

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

**MULTI-SPECTRAL OPTICAL SYSTEM DESIGN AND
ANALYSIS FOR DEFENSE AND SURVEILLANCE
APPLICATIONS**

ÖMER ÖZTÜRK

**A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF PHYSICS**

ADVISOR: PROF. DR. NURCAN DOĞAN BİNGÖLBALİ

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GEBZE TEKNİK ÜNİVERSİTESİ
LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

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*With gratitude, to my spouse, the
inspiration of my life, and to my nation,
which renews my faith in the future...*

ABSTRACT

This thesis presents the optical design, performance evaluation and analysis of a Cassegrain structured multi-spectral imaging system combining visible (VIS), short-wave infrared (SWIR) and mid-wave infrared (MWIR) channels through a common entrance aperture. The aim is to develop a compact, lightweight and high-performance optical system optimized for gimbal platforms in aerospace and defense applications. The proposed architecture addresses critical challenges such as resolution, thermal robustness, optical alignment and manufacturability in multi-spectral electro-optic systems.

Optical modeling and optimization were performed using Zemax OpticStudio. Key system parameters such as focal length, entrance pupil diameter and optical material selection were carefully refined to meet image quality requirements across all spectral bands. Performance metrics such as Modulation Transfer Function (MTF), Spot Diagram analysis and Airy disk evaluation were used to evaluate the spatial resolution and aberration control of the system.

The VIS and SWIR channels are designed to share a common diffraction path with late-stage spectral separation, while the MWIR channel operates with an independent optical configuration optimized for the 3–5 μm range. Thermal tolerance studies have also been conducted for environmental robustness.

The resulting system demonstrates high optical quality, reduced size and weight, and suitability for integration into next-generation multispectral gimbal systems. This work contributes to the advancement of compact, high-resolution multispectral imaging solutions for airborne ISR (Intelligence, Surveillance and Reconnaissance), border security, and industrial inspection applications.

Keywords: MWIR, SWIR, Visible, Cassegrain, ZEMAX, MTF.

ÖZET

Bu tez, görünür (VIS), kısa dalga kızılötesi (SWIR) ve orta dalga kızılötesi (MWIR) bantlarını ortak bir giriş açıklığı üzerinden birleştiren Cassegrain yapısına sahip çok bantlı bir görüntüleme sisteminin optik tasarımını, performans değerlendirmesini ve analizini sunmaktadır. Çalışmanın amacı, havacılık ve savunma uygulamalarına yönelik gimbal platformları için optimize edilmiş, kompakt, hafif ve yüksek performanslı bir optik sistem geliştirmektir. Önerilen mimari, çok bantlı elektro-optik sistemlerde karşılaşılan çözünürlük, termal dayanıklılık, optik hizalama ve üretilebilirlik gibi kritik zorluklara çözüm sunmayı hedeflemektedir.

Optik modelleme ve optimizasyon çalışmaları Zemax OpticStudio yazılımı kullanılarak gerçekleştirilmiştir. Odak uzaklığı, giriş açıklığı çapı ve optik malzeme seçimi gibi temel sistem parametreleri, tüm spektral bantlarda görüntü kalitesi gereksinimlerini karşılayacak şekilde titizlikle optimize edilmiştir. Modülasyon Transfer Fonksiyonu (MTF), Nokta Diyagramı (Spot Diagram) analizi ve Airy disk değerlendirmesi gibi performans metrikleri, sistemin uzamsal çözünürlüğünü ve aberasyon kontrolünü değerlendirmek amacıyla kullanılmıştır.

VIS ve SWIR kanalları, geç ayırıştırırmalı ortak bir kırıcı optik yol üzerinden çalışacak şekilde tasarlanmışken, MWIR kanalı ise 3–5 μm spektral aralığına özel olarak optimize edilmiş bağımsız bir optik yapı ile çalışmaktadır. Ayrıca, çevresel dayanıklılığı sağlamak amacıyla sistemin termal tolerans analizleri de gerçekleştirilmiştir.

Ortaya çıkan sistem; yüksek optik kalite, azaltılmış boyut ve ağırlık ile yeni nesil çok bantlı gimbal sistemlerine entegrasyon için uygunluk sergilemektedir. Bu çalışma, hava platformlarında keşif, gözetleme ve istihbarat (ISR), sınır güvenliği ve endüstriyel denetim uygulamaları için kompakt ve yüksek çözünürlüklü çok bantlı görüntüleme çözümlerinin geliştirilmesine katkı sağlamaktadır.

Anahtar Kelimeler: MWIR, SWIR, Visible, Cassegrain, ZEMAX, MTF.

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LIST OF SYMBOLS AND ABBREVIATIONS

λ	: Wavelength
VIS	: Visible
MWIR	: Mid wave infrared
a, b	: Sensor width (a), sensor height (b)
Å	: Angstrom
α	: Coefficient of thermal expansion
AS	: Aperture stop
BFL	: Back focal length
c	: Speed of light
CCD	: Charge Coupled Device
CMOS	: Complementary Metal-Oxide Semiconductor
CTE	: Coefficient of thermal expansion
d_{airy}	: Airy disk diameter
D_{Enp}	: Entrance pupil diameter
DOF	: Depth of field
EFL / f	: Effective focal length / Focal length
F	: Focal point
F/#	: F-number (relative aperture)
FOV	: Field of View
FOV_H	: Horizontal field of view
FOV_V	: Vertical field of view
FOV_D	: Diagonal field of view
FS	: Field stop
H	: Principal points
ISR	: Intelligence, Surveillance, Reconnaissance
k	: Conic constant
LDE	: Lens Data Editor
LED	: Light Emitting Diode
MTF	: Modulation Transfer Function
MWIR	: Mid-Wave Infrared
n	: Refractive index
N	: Nodal points
N-BK7	: Optical glass
NIR	: Near-Infrared
nm	: Nanometer
OPD	: Optical Path Difference
OPL	: Optical Path Length
P	: Principal points
R1, R2	: Radii of curvature
SNR	: Signal-to-Noise Ratio
SPDT	: Single Point Diamond Turning
SWIR	: Short-Wave Infrared
t	: Thickness
d	: Distance between surfaces
V_D	: Abbe number (material dispersion)
ΔT	: Temperature change

dn/dt	: Thermo-optic coefficient
μm	: Micrometer
n_d, n_F, n_C	: Refractive indices at d, F, C spectral lines
θ_1, θ_2	: Incident/refraction angles
CSH	: Cold Shield Height

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1. INTRODUCTION

Optical imaging systems play a vital role across a wide range of applications, including defense and aerospace, biomedical imaging, and industrial inspection. The primary objective of such systems is to capture and resolve objects within a defined field of view (FOV) while ensuring adequate resolution and image quality. The ability to distinguish fine visual details depends on several parameters, such as aperture size, optical aberrations, and detector characteristics [1].

This thesis focuses on the optical design and analysis of a common-aperture multispectral camera system operating across the MWIR (Mid-Wave Infrared), SWIR (Short-Wave Infrared), and visible (VIS) spectral bands. These multispectral systems offer significant advantages in tasks such as target detection and identification by enabling the simultaneous imaging of different wavelength bands. However, designing such systems introduces several engineering challenges, including the management of chromatic aberrations, maintaining high resolution across all spectral bands, and ensuring manufacturability under practical constraints.

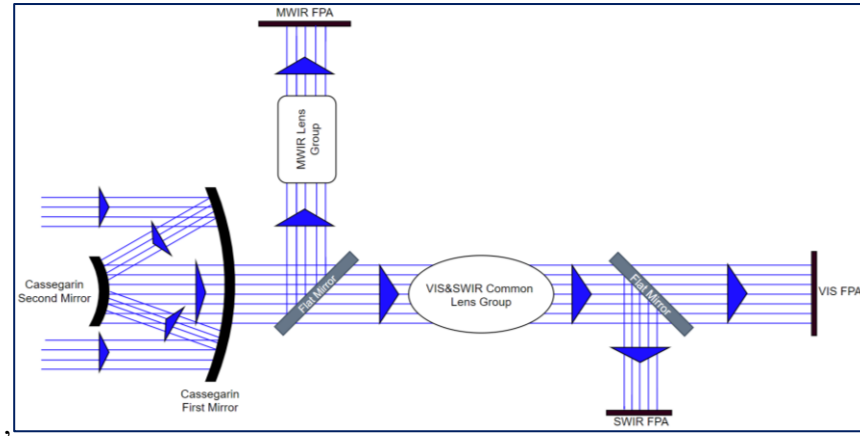


Figure 1.1: Schematic Diagram of the Common-Aperture Optical System for MWIR, SWIR, and VIS Spectral Bands.

Figure 1.1 above illustrates the initial conceptual schematic layout of the optical system developed in this thesis. The design incorporates a Cassegrain telescope configuration to collect the scene image, which is subsequently directed to three distinct spectral channels MWIR, SWIR, and VIS with reflective folding mirrors.

While the VIS and SWIR channels share a common lens group, the MWIR channel utilizes a separate optical path and lens configuration.

In such multispectral systems, resolution limits are determined by both diffraction and the pixel size of the detector. Therefore, achieving an optimal match between the optical resolution and the detector's pixel pitch is of critical importance. Key design parameters such as focal length, F-number, and entrance pupil diameter must be carefully selected to meet these performance requirements. Moreover, the selection of optical materials must account for refractive and transmission properties across the targeted spectral bands.

To enhance image quality and control optical aberrations, multi-element lens configurations are employed, often incorporating aspherical surfaces when necessary. In common-aperture system designs, achieving accurate spectral alignment is especially crucial, which makes the use of achromatic and apochromatic lens groups highly beneficial.

The design and optimization processes in this thesis are conducted using advanced optical simulation software, specifically Zemax OpticStudio. Performance analysis includes metrics such as spot diagrams, Modulation Transfer Function (MTF), field curvature, and optical path difference (OPD), all of which are evaluated to ensure compliance with system requirements.



Figure 1.2: A face imaged in the (a) Visible camera, (b) SWIR camera, (c) MWIR camera [2].

Beyond optical performance, mechanical robustness and thermal stability are also considered to guarantee reliable operation in real-world conditions. This thesis presents a comprehensive approach to the design and optimization of high-performance multispectral optical systems, aiming to contribute both theoretically and practically to the field of optical engineering.

2. OPTICAL CONCEPTS

2.1 Electro Magnetic Spectrum

Optics and the electromagnetic spectrum encompass cover a range of wavelengths, including both visible and invisible forms of light. Traditionally, optics focused on light visible to the human eye, however, modern applications have expanded to include infrared and ultraviolet regions. The full electromagnetic spectrum spans from high-energy cosmic rays to low-energy radio waves. While all electromagnetic waves travel through a vacuum at a constant speed ($c = 2,998 \times 10^{10} \text{ cm/s}$), their behaviors change depending on their wavelength.

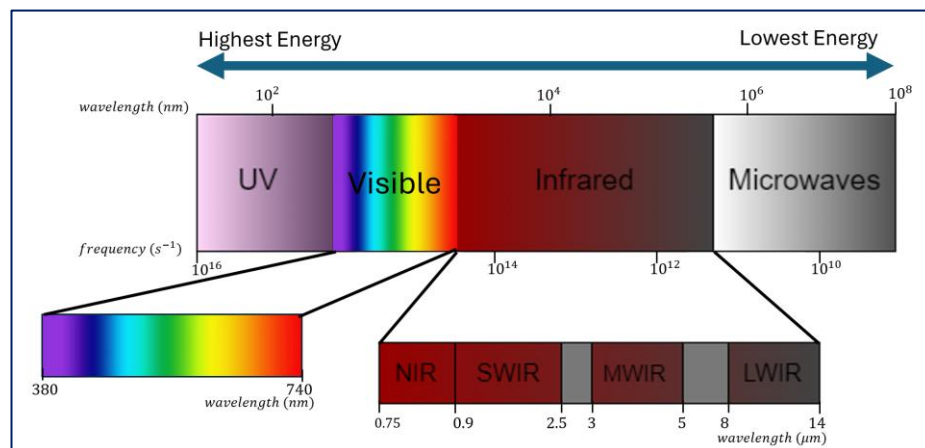


Figure 2.1: Electromagnetic spectrum.

The optical range, which lies between these extremes, displays both wave-like and particle-like characteristics, a phenomenon described by the wave-particle duality of light. For example, gamma rays, with shorter wavelengths, primarily behave as photons, while radio waves, with longer wavelengths, predominantly exhibit wave properties. The visible spectrum is a very small portion of the electromagnetic spectrum, covering wavelengths from approximately violet ($0.4 \mu\text{m}$) to red ($0.76 \mu\text{m}$). Beyond the red end of the visible range is the infrared region, which transitions into the microwave spectrum, extending down to about one millimeter. At the lower end of the visible range is the ultraviolet region begins just below $0.4 \mu\text{m}$ and extends to

approximately 0.01 μm . Below 0.01 μm , the spectrum enters the x-ray region. Each region of the electromagnetic spectrum has unique physical effects due to the varying energies of the photons. For instance, gamma rays can ionize biological tissues, breaking chemical bonds, while radio waves do not have this effect.

Optical wavelengths are usually measured in angstroms ($\text{\AA}$), nanometers (nm), or micrometers (μm). One micrometer equals one-millionth of a meter and one angstrom is equal to one ten-thousandth of a micron. Frequency is derived by dividing the speed of light by the wavelength, and the wave number, commonly expressed in cm^{-1} , is the inverse of the wavelength. Both frequency and wave number are standard metrics for describing optical radiation. To better understand the behavior of electromagnetic waves, the relationship between wavelength (λ) and frequency (f) can be described by the equation:

$$c = \lambda \cdot f \tag{2.1}$$

where c is the speed of light, λ is the wavelength, and f is the frequency. While the speed of electromagnetic waves remains constant in a vacuum, their frequency and energy vary with changes in wavelength.

2.2 Refractive Index

The refractive index is a fundamental optical property that describes how light changes its direction and speed when transitioning between different media. This phenomenon, known as refraction, occurs when light interacts with materials, such as when a light ray passes through the surface of a lens. The refractive index is crucial for understanding how light bends at the interface between different media and is a key parameter in optical design. The refractive index, denoted as $n(\lambda)$ depends on the wavelength λ and this wavelength dependence is critical in many optical applications. Different wavelengths are refracted by different amounts, which affects the performance of optical systems across the spectrum. The refractive index of a material is modeled using several empirical formulas, such as the Schott, Sellmeier, and Herzberger equations. These models help predict the refractive index for specific wavelengths of light.

The Schott formula is an empirical model that developed by Schott AG, a Germany-based optical glass manufacturer, to express the refractive index as a polynomial function of wavelength. This formula is widely used in the optical industry, particularly for characterizing optical materials like glasses. The refractive index in this model is expressed as:

$$n(\lambda)^2 = a_0 + a_1\lambda^2 + a_2\lambda^{-2} + a_3\lambda^{-4} + a_4\lambda^{-6} + a_5\lambda^{-8} \quad (2.2)$$

where $a_0, a_1, a_2, \dots, a_5$ are material-specific constants and λ is the wavelength of light. These constants are determined empirically for each type of optical glass, allowing precise control over how light interacts with the material at different wavelengths [3].

When designing a multi-spectral camera system operating in the Visible, SWIR, and MWIR bands, it is crucial to account for the wavelength-dependent variation of the refractive index. Different materials exhibit unique optical properties in these spectral regions, and refractive index models are indispensable for selecting the appropriate lens materials. Since the refractive index affects the refraction, dispersion, and focusing of light, these models ensure that the right material is chosen to optimize system performance. The Schott formula plays a pivotal role in this process by allowing for the precise analysis of light refraction at different wavelengths. This is especially important in high-precision systems, such as multi-band camera designs, where optimal performance across multiple spectral bands must be ensured. The ability to select materials with the correct refractive properties is essential to minimizing distortions and maximizing the efficiency and clarity of the optical system.

Therefore, it plays a vital role in the development of high-precision multi-band camera systems. Therefore, the Schott formula, along with other refractive index models, is vital in the development of multi-spectral camera systems, lens design, and optical performance optimization.

2.3 Abbe Number

The Abbe number (V or ν) is a key optical parameter that quantifies the chromatic dispersion of a material, essentially, how much the material spreads different wavelengths of light as they pass through it. A higher Abbe number indicates lower

dispersion, meaning the material causes less separation of colors, while a lower Abbe number corresponds to higher dispersion, leading to more pronounced color spreading. This characteristic is especially critical in precision optical systems where minimizing chromatic aberration is essential.

When designing a multi-spectral camera system operating across the Visible, SWIR, and MWIR bands, both the Abbe number and the refractive index must be carefully considered to optimize optical performance. These parameters help determine the best combination of materials to minimize image distortion, color fringing, and focus shift across different spectral bands.

The Abbe number (V_D) is traditionally calculated using the refractive indices at three specific Fraunhofer spectral lines in the visible spectrum:

The formula for the Abbe number is:

$$V_D = \frac{n_D - 1}{n_F - n_C} \quad (2.3)$$

where:

- n_D is the refractive index at the d-line (587.6 nm, Helium),
- n_F is the refractive index at the F-line (486.1 nm, Hydrogen),
- n_C is the refractive index at the C-line (656.3 nm, Hydrogen).

This formula provides a measure of the material's dispersion in the visible spectrum. However, for applications extending into the SWIR and MWIR regions, modified or alternative dispersion parameters are often used, as the traditional Abbe number is limited to visible wavelengths. In such cases, material manufacturers may provide extended dispersion data or infrared Abbe numbers based on wavelengths more relevant to those spectral bands.

Selecting materials with appropriate Abbe numbers and refractive indices ensures that optical components maintain consistent focal lengths and minimal chromatic aberration across multiple wavelength regions—crucial for multi-band imaging systems such as remote sensing instruments, surveillance optics, and scientific cameras.

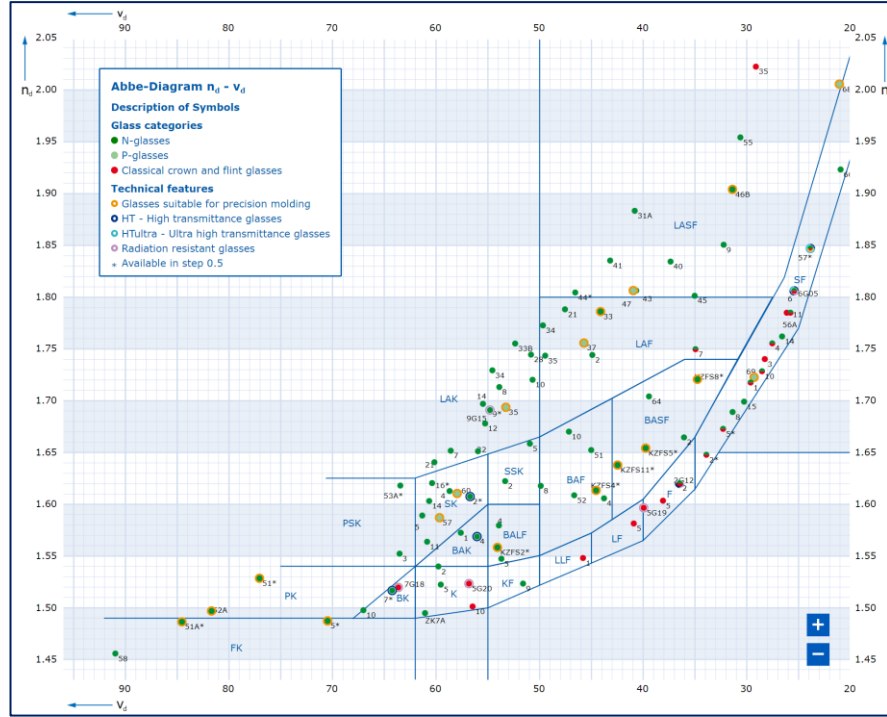


Figure 2.2: Schott glass index versus Abbe number diagram [4].

In optical design, choosing the right lens material requires balancing refractive index and dispersion. Abbe diagrams (glass maps) illustrate the inverse relationship between refractive index and Abbe number, showing that high-index materials generally have lower Abbe numbers. This relationship is critical for minimizing chromatic aberration and selecting appropriate materials in multi-spectral optical systems. For example, SCHOTT's refractive index versus abbe number diagram is shown in **Figure 2.2**.

2.4 Snell's Law

Snell's Law governs the refraction of an optical ray as it passes between two media with different refractive indices. It is as a fundamental principle in geometric optics, explaining how the direction of a light changes at the boundry between two materials due to the difference in the speed of light in each medium. This change in direction is a direct consequence of the conservation of energy and momentum at the optical interface. The mathematical expression of Snell's Law is given as:

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \quad (2.4)$$

Where, n_1 and n_2 represent the refractive indices of the initial and secondary media, respectively, while θ_1 is the angle of incidence and θ_2 is the angle of refraction, both measured relative to the surface normal at the point of interaction. This relationship shows that light bends toward the normal when entering a medium with a higher refractive index ($n_2 > n_1$), and away from the normal when entering a medium with a lower refractive index ($n_2 < n_1$). The extent of bending depends on both the incident angle and the relative refractive indices of the two media [5].

Snell's Law is essential for designing a wide range of optical components, including lenses, prisms, optical fibers, and multi-element imaging systems. It allows optical engineers to predict and control the path of light rays as they traverse interfaces between different materials, which is critical for achieving desired focusing, imaging, and beam steering characteristics.

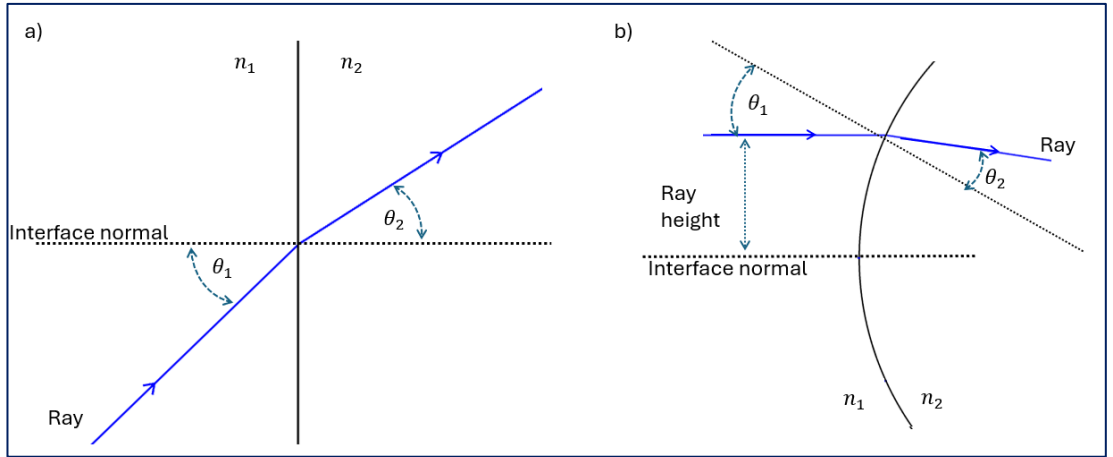


Figure 2.3: Refraction of an optical ray, at two different interfaces: a) A planar interface where $n_1 < n_2$ when. b) A spherical interface with the same refractive index condition $n_1 < n_2$.

In multi-spectral systems, where multiple wavelengths are involved, Snell's Law must be applied wavelength-by-wavelength, since the refractive index varies with wavelength (i.e., dispersion). Accurate modeling of refraction across spectral bands is thus necessary to maintain alignment and image quality in complex optical system

Figure 2.3 illustrates how planar and spherical optical surfaces alter the path of a ray through refraction.

2.5 Optical Axis and Focal Points

The optical axis of a lens or optical system is defined as the line that passes through the center of curvature of all optical surfaces and represents the axis rotational symmetry. It serves as a fundamental reference line for analyzing how light propagates through symmetric optical elements. As illustrated in **Figure 2.5**, the behavior of light rays with respect to the optical axis varies depending on whether the lens is positive (converging) or negative (diverging).

In the case of a positive lens, such as a convex lens, light rays that are parallel to the optical axis and incident from left to right are refracted by the lens and converge to a single point along the optical axis. This point is known as the focal point (or principal focus) of the lens. If parallel rays enter the lens from the opposite direction (right to left), they converge at a second focal point located symmetrically on the other side of the lens. These two points define the primary and secondary focal points, which lie at equal distances from the optical center in an ideal lens with symmetric geometry.

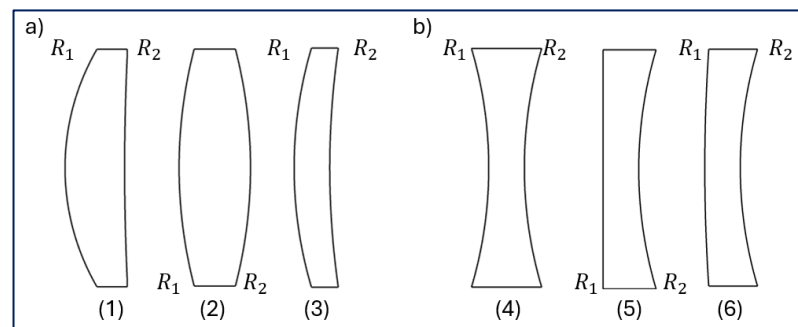


Figure 2.4: a) Three examples of positive and b) three examples of negative lenses.

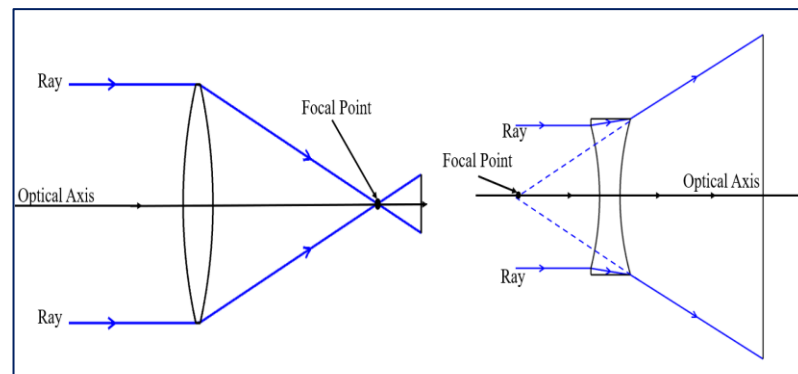


Figure 2.5: Optical axis and focal point of a positive lens (left side) and a negative lens (right side), respectively.

In contrast, a negative lens, such as a concave lens, causes incoming parallel rays to diverge after refraction. These rays do not converge to a real point on the optical axis. However, if the diverging rays are extended backward (i.e., geometrically extrapolated in the reverse direction), they appear to originate from a single point on the same side of the lens as the incoming rays. This virtual point is referred to as the focal point of the negative lens. As with the positive lens, a second focal point exists on the opposite side, defined in the same manner for rays entering from the reverse direction.

These focal points real for converging lenses and virtual for diverging lenses are critical in image formation, ray tracing, and lens design. They determine how an optical system focuses or diverges light and play a central role in the geometric modeling of optical paths [5].

2.6 Thin Lenses and Thick Lenses

2.6.1 Thin Lenses

If the central thickness d of a lens is significantly smaller compared to the radii of curvature of its surfaces, the lens can be treated as a thin lens, as illustrated in **Figure 2.6a**. The focal length f of a thin lens can be approximately expressed by the following equation:

$$\frac{1}{f} \approx (n - 1) \left(\frac{1}{R_1} - \frac{1}{R_2} \right) \quad (2.5)$$

In this case, $n > 1$ indicates the refractive index of the lens material, and R_1 and R_2 represent the curvature radii of the lens's two surfaces. The following rules are used to determine the sign of the radius of curvature:

1. The radius is positive if the vertex of the surface is on the left side of the center of curvature.
2. The radius is negative if the vertex is on the right side of the center of curvature.

Figure 2.7 illustrates examples where the signs of the curvature radii for the lenses are labeled accordingly [5].

2.6.2 Thick Lenses

When the central thickness d of a lens is comparable to the radii of curvature of its two surfaces, the lens is classified as a thick lens, as depicted in **Figure 2.7b**. The formula for determining the focal length f of a thick lens is provided in below [5].

$$\frac{1}{f} = (n - 1) \left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n - 1)d}{R_1 R_2} \right] \quad (2.6)$$

We can see that when $\frac{d}{R_1 R_2}$ approaches 0, Equation 2.6 reduces to Equation 2.5.

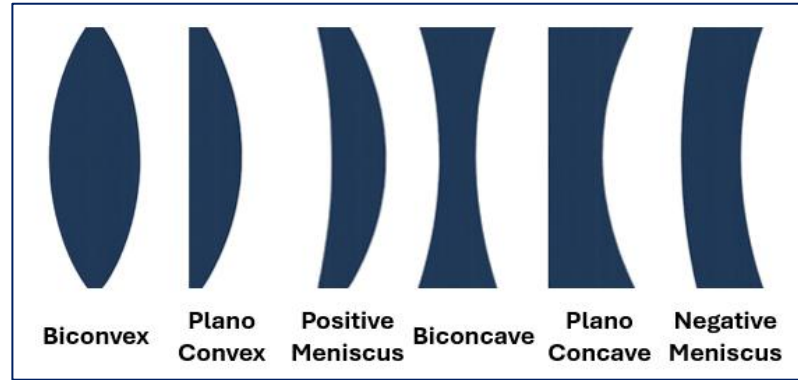


Figure 2.6: Commonly used lens shapes.

2.6.3 Sign and Focal Length

We can now apply Equation 2.5 and the sign convention for surface radii to determine the focal length signs for the different lens shapes shown in **Figure 2.4**. For lens (1), where $R_1 > 0$ and $R_2 \rightarrow \infty$, we find that $f > 0$. For lens (2), with $R_1 > 0$ and $R_2 < 0$, we also have $f > 0$. In lens (3), where $R_1 > 0$ and $R_2 > R_1$, the focal length is $f > 0$. It's important to note that lenses (1) – (3) are all positive lenses.

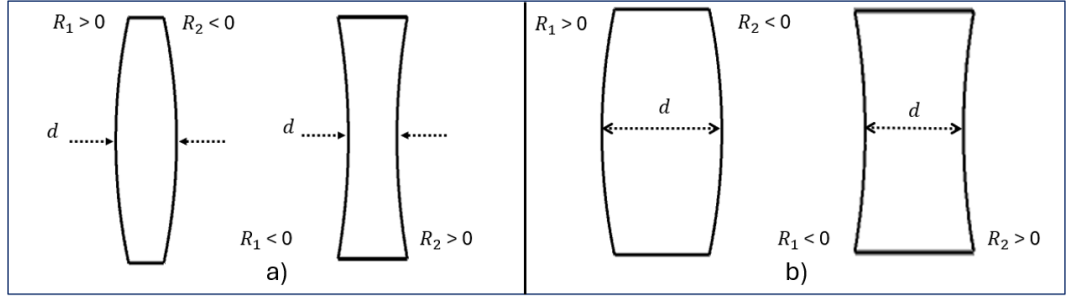


Figure 2.7: Illustration of thin lenses and thick lenses.

On the other hand, for lens (4), with $R_1 < 0$ and $R_2 > 0$, we find $f < 0$. In lens (5), where $R_2 \rightarrow \infty$ and $R_2 > 0$, $f > 0$. Finally, in lens (6), where $R_1 > 0$ and $R_2 < R_1$, $f < 0$. Lenses (4) – (6) are all negative lenses. Thus, we conclude that the focal length of positive lenses is positive, while the focal length of negative lenses is negative. For thick lenses, determining the focal length sign is somewhat more complicated, but the general conclusion remains valid.

2.7 Cardinal Points and Principal Points

A lens system is characterized by three pairs of fundamental optical reference points: principal points, focal points, and nodal points. These are collectively known as the cardinal points and form the foundation of first-order, or paraxial, optical system modeling.

The focal length of a lens is defined as the distance between a principal point and its corresponding focal point. These principal points also define the principal planes, which serve as reference surfaces from which object and image distances are measured in complex optical systems [5].

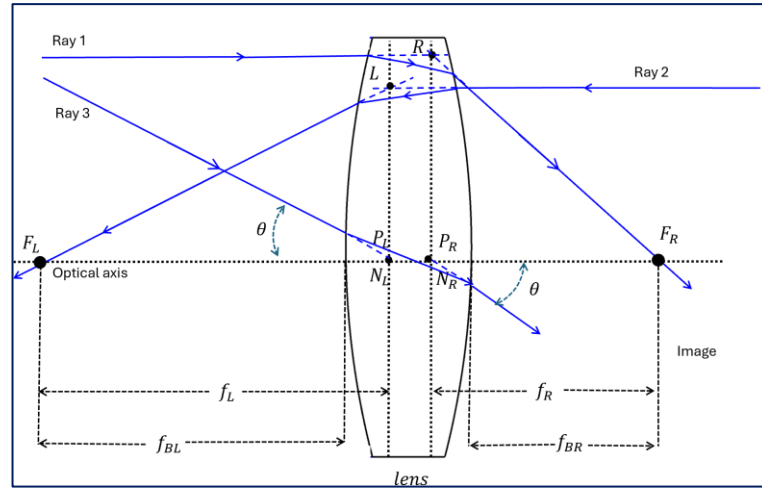


Figure 2.8: Illustration of the two principal points P_L and P_R , the two nodal points N_L and N_R , the two focal lengths f_L and f_R , and the two back focal length f_{BL} and F_{BR} .

