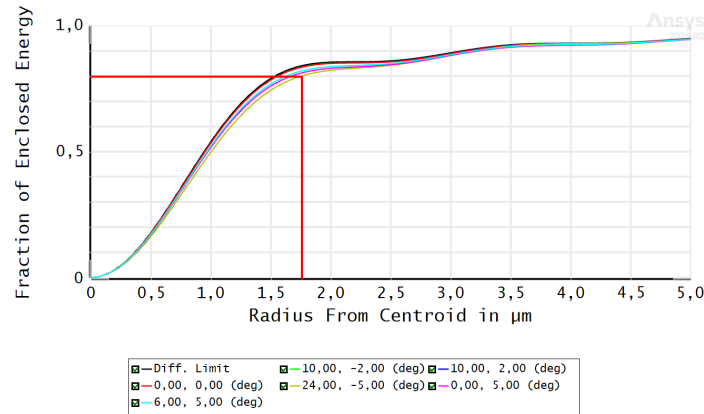
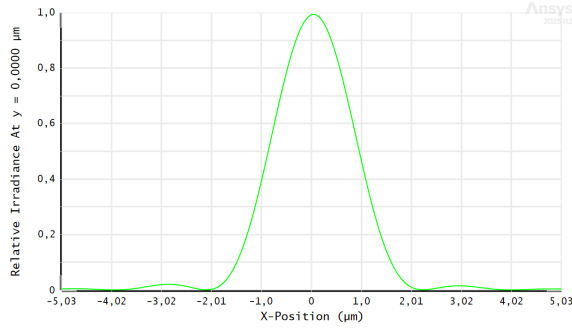


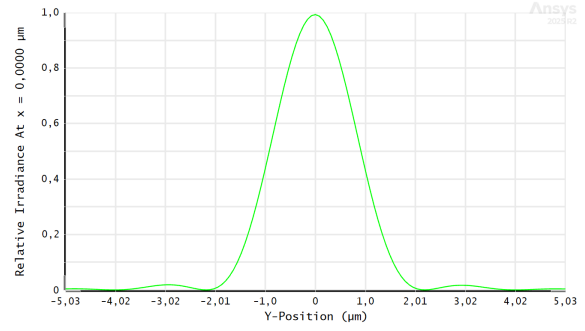
Figure 3.21: Diffraction Encircled Energy of the 2D scanning multispectral imager with F/8 for the selected subset of field points. The EE of all the other fields will be between the two extremes. The red marking shows a performance requirement of 80% of the EE. Pupil sampling: 256 $\times$ 256. Image sampling: 256 $\times$ 256.

The PSF of the best ($10^\circ \times -2^\circ$) and worst ($24^\circ \times -5^\circ$) performing fields is given in Figure 3.22 and Figure 3.23, respectively. The PSF of both fields in the X and Y direction reaches a Strehl ratio ≥ 0.8 and proves again that the system is diffraction-limited.

The MTF is evaluated at the Nyquist frequency $f_{\text{Nyq}} = 50$ cycles/mm, because the same detector pixel pitch is used for all the designs. The diffraction-limited design shows an MTF ≥ 0.93 at f_{Nyq} . This is well above the required MTF > 0.5 .

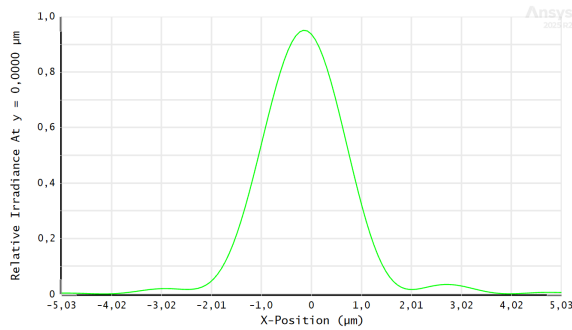


(a)

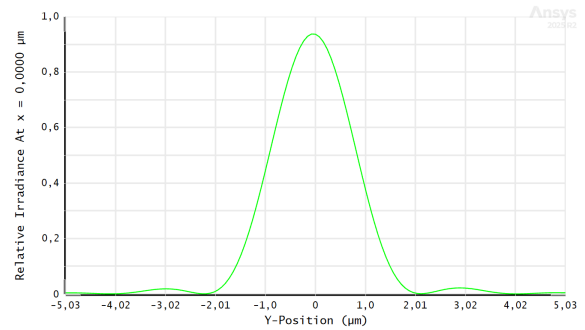


(b)

Figure 3.22: Huygens PSF of the best field ($10^\circ \times -2^\circ$). The achieved Strehl ratio is ≥ 0.8 for both dimensions. Pupil sampling: 512×512 . Image sampling: 128×128 . (a) X dimension. (b) Y dimension.



(a)



(b)

Figure 3.23: Huygens PSF of the worst field ($24^\circ \times -5^\circ$). The achieved Strehl ratio is ≥ 0.8 for both dimensions. Pupil sampling: 512×512 . Image sampling: 128×128 . (a) X dimension. (b) Y dimension.

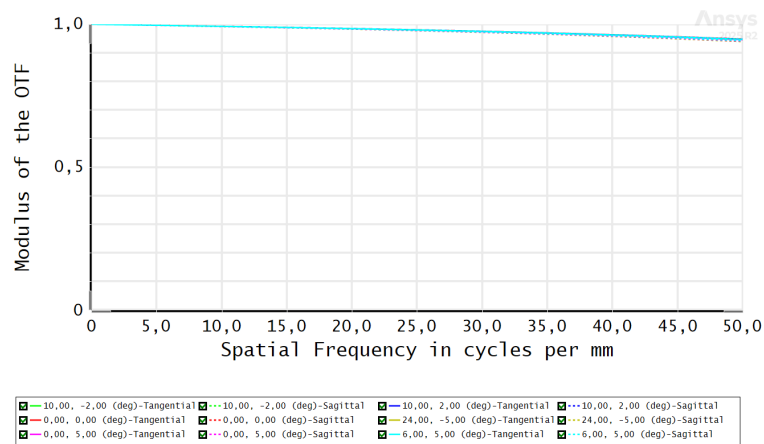


Figure 3.24: MTF of the 2D scanning multispectral imager with F/8 for the selected subset of field points. $MTF \geq 0.93$ @ 50 cycles/mm (Nyquist frequency). Pupil sampling: 512×512 . Image sampling: 128×128 .

3.4.2.2 Reoptimized design (F/4.5)

The performance of the F/8 design has a large margin for improvement in terms of throughput and AOI on the discrete filter. A fully reoptimized faster design (F/4.5) with a smaller AOI (8.5°) on the discrete filter has been realized. With the reduction of the F/#, also comes a reduction in Airy disk diameter. Using (2.15), the recalculated Airy disk diameter becomes $2.4\text{ }\mu\text{m}$. This puts a stricter design constraint to reach the diffraction limit.

The footprint, shown in Figure 3.25, shows the real image plane position of the field sampling used for the optimization of this faster design. There is a slight deformation compared to the footprint of the slower design (Figure 3.17). However, the fields remain within the detector area.

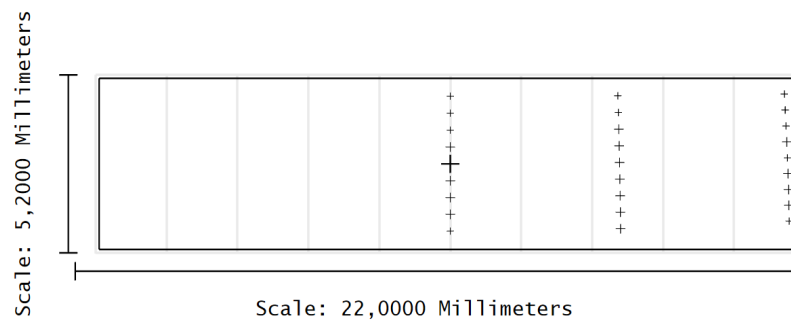


Figure 3.25: Footprint diagram at the image plane (detector) of the 2D scanning multispectral imager with F/4.5. The black crosses represent the real field positions imaged at the image plane.

The distortion shows the same general behavior as in the original F/8 design. However, due to the more constrained F/4.5 configuration, the maximum radial distortion increases from 1.29% to 7.30%. This still remains within the proposed 10% requirement. Compared to the F/8 design, the distortion pattern now shows a more pronounced barrel-like behavior.



Figure 3.26: Grid distortion of the 2D scanning multispectral imager with F/4.5 for the on-axis field. Green crosses inside the black contour represent the real grid points, and the black lines represent the vectors connecting the real with the ideal grid points. The grid size is 50×50 . Field width is 48° . Aspect ratio is 0.208.

The RMS wavefront error map, shown in Figure 3.27, has certain fields that have a wavefront error larger than 0.0714 waves ($\lambda/14$). The system is, therefore, not fully diffraction-limited. Residual aberrations will play a role in the final performance. The section of a subset of the best- and worst-performing fields, including the absolute best and worst fields, is given in Table 3.5.

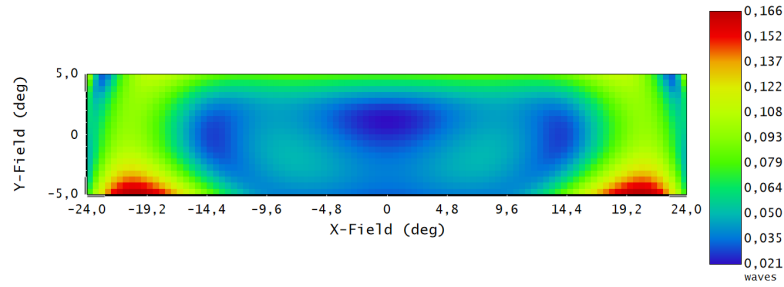


Figure 3.27: RMS wavefront error of the 2D scanning multispectral imager with F/4.5. The RMS wavefront error map shows variation across the field relative to the diffraction limit, with edge regions slightly exceeding it but remaining detector-limited. The RMS wavefront error is evaluated using a ray density of 64×64 and a field sampling of 100×20 .

Table 3.5: Subset of the best-performing and worst-performing fields of the 2D scanning multispectral imager with F/4.5. The absolute best and worst fields are highlighted in bold.

Best-performing	worst-performing
$0^\circ \times 1^\circ$	$20^\circ \times -5^\circ$
$14^\circ \times 0^\circ$	$17^\circ \times -5^\circ$
$22^\circ \times 5^\circ$	$20^\circ \times -3.75^\circ$

The spot diagram in Figure 3.28 shows that the RMS spots are not fully confined inside the Airy disk. This means that not all fields are diffraction-limited. The spot diagram of the worst field ($20^\circ \times -5^\circ$) shows an elongated spot in the X direction. From numerical aberration decomposition, the spot is a result of defocus, negative astigmatism in the X direction, and positive astigmatism in the Y direction.

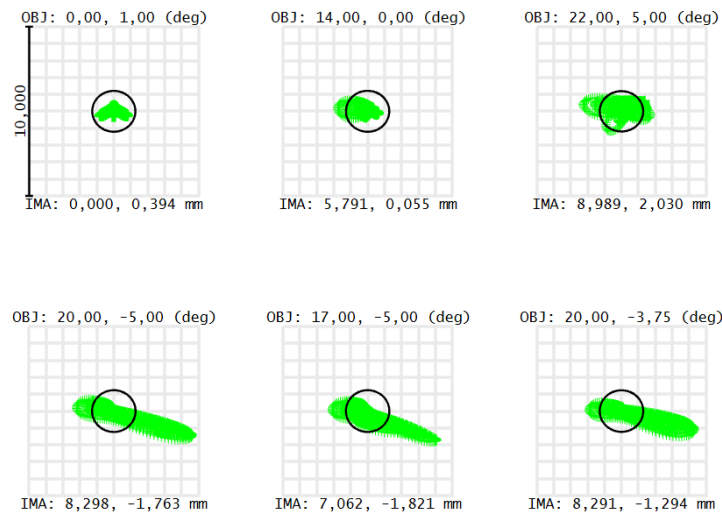


Figure 3.28: Spot diagram of the 2D scanning multispectral imager with F/4.5 for the selected subset of field points. The black circle indicates the Airy disk diameter for comparison with the diffraction-limited spot size. For a wavelength of 220 nm, the Airy disk diameter is $2.4 \mu\text{m}$.

The EE is shown in Figure 3.29. Even if not every field is diffraction-limited, 80% of the energy for the worst field lies within a radius of 2.15 μm from the centroid, which is comfortably within one detector pixel (half of the 10 μm pixel pitch). The system is considered detector-limited.

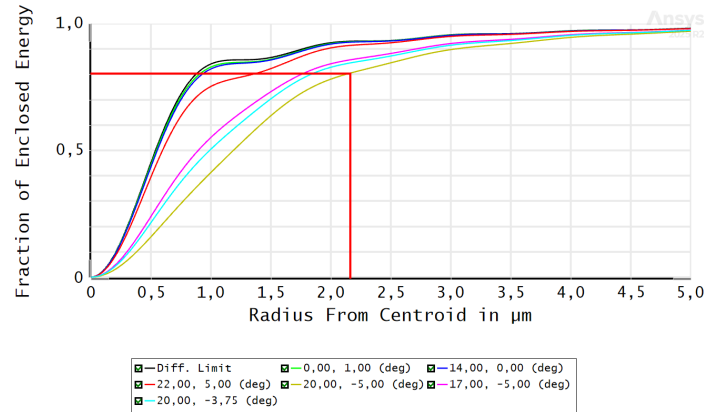


Figure 3.29: Diffraction Encircled Energy of the 2D scanning multispectral imager with F/4.5 for the selected subset of field points. The EE of all the other fields will be between the two extremes. The red marking shows a performance requirement of 80% of the EE. Pupil sampling: 256×256 . Image sampling: 256×256 .

The PSF for the best (Figure 3.30) and worst (Figure 3.31) fields shows the difference between diffraction-limited performance and detector-limited performance. In this representation, only the best field reaches a Strehl ratio ≥ 0.8 for both the X and Y direction.

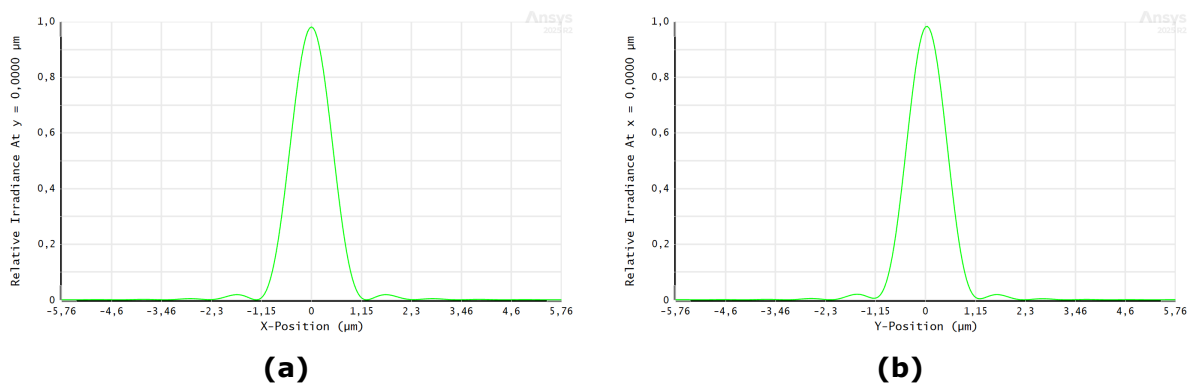


Figure 3.30: Huygens PSF of the best field ($0^\circ \times 1^\circ$). The achieved Strehl ratio is ≥ 0.8 for both dimensions. Pupil sampling: 512×512 . Image sampling: 256×256 . (a) X dimension. (b) Y dimension.

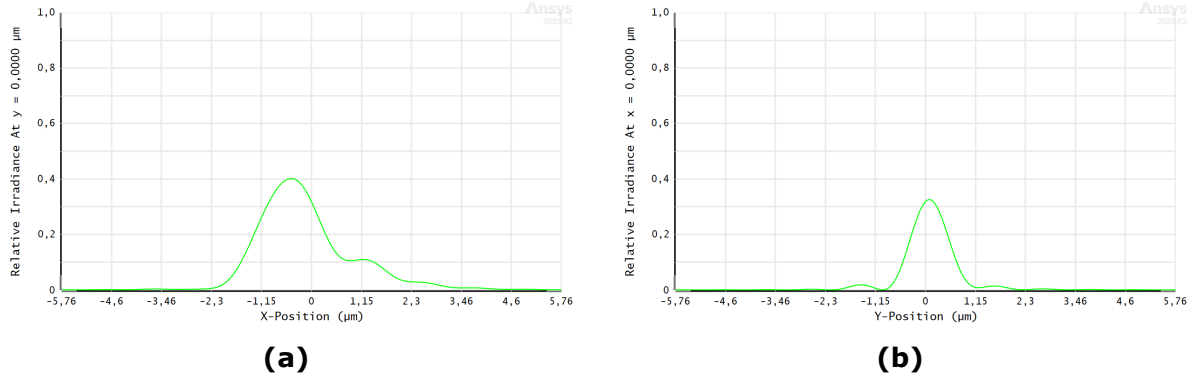


Figure 3.31: Huygens PSF of the worst field ($20^\circ \times -5^\circ$). The achieved Strehl ratio is ≤ 0.8 for both dimensions. However, 80% of the energy remains within the detector area. Pupil sampling: 512×512 . Image sampling: 256×256 . (a) X dimension. (b) Y dimension.

MTF ≥ 0.91 at $f_{Nyq} = 50$ cycles/mm, which means that even though the system is not fully diffraction-limited, the contrast still exceeds the MTF = 0.5 at f_{Nyq} requirement. The MTF is shown in Figure 3.32.

