DESIGN CONSIDERATION, TRADE-OFF AND PERFORMANCE ANALYSIS OF A HIGH-RESOLUTION OPTICAL TELESCOPE DESIGN FOR A SATELLITE

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This dissertation is submitted in partial fulfilment of the requirements for the degree of Master of Philosophy in Space Studies

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ABSTRACT

High-resolution satellite imagery serves a more and more important role in applications ranging from environmental protection, disaster response, and precision farming to defence and security. The design of a high-resolution optical satellite payload requires relevant technical expertise, expensive equipment and software. Different aspects of telescopes have been researched separately but the process of translating system requirements into the actual optical design of a high-resolution payload is unique and challenging work for this dissertation. This research will help to understand system level approach to design complex systems.

The scope of this research is to identify optics requirements from system requirements, explore optical design concepts and trade-offs of concepts based on system requirements of high-resolution optical payload. Basically, this research will follow the SMAD processes to explore the design engineering of optical payloads from the objective and the requirement to the detailed design phase. This research will also include different optical layout and their performance analysis in terms of MTF and tolerances.

This research does not include the opto-mechanical design, thermal design, focal plane array assembly, manufacturing, and the detailed AIT procedure.

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LIST OF ACRONYMS

AIT	Assembly, Integration and Assembly
CDR	Critical Design Review
DCX	De-Centre in X axis
DCY	De-Centre in Y axis
ECSS	European Corporation of Space Standard
EFL	Effective Focal Length
EM	Engineering Model
FOV	Field of View
GSD	Ground Sampling Distance
GSE	Ground Support Equipment
ICD	Interface Control Document
LEO	Low Earth Orbit
MDR	Mission Definition Review
MRR	Manufacturing Readiness Review
MS	Multispectral
MTF	Modular Transfer Function
PAN	Panchromatic
PDR	Preliminary Design Review
PM	Primary Mirror
PRR	Preliminary Requirement Review

PSF	Point Spread Function
RC	Ritchey Chrétien
RMS	Root Mean Square
SMAD	Space Mission Analysis and Design
SNR	Signal to Noise
TDI	Time Delay Integration
TMA	Three Mirror Anastigmatic

1 INTRODUCTION

1.1 Background

Satellite imagery data serves humanity in many ways that help in monitoring various applications such as from environmental protection, disaster response and precision farming to defense and security. Remote sensing satellite imagery has different classifications with respect to its spectral, spatial and temporal resolution. Spectral resolution defines several energy bands that are involved to classify elements. Temporal resolution helps to identify land cover, crop growth, and transportation planning. Spatial resolution is a very important specification of imagery that defines the smallest elements that you can see on the ground and the higher the resolution, the more details you can see in the image. High-end satellite images for different applications are taken from Earth observation satellites with high resolution optical payloads. Furthermore, high resolution satellites have very narrow swath widths, so the coverage of these satellites is typically small. Consequently, up-to-date high resolution images of many regions of Earth are not easily available. Constellations of high-resolution satellites provide a solution, but this is not economically feasible. High resolution satellite imagery with a resolution of less than 1m is currently obtained from commercial operators such as Pleiades, Geo-Eye, and Worldview.

1.2 Problem Statement

The quality of satellite imagery mainly depends upon satellite telescope specifications and performance. These telescope specifications derive from system requirements through a certain process and serve as baseline design requirements for the optical engineer. The telescope is a unit in the payload subsystem and does not have a direct relation with the satellite system, so system requirements may not state any direct requirements for a telescope, Optical system design is tricky and depends upon many satellite bus parameters and an optical design engineer should know about every parameter that affects optical design. Figure 1-1 the shows allocation and planning of system objectives and requirements.

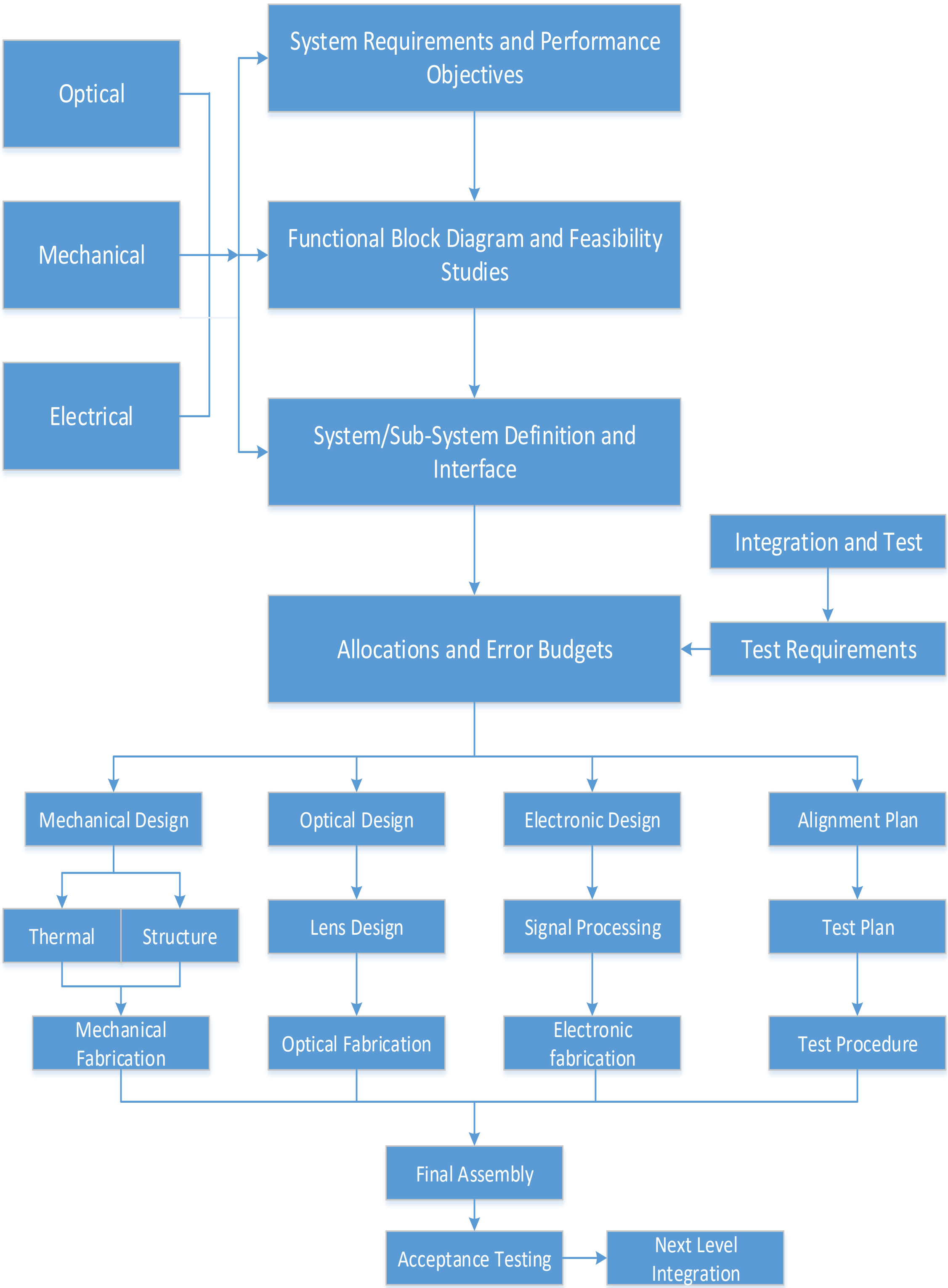


Figure 1-1: System Requirements Allocation Flow. [1]

1.3 Goal and Scope

The goal of this thesis is to demonstrate a system engineering approach to high resolution optical design as per compliance with requirements and constraints. System engineering is an iterative process of top-down synthesis design and operation in a real world system that satisfies system requirements and constraints [2]. It may require many iterations of the system engineering process to achieve the required levels of system performance. System engineering is based on a typical mission planning cycle and each cycle has its typical reviews and milestones.

Table 1-1: Mission Planning Life Cycle. [1]

Phase	**Description**	**Review**	**Milestone**
Phase 0: Mission analysis-need identification	- Support the customer in identifying his needs. - Propose possible system concepts	MDR (Mission Definition Review)	Mission description definition Preliminary requirement
Phase A: Feasibility	- Finalize the expression of the needs identified in Phase 0. - Propose solutions (including identification of criticalities and risks) to meet the perceived needs	PRR (Preliminary Requirement Review)	- Demonstrated feasibility - Requirements document - Preliminary development plans - Preliminary technical system specification including interface specs

Phase B: Preliminary definition	- Establish the system's preliminary definition for the solution selected at end of Phase A - Demonstrate that the solution meets the technical requirements according to the schedule, the budget, the target cost and the organization requirements.	- SRR (System Requirement Review) - PDR (Preliminary Design Review)	- Specifications - Design Justification documentation - Management Plans - Specs for all products - Draft Design Justification Files - ICDs
Phase C: Detailed definition	- Establish the system detailed definition. - Demonstrate its capability to meet the technical requirements of the system technical requirements specification.	CDR (Critical Design Review)	- Design Definition documentation - Design Justification File
Phase D: Qualification and production	- Finalize the development of the system by qualification and acceptance.	- QR (Quality Review) - AR (Acceptance Review)	

	- Finalize the preparation for operations and utilization.		
Phase E: Operations / utilization	- Support the launch campaign - Support the entity in charge of the operations and utilization of the terms of a business agreement.	FRR (Flight Readiness Review) ORR (Operational Readiness Review) LRR (Launch Readiness Review)	- Orbit debris mitigation plan, - Product user manual
Phase F: Disposal	- Support the entity in charge of the disposal following the terms of a business agreement	MCR (Mission Closed-out Review)	

The design of a high-resolution optical telescope requires relevant technical expertise, expensive equipment and software. Different aspects of telescopes have been researched separately but the process of translation of system requirements into the actual optical design of high-resolution payload is unique and resembles a challenging work for this dissertation. This research will help to understand system level approach to design complex system.

A telescope consists of optical elements such as mirrors and lenses, the mechanical structure to support and strength optical elements, the thermal design to keep the optical design in its relative distances and shape and finally the sensors and electronics design to acquire the images. Due to its complexity, it is unrealistic to discuss all aspects of a telescope within a single thesis project. Therefore, a clear scope must be defined.

This research will primarily focus on the system engineering approach to select the baseline of an optical design. The scope of this research is to identify optics requirements from system requirements, explore optical design concepts and trade-offs of concepts based on the system requirements of the high-resolution optical payload. Basically, this research will follow the SMAD process to explore the design engineering of an optical payload from the objective and the requirement phase to the baseline design.

This research will not include detailed optical analyses such as baffling, stray light, and tolerance analysis. It will also not include any opto-mechanical design, thermal design, focal plane unit design, manufacturing and AIT procedures.

1.4 Thesis Outline

The remainder of this thesis is structured as follows:

In Chapter 02, the basic terminology of optics design will be defined to understand the aberration theory and various optical performance indicators.

In Chapter 03, system technical requirements and constraints for the optical system will be presented with the help of the mission statement and objectives. Furthermore, the baseline of first order optical design properties will also be established for further design exploration.

In Chapter 04, different conceptual optical configurations will be discussed with their pros and cons and later, after trade-off analysis keeping in mind our requirements, two optical design configurations will be chosen for further elaboration.

In Chapter 05, two selected optical concepts will be traded off based on manufacturability, assembly, integration and testing, optical performance etc. and in the end one optical design will be baselined.

In Chapter 06, the baselined optical design will be elaborated further in terms of different performance indicators such as MTF, spot diagram, sensitivity analysis, optical transmission etc. to demonstrate compliance with the requirements.

In Chapter 07, the requirement compliance matrix and the preliminary level verification plan will be discussed.

Lastly, in Chapter 08, we present our conclusion and recommendations for future work.

2 LITERATURE REVIEW

2.1 Background

Richard John Tomlinson, in his doctoral thesis titled “lens design for manufacture [3]”, described the process of lens design from optical packages design to mechanical design. He broke down the manufacturing process of a complete optical system into three stages: (i) the optical and mechanical design, (ii) the production of both assemblies and (iii) their assembly and testing. He discussed some optical design theories and optical design packages, but his research was more concerned about manufacturing techniques, their tolerance and optical testing.

Different variants of TMA (Three Mirror Anastigmat) have been compared by Lampton & Sholl [4] who describe optical layout and parameters with requirements and design description, they also discussed the advantages and disadvantages of each variant of TMA.

A feasibility study for an optical near-infrared wide field imager (WFI) using ESA’s Concurrent Design Facility (CDF) has been done in [5]. The Mission of this project is to search for Type Ia Supernova over a given redshift range with optical and near-infrared wavelength coverage. One of the objectives is to perform a preliminary payload design from mission requirements and design drivers. They also discussed the optical design flow from requirements, design drivers, trade-off criteria and different optical configurations with their feasibility [5].

2.2 Optics Theory

2.2.1 Overview

In this section, some relevant optical theories will be provided.

2.2.2 Generalized Model of an Optical System

Consider an optical system with its symmetry about an optical axis so that each surface is rotating about the optical axis. The object point is lying on the y axis and its distance from the optical axis h is defined in object space as shown in Figure 2-1. We assume the ray to be starting from the object point to pass through the system aperture defined by polar coordinates (s, θ). The ray intersects the image space at points x' and y'.

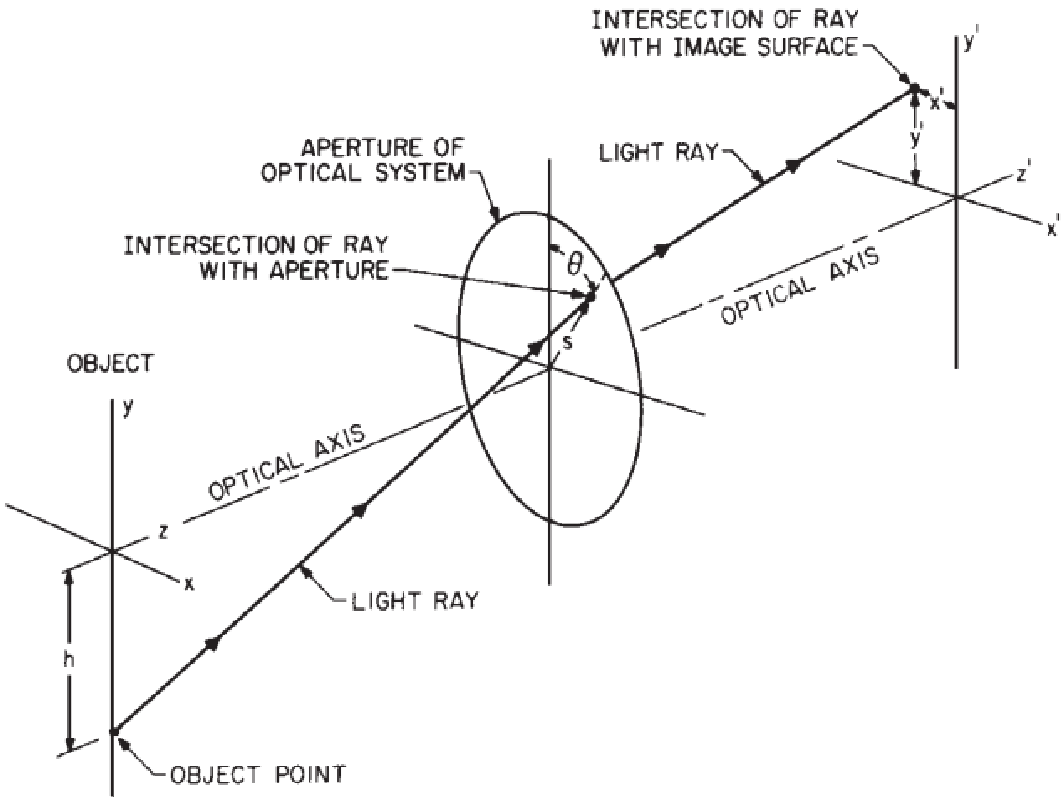


Figure 2-1: Generalized Optical Model. [6]

We are interested to know the equation for x' and y' coordinates as a function of s, θ and h. Without going into any complexity, the general form of equations is written below;

$$y' = A_1 s \cos\theta + A_2 h + B_1 s^3 \cos\theta + B_2 s^2 h (2 + \cos 2\theta) + (3B_3 + B_4) s h^2 \cos\theta + B_5 h^3 + C_1 s^5 \cos\theta + (C_2 + C_3 \cos 2\theta)\, s^4 h + (C_4 + C_6 \cos^2\theta) s^3 h^2 \cos\theta + \cdots \tag{2.1}$$

$$x' = A_1 s \sin\theta + B_1 s^3 \sin\theta + B_2 s^2 h \sin 2\theta + (B_3 + B_4) s h^2 \sin\theta + C_1 s^5 \sin\theta + (C_3 s^4 h \sin 2\theta) + (C_4 + C_6 \cos^2\theta) s^3 h^2 \sin\theta + \cdots \tag{2.2}$$

Where A_n, B_n and C_n are the constant and s, θ and h are defined in Figure 2-1.

From equations (2.1) and (2.2), it is obvious that the above equations have only odd-order terms and there are no even order terms because of the symmetric system but even order terms may be introduced by inducing a tilting surface or any other nonsymmetrical surface.

2.2.3 Optical Aberrations

The optical aberration of a system can be determined by tracing a large number of rays through an aperture and then looking in image space to determine the amount that deviates from the paraxial image point. From Figure 2-1 and equations (2.1*)* and (2.2), the Seidel aberrations can be defined as;

The A terms are paraxial or first-order imagery parameters. A1 is the lateral distance from the paraxial focus to the image plane and A2 is the magnification of the system. The B term is called third order or primary aberration, B1 is the spherical aberration, B2 is the coma, B3 is the astigmatism, B4 is the field curvature and B5 is the distortion [6].

C and D have high order aberrations but in this thesis, we will discuss only third-order term aberrations.

2.2.3.1 Spherical Aberration

The spherical aberration can be characterized as a variation of focus as a function of the aperture of the system. As the ray height at the aperture increases, the focus position in the optical axis moves farther away from the paraxial focus. It is mainly present in spherical optics. Spherical aberration can be minimized by refocusing the image but in a large aperture system, it will not be a useful option. The best way to correct spherical aberration is using a compensating glass (field correcting lens) or an aspherical surface [6].

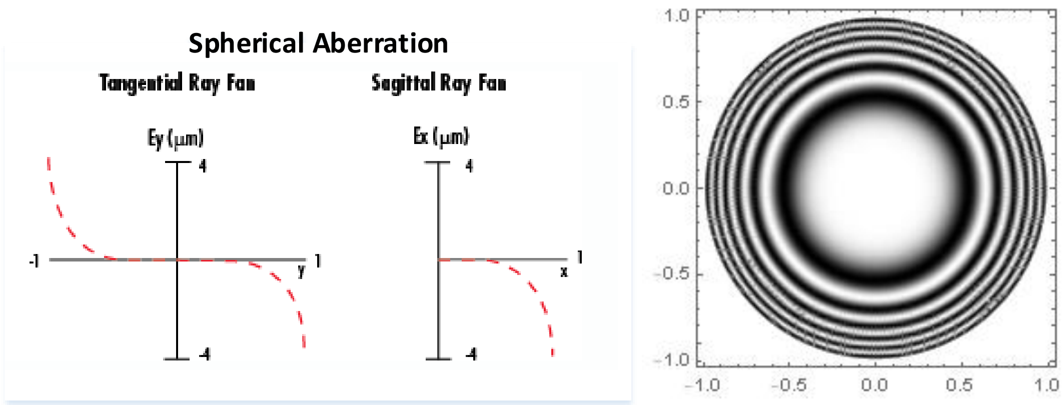


Figure 2-2: Spherical Aberration- Ray fan and wavefront map. **[7]** [8]

2.2.3.2 Coma

The coma is an off-axis aberration and is defined as the ray height increase with aperture. It focuses light on different points laterally. This aberration causes a comet shaped blur that it has been named after. It is an off-axis aberration and is present in parabolic optics [6].