Figure 2.8 illustrates the interaction of three rays with a positive (converging) lens. Two of these rays, Ray 1 and Ray 2, travel parallel to the optical axis:

- Ray 1, entering from left to right, is refracted and passes through the right focal point (f_R).
- Ray 2, entering from right to left, refracts through the left focal point (f_L).

By extending the incident and refracted segments of Ray 1 inside the lens, they intersect at a point labeled R . A similar extension of Ray 2 defines a point L . When vertical lines are dropped from these points to the optical axis, their intersection points define the right principal point (P_R) and the left principal point (P_L), respectively.

These two points define the positions of the principal planes. The principal point P_R represents the optical location of the lens when viewed from the right side, where the focusing of Ray 1 appears to occur. Conversely, P_L defines the optical position when the system is observed from the left side, corresponding to Ray 2.

Figure 2.8 provides a complete geometric representation of all six cardinal points in a lens system. It visually clarifies the spatial relationships among the principal points, focal points, and nodal points, as well as the front and back focal lengths. This figure is particularly valuable when analyzing thick lenses, where these points do not coincide and must be considered individually in ray tracing and optical modeling.

In any thick lens, the two principal points (and thus the two principal planes) are distinct and may be spatially separated due to the internal structure and curvature of

the lens elements. However, in a thin lens approximation, where the thickness of the lens is negligible compared to its focal length, these points are assumed to coincide, simplifying the analysis.

The concept of principal points is rooted in the paraxial approximation, where all rays make small angles with the optical axis. This allows for linear ray tracing and the use of Gaussian optics.

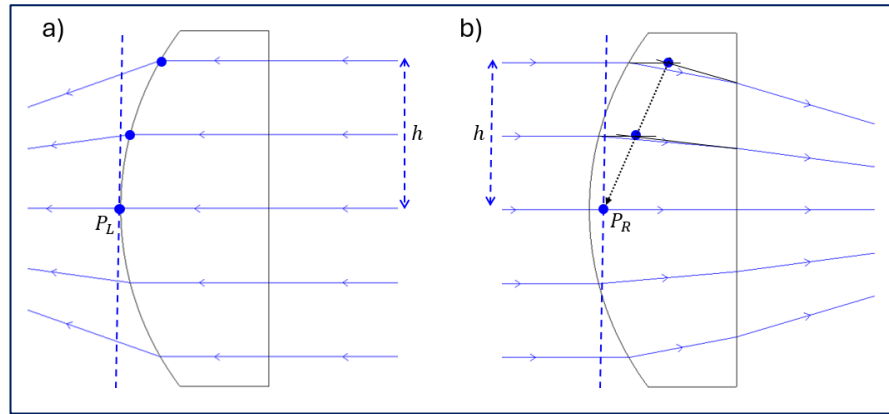


Figure 2.9: Determination of principal points in a convex plano lens.

In **Figure 2.9a**, a ray tracing simulation performed using Zemax shows a convex-planar lens made of N-BK7, a commonly used optical glass. Rays parallel to the optical axis are launched from right to left. The incident and refracted rays, when extended into the lens, intersect at positions that vary with the ray height h . As $h \rightarrow 0$, the rays fulfill the paraxial condition, and the intersection converges to the left principal point (P_L), as indicated in the figure.

In **Figure 2.9b**, the same lens is analyzed with rays entering from the left side. Once again, the intersection of incident and refracted ray paths is traced. When ray height approaches zero, the intersection occurs near the vertex of the convex surface, aligning with the right principal point (P_R).

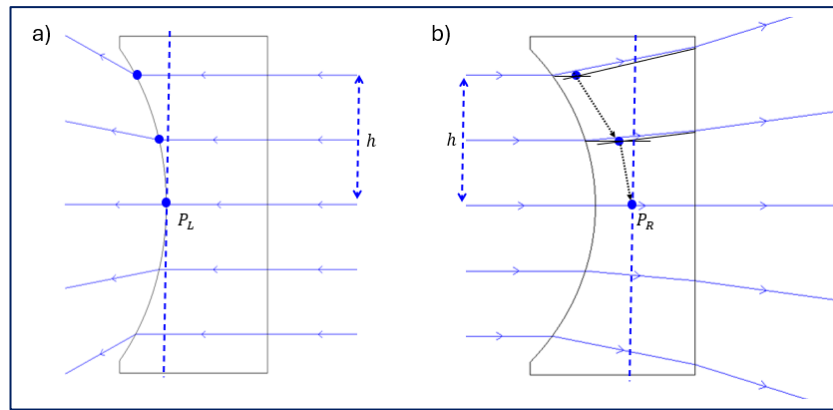


Figure 2.10: Determination of principal points in a negative lens.

For negative lenses, the same geometric ray extension technique can be applied to determine principal points. **Figure 2.10** illustrates how the locations of P_L and P_R are derived for a diverging lens, where the rays diverge outward and must be extrapolated backward to determine their intersections.

Finally, **Figure 2.11** demonstrates how lens geometry affects the location of the principal planes. Depending on curvature and asymmetry, these planes can sometimes extend beyond the physical limits of the lens body, particularly in meniscus or strongly curved elements. This behavior must be taken into account when aligning lenses in precision optical systems.

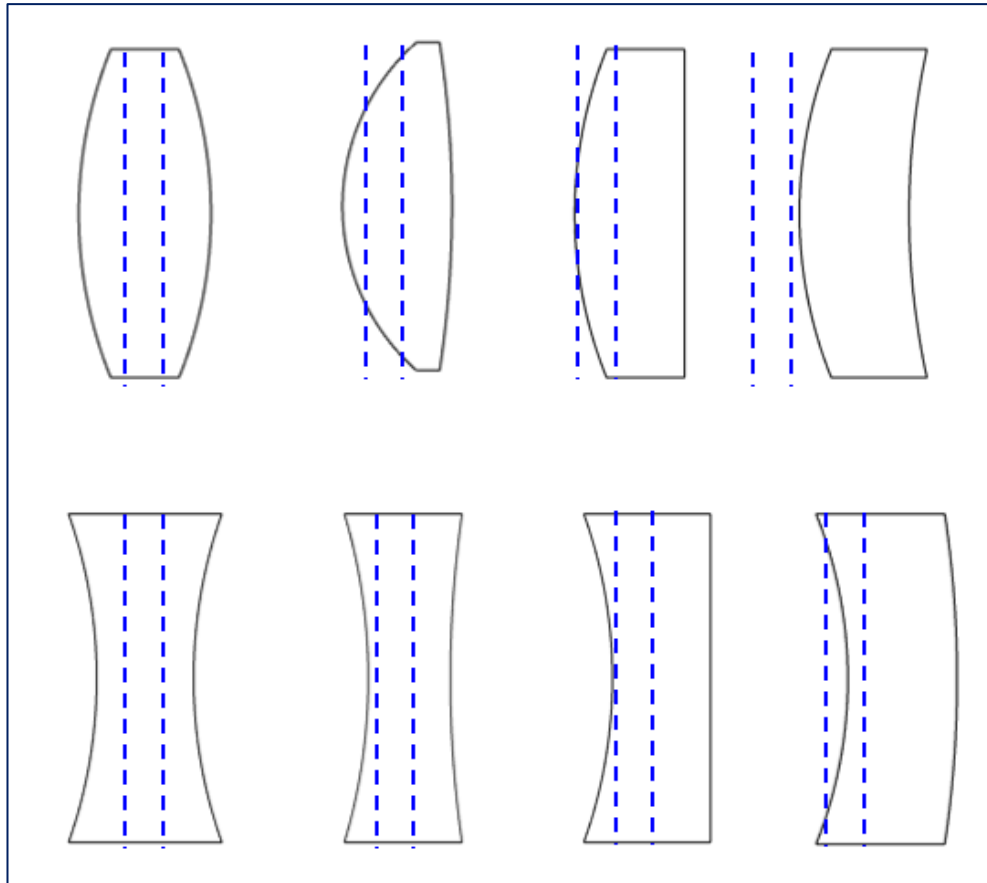


Figure 2.11: Principal planes commonly seen shapes.

2.8 Focal Length and Back Focal Length

The focal length of a lens refers to the distance between a focal point and its corresponding principal point. In **Figure 2.8**, this is represented by f_L and f_R . Regardless of the differences in curvature or shape of the two lens surfaces, f_L and f_R are always equal.

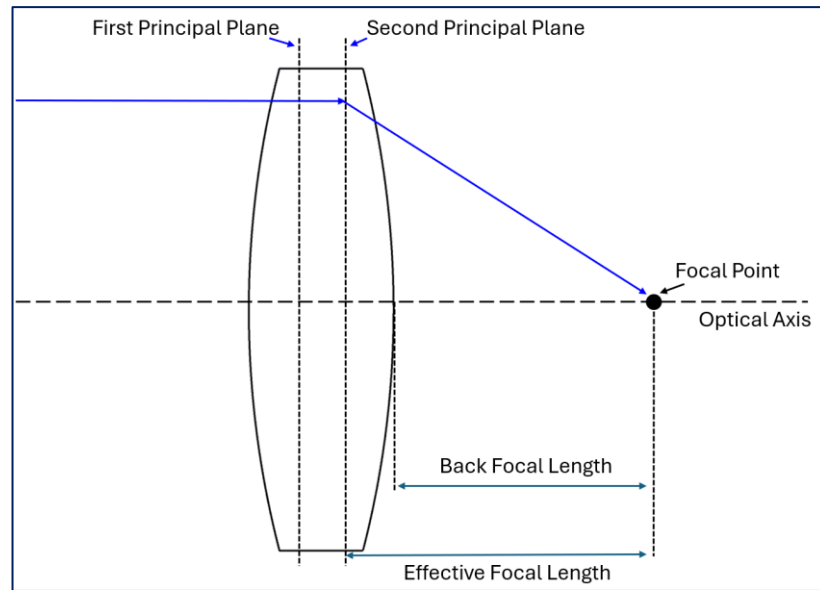


Figure 2.12: Effective Focal length and back focal

The back focal length of a lens, on the other hand, is the distance measured from a focal point to the nearest surface vertex of the lens. These distances are labeled as f_{BL} and f_{BR} in **Figure 2.8**. Unlike the focal lengths, f_{BL} and f_{BR} may differ unless the lens surfaces have radii of curvature that are equal in magnitude but opposite in sign.

2.9 Stops and Pupils

All optical systems contain an aperture stop, a field stop, an entrance pupil, and an exit pupil. These stops are essential optical components and may consist of lenses or various other structures within the system. The entrance pupil and exit pupil are representations of the aperture stop on object side and the image side, respectively [6].

2.9.1 Aperture Stop and Field Stops

Figure 2.11 illustrates the stops in a dual-lens system. The aperture of the first lens constrains the cone angle of the light rays entering the optical system from the object. This aperture serves as the aperture stop for the optical arrangement. Conversely, the aperture of the second lens limits the field angle, defined as the angle between the optical axis and the ray that extends from the center of the aperture stop to the boundary of lens 2's aperture, as shown in **Figure 2.13**. Light rays from the upper part of the

object cannot pass through this two-lens system because their field angles exceed the limits imposed by the field stop.

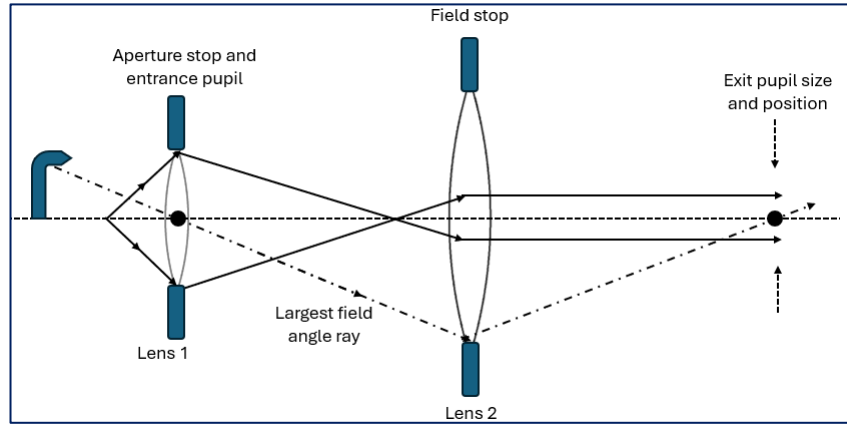


Figure 2.13: Illustration of aperture stop, field stop, entrance pupil, and exit pupil for a two-lens system without additional apertures.

Figure 2.14 shows the same two-lens system, now with two additional apertures. As observed, aperture 1 has become the aperture stop, which regulates the size of the incoming light bundle, while lens 1 is no longer the aperture stop. Meanwhile, aperture 2 is now the field stop, controlling the field angle, and lens 2 is no longer regarded as the field stop [5].

2.9.2 Entrance Pupil and Exit Pupil

The entrance pupil of an optical system is defined as the image of the aperture stop in the object region. In the example shown in **Figure 2.13**, since there is no lens positioned to the left of the aperture stop, the aperture stop itself acts as the entrance pupil.

The exit pupil of an optical system is described as the representation of the aperture stop in the image region. In the scenario depicted in **Figure 2.13**, the location of the exit pupil can be determined by tracing rays that emanate from the center of the aperture stop and proceed rightward through lens 2, as illustrated by the dashed line in **Figure 2.13**. The point of intersection between this ray and the optical axis indicates the position of the exit pupil, marked by the solid dot in **Figure 2.13**. The size of the exit pupil is equivalent to the dimensions of the ray bundle at that location.

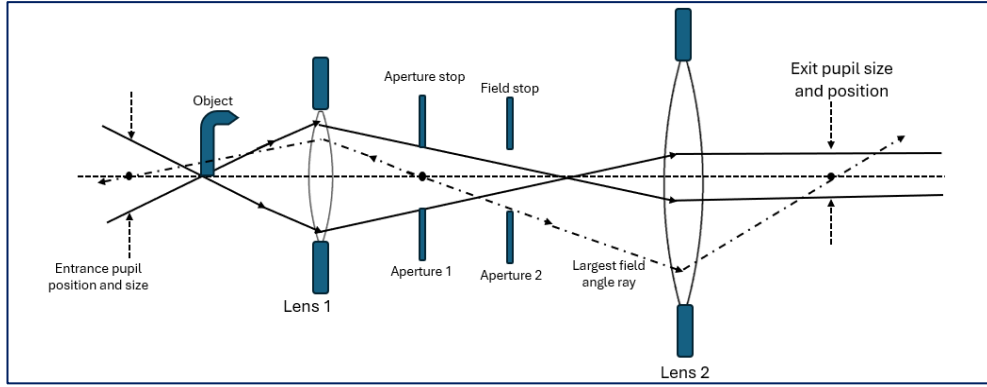


Figure 2.14: Illustration of aperture stop, field stop, entrance pupil, and exit pupil for the same two-lens system shown in **Figure 2.13** with two additional apertures.

In the situation presented in **Figure 2.14**, the positions of the entrance and exit pupils can be identified by following rays from the center of the aperture stop leftward through lens 1 and rightward through lens 2, respectively, as shown by the dashed lines in **Figure 2.14**. The two points where the rays intersect the optical axis define the locations of the entrance and exit pupils, respectively, denoted by the two solid dots. The dimensions of the entrance and exit pupils correspond to the sizes of the ray bundles at their respective positions [5].

2.10 F Number and Depth of Field

In optical systems, the F-number ($F\#$) is a crucial parameter that determines the light-gathering ability and optical resolution of a lens system. The F-number is defined as the ratio of the focal length (f) to the entrance pupil diameter (D_{En}) and is expressed as:

$$F\# = \frac{f}{D_{En}} \quad (2.7)$$

Here, D_{En} represents the entrance pupil diameter on the object side. This value dictates the light collection capability of the lens and its ability to form an image. A lower F-number corresponds to a larger entrance pupil and, consequently, greater light-gathering capacity.

The F-number directly influences the focusing performance and resolution of an optical system. The smallest focused spot, known as the Airy disk, is proportional to

the F-number. Consequently, a lens with a smaller F-number theoretically produces a smaller focal point and higher resolution. However, this advantage is only realized when the optical design is optimal. For instance, a well-designed F/2 lens should provide approximately 1.5 times higher resolution than an equally well-designed F/3 lens. However, a poorly designed F/2 lens may deliver lower image quality than a well-crafted F/3 lens.

There is also a distinction between the working F-number and the image space F-number. The working F-number is defined based on the entrance pupil and the focal length, representing the system's light-gathering efficiency in object space. In contrast, the image space F-number is derived from the beam size at the final optical surface and the back working distance. While both values are closely related, the image space F-number is often used in practical measurements when detailed ray tracing is unavailable.

Additionally, theoretical estimation of F-number can also be approached using angular aperture definitions. For small angles in a first-order paraxial system, the F-number can be approximated by:

$$F\# \approx \frac{1}{\tan\theta} \quad (2.8)$$

In an aplanatic system, angular deviations of incoming rays are more accurately accounted for, thereby improving image quality especially in high-precision optical configurations- system, where sine condition applies, the more precise formula becomes:

$$F\# \approx \frac{1}{\sin\theta} \quad (2.9)$$

These approximations help relate ray angles at the aperture stop to system brightness and resolution [7].

Table 2.1: Effect of F-number on aperture size, depth of field, focus range, and image brightness.

				
F/1.5	F/2.9	F/5.8	F/10.6	F/20
Very Large Aperture	Large Aperture	Medium Aperture	Small Aperture	Very Small Aperture
Very Small Depth of Field	Small Depth of Field	Medium Depth of Field	Large Depth of Field	Very Large Depth of Field
Almost Nothing in Focus	Little In Focus	Some In Focus	Much In Focus	Almost All In Focus
Brightest	Bright	Medium	Dark	Darkest

In practical terms, the effect of the F-number on image brightness, depth of field, and focus range can be visualized as shown in **Table 2.1**. As the F-number increases from F/1.5 to F/20, the aperture size decreases, resulting in reduced light transmission but increased depth of field. A very low F-number (e.g., F/1.5) corresponds to a wide aperture that produces a brighter image but with very shallow focus, making "almost nothing in focus." Conversely, a high F-number (e.g., F/20) provides a much smaller aperture, leading to darker images but a greater depth of field where "almost all is in focus." These relationships reinforce the theoretical definition of F-number, emphasizing its impact on both radiometric and spatial performance.

2.11 Field of View

Field of View (FOV) refers to the angular extent of the scene that an optical system can capture at a given moment. In optical design, it determines the area observed by a lens system on a sensor or by an observer, typically measured in degrees ($^{\circ}$). FOV calculations depend on parameters such as the focal length (f) of the lens and the sensor size.

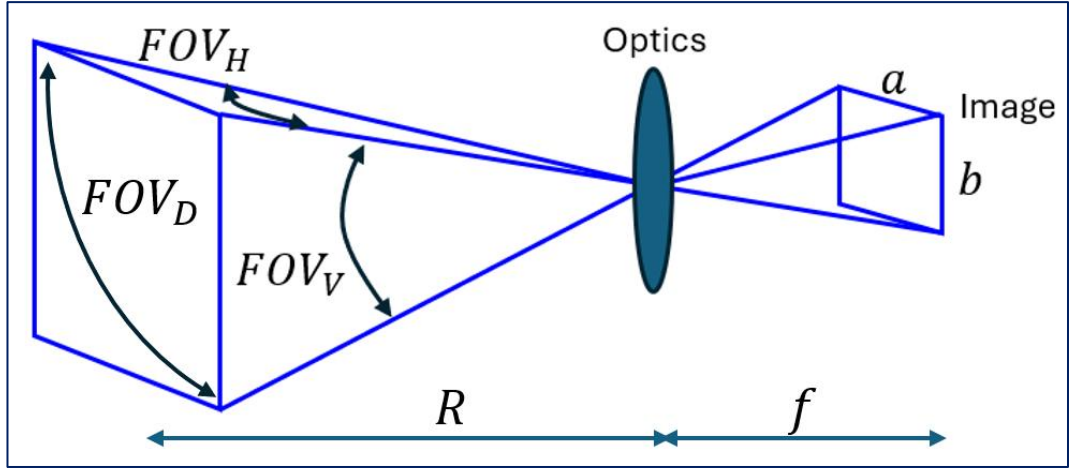


Figure 2.15: Field of view.

If the lens focal length and sensor size are known:

$$FOV_H = 2 \times \tan^{-1} \left(\frac{a}{2f} \right) \quad (2.10)$$

$$FOV_V = 2 \times \tan^{-1} \left(\frac{b}{2f} \right) \quad (2.11)$$

$$FOV_D = 2 \times \tan^{-1} \left(\frac{\sqrt{a^2 + b^2}}{2f} \right) \quad (2.12)$$

$a \rightarrow$ Sensor width

$b \rightarrow$ Sensor height

$f \rightarrow$ Lens focal length

$FOV_H \rightarrow$ Horizontal field of view in degrees ($^\circ$)

$FOV_V \rightarrow$ Vertical field of view in degrees ($^\circ$)

$FOV_D \rightarrow$ Diagonal field of view in degrees ($^\circ$)

3. ABERRATION THEORY

In an ideal optical system, light rays originating from a single point should converge precisely at a single point to form a sharp image. However, real optical systems exhibit aberrations, which prevent perfect image formation. Optical aberrations are classified into two main categories: monochromatic aberrations, which arise due to the geometric properties of the optical system, and chromatic aberrations, which result from the variation of the refractive index with wavelength.

Spherical surfaces are widely used in optical design due to their ease of fabrication, allowing multiple lenses to be processed simultaneously. However, these surfaces inherently introduce aberrations because their geometric method of focusing is imperfect. Paraxial optics, which assumes small-angle approximations in Snell's law, eliminates aberrations in theory. Yet, in practical systems, large-angle rays deviate from this ideal behavior, leading to image degradation.

To mitigate aberrations, aspherical surfaces are often employed, as they can significantly reduce optical defects by deviating from a purely spherical shape.

However, they do not completely eliminate aberrations, and their manufacturing complexity and cost limit their widespread use. Aspherical lenses are commonly produced via injection molding, glass compression molding, or SPDT (Single Point Diamond Turning). Despite their advantages, spherical lenses remain dominant due to cost-effectiveness and practicality.

Additionally, chromatic aberrations occur due to material dispersion, where the refractive index changes with wavelength, causing different colors to focus at different points. Optical designers use multiple lens elements and different materials to correct for both monochromatic and chromatic aberrations, optimizing image quality and achieving near-diffraction-limited performance, especially in large-aperture systems.

3.1 Monochromatic Aberrations

Monochromatic aberrations, also known as Seidel aberrations, arise in optical systems when imaging rays of a single wavelength. These aberrations are the result of the

geometrical structure of the system rather than any wavelength-dependent behavior. Even under ideal alignment and for monochromatic light, deviations from paraxial assumptions such as large aperture angles or field heights lead to image defects. Unlike chromatic aberrations, which are material-dependent, monochromatic aberrations are primarily governed by lens shapes, curvatures, surface spacing, and system layout.

There are five primary types of monochromatic aberrations that are most commonly encountered in optical design: spherical aberration, coma, astigmatism, field curvature, and distortion. Each type affects image formation in a different way and requires specific strategies for minimization or correction. In practical systems, these aberrations are rarely isolated; they often occur simultaneously, necessitating a careful balance during the design and optimization process.

3.1.1 Spherical Aberration

Spherical aberration is a fundamental optical defect inherent in spherical lenses and mirrors, where light rays striking the periphery of a spherical surface are focused at different points compared to those passing near the optical axis. This discrepancy arises because spherical surfaces do not bring all incoming parallel rays to a single focal point, leading to a blurred or distorted image, as shown in **Figure 3.1**.

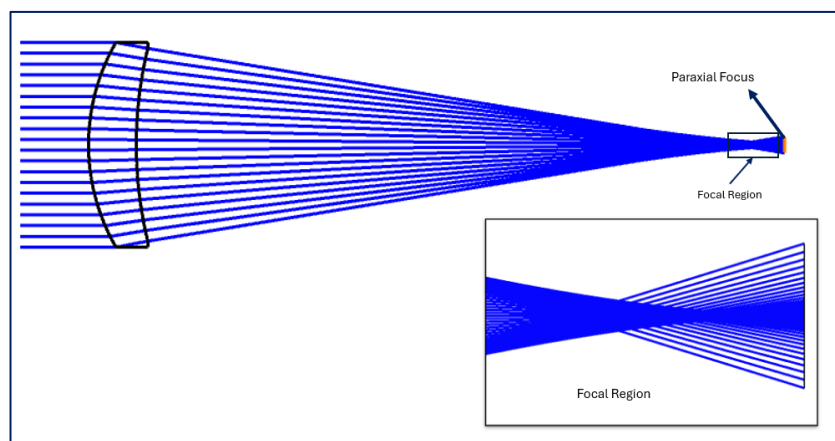


Figure 3.1: Spherical Aberration.

The severity of spherical aberration is influenced by the height of incoming light rays relative to the optical axis. Rays entering the lens or mirror at greater distances from the optical axis (high paraxial angles) experience stronger refraction or reflection, causing them to focus closer to the optical element compared to paraxial rays.

Additionally, the curvature of the optical element plays a crucial role in determining the extent of spherical aberration. A lens or mirror with a higher curvature (tighter curve) generally exacerbates the aberration, while a flatter curvature helps to reduce its effects to some extent.

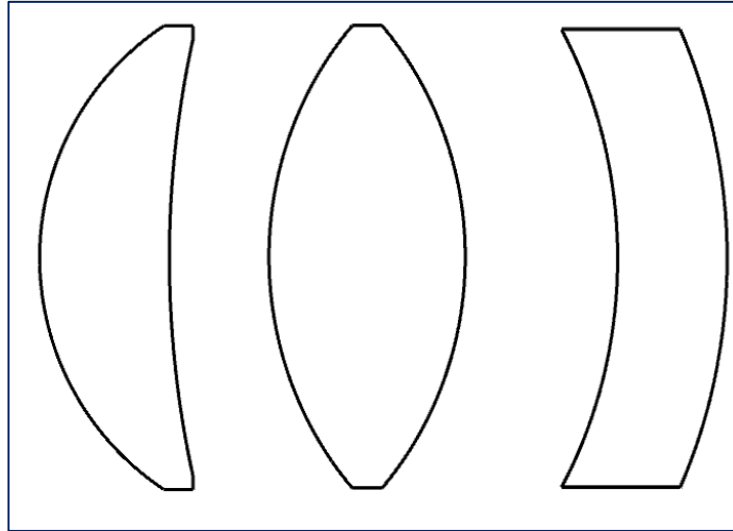


Figure 3.2: Different Bending Lenses with The Same Focal Length

Spherical aberration affects optical systems in various ways. First, it causes image blurring as light rays fail to converge at a single point, reducing sharpness and preventing the formation of a clear and well-defined image. Additionally, spherical aberration alters the depth of field by either increasing or decreasing the focal range, impacting the system's focusing accuracy. Finally, by preventing precise light convergence, it lowers contrast and resolution, thereby degrading the overall performance of the optical system.

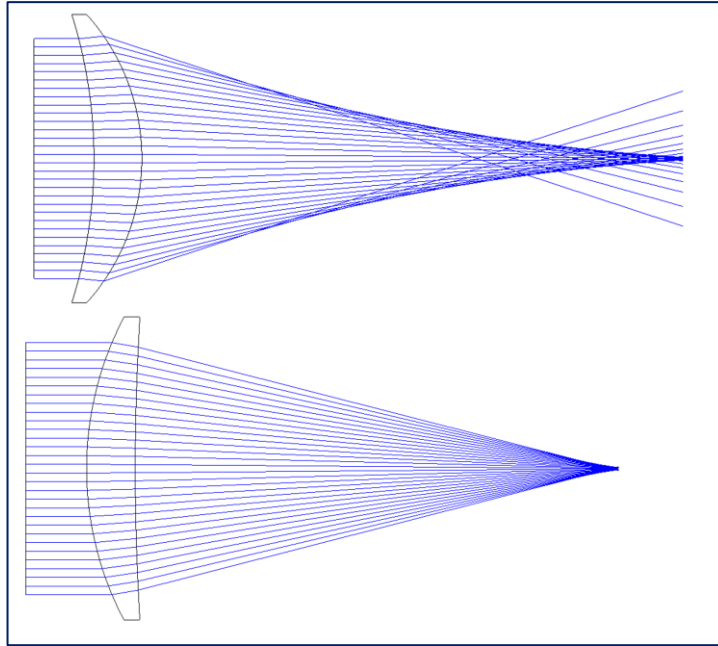


Figure 3.3: Spherical Aberration as a Function of Lens Bending

Several methods can be employed to minimize spherical aberration in optical systems. First, using aspherical surfaces in lenses or mirrors ensures that incoming rays converge more uniformly, significantly reducing spherical aberration. Second, apochromatic designs, which incorporate multiple lens elements with different curvatures and refractive indices, can correct both spherical and chromatic aberrations. Lastly, controlling the aperture size or strategically positioning the aperture stop helps limit the entry of high-angle rays, further minimizing spherical aberration.

Spherical aberration is a crucial factor in the design and optimization of optical systems. Its impact on image quality necessitates careful selection of optical components and strategic design choices. Advances in materials science and optical engineering continue to provide innovative solutions for reducing spherical aberration, enhancing the performance of lenses and mirrors in various applications, from photography and microscopy to astronomical telescopes and advanced imaging systems.

As shown in **Figure 3.3**, the $f/1.5$ lens at the top exhibits a significant amount of spherical aberration. In contrast, the $f/1.5$ lens at the bottom has been bent to minimize spherical aberration.

3.1.2 Coma

Coma aberration is a significant optical distortion encountered in lenses and mirrors, particularly in systems where light rays strike surfaces at oblique angles. This aberration manifests as a comet-like deformation in point light sources, resulting in elongated and asymmetrical appearances instead of sharp points as shown in **Figure 3.4**.

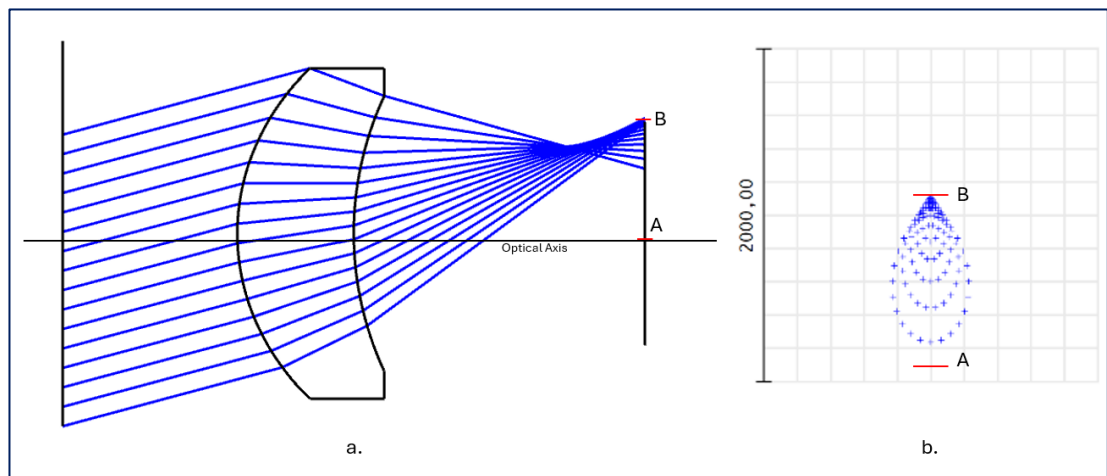


Figure 3.4: Coma

The primary cause of coma aberration is the interaction of off-axis light rays with the optical surface; these rays experience greater deviations in their paths compared to those that are closer to the optical axis. The geometry of optical elements, especially spherical lenses and mirrors, contributes to this issue by causing variations in focal points for rays incident at different angles.

Coma aberration predominantly impacts the outer regions of the image field, causing degradation in resolution and fine detail an issue of particular concern in fields like astronomy, where accurate rendering of stellar objects is essential.