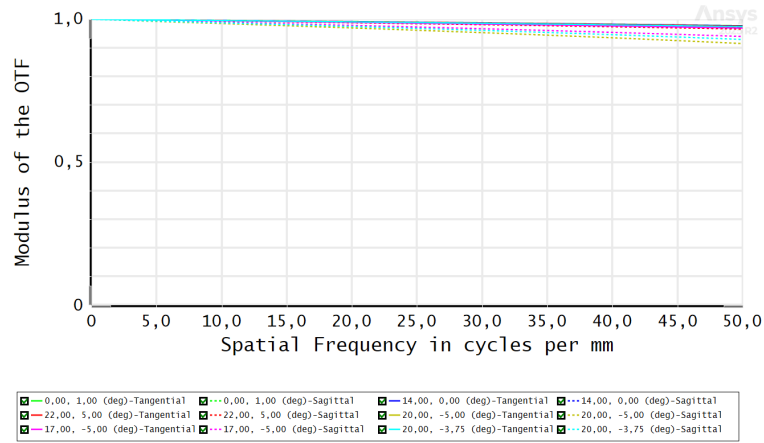


Figure 3.32: MTF of the 2D scanning multispectral imager with F/4.5 for the selected subset of field points. MTF ≥ 0.91 @ 50 cycles/mm (Nyquist frequency). Pupil sampling: 512×512 . Image sampling: 128×128 .

3.4.3 Performance summary

Both scanning designs meet all proposed requirements, and in some aspects, the achieved performance exceeds the specified values, as summarized in Table 3.6. Design 1 (F/8) is fully diffraction-limited, while Design 2 (F/4.5) is only partially diffraction-limited. However, it remains detector-limited with a comfortable margin relative to the 10 μm pixel pitch. Compared to the 2D non-scanning architecture, the scanning configuration is optimized towards a faster F/#, increasing the optical throughput and therefore the radiometric signal strength. This reduction in F/# comes at the cost of increased distortion, which must be carefully controlled during the design process. In the reoptimized design, the maximum marginal-ray AOI is reduced from 12° to 8.5° , representing a significant improvement in terms of spectral shift reduction. Further AOI reduction will require additional complexity or relaxation of other system specifications.

Table 3.6: Comparison between the MIDIM requirements and the achieved performance of the 2D scanning multispectral imager designs.

Parameter	MIDIM requirements	Scanning F/8	Scanning F/4.5
FOV	$48^\circ \times 10^\circ$	$48^\circ \times 10^\circ$	$48^\circ \times 10^\circ$
EFL	22.46 mm	22.51 mm	22.91 mm
GSD	2.55 km	2.54 km	2.50 km
F/#	$\leq F/8$	F/8.08	F/4.63
EE	80% < 5 μm	80% at 1.75 μm	80% at 2.15 μm
Distortion	< 10%	1.29%	7.30%
MTF	> 0.5	≥ 0.93	≥ 0.91
Volume	$\leq 220 \times 200 \times 150 \text{ mm}^3$	$150 \times 130 \times 120 \text{ mm}^3$	$170 \times 150 \times 135 \text{ mm}^3$

The initial F/8 design uses freeform terms up to 6th order. Only even single-axis and mixed terms are included, except the odd Y^3 term (see Table 3.1). Five main trends can be observed from the freeform coefficient magnitudes. i) The coefficients show a generally decreasing envelope towards higher orders, indicating that the dominant surface departure is captured by the lower-order terms. ii) M3 shows the largest contribution for the even-order terms, including the mixed even terms. iii) M1 shows the largest contribution for the only odd-order term, namely Y^3 . iv) For the even-order single-axis terms, the X and Y contributions are of comparable magnitude. v) The mixed XY terms are generally of similar magnitude to the single-axis terms but do not show a distinct overall trend, indicating that they mainly provide coupling between both transverse directions.

The reoptimized faster design (F/4.5) uses the full set of freeform terms up to 6th order listed in Table 3.1. The same general decreasing envelope towards higher orders is observed, and M3 again provides the largest contribution for the even-order terms, including the mixed even terms. The main difference compared to the F/8 design is the inclusion of additional odd-order terms. For these terms, including the mixed odd terms, M1 shows the largest coefficient magnitudes, which is consistent with the trend already observed for the Y^3 term in the F/8 design. The even-order single-axis X and Y terms remain of comparable magnitude, while the mixed XY terms are again similar in magnitude to the single-axis terms and do not show a distinct overall trend. When comparing identical orders between both designs, no consistent increase or decrease in coefficient magnitude is observed. Some terms increase while others decrease, indicating that the faster F/4.5 optimization redistributes the freeform correction rather than simply scaling the F/8 solution.

Overall, the 6th-order freeform description provides sufficient performance for both scanning designs. Further reduction of the residual aberrations in the reoptimized design would likely require increasing the freeform description to 8th order or relaxing other design constraints. However, the spots are concentrated on the active pixel area with good margins and a very high contrast. Therefore, the added complexity to reduce the aberrations will not result in significant performance improvement.

3.5 Architecture 3: 1D pushbroom multispectral spectrometer

3.5.1 Design layout and challenges

The 1D pushbroom multispectral imager architecture features a one-dimensional FOV of $48^\circ \times 0.03^\circ$. A line will be scanned over the planetary surface while the instrument will be moving along the satellite orbit. Instead of discrete filters, a diffraction grating will be used to disperse the wavelengths. A 2D sensor will be used, showing the spatial information in one dimension and the spectral information in the other. The design is based on the spectrometer found in the ECO mission [18] (Section 2.1.4).

Compared to the 2D multispectral designs, a more extended optical design is required, featuring a 2-mirror freeform telescope, a slit, a collimating mirror, and a freeform spectrometer. The freeform spectrometer comprises three freeform mirrors, a reflective diffraction grating, and a detector with its associated electronics. In the final product, a blazed grating will likely be used (see Section 2.2.2). Figure 3.33 shows the conceptual design together with a conceptual blazed grating.

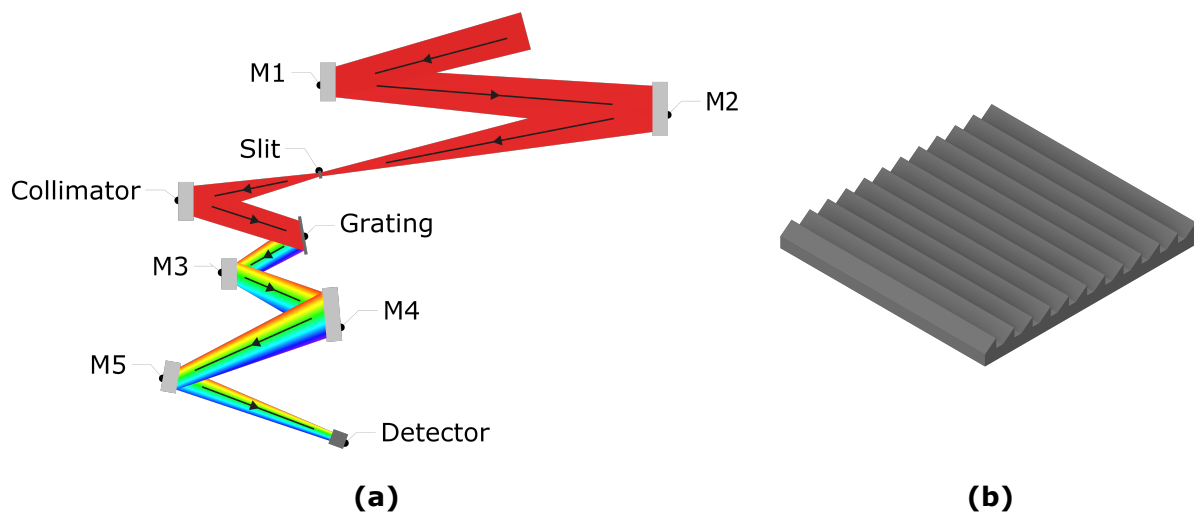


Figure 3.33: Conceptual layout of the 1D pushbroom multispectral imager, illustrating the telescope, slit, collimator, blazed grating, spectrometer, beam propagation, and the placement of the detector. The optics before the slit is the telescope, and after the slit is the spectrometer. The colors in the spectrometer are not representative of the wavelengths used in this thesis. They are included for illustrative purposes. (a) Conceptual layout. (b) Blazed diffraction grating.

The UV channel is not the only channel intended to operate within the 1D pushbroom multispectral imager architecture. The design can be extended to include additional spectral channels in future iterations. Therefore, only part of the total incoming optical energy is assumed to be allocated to the UV spectrometer. This energy splitting could, for example, be implemented using a beam splitter.

The full system consists of two parts: the telescope and the spectrometer. The telescope comprises two freeform mirrors, up to the 2nd order, that map the fields onto a 20 × 3 mm slit. The slit size was selected such that the spectrometer has approximately unit magnification from the slit to the detector. In a first-order representation, this magnification can be approximated by Eq. 3.2

$$M \approx \frac{f_{\text{cam}}}{f_{\text{coll}}}, \quad (3.2)$$

where f_{coll} and f_{cam} are the effective focal lengths of the collimating and imaging parts of the spectrometer, respectively. Choosing $M \approx 1$ therefore keeps both focal lengths of the same order and avoids unnecessary magnification or demagnification of the slit image. This provides a balanced starting point between spectrometer size and optical complexity. Other magnifications are possible, but would require a different trade-off between slit size, optical complexity, and the overall system envelope.

Following the slit is the collimating mirror. The axial distance between the slit and the mirror is critical, and the only variable that can result in an improvement of the GSD. The relation can be derived from first-order geometrical parameters, and is given by Eq. 3.3

$$\text{GSD} = \frac{A \cdot p \cdot f_{\text{col}}}{f_{\text{tel}} \cdot f_{\text{cam}}} \quad (3.3)$$

Where GSD is the ground sampling distance, A is the orbital altitude, p is the pixel pitch of the detector, and f_{tel} is the focal length of the telescope.

The choice for a magnification $M = 1$ ($w_{\text{slit}} = w_{\text{det}}$) results in a maximal telescope and spectrometer focal length given by Eq. 3.4 and 3.5

$$f_{\text{tel}} = \frac{w_{\text{slit}}/2}{\tan(\text{FOV}/2)} \quad (3.4)$$

$$f_{\text{cam}} = \frac{w_{\text{det}}/2}{\tan(\text{FOV}/2)} \quad (3.5)$$

With w_{slit} and w_{det} , the width of the telescope slit and the detector, respectively.

The only parameter that can change the GSD is the collimator focal length. Therefore, the positioning of the collimating mirror is crucial. To achieve a GSD of 2.55 km, the collimating mirror should be placed at a distance of approximately 22.46 mm from the telescope slit.

The $F/\#$ differs from the proposed $F/8$ configuration. The reason is purely radiometric. As mentioned before, the UV channel will only use a fraction of the energy departing from the collimator. Therefore, a faster design ($F/5$) is used to achieve the radiometric needs of the system (see Section 4.3). Mathematically, the incoming photon flux is related to the $F/\#$ as is given in Eq. 3.6 [21, Chapter 5.3]

$$\Phi \propto \frac{1}{(F/\#)^2} \quad (3.6)$$

Consequently, the reduction from F/8 to F/5 results in a flux increase of approximately $2.5\times$. This gives enough room for other loss factors, while still having enough flux to reach the radiometric requirements. However, take note that the F/# of the telescope and spectrometer are not necessarily the same. The telescope has an F/6, while the spectrometer has an F/5.

The final spectral resolution $\Delta\lambda$ can be calculated using the linear dispersion ($dx/d\lambda$) and the pixel pitch p using Eq. 3.7

$$\Delta\lambda = \frac{p}{dx/d\lambda} \quad (3.7)$$

As the main design challenge, we tackled the reduction of the spot size of the dispersed wavelengths. Initially, the system was optimized by minimizing the wavefront error for all wavelengths simultaneously. However, this did not lead to the best result, because the different wavelengths introduced competing optimization constraints. As a result, the optimizer attempted to balance the spot sizes across the full wavelength range rather than minimizing the performance at the most representative wavelength. The spot shapes differ between wavelengths, and the Airy disk size also varies with wavelength. Therefore, the final optimization was performed primarily at the center wavelength. This places the optimization point in the middle of the spectral range, so that the wavelength-dependent residual errors remain distributed on both sides of the optimized wavelength instead of being biased towards one edge of the spectrum. Since the total linear dispersion over the considered wavelength range is small, approximately 0.1 mm, compared with the system scale, optimizing the center wavelength also keeps the spot sizes of the other wavelengths close to their minimum.

A second challenge was the presence of keystone distortion of the dispersed wavelengths on the detector. For the farthest field point, the vertical separation between wavelengths initially covered approximately two detector pixels in the spatial direction. Ideally, all wavelengths and field points should remain within a one-pixel sampling region in this direction. Therefore, an additional constraint is introduced to align the wavelength traces within a single pixel. This constraint slightly increased the spot size, but the final still performance remains close to the diffraction limit.

3.5.2 Optical performance

The final 1D pushbroom multispectral imager design meets all the required specifications for wavelengths between 195 nm and 345 nm, considering a spectral resolution of 25 nm. All but one wavelength (being 195 nm) operate at the diffraction limit. This architecture had no constraints in terms of AOI, as discrete filters will not be used, but rather a diffraction grating. The discussion is divided into two parts: the telescope and the spectrometer. The telescope consists of two freeform mirrors, described up to 2nd order, while the spectrometer consists of the collimating mirror, a diffraction grating, a three-freeform-mirror spectrometer (described up to 6th order), and a detector with its associated electronics. Figure 3.34 shows the 3D layout of the 1D pushbroom multispectral imager.

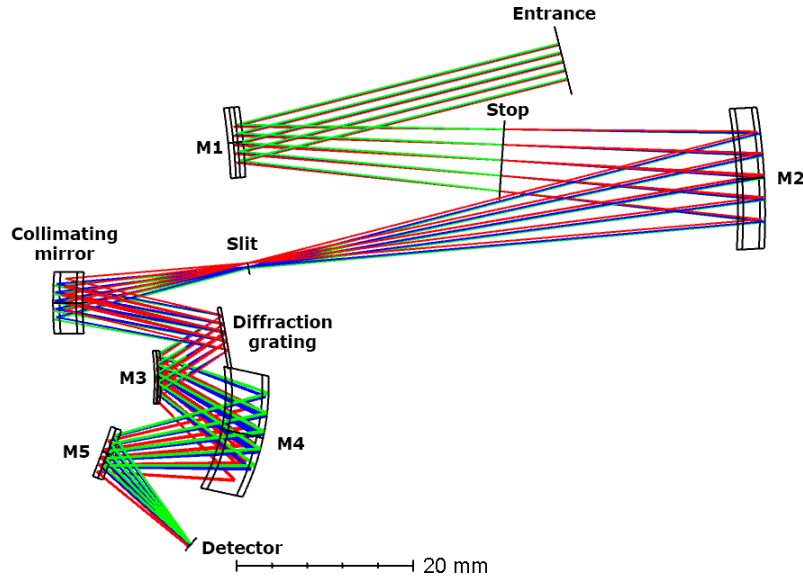


Figure 3.34: Final 3D layout of the 1D pushbroom multispectral imager. M denotes a mirror.

3.5.2.1 Freeform 2-mirror telescope

The telescope design follows a similar design process mentioned in Section 3.1, but with two mirrors rather than the three mirrors in the TMA architecture. As mentioned earlier, the slit width is set to match the detector width to achieve a magnification of $M = 1$. Five fields are used to optimize the full system, again with a symmetry in the X dimension. Three fields (at 0° , 12° , and 24°) are used within this performance analysis, selected to represent the full footprint while capturing the worst and best case scenarios.

The footprint in Figure 3.35 shows the position of all the fields on the slit. There is a smile distortion present, with a 0.6 mm maximal vertical displacement. However, it does not pose an issue as long as the slit ($22 \times 1.4 \text{ mm}^2$) remains properly illuminated and the field mapping is accounted for in the full system design.

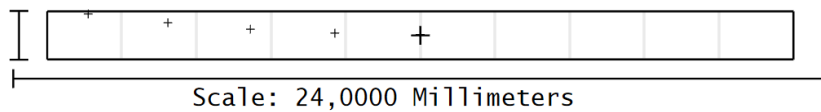


Figure 3.35: Footprint diagram at the image plane (slit) of the 1D pushbroom telescope. The black crosses represent the used fields during the optimization process. The y-axis has a scale of 1.42 mm.

The largest RMS wavefront error exists at the edges of the field. The difference between the inner and outer fields is still relatively small (0.0132 waves), and all the fields comply with the Maréchal criterion (RMS wavefront error must be below 0.0714 waves to be diffraction-limited). Reaching the diffraction limit for the telescope is important for the rest of the system, as this impacts the performance of the full design.

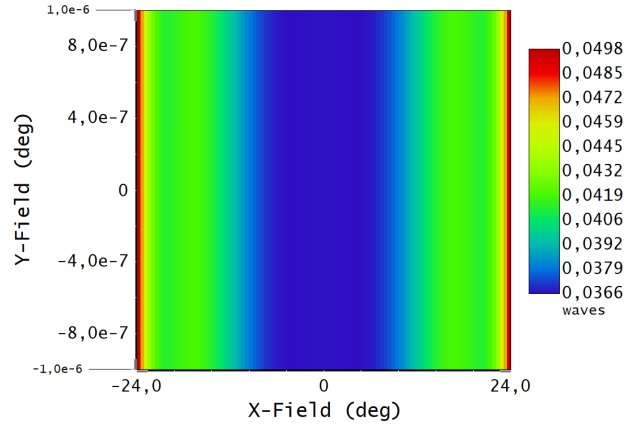


Figure 3.36: RMS wavefront error of the 1D pushbroom telescope. The RMS wavefront error map shows variation across the field relative to the diffraction limit. All the fields show diffraction-limited performance. The RMS wavefront error is evaluated using a ray density of 64×64 and a field sampling of 100×20 .