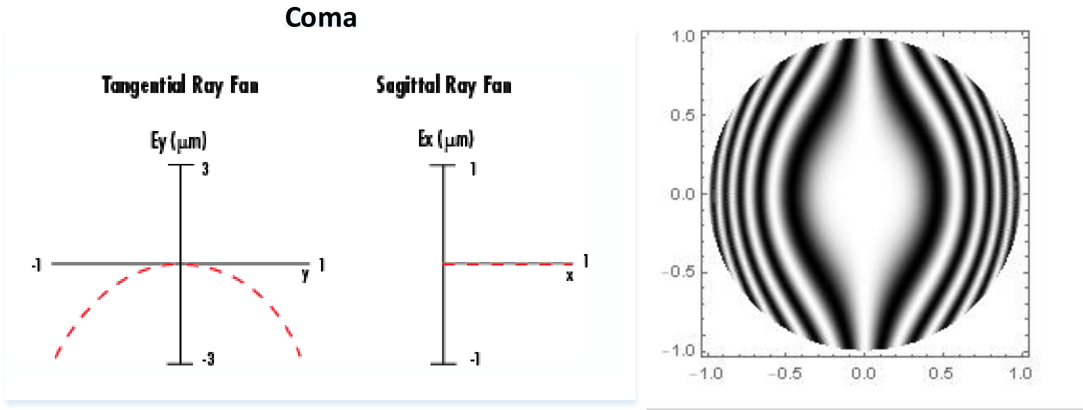


Figure 2-3: Coma- Ray fan and wavefront map. **[7]** [8]

2.2.3.3 Astigmatism

An astigmatism occurs when light passing through the pupil is focused on different locations in the tangential plane and sagittal plane (both planes are 90° apart). If an image is focused in the tangential or sagittal plane, the results are in an elliptical blur on the wavefront map. By refocusing, astigmatism can get circular blur by a substantially smaller magnitude. Astigmatism always happens with conjunction on field curvature and it can only be minimized by adding a stop location, increasing the optical elements or the degree of freedom [6].

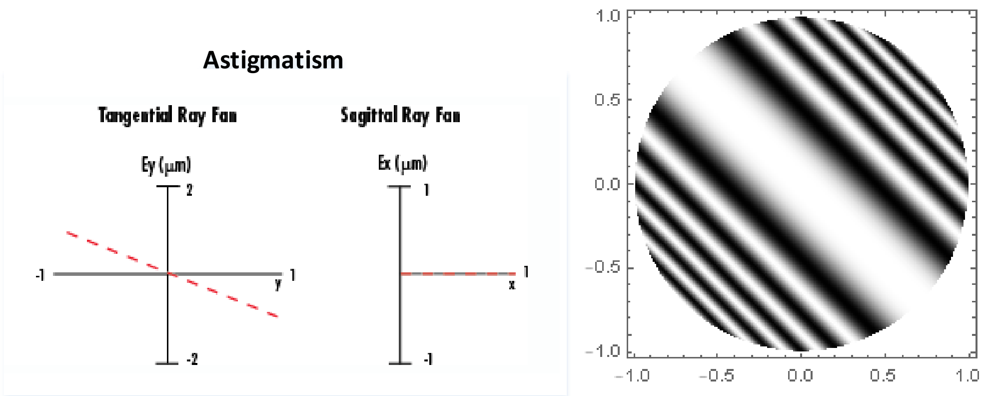


Figure 2-4: Astigmatism- Ray fan and wavefront map. **[7]** [8]

2.2.3.4 Field Curvature

The field curvature aberration is defined as light that focused on a curved image plane rather than a linear plane. A field curvature is a function of the index of refraction of lens elements and surface curvature. When an optical system has no astigmatism, both the tangential and sagittal image surfaces coincide with each other and lie on a flat linear image plane [6].

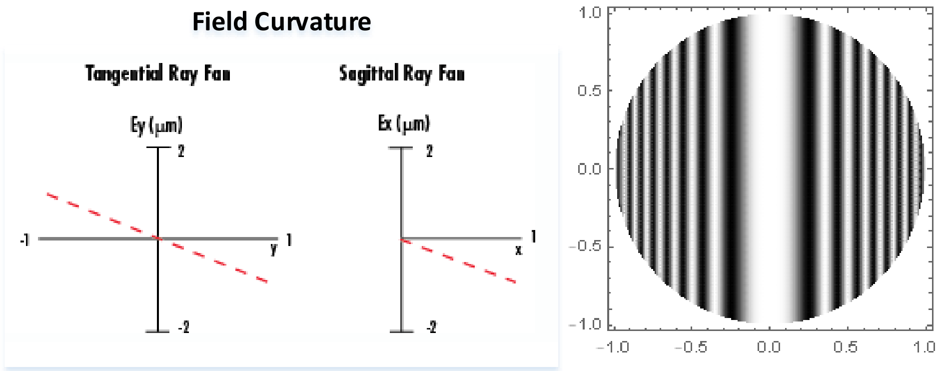


Figure 2-5: Field Curvature- Ray fan and wavefront map. **[7]** [8]

2.2.3.5 Distortion

The distortion is defined as the displacement of the image from its paraxial position and can be expressed as a percentage of the ideal image height. Distortion does not produce blur in the image as its focus produces a sharp image on the image plane however this focus is not at the expected location. A distortion in an optical system can be one of two types, positive or pincushion distortion and negative or barrel distortion [6].

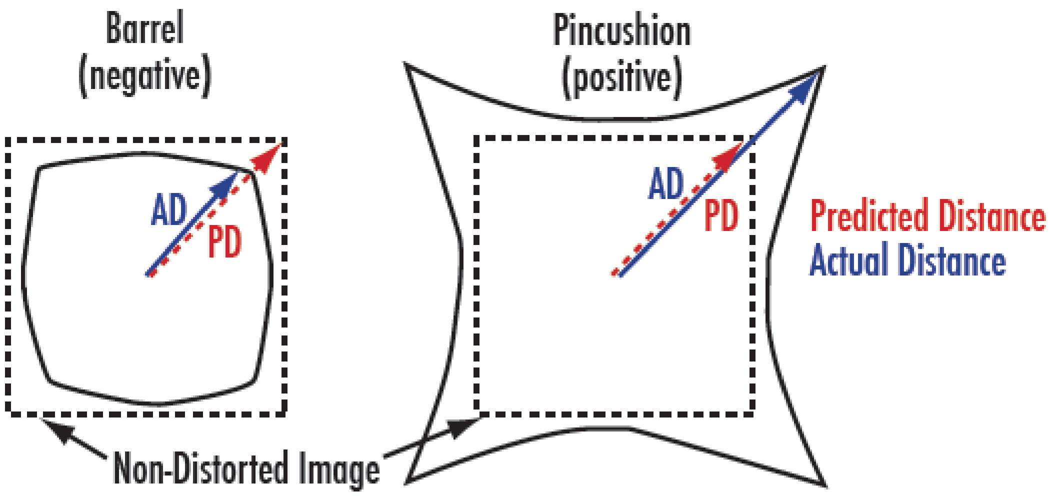


Figure 2-6: Illustration of Distortion. **[9]**

2.2.3.6 Chromatic Aberration

The chromatic aberration can be defined as the variation of the focus as a function of the wavelength. It is all about the index of refraction which changes with respect to the wavelength. The index of refraction of optical elements is high for shorter wavelengths than for longer wavelengths, so blue light focuses closer to the image plane than red light. It produces blur as well as fringes near sharp edges. Chromatic aberration occurs only in optical designs where glass is used [6].

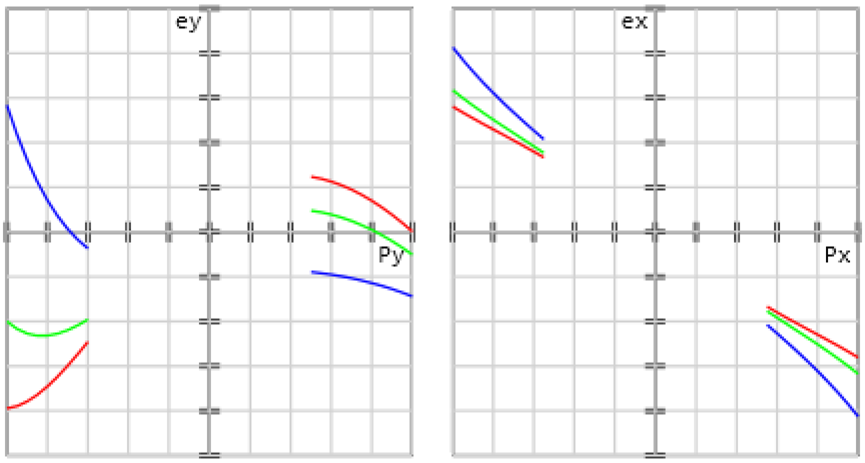


Figure 2-7: Chromatic Aberration Ray Fan.

2.3 Optical Performance Indicator

Optical performance indicators are used for evaluating optical designs to check performance requirements. A brief description of significant optical performance indicators is presented in this section.

2.3.1 Modulation transfer function

The main purpose of an optical system is to take sharp images of a scene under observation. The Modulation Transfer Function (MTF) is the parameter that can be used as a tool to determine whether images will be sharp or not. MTF provides the contrast value over the spatial frequency which will tell us if the spatial feature of object side is still visible within image side.

The MTF of an optical system is defined as the ratio between modulation or contrast observed on the image side and modulation or contrast in the object side [6], and can be written as;

$$MTF = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \quad (2.3)$$

Where I_{max} and I_{min} are intensities of images being analyzed. The MTF is mainly dependent on the spatial frequency of the image patterns. Spatial frequency is measured in line pairs per radians (lp/rad) or line pairs per millimeters (lp/mm). Figure 2-8 shows a visualization interpretation of the MTF concept.

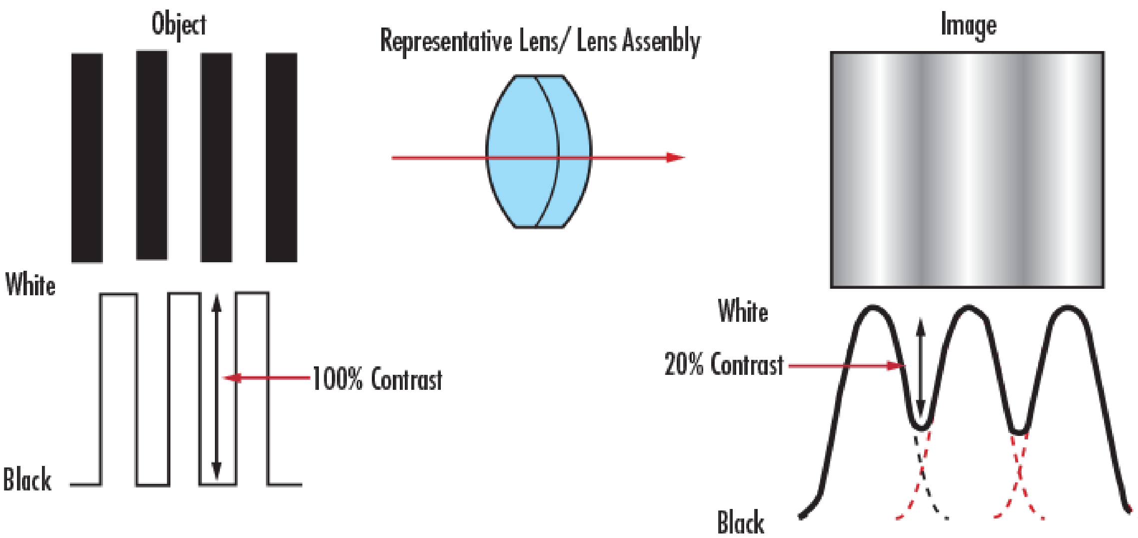


Figure 2-8: MTF Comparison at object and image space. **[10]**

Diffractions and aberrations cause a large degradation of contrast loss in sharp images or fine spatial features. An image pattern with spatial frequency is larger than the cut-off frequency that will not be visible at all.

$$f_{cutt-off} = \frac{1}{\lambda f\#} \quad (2.4)$$

where

λ = Wavelength of the spectral band

f# = System f# (ratio of effective focal length and aperture diameter)

MTF is calculated at the system level, and it includes detector MTF, as well as spacecraft errors due to misalignments and instabilities. System MTF gives a more comprehensive overview of optical performance but in this thesis, we will focus on MTF optics only.

$$MTF_{system} = MTF_{Detector} MTF_{Optics} MTF_{Motion} MTF_{Atmosphere}\, MTF_{TDI} MTF_{Electronics} MTF_{Display} MTF_{Eye} \quad (2.5)$$

2.3.2 Ray Fan

A ray fan plot shows the ray aberration as a function of pupil coordinates. The main purpose of the ray fan plot is to determine what type of optical aberrations are appearing in the optical design; it is not a complete explanation of the optical performance, especially for systems without rotational symmetry. Recognition of aberration in the early stages of design is the first step for correcting them using optical optimization techniques. The purpose of correcting aberrations is to get diffraction-limited performance which means that all aberrations will be enclosed in the airy disk region. Figure 2-9 shows a ray fan plot of optical aberration as a function of pupil size.

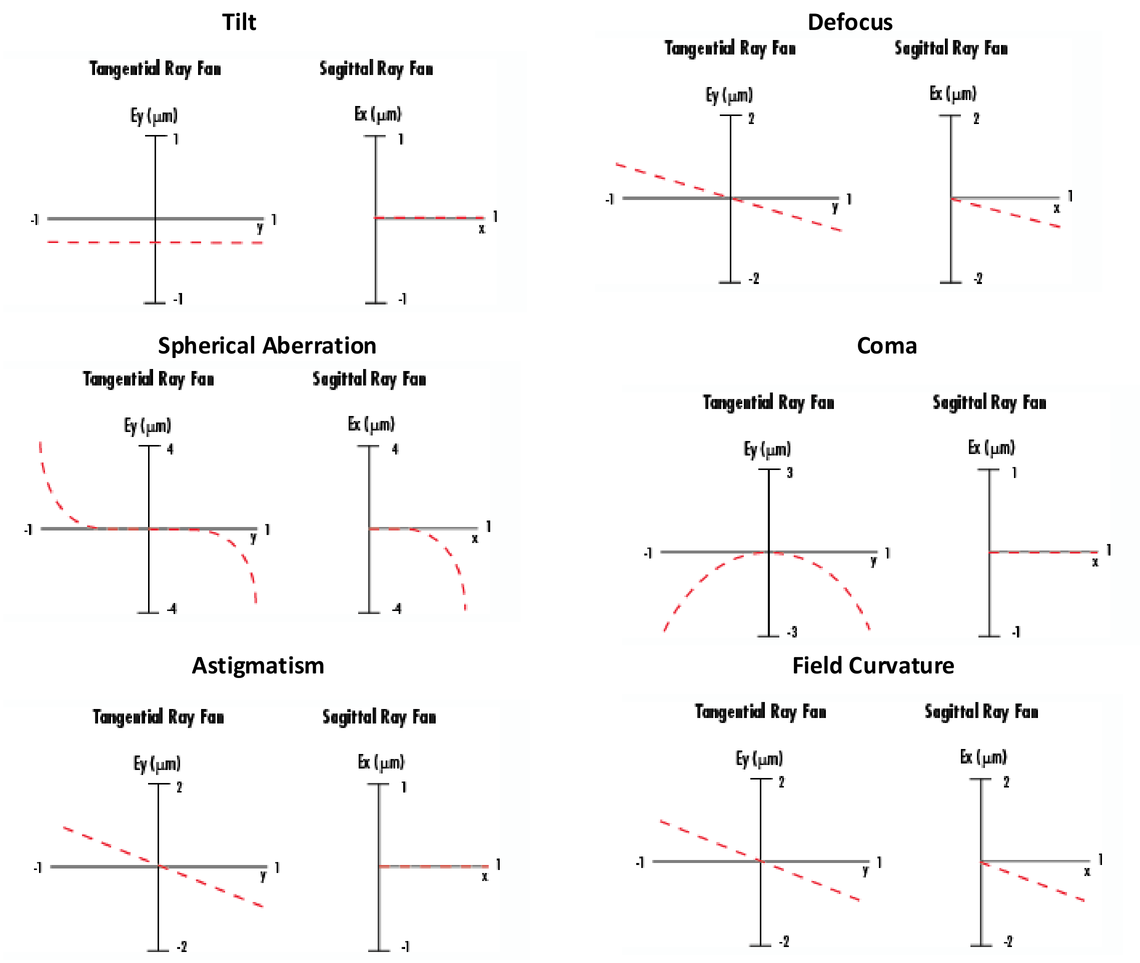
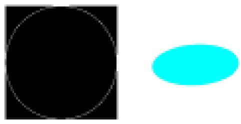
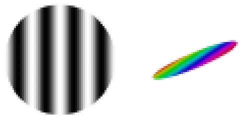
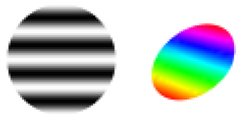
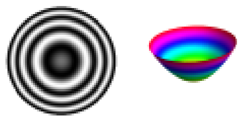
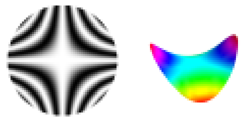
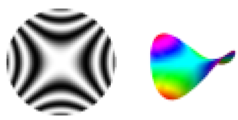
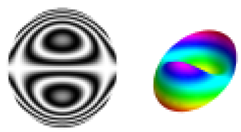
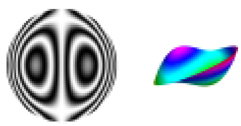
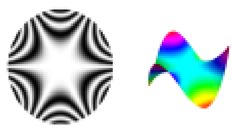


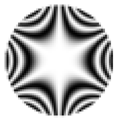
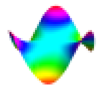
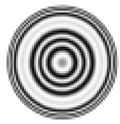
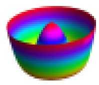
Figure 2-9: Ray Fan of Optical Aberration. **[7]**

2.3.3 Wavefront Map

The wavefront map shows the wavefront error across the pupil. It does not happen that only a single aberration is presented in the optical system and it becomes difficult to determine the effects of extend to each aberration on the performance of the optical design. The wavefront map provides the shape of the wavefront that can be easily identified as an aberration type. Moreover, it also provides a peak to the valley and the RMS wavefront error of the system. The aberration within a wavefront map can be decomposed using Zernike polynomials. Table 2.1 shows the Zernike polynomial of initially 11 aberrations.

Table 2.1: Zernike polynomial of first 11 Aberrations. [11]

Zernike Coefficients	**Polynomial**	**Aberration**	**Wavefront Shape**
Z1	1	Piston	
Z2	$\rho\ cos\varphi$	X-Tilt	
Z3	$\rho\ sin\ \varphi$	Y-Tilt	
Z4	$2\rho^2 - 1$	Focus	
Z5	$\rho^2 sin2\varphi$	Astigmatism (45°) and focus	
Z6	$\rho^2 cos2\varphi$	Astigmatism (0°) and focus	
Z7	$(3\rho^2 - 2)\rho\ sin\ \varphi$	Coma and Y Tilt	
Z8	$(3\rho^2 - 2)\rho\ cos\ \varphi$	Coma and X Tilt	
Z9	$\rho^3 sin3\varphi$	Y- Trefoil	

Z10	$\rho^3 cos3\varphi$	X- Trefoil	 
Z11	$(6\rho^4 - 6\rho^2 + 1)$	Spherical Aberration and Focus	 

2.3.4 Point Spread Function

The point spread function is a mathematical representation of the normalized energy intensity distribution of a point source image. It is considered a fundamental unit of an image in the theoretical model of optical design. Focused light converges at the focal point to produce a diffraction pattern of concentric rings. The radius of the rings is determined by numerical aperture so the resolving power of an objective can be determined by measuring the airy disc [12].