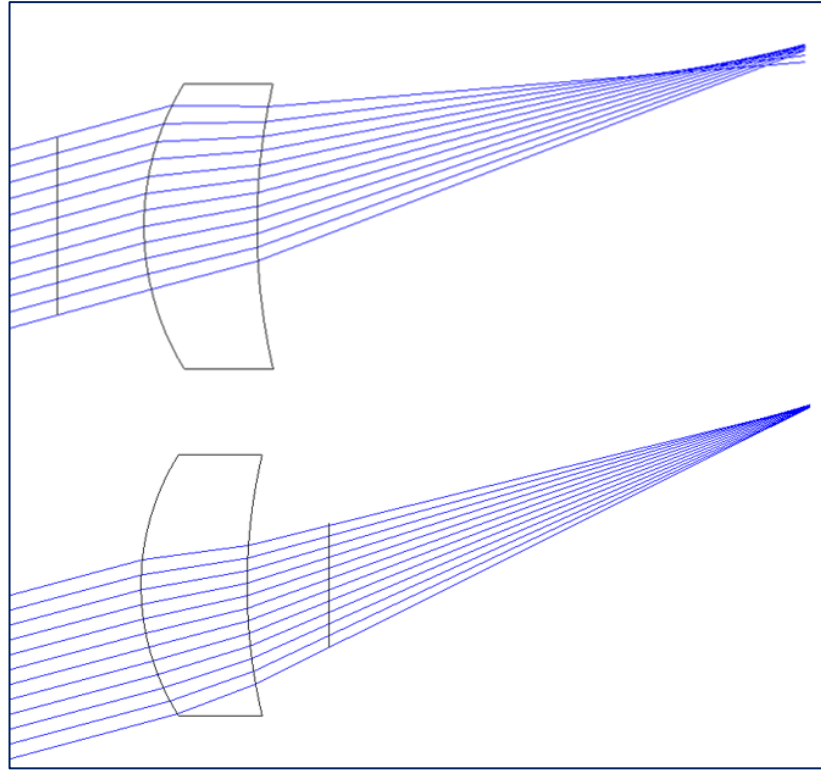


Figure 3.5: Reduced Coma with stop behind the lens.

Various strategies can be employed to mitigate coma aberration. Aspheric lenses, with their non-spherical surfaces, can effectively correct the paths of off-axis light rays. Adjustments in optical configuration, such as modifying the arrangement of lens elements or adjusting the stop position, can also help reduce coma as shown in **Figure 3.5**. Properly positioning the stop controls the incident angles of light rays, thereby minimizing off-axis deviations. Additionally, the use of field stops to limit aperture size can reduce the influence of off-axis rays, while incorporating specially designed corrective optical elements can enhance image quality across the entire field of view. By understanding the causes and effects of coma aberration, optical system designers can implement effective solutions to ensure accurate representation of point light sources.

3.1.3 Astigmatism

Astigmatism is an off-axis optical aberration that arises when light rays in the tangential (meridional) and sagittal planes come to focus at different image distances. As a result, a point source does not form a sharp point image but instead appears as a blurred ellipse or circle, depending on the observation plane. The smallest blur, known

as the circle of least confusion, occurs at the midpoint between the tangential and sagittal focal planes.

The severity of astigmatism increases proportionally with the square of the field angle and linearly with the aperture size, making it particularly prominent in wide-field or low-F-number systems. It occurs when an oblique cone of light intersects a curved surface, such as a spherical lens or mirror. In such cases, tangential rays are refracted more strongly and focus closer to the optical surface, while sagittal rays converge farther away. This difference in image location creates astigmatic blur. Furthermore, astigmatism is often accompanied by oblique spherical aberration, especially in systems with large fields of view.

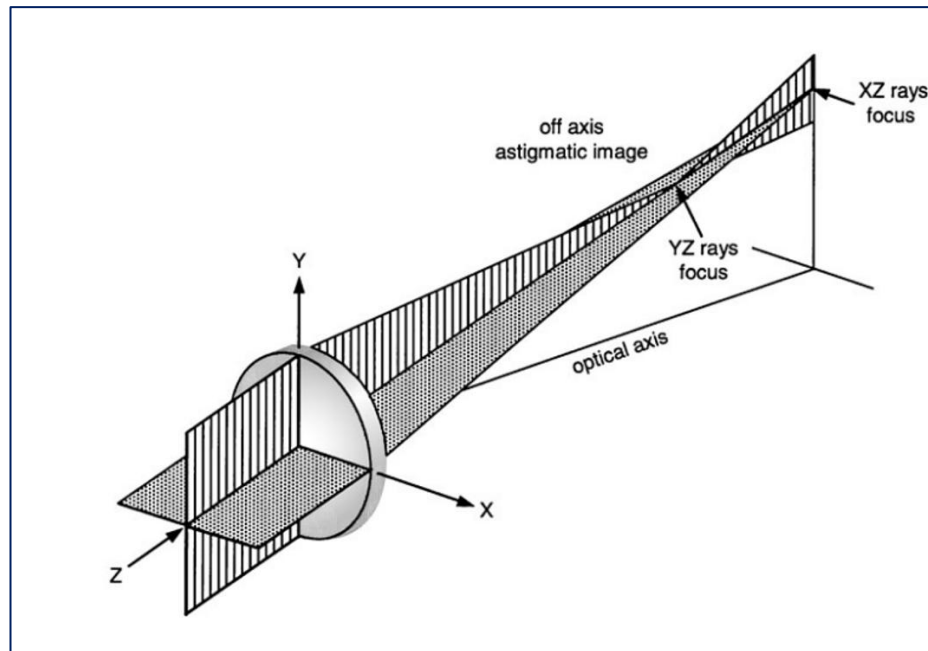


Figure 3.6: Illustration of Astigmatism [8].

Several design strategies can be used to reduce or correct astigmatism. One method is to adjust the curvature and shape of optical surfaces, particularly for elements encountered by off-axis rays. The position of the aperture stop also has a critical effect, as it governs the distribution of ray angles entering the system. In addition, incorporating a weak meniscus lens near the image plane can effectively act as a tilted plate within the light cone, reducing the difference in focal distances between the tangential and sagittal rays. **Figure 3.6** illustrates this principle in practice.

Astigmatism is frequently one of the dominant residual aberrations in small-field achromatic lens systems. However, its effect can be significantly mitigated by introducing corrective elements such as weak meniscus components—and re-optimizing the optical layout. Contemporary optical design software routinely employs such balancing techniques to minimize astigmatism and achieve high-resolution, well-corrected imaging across the intended field of view.

3.1.4 Field Curvature

Field curvature is an optical aberration in which the image formed by a lens or optical system lies along a curved surface rather than a flat plane. This leads to a mismatch between the curved focal surface and a planar image receiver, such as a sensor or film. As a result, when the center of the image is in focus, the peripheral areas appear blurred, and vice versa. This aberration becomes more noticeable in systems with large fields of view, where off-axis rays are refracted differently and focus at different image distances compared to on-axis rays.

The root cause of field curvature lies in the geometry of spherical surfaces, which tend to focus incoming light onto a Petzval surface—a naturally curved focal surface. In practical systems where a flat image plane is required, this curvature leads to partial defocus across the image field, limiting the ability to simultaneously achieve sharp focus both at the center and edges.

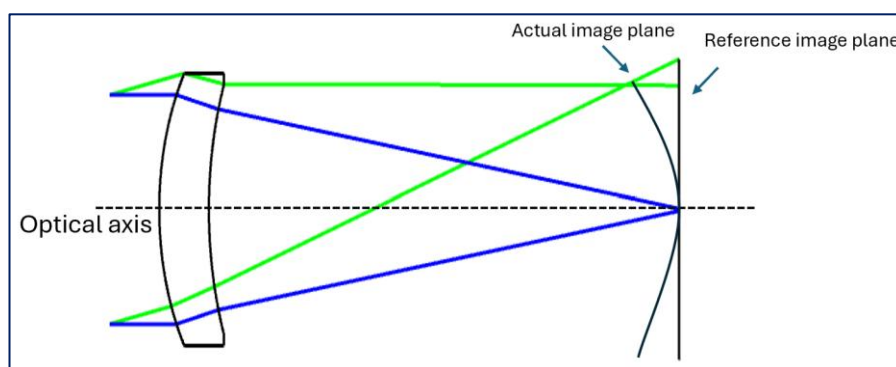


Figure 3.7: Illustration of field curvature aberration. The curved focal surface leads to peripheral blur on a flat sensor, even when the center is in perfect focus.

Several strategies are employed to minimize or correct field curvature. One common approach is the use of field-flattening elements, which are optical components

specifically designed to counteract the curvature of the focal surface and project a flat image onto the sensor. Additionally, reducing the aperture size increases the depth of field, thereby masking the visible effects of curvature. However, this comes at the cost of reduced light collection and resolution. Modern optical systems such as photographic lenses, telescopes, and microscopes often incorporate dedicated design features to balance field curvature against other aberrations and ensure uniform sharpness across the image plane.

3.1.5 Distortion

Distortion is a third-order geometric aberration that manifests as a deviation in the spatial positioning of image points, without inducing image blur. In an optically corrected system where all blur-related aberrations are minimized or eliminated, distortion remains observable as a systematic shift of image points from their ideal paraxial locations. This results in a geometrically deformed image, particularly evident in scenes containing rectilinear structures, which appear curved or warped despite being in perfect focus.

The quantitative measure of distortion is defined as the deviation of the actual image height y from the ideal paraxial image height y_p and is expressed as [5]:

$$\text{Distortion} = \frac{y - y_p}{y_p} \quad (3.1)$$

This deviation may be reported in either absolute units (e.g., millimeters) or as a percentage. The distortion increases approximately with the cube of the field angle, and therefore becomes increasingly significant in wide-angle optical systems. Its origin is attributed to differences between the actual chief ray path and the idealized paraxial chief ray, particularly in systems with thick elements or off-centered aperture stops.

As illustrated in **Figure 3.8**, the displacement of the real chief ray from the paraxial prediction introduces a positional error in the image plane. The nature of this error defines the sign of distortion: positive distortion (pincushion) occurs when image points are displaced outward, and negative distortion (barrel) when they are displaced

inward. Notably, distortion vanishes in the paraxial limit and in thin-lens systems where the aperture stop coincides with the principal plane.

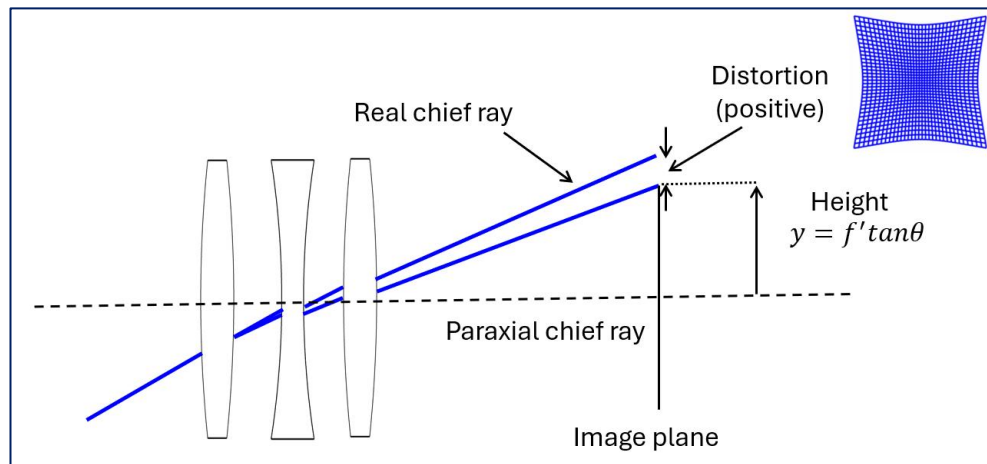


Figure 3.8: Distortion formation with the deviation of the real chief ray from its paraxial counterpart.

In practical systems, the distribution of distortion is strongly influenced by the location of the aperture stop relative to the lens elements. **Figure 3.9** presents a Zemax ray tracing in which image height does not scale linearly with object height, revealing the presence of distortion. Specifically, when the object height is doubled, the image height increases sublinearly as direct indicator of positive distortion.

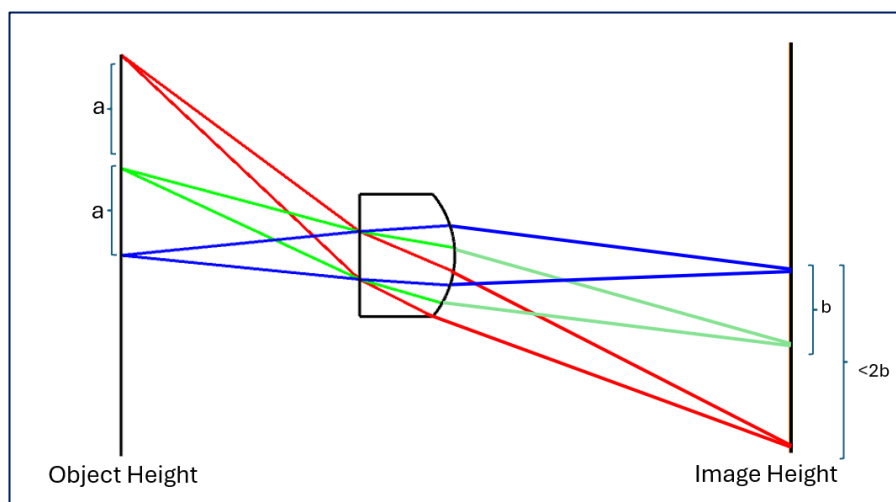


Figure 3.9: A Zemax generated raytracing showing a lens has longer distortion. When the object is doubled, the image height is less doubled

Moreover, distortion demonstrates a form of reversibility: when object and image spaces are interchanged, the direction of distortion is inverted. For instance, a lens

system that introduces barrel distortion in object space will produce pincushion distortion in image space. This principle is essential in the analysis of systems designed for bidirectional imaging or scanning applications.

Figure 3.10 demonstrates the two canonical forms of distortion. When the stop is placed anterior to the lens, the ray bundle geometry favors barrel distortion. Conversely, when the stop is located posterior to the lens, pincushion distortion arises. These effects are particularly important in visual systems where spatial fidelity is perceptually significant.

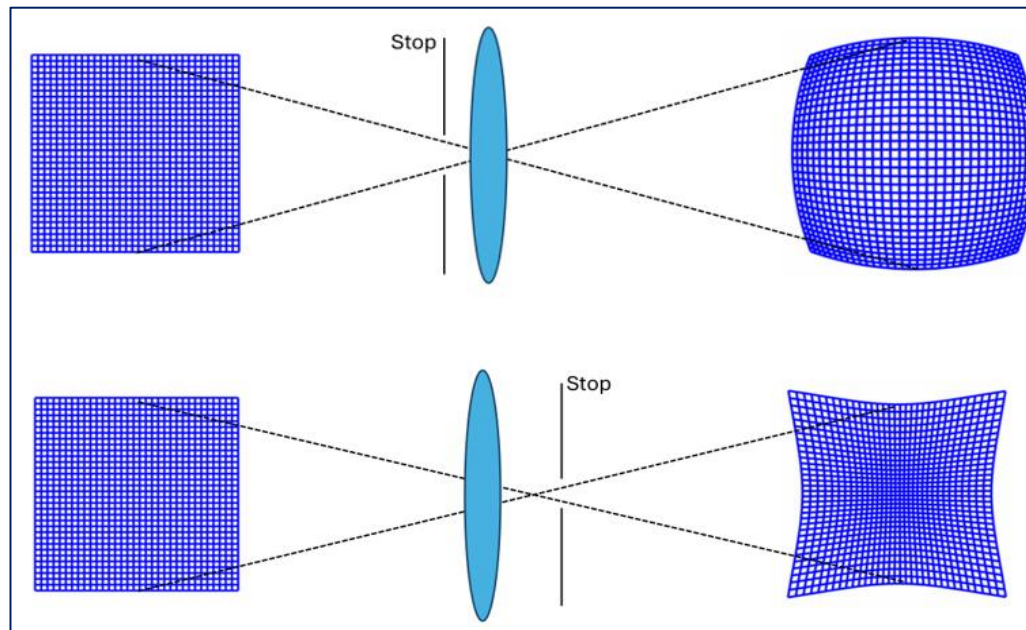


Figure 3.10: Barrel (top) and pincushion (bottom) distortion example

Although distortion does not impact modulation transfer function (MTF) or resolution metrics, it adversely affects the geometric accuracy of the rendered image. In applications such as aerial mapping, photogrammetry, or high-precision machine vision, distortion must be minimized through advanced design strategies such as stop placement optimization, lens bending control, and incorporation of distortion-corrective elements. For most visual systems, distortion levels below 2–3% are deemed acceptable, though tighter tolerances are required in metrology-grade instruments [5].

Distortion's cosmetic impact makes it especially important in visual systems, even though it does not degrade image resolution.

3.2 Chromatic Aberrations

Chromatic aberrations arise from the wavelength-dependent nature of the refractive index in optical materials. Unlike monochromatic aberrations, which are purely geometric, chromatic aberrations result from dispersion—where different wavelengths of light are bent by different amounts as they pass through a refractive surface. This causes light of varying colors to focus at different positions either along the optical axis or perpendicular to it, leading to color fringing and degraded image sharpness.

Chromatic aberrations are broadly classified into two main types: axial (longitudinal) and lateral (transverse). Axial chromatic aberration occurs when different wavelengths come to focus at different axial distances from the lens, while lateral chromatic aberration arises from a variation in magnification across wavelengths, resulting in color separation in the image plane. These aberrations are particularly prominent in broadband imaging systems, where multiple wavelengths must be brought to a common focus.

Minimizing chromatic aberrations requires careful selection of optical materials with complementary dispersion properties, as well as the use of achromatic or apochromatic doublets that combine lenses of different glass types. In high-performance systems, chromatic correction is essential to achieve diffraction-limited imaging across the spectral range of interest.

3.2.1 Axial Chromatic Aberration

Chromatic aberration originates from the dispersion of optical materials, whereby the refractive index varies as a function of wavelength. This phenomenon causes polychromatic light to be refracted differently depending on its spectral composition, resulting in wavelength-dependent focal shifts within optical systems.

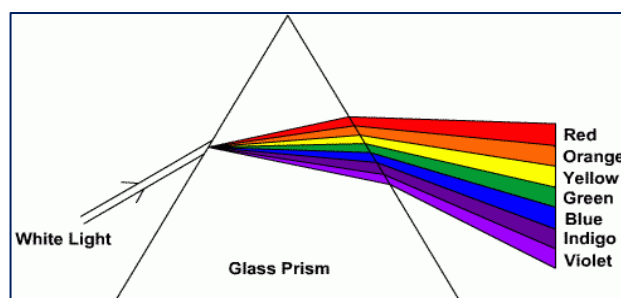


Figure 3.11: Dispersion of white light through a glass triangle prism.

As illustrated in **Figure 3.11**, when white light passes through a dispersive medium such as a glass prism, each wavelength component is refracted at a different angle, with shorter wavelengths (e.g., violet and blue) experiencing greater angular deviation than longer wavelengths (e.g., red). This fundamental behavior also governs the chromatic performance of lenses.

When collimated white light is incident on a simple converging lens, the lens bends shorter wavelengths more strongly than longer ones due to their higher refractive indices. As depicted in **Figure 3.12a**, this leads to a situation in which blue light focuses at a position closer to the lens than green or red light, producing an extended focal region along the optical axis. This form of aberration is referred to as axial or longitudinal chromatic aberration, and it results in reduced sharpness and colored fringes, particularly noticeable around high-contrast edges.

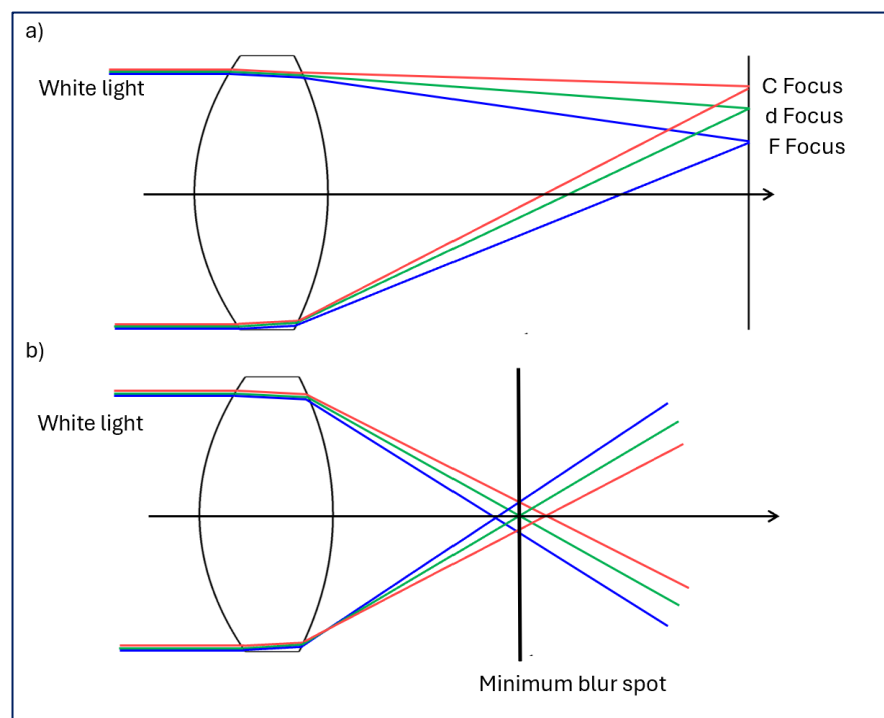


Figure 3.12: a) Axial (longitudinal) chromatic aberration of a single positive lens b) Lateral (transverse) chromatic aberration of a single positive lens

Even in systems free from spherical aberration, axial chromatic aberration can produce a bright central image surrounded by a purplish halo, resulting from the superposition of defocused red and blue components. The degree of axial spread directly correlates with the dispersive properties of the optical elements used.

A common corrective strategy involves the use of an achromatic doublet, a compound lens consisting of two optical elements with opposite powers and differing Abbe numbers. As shown in **Figure 3.13**, the positive element is typically fabricated from crown glass (low dispersion), while the negative element is made from flint glass (high dispersion). This configuration enables two selected wavelengths (commonly the C and F Fraunhofer lines) to converge at the same axial location, significantly reducing longitudinal chromatic aberration over a designated spectral band. The intermediate wavelength (e.g., d-line) is brought to a nearby position, resulting in minimal residual color error.

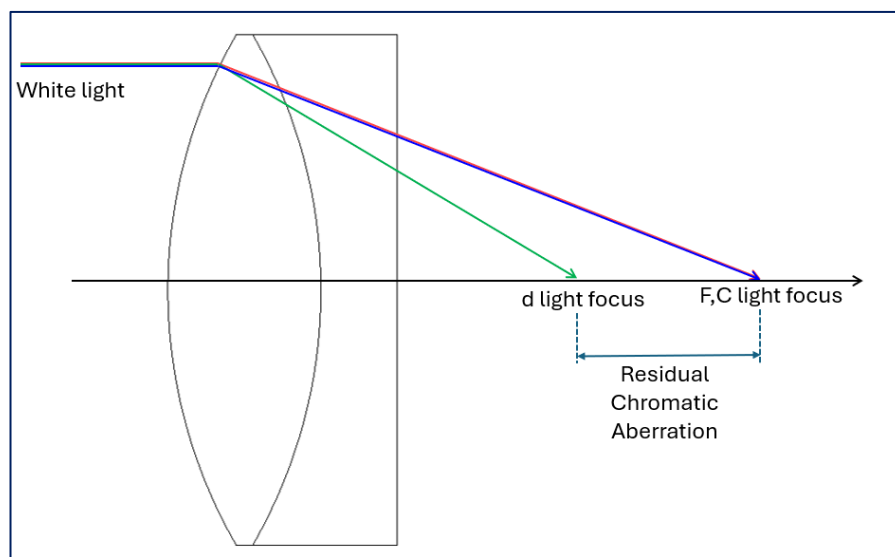


Figure 3.13: Achromatic doublet lens correcting for primary longitudinal chromatic aberration.

This approach is fundamental in the design of high-resolution imaging systems, including photographic lenses, telescope objectives, and broadband surveillance optics, where chromatic performance is a critical parameter.

3.2.2 Lateral Chromatic Aberration

Lateral chromatic aberration, also referred to as chromatic difference of magnification, occurs when an optical system forms off-axis images of different wavelengths at different heights in the image plane. Unlike axial chromatic aberration, which manifests as variation in focus along the optical axis, lateral chromatic aberration appears as a transverse displacement of colored images, typically observed near the

periphery of the field. This phenomenon leads to the familiar visual artifact known as color fringing, particularly around high-contrast edges.

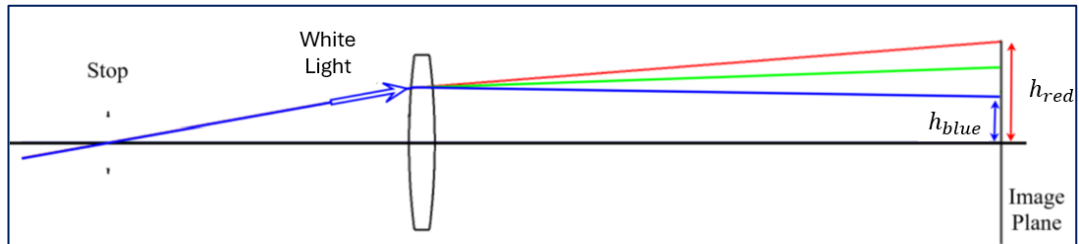


Figure 3.14: Illustration of lateral chromatic aberration. $h_{blue} < h_{red}$.

As shown in **Figure 3.14**, this aberration arises because the refractive index varies with wavelength, causing rays of different colors to refract at different angles. Blue rays, which are more strongly refracted, converge closer to the optical axis, whereas red rays, which bend less, intersect the image plane at larger field heights. The result is a separation of image points for different wavelengths, with the magnitude of the displacement increasing with field angle.

Lateral color is most pronounced in systems with wide fields of view or high chief ray angles, particularly when the contributing lens elements are positioned far from the aperture stop. Optical components with large effective apertures and high off-axis ray heights exacerbate the effect. Consequently, lenses situated far from the stop, especially in the eyepiece assemblies of visual instruments, tend to dominate the system's lateral chromatic behavior.

Instruments such as binoculars or visual telescopes frequently exhibit detectable lateral color, especially at the edges of the field. However, since human vision typically fixates on the center of the field, this aberration is often perceptually tolerated. As a result, visual systems are generally designed with looser constraints on lateral color compared to imaging systems used for metrology or multispectral detection.

Mitigation of lateral chromatic aberration may involve the use of low-dispersion glasses, optical symmetry, or diffractive optical elements that introduce chromatic corrections opposite to those caused by refractive materials. Nevertheless, full correction across wide fields often requires specialized design techniques or costly materials.

In summary, optical aberrations both monochromatic and chromatic play a critical role

in limiting image quality across optical systems. Understanding their physical origins and propagation characteristics is essential for evaluating system performance and implementing corrective design strategies. As discussed throughout this chapter, each aberration manifests differently, requiring specific approaches for effective mitigation.

Table 3.1: Major optical aberrations and commonly used correction methods.

Aberration Type	Cause	Correction Methods
Spherical Aberration	Marginal rays focus closer than paraxial rays	Aspheric surfaces, stop control, lens bending
Coma	Asymmetric refraction of off-axis rays	Symmetric layout, stop placement, aspheric surfaces
Astigmatism	Sagittal and tangential rays focus at different planes	Meniscus lens near image plane, stop tuning
Field Curvature	Curved Petzval image surface	Field flattener lens, reduced field angle, telecentric design
Distortion	Magnification varies with field angle	Stop position optimization, symmetric optics, distortion-corrective lens elements
Axial Chromatic Aberration	Wavelength-dependent focal shift along optical axis	Achromatic doublets (crown + flint), apochromatic systems
Lateral Chromatic Aberration	Lateral color displacement due to magnification mismatch	Low-dispersion materials, diffractive elements, optical symmetry

To consolidate this discussion, **Table 3.1** provides a comprehensive summary of the major optical aberrations, their physical origins, and commonly used correction methods. The table serves as a practical guide for identifying suitable mitigation strategies during the optical system design process.

4. OPTICAL ANALYSIS

The successful realization of an optical system is intrinsically linked to a rigorous performance evaluation process. Such analyses are indispensable for validating the design and ensuring that critical optical specifications are met. Key assessment tools include spot diagrams, modulation transfer function (MTF) plots, wavefront error maps, encircled energy and ray tracing diagnostics. Advanced optical design platforms such as Zemax OpticStudio enable detailed visualization of these parameters, allowing iterative refinement throughout the design cycle.

It is important to note that no optical system is free from imperfections. Aberrations, diffraction effects, fabrication tolerances, and alignment errors all contribute to performance degradation. Moreover, the final image quality is influenced not only by optics but also by system-level components such as detectors, signal processing electronics, and display technologies. While the human visual system can compensate for certain distortions such as field curvature image sensors like CCDs and CMOS arrays cannot. Accordingly, this chapter focuses specifically on the optical contributions to imaging performance.

4.1 Resolution

Spatial resolution characterizes an optical system's ability to distinctly image two adjacent object points and is intrinsically constrained by diffraction in aberration-free conditions. In a perfect optical system, the imaging of a point source produces a diffraction pattern known as the Airy distribution, rather than a geometric point. The radial intensity profile of this pattern defines the system's diffraction-limited resolution.

The Rayleigh criterion quantitatively describes the minimum resolvable separation between two incoherent point sources. According to this principle, two Airy disks are considered just resolvable when the maximum of one coincides with the first minimum of the other. This corresponds to an intensity dip of approximately 26% between peaks, or 74% of the peak value at the saddle point, as shown in **Figure 4.1**.

This limit is governed by the following parameters:

$$\delta_{Airy} = 1.22 \frac{\lambda}{D} \quad (4.1)$$

where δ is the minimum resolvable angular separation, λ is the wavelength of incident light, and D is the entrance pupil diameter. Thus, resolution can be improved either by decreasing the operating wavelength or by increasing the aperture size.

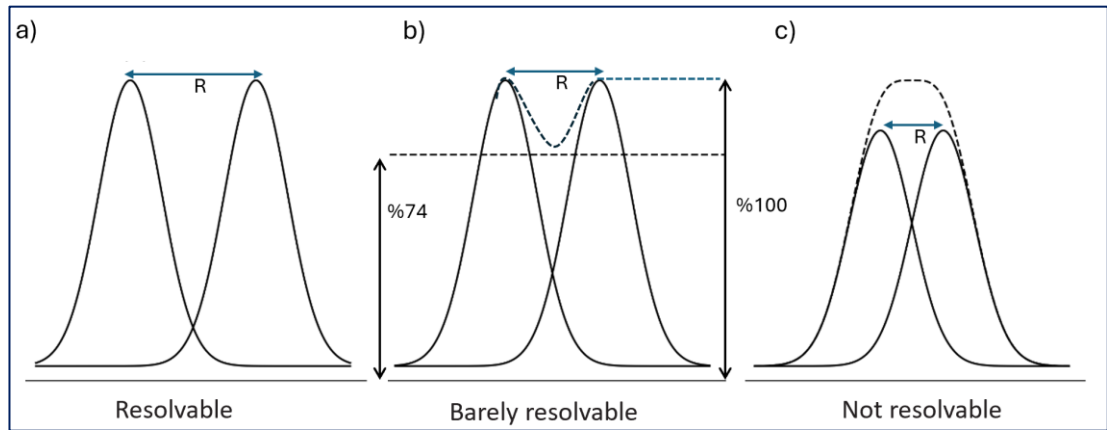


Figure 4.1: Resolution

In **Figure 4.1** above, Criteria for distinguishing two point sources. Solid lines show individual intensity distributions; dashed line represents their combined profile. (a) Sufficiently separated and distinctly resolved, (b) marginally resolved per Rayleigh criterion, (c) too closely spaced to be distinguished.

4.2 Spot Diagram

Spot diagrams are essential tools in optical performance assessment, offering insight into the spatial distribution of ray intersections at the image plane. These diagrams help evaluate both geometric fidelity and wave-optical constraints, especially in identifying aberration-induced deviations from ideal imaging.

The theoretical limit of focusing precision in any optical system is governed by diffraction, even in the absence of geometrical aberrations. The diffraction-limited spot, described by the Airy disk, sets a lower bound on the smallest achievable focal region. Its diameter is given by:

$$d_{Airy} = 2.44 \frac{\lambda \cdot f}{D} \quad (4.2)$$

where λ is the wavelength, f is the focal length, and D the aperture diameter. As illustrated in **Figure 4.2**, this diffraction boundary dictates that even an aberration-free system cannot converge light into an infinitesimal geometric point.