The telescope spot diagram is evaluated at the shortest wavelength of 195 nm with the smallest Airy disk diameter ($2.85 \mu\text{m}$). Figure 3.37 shows the spot diagram of the selected analysis fields. The RMS spot size is larger than the smallest Airy disk, but the spot diagram only represents the geometrical ray distribution and does not include energy distribution. Therefore, this does not contradict the RMS wavefront error result, which shows that the telescope remains diffraction-limited.

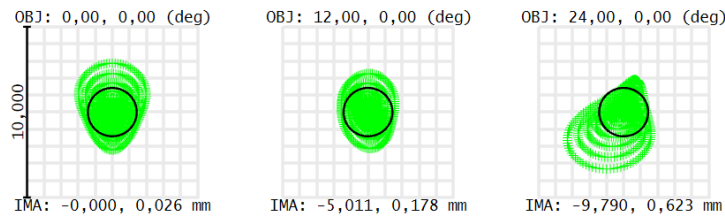


Figure 3.37: Spot diagram of the 1D pushbroom telescope. The black circle indicates the Airy disk diameter for comparison with the diffraction-limited spot size. For a wavelength of 195 nm and F/6, the Airy disk diameter is $2.85 \mu\text{m}$.

The encircled energy (EE) of the telescope, shown in Figure 3.38, further confirms the diffraction-limited performance. The 80% EE radius is approximately $1.5 \mu\text{m}$, which is close to the Airy disk radius of $1.43 \mu\text{m}$ at 195 nm. This shows that the energy remains concentrated near the diffraction-limited core, confirming that the telescope performance is not limited by geometrical aberrations.

The telescope design is also evaluated for a minimal MTF of 0.5 at the Nyquist frequency f_{Nyq} . Figure 3.39 shows an $\text{MTF} \geq 0.96$ at 50 cycles/mm. This exceeds the minimal MTF requirement by a large margin.

Overall, the freeform telescope has a very good diffraction-limited performance in terms of spot concentration, wavefront error, and contrast. Therefore, it does not pose a limitation on the full system. Figure 3.40 shows the final freeform telescope design.

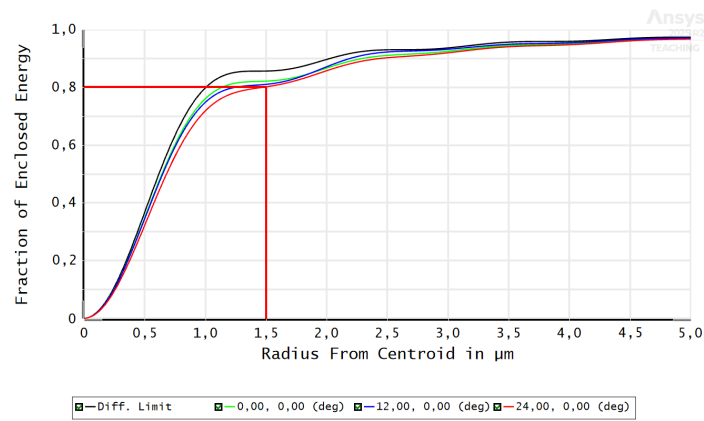


Figure 3.38: Diffraction Encircled Energy of the 1D pushbroom telescope. The red marking shows a performance requirement of 80% of the EE. Pupil sampling: 256×256 . Image sampling: 256×256 .

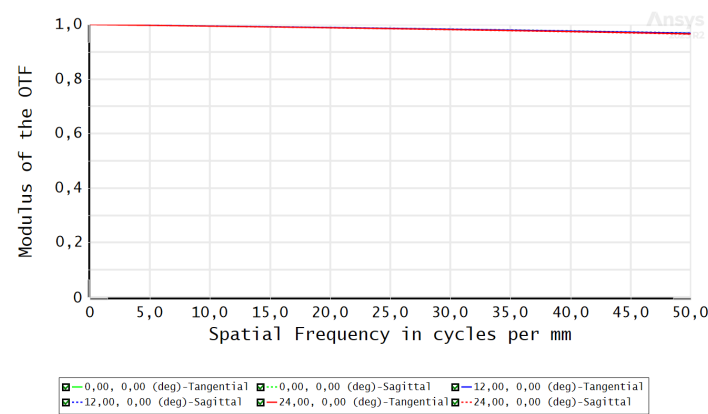


Figure 3.39: MTF of the 1D pushbroom telescope. $MTF \geq 0.96$ @ 50 cycles/mm (Nyquist frequency). Pupil sampling: 512×512 . Image sampling: 128×128 .

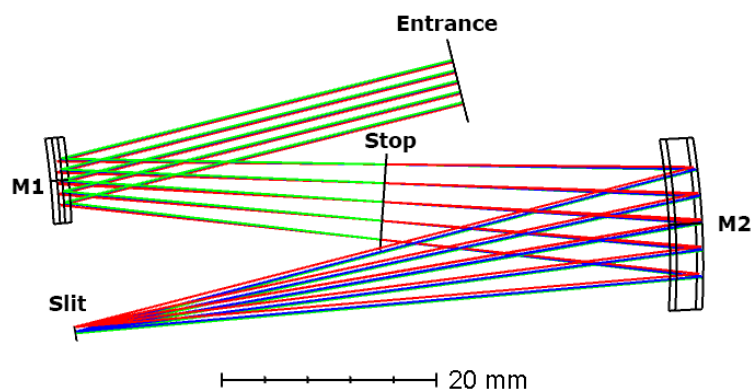


Figure 3.40: Final 3D layout of the 1D pushbroom telescope. M denotes a mirror.

3.5.2.2 Spectrometer design

The spectrometer consists of a collimating mirror, a diffraction grating, three freeform mirrors, and a detector. The same fields as the telescope will be considered in this part of the design. The groove density of the diffraction grating is initially set to be 0.018 lines/ μm as a first-order approximation (see Section 2.2.2). At the final stage of the optimization, the groove density is subsequently optimized by mapping the wavelengths to their corresponding detector pixels. A clear separation of the considered wavelengths (195 - 345 nm) on the detector plane is achieved. The linear dispersion between each central wavelength is 12 μm , which exceeds one pixel size (10 μm). A spectral resolution of 21 nm can be calculated using Eq. 3.7.

The footprint of the sampled fields on the detector plane is shown in Figure 3.41. The footprint shows a slight curvature of the monochromatic field line, corresponding to the smile distortion ($\approx 0.30 - 0.37$ mm maximal vertical displacement). This does not necessarily pose an issue for the final performance, since only a small rectangular region of the full detector is used for the spectral image. As long as the curved footprint remains within the allocated detector region, a vertical displacement of some fields with respect to the on-axis field does not directly degrade the optical performance and can be accounted for during calibration.

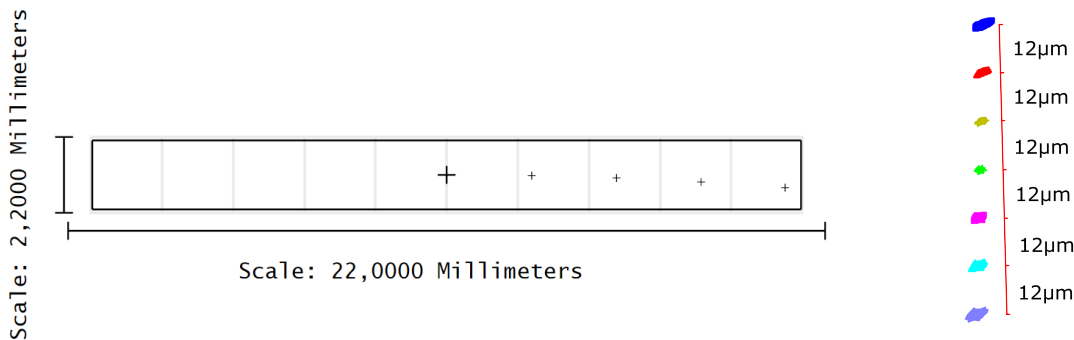


Figure 3.41: Footprint diagram at the image plane (detector) of the 1D pushbroom multispectral imager. The black crosses represent the used fields during the optimization process. The figure on the right shows the linear dispersion on the detector plane of the wavelengths.

The radial distortion can be used to quantify the distortion of the image with the on-axis field as a reference. Figure 3.42 shows a maximum radial distortion of 7.40%, which remains within the proposed requirement of $< 10\%$.

The RMS wavefront error map, shown in Figure 3.43, shows that the 195 nm wavelength is not fully diffraction-limited (> 0.0714 waves). This is due to residual aberrations that are still present in the system.

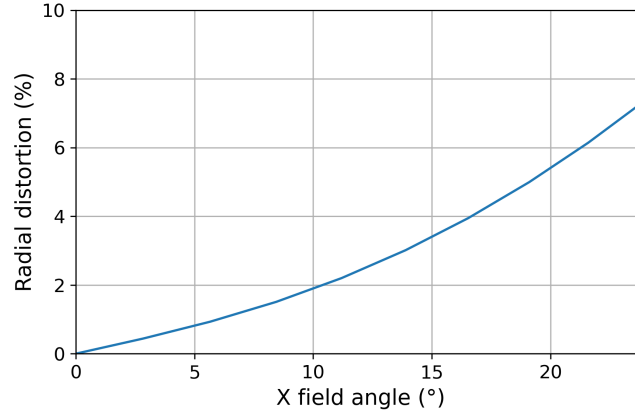


Figure 3.42: Grid distortion of the 1D pushbroom multispectral imager for the on-axis field. The values are extracted from the grid distortion plot in Zemax. grid size is 50×50 . Field width is 48° . Aspect ratio is 0.005.

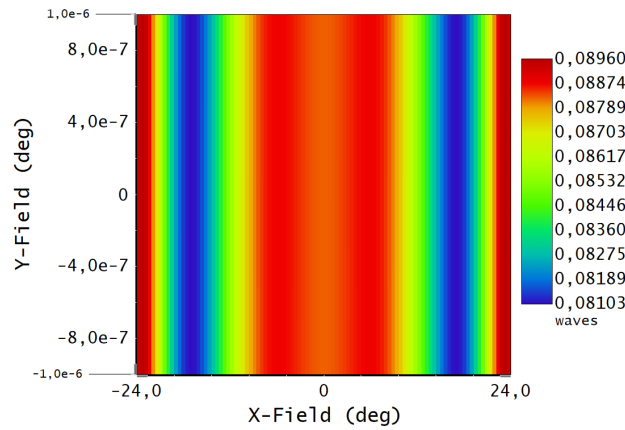


Figure 3.43: RMS wavefront error of the 1D pushbroom multispectral imager. The RMS wavefront error map shows variation across the field relative to the diffraction limit, with the full field slightly exceeding it. The RMS wavefront error is evaluated using a ray density of 64×64 and a field sampling of 100×20 .

First, a polychromatic spot diagram is shown in Figure 3.44. Here, it is clear that all the wavelengths have similar spot sizes. Even though smile distortion is present in the spatial dimension, there is no keystone distortion present in the spectral dimension. Three wavelengths (195 nm, 270 nm, 345 nm) are selected to represent the full spectrum in the performance analysis. Those are the center and outer wavelengths that are considered in the optimization process. The performance of all the other wavelengths will fall in between the two outer wavelengths. A spot diagram of the selected wavelengths is shown in Figure 3.45.

The RMS spot sizes, when considering 270 nm and 345 nm, are contained within their respective Airy disks. However, the 195 nm spots are slightly elongated and do not fully fall inside the Airy disk. Keep in mind that the Airy disk of the 195 nm wavelength is significantly smaller than the Airy disk of the other wavelengths ($d_{\text{airy}} = 2.4 \mu\text{m}$).

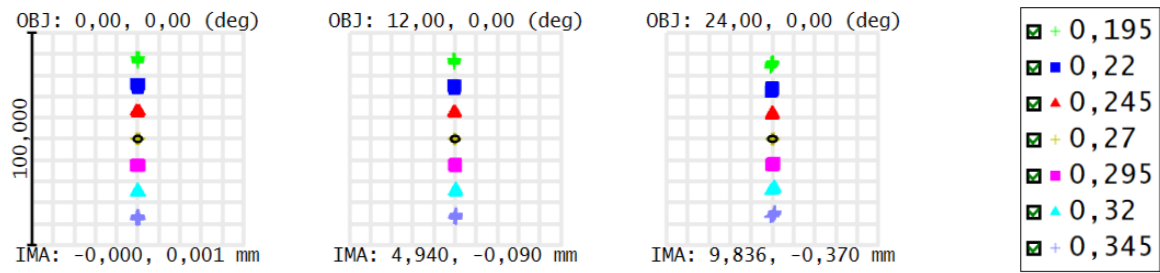


Figure 3.44: Spot diagram of the 1D pushbroom multispectral imager for the selected subset of field points and all the used wavelengths (195 - 345 nm). The black circle indicates the Airy disk diameter for comparison with the diffraction-limited spot size. For a wavelength of 195 nm and F/5, the Airy disk diameter is 2.4 μm .

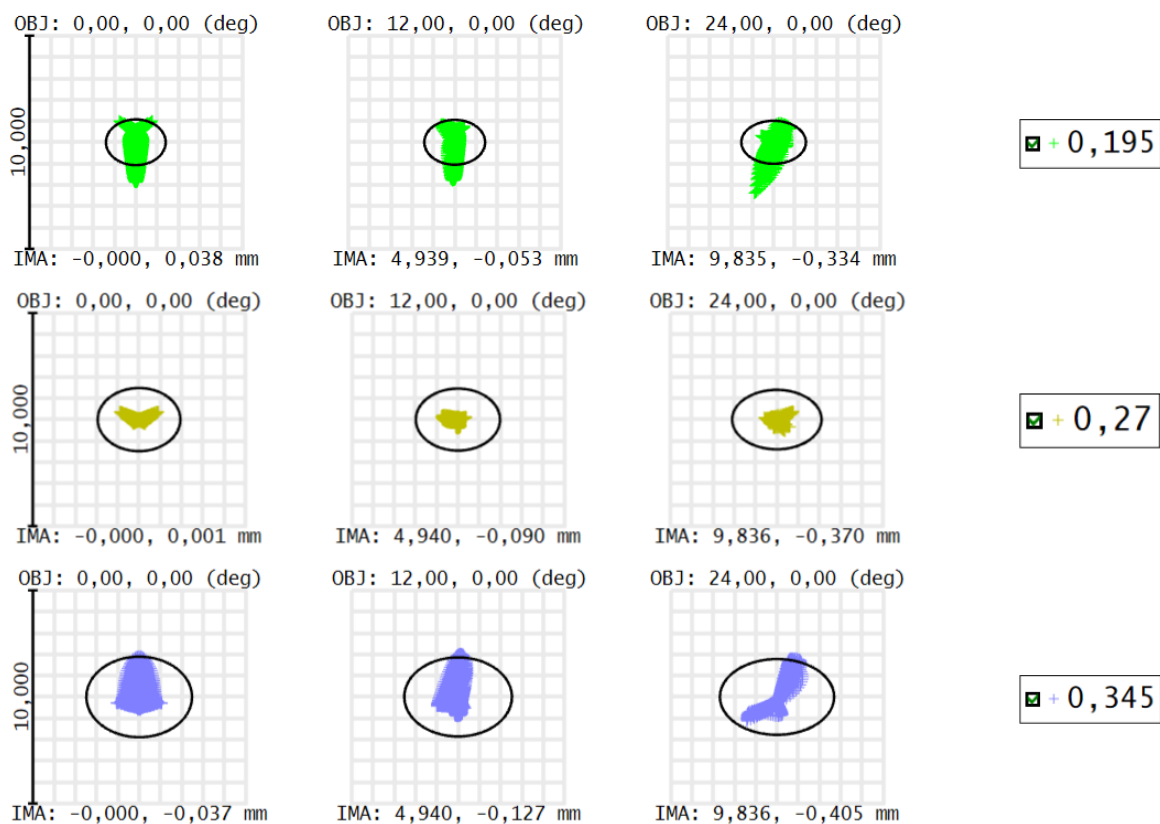


Figure 3.45: Spot diagram of the 1D pushbroom multispectral imager for the selected subset of field points and wavelengths (195 nm, 270 nm, 345 nm) is shown separately. The black circle indicates the Airy disk diameter for comparison with the diffraction-limited spot size. For F/5, the Airy disk diameter is 2.4 μm , 3.3 μm , and 4.2 μm for 195 nm, 270 nm, and 345 nm, respectively.

The aberration analysis is performed for the worst-performing field, located at $24^\circ \times 0^\circ$. Numerical analysis of the aberrations shows a mainly astigmatic spot. Starting from the on-axis field, the astigmatism contribution is mainly in X. However, for larger fields, the contribution of X decreases, while the contribution of Y increases. Compared to the other architectures, defocus is not a significant aberration for this system.

Figure 3.46 shows the encircled energy (EE) of the different wavelengths. The EE shows that 80% of the energy of all the wavelengths and all the fields falls within a radius from the centroid smaller than 2 μm . This gives a considerably large margin compared to the 5 μm half-width of the pixel pitch. Even if some fields and wavelengths are not diffraction-limited, they still remain fully detector-limited.