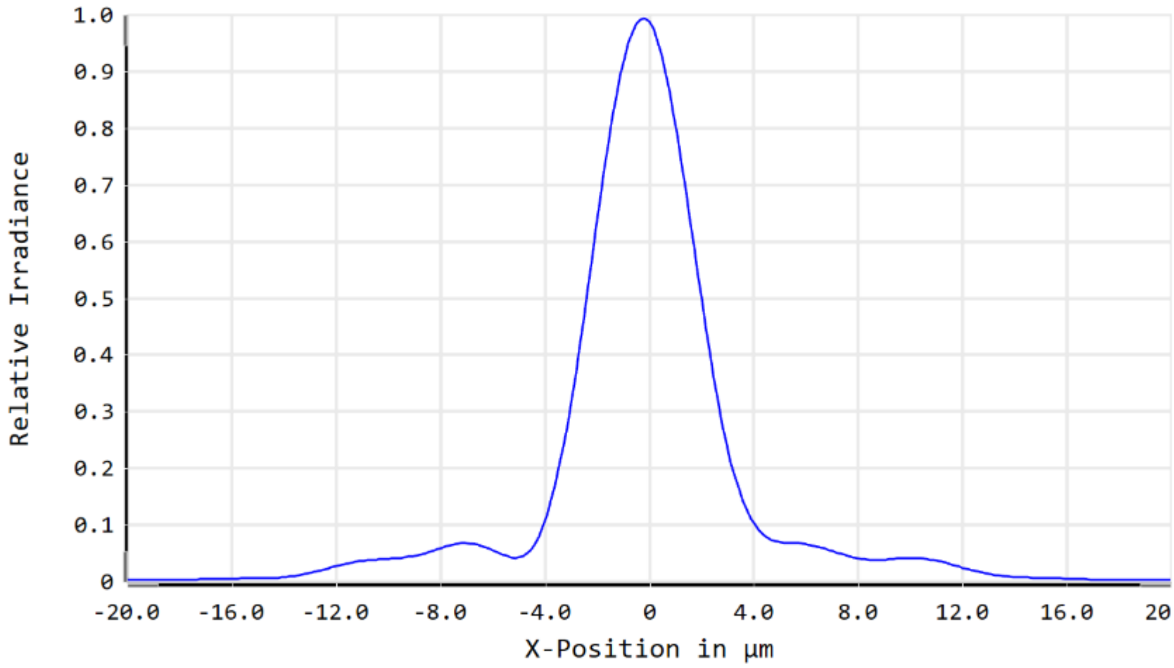


Figure 2-10: Point Spread Function of an Optical System.

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3 MISSION OBJECTIVES

Mission objectives are qualitative statements derived from the mission statement. These are the comprehensive goals which the system must accomplish to be productive. Space missions may have several types of objectives, primary objectives, secondary objectives and hidden objectives. Good mission objectives incorporate user needs and, at least indirectly, the space characteristics we are exploiting to achieve them [1]. Firstly, the system's main objectives will be defined and in the light of system objectives, optical design objectives will be presented.

The mission objectives of a high-resolution Earth observation satellite system may be written as;

3.1 Primary Objective

- Design and develop a high quality and high-resolution spacecraft that deliver earth surface imagery for various remote sensing applications such as land use and land cover, vegetation and forest, agriculture, disaster management, mapping and geographic information service, surveillance and for R&D purpose.

3.2 Secondary Objective

- To learn a systematic approach to develop a spacecraft system for human needs applications.

In the light of the above-mentioned mission objective, the optical system design objective can be deduced as;

3.3 Primary objective of optical design

- To build an optical design which provides required ground sampling distance (GSD) and other system performances as per system requirements and constraints.

3.4 Secondary objective of optical design

- To present a system-level approach to design any optical design from scratch to final design.

- Learn in depth knowledge of optical design theory and hands-on experience of optical design software

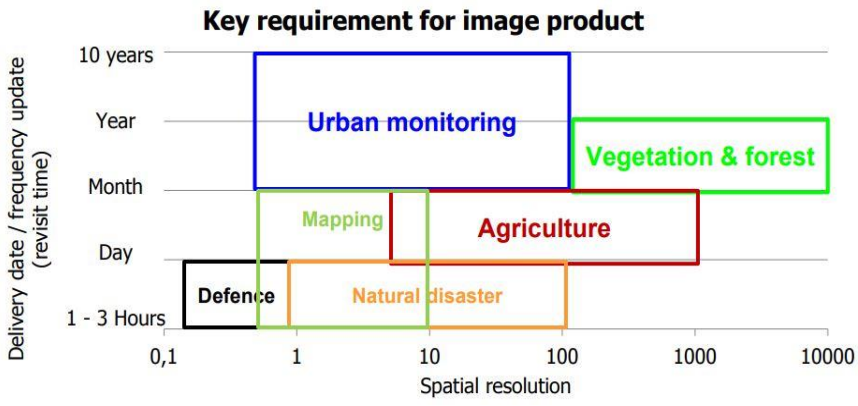
3.5 Constraints

- To fulfill all system technical requirements specifications
- To be consistent with system budgets

3.6 Optical System Requirements

Requirements are quantitative mission statements derived from the mission objectives. In this context, we will present all requirements which are directly applicable to the optical design of a telescope. Some will be direct requirements from mission requirements, and some will be derived requirements for optical design.

<table>
<tr><td>Requirement # 01</td><td colspan="4">Ground Sampling Distance (GSD) of the Payload shall be less than 1 meter in the Panchromatic band at the orbital height of 600 Km.</td></tr>
<tr><td>Type</td><td>System Requirement</td><td>Y</td><td>Derived Requirement</td><td></td></tr>
<tr><td>Rationale</td><td colspan="4">GSD is the smallest object on the ground that can be seen by the detector. The GSD requirement derives from the mission objectives that describes the application of the spacecraft that is being built for. Currently, the state-of-the-art systems such as SPOT, IKONOS and Worldview are using sub meter resolution [13] satellites for above mentioned objective so keeping in mind of current state of art and future trends 1m GSD has been selected. Figure 3-1 shows the image resolution requirement with respect to its application mention in mission objective.</td></tr>
</table>

	 **Figure 3-1:** Image GSD requirement as a function of Satellite Application. **[13]**

Requirement # 02	The Swath Width of the Payload during imaging, shall be greater than or equal to 12 Km at any point in mission orbit			
Type	System Requirement	Y	Derived Requirement	
Rationale	A swath is the area of ground that optical payloads will be able to see in each orbit or can image in one instant, the wider the swath the greater the ground coverage, but generally a wider swath means lower spatial resolution. From an optical perspective, it is directly proportional to the field of view (FOV) and focal length of an optical payload. However, focal length and usable (aberration-minimized) field of view are inversely related to each other. A large FOV creates tough challenges for optical design to be in diffraction limited performance. As a rule of thumb, the larger the swath width is, the greater the number of sensors are required within the image plane, the higher is the design complexity and the greater are the compromises on performance. In sub-meter GSD satellites, the swath width of Panchromatic and Multispectral bands is generally the same.			

<table>
<tr><td></td><td colspan="4"></td></tr>
<tr><td>Requirement # 03</td><td colspan="4">The payload shall have one Panchromatic band and three Multispectral bands with the wavelengths ranges as mentioned below;
<table><tr><td>Panchromatic</td><td>450-800 nm</td></tr><tr><td>Blue</td><td>450-510 nm</td></tr><tr><td>Green</td><td>510-580 nm</td></tr><tr><td>Red</td><td>630-690 nm</td></tr></table></td></tr>
<tr><td>Type</td><td>System Requirement</td><td>Y</td><td>Derived Requirement</td><td></td></tr>
<tr><td>Rationale</td><td colspan="4">The panchromatic waveband encompasses several wavelengths that typically coincide with the visible region of light and additional wavelengths, such as near infrared (NIR). The selection of the panchromatic waveband is a compromise between optimizing image sharpness and maximizing flux, and for a colored sensor, making the panchromatic image resemble what the human eye can see.

Additionally, extending the panchromatic bandwidth increases the photon flux. Flux maximization can also be achieved by increasing the TDI (time delayed integration) stages of the sensor by a large number, but this makes the stability requirements for the spacecraft more stringent. It may therefore be desirable to use a larger PAN waveband and fewer TDI stages to achieve a certain photon flux.

Band 0: 450-800 nm (Pan)

A Panchromatic band is used to detect the boundaries of the target and accumulate energy from the complete band. The range of a Panchromatic band can be extended up to 0.9 µm with a high SNR value (because of increase in the photon flux or energy) but it will reduce the overall MTF value (due to overall low optical cut-off</td></tr>
</table>

	frequency by the increase in spectral range). Therefore, the panchromatic band range is taken as 0.45-0.8 μm [14]. Band 1: 450-510 nm (blue) This band is used to identify water bodies object and helps in the analysis of different types of land use, soil, and vegetation characteristics [14]. Band 2: 510-580 nm (green) This band shows the green reflectance of healthy vegetation and it is used to identify the region between the blue and red chlorophyll concentration [14]. Band 3: 630-690 nm (red) This band represent the most important band for vegetation discrimination. It helps to identify the red chlorophyll concentration of healthy green vegetation [14].

Requirement # 04	The MTF of the telescope in the Panchromatic band shall be greater than 0.2 at the Nyquist frequency.			
Type	System Requirement		Derived Requirement	Y
Rationale	The optical modulation transfers function (MTF) is a representation of how well an optical system transfers the contrast from the object space (ground target) to the image space. The MTF performance of an optical satellite results from the contribution of the optical payload and the stability and alignment of the satellite bus. Contributors to MTF on the optical payload side are the following:			

	a) Contribution of diffraction, which is a physical phenomenon, determined by the dimensions and shape of the entrance pupil of the telescope and the solid angle of a ground sample at the altitude of the satellite. Wider wavelength bands are more difficult to optimize to yield higher optical MTFs than narrower wavebands. To make the situation simpler, it can be stated that the larger the optical aperture is, the better the diffraction MTF is. b) Contribution of the actual optical configuration (one mirror, two-mirror, three-mirror, Catadioptric, refractive telescopes). c) Contribution of the workmanship of the mirrors (polishing and figuring aim to be but cannot be perfect). d) Contribution of the misalignment of the optical components regardless of whether they are mirrors or lenses or filters or the detector package. e) Contribution of the detector. Contributors to MTF on the platform/bus side include: a) The smearing effect due to the satellite motion. b) The jittering effect is due to low frequency satellite vibrations or jitter (it may be due to micro vibration of reaction wheels or agility maneuvering of satellite). c) The smearing effect due to misalignments and instability; i) If the line of sight (LOS) is not stable enough during the image acquisition (i.e., the time of scanning a ground pixel). ii) In the case of TDI operation, misalignment of the detector principal axes with apparent satellite motion. The spacecraft should be controlled in terms of yaw steering of the line of sight (LOS) during TDI acquisition and potentially, in case of off nadir viewing, pitch steering as well.

	The design must take all these effects into account while calculating the performance budget. It must properly allocate the yaw and pitch steering accuracy values to the attitude and control system. In this thesis, we will only be interested in calculating telescope MTF. System MTF will be less than optical MTF as per Eq (2.5) which includes all factors mentioned above.			
Requirement # 05	The Mass of the payload shall be less than 40 Kg.			
Type	System Requirement		Derived Requirement	Y
Rationale	The payload mass is usually derived from the system mass budget and it is normally 30-40% of the total satellite mass [1]. But as we do not know the parameters of the satellite bus, so we calculate payload mass by using the empirical formula with the help of the primary aperture value; $$Payload\ mass = 697.aperture^{2.95} \quad (3.1)$$ Aperture value should be in meters and mass will be in kg. This is a rule of thumb, so the values listed are estimates only. However, these values compare favorably with available data on other existing satellite imagers.			

Requirement # 06	The Transmission of the Telescope shall be greater than 50% over the whole spectral band.			
Type	System Requirement		Derived Requirement	Y

Rationale	The Optical designer should keep in mind the obscuration ratio, the number of optical elements and coatings that take part in the calculation of transmission of the optical system which can affect the SNR requirements of the system. Although the SNR is a direct requirement for the payload and also a function of other parameters (sensor details, atmosphere, Satellite bus) however when it comes to the optical design, the transmission is a critical parameter for calculating the SNR.

Requirement # 07	The Dimensions of the Telescope shall be less than or equal to 500 X 500 X 1000 mm.			
Type	System Requirement		Derived Requirement	Y
Rationale	The Dimensions of the telescope derive from the overall dimension of the satellite which should be compliant with the selected launch vehicle fairing size.			

Requirement # 08	The Telescope shall have a Wavefront Error less than λ/14 RMS.			
Type	System Requirement		Derived Requirement	Y
Rationale	According to the Rayleigh criterion, an optical system will be diffraction limited, if the wavefront error is less than λ/4 RMS and the decrease of the irradiance in the image will be less than 20%, but this criterion refers to the spherical aberration within system. Marechal's criterion extends this theory to other aberrations and considers that the system is diffraction limited, if the wavefront error is less than λ/14 (0.07 λ) RMS [15].			

3.7 First order optical properties

A system which has no wavefront aberration is known as a perfect optical system or paraxial optics and usually can be described with first order optics. The first order equations can be derived from trigonometric expressions with term reduction when ray angle and height value are close to zero. The value of first order properties will follow exactly for well corrected optical systems and provide a reference for first order image position and size.

For a given optical system design, three values are very important to start with, Effective focal length, Aperture diameter and Field of view. In below listed sections, these values will be determined with the help of quantitative values from the requirements stated in section 3.6

3.7.1 Sensor Baseline

Although the focus of this thesis lies on the optical design aspects of the telescope, it is important to briefly look at the detector pitch size which is an important design driver and which dictates the SNR of the payload. Many optical properties such as focal length, depend upon this choice. Achieving a ground resolution of 1m from LEO orbit requires a detector that is both very fast and sensitive. A Time Delay and Integration (TDI) detector will be used that features multiple lines in the along-track direction.

A detector with small pixels is preferred because the detector size dictates the overall size of the instrument as a large pixel size results in a long focal length as shown by equation (3.3). TDI detectors datasheet are currently not available easily because this information is often not openly accessible but rather considered to be of restricted nature.

3.7.2 Effective Focal length

The Effective focal length (EFL) of an optical system is dependent on the pixel size, the orbit altitude (Alt) and the required ground resolution (GSD) and can be found using the simple vertically opposite angle theorem;

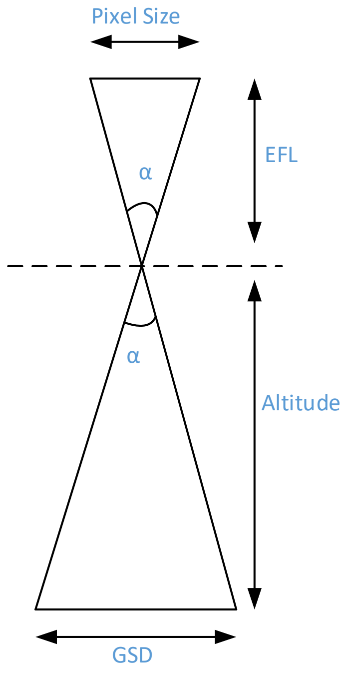


Figure 3-2: Trigonometric Relation to Calculate Effective Focal Length.

$$\frac{EFL}{PixelSize} = \frac{Altitude}{GSD} \tag{3.2}$$

$$EFL = Altitude\ X\ \frac{Pixel\ Size}{GSD} \tag{3.3}$$

The ratio of sensor pixel size and GSD is the same as the ratio between swath width and cross track dimension of the image plane. The first order EFL also can be calculated from these two parameters.

Orbital height and GSD are defined in the mission requirement document and these are the first things to think about in terms of satellite requirements. The pixel size of the sensor is one of the variables that can dictate the system focal length. It is a good practice to select the sensor size in the early stage of the optical design process as this will co-dictate overall telescope size.

As mentioned in section 3.6, the system shall have a GSD of 1m from an altitude of 600 km. A pixel size of 5.4 microns has been chosen as described in section 3.7.1. When using these values, the EFL of optical design comes out to be 3.3 meters.

3.7.3 Aperture Diameter

The choice of the aperture diameter basically has two functions. First, a certain size is required to capture enough light to reach the detector and secondly, the aperture diameter has to be chosen with a proper value to obtain the required ground resolution.

Any star on the sky observed through a telescope with a fixed aperture creates diffraction due to a single slit diffraction and this process will limit the resolution of an image. In a high-resolution system, the diffraction is usually driving the aperture size choice. The larger the aperture of an optical system the better is the resolution that we will get.

The resolution of the telescope is defined as the ability to resolve two point sources of light with small angular separation of $1.22\ \frac{\lambda}{D}$ which is called the Rayleigh limit criterion, where the depth between two PSF is at nearly 3/4 of the peak intensity as shown in Figure 3-3. By reducing the separation between two PSF to $\frac{\lambda}{D}$ reduces the depth intensity to less than 2% below the peak, this diffraction resolution limit for two points sources below the empirical two-star resolution limit, is known as Dawes's limit and usually used for space telescope calculation.

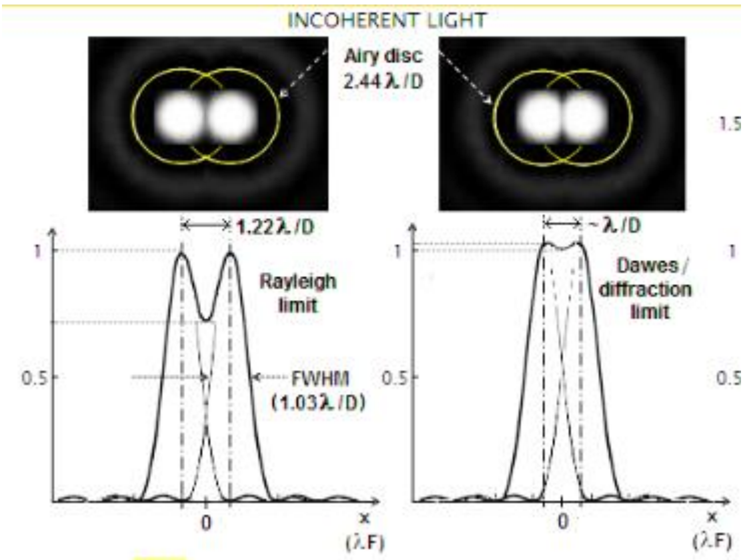


Figure 3-3: Rayleigh Criteria and Dawes's Limit. **[16]**

As per Dawes's Limit Criterion,

$$q_1 = \frac{f\ .\ \lambda}{D} \qquad (3.4)$$

Where λ is the central wavelength of band, f is the effective focal length of the system, D is the aperture size and q_1 is the radius of the airy disk. When designing a space telescope the requirement is set as such that the system must allow for a sufficient ground resolution which the system must able to resolve. For a space telescope, which looks at the Earth equation changes to,

$$q_1 = \frac{f\ .\ GSD}{Altitude} \tag{3.5}$$

By combining equation (3.4) and (3.5), we get

$$D = \frac{Altitude\ .\ \lambda}{GSD} \tag{3.6}$$

Using equation (3.6), the minimum aperture diameter can be calculated for an orbital height of 600 km, a central wavelength of 625 nm (PAN band) and for the required ground sampling distance of 1m, leading to the result that an aperture size of 375mm is required.

This aperture size was calculated based on the theory of light diffraction. A larger aperture may be required to collect more light for the system from a radiometric point of view (high system transmission value for high SNR). However, for a high resolution system is typically the diffraction that drives the aperture choice.

3.7.4 Field of View

The field of view of telescope dictates the image plane diameter which is a function of the swath width. As the FOV becomes larger, the system is bound to experience an off-axis aberration which leads to a more complex optical design.

$$FOV = \frac{Swath\ Width}{Altitude} \tag{3.7}$$

$$Image\ Plane\ Dia = EFL\ X\ FOV \tag{3.8}$$

Using Equations (3.7) and (3.8), the FOV of the telescope for a swath width of 12 km at an altitude of 600 km, is calculated at 1.146 degrees and the image plane diameter to place detectors takes on a size of 66 mm.

3.7.5 Nyquist Frequency

The resolution of Earth observation optical systems is described in units of length, rather than in angular units. Therefore, instead of the ability to resolve two-point sources for specifying angular resolution, line pairs of alternating contrast (black and white) over specific units of length are used. Generally, line pair/mm is used since it correlates well with test targets typically used in laboratory and test environments.