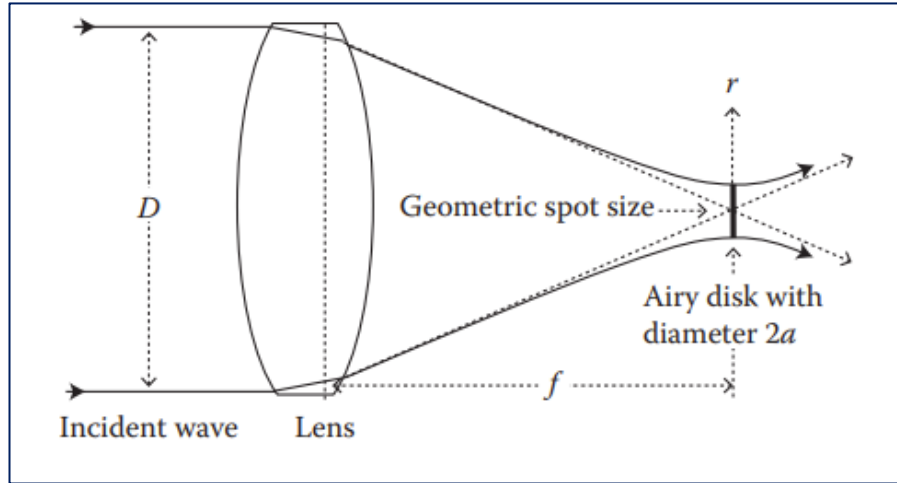


Figure 4.2: Idealized lens focusing a collimated wavefront. Geometric spot size is diffraction-limited by the Airy disk diameter [3].

Zemax OpticStudio enables the overlay of ray intersections on the Airy disk boundary within spot diagrams, facilitating direct comparison between actual and theoretical system performance. A spot pattern tightly confined within the Airy circle indicates diffraction-limited imaging, while any significant spread signals the presence of aberrations or alignment errors.

To quantify the spread of rays, the Root Mean Square (RMS) Spot Radius is often computed:

$$r_{RMS} = \sqrt{\frac{\sum_{i=0}^N r_i^2}{N}} \quad (4.3)$$

Where;

N is the total number of rays considered in the spot diagram.

r is the radial distance of the i th ray from the centroid (ideal image point).

This metric provides a statistical measure of spot compactness, serving as a performance index for optimization routines. If the RMS radius remains within the Airy disk, the system is considered to operate at diffraction-limited conditions.

Wavefront diffraction originating from a circular aperture produces a central Airy disk surrounded by concentric rings, as visualized in **Figure 4.3**. The central lobe contains approximately 84% of total energy and its radius a .

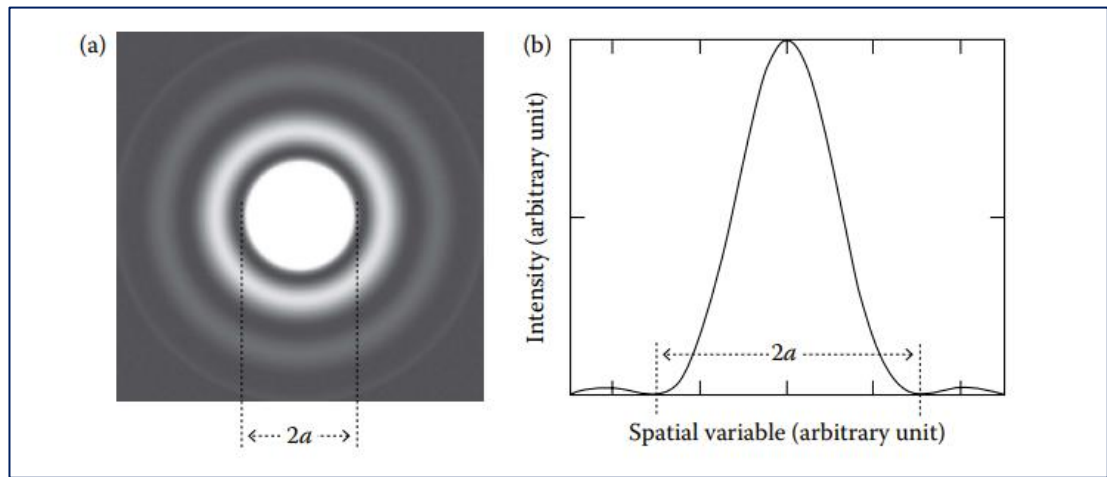


Figure 4.3: (a) Simulated two-dimensional circular diffraction pattern. (b) Intensity profile of a circular diffraction. The radius a of an Airy disk is defined as the radius of the first dark ring [5].

The emergence of this pattern can be described by Kirchhoff's diffraction integral, whose solution shows that:

- Increasing wavelength broadens the Airy disk,
- Enlarging the aperture D narrows it.

Therefore, to achieve higher resolution, designers often aim to increase aperture size or reduce focal length. This strategy is particularly relevant in systems like microlens arrays or compact imaging sensors, where diffraction-limited performance is desired in a small form factor.

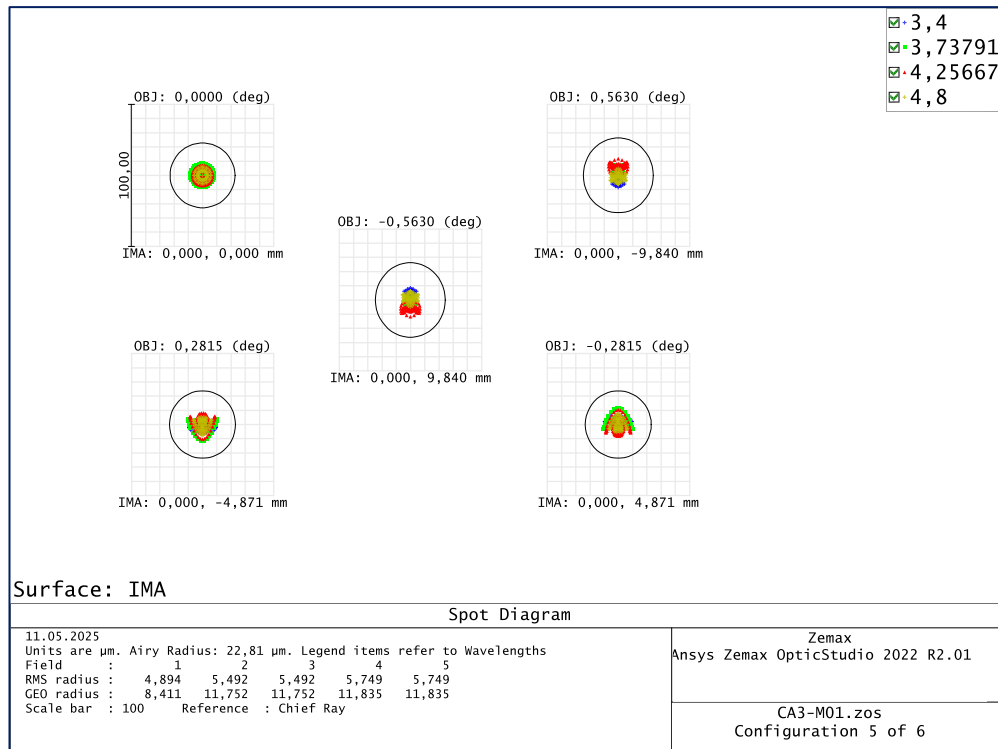


Figure 4.4: Spot Diagram Example at Zemax OpticStudio.

In multi-wavelength designs, spot diagrams must be evaluated across all relevant spectral bands. Since $d_{\text{Airy}} \propto \lambda$, the diffraction limit varies with wavelength, complicating chromatic aberration control. Zemax-based spot diagram comparisons at various field points and wavelengths support informed decisions on glass types, element spacing, and corrective optics.

Figure 4.4 shows the spot diagram of a system in Zemax OpticStudio as an example. This spot diagram shows the distribution of light rays in the image plane for different field angles in the optical system. Each dot represents how well the system focuses the light, and the circle indicates the theoretical diffraction limit (Airy disk). Smaller and more consistent dots across the field indicate good image quality and minimal aberrations. The colors correspond to different wavelengths and help evaluate chromatic aberrations. Larger or irregular dots in off-axis positions may indicate problems such as field curvature or coma. This analysis is important for evaluating the overall optical performance, especially in multispectral systems.

In summary, spot diagrams, RMS spot size analysis, and Airy disk overlays provide a comprehensive framework for analyzing and optimizing imaging performance near the physical limits imposed by diffraction.

4.3 MTF

The Modulation Transfer Function (MTF) is one of the most fundamental metrics for evaluating the imaging performance of optical systems. It quantitatively describes the system's capability to reproduce spatial details from the object to the image. MTF analysis is extensively employed throughout the optical design process as well as in final performance validation, serving as a critical indicator of resolution and image quality.

The image signal passing through an optical system is typically characterized by certain levels of contrast and detail. In evaluating these signals, the concept of modulation is employed. Modulation is defined based on the maximum (I_{max}) and minimum (I_{min}) intensity values of a signal, and is expressed as:

$$Modulation = \frac{(I_{max} - I_{min})}{(I_{max} + I_{min})} \quad (4.4)$$

This expression quantifies the contrast level of a spatial signal and forms the foundation for the Modulation Transfer Function (MTF) in optical system analysis.

The Modulation Transfer Function (MTF) is obtained by comparing the modulation in the object plane to that in the image plane. It is defined as:

$$MTF = \frac{\text{Modulation in the Image}}{\text{Modulation in the Object}} \quad (4.5)$$

An MTF value close to 1 indicates that the system can accurately transfer fine details from the object to the image. Conversely, an MTF value approaching 0 signifies a significant loss of detail in the image [8].

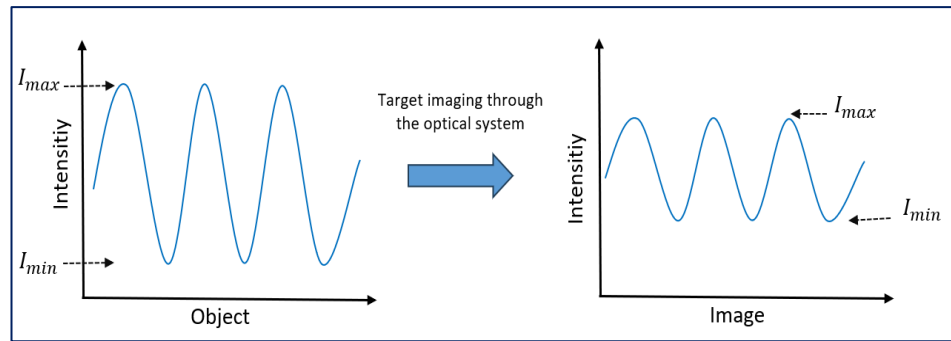


Figure 4.5: Understanding the Modulation Transfer Function Through Illustration.

Figure 4.5 illustrates the basic principle of the Modulation Transfer Function (MTF), which quantifies the ability of an optical system to maintain contrast as it passes from object to image.

On the left side of the **Figure 4.5**, the sinusoidal curve representing the Intensity value of the object is a target with ideal modulation characterized by prominent peaks. As light propagates through the optical system, imperfections such as diffraction, aberrations, and scattering reduce the amplitude of this pattern. On the right side of the **Figure 4.5**, the corresponding image intensity distribution is shown. The general shape is preserved, but the contrast is reduced; this reduction in modulation (contrast), especially at higher spatial frequencies, directly affects image sharpness and resolution.

This figure effectively demonstrates how spatial information is attenuated throughout the imaging chain and why MTF is a critical metric for evaluating optical performance, especially in systems that require high-resolution accuracy, such as aerial imaging, reconnaissance, and surveillance optics.

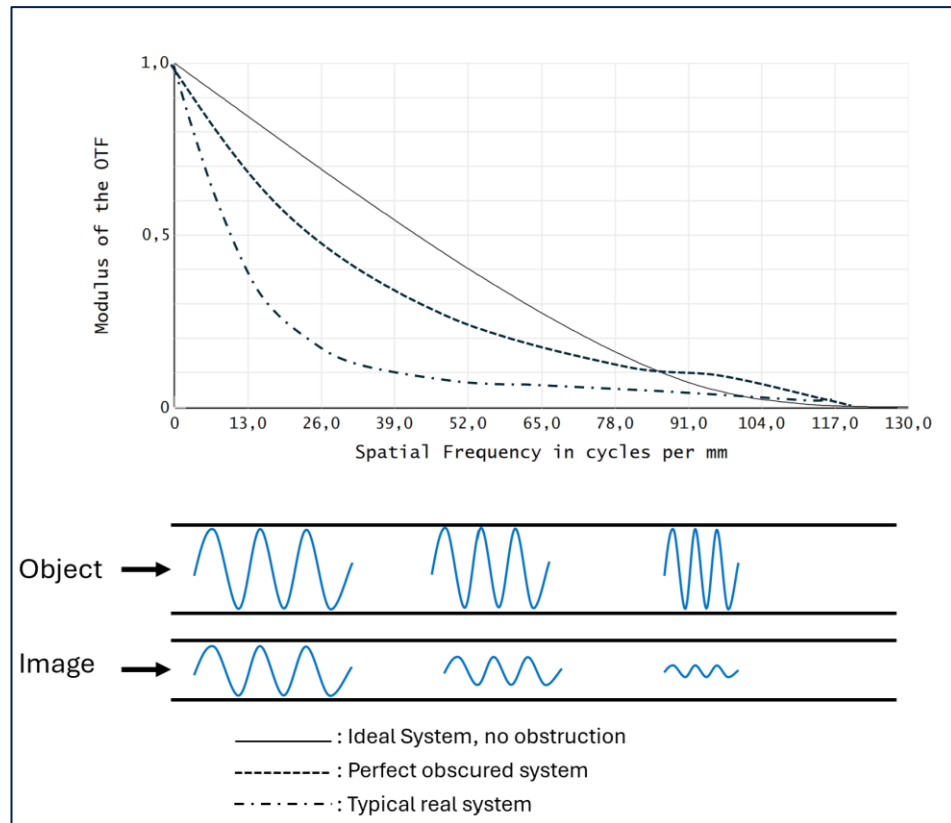


Figure 4.6: Typical MTF System

Cut off Frequency

The spatial frequency at which the MTF drops to zero is referred to as the cutoff frequency, and it represents the theoretical resolution limit of the system. For a diffraction-limited system, this value is expressed as:

$$f_{cutoff} = \frac{1}{\lambda(F/\#)} \quad (4.6)$$

Where;

λ = Wavelength of the system

$F/\#$ = F number of the system

Nyquist Frequency

The highest spatial frequency that the image sensor can sample without aliasing, defined by the pixel pitch.

The Nyquist frequency is defined as:

$$f_{Nyquist} = \frac{1}{2 \cdot p} \quad (4.7)$$

Where; p is the pixel size

This expression defines the physical limit of the system. For example, a system operating at F/3 with a wavelength of 4 μm has a cutoff frequency of approximately 83.3 line pairs per millimeter (lp/mm).

Moreover, achieving MTF values above 0.3 at or near Nyquist especially as observed in Section 6.4.1 demonstrates that the system is not only well-matched to the sensor but also exhibits efficient optical correction, consistent with high-resolution imaging standards [3].

This balance between optical resolution and sensor sampling is essential for avoiding aliasing and for maximizing image quality across varying operating conditions.

4.4 Encircled Energy Analysis

Encircled energy describes the proportion of optical power that is concentrated within a specified radial distance from a point image on the focal plane. This performance metric is commonly visualized through a curve that plots the cumulative energy percentage as a function of radius, serving as a practical indicator of an optical system's focusing capability.

In imaging systems utilizing CCD or CMOS sensors, encircled energy analysis is particularly relevant for aligning optical performance with sensor characteristics. A critical design consideration is the match between the energy-concentrating ability of the optical system and the detector's pixel pitch. For instance, in systems where the sensor has a 10 μm pixel pitch, design requirements might specify that 80% of the optical energy should fall within a 10 μm radius spot. This ensures that most of the light is captured by a single pixel, thereby maximizing spatial resolution and allowing tolerance for minor manufacturing deviations.

As illustrated in **Figure 4.7**, a representative encircled energy plot for an example system demonstrates that 80% of the light energy is enclosed within a 10 μm radius.

This result confirms good compatibility with typical sensor resolutions and indicates sufficient design margin.

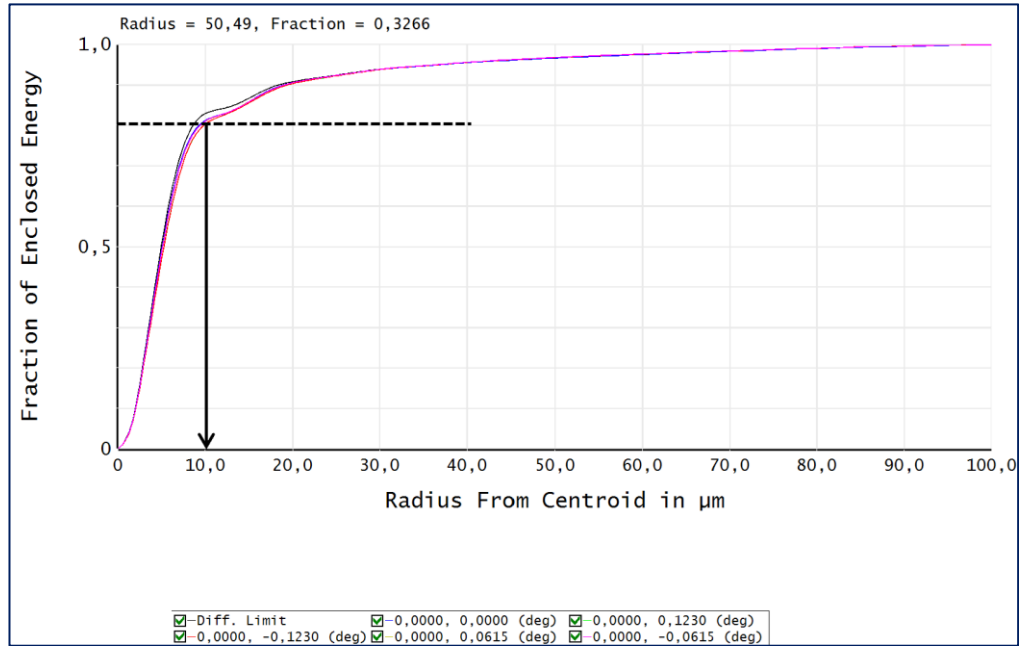


Figure 4.7: Encircled energy.

Encircled energy curves are influenced by several factors, including diffraction effects and residual aberrations. Departures from ideal accumulation patterns can reveal imperfections in lens design or misalignment. Therefore, this analysis plays a vital role in validating optical quality and is especially useful for evaluating image sharpness across the field of view.

In encircled energy analysis, key factors include the percentage of energy contained within a given radius, the image size (which should correspond to the sensor pixel size), and the effects of diffraction or aberrations. Variations in energy accumulation can be caused by diffraction or optical aberrations, which can distort the expected results.

4.5 Wavefront and OPD Analysis

Up to this point, we have frequently used the term "ray" to describe light. However, since light behaves as an electromagnetic wave, the concept of the "wavefront" is also commonly employed. A wavefront is an imaginary surface where all points share the

same phase. The propagation direction of any point on a wavefront aligns with the ray passing through it. Each ray represents the local normal to the wavefront [5].

When dealing with a set of parallel rays, the wavefront takes the form of a plane (illustrated in two dimensions in **Figure 4.8a**). Conversely, for rays emerging from an infinitesimally small point, the wavefront forms a sphere (depicted in two dimensions in **Figure 4.8b**). A sharp image point can only be formed by a converging spherical wavefront. However, in practical optical systems, the converging wavefront generated by a lens typically deviates from a perfect sphere. The Optical Path Difference (OPD) refers to the deviation between the actual wavefront and the ideal reference sphere.

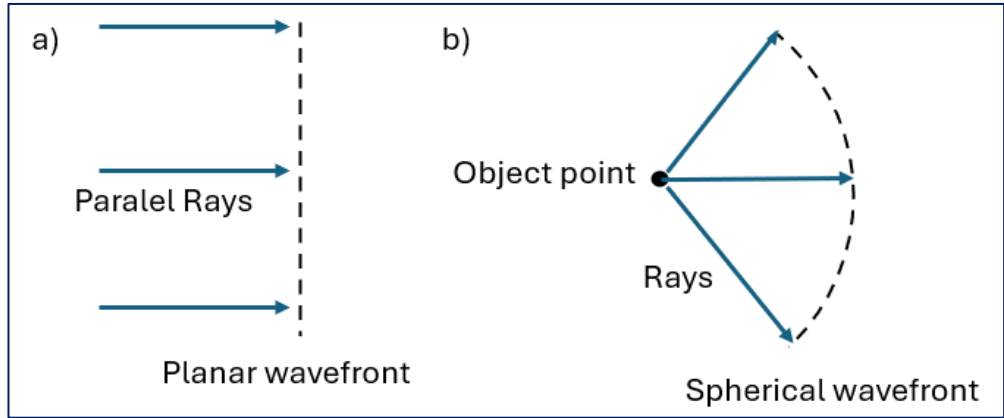


Figure 4.8: (a) Parallel rays have a planar wavefront. (b) Rays from a small object point have a spherical wavefront.

A real wavefront can take on a complex shape due to the presence of aberrations, causing variations in Optical Path Difference (OPD) at different points. The way OPD is calculated affects its value. The root-mean-square (RMS) OPD (OPD_{RMS}) is the most commonly used measure, while the peak-to-valley (PV) OPD (OPD_{PV}) is sometimes considered as well. **Figures 4.9a** and **4.9b** depict examples of OPD_{PV} for wavefronts with different geometries.

The is mathematically expressed as:

$$OPD_{RMS} = \sqrt{\frac{\sum_{i=1}^n OPD_i^2}{n}} \quad (4.8)$$

where n represents the number of sampled points on the wavefront. Although there is no fixed rule for choosing n , logical mathematical principles are typically applied to ensure a meaningful result.

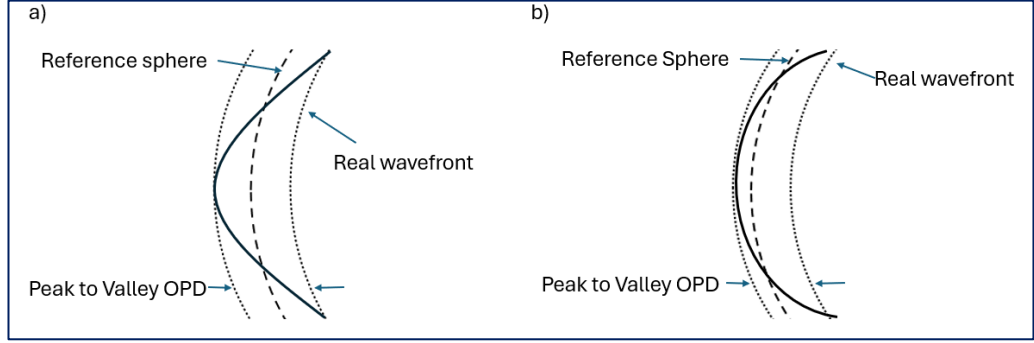


Figure 4.9: Solid curves show real wavefront. The dash curves are the reference sphere. The dotted curves define the OPD_{PV} . The OPD_{RMS} in (a) is larger than the OPD_{RMS} in (b). While the OPD_{PV} in (a) and (b) are the same.

Since wavefronts can take various forms, there is no direct mathematical correlation between OPD_{PV} and OPD_{RMS} . However, OPD_{PV} is generally several times greater than OPD_{RMS} . In **Figure 4.9a**, the OPD_{RMS} value is higher than that of the wavefront in **Figure 4.9b**, though both have identical OPD_{PV} values.

OPD is a key parameter for assessing the quality of both the wavefront and the optical system responsible for generating it. It is widely used in optical system analysis. According to the Rayleigh criterion, an optical system is considered nearly ideal if OPD_{PV} does not exceed 0.25 of the operating wavelengths [6].

4.6 Ray Trace Curves (Ray Fan)

In optical design, metrics such as Modulation Transfer Function (MTF), Point Spread Function (PSF), and Encircled Energy are commonly used to assess image quality. While these methods effectively represent system performance, they have two key limitations. First, their computation can be time-consuming, though modern computing power has mitigated this issue. More importantly, these metrics do not provide direct insights into the specific types and magnitudes of aberrations affecting the system. This lack of detailed aberration information makes it challenging for designers to determine the necessary corrective measures.

To address this issue, transverse ray aberration curves are used. These graphical representations allow designers to quickly identify and analyze aberrations such as spherical aberration, coma, astigmatism, field curvature, axial color, and lateral color. By visualizing these aberrations, optical designers can diagnose problems more efficiently and make informed decisions for further lens optimization.

Transverse ray aberration curves are generated by tracing rays through the exit pupil of a lens and plotting their deviations from the principal ray at the image plane. The X-axis represents the normalized pupil coordinate, while the Y-axis indicates the deviation (Δy) of the ray from the principal ray. In the case of third-order coma, for instance, the resulting curve follows a parabolic shape. If an additional coordinate system is introduced, where the X-coordinate represents the horizontal position in the exit pupil and the X-axis represents lateral ray shift (Δx), the tangential ray fan exhibits a parabolic curve, while the sagittal ray fan remains a straight line.

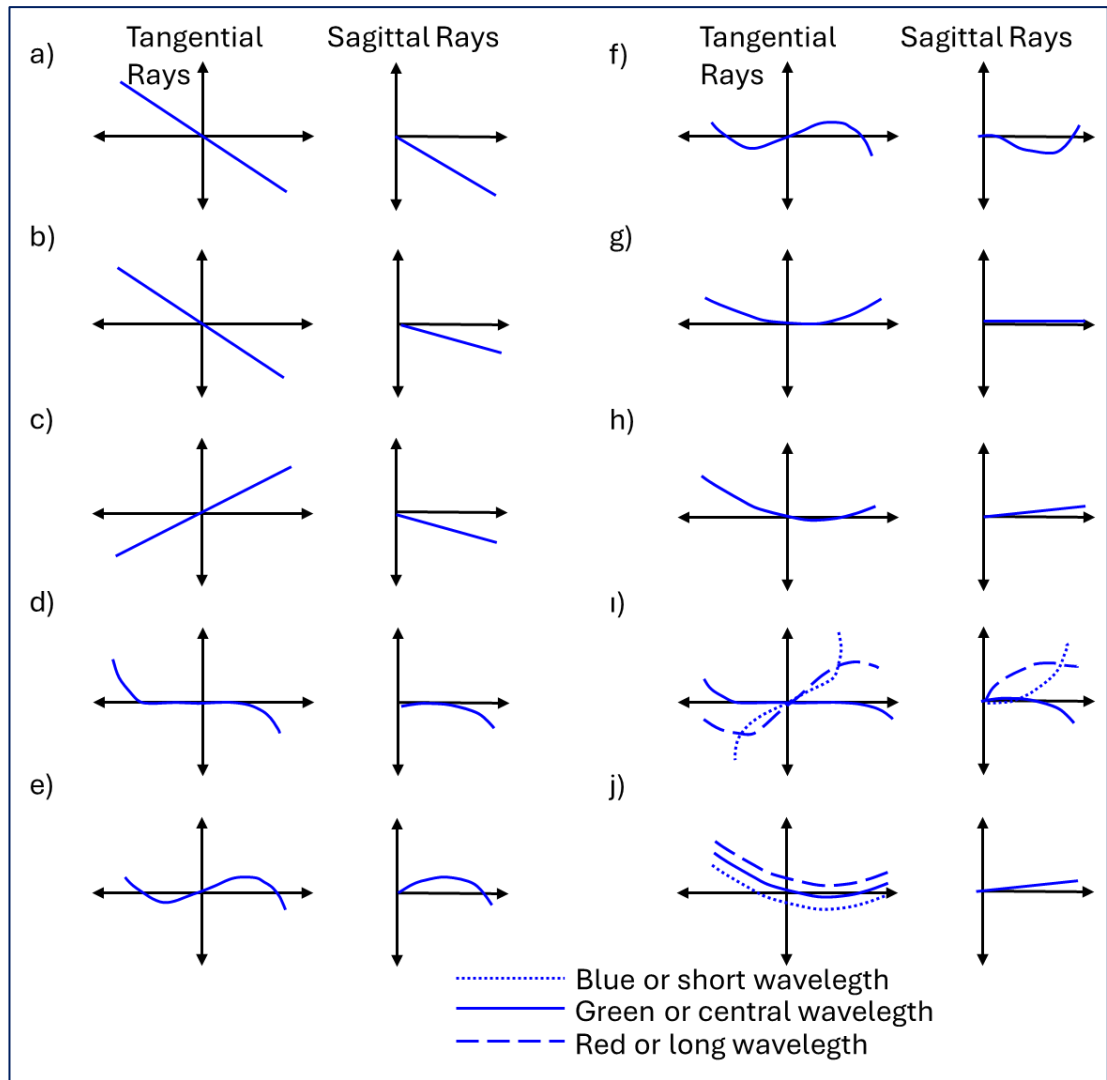


Figure 4.10: Typical transverse ray aberration curves.

Despite their usefulness, transverse ray aberration curves have certain subtleties that must be considered. For example, although coma may not show a shift along the X-axis in these plots, it still causes image blurring in that direction. This discrepancy arises because transverse ray aberration curves typically represent only the tangential and sagittal components, without fully capturing the three-dimensional nature of ray deviations. Additionally, the shapes of these curves vary depending on the field position and wavelength used in the analysis.

In conclusion, transverse ray aberration curves provide a powerful tool for identifying and understanding optical aberrations. Unlike conventional image quality metrics, they allow designers to directly visualize aberrations and their magnitudes, facilitating more precise and efficient lens optimization.

The distinct ray fan patterns corresponding to various optical aberrations are illustrated in **Figure 4.10**. To aid interpretation, **Table 4.1** provides a detailed summary of each subfigure, describing the aberration type, characteristic shape of tangential and sagittal ray fans, and associated optical implications.

Table 4.1: Description of typical transverse ray aberration curves corresponding to different optical aberrations shown in **Figure 4.10**.

Label	Aberration Type	Tangential Ray Fan	Sagittal Ray Fan	Description
a	Defocus	Linear curve with constant slope	Same slope as tangential	Pure defocus; both fans are straight lines with identical slope.
b	Astigmatism + Defocus	Straight line with slope	Straight line with different slope	Defocus plus astigmatism; difference in slope indicates astigmatic separation.
c	Astigmatism (Best focus)	Equal and opposite slope curves	Equal and opposite slope curves	System focused at midpoint between sagittal and tangential foci.
d	Under corrected 3rd-Order Spherical Aberration	Cubic curve (negative spherical)	Cubic with smaller amplitude	Aberration increases with aperture radius.
e	3rd-Order Spherical (Re-focused)	Flatter cubic curve centered at optimal focus	Same as tangential	Focus adjusted to reduce blur.
f	3rd + 5th Order Spherical Aberration	Compound curve	Similar compound shape	High-order correction applied to balance 3rd order.
g	3rd-Order Coma	Parabolic shape	Flat line	Sagittal fan appears zero due to coma symmetry; misleading for blur extent.
h	Coma + Astigmatism	Tilted parabola	Combination of tilt and curvature	Mixed aberrations produce asymmetric patterns.
i	Secondary Axial Color + Spherical Aberration	Multi-wavelength curves with varying focal lengths	Same	Color focus shift between red, green, blue; wavelength-dependent spherical aberration.
j	Lateral Color + Coma + Astigmatism	Wavelength-separated ray fans	Wavelength-separated curves	Off-axis lateral color causing color fringing, combined with mild coma and astigmatism.

5. OPTICAL SYSTEM TYPES

5.1 Dioptric Systems

Dioptric (all-refractive) optical systems present several advantages in imaging design. A primary benefit is the absence of central obscuration, which enables improved optical throughput and typically higher Modulation Transfer Function (MTF). These systems can support larger fields of view and faster f-numbers due to the efficient transmission of refractive elements. Moreover, designs incorporating only spherical surfaces can simplify manufacturing and reduce fabrication costs.

However, dioptric systems are generally longer and heavier compared to reflective counterparts. Chromatic aberration is a significant drawback, requiring additional lens elements for correction, especially in broadband or infrared (IR) applications. Optical materials suitable for IR wavelengths tend to be expensive, and thermal sensitivity (athermalization challenges) further complicates system performance.

An example of a classical dioptric configuration is illustrated in **Figure 5.1**, which shows a Cooke Triplet lens.