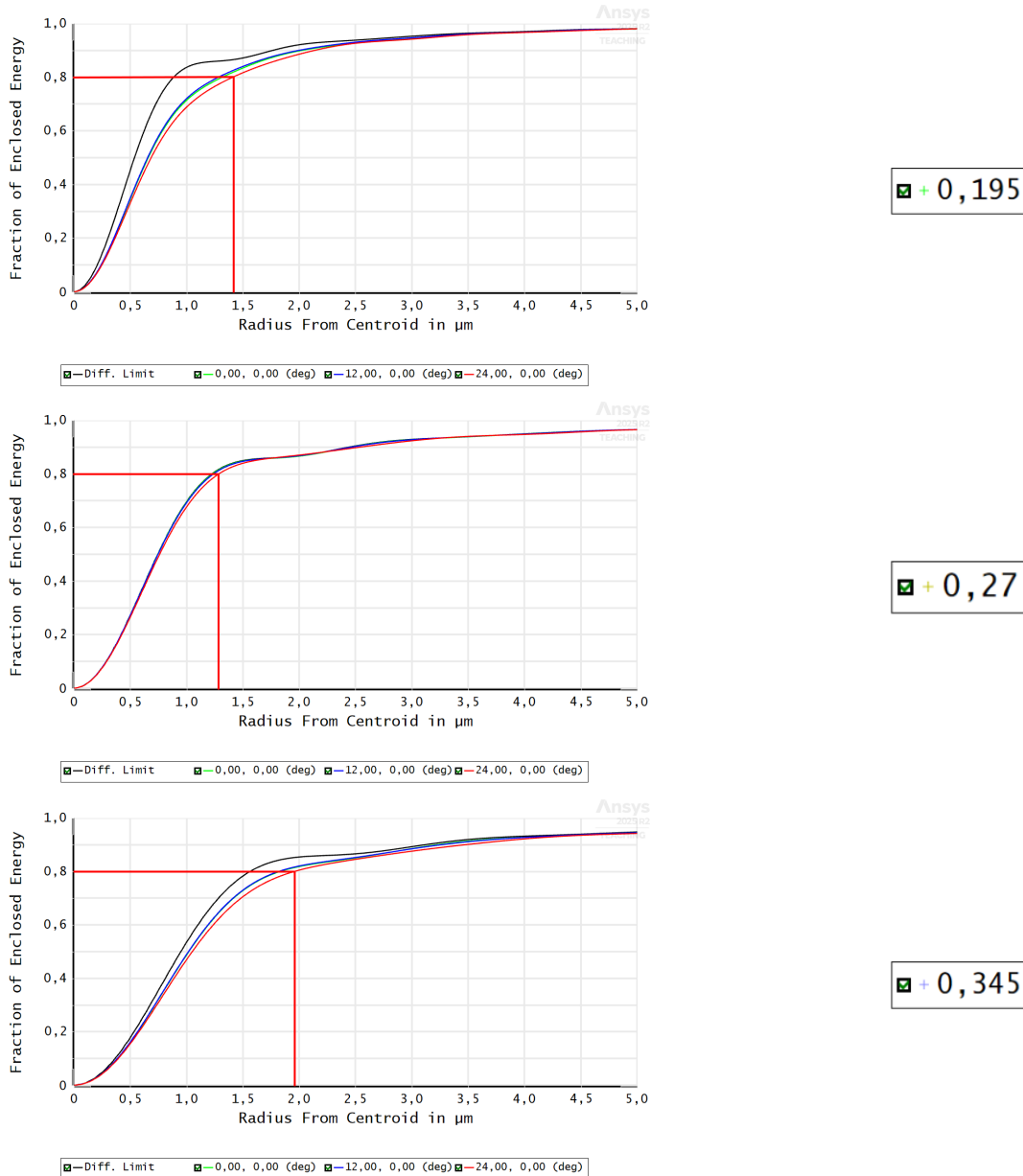
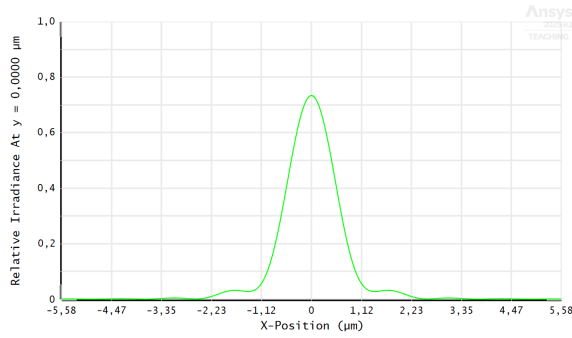
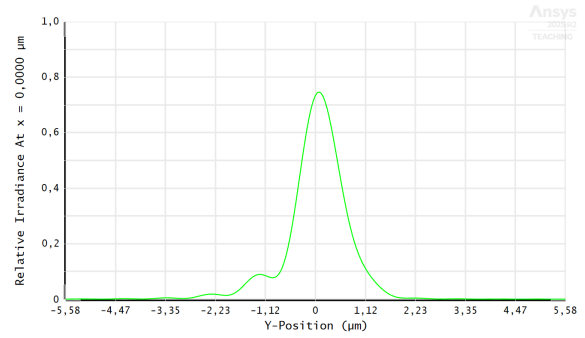


Figure 3.46: Diffraction Encircled Energy of the 1D pushbroom multispectral imager for the selected subset of field points and wavelengths (195 nm, 270 nm, 345 nm) is shown separately. The EE of all the other fields will be between the two extreme fields and wavelengths. The red marking shows a performance requirement of 80% of the EE. Pupil sampling: 256×256 . Image sampling: 256×256 .

The Point Spread Function, shown in Figure 3.47 and Figure 3.48, of the best and worst field of the worst performing wavelength (195 nm) proves that the system is not diffraction-limited. A field where the diffraction limit has been reached is shown in Figure 3.49.

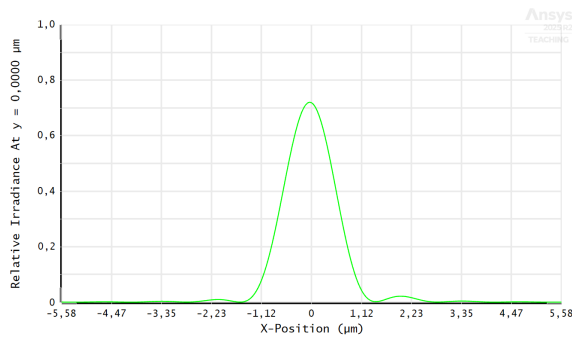


(a)

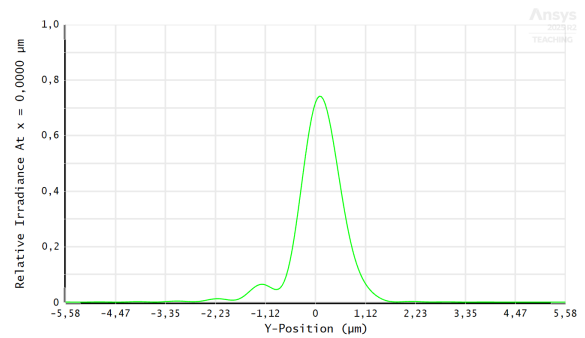


(b)

Figure 3.47: Huygens PSF of the best field ($0^\circ \times 0^\circ$) at a wavelength of 195 nm. The achieved Strehl ratio is ≤ 0.8 for both dimensions. This field is not diffraction-limited, but rather detector-limited. Pupil sampling: 512×512 . Image sampling: 128×128 . (a) X dimension. (b) Y dimension.

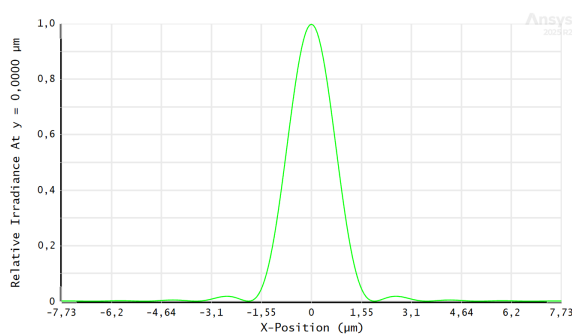


(a)

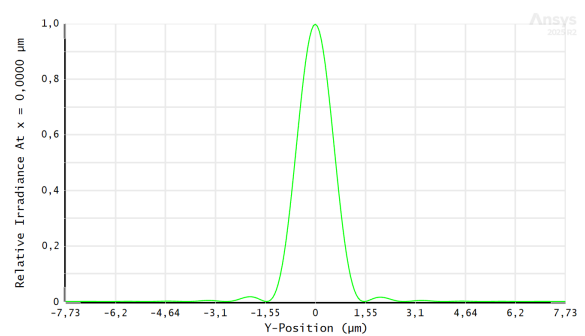


(b)

Figure 3.48: Huygens PSF of the worst field ($24^\circ \times 0^\circ$) at a wavelength of 195 nm. The achieved Strehl ratio is ≤ 0.8 for both dimensions. This field is not diffraction-limited, but rather detector-limited. Pupil sampling: 512×512 . Image sampling: 128×128 . (a) X dimension. (b) Y dimension.



(a)



(b)

Figure 3.49: Huygens PSF of the best field ($24^\circ \times 0^\circ$) at a wavelength of 270 nm. The achieved Strehl ratio is ≥ 0.8 for both dimensions. The field is diffraction-limited. Pupil sampling: 512×512 . Image sampling: 256×256 . (a) X dimension. (b) Y dimension.

The MTF is shown in Figure 3.50. An $MTF \geq 0.93$ has been achieved for $f_{Nyq} = 50 \text{ cycles/mm}$ for all the fields and wavelengths. The system exceeds the MTF requirement of 0.5 with a considerable margin.

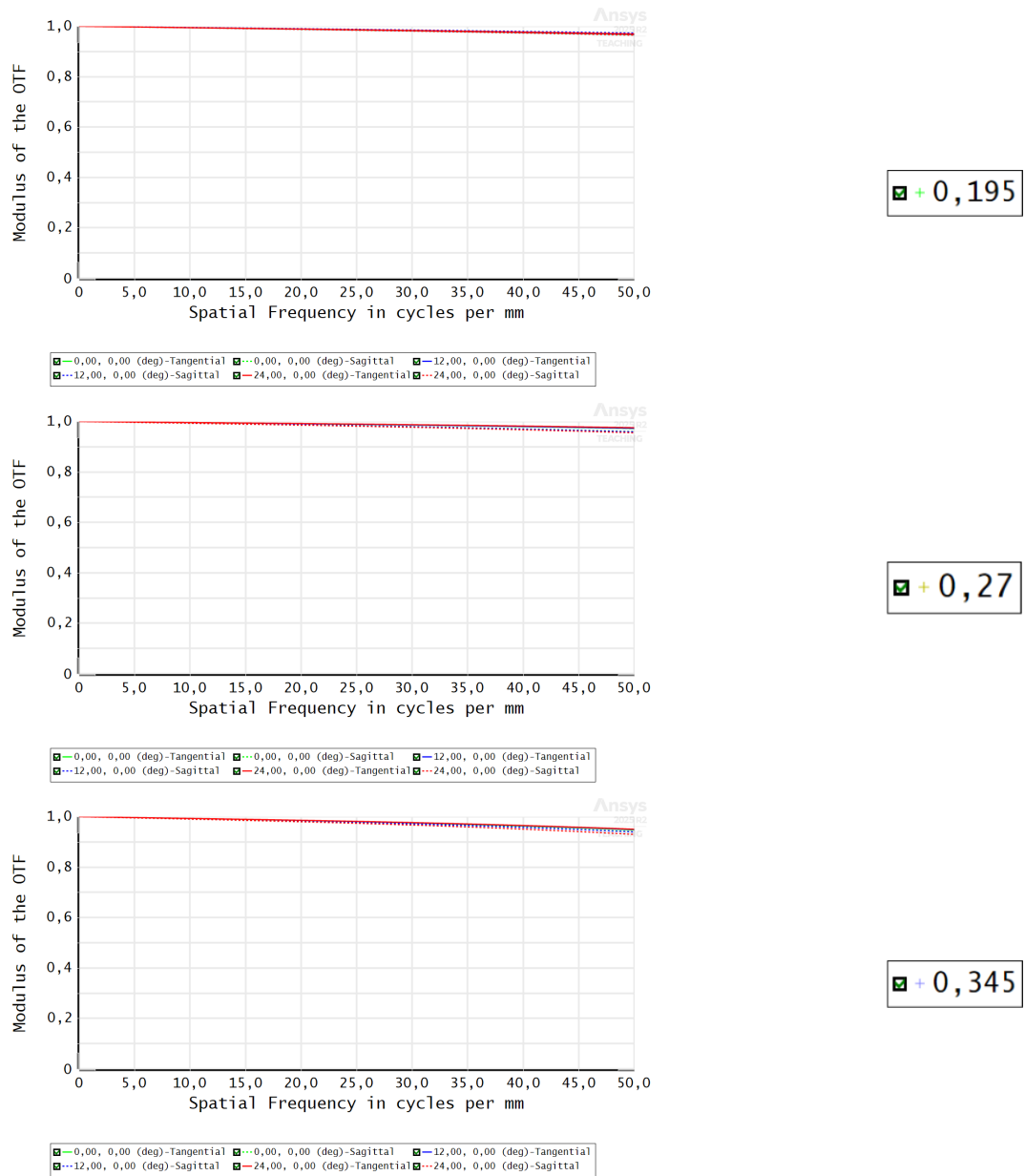


Figure 3.50: MTF of the 1D pushbroom multispectral imager for the selected subset of field points and wavelength. $MTF \geq 0.93$ @ 50 cycles/mm (Nyquist frequency). Pupil sampling: 512×512 . Image sampling: 128×128 .

3.5.3 Performance summary

The design has reached all the proposed specifications. It is fully diffraction-limited, except for the 195 nm wavelength. Nevertheless, this wavelength stays close to the diffraction limit and is still comfortably detector-limited. The current system is a good balance between system performance and design complexity, enabling to fulfil the requirements of the MIDIM instrument. In addition, the spectral resolution can be improved slightly for better spectral performance. However, this depends highly on the grating architecture. Therefore, no immediate conclusions about the achievable spectral resolution can be made. A summary of the specifications is given in Table 3.7. In terms of volume constraints, the complete system takes up less than half of the required volume. It opens the potential to add additional imaging channels to the design.

Table 3.7: Comparison between the MIDIM requirements and the achieved performance of the 1D pushbroom multispectral imager.

Parameter	MIDIM requirements	1D pushbroom design
FOV	$48^\circ \times 0.03^\circ$	$48^\circ \times 0.03^\circ$
EFL	22.46 mm	22.17 mm
GSD	2.55 km	2.58 km
Spectral bandwidth	25 nm	21 nm
F/#	F/5	F/5.06
EE	80% < 5 μm	195 nm: 80% at 1.4 μm 220 nm: 80% at 1.3 μm 245 nm: 80% at 1.2 μm 270 nm: 80% at 1.3 μm 295 nm: 80% at 1.45 μm 320 nm: 80% at 1.66 μm 345 nm: 80% at 1.95 μm
Distortion	< 10%	7.40%
MTF	> 0.5	195 nm: ≥ 0.96 220 nm: ≥ 0.96 245 nm: ≥ 0.96 270 nm: ≥ 0.95 295 nm: ≥ 0.94 320 nm: ≥ 0.93 345 nm: ≥ 0.93
Volume	$\leq 220 \times 200 \times 150 \text{ mm}^3$	$80 \times 60 \times 60 \text{ mm}^3$

Reducing the aberrations at the 195 nm wavelength further would require greater system complexity. However, as was the case for the other architectures, the increased complexity would not directly translate to increased performance. Therefore, the design is kept as is.

The telescope uses freeform terms up to 2nd order (X^2 and Y^2). For this part of the system, the X and Y contributions are of comparable magnitude for all mirrors (M1 - M2), indicating that the freeform correction remains approximately balanced between both transverse directions.

The spectrometer uses freeform terms up to 6th order, including even X terms, even and odd Y terms, and the corresponding mixed terms. Three main trends can be observed from the freeform coefficient magnitudes. i) The coefficients show a generally decreasing envelope towards higher orders, indicating that the dominant surface departure is captured by the lower-order terms. ii) The even Y terms generally have larger magnitudes than the corresponding even X terms, showing that the dominant residual correction is more strongly associated with the Y direction. iii) M3 and M5 consistently show larger coefficient magnitudes than M4, indicating that the strongest freeform correction is mainly carried by the outer mirrors of the spectrometer.

3.6 Summary: Performance comparison between design architectures

All architectures meet the proposed system requirements, but they do so with different trade-offs in optical complexity, spatial coverage, spectral capability, and system volume. Table 3.8 summarizes the achieved specifications of the three design architectures.

The 2D non-scanning multispectral imager is the most constrained architecture. It has the least margin in the specifications, the largest AOI on the discrete filter (12.5°), the largest F/# (F/8.47), and the largest volume ($220 \times 200 \times 150 \text{ mm}^3$). Its main advantage is that it provides full-frame imaging without the need for a scanning mechanism. However, this also makes the final design less flexible: improving one performance parameter, such as reducing the F/#, would require compromises in other specifications. This is reflected in the freeform description, which is the most complex of the three architectures and extends up to 8th order. Additional freeform terms will increase mechanical and manufacturing complexity.

The 2D scanning multispectral imager provides a less constrained optical configuration because the FOV is reduced in the scanning direction. This results in improved optical performance and larger design margins compared with the non-scanning architecture (improvements of 4% GSD, 45% F/#, 33% EE, 1.8% distortion, and 6% MTF). Although the design still requires freeform terms up to 6th order, its freeform complexity remains lower than that of the 2D non-scanning architecture. The inclusion of a scan mirror introduces additional mechanical complexity, as well as potential challenges related to durability, temporal sampling, and image reconstruction during post-processing. Since the achieved specifications do not approach the limits of the proposed requirements, the system could potentially be made faster if radiometric calculations indicate that a higher throughput is required.

The 1D pushbroom multispectral imager also satisfies the proposed requirements. Similar to the 2D scanning design, this design likewise uses freeform terms up to 6th order. The design offers improved spectral sampling by dispersing the incoming light rather than relying on discrete filters. As a result, this architecture provides the strongest spectral capability when spectral discrimination is the primary objective. From a packaging standpoint, it also has the smallest volume, allowing the addition of other spectroscopy channels.