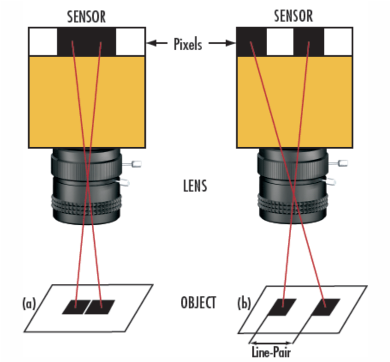


Figure 3-4: Camera Resolution Limit. **[17]**

As shown in Figure 3-4, the bigger the separation between squares, the more robust is the ability to resolve the image. In order to differentiate the two squares, at least one-pixel distance is required. The Nyquist frequency is the highest frequency that can be resolved by the sensor. It is effectively two pixels or one-line pairs. Using equation (3.9) Nyquist frequency on which the MTF of optical design will be measured with a pixel size of 5.4µm, comes out to be 92.6 lp/mm [17].

$$Nyquist\ Frequency = \frac{1000}{2*pixel\ Size} \tag{3.9}$$

4 OPTICAL DESIGN CONCEPT

4.1 Overview

The optical design consists of (utilizing diffraction, refraction and reflection) lenses and mirrors in a variety of configurations to form an image. Optical designs can be made using only refractive, reflective elements or hybrid. Each optical design shall be defined as per applications and specifications. Table 4.1 describes the key features as well as the pros and cons of the dioptric, cataoptric and catadioptric systems.

Table 4.1: Classification of Optical System.

Parameter	**Dioptric**	**Catoptric**	**Catadioptric**
Configuration	Composed of lenses only	Composed of mirror only	Composed of mirrors and lenses combinatio n
Aperture	Limited to 150-200 mm	Diffraction limited aperture	Diffraction limited aperture
Effective Focal Length	Used for short focal length	Can be used for longer focal lengths	Best for longer focal lengths
Performance	Spectral range is limited by chromatic aberration due to the dispersion of light	Optical performance will be better but affected by spherical aberration and coma	Best diffraction limited performance can be achieved
Total Length	General dimension longer than focal length	Overall length is less than focal length	Overall length is less than focal length
Mass/ Volume	High weight/ high volume	Low weight/ low volume	High weight/ low volume

As per the above comparison, it is obvious that the dioptric and catoptric systems cannot be used because a dioptric system is limited by aperture size, poor performance and big dimension and a catoptric system is restricted to a short focal length and features a poor optical performance.

A Catadioptric system will be the best choice for the envisaged optical design as it has a diffraction-limited aperture with a long focal length which is required for a high-resolution telescope. The long focal length of the telescope can be managed by two-mirror optical designs (catadioptric system) which give benefit in terms of telescope mass and volume constraints with diffraction-limited performance. It is the best approach to start the optical design process based on some baseline optical configuration. Therefore, we will now look for different telescope designs by taking into consideration our requirements.

As per section 3.7, the first-order properties of optical design have been evaluated in compliance with system technical requirements. Table 4.2 shows a summary of optical design specifications which are derived from system requirements and analytics formulas;

Table 4.2: Optical Design Specifications.

S.No	Parameters	Value	Unit
1	Altitude	600	km
2	GSD	1	m
3	Aperture Diameter	375	mm
4	Effective Focal Length	3300	mm
5	Field of View	1.146	degrees
6	PAN Wavelength	450-800	nm
7	Total Length	1000	mm
8	F#	8.8	
9	Swath Width	12	km

10	Nyquist Frequency	93	lp/mm

4.1.1 Schmidt Cassegrain

A Schmidt Cassegrain is a Catadioptric design that combines a Cassegrain optical path with a Schmidt corrector plate at the entrance pupil. It has a spherical primary and secondary mirror and an aspheric corrector lens at the front and flat at the back which is used to correct spherical aberration. This also has the benefit to remove spiders to hold a secondary mirror within mechanical design. This design is most popular in amateur astronomy. The overall weight of this system is relatively high due to the Schmidt corrector plate and field corrector near the focal plane. [18]

4.1.2 Maksutov Cassegrain

A Maksutov Cassegrain features a similar configuration as a Schmidt Cassegrain with a spherical primary and secondary mirror. The main difference is the corrector plate at the front of the telescope. The Maksutov corrector lens at the front of the telescope has a meniscus shape. A Maksutov corrector is much thicker (usually 10% of the aperture, compared to 3% of SCT) than a Schmidt corrector [19].

4.1.3 RC Cassegrain

A Ritchey–Chrétien telescope (RC) is a modified version of the Cassegrain telescope that has a hyperbolic primary mirror and a hyperbolic secondary mirror aimed to reduce off-axis optical aberrations (coma). This configuration has a wider FOV with free of optical aberrations as compared to more traditional configurations [20].

4.1.4 Three Mirror Anastigmat (TMA)

A three-mirror anastigmat is a telescope that consists of three curved mirrors, allowing it to correct all main optical on axis (spherical aberration) and off axis (coma, and astigmatism) aberrations. This configuration is used for a wide field of view which provides a larger swath field than two mirror configurations.

4.1.5 Dall Kirkham

The Dall Kirkham is a variation of the classic Cassegrain (primary mirror parabolic, secondary mirror hyperboloid). A Dall Kirkham telescope consists of an ellipsoid primary mirror which eliminates spherical aberration and a spherical secondary mirror which is easier to manufacture and test. Pairs of corrected lenses can be used to minimize all types of aberration [21].

4.2 Optical Design Configuration Concept

Different alternative configurations have been chosen for brainstorming by keeping in mind above mentioned configurations. Three concepts with different variations of Cassegrain and two concepts of variation of TMA have been chosen to analyse different aspects of configuration. The selected concepts will be compared based on;

- Optical Performance
- Alignment
- Testing
- Manufacturability

Table 4.3: Optical Design Concepts.

Concept	**Concept 01**	**Concept 02**	**Concept 03**	**Concept 04**	**Concept 05**
Type	Variation of Cassegrain (MCT-SCT)	Variation of Cassegrain (RC)	Variation of Cassegrain	Variation of TMA (Korsch)	Variation of TMA (Unobstructed)
Primary Mirror	Spherical	Aspherical	Spherical	Aspherical	Aspherical
Secondary Mirror	Spherical	Aspherical	Aspherical	Aspherical	Aspherical
Tertiary Mirror	NO	NO	NO	Aspherical	Aspherical
Folding Mirror	NO	NO	NO	YES	NO

Additional Field Lens/Corrector/ Mirror	YES	YES	YES	NO	NO

4.2.1 Concept 01

Concept 01, called Schmidt/Maksutov type Cassegrain, consists of a primary and secondary mirror and both have spherical surfaces. It will require more field lenses and correctors to achieve the required performance.

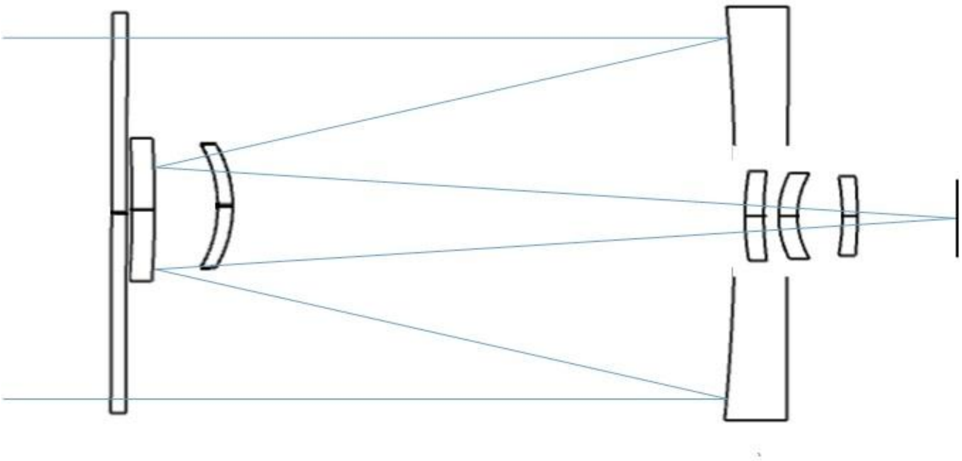


Figure 4-1: Conceptual Design of Concept 01**.**

4.2.1.1 Pros

- Manufacturing a spherical optical surface is easy as compared to aspherical surfaces.
- AIT of this telescope will be easy due to all spherical surfaces and it does not require special testing equipment.

4.2.1.2 Cons

- Transmission of light will be reduced due to many surfaces.
- This concept will require more field lenses and a corrector as compared to others to minimize all types of aberrations.
- Due to many field lenses and correctors, this system will be heavier.
- Optical performance may not be as good as required due to aberration in the spherical surfaces.

4.2.2 Concept 02

Concept 02 is also a type of Cassegrain telescope in which both mirrors have aspherical surfaces. Additional field lenses will be used to correct chromatic and off axis aberration near the image plane. This configuration is called the Ritchey Chretien Cassegrain telescope.

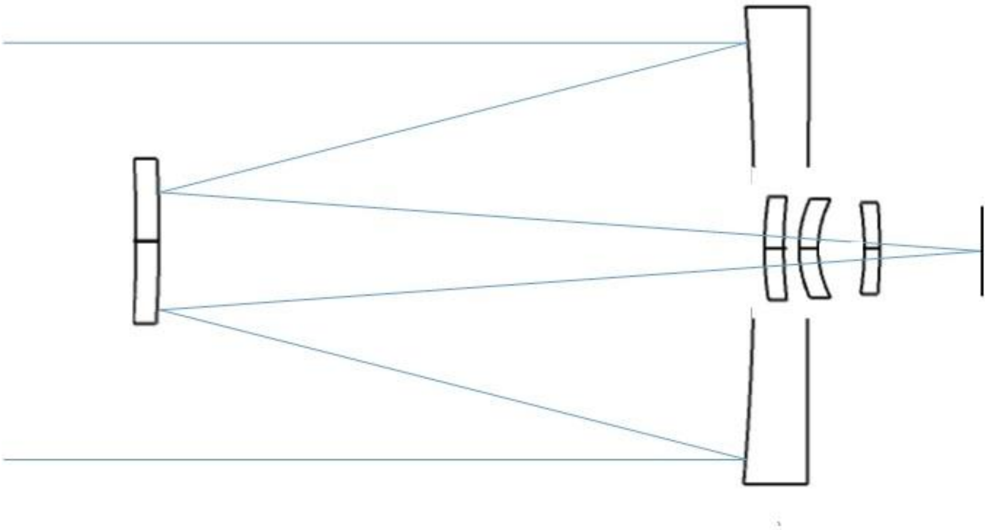


Figure 4-2: Conceptual Design of Concept 02**.**

4.2.2.1 Pros

- Transmission of this concept will be relatively higher due to fewer surfaces.
- This concept will have very good performance due to the excellent correction of chromatic and off axis aberrations.
- The alignment of this concept will be simple as all optical elements are on the same optical axis as compared to the off-axis TMA configuration.
- The tolerance budget for mechanical assembly will not be very tight relative to the TMA concept.

4.2.2.2 Cons

- Both primary and secondary have aspherical surfaces and aspheric surfaces are relatively difficult and costly to manufacture.
- AIT of the spherical surfaces is easy as compared to aspherical surfaces. Due to primary and secondary aspherical surfaces, it becomes difficult to test and requires special testing equipment.

4.2.3 Concept 03

Concept 03 is a type of the Cassegrain design in which the primary mirror has a spherical surface and the secondary will be an aspherical surface. Due to the spherical surface of the primary, it will produce spherical aberration and to reduce this aberration the secondary group will consist of a Mangin mirror and meniscus lens. A Mangin mirror is a type of negative meniscus lens with the reflective surface on the back side of the glass forming a curved mirror that reflects light without spherical aberration. Field lenses will be required to nullify chromatic and off axis aberrations at the edge of the field.

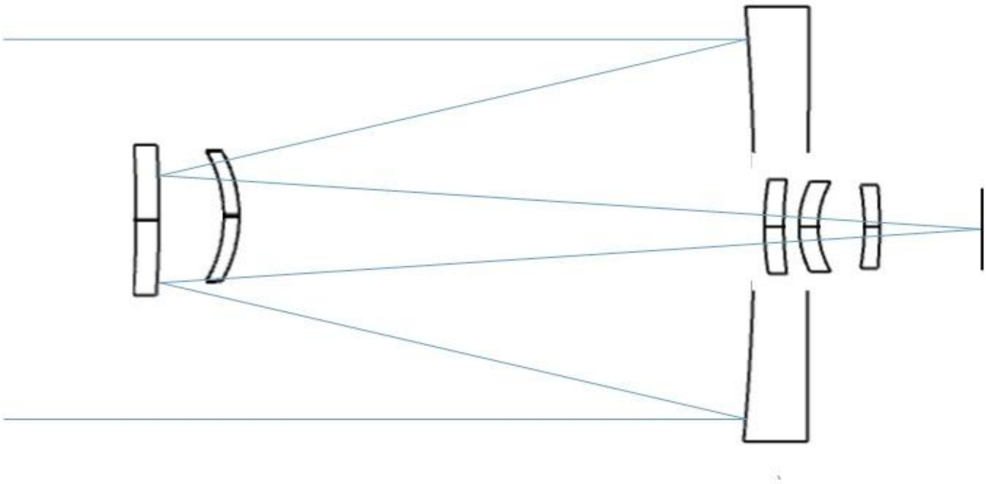


Figure 4-3: Conceptual Design of Concept 03**.**

4.2.3.1 Pros

- The alignment of this concept will be simple as all optical elements are on the same optical axis.
- Manufacturing of spherical surfaces is easy as compared to aspherical surfaces and due to the primary spherical surface, it becomes easy to manufacture.

4.2.3.2 Cons

- This concept will require more field lenses and correctors to minimize all types of aberrations.
- Transmission of light will be reduced due to many surfaces.
- One secondary aspheric surface will be used in this concept. Aspheric surfaces are relatively difficult to align, test and manufacture.

4.2.4 Concept 04

Concept 04 is the type of three-mirror anastigmat system in which three mirrors are used, allowing it to correct optical aberrations like spherical and off axis aberrations coma and astigmatism. A Korsch (type of TMA) telescope can correct all types of aberrations (on axis spherical aberration, off axis, coma, astigmatism, and field curvature) with a wide field of view to maximize swath width while ensuring very little stray light in the focal plane due to field stop at the Cassegrain focus. All three mirrors (primary, secondary and tertiary) are aspheric and a flat folding mirror is used to fold the light to get a more compact system.

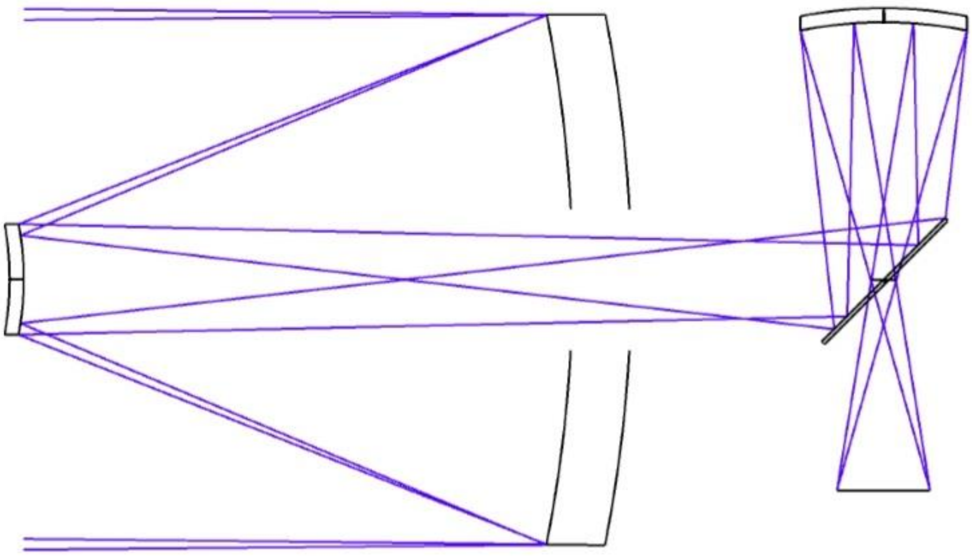


Figure 4-4: Conceptual Design of Concept 04.

4.2.4.1 Pros

- This concept will provide very satisfactory performance due to the minimization of all aberrations.
- It provides a wide field of view with a long focal length.
- Effects of stray light are much less as compared to a Cassegrain configuration.

4.2.4.2 Cons

- AIT of this concept will be challenging due to having optical elements being off the optical axis.
- Manufacturing of aspherical mirrors will be difficult and costly.

4.2.5 Concept 05

Concept 05 is also the type of TMA configuration, but it is unobstructed which gives a good performance as compared to obstructed TMA. All three mirrors are aspherical surfaces.

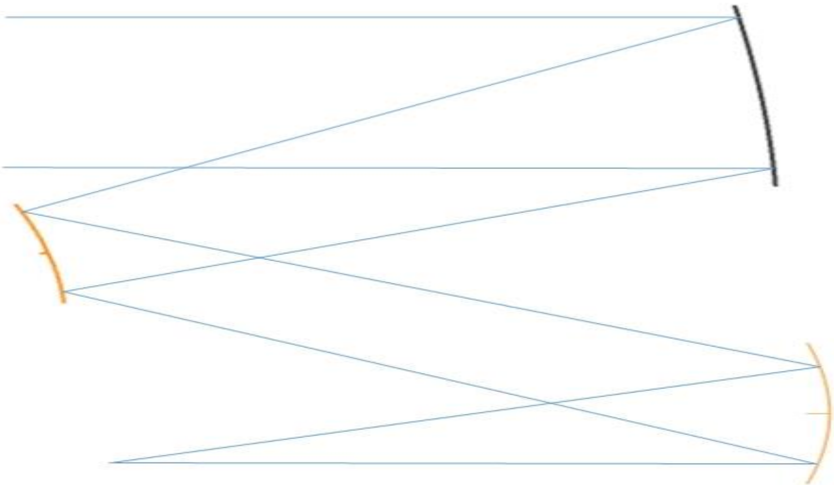


Figure 4-5: Conceptual Design of Concept 05.

4.2.5.1 Pros

- This concept will provide excellent performance as compared to concept 04 due to un-obstruction in the primary mirror.
- It provides wide FOV with a long focal length.
- Effects of stray light are very less as compared to Cassegrain configuration.

4.2.5.2 Cons

- AIT of this concept will be more challenging due to optical elements being off the optical axis.
- The volume of this concept will be very high and may not be compliant with launcher fairing with a large aperture telescope.

All five chosen concepts have been analysed in a brainstorming session and the advantages and disadvantages of all configurations have been discussed. Therefore, now we can trade off among configurations and can be in a position of deciding on which configurations will be selected as per system requirements.

4.3 Trade- Off Evaluation Criteria

The selection of optical configuration will be discussed by the trade-off method. The following parameters have been defined as criteria of trade-off in Table 4.4.

Table 4.4: Criteria and Definition

Criteria	**Definition**
Manufacturability	How easy or difficult to manufacture optical elements in terms of complexity?
Availability	Is this configuration/technology available?
Performance	Which has good or bad performance?
Cost	Which configuration cost more?
Mass	Which configuration has low or high mass?
Ease of AIT	Which configurations will have difficult or easy AIT?
Compactness	Which configurations are compact?
Time	How much time will require building optical configurations?

Weighting factors for each of the criteria have been defined, keeping in mind what is more important or critical to optical configuration. Each concept’s final weighting has been obtained by the matrix multiplication method (0.05*6 + 0.2*7 +……..).

Table 4.5: Trade-off among different configurations.

Weighting scale range 1-10; 10 is best , 1 is worst

PM= Primary Mirror, SM= Secondary Mirror, TM= Tertiary Mirror, Sph= Spherical, Asph= Aspherical

S.No	**Criteria**	**Criteria Weighting factor**	**Concept 01** Cassegrain PM-Sph SM-Asph	**Concept 02** Cassegrain PM- Asph SM-Asph	**Concept 03** Cassegrain PM-Sph SM- Sph	**Concept 04** TMA (Korsch) PM- Asph SM-Asph TM-Asph	**Concept 05** TMA (unobstructed) PM- Asph SM-Asph TM-Asph
1	Manufacturabilit	0.1	6	5	7	5	3
2	Availability	0.05	7	6	8	5	3
3	Performance	0.4	4	7	3	8	9
4	Cost	0.1	6	5	7	4	2
5	Mass	0.05	8	8	4	5	5
6	Ease of AIT	0.15	8	7	9	4	3
7	Compactness	0.1	6	6	6	8	8
8	Time	0.05	8	7	9	7	4
			5.75	6.50	5.60	6.35	5.95

The main idea of the conceptual design phases was to discuss and analyses different concepts and their approaches, merit, demerit and applicability with respect to the technical requirements. Consequently, two concepts (Concept A, and Concept B) will emerge as the best designs to investigate in a more detailed manner.