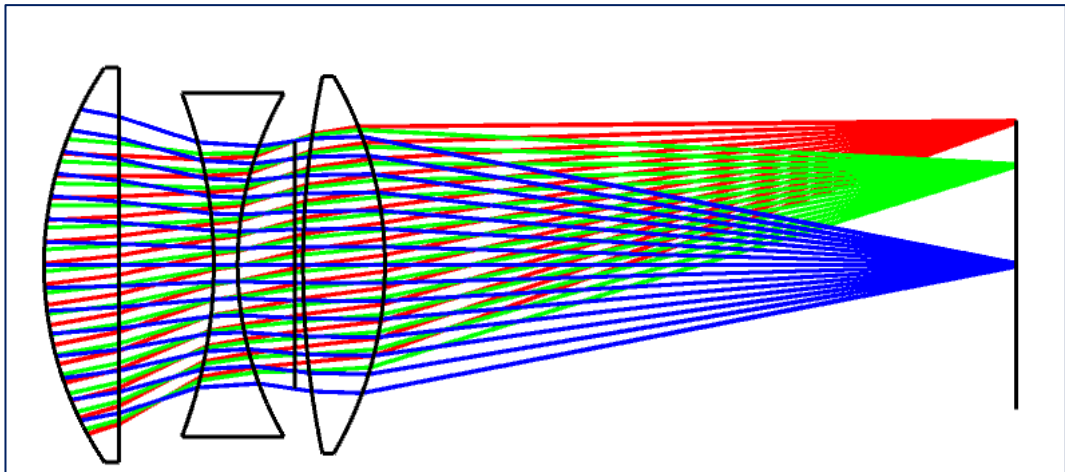


Figure 5.1: Cooke Triplet.

5.2 Catoptric Systems

Catoptric (all-reflective) systems offer distinct advantages, notably the complete elimination of chromatic aberration, since reflection is wavelength-independent. Furthermore, when mirrors and structural components are fabricated from similar materials, these systems can be inherently athermal, providing enhanced thermal stability. Their compact geometry and lower mass make them favorable in weight-sensitive or spatially constrained applications. This is particularly advantageous in IR systems, where high-quality transmissive materials are costly.

On the other hand, catoptric systems often suffer from central obscuration due to secondary mirror placement, which can reduce image contrast and degrade the MTF. Off-axis configurations can eliminate this issue, but at the cost of increased physical size and complexity. Additionally, achieving optimal performance typically requires the use of aspheric mirrors, which complicates manufacturing and increases cost. Catoptric systems generally have narrower fields of view and higher f-numbers, limiting their use in wide-angle or high-throughput applications.

Figure 5.2 presents a three-mirror anastigmatic system as a representative catoptric configuration.

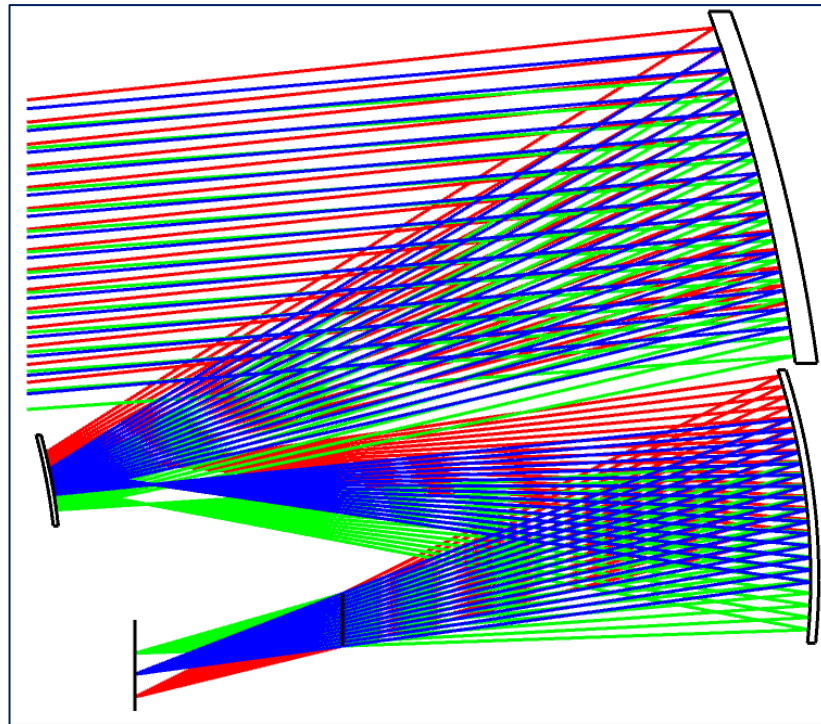


Figure 5.2: Three mirror cook objective design templates [9].

5.3 Catadioptric Systems

Catadioptric systems integrate both refractive and reflective elements, combining the strengths of dioptric and catoptric architectures. This hybrid approach enables more compact designs than all-refractive systems while maintaining a degree of chromatic correction and cost efficiency. The reflective components help reduce overall chromatic aberration, and faster f-numbers can be achieved, enhancing the light collection efficiency an important factor in low-illumination scenarios.

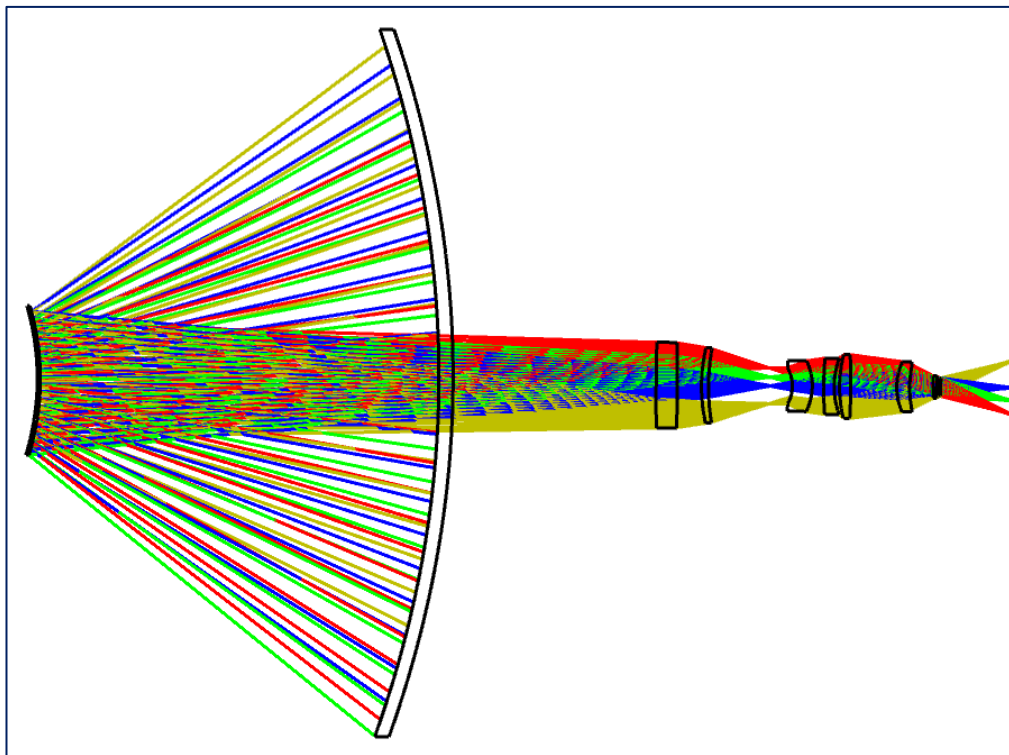


Figure 5.3: Cassegrain Cooled Infrared camera design.

Despite these benefits, catadioptric systems may still exhibit some level of chromatic aberration due to their refractive elements. Nonetheless, the presence of mirrors mitigates this issue to a certain extent. Thermal sensitivity remains a consideration, though catadioptric systems are generally easier to athermalize than purely refractive designs. As such, these systems offer a balanced solution that performs well in multispectral and infrared imaging, particularly in applications requiring compact size, broad spectral range, and moderate cost.

An example configuration of a catadioptric MWIR camera is shown in **Figure 5.3**.

Table 5.1: Comparison of optical system types

Feature	Dioptric	Catoptric	Catadioptric
Chromatic Aberration	High	None	Low–Moderate
Athermalization	Difficult	Easier	Moderate
Field of View (FOV)	Wide	Narrow	Moderate
F-number	Fast (low F/#)	Slow (high F/#)	Fast–Moderate
Weight	High	Low	Moderate
System Length	Long	Short	Short–Moderate
Manufacturing Complexity	Low	High (aspheric)	Moderate
IR Cost Effectiveness	Low	High	Moderate–High

6. OPTICAL DESIGN AND ANALYSIS

The design of multispectral optical systems requires the development of integrated solutions that can accommodate the varying wavelength requirements of different spectral bands while simultaneously meeting challenging criteria such as compactness, high resolution, and stable performance across a wide temperature range. In this context, the technical requirements, optical design process, and detailed performance analyses of the developed system are presented in the following sections.

This chapter focuses on the design and analysis process of a multispectral optical system developed for defense and surveillance applications, operating across the visible, SWIR, and MWIR spectral bands, and providing dual focal lengths for each band at common aperture.

Initially, the operational requirements, sensor parameters, targeted fields of view, focal lengths, and optical F-numbers for each band are outlined. Based on these requirements, the appropriate optical architecture was selected, and the material selections, surface types, and layout strategies for the optical components were determined. Subsequently, the optical modeling, optimization processes, and performance evaluations conducted using Zemax OpticStudio are detailed. The optical performance is assessed through spot diagrams, modulation transfer function curves, field curvature, and distortion analyses. Furthermore, measures taken to enhance manufacturability and environmental robustness, as well as the optimization strategies employed throughout the design process, are discussed in detail. In this study, a common entrance aperture and some shared optical path was implemented for different spectral bands to maintain system compactness while achieving high resolution and effective performance in each band.

In this study, a common entrance aperture and shared optical path configuration were implemented across spectral channels to ensure compactness and alignment integrity while maintaining high imaging performance. This architecture enables consistent optical performance under varying environmental conditions and supports effective imaging across a broad spectral range. Beyond its physical integration benefits, the developed system offers a significant contribution to multispectral imaging technology

by enhancing imaging capabilities in demanding application scenarios—particularly where both long-range detection and fine spatial detail are required. These advancements present clear advantages for defense and surveillance platforms, notably in terms of system integration, operational versatility, and overall performance-to-size efficiency.

6.1 System Architecture and Optical Configurations

This section presents the overall architecture of the developed multispectral optical system, including the use of a common entrance aperture, spectral channel separation strategies, and optical alignment principles. The configurations were selected with consideration of compactness, thermal and mechanical compatibility, and are detailed in terms of optical performance and integration efficiency.

6.1.1 Common Aperture and Cassegrain Optical Configuration

To meet the compactness, alignment, and weight constraints of airborne defense systems, a common entrance aperture was implemented in the optical system architecture. This design allows all three spectral channels VIS, SWIR, and MWIR to share the same input aperture and front optical structure, reducing system volume and simplifying mechanical integration.

The front-end of the system adopts a Cassegrain reflector configuration, consisting of a large parabolic primary mirror and a hyperbolic secondary mirror. The incoming radiation from all spectral bands is first collected by the primary mirror and then reflected towards the secondary mirror. The secondary mirror, which is centrally aligned with the system's optical axis, reflects the light back through a central hole in the primary mirror, directing it toward the rear optical assembly. This Cassegrain structure offers multiple advantages:

- It enables long effective focal lengths to be achieved within a short physical package.
- The reflective nature of the mirrors ensures broadband performance, minimizing chromatic aberrations across the VIS to MWIR range.

- The central obscuration caused by the secondary mirror was optimized to balance optical throughput and modulation transfer function (MTF) performance.
- Mirror diameters, separation distance, curvature radii, and surface coatings were selected and optimized based on the wavelength-dependent reflectivity and mechanical constraints of the payload envelope. The use of protected silver or gold coatings was considered for high reflectivity in infrared bands, particularly in the MWIR region.

The Cassegrain system serves as a shared optical backbone, after which spectral separation is performed to direct each wavelength band to its dedicated image sensor. This configuration not only enables multi-band imaging through a single aperture but also facilitates modular sensor placement and field of view matching across channels.

6.1.2 VIS-SWIR Shared Optical Path

In the developed system, the visible and shortwave infrared (SWIR) channels are designed to operate through a shared refractive optical group. After reflecting off the Cassegrain mirror assembly, the light from both spectral bands follows the same optical axis and enters a common set of lenses. These lenses are composed of optical materials optimized to perform efficiently over a broad spectral range, approximately 400 nm to 1700 nm.

Each channel is capable of providing two different focal lengths through an integrated zoom functionality. The zoom mechanism is realized by translating specific lens elements within the shared optical group. Importantly, the zoom groups are physically shared between the VIS and SWIR channels; however, they are controlled with separate movement profiles tailored to the optical requirements of each spectral band. In other words, while the same optical components are used, they are repositioned differently depending on whether the system is operating in the VIS or SWIR band.

This configuration enables the system to operate in a total of four optical states: VIS short focal length (HFOV:0.322°), VIS long focal length (HFOV:0.212°) and SWIR short focal length (HFOV:0.367°), SWIR long focal length (HFOV:0.244°)

Throughout zoom transitions, the optical axis of the system remains aligned. Changes in focal length are achieved solely by adjusting the positions of the movable elements.

Zemax OpticStudio was used to perform the optical optimization, ensuring that each zoom configuration meets the image quality requirements for its respective channel, particularly in terms of resolution and modulation transfer function (MTF).

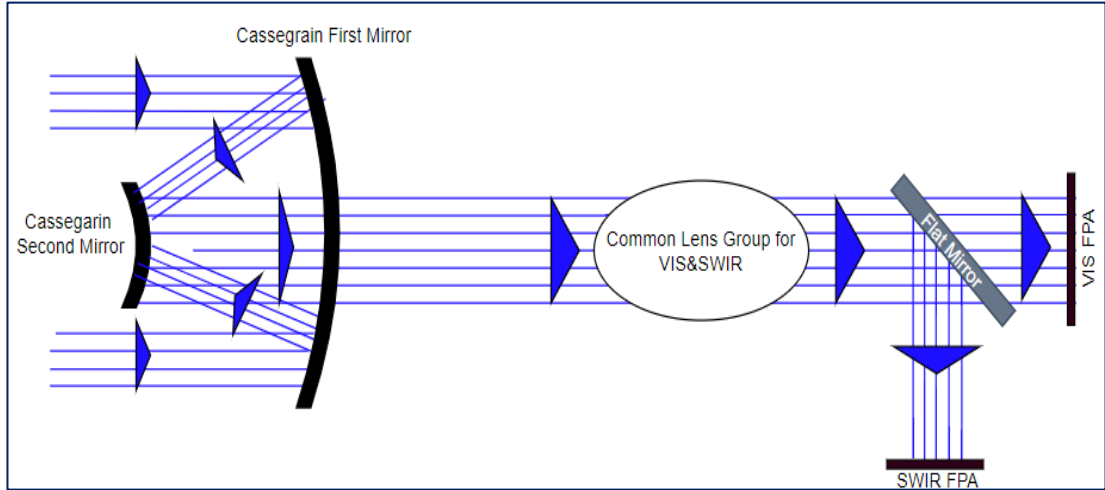


Figure 6.1: Schematic Layout of VIS&SWIR Channel.

Spectral separation between the VIS and SWIR optical paths is implemented near the end of the optical path using a mechanically actuated fold mirror. When positioned within the optical path at a 45° angle, the mirror reflects the SWIR wavelengths toward the SWIR sensor. When retracted from the optical axis, it allows VIS wavelengths to pass directly to the VIS sensor without obstruction. Although both channels share the same optical elements up to the separation point, each maintains a dedicated optical path and channel-specific imaging characteristics beyond this juncture.

In summary, by utilizing a shared lens system with channel-specific zooming and a flexible spectral splitting mechanism, the architecture achieves a compact, versatile, and high-performance multispectral imaging platform tailored to the unique requirements of each spectral band.

6.1.3 MWIR Channel Separation and Optical Isolation

In the developed system, the MWIR channel is designed to be optically separated from the visible and SWIR channels at an early stage. This decision was taken due to the different optical requirements of the MWIR band (e.g. wavelength range, F#, detector

type, cooling requirements and material selection). The MWIR channel is configured with a unique optical path and lens assembly to ensure high optical performance.

While the light reflected from the Cassegrain mirrors proceeds along the optical axis through the central aperture, the MWIR path is folded off-axis using a 45° mirror similar to the mechanism used in the VIS and SWIR channels. This deflection takes place immediately after the central aperture and before the onset of the shared refractive path for VIS and SWIR, enabling the MWIR channel to be independently optimized without influencing the remaining optical system.

The separated MWIR light is directed through its own dedicated lens assembly to the cooled IR detector. The lens materials used in this channel are selected from Germanium (Ge), Zinc Selenide (ZnSe) Silicon (Si) or similar special materials with IR transmission. In addition, this system operates with an optical aperture ratio of F/5, which is determined as the sensor criterion and will be mentioned in section 6.2.1, and is designed to provide high performance at low light levels.

The optical isolation of the MWIR channel provides the following advantages:

- Specific optimization for MWIR, independent of the spectral requirements of VIS and SWIR systems.
- The optical-mechanical integration required by the cooled detector is relaxed.
- The number, placement and diameters of the lenses used in the MWIR channel have been optimized for this band only, improving the performance of the system.
- In addition, the fact that the MWIR channel operates on a separate optical path has been integrated into the overall system to meet the needs of this band for a different focal plane position, lower dispersion and more stable optical structure against environmental conditions.

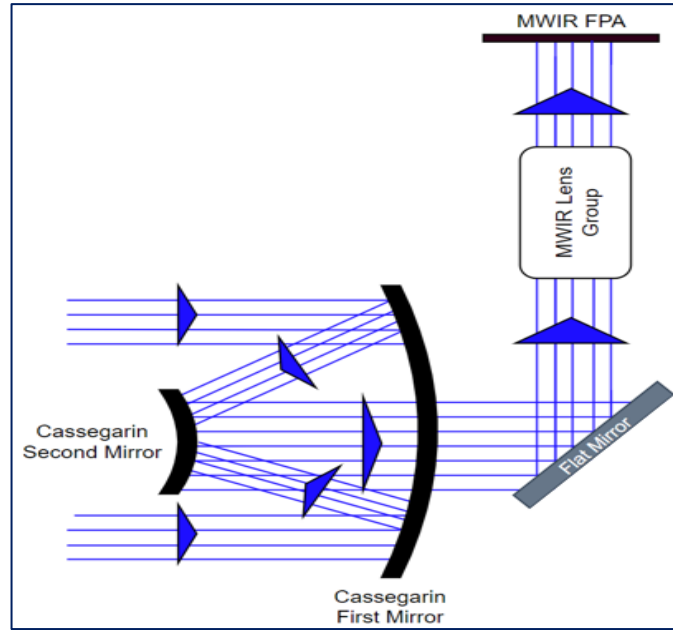


Figure 6.2: Schematic Layout of MWIR Channel

As a result, the optical separation of the MWIR channel from the VIS-SWIR line has enabled the system to achieve a multiband but optimized structure and has brought significant advantages in terms of performance, stability and manufacturability in this band.

6.2 Theoretical Design Stages

The initial phase of multispectral optical system design involves the development of theoretical models that define key optical parameters aligned with specific performance goals. This stage is essential for establishing a structured framework that ensures compatibility between optical functionality and system-level constraints such as physical volume, spectral coverage, and platform integration.

Before engaging in detailed optical modeling, the operational role and imaging requirements of each spectral channel must be clearly defined. This process includes both qualitative and quantitative assessments of mission-specific parameters such as spatial resolution, field coverage, and detection range. Based on this evaluation, initial design specifications including focal length, F-number, and entrance pupil size are determined individually for the VIS, SWIR, and MWIR channels.

Theoretical design activities primarily focus on first-order optical calculations that approximate the core functional parameters of the system. These include the estimation

of entrance pupil diameter, total optical path length, back focal distance, field of view (FOV), and expected image resolution. The geometric layout of the Cassegrain optical assembly is also analyzed to assess its impact on obscuration, optical throughput, and packaging efficiency.

The objective at this stage is to establish a design baseline that balances optical performance with practical implementation constraints. Key considerations include:

- Defining FOV ranges appropriate to the operational needs of each spectral band
- Setting resolution targets that match sensor formats and pixel dimensions
- Constraining the system envelope to enable compact integration into airborne platforms
- Planning the zoom mechanism, including lens group mobility and actuation limits
- Determining the location and diameter of the entrance pupil to optimize light collection

The outcomes of this theoretical framework serve as the basis for subsequent modeling and optimization in Zemax OpticStudio or equivalent design software. The precision of these calculations directly influences the efficiency of the iterative design process and the system's ability to meet image quality criteria in later phases.

Additionally, although each spectral channel operates under distinct wavelength-dependent constraints, this stage involves making critical system-level architectural decisions such as implementing a shared entrance aperture, defining spectral separation strategies, and aligning image planes. These foundational choices play a pivotal role in ensuring optical coherence, mechanical compatibility, and manufacturability of the overall multispectral imaging system. In the following subsections, quantitative calculations and design parameters related to all these factors will be detailed.

6.2.1 Sensor Features Used and Their Effects on Design

In multispectral optical system design, the structural and optoelectronic characteristics of the sensors directly shape key optical parameters. Attributes such as resolution,

pixel pitch, active area dimensions, and spectral sensitivity critically affect decisions regarding focal length, field of view (FOV), and system resolution.

The developed system includes three dedicated channels operating in the VIS (400–700 nm), SWIR (900–1700 nm), and MWIR (3000–5000 nm) spectral bands. Each channel is paired with a sensor specifically selected to satisfy mission requirements, detector availability, integration constraints, and spectral performance criteria.

The optical design implications of sensor parameters can be summarized as follows:

- **Active Area Size:** Together with the focal length, it determines the system’s horizontal and vertical FOV. Larger formats increase scene coverage but necessitate larger optics.
- **Pixel Pitch:** Smaller pixel sizes demand higher optical resolution and superior MTF performance. Achieving diffraction-limited quality becomes critical at this stage.
- **Spectral Sensitivity Range:** Influences lens material selection, anti-reflective coating types, and spectral separation component placement.
- **Cooling Requirements:** Particularly relevant for the MWIR channel, cryogenic sensors impose stricter optical-mechanical constraints, including thermal compensation and housing design.

Each sensor was positioned not only to meet its band-specific imaging goals but also to align with the shared system architecture and folding geometry. These specifications directly informed focal length definition, zoom group layout, and aperture design throughout the system.

The core technical specifications of the sensors used in the VIS, SWIR, and MWIR channels are summarized in **Table 6.1**.

Table 6.1: Key Specifications of Imaging Sensors Used in the System.

Specification	VIS Channel	SWIR Channel	MWIR Channel
Spectral Sensitivity Range	400 – 700 nm	900 – 1700 nm	3400 – 4800 nm
Resolution	1920 × 1080 pixels	1280 × 1024 pixels	1280 × 1024 pixels
Pixel Pitch	5.86 μm	10 μm	12 μm
F-Number	-	-	F/5 (CSH=5.1mm)
Sensor Type	CMOS	InGaAs	InSb
Cooling Requirement	None	None	Yes (cryogenic)
Active Area (approx.)	11.3 mm × 6.3 mm	12.8 mm × 10.2 mm	15.4 mm × 12.3 mm

6.2.2 Field of Views and Focal Lengths

In optical imaging systems, the Field of View (FOV) represents the angular extent of the scene that can be captured by the sensor at a given moment. It is a fundamental parameter that directly influences the operational capability and mission efficiency of the system, particularly in defense and surveillance applications.

The relationship between FOV and focal length is governed by geometric optics principles: as the focal length increases, the FOV narrows, enabling high-resolution observation over a limited area; conversely, shorter focal lengths yield wider FOVs, allowing broader scene coverage at lower spatial detail. For this reason, long focal lengths are typically preferred for detection and recognition tasks, while short focal lengths are better suited for situational awareness and wide-area surveillance.

In multispectral systems, this relationship becomes more complex due to the use of different sensor formats and pixel geometries across the VIS, SWIR, and MWIR spectral channels. Additional design constraints such as system compactness, alignment, and the use of common optical elements further influence focal length and FOV selection.

Table 6.2: Field of View Parameters for Each Spectral Band and Focal Length.

Channel	Focal Length (mm)	Sensor Size (H, V, D) (mm)	HFOV (°)	VFOV (°)	DFOV (°)
VIS	3000	11.26 - 6.34 - 12.96	0.215	0.121	0.247
VIS	2000		0.322	0.181	0.371
SWIR	3000	12.80 - 10.24 - 16.36	0.244	0.195	0.312
SWIR	2000		0.367	0.292	0.468
MWIR	1000	15.36 - 12.29 - 19.68	0.881	0.705	1.123
MWIR	625		1.408	1.125	1.782

Accordingly, specific field-of-view targets are determined for each spectral band, based on sensor dimensions and mission requirements. The horizontal, vertical, and diagonal fields of view for each configuration were computed using the fundamental trigonometric formulas presented in Equations 2.10-12, of Section 2.11, and are summarized in **Table 6.2**.

6.2.3 Entrance Pupil and F-Number

In the optical system developed, the selection of entrance pupil diameter and F-number values was determined by jointly evaluating the optical requirements of each spectral channel and the structural constraints of the system. As the primary reference point, the aperture requirement of the cryogenically cooled detector used in the MWIR channel was considered.

This detector is specified by the manufacturer to operate at an aperture ratio of F/5, which directly defines the aperture parameter of the MWIR optical path. For the MWIR channel's narrow field configuration, a focal length of 1000 mm was selected, and together with the fixed F/5 value, this defines the maximum entrance pupil diameter of the system as 200 mm.

Throughout the design process, this 200 mm value was adopted as the system-wide maximum optical aperture. This decision impacts not only the MWIR channel's optical structure but also directly influences the aperture limits of the VIS and SWIR channels. Thus, aperture alignment, optical compatibility, and structural integrity were maintained across the entire multispectral system.

6.2.3.1 Cold Stop Implementation (MWIR Channel)

In MWIR imaging systems, the cold stop plays a critical role in maintaining thermal signal integrity by ensuring that only radiation from the external scene reaches the detector. Located in a cryogenically cooled dewar, the cold stop acts as a thermal aperture, suppressing stray thermal radiation from internal optical and mechanical surfaces. This prevents background noise from degrading image quality and contributes directly to minimizing the Noise Equivalent Temperature Difference (NETD) of the system.

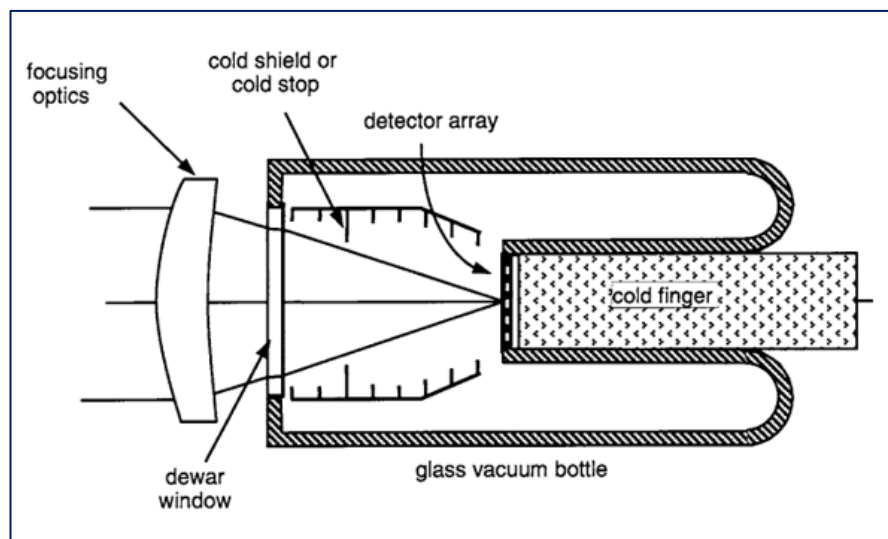


Figure 6.3: Structure of Cooled detector [8].

As shown in **Figure 6.3**, the cold stop (also called the cold shield) is precisely aligned with the detector array and housed in a vacuum-sealed enclosure to isolate it from ambient thermal emissions. The efficiency of this component depends on its alignment with the optical cone defined by the imaging optics.

To ensure maximum cold stop efficiency, the geometry of the optical system must ensure that the entire light cone entering the detector lies within the acceptance angle of the cold stop. This can only be achieved when the F-number ($F/\#$) of the optical system matches the F-number of the detector's internal cold aperture.



Figure 6.4: Cooled MWIR Detector [10].

In the current MWIR channel design, the optical path is specifically designed to achieve this condition. The entrance pupil diameter and F/5 value are specifically chosen to ensure that the cold stop geometry perfectly matches the light cone of the optics and that cold stop efficiency is 100%. This is visualized in **Figure 6.4**, which shows a typical cooled MWIR detector module and its mechanical structure.

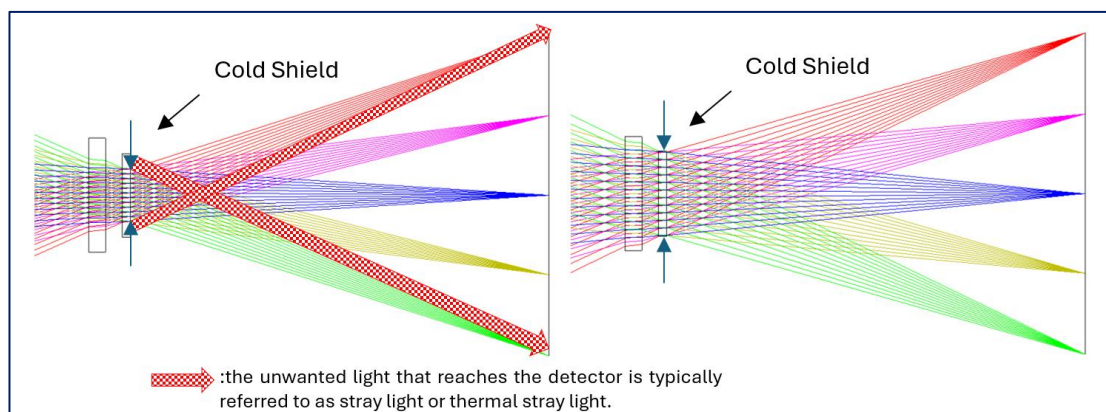


Figure 6.5: Effect of F number matching on cold stop performance.

The comparative schematic in **Figure 6.5** highlights the effect of F number mismatch. On the left, the optical F number and the detector f number are mismatched, causing thermal stray light to bypass the aperture and contaminate the detector. On the right,

the system is properly matched, and the cold stop blocks all radiation outside the cone, allowing only the scene-based signal to reach the detector.

This alignment strategy offers multiple benefits:

Reduces unwanted thermal background, improving the signal-to-noise ratio.

Maintains image uniformity across the field of view.

Prevents thermal blooming and contrast degradation.

By meeting this geometric constraint, the MWIR system achieves high thermal sensitivity without requiring additional stray light suppression measures. These design considerations facilitate system integration by supporting a consistent aperture configuration across all spectral bands while ensuring efficient radiometric performance under MIL-STD-810H environmental conditions.

Table 6.3: Entrance Pupil and F-Numbers by Channel

Channel	Focal Length (mm)	Entrance Pupil Diameter (mm)	F/#
VIS	3000	200	15.0
VIS	2000	200	10.0
SWIR	3000	200	15.0
SWIR	2000	200	10.0
MWIR	1000	200	5.0
MWIR	625	125	5.0

The **Table 6.3** in above shows entrance aperture diameter and F-number against the focal length for all spectral channels (VIS, SWIR, MWIR). This table is referenced during the optical design process to ensure the light collection efficiency, cold stop compatibility and compact layout requirements of the systems.

6.3 Optical Modelling and Design Process

The detailed optical design and system performance optimization were conducted using Zemax OpticStudio in Sequential Mode. The modeling process was based on system-level constraints and spectral requirements defined in earlier sections, and involved six configurations across three spectral bands Visible, SWIR, and MWIR each supporting two distinct focal lengths.

The layout diagram shown in **Figure 6.6** represents the Cassegrain type common reflective optical structure. This structure, which constitutes the initial configuration of the system, consists of a primary concave mirror and a secondary convex mirror. The Cassegrain architecture was chosen because it provides a common entrance aperture for the VIS, SWIR and MWIR bands, as well as allowing long focal lengths to be achieved in a compact optical layout.