Overall, the three architectures are considered feasible from an optical design perspective. The achieved EFL values result in a GSD between 2.50 km and 2.61 km, remaining close to the proposed 2.55 km spatial sampling requirement. This indicates that the optical designs preserve the intended ground sampling capability of the mission. The EE requirement is satisfied for all architectures, with 80% of the energy contained within less than 5 μm . This limits the optical blur contribution relative to the detector sampling and supports the preservation of the required GSD. The distortion remains below the proposed 10% requirement for all designs. This limits geometric deformation to a level that can be corrected during calibration and post-processing of the final image products. The MTF requirement is also satisfied in all cases, indicating that sufficient contrast is retained at the evaluated spatial frequency (50 cycles/mm) to support feature discrimination at the required GSD.

From a mechanical implementation perspective, all architectures remain within the proposed volume envelope of $220 \times 200 \times 150 \text{ mm}^3$. The 2D non-scanning multispectral imager uses the full allocated volume and remains closest to the imposed optical limits. However, it has the fewest optical components, which makes the design mechanically simpler and reduces the number of interfaces that require alignment and tolerance control. In contrast, the 2D scanning and 1D pushbroom architectures require smaller optical volumes, but include more optical components, such as a scanning system or a telescope, a collimator, and a grating. Therefore, the final architecture selection is not based only on optical feasibility, but on the mission-level trade-off between full-frame acquisition simplicity, radiometric margin, spectral capability, mechanical accommodation, and system complexity.

Table 3.8: Comparison between the proposed system specifications and the achieved performance of the different architectures.

Parameter	MIDIM requirements	Architecture 1: 2D non-scanning multispectral imager	Architecture 2: 2D scanning multispectral imager	Architecture 3: 1D pushbroom multispectral imager
FOV	2D non-scanning: $48^\circ \times 48^\circ$ 2D scanning: $48^\circ \times 10^\circ$ 1D pushbroom: 48°	$48^\circ \times 48^\circ$	$48^\circ \times 10^\circ$	48°
EFL	22.46 mm	21.93mm	22.91 mm	22.17 mm
GSD	2.55 km	2.61 km	2.50 km	2.58 km
Spectral bandwidth	25 nm	25 nm	25 nm	21 nm
F/#	2D non-scanning: F/8 2D scanning: F/4.5 1D pushbroom: F/5	F/8.47	F/4.63	F/5.06
EE	$80\% < 5 \mu\text{m}$	80% at $3.2 \mu\text{m}$	80% at $2.15 \mu\text{m}$	195 nm: 80% at $1.40 \mu\text{m}$ 220 nm: 80% at $1.30 \mu\text{m}$ 245 nm: 80% at $1.20 \mu\text{m}$ 270 nm: 80% at $1.30 \mu\text{m}$ 295 nm: 80% at $1.45 \mu\text{m}$ 320 nm: 80% at $1.66 \mu\text{m}$ 345 nm: 80% at $1.95 \mu\text{m}$
Distortion	$<10\%$	9.09%	7.30%	7.40%
MTF	>0.5	≥ 0.85	≥ 0.91	195 nm: ≥ 0.96 220 nm: ≥ 0.96 245 nm: ≥ 0.96 270 nm: ≥ 0.95 295 nm: ≥ 0.94 320 nm: ≥ 0.93 345 nm: ≥ 0.93
Volume	$\leq 220 \times 200 \times 150 \text{ mm}^3$	$220 \times 200 \times 150 \text{ mm}^3$	$170 \times 150 \times 135 \text{ mm}^3$	$80 \times 60 \times 60 \text{ mm}^3$

Chapter 4

Practical Feasibility Assessment of the Final Designs

The previous chapter focused on the nominal optical performance of the three proposed architectures. However, meeting the optical requirements in the nominal design does not guarantee that the systems are practically feasible to manufacture, align, and prototype. Therefore, this chapter evaluates several practical design considerations that are relevant for moving the final designs towards experimental implementation. These include tolerance sensitivity, coating selection, discrete filter availability and performance, and a first-order radiometric SNR estimation. Together, these aspects provide an assessment of the robustness, manufacturability, and expected practical performance of the final architectures.

4.1 Tolerancing

The designs presented in the previous chapter meet the requirements under nominal conditions, meaning that the optical components are assumed to be manufactured and positioned exactly according to their optimized design parameters. In order to assess the robustness and practical feasibility of the final optical designs, a tolerance analysis is performed, including both component fabrication tolerances and system assembly tolerances. The same tolerance set is applied to the three designs at their shortest operating wavelength: 220 nm for the 2D imagers and 195 nm for the 1D imager. The applied tolerances are summarized in Table 4.1.

The tolerance values are not taken directly from a single manufacturer, but are selected to represent precision to high-precision manufacturing and alignment capabilities that are commercially achievable [33] [34] [35]. Some of the surface tolerances are expressed in interferometric units, such as fringes, which are linked to the reference wavelength used during testing. In this context, one fringe corresponds to a surface departure of $\lambda/2$. Therefore, the applied spherical and astigmatism (S+A) irregularity tolerance of 0.2 fringes corresponds to $\lambda/10$ [36]. This irregularity value lies between typical precision and high-precision surface-form tolerances [33]. For the radius tolerance, however, the fringe value should be interpreted as a surface-power or sag departure over the clear aperture, rather than as a fixed absolute change in radius of curvature. The equivalent radius change, therefore, depends on the nominal radius of curvature, the clear aperture, and the reference wavelength.

Table 4.1: Summary of the fabrication and assembly tolerances applied in the tolerance analysis of the final designs.

Surface tolerances	Value
Radius	1 Fringe
Thickness	0.01 mm
Tilt X	0.0167°
Tilt Y	0.0167°
S + A Irregularity	0.2 Fringes
Element tolerances	Value
Decenter X	0.01 mm
Decenter Y	0.01 mm
Tilt X	0.01°
Tilt Y	0.01°
Options	Value
Testing wavelength	2D imagers: 220 nm 1D imager: 195 nm

It should also be noted that, for a more accurate estimation of surface-form sensitivity, future tolerance analyses should specify surface irregularity according to ISO 10110-5 [37], especially for the freeform surface. Instead of relying only on a conventional spherical and astigmatism (S + A) irregularity value, ISO-based tolerance descriptions [31] such as ISOA, ISOB, and ISOD should be considered, since they allow power, peak-to-valley irregularity, and RMS irregularity to be treated separately.

The designs are evaluated using the criterion that the radius containing 80% of the encircled energy (EE) must remain below half the detector pixel pitch. Since the pixel pitch is 10 μm , the maximum allowed 80% EE radius is therefore 5 μm . A Monte Carlo (MC) tolerance analysis is performed in the sequential mode of Zemax OpticStudio using 5000 iterations. A design is considered tolerance-compliant if 98% of the MC runs satisfy the proposed EE requirement. In addition, a sensitivity analysis is performed by varying all component tolerances to identify the dominant contributors to the degradation in optical performance. This provides insight into the most sensitive parts of the design and indicates which parameters could be optimized further if required.

4.1.1 2D non-scanning multispectral imager

The 2D non-scanning multispectral imager shows low sensitivity to surface manufacturing and alignment errors. The Gaussian approximation has a mean value of 3.185 μm and a standard deviation of 0.175 μm . At P98, the radius of the 80% encircled energy remains below 3.582 μm , which is well within the P98 requirement of 5 μm .

The most sensitive parameters are the axial spacing between M3 and the detector, the axial spacing between the filter wheel/stop and M3, and the x- and y-tilts of M2. However, the corresponding changes in the 80% encircled energy radius remain below 0.26 μm . This is less than 10% of the nominal value of 3.170 μm , indicating that the system is sufficiently tolerant for the given manufacturing and alignment tolerances, ensuring a manufacturable design. The corresponding Monte Carlo distribution and sensitivity analysis are shown in Figure 4.1.

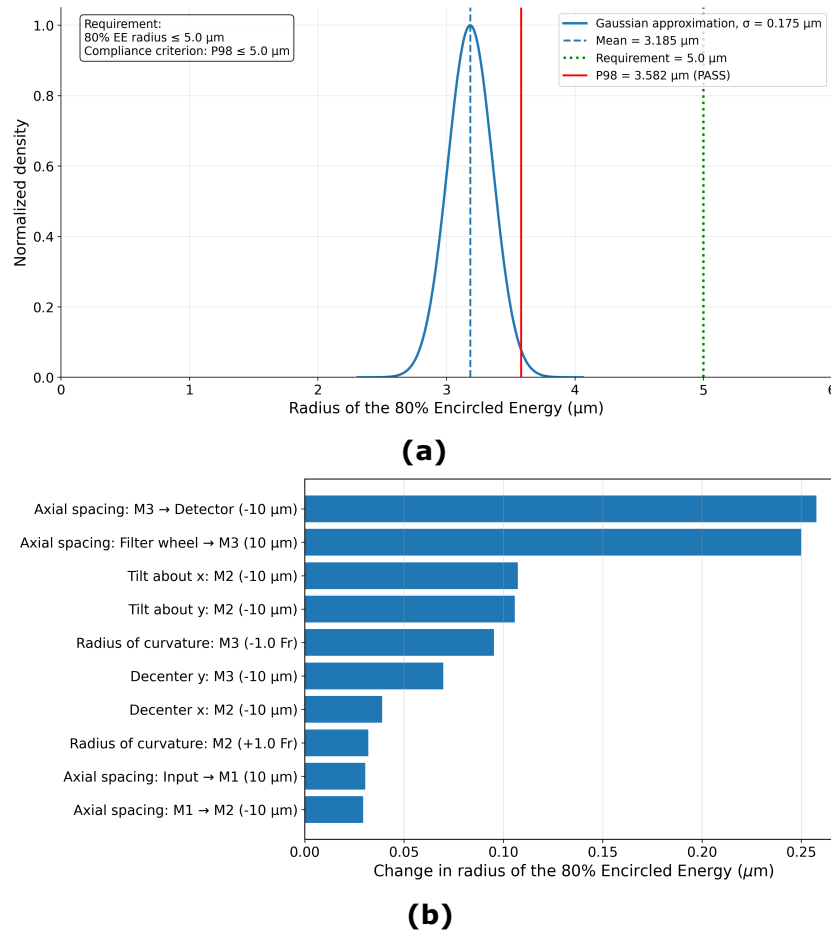


Figure 4.1: Tolerancing of the 2D non-scanning multispectral imager design with the conditions from Table 4.1. (a) Gaussian distribution approximation from 5000 Monte Carlo runs. (b) Worst offenders for the sensitivity analysis.

4.1.2 2D scanning multispectral imager

The 2D scanning multispectral imager is slightly more sensitive to surface manufacturing and alignment errors than the 2D non-scanning multispectral imager. The Gaussian approximation has a mean value of 2.217 μm and a standard deviation of 0.440 μm . At P98, the radius of the 80% encircled energy remains below 3.277 μm , which satisfies the P98 requirement of 5 μm .

The dominant sensitivity contributors are the axial spacing between the filter wheel and M3, the axial spacing between M3 and the detector, and the radius of curvature of M2. The corresponding changes in the 80% encircled energy radius remain below $0.70\text{ }\mu\text{m}$. This corresponds to less than 35% of the nominal value of $2.126\text{ }\mu\text{m}$. Therefore, although the design is more sensitive than the 2D non-scanning multispectral imager, it still satisfies the tolerance requirement with a comfortable margin and can be considered tolerance-compliant. The corresponding Monte Carlo distribution and sensitivity analysis are shown in Figure 4.2.

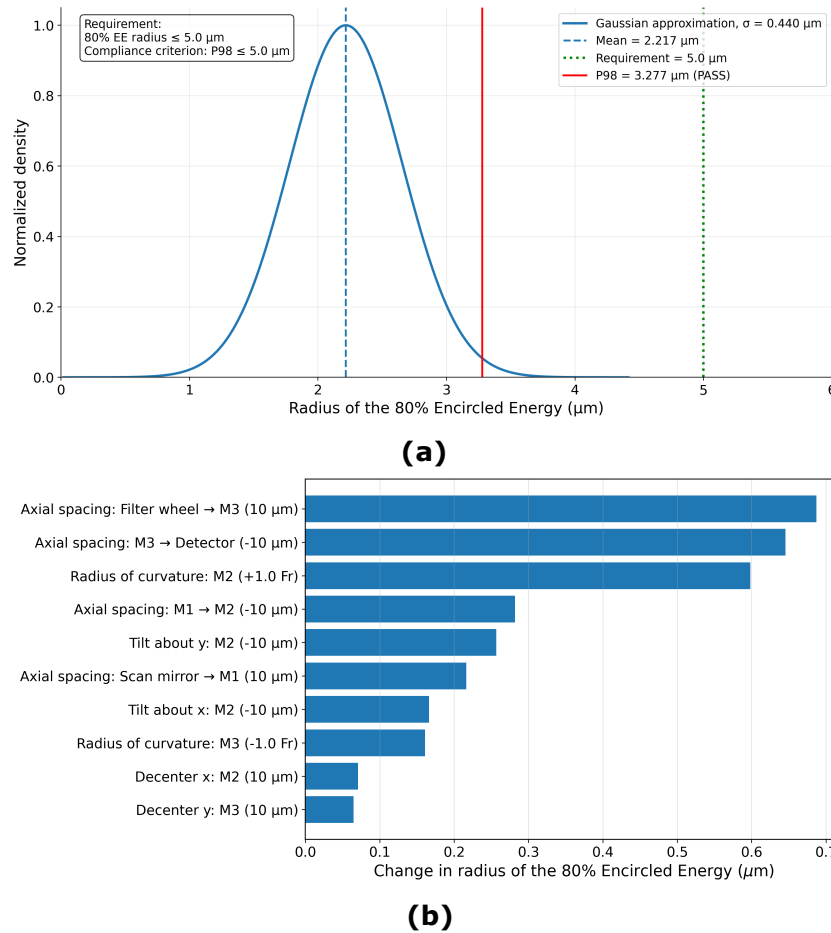


Figure 4.2: Tolerancing of the 2D scanning multispectral imager design with the conditions from Table 4.1. (a) Gaussian distribution approximation from 5000 Monte Carlo runs. (b) Worst offenders for the sensitivity analysis.

4.1.3 1D pushbroom multispectral imager

The 1D pushbroom multispectral imager is the most sensitive of the three designs. The Gaussian approximation has a mean value of $2.570\text{ }\mu\text{m}$ and a standard deviation of $1.034\text{ }\mu\text{m}$. At P98, the radius of the 80% encircled energy reaches $5.387\text{ }\mu\text{m}$, which slightly exceeds the P98 requirement of $5\text{ }\mu\text{m}$.

The dominant sensitivity contributors are the axial spacing between M3 and M4, the axial spacing between M4 and M5, and the axial spacing between M3 and M4 with the opposite tolerance direction. These changes in the 80% encircled energy radius are of the same order as the mean value of the Gaussian approximation.

The largest sensitivity contribution is approximately 1.8 times the nominal value of $1.409\ \mu\text{m}$, indicating that the system is highly sensitive to the applied surface manufacturing and alignment tolerances. The corresponding Monte Carlo distribution and sensitivity analysis are shown in Figure 4.3.

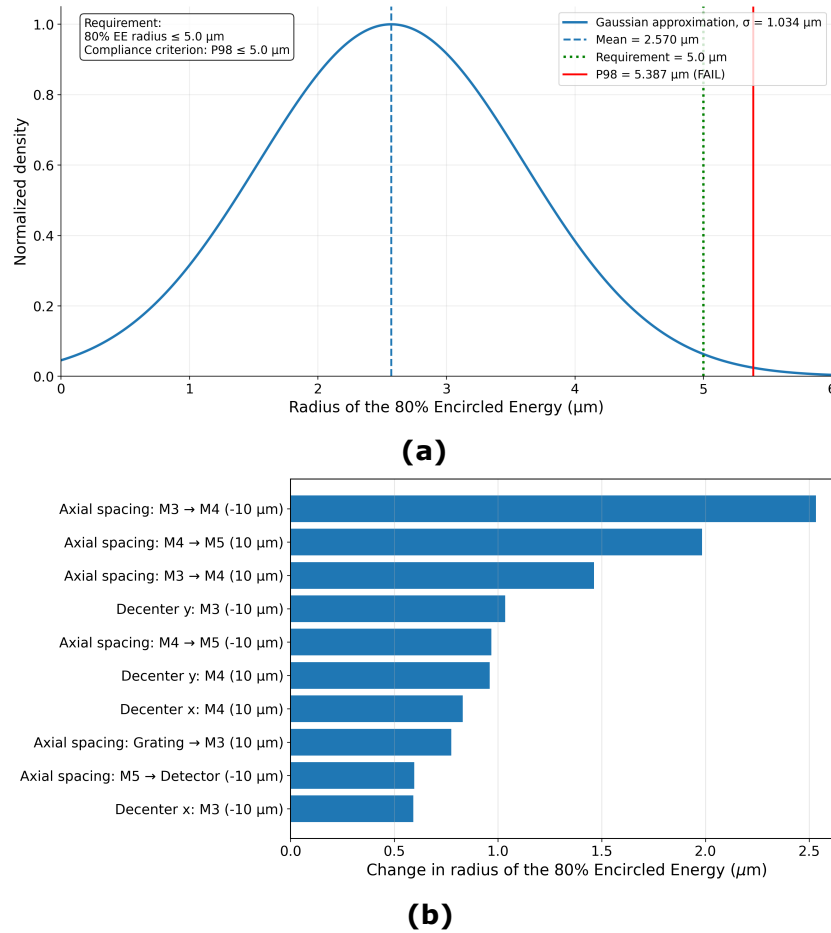


Figure 4.3: Tolerancing of the 1D pushbroom multispectral imager design with the conditions from Table 4.1. (a) Gaussian distribution approximation from 5000 Monte Carlo runs. (b) Worst offenders for the sensitivity analysis.