Based on a trade-off exercise and maximum weightage score following configurations have been selected for more detailed design.

Concept A

- Concept 02 Cassegrain with both primary and secondary aspherical surfaces

Concept B

- Concept 04 Korsch TMA with obstructed primary with three curved aspheric mirrors

Concept A configuration got the best ranking due to;

- Moderate performance
- Low mass
- Moderate ease of AIT

4.4 Evaluation of Selected Concepts

Selected optical concepts will be modelled in an optical design package [22] as per requirements and will be analysed for further comparisons.

4.4.1 Concept A

4.4.1.1 Description

Concept A is a Cassegrain based Ritchey–Chrétien design that was proposed in the early 1910s. The Primary and secondary mirrors are hyperbolic to eliminate spherical and off axis aberrations. Higher order aberrations, astigmatism and field curvature can be corrected by a field lens near the focal plane. Concept A will be analysed based on the baseline requirements that have been mentioned in Table 4.2.

4.4.1.2 Design Approach

Ritchey-Chretien (RC) Cassegrain design consists of two mirrors for which different parameters must define to start the design process. The RC design produces some spherical, chromatic and off axis aberrations and to reduce these aberrations an achromatic doublet with an air gap is used to eliminate chromatic aberrations. The field corrector lenses are composed of two or three individual lenses made of glasses material with different Abbe numbers corresponding to different amounts of dispersion. Typically, one lens is a concave element made of flint glass e.g. BF2, which has relatively high dispersion, and the other lens is a convex element with crown glass e.g. BK7, which has lower dispersion. The third lens with a low index of reflectance is used to reduce coma at the edge of the field.

The curvatures of two mirrors of RC Cassegrain are described by the following relationship;

$$\boldsymbol{C_1} = \frac{b-F}{2dF} \tag{4.1}$$

$$\boldsymbol{C_2} = \frac{b+d-F}{2db} \tag{4.2}$$

where;

C1 and C2 are curvatures of the primary and secondary mirror

F= effective focal length of the optical system

b= back focal length (distance from last optical surface to image plane)

d= Distance between Primary and secondary mirror (as a thumb rule it is taken EFL/3 to start design)

The optical design has been optimized in Optic Studio by Zemax [22]. Figure 4-6 shows the basic steps generally to follow for achieving the required optical design.

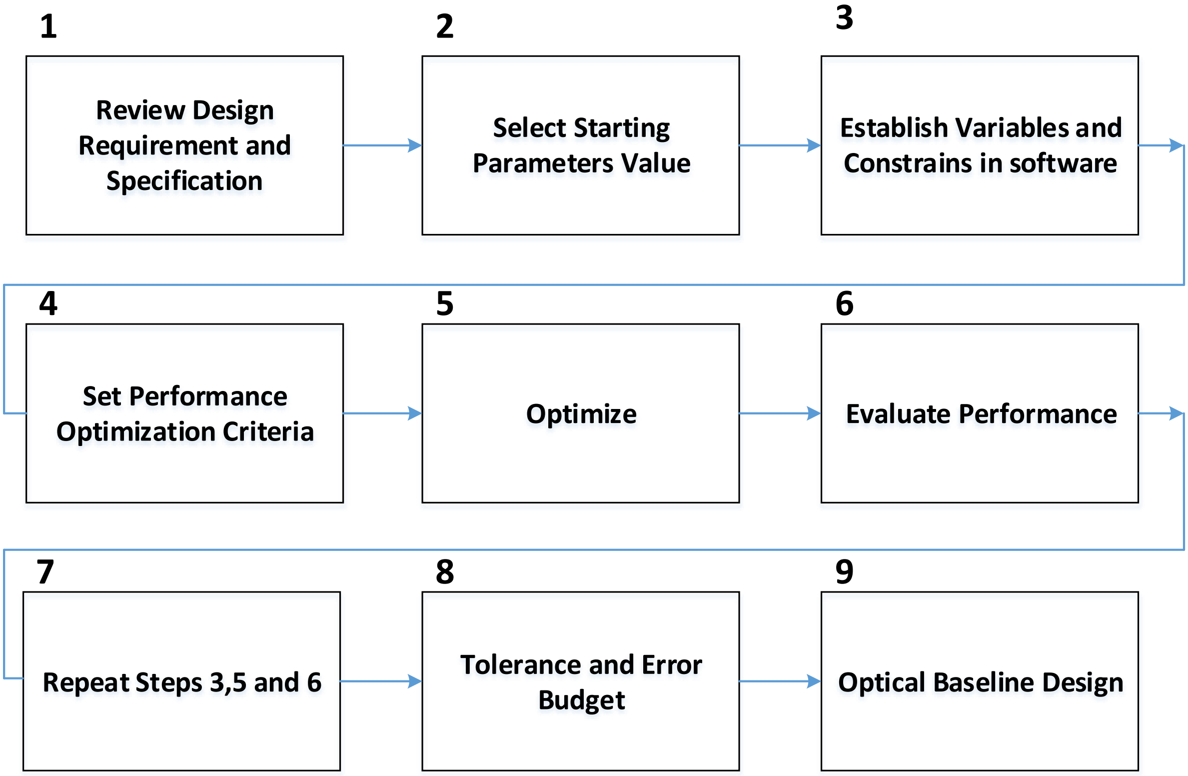


Figure 4-6: Optical Design and Optimization Procedure.

Table 4.6 describes the detailed characteristics of each element used in optical design;

Table 4.6: Definition of Optical Elements.

Element	Surface Shape	Radius of Curvature (mm)	Clear Aperture (mm)	Conic
Primary Mirror (M1)	Concave	-2246.884	375 Ø	-1.178
Secondary Mirror (M2)	Convex	-1068.192	131 Ø	-6.714
Field Lens 1 (FL1)	Convex	140.670	75 Ø	Nil
	Concave	183.074	75 Ø	Nil
Field Lens 2 (FL2)	Convex	129.356	71 Ø	Nil
	Concave	89.136	71 Ø	Nil
Field Lens 3 (FL3)	Concave	-80.352	69 Ø	Nil
	Convex	-84.669	69 Ø	Nil

Table 4.7 shows the intra-optical distance of RC optical design.

Table 4.7: Description of Intra Optical Distances.

Intra Optical Element	Distance	Unit
M1-M2	780	mm
FL1-FL2	6	mm
FL2-FL3	36	mm
FL3-Image Plane	111	mm
Total Track Length	970	mm

Figure 4-7 shows the optical layout of the design which consists of optical elements M1, M2 and Field lens (FL1, FL2 & FL3). An obscuration has been made at the secondary mirror position for secondary mirror mountings and baffles.

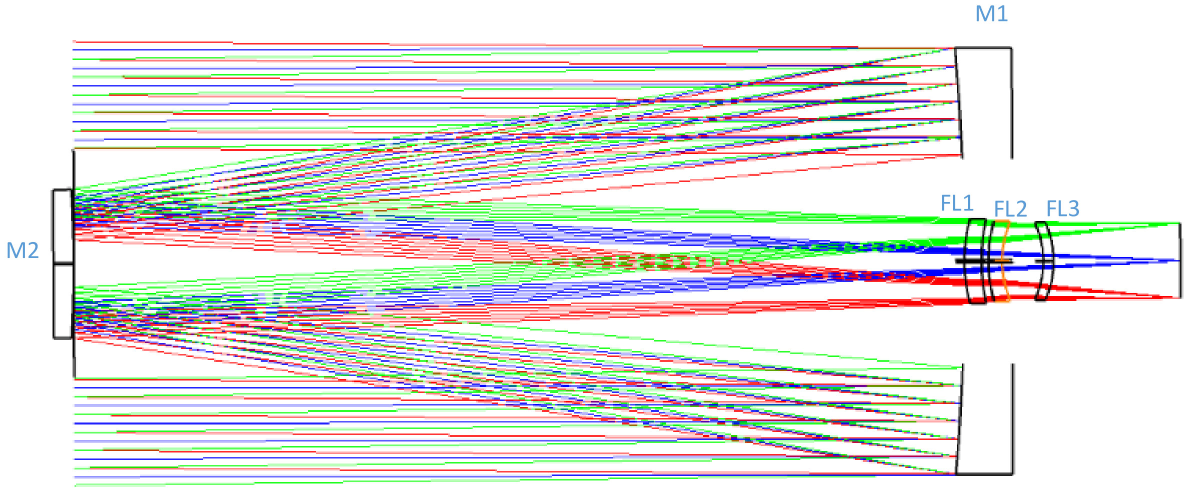


Figure 4-7: RC Optical Design Layout

4.4.2 Optical Performance Analysis

The Optical design has been modelled and analyzed in a vacuum and a temperature of 23 °C at which a telescope will be built and all the optical performance indicators will be presented on above mentioned environment condition.

4.4.2.1 MTF

Figure 4-8 shows the worst case theoretical MTF graph of the panchromatic band (450nm-800nm) calculated at a Nyquist frequency of 93 lp/mm over the field of view of the telescope.

Band	**Average MTF at Spatial frequency of 93 lp/mm**
PAN (450 nm-800 nm)	22%

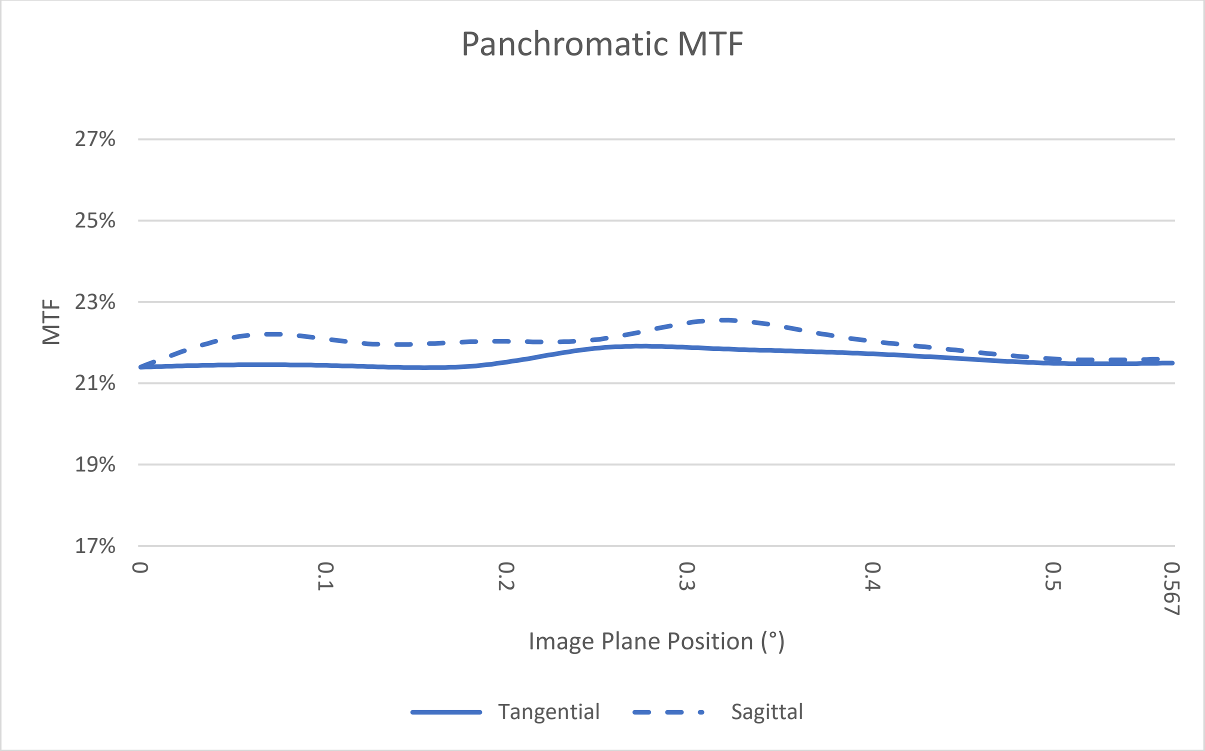


Figure 4-8: RC Optical Design-PAN MTF as a function of Image Plane Position.

4.4.2.2 Transmission Efficiency

The Transmission efficiency across the image plane has been calculated for the required spectral band (450nm – 800nm).

Anti-reflective coatings were taken with 99% transmissivity across the specified spectral band, and reflective coatings (Protected Silver) were taken with 98% reflectivity across the specified spectral band [23].

First order transmission of RC optical design can be calculated by using the below mention formula;

$$\boldsymbol{\tau_{optics} = optics\ effceincy * \tau^{N}_{Mirror\ coating} * \tau^{N}_{AR\ coating}} \qquad (4.3)$$

where;

$\tau_{Mirror\ Coating}$ = % of reflectivity of mirror surface

$\tau_{AR\ Coating}$ = % of transmissivity of glass surface

N = number of surfaces

$$Optics\ efficiency = 1 - obscuration\ ratio$$

Table 4.8 shows the calculation of transmission efficiency for an RC optical design.

Table 4.8: RC Optical Design-Transmission Efficiency.

Parameter	**Unit**	**Values**
EFL	mm	3300
Aperture Diameter	mm	375
Centre Wavelength	nm	625
Mirror Surfaces	No.	2
Mirror Coating (Protected Silver)	%	98
Secondary Diameter	mm	200
Optical Efficiency	%	71
AR Coating	%	99
Lens Surfaces	No.	6
Total Transmission	%	64

A Ritchey-Chretien Cassegrain telescope was selected as concept A and analysed to determine the performances as per specifications stated in Table 4.2.

- RC Cassegrain has a long total optical track length which will have to meet the constraint of the launcher and an additional baffle structure for stray light is also required in Cassegrain design.
- RC Cassegrain design also has a large obscuration because of the large size of the secondary mirror and it also creates a bulge in the MTF graph that decreases the optical performance of this design.

- RC Cassegrain design has colour aberration due to the lens elements and it can be minimized by using the right choice of glasses.
- Due to colour aberration, the spot size of RC Cassegrain is a little bit big but within an airy disk.
- The sensitivity of optical elements is much more relaxed in RC Cassegrain as all optical elements are at distinct distances and on a single axis.

4.5 Concept B

4.5.1.1 Description

From the trade-off mentioned in section 4.3, the second concept that was selected was based on the Korsch Three Mirror Anastigmat type telescope optics. The Korsch TMA has three powered optical elements primary, secondary and tertiary and one flat folding mirror to project an intermediate image to the tertiary mirror to eliminate all off-axis aberration. Concept B will be analyzed based on the baseline requirements that have been mentioned in Table 4.2.

4.5.1.2 Design Approach

A Korsch TMA has two foci, one is the Cassegrain focus and is made near the vertex of the primary mirror and the other is on the image plane. Primary mirror speed (F#) should be fast to get the Cassegrain focus at the desired position. The separation between primary and secondary should be taken equal to the diameter of primary for starting. The Tertiary mirror position should be kept in the primary mirror envelope to fulfil the constraints of dimension. The Folding mirror will be tilted of angle 45° and is placed at the position where the chief ray height is zero. The main advantage of the Korsch design is that with careful selection of the separation and the conic constants of the aspheric surfaces all the three aberrations spherical, coma and astigmatism can be removed.

Design steps for the Korsch TMA are the same as defined in the previous optical configuration in Figure 4-6.

Table 4.9 describes the detailed characteristics of each element used in optical design;

Table 4.9: Definition of Optical Elements.

Element	**Surface Shape**	**Radius of Curvature (mm)**	**Clear Aperture (mm)**	**Conic**
Primary Mirror (M1)	Concave	-956.782	375 Ø	-0.974
Secondary Mirror (M2)	Convex	-216.056	80 Ø	-1.787
Tertiary Mirror (M3)	Concave	277.613	120 Ø	-0.570
Folding Mirror (FM)	Plano	Infinity	130x40	Nil

Table 4.10 shows the intra-optical distance of Korsch TMA optical design.

Table 4.10: Description of Intra Optical Distances**.**

Intra Optical Element	**Distance**	**Unit**
M1-M2	390	mm
M2-FM	380	mm
FM-M3	166	mm
M3-Image Plane	306	mm
Total Track Length	740	mm

Figure 4-9 shows the optical layout of the design which consists of optical elements M1, M2, M3 and FM. An obscuration has been made at the secondary mirror position for secondary mirror mountings.

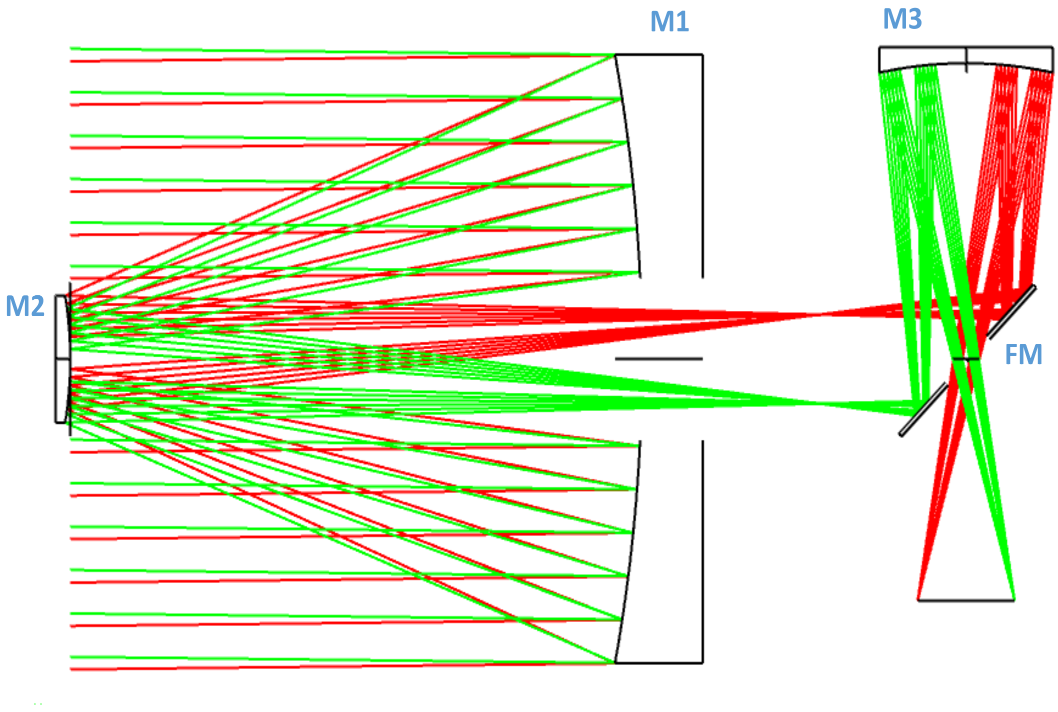


Figure 4-9: Korsch Optical Design Layout.

4.5.2 Optical Performance Analysis

The optical design has been modelled and analysed in a vacuum and at a temperature of 23 °C at which a telescope will be built and all optical performance indicators will be presented on above mentioned environment condition.

4.5.2.1 MTF

Figure 4-10 shows the worst case theoretical MTF graph of the panchromatic band (450nm-800nm) calculated at a nyquist frequency of 93 lp/mm over the telescope field of view.