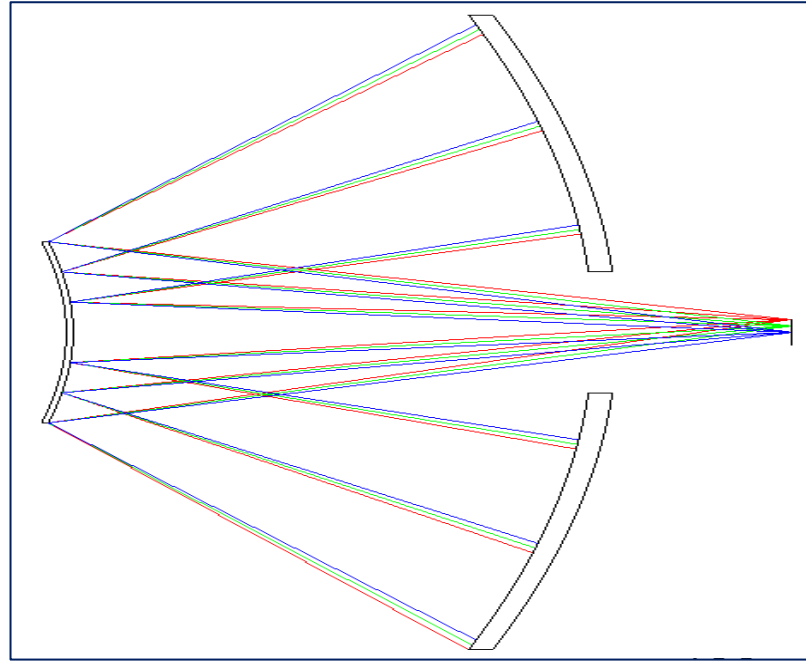


Figure 6.6: Creating a Cassegrain structure.

In the developed architecture, the VIS and SWIR channels share a common optical path up to the final stage of the refractive group. After the initial reflection from the Cassegrain mirror assembly, light from both bands propagates along the same optical axis and enters a shared lens group composed of broadband-compatible materials. Spectral separation between these two bands is performed near the end of the optical path using a mechanically actuated fold mirror. This mirror operates in two discrete positions: at 45 degrees, it reflects SWIR wavelengths toward the SWIR sensor, while in the retracted (0°) position, it allows visible wavelengths to transmit directly to the VIS sensor.

In contrast, the MWIR channel is spectrally and geometrically separated from the VIS-SWIR path at an earlier point in the optical train. After reflection from the Cassegrain secondary mirror, MWIR radiation is diverted using a dedicated 45-degree fold mirror

located just behind the primary mirror's central aperture. This redirection occurs before the common refractive optics used by VIS and SWIR, allowing the MWIR channel to operate through an independent optical assembly optimized for its specific spectral and thermal requirements. This configuration enables full optimization of MWIR optics such as lens materials, spacing, and alignment without being constrained by the VIS-SWIR design.

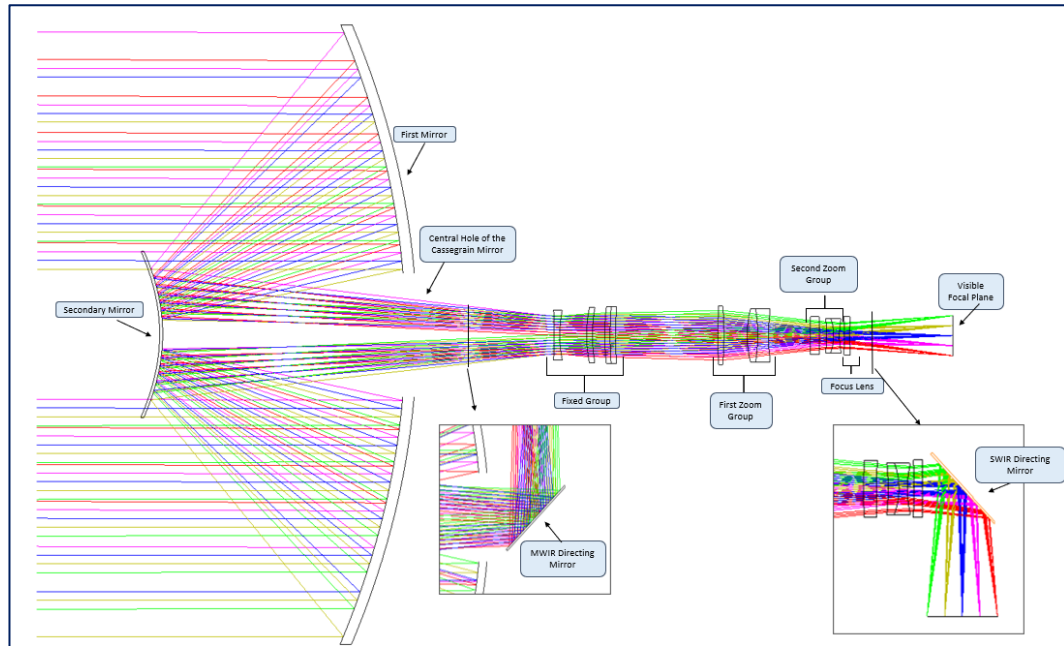


Figure 6.7: Common Aperture Layout

By implementing spectral separation through fold mirrors at two distinct locations early for MWIR and late for SWIR the system achieves compact multispectral integration while preserving optical independence where necessary for performance optimization.

Figure 6.7 illustrates the optical layout of the multispectral imaging system, highlighting the distinct light path configurations for the VIS, SWIR, and MWIR channels. Incoming radiation from the scene first enters the system through a common 200 mm aperture defined by the Cassegrain mirror assembly. The primary mirror collects the incident light and reflects it toward the hyperbolic secondary mirror, which then directs the beam through the central hole in the primary mirror.

At this point, the MWIR spectral band is folded away from the main optical axis via a fixed 45-degree mirror positioned immediately behind the primary mirror. This

redirection occurs prior to the shared refractive group and allows the MWIR path to be completely separated, enabling dedicated optimization for this channel.

The remaining VIS and SWIR bands continue along the main optical axis and enter a shared refractive optical group composed of lenses optimized for broadband performance. At the terminal section of this shared path, a fold mirror is mechanically actuated to enable spectral separation between VIS and SWIR. When positioned at 0 degrees, the mirror allows visible light to transmit directly to the VIS sensor; when rotated to 45 degrees, it reflects the SWIR band toward its respective detector.

This spatial configuration allows each spectral channel to follow a uniquely optimized optical path while maintaining compact system geometry and common entrance aperture alignment

6.3.1 Visible Channel

The optical architecture of the visible channel begins at the system's common entrance aperture and follows a reflective Cassegrain assembly, after which light proceeds through a refractive lens group shared with the SWIR channel. No spectral separation occurs prior to the image plane, enabling the VIS and SWIR channels to operate through a common optical path until the final detection stage. The modeling and optimization of this shared structure were carried out specifically to meet the resolution and contrast requirements of the VIS band.

The VIS channel comprises four sequential lens groups, each designed to contribute to image formation while minimizing aberrations across both zoom states:

- **Fixed Group:** This group consists of three lenses, one of which is a cemented doublet. Located immediately after the Cassegrain exit, this group performs initial beam shaping and corrects most of the system's primary aberrations before any zooming action occurs. The fixed group defines the fundamental geometry and image-forming characteristics of the system and provides a stabilized optical baseline for subsequent zoom operations.
- **First Zoom Group:** This is a positive lens group comprising two elements, including one doublet. It is the first moving group and initiates the change in focal length. Its optical power was optimized to preserve resolution while

expanding or narrowing the field of view without introducing excessive aberrations.

- **Second Zoom Group:** The second zoom group is a negative lens group, also containing two lenses with a doublet configuration. It completes the focal length transition and balances the magnification. The negative-positive pairing between the zoom groups is deliberately chosen to minimize chromatic and spherical aberrations across the entire zoom range, thereby maintaining consistent modulation transfer function (MTF) performance.
- **Focusing Group:** Positioned close to the image plane, this final static element compensates for residual aberrations that may remain after zoom transitions. It serves to refine the focus and maintain alignment with the detector across temperature variations and configuration changes.

Zoom operation within the VIS channel is accomplished by synchronously moving the first and second zoom groups along the optical axis. Their positions were independently optimized in Zemax OpticStudio using the Multi-Configuration Editor to ensure diffraction-limited imaging in both long (3000 mm) and short (2000 mm) focal length configurations.

This multi-group structure with strategically placed doublets and positive-negative balancing was essential to achieve high image quality, effective aberration control, and seamless zoom transitions.

The optical glasses used throughout the VIS channel were selected from CDGM, SCHOTT, and OHARA catalogs. This diverse selection provided the necessary flexibility in refractive index and Abbe number to support achromatic performance and thermal stability across the operating temperature range.

Figures 6.8 and **6.9** illustrate the optical layouts corresponding to the two focal length states of the VIS channel. Additionally, the visible channel lens configuration is shown in **Table 6.4** below, taken from the Lens Data Editor.

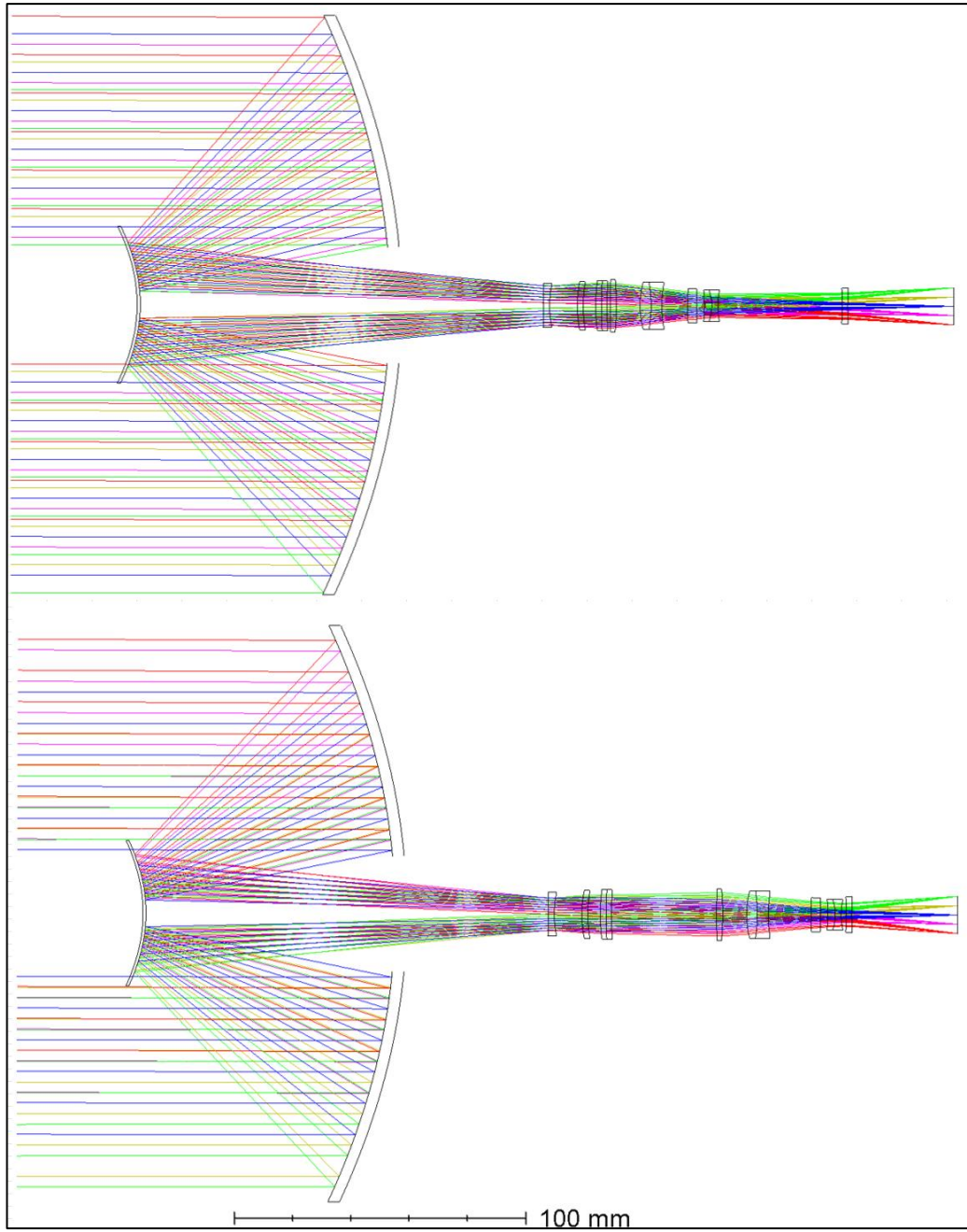


Figure 6.8: Visible 3000 mm (above), 2000 mm (below).

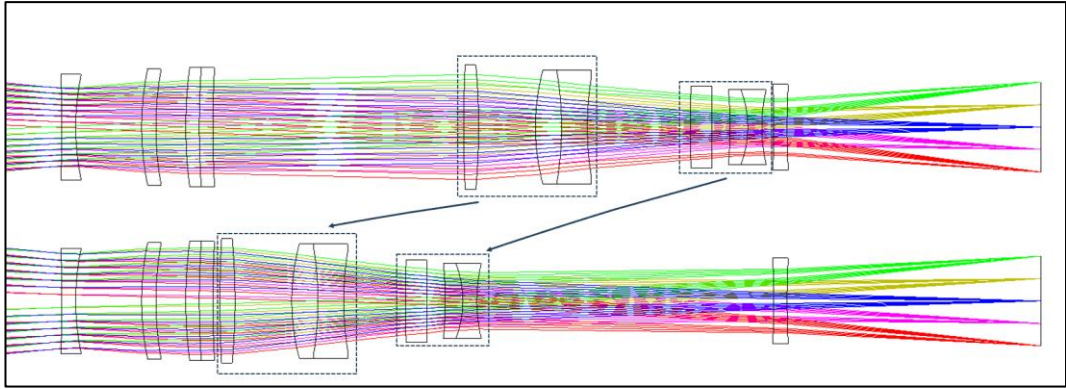


Figure 6.9: Visible Detailed Zoom Movement.

Table 6.4: LDE of Visible Channel.

	Surface Type	Radius (mm)	Thickness (mm)	Material	Semi Diameter
1*	Standard	-217.456	-85.70	MIRROR	100.00
2*	Standard	-51.717	112.83	MIRROR	28.00
3	Standard	Infinity	25.39		10.00
5	Standard	-163.400	1.98	H-ZK50	8.0
6	Standard	36.592	9.49		7.5
7	Standard	41.028	2.05	S-TIH6	9.0
8	Standard	46.534	4.30		8.5
9	Standard	66.551	1.95	N-SF10	9.0
10	Standard	131.991	1.95	N-SK4	9.0
11	Standard	154.454	[1.02]		8.5
12	Standard	180.712	2.16	H-ZLAF68N	9.0
13	Standard	-100.921	8.18		8.5
14	Standard	31.905	3.76	N-SK4	8.0
15	Standard	-47.234	3.71	H-ZF6	7.0
16	Standard	44.440	[8.86]		7.0
17	Standard	156.995	3.13	N-BAK2	5.5
18	Standard	1145.459	2.63		5.0
19	Standard	-52.323	2.52	N-SF10	5.5
20	Standard	-15.076	2.02	N-SK4	5.5
21	Standard	23.161	[42.70]		5.0
22*	Standard	-166.978	1.95	SK5	5.5
23	Standard	123.883	36.49		5.0

The surfaces marked with an asterisk (*) in **Table 6.4** represent non-spherical (aspheric) surfaces, and their corresponding aspheric coefficients are provided in **Table 6.5**.

Table 6.5: Conic constants.

Surface	k
1	-1.03
2	-1.73
22	-6.12

The aspheric equation describing an aspheric surface can be stated as follows:

$$Z = \frac{cr^2}{1 + \sqrt{1 - (1+k)c^2r^2}} + \sum_{i=1}^N a_i r^{2i} \quad (6.1)$$

Where c is the curvature of the surface, k is the conic constant, r is the radial coordinate and a is the aspheric coefficient.

Additionally, thickness values enclosed in square brackets [] indicate variable distances associated with movable elements during zoom operation; their displacement profiles are detailed in **Table 6.6** below.

Table 6.6: Distance of zoom lenses for Visible channel.

Surface	f=3000 mm	f=2000 mm
11	1.02 mm	36.07 mm
16	8.86 mm	14.80 mm
21	42.70 mm	1.70 mm

6.3.2 SWIR Channel

The SWIR channel shares the same optical path as the VIS channel up to the image plane; therefore, the general optical structure is not repeated here in detail. Spectral separation is achieved near the end of the path using a 45° folding mirror that redirects SWIR wavelengths to its dedicated sensor.

Although the lens elements are common, the zoom group motion profiles were independently optimized for the SWIR channel, considering its specific sensor characteristics such as pixel size and active area. The mirror placement and detector alignment were carefully modeled to maintain imaging performance.

Materials and coatings were selected to provide high transmittance in the 0.9–1.7 μm range, and multi-band optimization was applied to ensure MTF compliance across both VIS and SWIR bands.

Figures 6.10 and **6.11** show the long and short focal length configurations of the SWIR channel, respectively, illustrating the shared lens elements and the spectral redirection via the folding mirror. A summary of the SWIR optical configuration, including all lens element specifications and positions, is provided in the lens data editor table at the end of this section in **Table 6.7**.

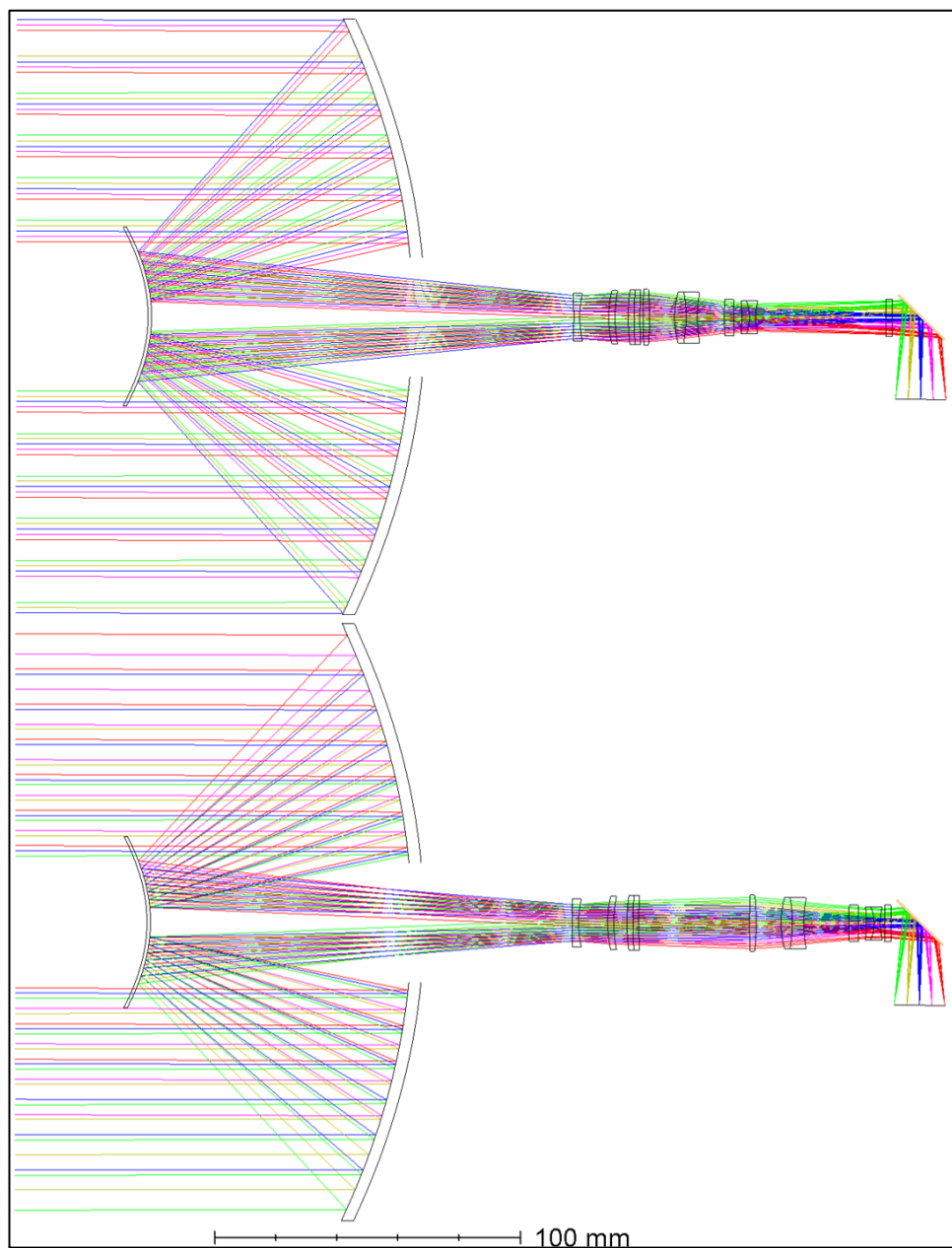


Figure 6.10: SWIR 3000 mm (above), 2000 mm (below).

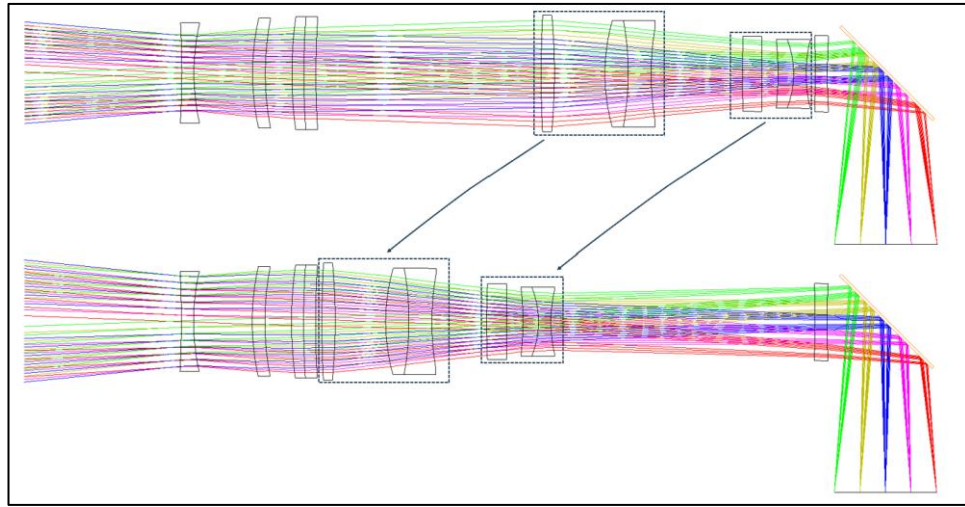


Figure 6.11: SWIR Detailed Zoom Movement.

Table 6.7: LDE of SWIR channel

	Surface Type	Radius (mm)	Thickness (mm)	Material	Semi Diameter
1	Standard	-217.456	-85.70	MIRROR	100.00
2	Standard	-51.717	112.83	MIRROR	28.00
3	Standard	Infinity	23.43		11.79
5	Standard	-163.400	1.98	H-ZK50GT	8.50
6	Standard	36.592	9.49		8.00
7	Standard	41.028	2.05	S-TIH6	9.50
8	Standard	46.534	4.30		9.00
9	Standard	66.551	1.95	N-SF10	9.50
10	Standard	131.991	1.95	N-SK4	9.50
11	Standard	154.454	[1.01]		9.00
12	Standard	180.712	2.16	H-ZLAF68N	9.00
13	Standard	-100.921	8.18		8.50
14	Standard	31.905	3.76	N-SK4	8.50
15	Standard	-47.234	3.71	H-ZF6	8.50
16	Standard	44.440	[8.85]		8.00
17	Standard	156.995	3.13	N-BAK2	6.50
18	Standard	1145.459	2.63		6.00
19	Standard	-52.323	2.52	N-SF10	5.50
20	Standard	-15.076	2.02	N-SK4	5.50
21	Standard	23.161	[42.71]		5.00
22	Standard	-166.978	1.95	SK5	6.50
23	Standard	123.883	9.49		6.00
24*	Standard	Infinity	-27.49	MIRROR	10.60

The surface marked with an asterisk (*) in the table refers to the 45° plane mirror responsible for directing the light path toward the SWIR sensor. This mirror is positioned at a fixed 45° angle relative to the optical axis to enable spectral separation near the image plane.

Furthermore, since all refractive lenses in the SWIR channel are shared with the visible channel, Surfaces 1, 2, and 22 conform to the same conic surface constants used in the VIS design.

The detailed zoom-dependent thickness variations of the relevant optical elements are presented in **Table 6.8** for SWIR channel, respectively.

Table 6.8: Distance of zoom lenses for SWIR channel

Surface	f=3000 mm	f=2000 mm
11	1.01 mm	36.31 mm
16	8.85 mm	14.77 mm
21	42.71 mm	1.49 mm

6.3.3 MWIR Channel

The Midwave Infrared optical path is configured as a fully independent sub-system within the overall multispectral imaging architecture, optimized specifically for the 3–5 μm spectral range. In contrast to the VIS and SWIR channels, which share a common refractive optical group following the Cassegrain assembly, the MWIR beam is spectrally and geometrically decoupled at an earlier stage in the optical path. After reflection from the hyperbolic secondary mirror, the MWIR radiation is folded off-axis via a fixed 45° mirror placed directly behind the primary mirror's central aperture. This early decoupling allows for a dedicated and fully optimized optical path, independent of constraints imposed by the other channels.

Following this spectral separation, the MWIR beam enters a fixed front lens group that performs initial beam shaping and forms an intermediate image plane. This architectural decision effectively implements a re-imaging configuration, where the first image is generated after the fixed group before the beam enters the zoom module. This approach offers several design advantages:

- It allows the separation of the imaging and zooming functions, leading to improved aberration control and image quality.
- It provides a stabilized intermediate image that facilitates better zoom tracking and reduced sensitivity to lens movement tolerances.
- It enables precise cold stop alignment by isolating the thermal and optical design constraints of the front group.

The refractive zoom group, placed after the intermediate image plane, supports two discrete focal lengths: 1000 mm and 625 mm, corresponding to narrow and wide FOV modes, respectively. The zoom module includes a movable pair of lens assemblies a negative lens group and a positive group designed such that the negative group translates toward the positive group to achieve the shorter focal length and retracts to increase the focal length. This zoom architecture ensures that the image plane remains fixed and conjugate to the cryogenic detector's cold stop aperture throughout zoom transitions.

The optical system is constructed using high-transmittance MWIR materials, including Germanium (Ge), Zinc Selenide (ZnSe), and Silicon (Si), all coated with broadband anti-reflective layers optimized for the 3–5 μm range. To further enhance optical performance, two surfaces are implemented as diffractive optical elements, primarily to mitigate chromatic dispersion, and four surfaces are designed as aspherics, enabling efficient correction of off-axis aberrations and improved MTF across the field.

Key image quality metrics including RMS spot radius, optical path difference (OPD), and MTF at the Nyquist frequency were used as merit function constraints during the design optimization. Final analyses confirm that both focal configurations deliver diffraction-limited performance and meet all system-level resolution requirements.

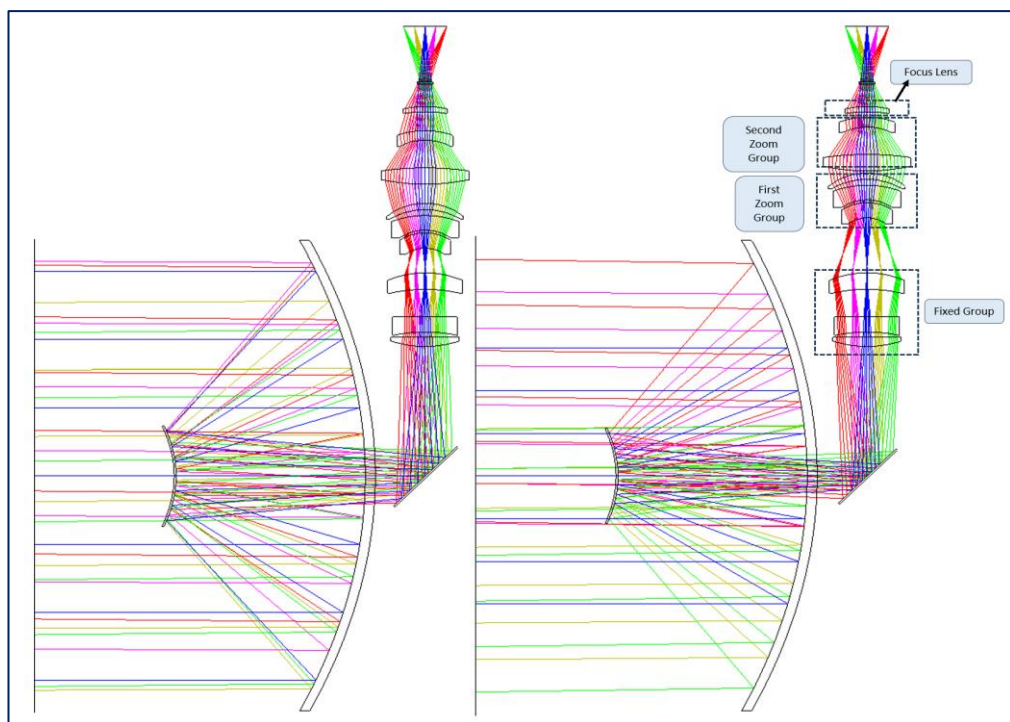


Figure 6.12: Optical layout of the MWIR channel at 1000 mm (left) and 625 mm (right).

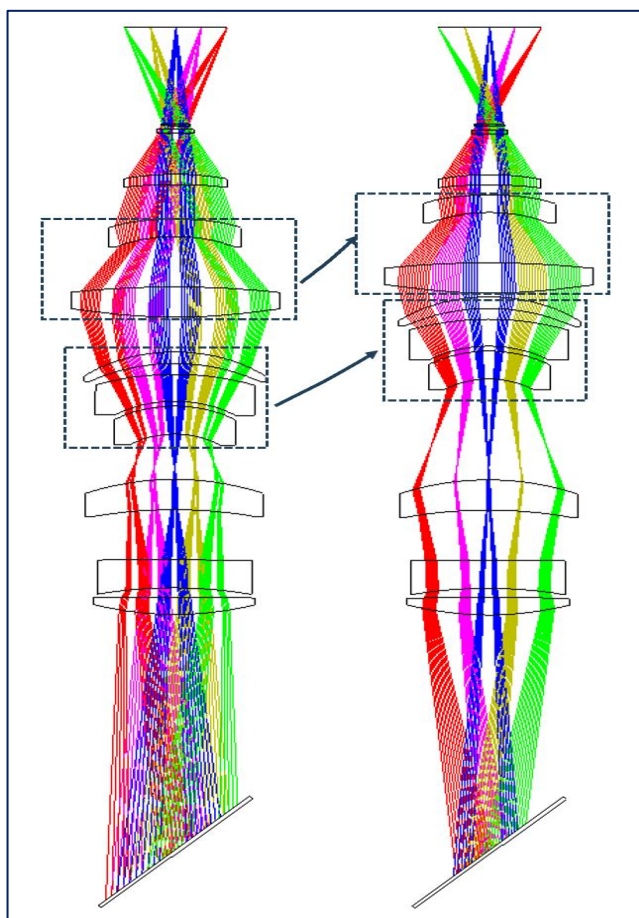


Figure 6.13: MWIR Zoom Details.

Figures 6.12 and **6.13** illustrate the optical layouts corresponding to the two focal length states of the MWIR channel. A lens data editor table summarizing the complete MWIR optical configuration, including element specifications and spacings, is provided at the end of this section at **Table 6.9**.

Table 6.9: LDE of MWIR Channel.

	Surface Type	Radius	Thickness	Material	Semi Diameter
1	Standard	-217.46	-85.70	MIRROR	100
2	Standard	-51.72	112.83	MIRROR	28
3	Standard	Infinity	-62.45	MIRROR*	20.5
4*	Binary 2	-45.55	-4.61	ZNSE	12.00
5	Standard	511.77	-2.41		11.50
7	Standard	65.05	-7.39	SILICON	10.50
8	Standard	2012.98	-13.25		10.00
9	Standard	66.85	-8.00	SILICON	10.00
10*	Even Asphere	41.79	[-11.96]		10.50
11	Standard	14.30	-7.37	SILICON	8.50
12	Standard	20.37	-1.29		10.50
13	Standard	19.91	-7.11	GERMANIUM	11.00
14	Standard	41.84	-2.88		14.00
15*	Even Asphere	28.96	-3.03	GERMANIUM	15.00
16	Standard	26.77	[-9.19]		16.00
17*	Even Asphere	-72.74	-8.00	SILICON	21.00
18	Standard	137.41	-13.31		20.00
19	Standard	24.74	-4.62	SILICON	12.00
20*	Even Asphere	46.33	[-9.09]		13.00
21*	Binary 2	83.59	-2.72	SILICON	10.00
22	Standard	40.53	-10.83		11.00
23	Standard	Infinity	-1.02	GERMANIUM	3.53
24	Standard	Infinity	-1.00		3.41
25	Standard	Infinity	-0.51	SILICON	2.88
26	STOP	Infinity	-25.50		2.55

Surfaces marked with an asterisk (*) in the table indicate the non-standard surfaces specifically implemented in the MWIR channel. These surfaces are designed to minimize edge field aberrations and to maintain high MTF performance across both zoom configurations. Among them, Surfaces 4 and 21 are modeled as diffractive elements (Binary 2), while the remaining four surfaces are defined as even aspheres. The general equation used to define even aspheric surfaces has been provided in the previous section 6.3.1. The specific surface coefficients for both aspheric and

diffractive surfaces are listed in **Table 6.10**. The formulation used for diffractive profiles is presented below as Equation 6.2.