This increased sensitivity can be explained by the compact geometry of the design. The axial distances between several components are approximately 10 - 20 mm, which is significantly smaller than the 50 - 150 mm distances used in the 2D designs. As a result, axial perturbations on the order of $10\ \mu\text{m}$ represent a larger relative change in the optical layout and therefore have a stronger effect on the image quality.

A second contributing factor is the large angle of incidence in the x-direction. The widest field reaches an angle of approximately 24° . In combination with the small axial distances and smaller component diameters, this leads to stronger coupling between alignment errors and optical performance. Consequently, although the nominal performance of the 1D pushbroom design is very good, the tolerance analysis shows that this architecture is less robust than the two multispectral designs and would require further tolerance optimization before practical implementation.

4.2 Practical implementation

To prototype the optical designs, real optical components need to be selected. These include mirror coatings, discrete filters, the detector, and a diffraction grating for the pushbroom system. For the final pushbroom design, the diffraction grating will require a custom component. Common manufacturers, such as Thorlabs [38] and Edmund Optics [39], offer off-the-shelf gratings, but none match the required combination of parameters. The present design requires a blazed grating operating over the 195 - 345 nm wavelength range with a groove density of 28 lines/mm. In particular, this groove density differs strongly from standard catalog values. Therefore, an off-the-shelf grating is not considered suitable for the final implementation.

4.2.1 Mirror coatings

The mirror coatings need to have a high reflectivity for a broad range of wavelengths (195 nm - 345 nm). In addition, the coating must be space-compatible because radiation degrades certain materials more rapidly than others. The Al + MgF₂ coating has proven space heritage. It has been used in, e.g., the Hubble telescope and Spektr-UF [40]. Therefore, it is also considered within this thesis.

As mentioned in Section 3.1, the AOI on the mirror will have an impact on the reflectivity. However, the AOI for the final designs does not exceed 45°. This value is conservative, but enables an easy comparison of the available coatings, since coatings are often characterized at angles of incidence of 45°.

An example of a possible coating with high reflectivity and space-compliance is the Teledyne Acton #1900 Broadband Al + MgF₂ coating [41]. It features an average reflectivity of 87% from the peak wavelength 225 nm to 600 nm. Two reflectance graphs (Figure 4.4 and Figure 4.5) are shown for the coating. Both graphs show a high reflectance of >85% at the relevant UV wavelength (195 - 345 nm) and >80% at the VIS/NIR wavelengths (435 nm - 850 nm). In addition, the incident angles are measured for 15° and 45°. The peak wavelength at 225 nm decreases approximately 2.5% between 15° and 45°. Meaning that if the AOI in the system stays under 45°, the mirror reflectances do not decrease significantly.

4.2.2 Filters

Two of the proposed architectures (2D non-scanning and 2D scanning multispectral imagers) use discrete filters to image the different wavelengths. These filters need to have a bandwidth that is small enough to separate the required wavelengths (220 nm, 260 nm, 320 nm). A bandwidth of 25 nm is proposed.

Secondly, the transmission of the filter will be one of the biggest sources of throughput loss in the optical system. Typical filter transmissions for UV wavelengths remain between 15% and 30% for a bandwidth around 25 nm. This is a significant loss, and consequently, will decrease the SNR (see Section 4.3).

Some examples of possible filters for prototyping are listed in Table 4.2, including both off-the-shelf and custom solutions. The off-the-shelf filters do not perfectly match the center wavelength of interest, but are still acceptable for prototyping.

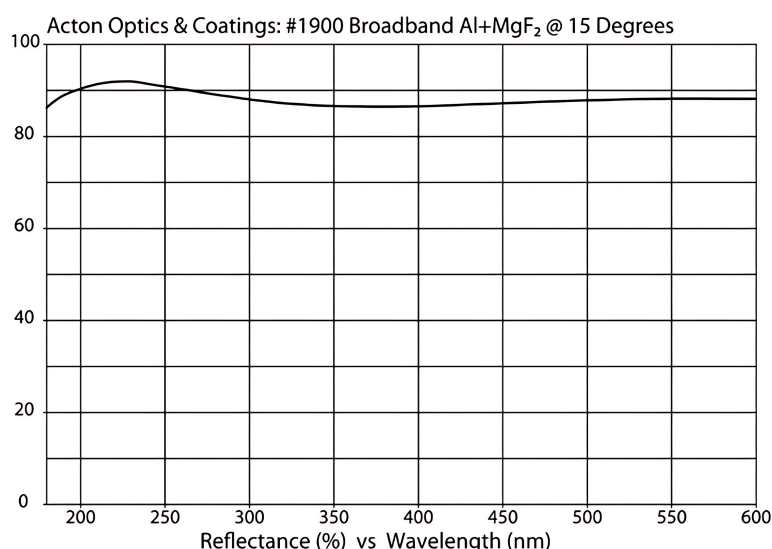


Figure 4.4: Teledyne Acton #1900 Broadband Al + MgF₂ coating featuring a reflectance from 190 nm to 600 nm for an incidence angle of 15° [41].

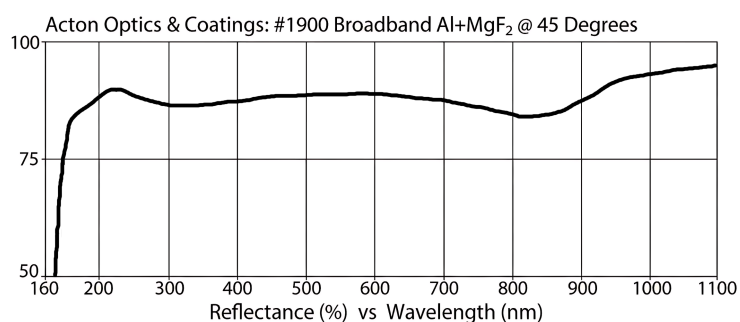


Figure 4.5: Teledyne Acton #1900 Broadband Al + MgF₂ coating featuring a reflectance from 160 nm to 1100 nm for an incidence angle of 45° [41].

For the final product, a custom filter will likely be used. The filters have been selected from Andover Corporation, because they provide space-compliant optical components [42]. A custom quote has been requested with an indication of how much the custom filters will cost and what their performance will be. The off-the-shelf solutions are significantly cheaper than the custom filters. The price of one filter (e.g., 254FS25-25) is around €260, while a custom filter with slightly better specifications costs around €2080. Therefore, for prototyping, the center wavelength of the filter can be slightly different from the required wavelengths, but for the final product, the more expensive custom filters need to be considered. The off-the-shelf filter spectra are shown in Figure 4.6.

The custom filter values in Table 4.2 represent possible specifications rather than a fully optimized filter design. In practice, a custom filter could be optimized not only for the exact centre wavelength, but also for higher transmission. Depending on the required spectral selectivity, it may be more beneficial to accept a small centre-wavelength offset if this results in a significant throughput increase, since the UV filter transmission has a strong impact on the final SNR.

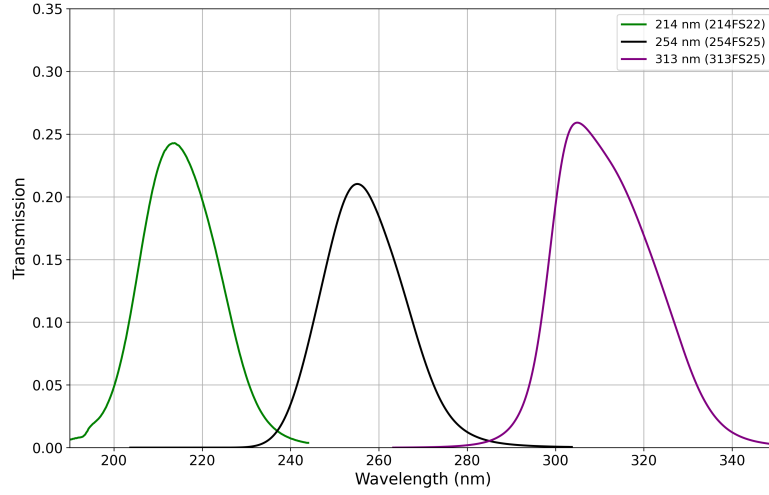


Figure 4.6: Spectra of the Andover Corporation filters [42]

Table 4.2: Summary of broadband filters (off-the-shelf and custom) together with performance specifications from Andover Corporation [42]

Ideal wavelength	Model name	Center wavelength	Bandwidth	Transmission (min)
220 nm	214FS22-25	214 nm	22 nm	20%
260 nm	254FS25-25	254 nm	25 nm	18%
320 nm	313FS25-25	313 nm	25 nm	20%
220 nm	Custom	220 nm	25 nm	20%
260 nm	Custom	260 nm	25 nm	20%
320 nm	Custom	320 nm	25 nm	30%

As mentioned in the challenges, a large AOI of the filter will introduce a wavelength shift towards smaller wavelengths (blue-shift). This shift can be calculated with Eq. 4.1 [32, Chapter 8.2.4]:

$$\lambda = \lambda_0 \sqrt{1 - \left(\frac{\sin(\theta_0)}{n_{\text{eff}}} \right)^2} \quad (4.1)$$

Where λ is the shifted center wavelength, λ_0 is the initial center wavelength, θ_0 is the AOI in air, and n_{eff} is the effective refractive index. The filter is a thin-film multilayer filter. This means that a series of low- and high-indexed thin layers is stacked on top of each other [32, Chapter 1.2]. The resulting effective refractive index can be calculated with Eq. 4.2 [32, Chapter 8.4.1]:

$$n_{\text{eff}} \approx \sqrt{n_H \cdot n_L} \quad (4.2)$$

Where n_H and n_L represent the high and low refractive indices of the thin layers. Common materials for UV filters are MgF_2 , LaF_3 , BaF_2 , CaF_2 , Al_2O_3 , HfO_3 , and SiO_2 [43]. The effective refractive index is estimated to be in a range between 1.5 and 2.1. The blue-shift estimation is applied to the spectra in Figure 4.6, and is shown in Figure 4.7.

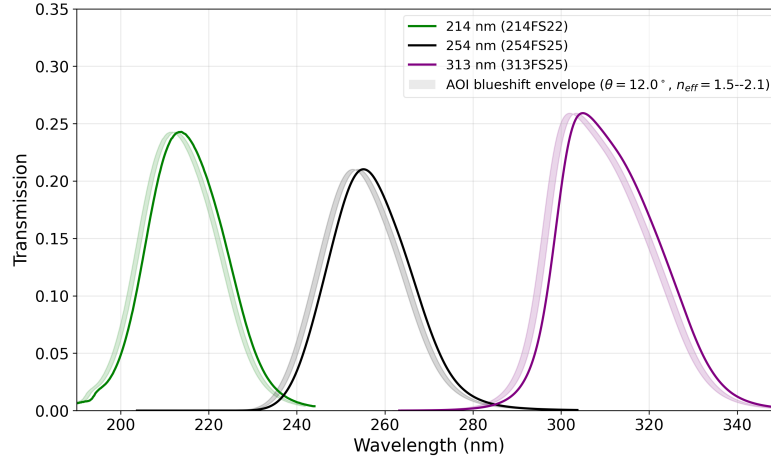


Figure 4.7: Incident angle induced blue-shift of the Andover Corporation filters [42]. An AOI of 12° is assumed, combined with an effective refractive index $n_{\text{eff}} = 1.5 - 2.1$.

The wavelength shifts are summarized in Table 4.3 for the bounds of the effective refractive index range. The values show a shift smaller than 1%. This means that the designs, even with an AOI of 12° , will not pose a major issue for the spectral selectivity.

Table 4.3: Summary table of the blue-shifted spectra of the Andover Corporation filters [42].

Filter	Centre wavelength	$n_{\text{eff}} = 1.5$	$n_{\text{eff}} = 2.1$
214FS22	214 nm	-2.07 nm	-1.05 nm
254FS25	254 nm	-2.45 nm	-1.25 nm
313FS25	313 nm	-3.02 nm	-1.54 nm

4.3 SNR estimation

4.3.1 Radiometric signal

For reliable detection, the signal generated by the optical system should be sufficiently larger than the combined noise contributions. This relation between signal and noise is known as the signal-to-noise ratio (SNR). For this thesis, an SNR requirement of 100 is proposed to keep the relative random noise below approximately 1%, while limiting the integration time and the resulting image smear. The signal on the detector can be calculated with [1, Chapter 5.4]:

$$S_e = S_p \cdot QE = \frac{E'_{s\lambda} \cdot r \cdot \cos(\sigma) \cdot A_d \cdot \Delta\lambda \cdot \lambda t_{\text{int}} \cdot QE}{\pi \cdot G\# \cdot h \cdot c} \quad \text{with} \quad G\# = \frac{1 + 4 \cdot (F/\#)^2}{\tau_t \cdot \tau_s \cdot \pi} \quad (4.3)$$

The generated electron signal is obtained by converting the incident optical radiation into photon flux and subsequently into photoelectrons. In this formulation, $E'_{s\lambda}$ denotes the spectral irradiance at the target, which includes the effects of solar illumination and propagation losses along the source–target path. The parameter r represents the spectral reflectance of the surface, describing the fraction of

incident radiation that is reflected toward the imaging system. The term $\cos(\sigma)$ accounts for the cosine projection factor associated with the solar zenith angle σ , and therefore represents the reduction in effective irradiance for non-normal illumination of the surface. The quantity A_d is the effective collecting area of the entrance pupil, which determines the amount of radiant energy intercepted by the optical system. The spectral bandwidth $\Delta\lambda$ defines the wavelength interval over which the detector integrates the incoming radiation, while λ represents the central wavelength of this band and is used to convert optical energy into photon flux through the photon energy relation. The integration time t_{int} specifies the duration over which photons are collected, thereby directly determining the accumulated signal level.

The conversion from photons to electrons is governed by the quantum efficiency (QE), which represents the fraction of incident photons that generate charge carriers in the detector. The QE is wavelength dependent and will be relatively small at UV wavelengths. The constants h and c correspond to Planck's constant and the speed of light, respectively, and together define the energy of a photon as function of wavelength. The factor $G\#$ represents the optical throughput of the system, which links the scene radiance to the irradiance at the detector plane. This term depends on the $F/\#$ of the optical system, which characterizes its light-collecting capability, as well as on the transmission efficiency τ_t of the optical system and the spectrometer transmission factor τ_{st} , which accounts for losses introduced by the diffraction grating and other spectrometer-specific elements. The normalization by π arises from the radiometric relation between radiance and irradiance in imaging systems.

Overall, this expression describes how the reflected spectral irradiance from the scene is collected by the optical system, converted into photon flux within the spectral band of interest, and ultimately transformed into an electron signal through the detector conversion process.

4.3.2 Noise

Without going into much detail, some of the most persistent noise sources will be explained. The main noise sources are divided into two categories: i) the signal noise (shot noise N_Φ) and ii) detector noise (dark N_{dark} and read noise N_e). The shot noise represents the Poisson distribution of the number of electrons generated by the discrete sampling of photons, and is estimated from the signal with Eq. 4.4 [44]:

$$N_\Phi = \sqrt{S_e} \quad (4.4)$$

Secondly, the detector noise is fully independent of the optics. It is a combination of detector dark current and read noise. The dark current I_{dark} is the rate at which thermally generated electrons are produced in the detector in the absence of incident radiation. Combined with the integration time t_{int} , the dark noise N_{dark} are be calculated using Eq. 4.5

$$N_{\text{dark}} = \sqrt{I_{\text{dark}} \cdot t_{\text{int}}} \quad (4.5)$$

Read noise refers to the electronic noise introduced during the conversion of the collected charge in a detector pixel into a measurable voltage or digital signal [44].

It is represented by N_r and expressed in electrons RMS. Using the linear noise model [44], the different noise contributions are combined in Eq. 4.6

$$N_{\text{tot}} = \sqrt{N_{\Phi}^2 + N_{\text{dark}}^2 + N_r^2} \quad (4.6)$$

Together with the signal expression in Eq. 4.3, the SNR is given by Eq. 4.7

$$\text{SNR} = \frac{S_e}{N_{\text{tot}}} = \frac{S_e}{\sqrt{N_{\Phi}^2 + N_{\text{dark}}^2 + N_r^2}} \quad (4.7)$$

4.3.3 SNR comparison between designs

An initial estimation of the SNR was included in the MIDIM project proposal [12], considering an F/8 optical system, and reporting an optical throughput of 75%. This includes 100% mirror reflectivity, 75% discrete filter transmission, and 100% energy within the pixel. In addition, a filter bandwidth of 25 nm is assumed. In practice, these throughput values are too optimistic. As was discussed in Section 4.2, a more realistic (and a bit conservative) mirror reflectivity can be estimated to be 85% across all the used wavelengths and incident angles. Secondly, the discrete filter transmissivity rarely exceeds 30% with a 25 nm filter bandwidth. Therefore, a more conservative transmissivity of 25% will be set. The encircled energy will also be considered at 80% to be consistent with the proposed requirements. Lastly, the F/# of the final designs will be used for the re-estimation of the SNR.

A summary table with the difference between the initial estimation, as present in the MIDIM proposal [12], and the updated values is given in Table 4.4. Considering the detector, the Teledyne CIS120 Back-Illuminated CMOS sensor [45] was selected. The relevant specifications are summarized in Table 4.5.

Table 4.4: Comparison between initial and final SNR estimation parameters.