Band	**Average MTF at Spatial frequency of 93 lp/mm**
PAN (450 nm-800 nm)	34%

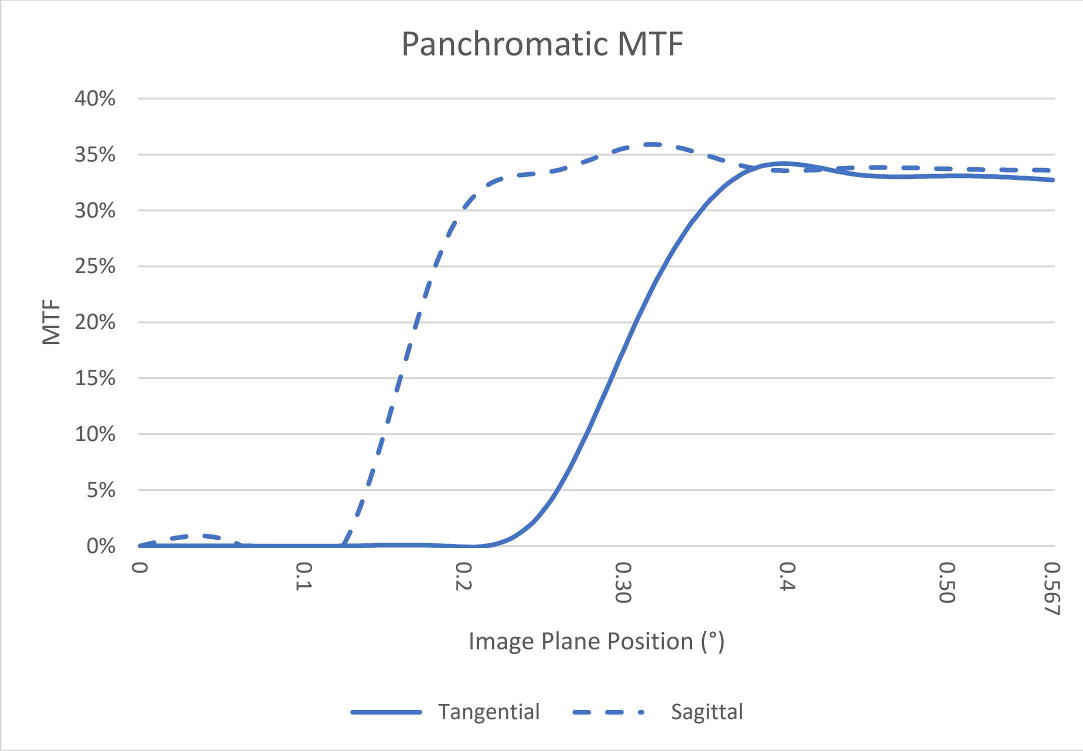


Figure 4-10: Korsch TMA Optical Design-PAN MTF as a function of Image Plane Position.

It has been observed in Figure 4-10 that MTF is not constant over the whole field of view because of the hole in the folding mirror which creates vignetting in the centre of the image plane. A Hole has been made in the folding mirror for passing light from the tertiary mirror to the image plane. Sensor placement will be only possible in the outer circle of the image plane as shown in Figure 4-11, where the grey area will be vignetted.

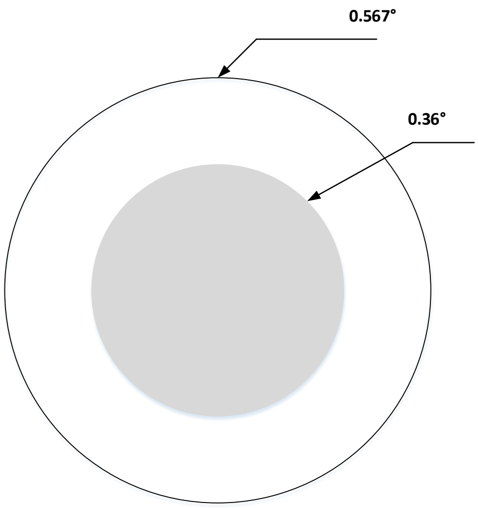


Figure 4-11: *Korsch TMA-Image Plane.*

4.5.2.2 Transmission Efficiency

Transmission efficiency across the image plane has been calculated for the required spectral band (450nm – 800nm).

Anti-reflective coatings were taken with 99% transmissivity across the specified spectral band, and reflective coatings (Protected Silver) were taken with 98% reflectivity across the specified spectral band [23].

First order transmission of Korsch optical design can be calculated by using below mention formula;

$$\boldsymbol{\tau_{optics} = optics\ effceincy * \tau^{N}_{Mirror\ coating} * \tau^{N}_{AR\ coating}}$$

(4.4)

where;

$\boldsymbol{\tau_{Mirror\ Coating}}$ = % of reflectivity of mirror surface

$\boldsymbol{\tau_{AR\ Coating}}$ = % of transmissivity of glass surface

N = number of surfaces

$\boldsymbol{Optics\ efficiency\ =\ 1 -\ obscuration\ ratio}$

Table 4.8 shows calculation of transmission efficiency for Korsch optical design.

Table 4.11: Korsch optical Design-Transmission Efficiency.

Parameter	Unit	Values
EFL	mm	3300
Aperture Diameter	mm	375
Centre Wavelength	nm	625
Mirror Surfaces	No.	4
Reflectivity Mirror Coating (Protected Silver)	%	98
Secondary Diameter	mm	100
Optical Efficiency	%	92
Anti-Reflection (Transmissivity) Coating	%	99
Lens Surfaces	No.	0
Total Transmission	%	85

The Korsch TMA was analyzed as per specifications, and the results are presented in the form of MTF graphs and transmission efficiency. From the analysis, it is evident that the Korsch TMA is compact and has a small obscuration ratio. There is no color aberration in the ray aberration curves. Further, the optical performance in terms of spot diagram and WFE remains constant over the whole field, from the center to the edge of the field. From the preliminary sensitivity analysis, it appears that the Korsch TMA has tight tolerance requirements in comparison with the RC Cassegrain.

5 TRADE-OFFS

5.1 Objective

The objective of the trade-off study is to check the feasibility of suitable designs of telescope that can fulfill the technical requirement with optimum resources.

5.2 Evaluation Criteria

Alternative design solutions for the optical design will be evaluated based on the broad criteria presented in Table 5.1. The different weighting attached to these criteria is also presented in the same table. These broad evaluation criteria are conceived keeping in view not just the telescopes' technical requirements but also the various programmatic risks associated with time, cost and design. Justification and further explanation of these evaluation criteria will be defined in the next section.

Table 5.1: Broad evaluation criteria for optical design.

1	Performance	0.35
2	Satellite/Launch Cost	0.2
3	Payload Cost	0.25
4	Implementation Risk	0.1
5	Implementation Schedule	0.1

$$\begin{aligned} Final\ Trade\ off\ Score \\ &= (0.35\ \times Performance\ Score) + (0.2\ \times Satellite\ Cost\ Score) \\ &+ (\ 0.25\ \times Payload\ Cost\ Score) \\ &+ (0.1\ \times Implementation\ Risk\ Score) \\ &+ (0.1 \times Implementation\ Schedule) \end{aligned}$$

5.2.1 Performance

The main criteria for the trade-off of two optical configurations are always their performance. That is the reason it is assigned the highest weighting in the evaluation criteria. This criterion is further divided into other evaluation criteria presented in Table 5.2.

Table 5.2: Performance Evaluation criteria.

1	Performance	0.35		
			MTF	0.5
			Transmission	0.3
			Scope of future upgrades	0.2

In order to quantify the performance of the optical configurations following parameters were mentioned

$$Performance\ Score = (0.5\ \times MTF\ Score) + (\ 0.3\ \times Transmission\ Score) + (0.2\ \times Scope\ of\ future\ upgrade\ score)$$

5.2.1.1 MTF

The main performance indicator of the optical system is its compliance with the diffraction limited MTF. The MTF of the optical system for different optical configurations may vary from the center to the edge of the field of view. To assess the worst value of the MTF, Edge of the field MTF is used for the trade-off. The MTF may degrade over time due to the optical surfaces involved. However careful selection of the coatings mitigates the effect of degradation of MTF at end of life.

MTF values for the RC Cassegrain and Korsch TMA designs are presented in Table 5.3. The MTF values for the RC Cassegrain are low compared to the Korsch TMA. The RC Cassegrain MTF is greatly limited by the Baffling required for the stray light.

Table 5.3: MTF Comparison of Optical Design**.**

Parameter	Unit	RC	Korsch
EFL	mm	3300	3300
Aperture Diameter	mm	375	375
Center Wavelength	nm	625	625
F#		8.8	8.8
F_{nyq}	lp/mm	93	93
FFOV	deg	1.146	1.146
Obscuration ratio achieved	%		
MTF	%	22	34

5.2.1.2 Transmission efficiency

Signal to noise ratio is always an important performance parameter for optical systems. SNR is also dependent on the transmission efficiency of the optical system. The transmission efficiency depends on the type and number of optical elements, and obscuration present in the optical configuration. The transmission efficiency degrades over a period of time for the lens surfaces due to the exposure to radiation in space.

Table 5.4: Transmission Efficiency Comparison of Optical Design**.**

Parameter	Unit	RC	Korsch
EFL	mm	3300	3300
Aperture Diameter	mm	375	375
Centre Wavelength	nm	625	625
Mirror Surfaces	No.	2	4
Reflectivity Mirror Coating (Protected Silver)	%	98	98
Secondary Diameter	mm	200	100
Optical Efficiency	%	71	92
Anti-Reflection (Transmissivity) Coating	%	99	99
Lens Surfaces	No.	6	0
Total Transmission	%	64	85

5.2.1.3 Scope of future upgrades

The design and development of the optical payload require the development of various facilities for AIT and manufacturing. Keeping in view the future needs and requirements for the optical payload in terms of high resolution, evaluation criteria of future upgradability is also incorporated into the trade-off.

Usage of the Higher IR bands: The current optical design is in the visible band, but in the future, there can be a need for the usage of the higher IR wavelengths, like the

NIR, SWIR and MIR. In that case, the Korsch TMA is most suitable as it provides a cold stop whereas RC Cassegrain does not have a cold stop [24].

Sub-meter resolution telescope has a wide field of view and the RC design is not suitable for wider FOV, it produces aberration and optical performance will not be as required. Although Korsch TMA is most suitable for sub-meter resolution as shown in Figure 5.1.

The current state of the art in the industry is the Korsch TMA as almost all the sub-meter resolution Earth Observation satellites currently operating are based on the different variants of the Korsch TMA.

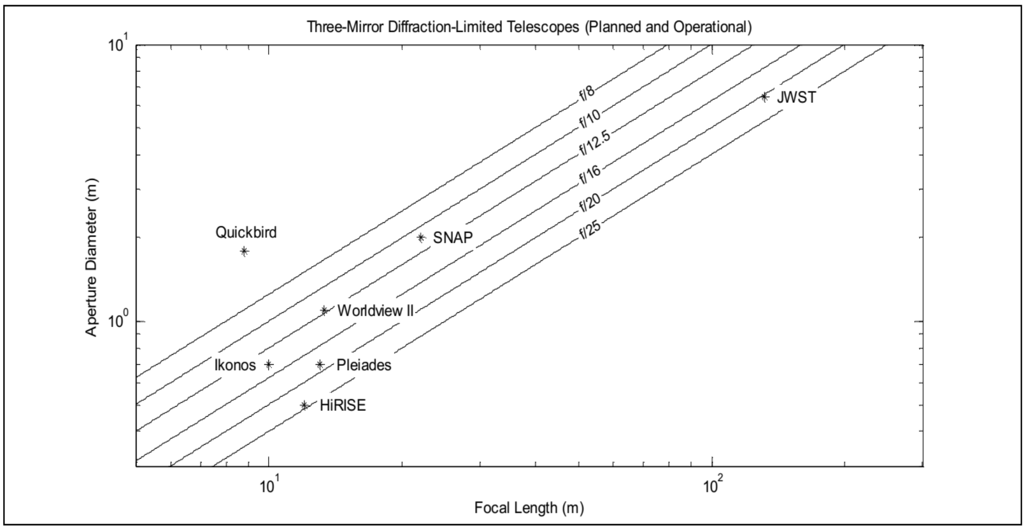


Figure 5-1: TMA Telescope Trend.

5.2.2 Satellite/Launch Cost

Satellite cost includes the cost of the development of the platform and payload. The Cost of Payload affects the overall cost of the satellite. A satellite with a bigger volume and mass would result in a higher overall satellite cost. The Launch cost also depends on the satellite mass and volume. As a result, payload mass affects the Satellite and launch cost. In order to assess the payload mass, four further criteria are considered like thermal control, athermalization, mass for the baffling and the parts count. The criteria defined at the third level are not assigned weighting factors, rather the average of their scores will be taken to calculate the score for the above level.

Table 5.5: Satellite/ Launch Cost Criteria.

2	Satellite/Launch Cost	0.2			
			Mass	0.80	
					Thermal control
					Athermalization
					Part count
			Size	0.20	

$$Satellite\ \&\ Launch\ Cost\ Score = (0.8\ \times Mass\ Score) + (0.2\ \times Size\ Score)$$

$$Mass\ Score\ = (Thermal\ Control\ Score + Athermalization\ Score + Part\ Count\ Score)/3$$

5.2.3 Payload Cost

Overall payload cost is the combination of the cost required for the design, AIT and manufacturing. Design, AIT and Manufacturing are further divided into other criteria. The various criteria with the weighting factors are given in Table 5.6. Payload Cost of payload AIT depends on the cost of the related GSE, facilities development and the required relevant expertise development.

Table 5.6: Payload Cost Criteria.

3	Payload Cost	0.25			
			Design	0.40	
					Required skill level of Design team
					Effort to perform optical design
					Part count
					Effort for Baffling and Athermalization
			AIT	0.30	
					Effort to build Telescope
					Required skill level of AIT team
					GSE (design, build, commissioning)
					Effort Planning
					Effort to align optics
					Effort to perform tests
			Manufacturing	0.30	
					Parts count
					Part complexity
					Optical elements

$$Payload\ Cost\ Score = (0.4\ \times Design\ Score) + (0.3\ \times AIT\ Score) + (0.3\ \times Manufacturing\ Score)$$

5.2.3.1 Design

In order to assess the payload cost, the cost of designing the payload is also included, which comprises other additional criteria.

- Required Skill level of the design team

This is defined as the cost involved in achieving the required level of skill to design the telescope. The higher the skill level required the higher the costs. The level of skill required depends upon the design complexity, part count and tolerance of design. Both selected designs have different approaches and technology to design optical configurations. RC Cassegrain system has all optical elements on the same axis and is easy to optimize due to the minimum number of variables, but Korsch TMA system has three powered elements and different stops to achieve design performance.

- Effort to perform optical design

This is defined as the cost involved in the design effort. The cost will increase with the increase of required effort to perform design analysis. Design effort depends upon the factors of design complexity, part count and tolerance of design. The Korsch TMA has tight tolerance and off-axis optical elements, so it requires more effort to design optical configuration as compared to RC Cassegrain.

- Effort for baffling and athermalization

Korsch TMA system does not need any baffling because all stray light can be blocked making a stop on Cassegrain focus. On the other hand, the RC Cassegrain design needs a baffle around the primary and secondary mirrors as well as an external baffle to block stray light.

Effort for athermalization may be the same for both designs but tolerance on the Korsch TMA will be tighter than the RC design.

- Part count

Design and analysis of two mirrors (RC) will be easy as compared to three mirrors (Korsch) because mirrors have strict surface error and lightweight requirements.

$$Design\ Score = (Required\ skill\ level\ of\ design\ team\ Score + Effort\ to\ perform\ optical\ design + Effort\ for\ baffling\ and\ Athermalization\ Score + Part\ Count\ Score)/4$$

5.2.3.2 AIT

Assembly, Integration and Testing of chosen optical concepts mainly depends upon tolerance of the budget of optical system which is directly related to the cost of building an AIT facility. An optical system with a relaxed tolerance budget and all optical elements on the same axis is relatively easy to plan, build, align and test as compared to the system with tight tolerance and excess optical elements with the different optical axis. The two concepts will be evaluated based on how the assembly, integration and testing effects the overall payload cost. The following key criteria were highlighted to assess the effect of assembly, integration and testing on the overall payload cost

- Effort to build Telescope

This includes the amount of skilled manpower and the time required to accomplish the AIT of the Telescope. The more the optical elements there are within the optical configuration the higher the manpower and the time required for the AIT.

- Required skill level of AIT team

The type of optical configuration also affects the required skill level of the team involved in the AIT. The required skill for the AIT of different type of curved mirror surface and the tolerances involved is different.

- GSE (design, build, commissioning)

The selection of the payload optical configuration also affects the overall design, build, commissioning and the reliability of the ground support equipment. Design of the GSE depends on the tolerance required by the optical system. Optical systems with tight tolerance will require complex and expensive GSE.

- Effort Planning

The selection of optical configuration affects the planning of the overall AIT. This includes the planning of the type and number of different facilities that will be required. Also, the planning of the facilities would need to consider the future expansion and usability.

- Effort to align optics

The selection of optical configuration directly affects the overall effort required for aligning the optics. Alignment of optics depends on the type of mirror surfaces involved. Spherical, aspherical and freeform optics require an incremental level of effort for alignment, with spherical optics requiring the least amount of effort. Also, the alignment of optics depends on whether all the optical elements are on the same optical axis or not. If all the optical elements are on the same optical axis and do not require any tilt or decenter than the required amount of effort for alignment would be less

- Effort to perform tests

Testing of optical systems mainly depends on the size of aperture diameter. A given dimension (aperture) of optical system requires the same level of testing (MTF, WFE) and GSE (interferogram, flat mirror and collimator).

$$\begin{aligned} AIT\ Score \ &= (Effort\ to\ build\ telescope\ Score \\ &\quad + Required\ skill\ level\ of\ the\ team\ Score + GSE\ Score \\ &\quad + Effort\ planning + Effort\ to\ align\ optics \\ &\quad + Effort\ to\ perform\ test)/6 \end{aligned}$$

5.2.3.3 Manufacturing

Manufacturing was also used to compare the two optical configurations. Manufacturing was further divided into the number of the optical elements, the complexity of the parts and the number of the parts involved. Increase in the number of parts affects the overall project cost and schedule.

- Parts Counts

Manufacturing cost has a direct relation with the number of part count. A higher part count means higher manufacturing cost.

- Part complexity

Manufacturing cost also depends on the part complexity and the term part complexity is referring to complex shapes and manufacturing tolerance. For complex parts specialized tools, machines and processes are required for manufacturing and the probability of rejection is also increased due to a very tight tolerance.

- Optical Elements

The manufacturing cost of the telescope is directly proportional to the cost of the optical element. cost of optical elements depends on the number of optical elements, size of the optical element, manufacturing tolerance and material used for optical elements to make it lightweight.

$$Manufacturing\ Score = (Optical\ Elements\ Score + Part\ Complexity\ Score + Part\ Count\ Score)/3$$

5.2.4 Implementation Risk

In the comparison of the optical configurations’ implementation risk was also used as a trade-off. The implementation risk was further divided into complicated parts, tolerances for the mechanical & thermal design, and the total number of critical and complex parts in both designs. Korsch TMA will have very tight tolerances [25] as compared to RC Cassegrain and complicated structure and thermal design impose implementation risk on design.

4.1.1.1.1 Complicated parts

Part complexity is referred to the complex shapes of parts, very tight tolerance for manufacturing and alignment, and sensitivity of the part to environmental conditions. If a part is difficult to manufacture, difficult to align due to high tolerance and more sensitive to changes in temperature or any other parameter of the environment then it will count as a complicated part.

4.1.1.1.2 Tolerances

The tolerance budget of both concepts is one of the main criteria to define the implementation risk of payload. Tight tolerances will put a high implementation risk on the optical payload rather than relaxed tolerance payload.

4.1.1.1.3 Part Count (Design Complexity/Reliability)

Part Count of the telescope has a negative impact on implementation risk. The higher the number of parts the more difficult it to align with each other and difficult to isolate from the impact of environmental changes. It makes the design more complex and reduces the performance reliability of the system.

Table 5.7: Implementation Risk Evaluation Criteria.

4	Implementation Risk	0.1		
			Complicated parts	0.25
			Tolerances	0.50
			Part Count (Design Complexity / Reliability)	0.25

$$Implementation\ Risk\ Score = (0.25 \times Complicatedd\ parts\ Score) + (0.5 \times Tolerances\ Score) + (0.25 \times Part\ count\ Score)$$

5.2.5 Implementation Schedule

The design solutions were also compared based on the impact of the particular design selection on the overall implementation schedule. In this regard, the complexity of the design and the number of parts of a particular optical solution would delay the major milestones like the manufacturing readiness review MRR, QM AIT and FM AIT.

Table 5.8: Implementation Schedule Evaluation Criteria.