In Zemax OpticStudio, binary optics are modeled not by physically simulating the wavelength-scale grooves, but by applying a local phase advance or delay to the passing wavefront. The Binary Optic 2 surface, in particular, is mathematically identical in shape to the Even Asphere surface, but its coefficients describe a phase function (in radians), not a physical sag. The phase change along the surface is represented by the polynomial expansion in equation 6.2 [11]:

$$\Phi(\rho) = M \sum_{i=1}^N a_i \rho^{2i} \quad (6.2)$$

Where N is the number of polynomial coefficients, a_i is the coefficient on the $2i^{th}$ power of ρ , which is normalized radial aperture coordinate, and M is the diffraction order.

This approach allows for rigorous modeling of phase-only diffractive optics in Zemax, ensuring accurate ray propagation and system performance analysis, while the detailed groove structure is implicitly captured through the phase coefficients. The corresponding coefficients for each diffractive and aspheric surface are reported in **Table 6.10**.

Table 6.10: Coefficient table

Surface	k	a_2	a_3	a_4	ρ^2	ρ^4
4	-0.461	-9.03213×10^{-7}	1.08797×10^{-8}	-1.45088×10^{-11}	12.40	-13.43
10	0.00	1.00128×10^{-5}	-5.84652×10^{-8}	9.07379×10^{-11}		
15	0.00	-2.06877×10^{-6}	-1.33872×10^{-9}	-1.77396×10^{-11}		
17	0.00	3.78666×10^{-6}	-1.362×10^{-9}	2.54914×10^{-12}		
20	0.00	2.4899×10^{-5}	-2.78129×10^{-8}	1.42042×10^{-11}		
21	0.00	1.98027×10^{-5}	-1.27163×10^{-8}	-3.73741×10^{-11}	-47.64	11.01

In addition, thickness values enclosed in square brackets [] denote dynamically varying optical distances associated with the zoom mechanism. These represent the positions of moving lens groups that control the transition between the 1000 mm and 625 mm focal length configurations. The step-specific changes in thickness are also

detailed in **Table 6.11**. It should be noted that negative thickness values in the table are not indicative of physical shortening, but rather denote the direction of optical propagation according to the coordinate system convention used in the Zemax OpticStudio model.

Table 6.11: Distance of zoom lenses for MWIR channel

Surface	f=1000 mm	f=625 mm
10	-1.01 mm	-36.31 mm
16	-8.85 mm	-14.77 mm
20	-42.71 mm	-1.49 mm

6.4 Optical Performances

6.4.1 VIS Channel Performance

The optical performance of the VIS channel was evaluated comprehensively using Zemax OpticStudio, employing a range of standard analysis tools including spot diagrams, polychromatic modulation transfer function (MTF), field curvature, distortion plots, optical path difference (OPD), and transverse ray fan graphs. These metrics are widely used in the optical engineering community for validating the image-forming quality of high-performance imaging systems [3].

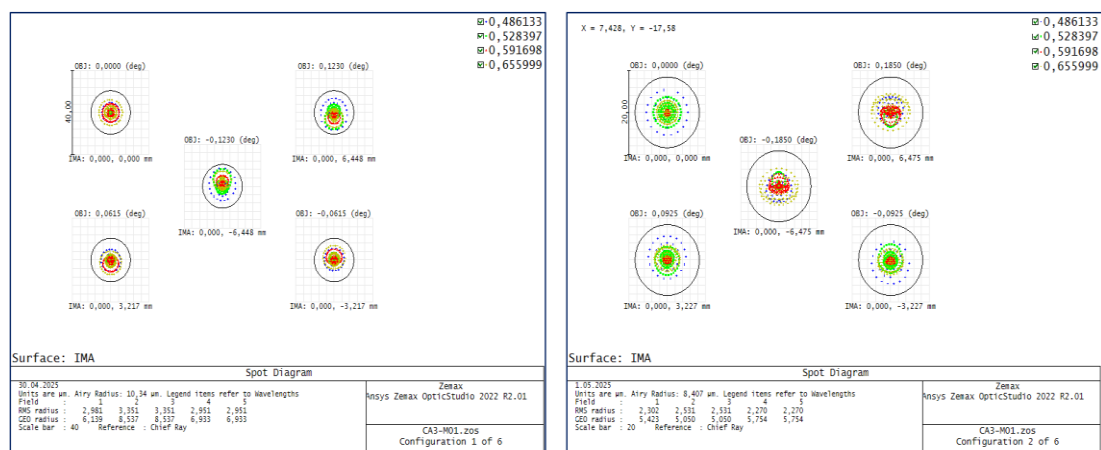


Figure 6.14: a) Spot Diagram for 3000 mm (left) b) Spot Diagram for 2000 mm (right).

The spot diagrams for both the 3000 mm and 2000 mm focal length configurations (**Figure 6.14a**, **6.14b**) demonstrate that all field points maintain root-mean-square

(RMS) spot sizes well within the Airy disk diameter. This alignment with the diffraction limit confirms that the VIS channel achieves near-diffraction-limited performance. As mentioned in section 4.1, According to the Rayleigh criterion and its application in design validation, spot radii remaining within the Airy disk indicate that the system is operating close to its theoretical resolution limit [8].

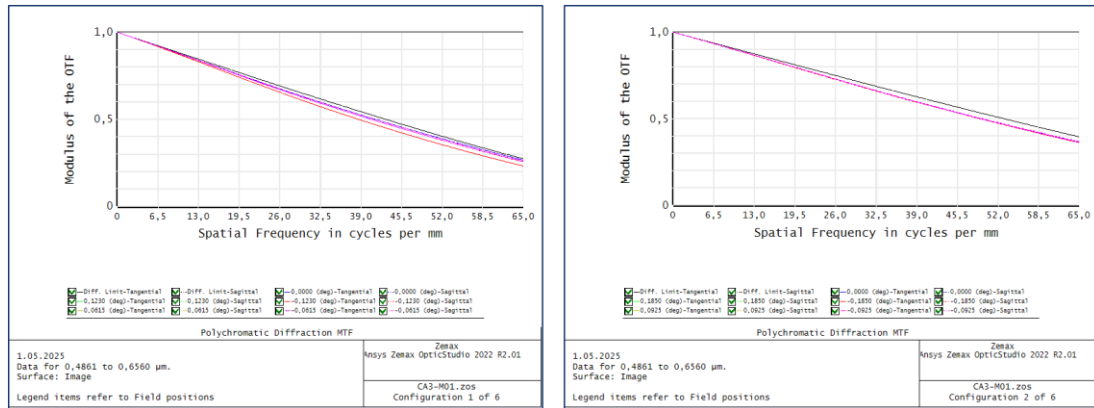


Figure 6.15: a) MTF diagram for 3000 mm (left) b) MTF Diagram for 2000 mm (right).

Polychromatic MTF plots (Figure 6.15a, 6.15b) show that contrast remains consistently above 0.3 at the 60 lp/mm spatial frequency. According to standard system performance criteria, this MTF level is generally acceptable for high-resolution visible imaging systems [6]. Moreover, the retention of contrast across the entire field confirms the system's stability and uniformity.

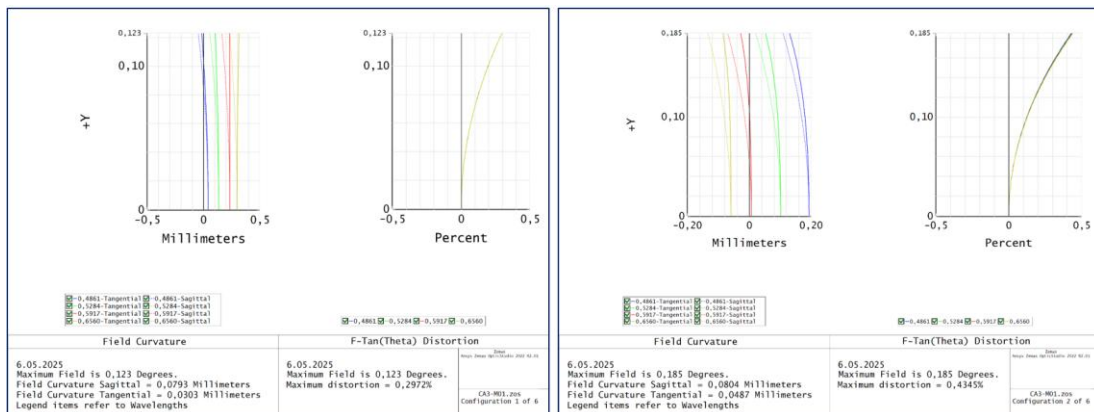


Figure 6.16: a) Field Curvature and Distortion for 3000 mm (left) b) for 2000 mm (right).

As illustrated in **Figure 6.16a**, the sagittal and tangential field curvatures remain under ± 0.08 mm, reflecting a nearly flat image plane a key requirement for systems using planar focal sensors such as CMOS arrays. These values are consistent with acceptable tolerances for high-resolution imaging over narrow FOV systems [3]. The measured barrel distortion values are under 0.5%, which is within commonly accepted limits for long focal length refractive designs [12].

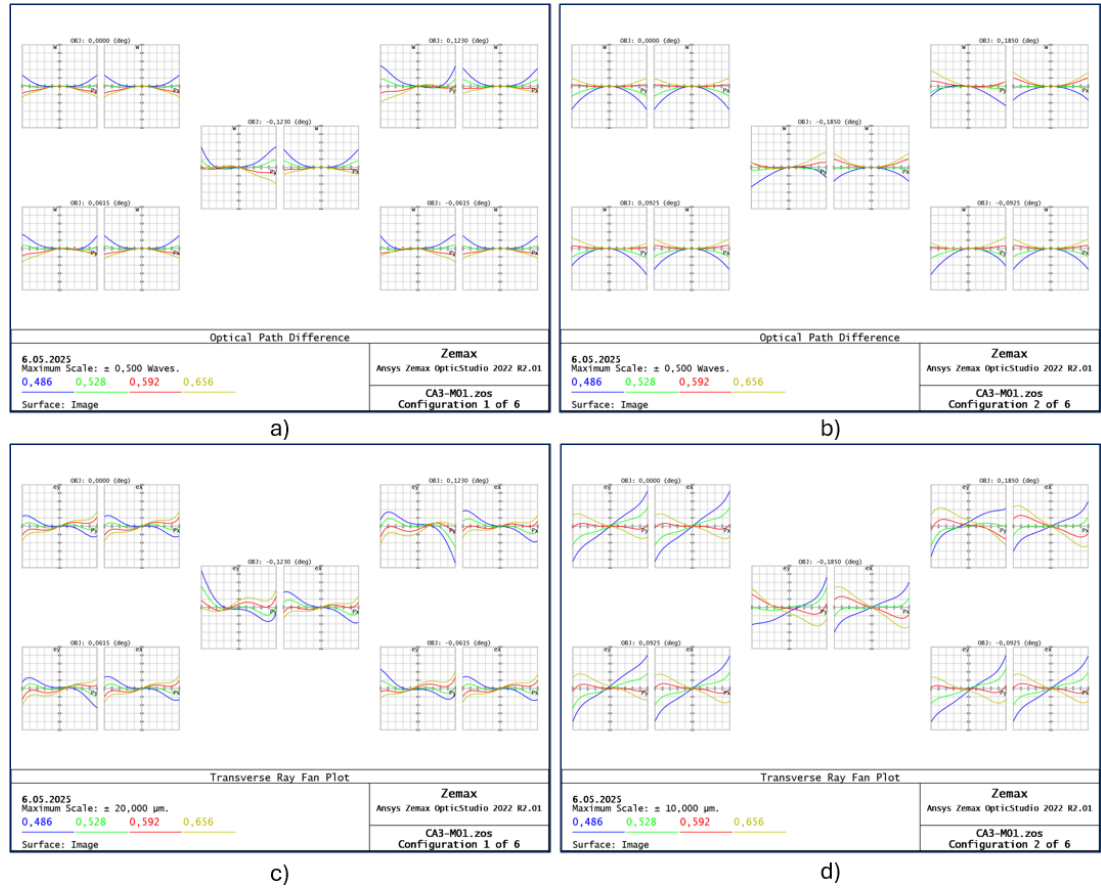


Figure 6.17: OPD fan and Ray Fan diagrams.

The OPD plots (**Figure 6.17a** and **6.17b**) show deviations below ± 0.5 waves across the pupil, which, based on Rayleigh's $\lambda/4$ criterion, implies that the system exhibits minimal wavefront error and thus maintains high optical fidelity [13]. The transverse ray fan plots (**Figure 6.17c** and **6.17d**) exhibit tightly grouped ray deviations without higher-order curvature, confirming that third-order aberrations such as coma and astigmatism are well corrected across the field.

These performance results validate that the VIS channel, under both zoom configurations, meets the optical resolution and imaging fidelity expectations typical for airborne surveillance and reconnaissance systems operating in the visible spectrum.

6.4.2 Optical Performance of SWIR Channel

The optical performance of the SWIR channel was evaluated for two focal length configurations: 3000 mm (narrow field of view) and 2000 mm (wide field of view). Performance metrics were assessed using spot diagrams, Modulation Transfer Function (MTF) curves, field curvature, distortion, Optical Path Difference (OPD), and ray aberration (ray fan) plots, based on simulations performed in Zemax OpticStudio.

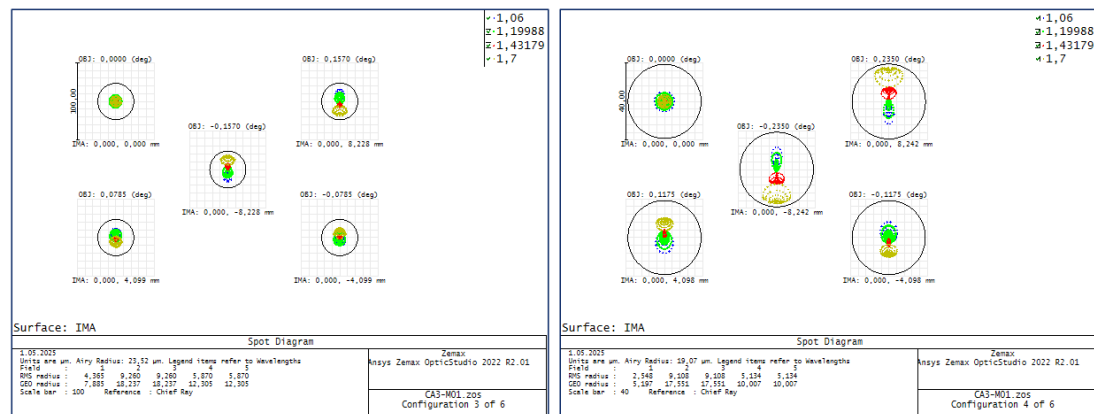


Figure 6.18: Spot diagram of the SWIR channel at a) 3000 mm (left) and b) 2000 mm (right) focal length.

As illustrated in **Figures 6.18a** and **6.18b**, spot diagrams across five field points demonstrate high-quality focusing behavior. At 3000 mm focal length (**Figure 6.18a**), all spots lie well within the Airy disk, indicating near-diffraction-limited performance across the full field. In the 2000 mm configuration (**Figure 6.18b**), slight broadening of spot sizes is observed, particularly at edge field points, yet spot diameters remain below the SWIR sensor pixel size (10 μm), validating adequate spatial resolution for target imaging.

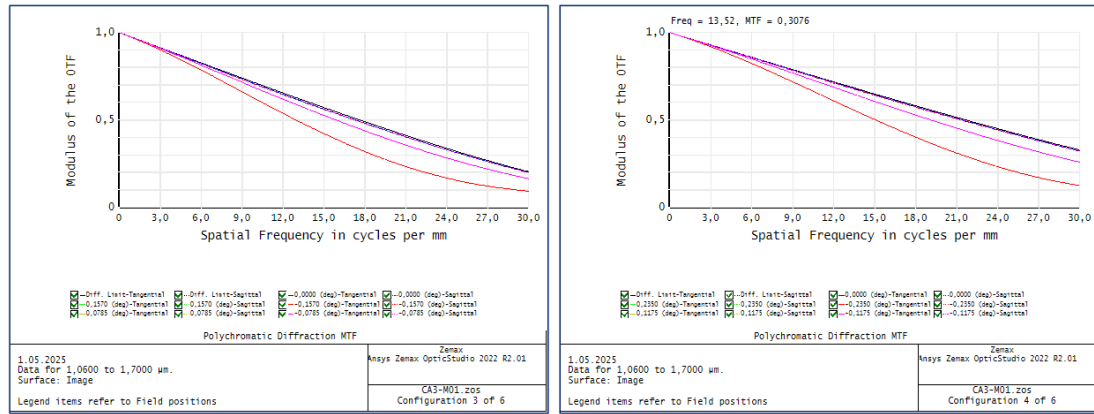


Figure 6.19: MTF curve at a) 3000 mm (left) and b) 2000 mm (right) focal length.

The polychromatic MTF curves (**Figure 6.19a** and **6.19b**) show the system's capability to preserve image contrast at various spatial frequencies. At 3000 mm, the system achieves ~0.5 MTF at 18 cycles/mm, which aligns well with performance expectations for tactical ISR (Intelligence, Surveillance, Reconnaissance) systems in SWIR imaging. The 2000 mm configuration exhibits slightly reduced contrast retention, particularly in the sagittal fields, but the system achieves 0.5 MTF at 18 cycles/mm, as at 3000 mm. This continues to maintain acceptable performance for high-resolution imaging tasks.

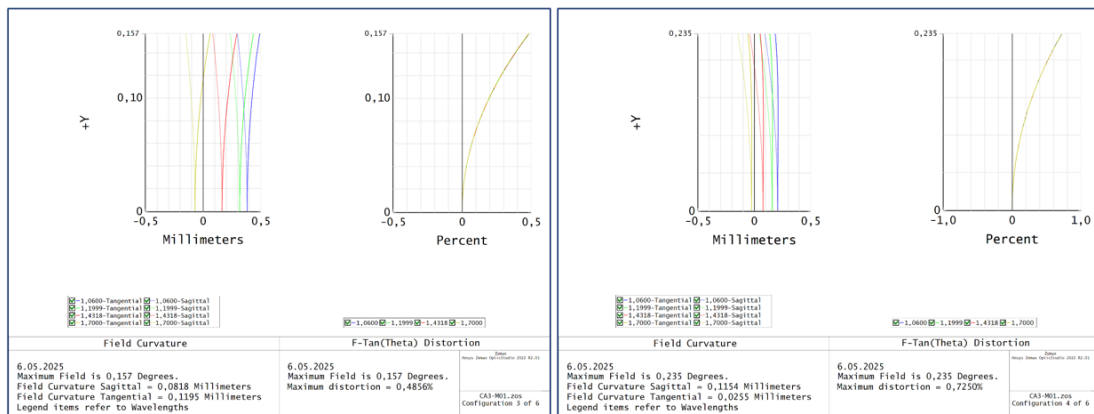


Figure 6.20: Field curvature and Distortion plot at a) 3000 mm (left) and b) 2000 mm (right) focal length.

Figures 6.20a and **6.20b** indicate that both sagittal and tangential field curvatures remain below ± 0.12 mm for both configurations, suggesting that the image plane remains nearly flat across the field. This is essential for ensuring consistent focus across the sensor surface. The distortion plots show values of 0.48% (3000 mm) and

0.72% (2000 mm), which are considered negligible and well within acceptable limits for tactical imaging systems.

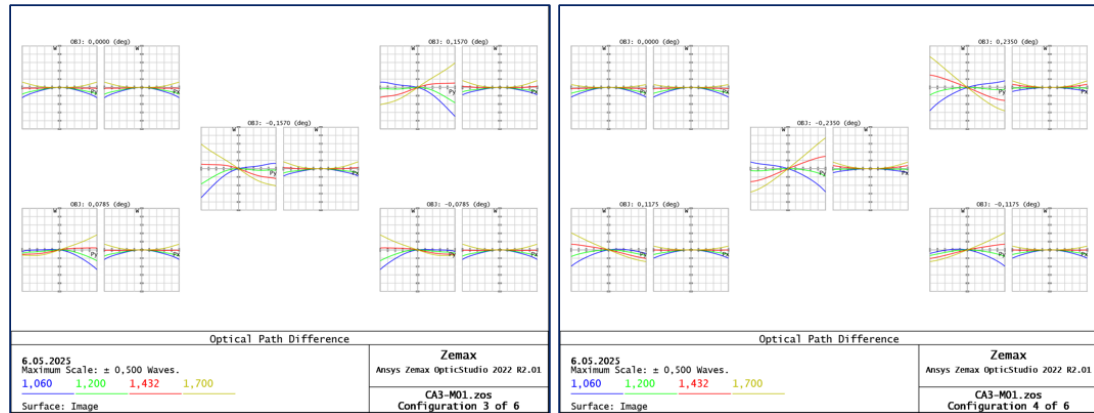


Figure 6.21: OPD analysis at a) 3000 mm (left) and b) 2000 mm (right) focal length.

The OPD plots in **Figures 6.21a** and **6.21b** demonstrate wavefront deviations from the ideal reference sphere. For both configurations, the deviations remain within the $\lambda/2$ threshold across all field points and wavelengths, consistent with the Rayleigh criterion for diffraction-limited optics. This indicates the SWIR channel exhibits high optical wavefront quality, enabling sharp image formation and low phase aberration error.

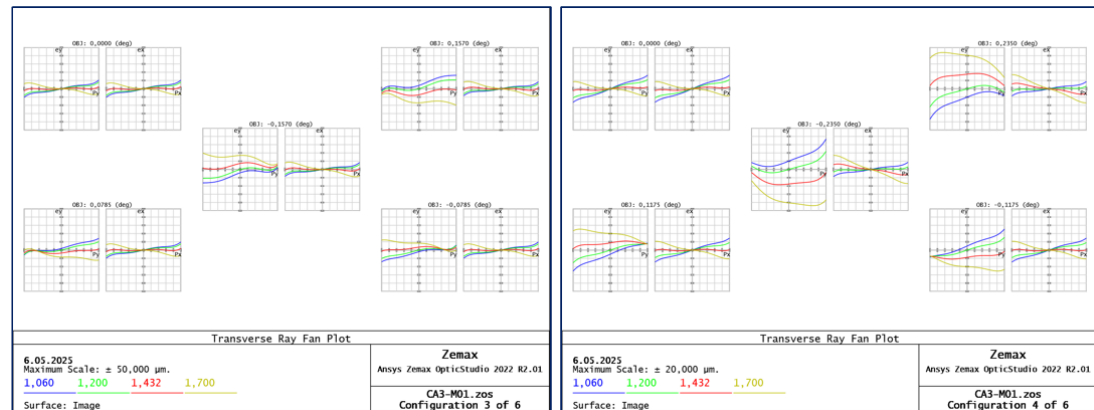


Figure 6.22: Ray fan diagram at a) 3000 mm (left) and b) 2000 mm (right) focal length.

Figures 6.22a and **6.22b** present transverse ray aberration data for tangential and sagittal rays. The fan plots reveal low-order aberration signatures such as minor coma and astigmatism particularly off-axis which are inherent to long focal length systems. However, the symmetry and scale of these aberrations remain tightly controlled. The

$$= \frac{1}{2 \times 0.012} = 41.67 \text{ lp/mm}$$

and the theoretical cutoff frequency based on the system's F/# and the design wavelength (4 μm) is [8]:

$$f_{cutoff} = \frac{1}{\lambda \cdot (F/\#)} \quad (6.4)$$

$$= \frac{1}{0.004 \times 5} = 50 \text{ lp/mm}$$

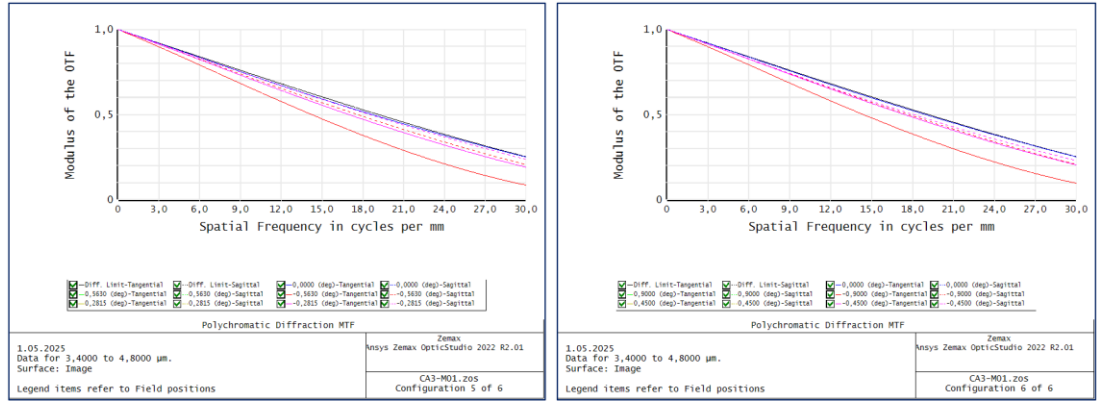


Figure 6.24: MTF plots for a) 1000 mm (left) b) 625 mm (right) across field points.

For the 1000 mm configuration, the MTF values reach the diffraction limit at the Nyquist frequency and exceed 0.5 at approximately at spetial frequency 20 lp/mm. For the 625 mm configuration, the MTF drops slightly at the field edge but still exceeds 0.5 at approximately at spetial frequency 20 lp/mm. These results indicate high image fidelity with sufficient contrast transfer for detailed thermal imaging.

In particular, although the Nyquist frequency remains below the diffraction limit, this is a deliberate design decision. Lowering the F number to extend the limit requires larger optics and compromises the compactness and thermal stability of the system. Therefore, the current configuration represents an optimized balance between resolution, optical aperture, and mechanical constraints [8].

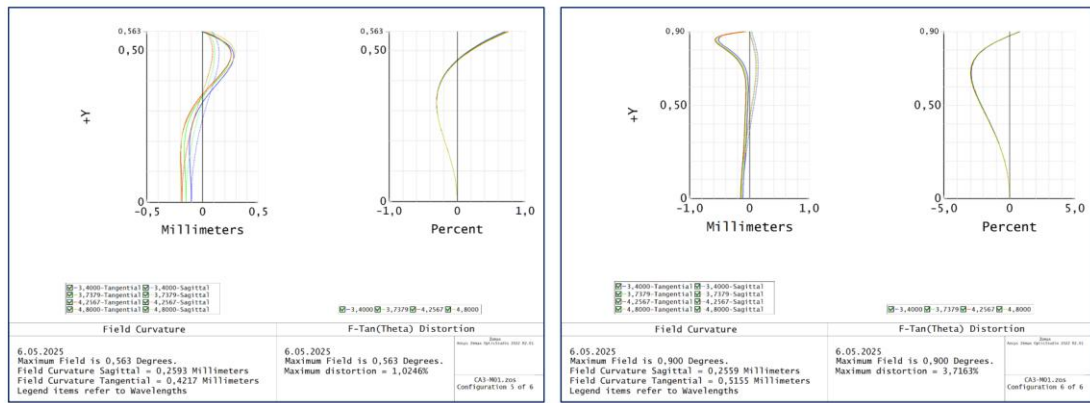


Figure 6.25: Field curvature and distortion for a) 1000 mm (left) and b) 625 mm (right).

Figures 6.25a and 6.25b show field curvature and distortion. For 1000 mm, tangential field curvature peaks at approximately 0.42 mm, while at 625 mm shows increased curvature up to 0.51 mm due to its shorter focal length.

Distortion levels are minimal: < 1.0% at 1000 mm and < 3.7% at 625 mm. These values remain well within acceptable ranges for MWIR imaging systems intended for surveillance and target detection [8].

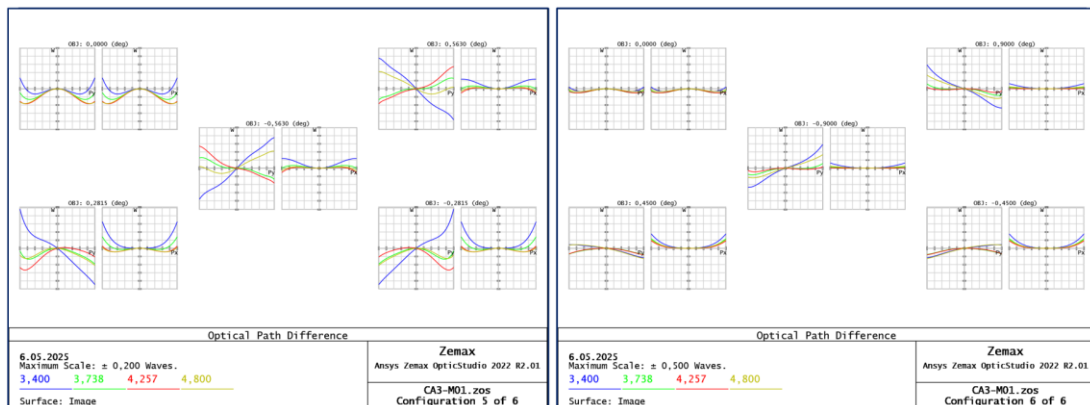


Figure 6.26. OPD fan for a) 1000 mm (left) and b) 625 mm (right).

Figures 6.26a and 6.26b depict OPD plots. Both configurations demonstrate peak-to-valley deviations within $\lambda/4$, satisfying the Rayleigh criterion. At 1000 mm exhibits lower RMS OPD due to reduced field angles, ensuring wavefront quality consistent with diffraction-limited performance [13].

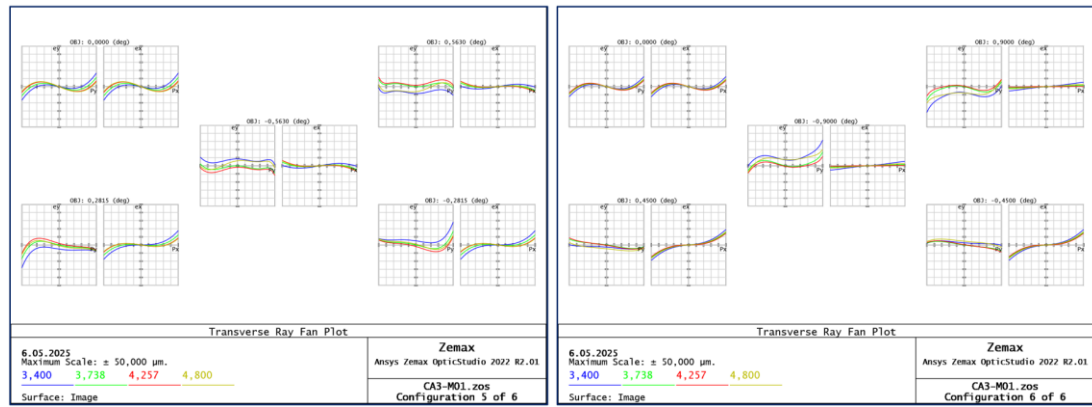


Figure 6.27: Ray fan diagram at a) 1000 mm (left) and b) 625 mm (right) focal length.

Figures 6.27a and **6.27b** illustrate transverse ray aberrations. Both configurations present symmetric and well-controlled ray deviations. 625 mm shows slightly elevated tangential deviations at edge fields due to the wider angular coverage, but the magnitude remains within tolerable limits. These plots confirm effective correction of primary aberrations [12].

In conclusion, the MWIR channel meets all targeted optical performance metrics. The results validate the design’s ability to deliver high-resolution thermal imagery across both zoom states, confirming that the optical system operates near its theoretical diffraction limit while fulfilling the system's size and operational constraints.

6.5 Athermalization

Ensuring thermal stability in optical systems is a critical design challenge, particularly for airborne defense and surveillance platforms operating under wide environmental temperature ranges. According to MIL-STD-810H, such systems are expected to maintain functionality between -40°C and $+60^{\circ}\text{C}$. Within this context, athermalization refers to optical and mechanical design strategies that preserve image quality across temperature variations—without requiring active focusing mechanisms.

Thermal sensitivity in optical assemblies originates from two main effects:

Thermo-optic effect (dn/dT): The change in refractive index of optical materials with temperature.

Thermo-mechanical effect (CTE): The expansion or contraction of lens elements and mechanical mounts due to their thermal expansion coefficients.