Parameter	MIDIM proposal	This thesis
Mirror reflectivity	100%	85%
Filter transmissivity	75%	25%
Blazed grating throughput	100%	40%
Encircled Energy	100%	80%
Filter bandwidth	25 nm	25 nm
F/#	F/8	2D non-scanning: F/8.47 2D scanning: F/4.63 1D pushbroom: F/5.06

Table 4.5: Teledyne CIS120 Back Illuminated CMOS sensor relevant specifications [45] [46]

Parameter	Value
Pixel pitch	10 μm
Image area	20.48 $\times$ 20.48 mm
Quantum efficiency @ 300 nm [46]	10%
Dark current at 20°C	50 $\text{e}^-/\text{pixel}/\text{s}$
Readout noise	4 e^- rolling shutter 11 e^- global shutter

The SNR will be estimated for four environmental scenarios:

- Worst case scenario: low dust optical depth, low Rayleigh scattering, 70° solar zenith angle, and 0° emission (i.e., nadir)
- High dust loading scenario: high dust optical depth, large Rayleigh scattering, 45° solar zenith angle, 45° emission angle, and 90° azimuthal angle
- Low dust loading scenario: low dust optical depth, large Rayleigh scattering, 45° solar zenith angle, 45° emission angle, and 90° azimuthal angle
- Scenario with ice clouds: low dust optical depth, ice cloud optical depth of 0.2, low Rayleigh scattering, 45° solar zenith angle, 45° emission angle, and 90° azimuthal angle

A full radiometric analysis is out of the scope of this thesis. Therefore, only a correction, based on the initial estimation [12], will be given. Consider the conversion formulas given in Eq. 4.8 and 4.9

$$S_{e,n} = \frac{\Delta\lambda_n \cdot \tau_{t,n} \cdot \tau_{s,n}}{\Delta\lambda_o \cdot \tau_{t,o} \cdot \tau_{s,o}} \cdot \frac{1 + 4 \cdot (F/\#)_o^2}{1 + 4 \cdot (F/\#)_n^2} \cdot S_{e,o} = K \cdot S_{e,o} \quad (4.8)$$

$$SNR_n = \frac{S_{e,n}}{\sqrt{N_{\Phi,n}^2 + N_{\text{dark}}^2 + N_r^2}} \approx \sqrt{S_{e,n}} = \sqrt{K} \cdot \sqrt{S_{e,o}} = \sqrt{K} \cdot SNR_o \quad (4.9)$$

Only the smallest wavelength (220 nm) will be used for the estimation. This is because the smallest wavelength is the limiting factor. It has the lowest radiance value [12], thus it requires the longest integration time out of all the wavelengths.

The movement and pointing stability of the orbiter, combined with a long integration time, will cause significant image smear, enlarging the effective spatial resolution, or GSD. To achieve the scientific objectives of MIDIM, the smeared spatial resolution should remain smaller than 10 km (GSD_o without smear is 2.55 km) [12].

The groundtrack speed (GTS) of the orbiter is 0.566 km/s, and the relative pointing error (RPE) is 0.0277 km/s [12]. The enlarged spatial resolution can be calculated using Eq. 4.10

$$\text{GSD}_{\text{smear}} = \text{GSD}_o + \text{GTS} \cdot t_{\text{int}} + \text{RPE} \cdot t_{\text{int}} \quad (4.10)$$

The initial SNR estimation, as mentioned before, for 220 nm is shown in Figure 4.8. Table 4.6 summarizes the integration time and smeared spatial resolution at SNR = 100 for the different scenarios.

The initial estimation has a comfortable margin of smeared spatial resolution. However, this initial throughput estimation was made prior to the optical design and appeared to be too optimistic. Therefore, we corrected the throughput values towards the real values, considering the final presented design architectures. The SNR of the final designs is discussed in the following sections.

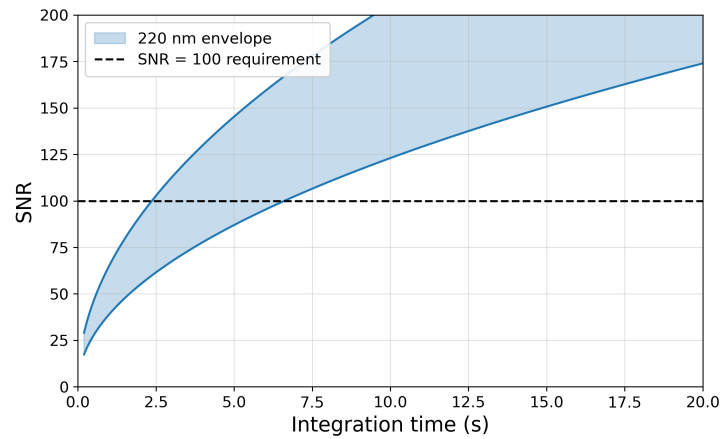


Figure 4.8: SNR envelope of the initial estimation at 220 nm. The envelope covers all environmental scenarios.

Table 4.6: Summary of the integration times and smeared spatial resolution at 220 nm, considering the different scenarios in the initial SNR estimation.

Scenario	Integration time	Spatial resolution
Large dust OD	2.37 s	3.95 km
Low dust OD	2.49 s	4.03 km
Clouds	2.78 s	4.20 km
Worst case	6.61 s	6.47 km

4.3.3.1 2D non-scanning multispectral imager

The 2D non-scanning multispectral imager is underperforming in terms of SNR. Figure 4.9 shows the SNR envelope. The system is already heavily constrained without much margin for improvement. Therefore, a reduction of $F/\#$ to increase the throughput will only be possible if system requirements are relaxed. This design is not the ideal choice in terms of SNR and spatial resolution. The integration times and smeared spatial resolutions are summarized in Table 4.7.

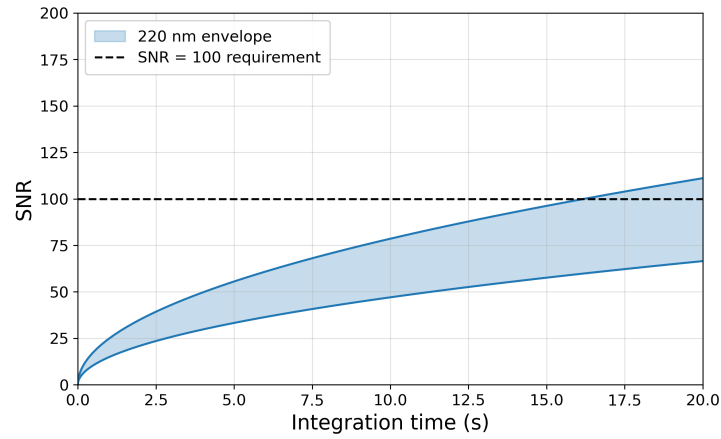


Figure 4.9: SNR envelope estimation of the 2D non-scanning multispectral imager at 220 nm. The envelope covers all environmental scenarios.

Table 4.7: Summary of the integration times and smeared spatial resolution at 220 nm of the different environmental scenarios of the 2D non-scanning multispectral imager.

Scenario	Integration time	Spatial resolution
Large dust OD	16.19 s	12.16 km
Low dust OD	17.06 s	12.67 km
Clouds	19.01 s	13.83 km
Worst case	45.20 s	29.37 km

4.3.3.2 2D scanning multispectral imager

For almost all the scenarios, the 2D scanning multispectral imager reaches the proposed resolution requirement (< 10 km). The SNR envelope of the 2D scanning multispectral imager is shown in Figure 4.10. For the worst case, the smeared resolution is slightly larger than 10 km. However, this is only for the worst case. Meaning that most of the time, the resolution will be within the requirement. Table 4.8 summarizes the integration times and the smeared spatial resolution.

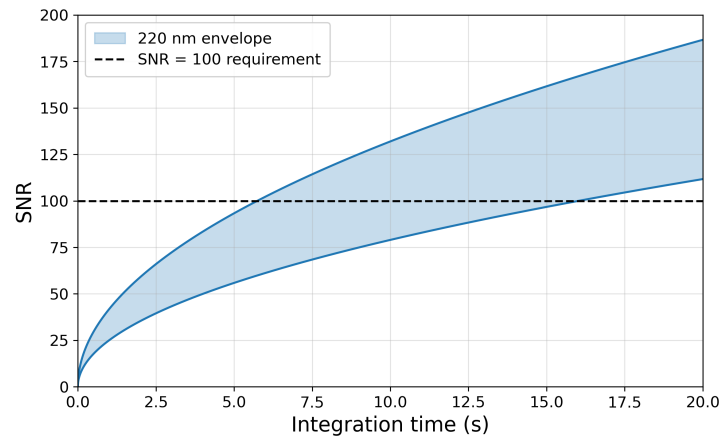


Figure 4.10: SNR envelope estimation of the 2D scanning multispectral imager at 220 nm. The envelope covers all environmental scenarios.

Table 4.8: Summary of the integration times and smeared spatial resolution at 220 nm of the different environmental scenarios of the 2D scanning multispectral imager.

Scenario	Integration time	Spatial resolution
Large dust OD	5.74 s	5.96 km
Low dust OD	6.05 s	6.14 km
Clouds	6.74 s	6.55 km
Worst case	16.02 s	12.06 km

Note that the throughput values are selected to be conservative. In practice, the overall throughput might be higher, resulting in a better spatial resolution. One of the main conservative drivers is the EE value. A value of 80% is considered to be consistent with the system specifications. However, because the system is mostly diffraction-limited. The EE inside the pixel exceeds 95% for all the fields.

In addition, the system still has some margin to reduce the $F/\#$ and achieve a higher throughput. However, as mentioned before, the distortion will be the limiting factor in the optimization. Taking all factors into account, it can be concluded that this design reaches the radiometric requirements of the project.

4.3.3.3 1D pushbroom multispectral imager

The 1D pushbroom imager reaches the proposed requirements, except for the worst-case environmental scenario. Figure 4.11 shows the SNR envelope of the 1D pushbroom multispectral imager. The reason for the underperforming worst-case scenario SNR is mainly due to the blazed grating efficiency. An efficiency of 40% was selected from off-the-shelf components [39]. However, a custom grating will likely be used. Therefore, this efficiency value might be conservative. Table 4.9 summarizes the integration times and the smeared spatial resolutions.

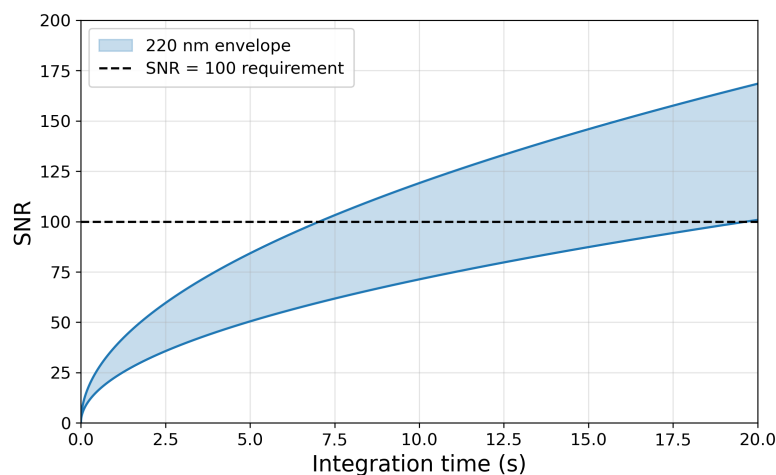


Figure 4.11: SNR envelope estimation of the 1D pushbroom multispectral imager at 220 nm. The envelope covers all environmental cases.

Table 4.9: Summary of the integration times and smeared spatial resolution at 220 nm of the different environmental scenarios of the 1D pushbroom multispectral imager.

Scenario	Integration time	Spatial resolution
Large dust OD	7.05 s	6.73 km
Low dust OD	7.42 s	6.95 km
Clouds	8.27 s	7.46 km
Worst case	19.67 s	14.22 km

Secondly, as was the case for the 2D scanning multispectral imager, the EE inside the pixel reaches more than 95% for a diffraction-limited system. Increasing the EE will reduce the integration time, and consequently the resolution smear.

Overall, the system fulfills the main practical considerations. The system specifications still provide some margin for improvement. An increase in throughput will mainly be achieved by reducing the $F/\#$, although this would require a reoptimization of the optical design to preserve image quality.

4.4 Summary

Overall, the tolerance analysis shows a clear trade-off between nominal optical performance and tolerance robustness. The 2D non-scanning and 2D scanning multispectral imagers both satisfy the P98 requirement with sufficient margin for the tolerances of Table 4.1. For both 2D imagers, the dominant tolerance contributors are the axial spacing between M3 and the detector and the axial spacing between the filter wheel and M3, both of which are significantly larger than the remaining contributors. This similarity is expected, since both multispectral imagers are based on a TMA architecture and therefore share comparable sensitivity to the spacing of the final mirror M3 and detector plane. For the 2D scanning design, the radius of curvature of M2 appears as an additional significant contributor. The 1D pushbroom multispectral imager slightly exceeds the tolerance requirement. Nevertheless, the pushbroom design also provides the best nominal performance, indicating that its limitation is not the achievable image quality, but rather its sensitivity to manufacturing and alignment tolerances. This result demonstrates that tolerance robustness is an important selection criterion in addition to nominal optical performance. The tolerance metrics are summarized in Table 4.10.

Table 4.10: Summary of the achieved tolerance metrics for the three final designs.

Parameter	Architecture 1: 2D non-scanning	Architecture 2: 2D scanning	Architecture 3: 1D pushbroom
Nominal	3.170 μm	2.126 μm	1.409 μm
Mean	3.185 μm	2.217 μm	2.570 μm
Std	0.175 μm	0.440 μm	1.034 μm
P98	3.582 μm	3.277 μm	5.387 μm
Max change	0.260 μm	0.687 μm	2.532 μm

The practical component assessment showed that suitable mirror coatings and discrete filters are available for prototyping. A broadband Al + MgF₂ coating provides sufficient reflectivity over the required UV wavelength range and has relevant space heritage. For the 2D architectures, off-the-shelf UV filters can be used during prototyping, while custom filters would likely be required for a final implementation. The estimated filter blue-shift caused by the maximum filter AOI remains below 1%, indicating that the selected filter positioning and AOI constraints do not significantly compromise the spectral selectivity. For the 1D pushbroom architecture, the diffraction grating is expected to require a custom design, since commercially available reflective gratings do not match the required specifications, particularly the groove density.

The 2D non-scanning multispectral imager design does not comply with the proposed radiometric requirements of SNR > 100, while still maintaining a spatial resolution of < 10 km. The other designs, 2D scanning multispectral and 1D pushbroom multispectral imagers, are comparable in radiometric performance. Both systems show a smeared spatial resolution better than 10 km, except when considering the worst-case environmental scenario. A summary of the integration times and the smeared spatial resolution ranges is given in Table 4.11.

Table 4.11: Summary of the SNR performances of the final designs.

Architecture	Integration time	Spatial resolution
2D non-scanning	16.19 - 45.20 s	12.16 - 29.37 km
2D scanning	5.74 - 16.02 s	5.96 - 12.06 km
1D pushbroom	7.05 - 19.67 s	6.73 - 14.22 km

Chapter 5

Conclusions

In this thesis, three freeform catoptric architectures to be used in the ultraviolet (UV) part of the Mars Imager for Dust and Ice clouds Monitoring (MIDIM) instrument are designed. The objective was to design and compare compact wide-field-of-view (WFOV) optical systems capable of observing key Martian atmospheric phenomena related to dust, ozone, and ice clouds at UV wavelengths. Key design challenges included tackling freeform optical design at UV wavelengths while still delivering kilometer-scale resolution at high orbital altitude within a compact volume. Different figures of merit were considered during the design evaluation, including requirements on field of view (FOV), ground sampling distance (GSD), spectral resolution, encircled energy (EE), distortion, modulation transfer function (MTF), volume, tolerancing, and signal-to-noise ratio (SNR).

Three multispectral architectures are proposed: i) a 2D non-scanning spectral imager, ii) a 2D scanning spectral imager, and iii) a 1D pushbroom spectral imager. All three concepts are successfully optimized using off-axis reflective freeform optics and are shown to satisfy the main nominal optical performance requirements. In all cases, the GSD near 2.55 km is achieved, while the EE exceeded 80% within one detector pixel (10 μm), the distortion remains below the proposed 10% limit, and the MTF remains above 0.5 at the detector Nyquist frequency ($f_{\text{det}} = 50 \text{ cycles/mm}$), all within the proposed volume constraints ($\leq 220 \times 200 \times 150 \text{ mm}^3$).

2D non-scanning multispectral imager

The 2D non-scanning multispectral imager provides the snapshot observation concept because it captures the full $48^\circ \times 48^\circ$ FOV without requiring a scanning mechanism (Figure 5.1). It also has the lowest expected system complexity from an acquisition and reconstruction point of view, providing a less complex mechanical assembly (fewer moving parts) and post-processing. In contrast, it is the most constrained system from an optical design point of view. The wide FOV in both X and Y dimensions, in combination with the UV operation wavelengths, makes this design particularly challenging. The proposed specifications were met, but without a significant margin compared to the 2D scanning (Section 3.4) and 1D pushbroom designs (Section 3.5). The large two-dimensional FOV complicates distortion reduction, detector mapping, volume compliance, and filter angle-of-incidence (AOI) control. Although the final design meets the optical specifications, it operates close to the imposed limits, with a distortion of 9.09% and an F-number of F/8.47. The SNR analysis shows that this architecture performs weakest radiometrically, especially at 220 nm, leading to long integration times (best case = 16.19 s).

and significant spatial smear (best case = 12.16 km). Therefore, while the 2D non-scanning architecture is feasible from a nominal optical design perspective (Section 3.3), its practical implementation might be hampered by its radiometric performance and resulting spatial resolution (Section 4.3.3.1).