5	Implementation Schedule	0.1		
			Design completion to MRR (EM)	0.50
			Qualification model	0.30
			Flight model	0.20

$$Implementaiton\ schedule\ Score = (0.5\ \times Design\ completion\ to\ MRR\ score) + (0.3\ \times Qualification\ model\ \ Score) + (0.2\ \times flight\ model\ \ \ Score)$$

5.3 Trade-Off

Table 5.9 shows the trade-off between two selected concepts on the basis of the evaluation criteria mentioned above with scoring. The scoring of level 4 has been normalized with respect to a higher value.

Table 5.9: Alternative Optical Design Concept Trade-off.

Level 1	Level 2	Weighing Factor	Level 3	Weighing Factor	Level 4	RC	Korsch
1	Performance	0.35				0.689	1.000
			MTF	0.50		$\frac{22}{34}=$ 0.647	$\frac{34}{34}=$ 1.000
			Transmission	0.30		0.752	1.000
			Scope of future upgrades	0.20		0.700	1.000
2	Satellite/Launch Cost	0.2				0.932	0.869

			Mass	0.80		1.000	0.837
					Thermal control	1.000	0.840
					Athermalization	1.000	1.000
					Part count	1.000	0.840
			Size	0.20		0.660	1.000
3	Payload Cost	0.25				0.920	0.596
			Design	0.40		0.800	0.512
					Required skill level of Design team	1.000	0.660
					Effort to perform design	1.000	0.700
					Part count	1.000	0.700
					Effort for Baffling and Athermalization	1.000	0.500

	AIT	0.30		1.000	0.603
			Effort to build Telescope	1.000	0.500
			Required skill level of AIT team	1.000	0.500
			GSE (design, build, commissioning)	1.000	0.660
			Effort Planning	1.000	0.660
			Effort to align optics	1.000	0.300
			Effort to perform tests	1.000	1.000
	Manufacturing	0.30		1.000	0.700
			Parts count	1.000	0.700
			Part complexity	1.000	0.700
			Optical elements	1.000	0.700

4	Implementation Risk	0.1				1.000	0.500
			Complicated parts	0.25		1.000	0.700
			Tolerances	0.50		1.000	0.300
			Part Count (Design Complexity / Reliability)	0.25		1.000	0.700
5	Implementation Schedule	0.1				1.000	0.750
			Design completion to MRR (EM)	0.50		1.000	0.750
			Qualification model	0.30		1.000	0.750
			Flight model	0.20		1.000	0.750
					Total	0.858	0.798

5.4 Conclusion

5.4.1 Design Solution 1 (RC Cassegrain)

5.4.1.1 Pros

- The RC Cassegrain results have fewer optical elements than the Korsch, which results in reduced overall Payload Costs in terms of design, AIT and manufacturing.
- The mechanical tolerance of the telescope is low, which results in ease of manufacturing, alignment and integration.
- Due to low mass, the overall launch cost would be less than the Korsch TMA.

5.4.1.2 Cons

- Optical Performance for the RC Cassegrain is much degraded in terms of optical MTF due to the high obscuration ratio.
- The large separation between the secondary and primary mirror results in a large volume as compared to the Korsch.
- It involves the refracting surfaces in the form of field lenses, which results in colour aberration.
- Requires excessive amount of baffling in order to avoid stray light. This results in reduced transmission efficiency and MTF.

5.4.2 Design Solution 2 (Korsch TMA)

5.4.2.1 Pros

- Good Optical Performance in terms of optical MTF, due to the low obscuration ratio that can be achieved from the design.
- Due to its compact design, it has a low volume as compared to the RC Cassegrain.
- Korsch design provides improved baffling compared to the RC Cassegrain.
- Due to the third mirror, the Korsch has a better edge of field performance than the RC Cassegrain.
- No refracting surfaces are involved in the design, so no colour aberration.

5.4.2.2 Cons

- The Korsch design requires very tight mechanical tolerances, which results in high Payload costs in terms of design, AIT and manufacturing
- The Korsch design has a high number of complex components and parts, which results in high costs and delays in the schedule
- The mass of the Korsch design is higher than the RC Cassegrain.

The recommended solution as given by the evaluation criteria is the RC Cassegrain, due to ease in design, AIT and manufacturing. Although the performance of the RC Cassegrain is not good as Korsch, it is still compliant with our requirements.

6 PERFORMANCE ANALYSIS

6.1 Design Overview

The optics design selected from the trade-off will be presented in this chapter, and it is based on Ritchey–Chrétien (RC) design which is very efficient to eliminate off-axis optical errors. The RC design has a wide field of view and is free of optical errors compared to a more traditional reflecting telescope configuration, which is a suitable choice to achieve specified spatial resolution requirements using hyperbolic primary and secondary mirrors. Although manufacturability and alignment of hyperbolic mirrors may be difficult compared to spherical ones, successful integration and assembly can be done with the help of the correct facilities, equipment and technical expertise. The optical design has two high-powered elements, namely the primary and secondary mirror, along with a three field corrector lens assembly. Optimization criteria have been set to achieve diffraction limited RMS wavefront with constraints of EFL. Field lens position and back focal length are the main merit functions to achieve requirements.

Table 6.1 shows the specifications of RC optical design.

Table 6.1: Optical Design Specifications.

Specifications	**Value**	**Unit**	**Remarks**
Aperture	375	mm	
Effective Focal Length	3300	mm	
F#	8.8		
FOV (Full angle)	1.146	degrees	
Nyquist Frequency (PAN)	93	lp/mm	Pixel Size = 5.4 µm
Image plane Size	66	mm	
Total Track Length	970	mm	

Table 6.2 lists the spectral bands for the optical design; these bands were used in all optical performance calculations reported on below.

Table 6.2: Spectral Bands**.**

Wavelength		**PAN**	**BLUE**	**GREEN**	**RED**
λ_{min}	nm	450	450	510	630
λ_{max}	nm	800	510	580	690
λ_{centre}	nm	625	480	545	660

Table 6.3 describes the detailed characteristics of each element used in the optical design. The left surface indicates surface normal to the +Z direction (nominally Earth facing) and the right surface indicates surface normal to the –Z direction.

Table 6.3: Definition of Optical Elements.

Element	**Description**	**Surface Indication**	**Clear Aperture (mm)**	**Radius of Curvature (mm)**
Primary Mirror	Concave aspherical front surface mirror with a hole through which the field lens group is mounted.	Left	375 Ø Obscuration 190 Ø	-2246.884 Conic -1.178
Secondary Mirror	Convex aspherical surface	Right	132 Ø	-1068.192 Conic -6.714
Field Lens 01	Convex-Concave Spherical N-Bk7 Lens	Left	76 Ø	140.670
		Right	76 Ø	183.074

Field Lens 02	Convex-Concave Spherical N-Bk7 Lens	Left	72 Ø	129.356
		Right	72 Ø	89.136
Field Lens 03	Concave-Convex Spherical N-Bk7 Lens	Left	70 Ø	-80.352
		Right	70 Ø	-84.669
Secondary Mirror Baffle	Flat Circular surface with aperture to block out of FOV lights	NA	200 Ø	∞
Primary Mirror Baffle	Flat Circular surface with aperture to block out of FOV lights	NA	116 Ø	∞

In Table 6.4, the element "left surface" indicates the surface normal in the +Z (nominally Earth-facing) direction, and "right surface" indicates the surface normal in the –Z direction. Vertex positions are given in the -Z direction.

Table 6.4: Description of Intra-Optical Element Spacing.

Element	**Surface Indication**	**Vertex axial position relative to PM vertex (mm)**
Primary Mirror	Left	0
Primary Mirror Baffle	NA	450
Secondary Mirror Baffle	NA	580
Secondary Mirror	Right	780
Field Lens 1	Left	0
	Right	-15
Field Lens 2	Left	-21
	Right	-33
Field Lens 3	Left	-69
	Right	-78
Image Plane	NA	-190

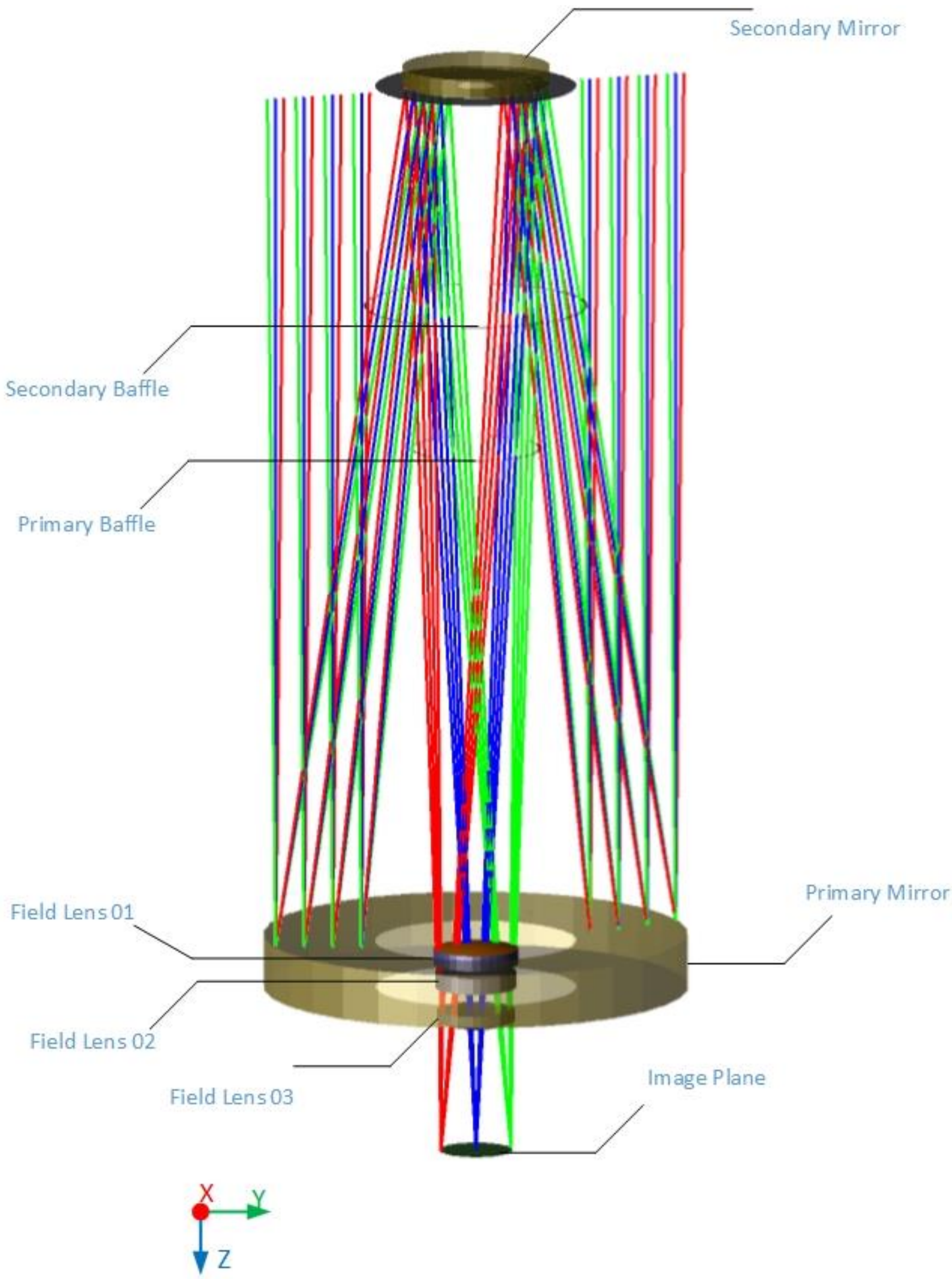


Figure 6-1: RC Cassegrain Optical Design Layout.

6.2 Optical Performance

The optical design has been evaluated and analyzed in a vacuum and temperature of 22.5 °C and all the optical performance indicators are being presented on mentioned environment conditions.

6.2.1 MTF

The worst calculated MTF values per band are summarized in Table 6.5. Figure 6-2 shows the Panchromatic MTF (calculated at 93 lp/mm) and Figure 6-3 shows the same for the multispectral MTF (calculated at 23 lp/mm) as a function of image plane position. Please note that these values do not make provision for thermal, integration and manufacturing tolerances.

Table 6.5: Worst Calculated MTF values.

Band	**MTF @ Spatial Frequency**			
	Nyq. Frequency 93 lp/mm	Image plane position Half Angle	Nyq. Frequency 23 lp/mm	Image plane position Half Angle
PAN	23 %	0.56°		
Blue			72 %	0.56°
Green			69 %	0.56°
Red			63 %	0.56°

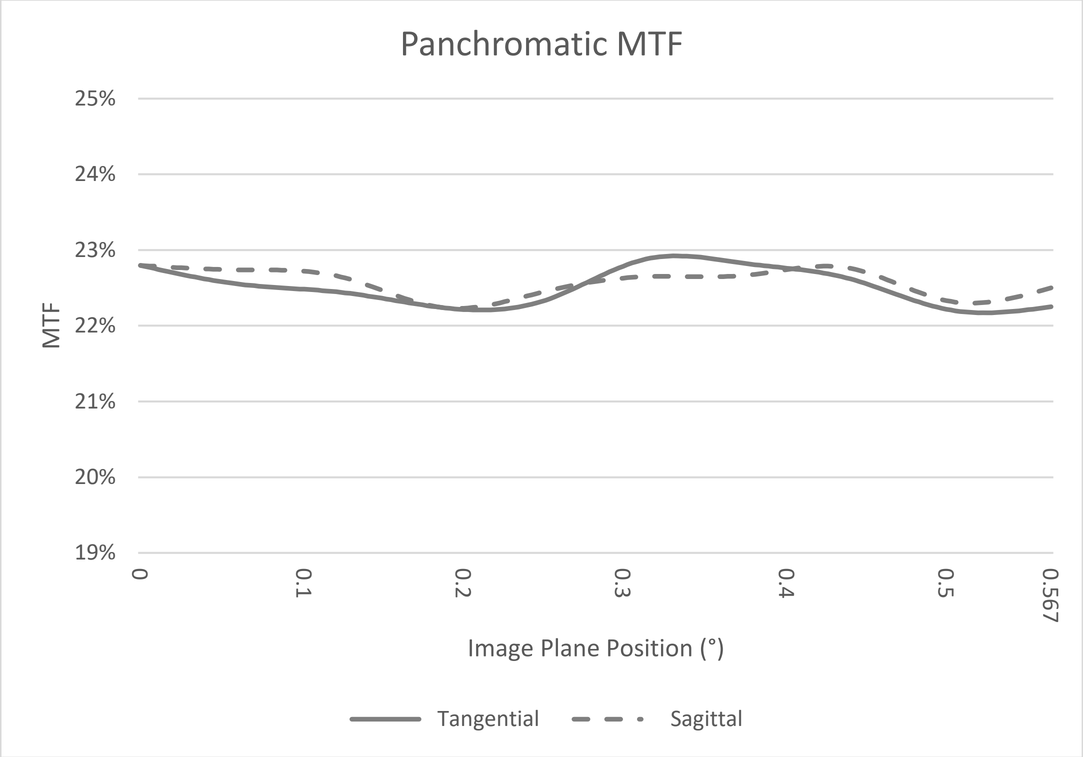


Figure 6-2: Optical Design-PAN MTF as a function of Image Plane Position.

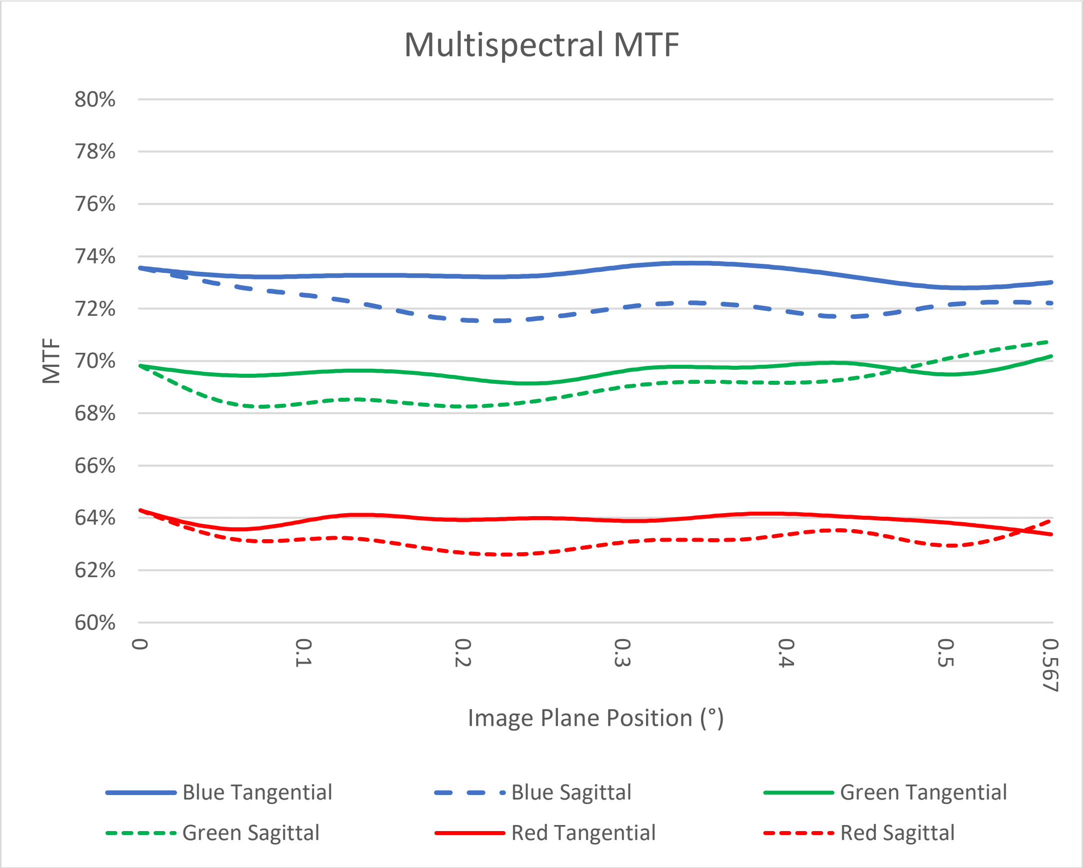


Figure 6-3: Optical Design-MS MTF as a function of Image Plane Position.

6.2.2 Radiance Transmittance

Radiance transmission across the image plane was calculated using Optic Studio software, shown in Figure 6-4 for the required spectral band (450nm – 800nm). Figure 6-4 shows the minimum transmission in the blue band (450nm – 510nm) at Edge-of-field as 51% and the average transmission over the whole spectral band is 63%.

Anti-reflective coatings were simulated with 99% transmissivity across the specified spectral band, and reflective coatings were simulated with 98% reflectivity across the specified spectral band. Both these values were based on a conservative estimation obtained from optics manufacturers' websites [26].