The combined impact of these effects manifests as a focal shift, which can be approximated by the first-order sensitivity expression [8]:

$$\Delta f = f \left(\frac{1}{n} \cdot \frac{dn}{dT} + \alpha \right) \cdot \Delta T \quad (6.5)$$

Where:

Δf : Focal length of the optical system

n : Refractive index of the lens material

$\frac{dn}{dT}$: Thermo-optic coefficient of the glass

α : Coefficient of thermal expansion (CTE) of the mechanical structure

ΔT : Change in ambient temperature from the nominal reference

In the developed multispectral system, a passive athermalization strategy was implemented for the VIS and SWIR channels. The mechanical housing is constructed from aluminum, selected for its high thermal conductivity, low mass, and structural simplicity. Although aluminum has a relatively high CTE ($\sim 23 \times 10^{-6}$ /K), optical alignment sensitivity was mitigated by using materials with tailored values and arranging the optical groups with thermally balanced spacing.

For the VIS and SWIR channels, glasses such as H-ZK50GT, N-BK7, and S-TIH6 were selected due to their moderate values and good broadband transmission. The lens groups in these channels were optimized so that differential thermal expansion contributes to passive image plane stabilization without the need for moving components.

In contrast, the MWIR channel presented greater sensitivity to thermal variations, due to both the use of high-index infrared materials (e.g., Germanium, Zinc Selenide) and the presence of a cryogenically cooled MCT detector. These materials exhibit larger behavior, and the system required a more nuanced approach.

To address this, a semi-passive athermalization mechanism was employed in the MWIR channel. Specifically, the final lens element in the MWIR path was designed with limited axial mobility, acting as a passive thermal compensator. This element shifts automatically in response to the thermal expansion of its mechanical housing,

effectively correcting for thermally induced defocus. Although not actively actuated, this movement is intentional and based on pre-characterized thermal behavior. The design ensures that the MWIR image plane remains properly aligned with the detector, even under significant environmental fluctuations. This approach bridges the gap between fully passive and active compensation, preserving simplicity while maintaining performance.

Additionally, this axial compensation is implemented through the lens barrel expansion, which is dimensioned to produce the required refocus over the MIL-STD-810H thermal range. The thermal behavior is derived from detector-side image processing feedback or design calibration data.

The shared use of a Cassegrain reflective configuration in all channels offers multiple advantages:

- Folded optical paths reduce physical system length, minimizing thermal expansion effects.
- Mirrors are immune to chromatic and thermo-optic effects, helping to stabilize system performance.

The impact of thermal variations on optical performance is further evaluated in the following subsections for all focal length and spectral band configurations. Zemax-based thermal analysis simulations conducted at -40 °C, 0 °C, and +60 °C demonstrate that the implemented athermalization strategies effectively preserve image quality, modulation transfer function (MTF), and focal stability. Below, detailed analysis results for each channel and zoom configuration are presented, validating the system's compliance with MIL-STD-810H thermal operating conditions.

6.5.1 Thermal Performance Evaluation for Visible Channel

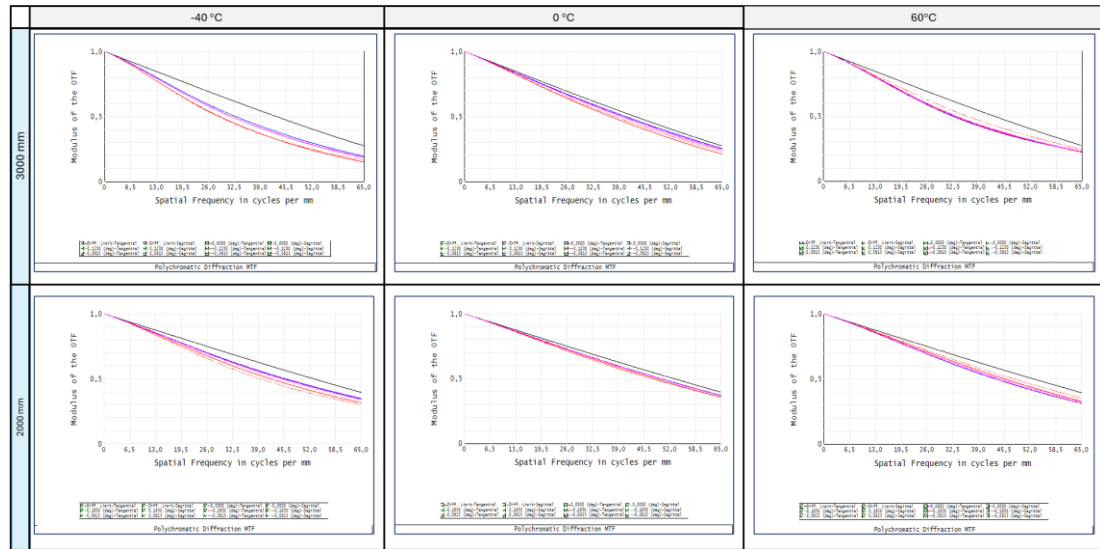


Figure 6.28: MTF Chart for Visible channel at -40°C, 0°C and +60°C for 3000 mm and 2000 mm focal length.

As shown in the MTF plots in the thermal analysis results in **Figure 6.28** above, the thermal response of the VIS channel was evaluated at -40 °C, 0 °C, and +60 °C for both 3000 mm and 2000 mm focal length configurations using a detector with 5.86 μm pixel pitch. In both configurations, the optical system exhibits stable contrast transfer characteristics under temperature variations, indicating effective passive athermalization.

At 3000 mm, the MTF performance remains close to the diffraction limit across the full field, with negligible degradation even at elevated temperatures. This confirms that the long focal length configuration maintains high-resolution capability under thermal stress. In the 2000 mm case, slightly more contrast loss is observed at peripheral field positions, particularly at +60 °C, due to the shorter focal length's increased sensitivity to thermal defocus. Nevertheless, the system still retains sufficient modulation and maintains image quality within acceptable limits.

Overall, the VIS channel sustains reliable performance across the full thermal operating range, enabled by material selection and carefully balanced optical spacing. These results validate the channel's robustness in field applications without relying on active thermal compensation mechanisms.

6.5.2 Thermal Performance Evaluation for SWIR Channel

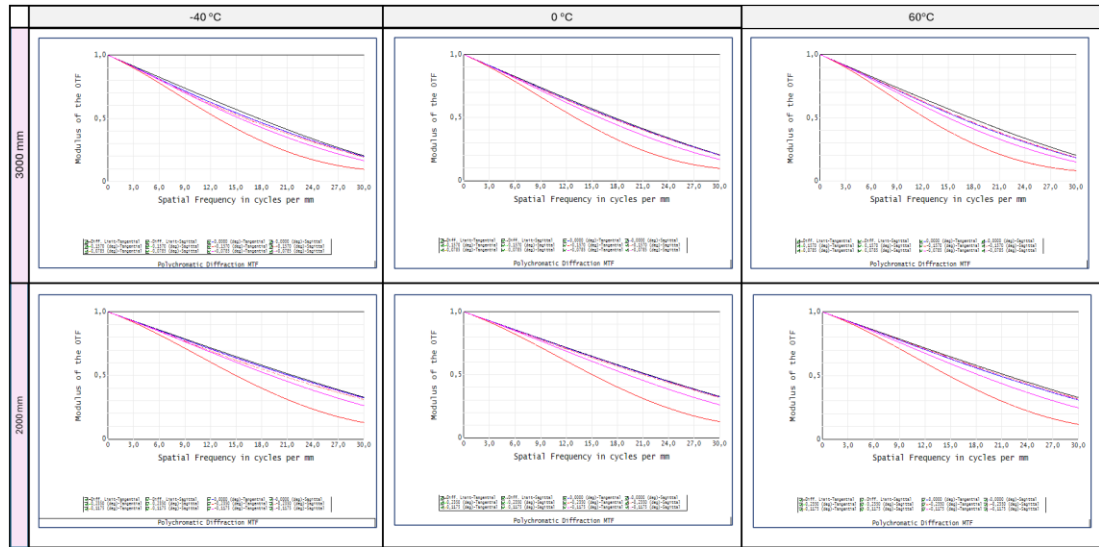


Figure 6.29: MTF Chart for SWIR channel at -40°C, 0°C and +60°C for 3000 mm and 2000 mm focal length.

As shown in the MTF plots in the thermal analysis results in **Figure 6.29** above, the thermal response of the SWIR channel was evaluated at -40°C, 0°C and +60°C for both zoom ranges using a 10 μ m pixel pitch detector. In both zoom cases, the system exhibits effective passive athermal behavior. At 3000 mm, the MTF curves remain close to the diffraction limit, showing minimal performance degradation across the field even at +60°C, indicating preserved resolution fidelity under thermal stress. The 2000 mm configuration shows slightly more contrast degradation at higher temperatures, especially in off-axis areas, but the MTF values still remain within the diffraction limit, maintaining acceptable image quality. This slight decrease is consistent with the wider field of view and increased thermal defocus sensitivity at shorter focal lengths.

Overall, both focal lengths demonstrate robust optical performance across thermal extremes, supported by the lens material selection and optimized group spacing. These results confirm that the SWIR channel design achieves passive thermal compensation without requiring active focusing, which is ideal for mission-critical systems in variable outdoor conditions.

6.5.3 Thermal Performance Evaluation for MWIR Channel

To maintain thermal consistency in the MWIR channel, a passive mechanical focus compensation strategy is integrated into the optical design. In particular, the last lens element positioned closest to the image plane is allowed to make a controlled axial movement in response to temperature changes. The lens that will make this compensator movement and the direction of movement are shown in **Figure 6.30**.

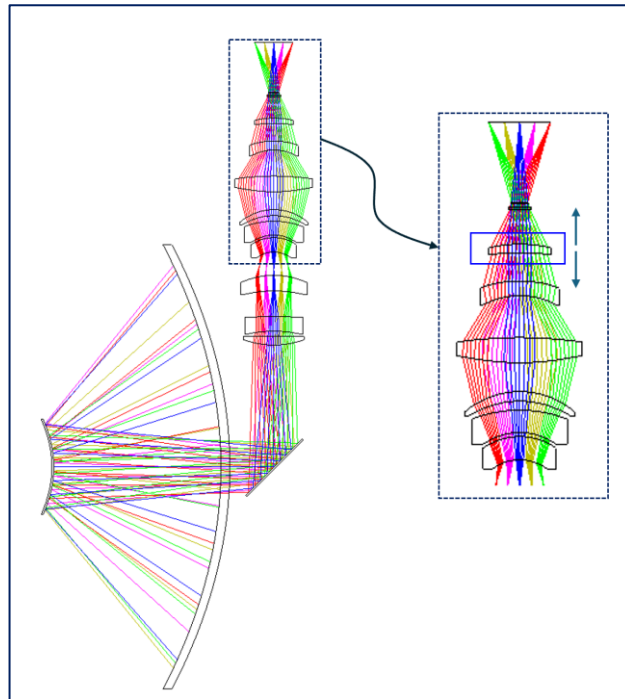


Figure 6.30: Thermal Compensator moving for MWIR.

This movement is governed by the combined effects of mechanical expansion and refractive index change and is calibrated according to feedback from the focus evaluation algorithms of the image processing system. In practice, image sharpness is evaluated digitally and the lens group is pre-adjusted accordingly at each operating temperature stage.

This approach offers high reliability, minimum complexity and robust field performance in MIL-STD-810H temperature conditions ranging from -40°C to $+60^{\circ}\text{C}$. The resulting thermal MTF behavior, shown in **Figure 6.31**, confirms the effectiveness of this compensation. At the focal length of 1000 mm, the MTF curves remain close to the diffraction limit throughout the field at all temperatures, demonstrating excellent thermal stability and preserved optical resolution. At the focal length of 625 mm, a

slight decrease in MTF is observed in the peripheral areas at high temperatures, attributable to the wider field of view.

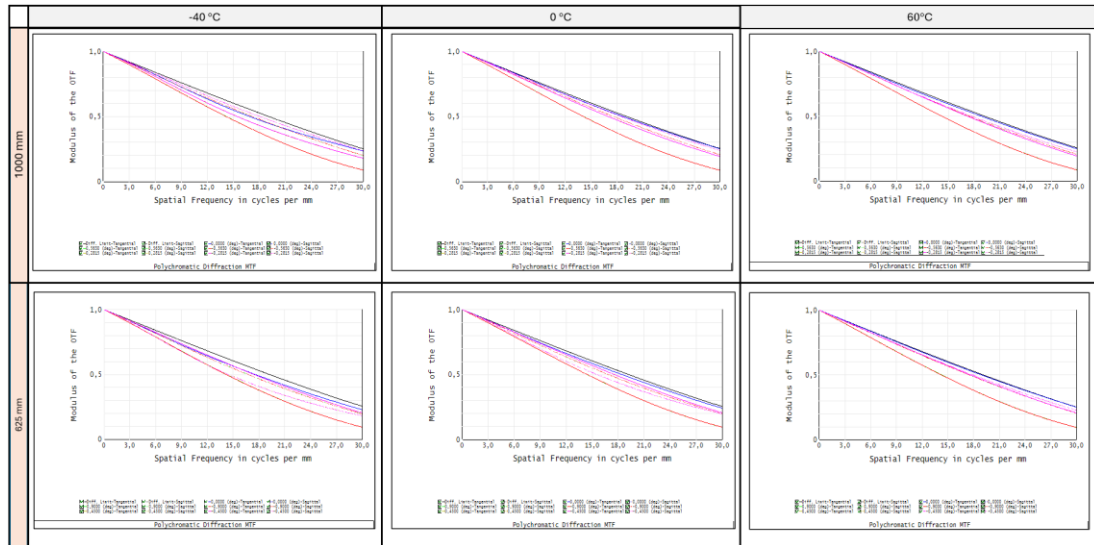


Figure 6.31: MTF Chart for MWIR channel at -40°C, 0°C and +60°C for 1000 mm and 625 mm focal length.

However, performance remains within acceptable optical criteria for MWIR imaging missions, confirming that passive compensation sufficiently reduces defocus even in thermally dynamic environments. In summary, the integration of a software-aware passive focus compensator in the MWIR channel provides stable imaging performance without the overhead of active correction hardware. This design balances mechanical simplicity with algorithm-driven calibration, providing a practical and thermally robust solution for high-precision defense-grade imaging systems.

As a conclusion for thermal analysis of common aperture imaging system; all three spectral channels exhibit robust thermal resilience, meeting mission-critical requirements for optical stability without active focus mechanisms. Through careful material selection, mechanical layout, and compensation strategies, the optical system achieves passive athermalization across a wide temperature range, making it well-suited for airborne and tactical ISR applications where temperature fluctuations are inevitable but high imaging fidelity is non-negotiable.

7. CONCLUSION

This thesis presents the comprehensive design and analysis of a multispectral optical imaging system operating in the visible, SWIR, and MWIR spectral bands. The system employs a shared entrance aperture based on a Cassegrain reflective configuration and supports six distinct optical configurations via two focal lengths per channel 3000 mm and 2000 mm for VIS and SWIR, and 1000 mm and 625 mm for MWIR. The main goal was to develop a compact, thermally stable, and high-resolution imaging solution suitable for airborne defense and surveillance applications.

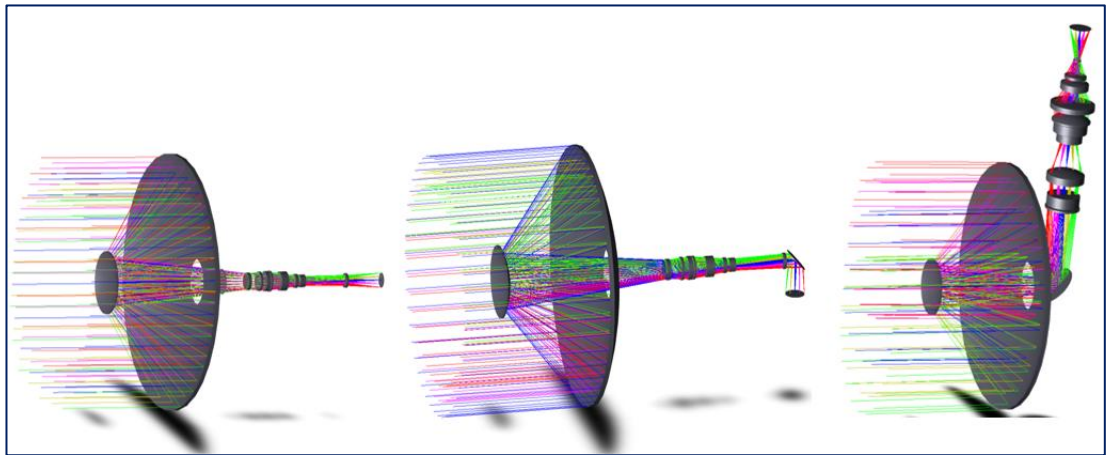


Figure 7.1 3D Layout Diagram of Visible Channel (left), SWIR Channel (middle) and MWIR Channel (Right)

A key performance factor addressed in this study is the narrow field of view (FOV) associated with long focal length systems. In strategic reconnaissance and aerial surveillance, small FOVs are critical for long-range detection tasks. The designed system achieves horizontal FOVs down to 0.21° in the visible spectrum, 0.24° in the SWIR and 0.88° in the MWIR band, reflecting a precise engineering effort to meet stringent operational requirements. Despite the optical challenges posed by such narrow FOVs such as increased sensitivity to aberrations and thermal defocus the system demonstrates consistently high image fidelity across all channels.

The VIS and SWIR channels share a common refractive optical path following the Cassegrain mirrors, with spectral separation achieved via a folding mirror near the image plane. Independent sensor-specific zoom optimization was applied to account

for differences in detector formats and pixel pitches. In contrast, the MWIR channel is optically and geometrically separated at an earlier stage, enabling a fully independent optical path optimized exclusively for the 3–5 μm range.

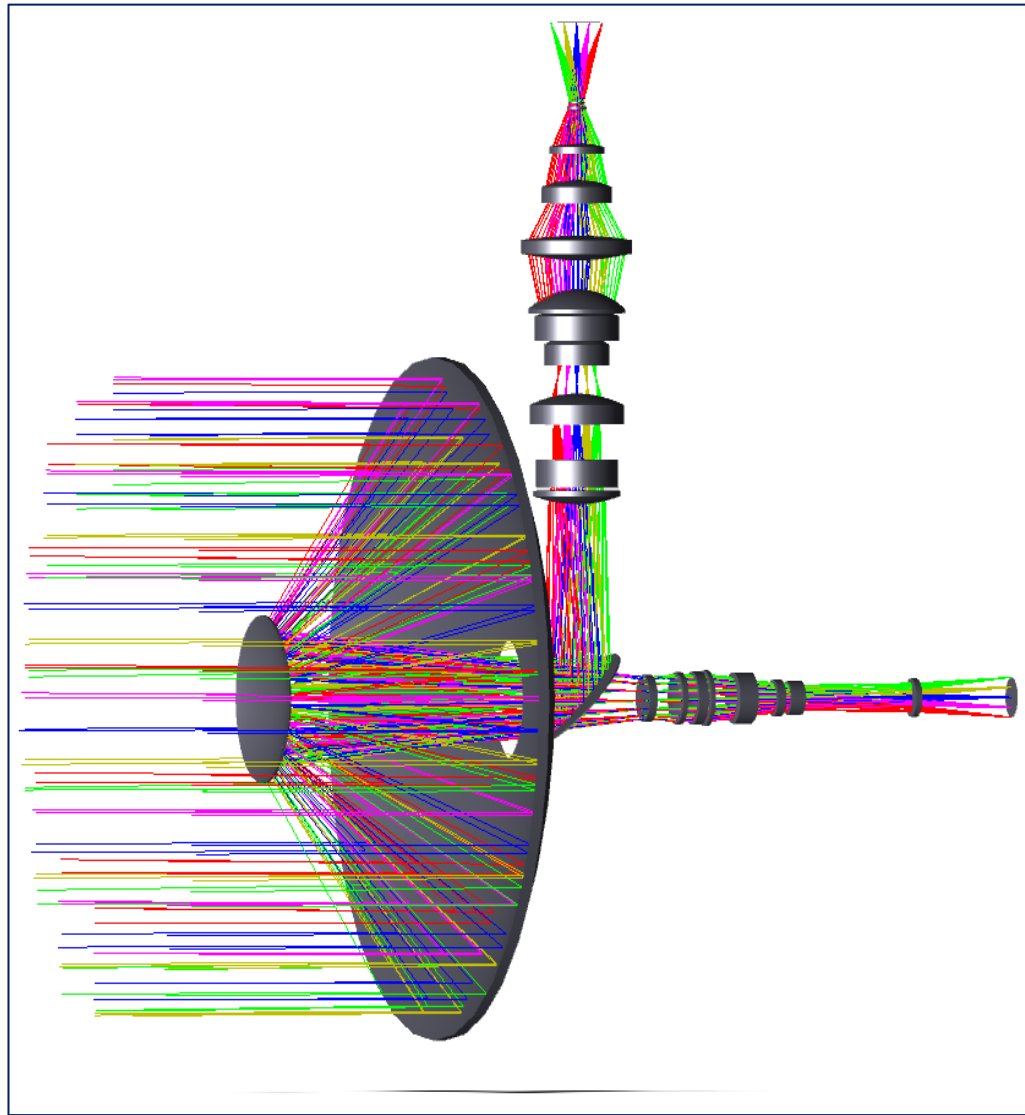


Figure 7.2: 3D Layout of Common Aperture System with all Channels.

Aberration correction in the MWIR channel was achieved using advanced optical surfaces, including two diffractive and four aspheric elements, strategically implemented to improve off-axis MTF performance and reduce element count. The VIS and SWIR channels were optimized using conventional glass types and cemented doublets without the need for complex surfaces, capitalizing on the shared optical design's symmetry and chromatic alignment.

All zoom configurations were modeled and optimized in Zemax OpticStudio using RMS spot size, wavefront error (OPD), and MTF at Nyquist frequency as merit criteria. Performance analyses validated that all configurations operate at or near the diffraction limit, with spot sizes well below pixel pitches and minimal wavefront deviation.

Thermal stability was addressed through channel-specific athermalization strategies. The VIS and SWIR optics employ a passive approach, using matched optical glasses (e.g., N-BK7, N-SF11, N-SK4) and symmetric spacing within an aluminum housing to counteract thermal expansion. The MWIR channel, requiring tighter focus tolerance due to its cryogenically cooled detector, utilizes an active mechanical compensator: a rear lens element mounted with controlled axial mobility to accommodate focus shifts induced by thermal variation. Zemax-based simulations confirmed that image plane stability and MTF retention remained within MIL-STD-810H limits (-40°C to $+60^{\circ}\text{C}$).

In conclusion, this thesis successfully demonstrates the design of a compact, high-resolution, and thermally stable multispectral imaging system. The narrow field-of-view performance, hybrid reflective-refractive architecture based on catadioptric structure, spectral separation strategies, and zoom capability collectively validate the system as a robust solution for advanced airborne ISR (Intelligence, Surveillance, Reconnaissance) platforms operating under demanding environmental and mission-specific constraints.

REFERENCES

- [1] Holst G. C., (2008), "Electro-Optical Imaging System Performance", 5th Edition, Society of Photo Optical.
- [2] Bhowmik M. K. et al. (2011), "Thermal Infrared Face Recognition – A Biometric Identification Technique for Robust Security system", Reviews, Refinements and New Ideas in Face Recognition. InTech., <https://doi.org/10.5772/18986>.
- [3] Smith, W. J., (2005), "Modern Optical Engineering" 3th Edition, McGraw-Hill.
- [4] Schott, (n. d.), "Interactive Abbe Diagram", <https://www.schott.com/en-gb/special-selection-tools/interactive-abbé-diagram>
- [5] Sun, H., (2016), "Lens Design: A Practical Guide", 1st Edition, CRC Press, <https://doi.org/10.1201/9781315181448>
- [6] Greivenkamp J. E., (2019), "OPTI-502 Optical Design and Instrumentation I: Section 9 Stops and Pupils", University of Arizona, <https://wp.optics.arizona.edu/jgreivenkamp/wp-content/uploads/sites/11/2019/08/502-09-Stops-and-Pupils.pdf>
- [7] Ihrke I., (2022), "F-number and focal length of light field systems: a comparative study of field of view, light efficiency, signal to noise ratio, and depth of field," Opt. Continuum 1, 919-933, <https://doi.org/10.1364/OPTCON.445077>
- [8] Fischer, Robert, Tadic-Galeb B., and Yoder P., (2008), "Optical System Design" 2nd Edition.
- [9] Zemax, (n.d.), Zemax design samples of libraries, ZMxtmp99CE.
- [10] Web 1, (2024), www.gst-ir.net/products/cooled-infrared-detectors/mid-wave-infrared-detectors/c1212m-mwir.html , Access Date: 11.09.2024
- [11] Zemax, "Zemax OpticStudio User Manual", <https://neurophysics.ucsd.edu/Manuals/Zemax/ZemaxManual.pdf>, Access Date: 21.08.2023.
- [12] Kingslake R., Johnson B. R., "Lens Design Fundamentals", 2nd Edition, Academic Press, ISBN 9780123743015, <https://doi.org/10.1016/B978-0-12-374301>
- [13] Huang Q., Chen Y., Gao Z., Zhai X, and Song B., (2009), "Athermalization and test validation of infrared imaging system", Proc. SPIE 7383, International Symposium on Photoelectronic Detection and Imaging 2009: Advances in Infrared Imaging and Applications, 73830P, <https://doi.org/10.1117/12.835009>
- [14] Fan Z., Cao J, Yang H, Qu E., and Wu D., (2011) "Design of high ratio middle infrared continuous zoom optical system", Proc. SPIE 8193, International Symposium

on Photoelectronic Detection and Imaging 2011: Advances in Infrared Imaging and Applications, 81931R, <https://doi.org/10.1117/12.900176>

[15] Sanson M. C. & Cornell J., (2010), "MWIR continuous zoom with large zoom range", Proc. SPIE 7660, Infrared Technology and Applications XXXVI, 76601X, <https://doi.org/10.1117/12.850375>

[16] Riedl M. J., (1995), "Diamond-turned diffractive optical elements for the infrared: suggestion for specification standardization and manufacturing remarks", Proc. SPIE 2540, Current Developments in Optical Design and Engineering V, <https://doi.org/10.1117/12.219529>

[17] Mann A., (1994), "Infrared zoom lenses in the 1990s", Optical Engineering 33(1), <https://doi.org/10.1117/12.151530>

[18] Mann A., (2009), "Infrared Optics and Zoom Lenses, Second Edition", <https://doi.org/10.1117/3.829008>

[19] Reibel Y., et al., (2013), "High-performance and long-range cooled IR technologies in France", Proc. SPIE 8704, Infrared Technology and Applications XXXIX, 87040B, <https://doi.org/10.1117/12.2015601>

[20] Vizgaitis J., N., (2005), "Dual f/number optics for third generation FLIR systems", Proc. SPIE 5783, Infrared Technology and Applications XXXI, <https://doi.org/10.1117/12.604328>

[21] Kuo C., Lin C., and Han C, (2010), "Dual field-of-view midwave infrared optical design and athermalization analysis," Appl. Opt. 49, 3691-3700, <https://doi.org/10.1364/AO.49.003691>

[22] MIL-STD, (2019), Military Standard, MIL-STD-810H, Department of Defense Test Method Standard.

[23] Berman R., et al. (2015), "Optical design study of a VIS-SWIR 3X zoom lens", Proc. SPIE 9580, Zoom Lenses V, 95800D, <https://doi.org/10.1117/12.2187103>

[24] Mann A., (2013), "Developments and trends in infrared zoom lenses from 2000 to 2010," Optical Engineering 52(1), 013001, <https://doi.org/10.1117/1.OE.52.1.013001>

[25] Neil I. A., (1997) "Optimization glitches in zoom lens design", Proc. SPIE 3129, Zoom Lenses II, <https://doi.org/10.1117/12.284237>

[26] de la Fuente M. C., and Rayces J. L., (2005), "Pupil aberrations control in fish-eye lens with diffractive surfaces", Proc. SPIE 5638, Optical Design and Testing II, <https://doi.org/10.1117/12.572750>

[27] Sasian J., (2019), "Introduction to Lens Design", Cambridge University Press.

[28] Ettehadgui-Atad E., Casali M. M., Hawarden T. G., Henry D. M., and Worswick S. P., (1999), "Optical design of a visible and infrared survey telescope for astronomy",

Proc. SPIE 3779, Current Developments in Optical Design and Optical Engineering VIII, <https://doi.org/10.1117/12.368234>

[29] Zhang X., Liu B., and Jia H., (2011), "Design of reimaging F/1.0 long-wavelength infrared optical system", Proc. SPIE 8193, International Symposium on Photoelectronic Detection and Imaging 2011: Advances in Infrared Imaging and Applications, 81930K, <https://doi.org/10.1117/12.898849>

[30] Grealish K., Kacir T., Backer B., and Norton P., (2005), "An advanced infrared thermal imaging module for military and commercial applications", Proc. SPIE 5796, Unattended Ground Sensor Technologies and Applications VII, <https://doi.org/10.1117/12.606946>

[31] Wolfe W. L., (1996), "Introduction to Infrared System Design", SPIE Press, <https://doi.org/10.1117/3.226006>.

[32] Daniels A., (2018), "Field Guide to Infrared Systems, Detectors, and FPAs, Third Edition", SPIE Press, <https://doi.org/10.1117/3.2315935>.

[33] Soskind Y. G., (2011), "Field Guide to Diffractive Optics", SPIE Press, <https://doi.org/10.1117/3.895041>.

[34] Braunecker B., Hentschel R., and Tiziani H. J. (2008), "Advanced Optics Using Aspherical Elements", SPIE Press, <https://doi.org/10.1117/3.741689>.

[35] Hecht E., (2017), "Optics", Pearson Education.

[36] Riedl M. J., (2009), "Optical Design: Applying the Fundamentals", SPIE Press, <https://doi.org/10.1117/3.835815>.

[37] Yoder P., (2002), "Mounting Optics in Optical Instruments", SPIE Press, <https://doi.org/10.1117/3.785236>.

[38] Terebizh, V. Y., (2019), "Survey Telescope Optics", SPIE Press, <https://doi.org/10.1117/3.2543429>.

[39] Driggers R. G., and Friedman M. H., (2012), "Introduction to Infrared and Electro-optical Systems, Second Edition", Artech House Publishers.

[40] Son B. R., Kim J. K., Choi Y. S., and Park C. (2023), "Transferability of Diffractive Structure in the Compression Molding of Chalcogenide Glass", Micromachines, 14(2), 273, <https://doi.org/10.3390/mi14020273>.

[41] Aslan S. H., (2022), "Analysis of narcissus effect in infrared optical systems with cooled detectors," Ph.D. - Doctoral Program, Middle East Technical University.

[42] Zhang X., Bai J., Yin S., (2016), "The optical design of highly efficient cold shield in IR detector based on ASAP", J. Phys.: Conf. Ser. 680 012015, <https://doi.org/10.1088/1742-6596/680/1/012015>

- [43] Reshidko D, Reshidko P, and Carmeli R.,(2015) "Optical design study and prototyping of a dual-field zoom lens imaging in the 1-5 micron infrared waveband", Proc. SPIE 9580, Zoom Lenses V, 95800C, <https://doi.org/10.1117/12.2187246>
- [44] Akram M. N., (2003), "A design study of dual-field-of-view imaging systems for the 3–5 μm waveband utilizing focal-plane arrays", J. Opt. A: Pure Appl. Opt. 5 308, <https://doi.org/10.1088/1464-4258/5/4/302>.
- [45] de la Fuente M. C., Herrero J. M. I., and Rivera L. (2012), "MWIR zoom with focal extender", Proc. SPIE 8550, Optical Systems Design 2012, 85500X, <https://doi.org/10.1117/12.999637>
- [46] Moskovich J., (1990), "Catadioptric zoom lens", U.S. Patent 4,971,428A.
- [47] Sato S., (2005), "Zoom Lens Systems", U.S. Patent 2005/0157403 A1.
- [48] S. Karp, and L. B. Stotts, (2012), "Fundamentals of Electro-Optic Systems Design: Communications, Lidar, and Imaging", Cambridge University Press.
- [49] Hazra L., (2022), "Foundations of Optical System Analysis and Design (1st ed.)", CRC Press, <https://doi.org/10.1201/9780429154812>.
- [50] Willers C. J., (2013), "Electro-Optical System Analysis and Design: A Radiometry Perspective", SPIE Press, <https://doi.org/10.1117/3.1001964>.
- [51] Boreman G. D., (2001), "Modulation Transfer Function in Optical and Electro-Optical Systems", SPIE Press, <https://doi.org/10.1117/3.419857>.

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