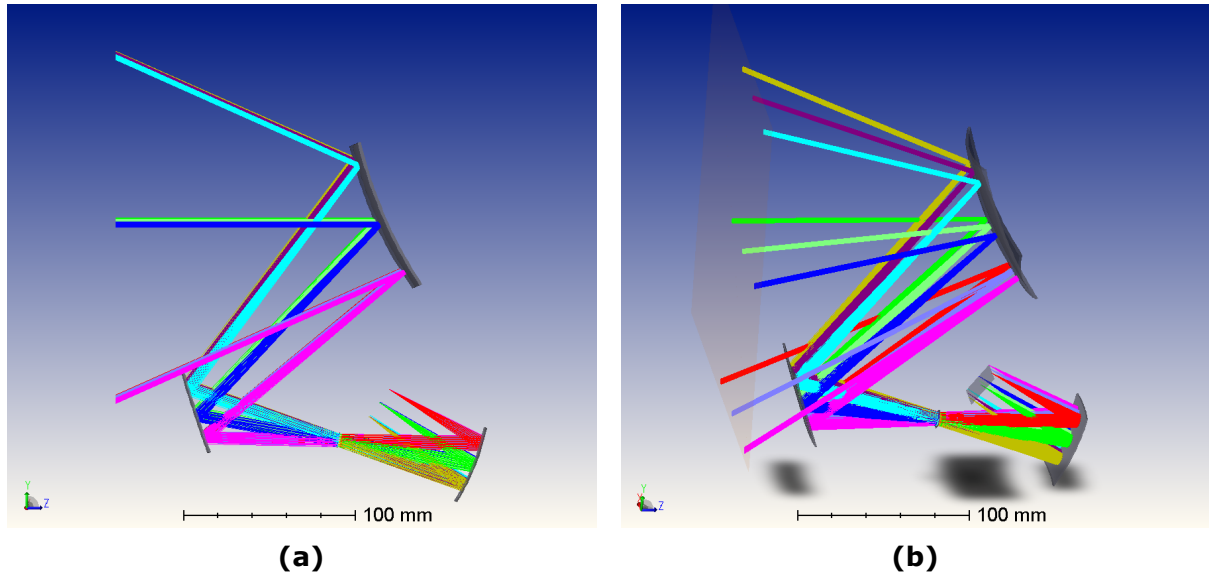


Figure 5.1: Final 3D model of the 2D non-scanning multispectral imager: (a) side view. (b) top view.

2D scanning multispectral imager

The 2D scanning multispectral imager offers a better compromise (Figure 5.2). By reducing the FOV to $48^\circ \times 10^\circ$ and using a scan mirror to cover the remaining spatial dimension, its optical parameters, such as freeform orders and tilt angles, become less constrained compared to the 2D non-scanning design (Section 3.3). Two design alternatives were proposed, resulting from an optimization towards light throughput: i) an F/8 design and ii) a faster F/4.5 design. This comparison provides insight into the influence of the F/# on the optical system. The initial F/8 design showed a significant margin relative to the proposed requirements, allowing the system to be further optimized towards a more radiometrically favorable configuration.

The F/8 design achieved diffraction-limited performance with large margins, while the F/4.5 design remained detector-limited despite not being diffraction-limited for all fields. The faster design achieved an MTF of at least 0.91 at the Nyquist frequency, 80% encircled energy within $2.15 \mu\text{m}$, and distortion of 7.30%, while enabling the enlargement of the optical throughput by a factor of 3. Based on an SNR analysis, it was validated that the F/4.5 design meets the spatial-resolution requirement for most atmospheric scenarios (5.96 - 6.55 km), except for the worst-case scenario with low dust optical depth, low Rayleigh scattering, a 70° solar zenith angle, and nadir viewing, which is the most conservative case considered (12.06 km). Its main disadvantages are the added scan mirror, mechanical complexity, temporal acquisition, and post-processing requirements. Nevertheless, among the multispectral concepts (Section 3.3 and Section 3.4), the 2D scanning architecture provides the best nominal GSD (2.50 km) with the smallest smeared spatial resolution (5.96 - 12.06 km) for an SNR = 100.

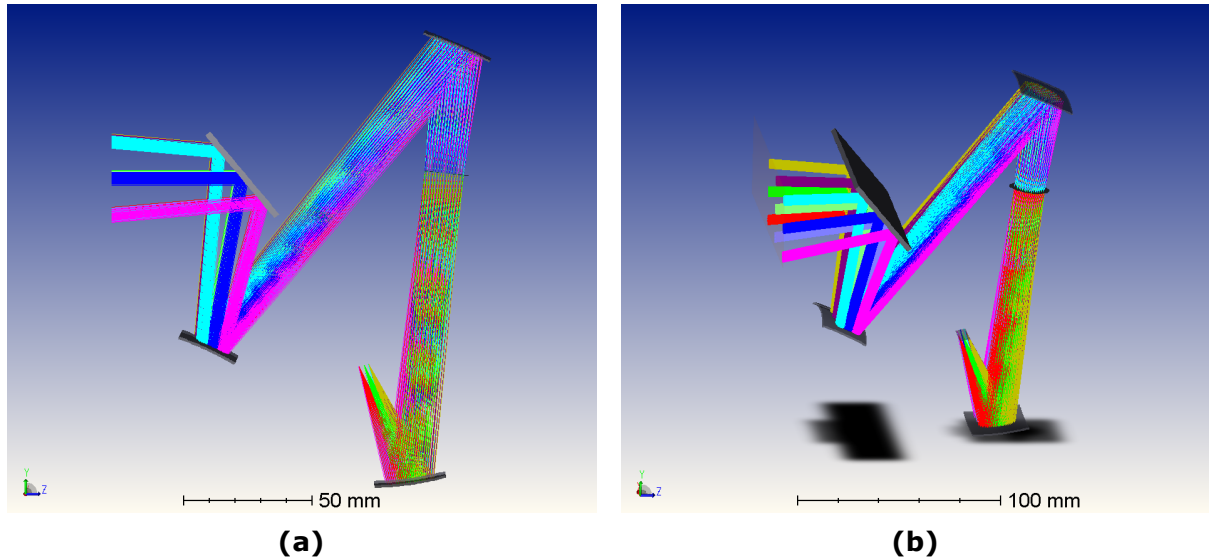


Figure 5.2: Final 3D model of the 2D scanning multispectral imager for F/4.5: (a) side view. (b) top view.

1D pushbroom multispectral imager

The 1D pushbroom multispectral imager provides the most extended spectral capability (Figure 5.3). It captures a one-dimensional line with an FOV of $48^\circ \times 0.03^\circ$ in a single spatial dimension (Section 1.1.2.1). Unlike the multispectral designs (Section 3.3 and Section 3.4), it does not rely on discrete filters but uses a diffraction grating to disperse the UV spectrum. The final design showed a spectral resolution of approximately 21 nm, within the 195 - 345 nm wavelength range, which meets the target specification of max 25 nm. It also achieved strong nominal image quality, with MTF values above 0.93 across the considered wavelength range, and 80% encircled energy ($< 2 \mu\text{m}$) well within one pixel size ($10 \mu\text{m}$). Its compact optical layout is another advantage, with the optimized UV channel occupying only a small fraction of the allowed volume. However, this architecture comprises a larger number of optical components (featuring 5 freeform mirrors), and shows the lowest tolerance robustness. The Monte Carlo tolerance analysis indicated that the P98 value of the 80 % encircled energy radius slightly exceeds the $5 \mu\text{m}$ requirement. This sensitivity is mainly caused by the compact geometry, short inter-component distances, and strong coupling between alignment errors and optical performance. The SNR performance is better than the 2D non-scanning architecture and comparable to the scanning architecture, although the worst-case scenario still exceeds the desired spatial-resolution limit ($14.22 \mu\text{m}$).

Practical feasibility assessment

The preliminary tolerance analysis shows that both 2D architectures, namely the 2D non-scanning design (Section 4.1.1) and the 2D scanning design (Section 4.1.2), are robust against the applied manufacturing and alignment tolerances. In both cases, the P98 encircled-energy radius remains below the required $5 \mu\text{m}$ limit. Among these two multispectral designs, the 2D non-scanning architecture is the least sensitive to the applied tolerances, while the 2D scanning architecture also

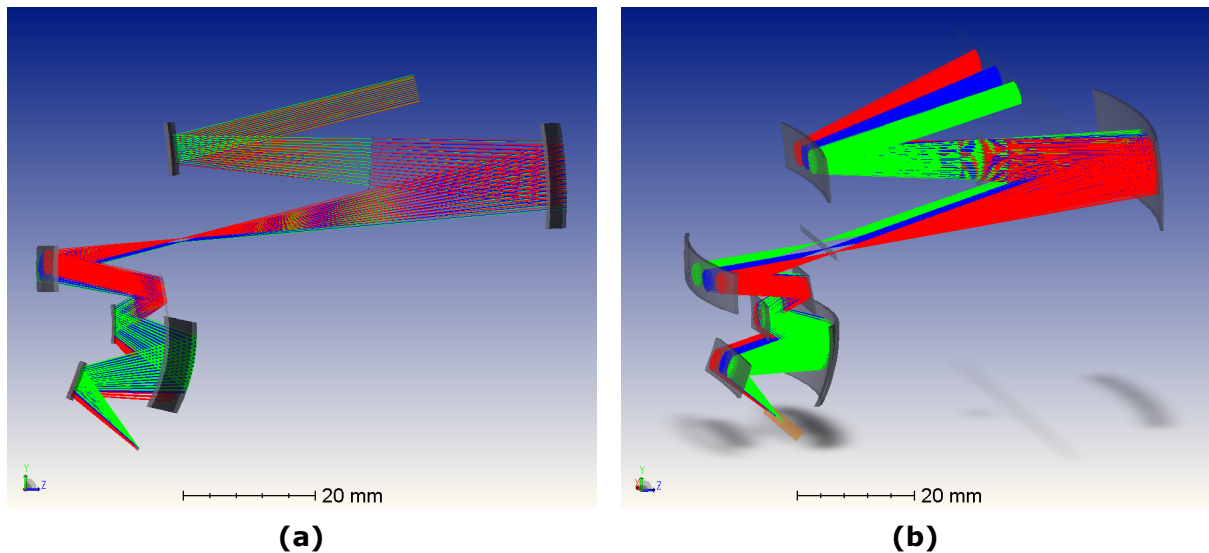


Figure 5.3: Final 3D model of the 1D pushbroom multispectral imager: (a) side view. (b) top view.

remains comfortably compliant. By contrast, the 1D pushbroom multispectral design (Section 4.1.3), although it has the best nominal performance, showed the highest sensitivity to the applied tolerances. Therefore, the tolerance results further emphasize the importance of considering manufacturability and alignment robustness alongside nominal image quality when comparing the proposed architectures.

The practical implementation and SNR analysis show that UV throughput is one of the dominant design limitations. The light throughput and corresponding measurement integration times were evaluated for each of the configurations, considering conservative component assumptions, including 85% mirror reflectivity, 25% filter transmission, 40% grating efficiency, and 80% encircled energy. The 220 nm channel is shown to be the limiting case for the multispectral imagers. The 2D non-scanning architecture (Section 4.3.3.1) requires integration times between approximately 16 s and 45 s, resulting in spatial resolutions between roughly 12 km and 29 km. The 2D scanning architecture (Section 4.3.3.2) shows the largest throughput, corresponding to a spatial resolution of 6 km to 12 km, while the 1D pushbroom architecture (Section 4.3.3.3) achieves approximately 7 km to 14 km. Therefore, the 2D scanning and 1D pushbroom architectures are more promising from a radiometric and spatial-resolution perspective.

Overall, the results show that all three proposed architectures are feasible in terms of nominal optical design. However, their practical suitability depends on the mission priority. If full-frame imaging without scanning is the main priority, the 2D non-scanning multispectral imager (Section 3.3) is the most straightforward solution, but it has a limited radiometric margin. If the best compromise between optical performance, radiometric performance, and practical feasibility is required, the 2D scanning multispectral imager (Section 3.4) is the preferred architecture. If spectral flexibility and improved spectral sampling are more important than tolerance robustness and component simplicity, the 1D pushbroom multispectral imager (Section 3.5) is the most attractive concept.

Conclusion

This thesis provides three novel WFOV UV multispectral imagers with a kilometer-scale resolution at a high altitude in a compact volume, fulfilling the specific thesis objectives. Broadband UV operation is achieved by using a catoptric optical design instead of refractive optics, thus eliminating chromatic aberration. Secondly, using freeform surface descriptions enables increasing the number of degrees of freedom in the design, thus allowing a WFOV optical design inside a compact volume. Manufacturability and radiometric feasibility are addressed by performing a preliminary tolerance analysis, revealing the robustness of the three designs, and an SNR estimation based on off-the-shelf optical components to assess the radiometric performance of each design. Table 5.1 gives a comparison between the three novel multispectral imagers.

Table 5.1: High-level qualitative comparison of the three proposed imaging architectures based on the main optical and practical design criteria discussed in this thesis. The symbols indicate the relative performance of each design, ranging from strong disadvantage (-), disadvantage (-), neutral or balanced (+/-), advantage (+), to strong advantage (++).

	Design 1: 2D non-scanning	Design 2: 2D scanning	Design 3: 1D pushbroom
UV operation	++	++	++
Resolution	+/-	++	+
Distortion	-	+/-	+/-
Volume	- -	+/-	++
Diffraction-limited	+/-	+	++
Freeform order	+/-	+	+
Tolerance robustness	++	+	-
SNR performance	- -	+	+

Novelty of this work. To the best of our knowledge, this thesis presents for the first time three compact wide-field-of-view UV spectral imaging architectures based on freeform reflective optics for Mars climate monitoring. The novelty lies in the combination of i) a fully reflective UV-compatible optical design, ii) wide-field spectral imaging in compact instrument envelopes, and iii) the use of freeform surfaces to control aberrations, distortion, and packaging constraints. In addition to the nominal optical design, the architectures are compared on tolerance robustness, practical implementation, and radiometric performance, providing a complete design-for-manufacturing assessment of this previously unexplored design space.

Future work

Several steps are required before a final MIDIM optical architecture can be selected and developed further.

First, a final design optimization step is advised, using a tolerance-driven optimization, since this might reduce the design sensitivity further. This is especially important for the 1D pushbroom multispectral imager, which slightly exceeds the proposed P98 tolerance requirement. The tolerance model should also be refined by treating the freeform-surface irregularity with a more representative ISO 10110-5-based description [37], rather than the simplified spherical and astigmatism (S + A) irregularity used in the present analysis.

Second, the diffraction grating for the pushbroom architecture should be developed in more detail. In this thesis, the grating was idealized and described by its groove density and dispersion behavior. A future design should include blaze angle optimization, diffraction efficiency, manufacturing constraints, and stray light considerations. This asks for more advanced physical optics simulations (using e.g., VirtualLab) that are outside of the scope of the current thesis work.

Third, the filter implementation for the multispectral architectures should be studied in-depth. Although suitable commercial or custom filters were identified, their actual transmission, angular sensitivity, thermal behavior, radiation stability, and out-of-band rejection should be verified experimentally. This is particularly relevant for the 2D scanning and non-scanning architectures, where the angle of incidence on the filters directly affects the spectral response.

Fourth, stray-light and baffling analyses should be performed. Since MIDIM observes in the ultraviolet and targets weak radiometric signals, stray light may become a critical performance driver. In the 1D pushbroom architecture, the diffraction grating is an additional potential source of stray light and scattering. Future work should therefore include non-sequential ray tracing, ghost analysis, scattering from mirror surfaces and the diffraction grating, and suppression of out-of-field radiation. Such an analysis is expected to be particularly important and challenging in the UV wavelength range, where optical performance is highly sensitive to surface defects, contamination, and microroughness, all of which can significantly increase scattering.

Fifth, the mechanical and thermal design should be integrated with the optical model. The designs in this thesis were evaluated mainly from an optical design perspective. A realistic spaceborne implementation requires structural support, thermal stability, launch-load resistance, alignment interfaces, detector electronics, filter-wheel or scan-mirror mechanisms, and calibration hardware. These elements may affect the available volume, mass, and alignment stability.

Finally, the architecture selection should be supported by a full mission-level trade-off. The 2D non-scanning imager offers acquisition simplicity, the 2D scanning imager offers the best overall compromise, and the 1D pushbroom imager offers the strongest spectral capability. A final decision should therefore include not only optical performance, but also mission operations, data processing, reliability, calibration complexity, mass, power, and cost.

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List of Abbreviations

AOI	Angle of Incidence
AR	Anti-Reflective
CCD	Charge-Coupled Device
CMOS	Complementary Metal-Oxide-Semiconductor
DEE	Diffraction Encircled Energy
ECO	Earth Climate Observatory
EE	Encircled Energy
EFL	Effective Focal Length
EPD	Entrance Pupil Diameter
FOV	Field of View
FUV	Far-Ultraviolet
FWHM	Full Width at Half Maximum
GSD	Ground Sampling Distance
GTS	Ground-Track Speed
IR	Infrared
MAVEN/IUVS	Mars Atmosphere and Volatile Evolution/Imaging Ultraviolet Spectrograph
MC	Monte Carlo
MIDIM	Mars Imager for Dust and Ice Clouds Monitoring
MRO/MARCI	Mars Reconnaissance Orbiter/Mars Color Imager
MTF	Modulation Transfer Function
MUV	Mid-Ultraviolet
NIR	Near-Infrared
OPD	Optical Path Difference
OTF	Optical Transfer Function
PSF	Point Spread Function
QE	Quantum Efficiency
RMS	Root Mean Square
RPE	Relative Pointing Error
SNR	Signal-to-Noise Ratio

SPICAM	Spectroscopy for the Investigation of the Characteristics of the Atmosphere of Mars
TMA	Three-Mirror Anastigmat
UV	Ultraviolet
VIS	Visible
VUB	Vrije Universiteit Brussel
WFOV	Wide Field of View