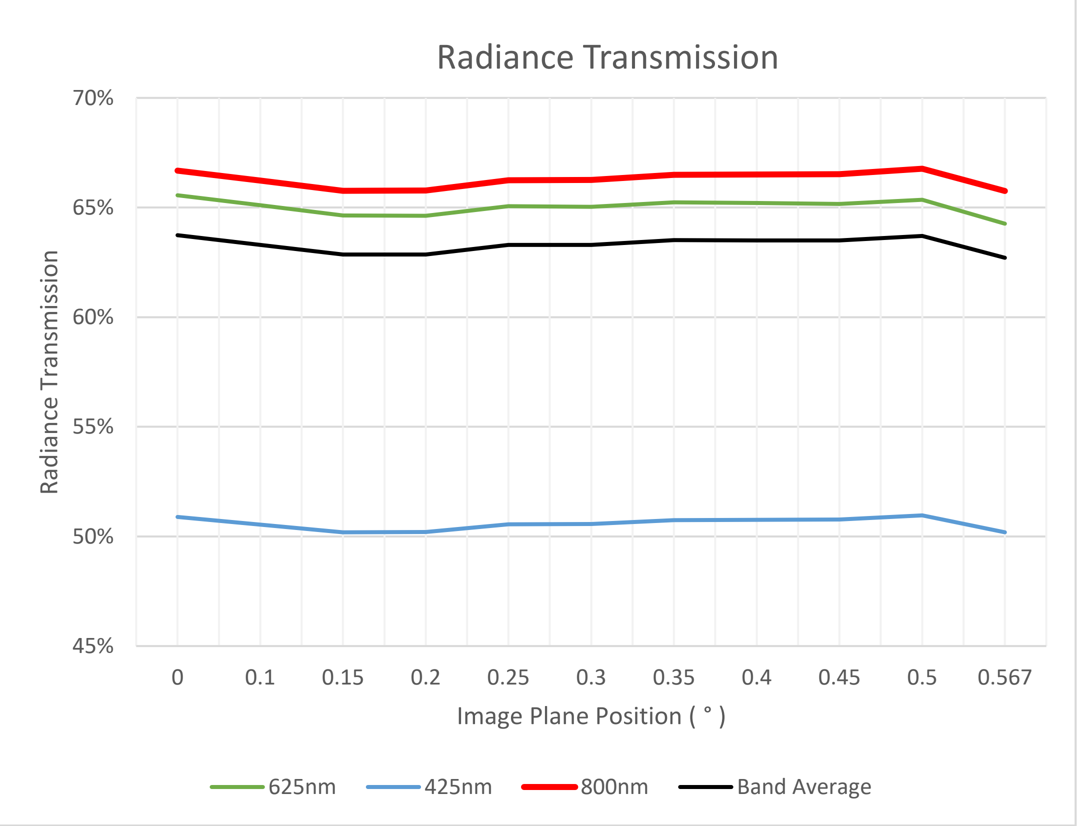


Figure 6-4: Radiance Transmission.

6.2.3 Wavefront Map

Figure 6-5 shows the wavefront error across the pupil. The optical design has achieved an RMS wavefront error of 0.0089 λ and Peak-to-Valley 0.0452 λ. Please note that these values do not make provision for thermal, integration and manufacturing tolerances.

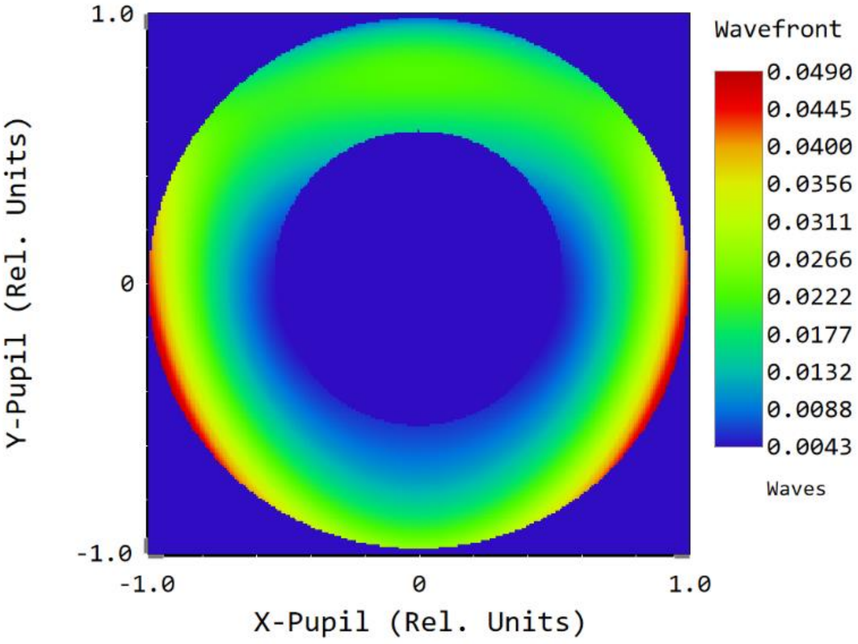


Figure 6-5: Optical Design Wavefront Error.

6.2.4 Optical Distortion

Figure 6-6 shows the grid of chief ray intercept points to indicate distortion. Optic Studio computes distortion of the optical system by tracing chief rays' position on the grid and calculates optical distortion with the following relationship;

$$P = \frac{R_{distorted}}{R_{predicted}} * 100\% \quad (6.1)$$

$$R_{real} = \sqrt{{x_r}^2 + {y_r}^2} \quad .(6.2)$$

$$R_{predicted} = \sqrt{{x_p}^2 + {y_p}^2} \quad (6.3)$$

$$R_{distorted} = \sqrt{(x_p - x_r)^2 + (y_p - y_r)^2} \quad (6.4)$$

Optical distortion of this optical design comes out to be 0.66% pincushion distortion as seen in Figure 6-6.

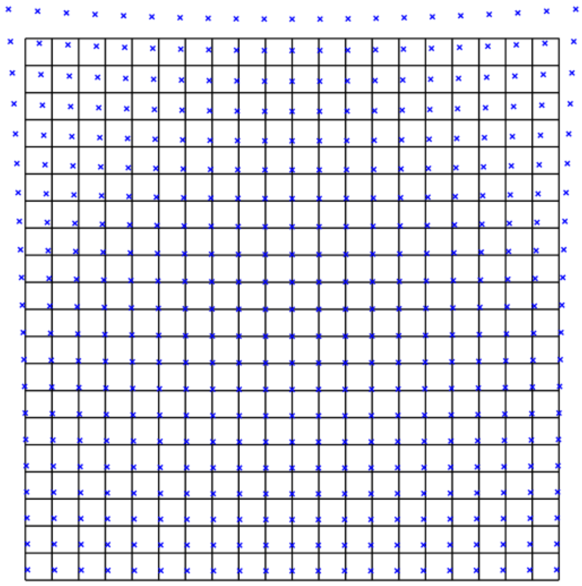


Figure 6-6: Optical Design Distortion.

6.2.5 Sensitivity Analysis

Table 6.6 shows how the optical elements are sensitive to their decentre and tilt. It is a first-order tolerance analysis of optical design which gives just an impression about sensitivity for design assembly, integration, and testing, but detailed tolerance analysis provides definite tolerances for each degree of freedom of optical elements which is not in the scope of this thesis.

Table 6.6: RC Design Sensitivity Analysis.

	DCX			DCY		
Mirror	Decenter (µm)	MTF	Change in MTF	Decenter (µm)	MTF	Change in MTF
	0	22.4%		0	22.4%	
Primary	200	19.5%	12.9%	200	20.3%	9.4%
Secondary	200	19.6%	12.5%	200	19.4%	13.4%

	Tilt X			Tilt Y		
Mirror	Tilt (arcsec)	MTF	Change in MTF	Tilt (arcsec)	MTF	Change in MTF
	0	22.4%		0	22.4%	%
Primary	36	20.6%	8.0%	36	19.3%	13.8%
Secondary	72	20.7%	7.6%	72	18.0%	19.6%

6.2.6 Encircled Energy

The encircled energy is the fraction of total integrated flux in the image contained within a given radius r. It provides a measure of the concentration of energy in an optical image. The airy disk of the point spread function where 86% of total integrated flux in the image is contained [27]. The smallest diameter of an airy disk for a perfect system is given by (2.44* λ * f#), but it does not take the central obscuration into consideration. The effective T# [F#/SQRT (transmission)] is calculated in replace of F# for obscuration. Effective airy disk diameter due to obscuration is about 17 μm, so 86% of energy will fall in the airy disk region.

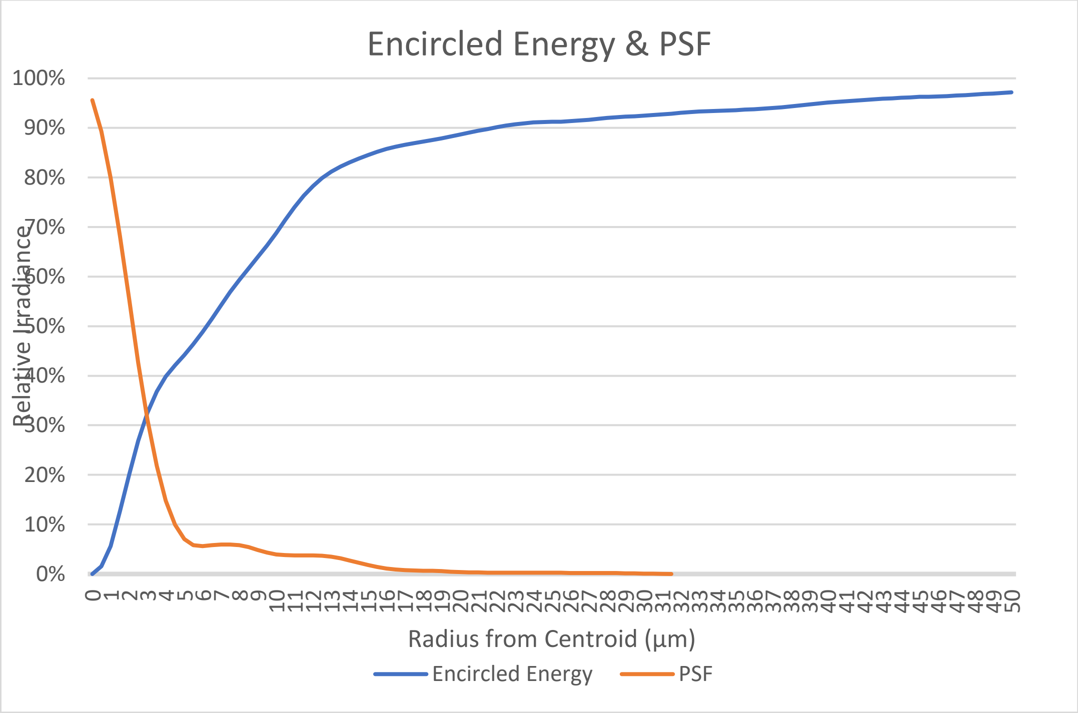


Figure 6-7: Optical Design Encircled Energy.

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7 DESIGN VERIFICATION

The objective of optical design verification is to assess and eventually demonstrate that the design meets the requirement specification mentioned in section 3.6.

The requirement verification process covers the entire development life cycle. During the design phase (downward branch of the V-model of system engineering), the planning of the verification activities for requirements specification is performed. Final design review of the sub-systems/units, through the manufacturing, integration and testing phase, the verification of the technical specifications which had been planned, is executed (upward branch of the V-model). The process must ensure traceability between the requirements and their verification, hence appropriate control of the process and the related documentation is in place.

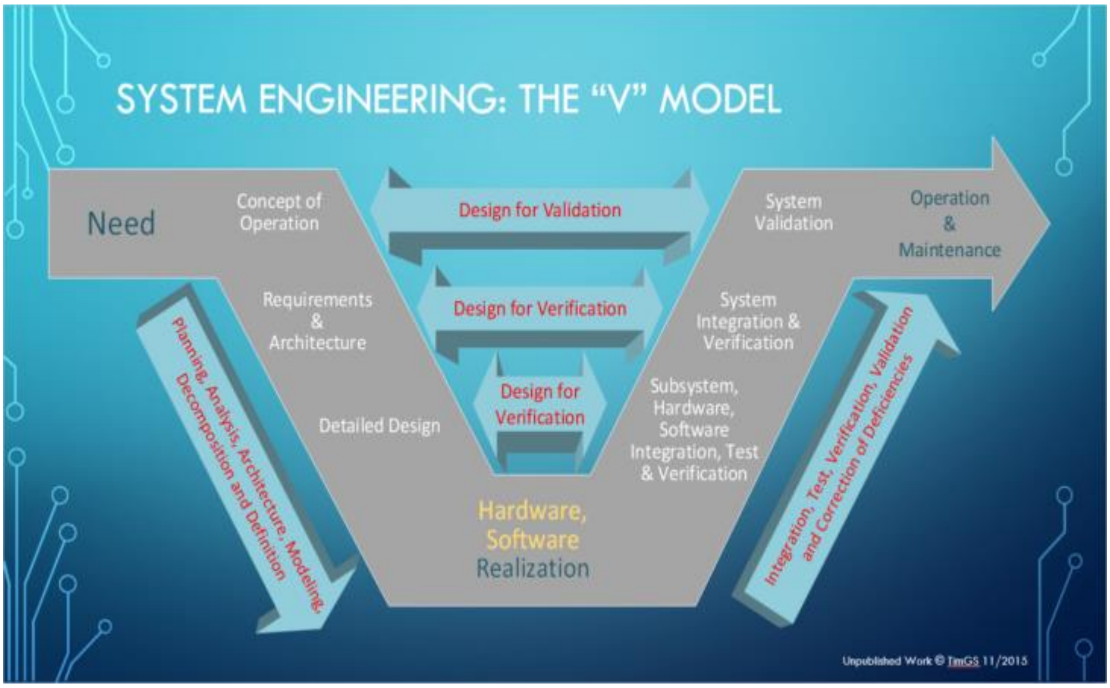

Figure 7-1: System Engineering Product Development plan-V model. [28]

7.1 Verification Method

Verification of requirements can be accomplished by at least one of the following verification methods.

7.1.1 Inspection

The inspection is a tool to verify that the design or the system is compliant with the set requirements is compliant without using any special lab apparatus, methods or ground test equipment. Inspection practices industry guidelines quality control techniques to validate compliance of specimen requirements of physical state, workmanship standards and technical drawing and document compatibility. An inspection does not emphasize performance rather than only the physical attributes of the specimen [29].

7.1.2 Analysis

Analysis by verification is a process used with other verification methods to demonstrate compliance to specifications. The analysis may include engineering design analysis, qualitative analysis, digital simulations, and analogue modelling [29].

Analysis may be used when it can be determined that:

- Accurate and rigorous analysis is required
- Testing equipment is costly and may not produce the result in the first go
- Inspection verification is not suitable for this specimen

7.1.3 Review

Review-of-design is a verification tool in which verification is completed by validation of the previous history of records, or by proof of authorized system design documents, or when authorized system design reports, validated technical descriptions reports and engineering drawings clearly indicate that the system is designed such that it is compliant with the preset requirements [29].

7.1.4 Test

The test is a tool to verify in a technical way in which the use of special laboratory apparatus, different analysis and simulations, and well-defined procedures and principle, which helps in the assessment of components to demonstrate compliance with system specifications. Testing of the specimen is the major tool of requirements verification and shall be only used when analytical methods do not produce the required results [29].

7.2 Verification Stages

The optical design verification process shall be implemented in subsequent verification stages all along the program life cycle.

The verification stages will be:

- ECSS Phase D (during the phase) - Qualification (Q) with qualification review
- ECSS Phase E (at the end of the phase) - Acceptance (A) with acceptance review

7.2.1 Qualification

In this stage, the verification objective shall be to demonstrate that, at all levels, the design meets all applicable requirements and includes proper margins as determined by the design authority for qualification as per ECSS Testing Standard [30].

7.2.2 Acceptance

In this stage, the verification objective shall be to demonstrate that the optical design components are free of industry manufacturing defects, assembly and integration errors and are compliant for following operational use. This stage is applicable at all levels.

7.3 Verification of Key Requirements

The optical Payload and Telescope may have many requirements, but we will focus on the verification process of key requirements of optical design. They are directly derived from the main requirements and their fulfillment will demonstrate the success of the optical design. Therefore, special relevance will be given to the verification of these key requirements. The main key requirements of optical design are;

- ➢ Telescope Panchromatic MTF Verification
- ➢ Telescope Wavefront Error Verification

7.3.1 Telescope Panchromatic MTF Verification

7.3.1.1 Description

This test verifies that the Panchromatic MTF across the field, for the specified spectral band, at the specified spatial frequency, conforms to the specification.

7.3.1.2 Verification Process

These requirements will be verified by testing and using appropriate spectral filters, projecting an edge target through a collimator into the Telescope aperture. Measure the response at the Telescope Image Plane to extract Line Spread Function, from which the MTF is then determined. Figure 7-2 shows the test setup for the MTF measurement of the telescope. Uniform light will be projected by an integration sphere to a test target. A collimator projects the edge target image as a collimation light in the subject telescope and will be imaged at the focal plane. MTF analysis software will be used for measuring the MTF across all field points.

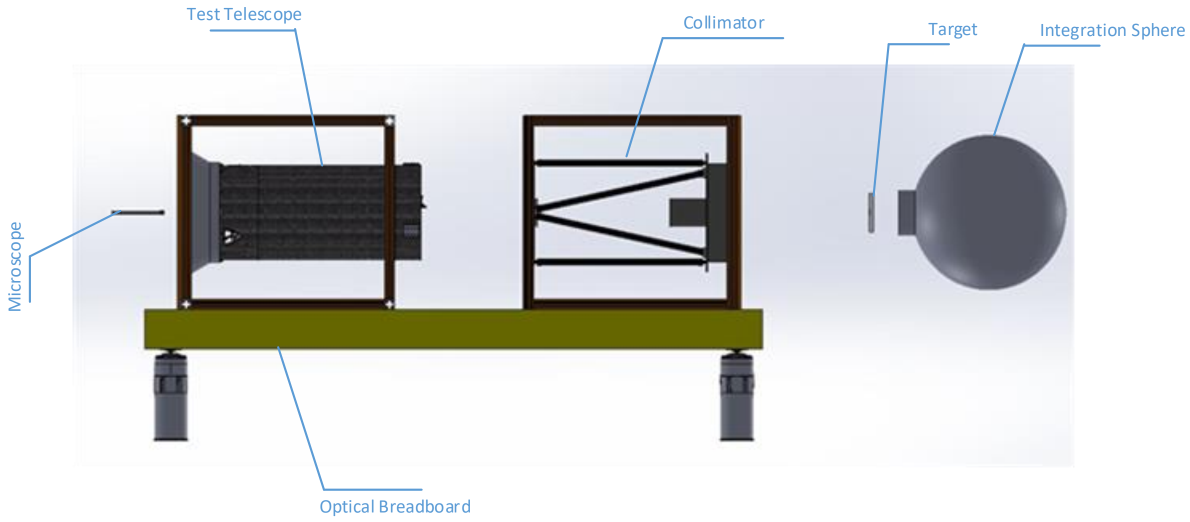

Figure 7-2: MTF Measurement Test Setup**.**

7.3.2 Telescope Wavefront Error Verification

7.3.2.1 Description

This test verifies that the Wavefront Error across the field, for 633 nm, conforms to the specification.

7.3.2.2 Verification Process

This requirement will be verified through testing. This test would normally be performed using an interferometer and mounting the telescope at the Optical Table with Vibration

Isolation, as shown in Figure 7-3. The calculation would be done using the interferogram analysis on computer programs.

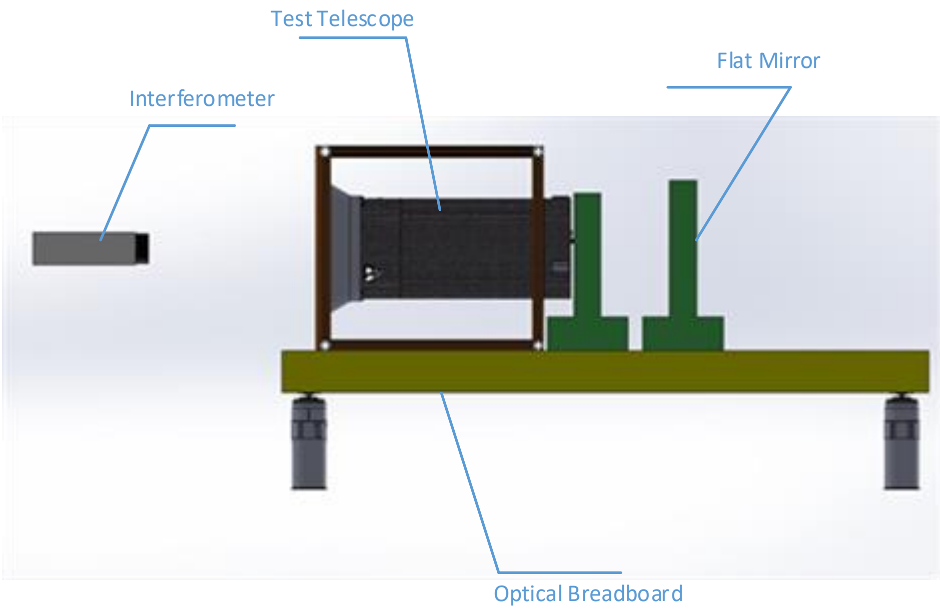

Figure 7-3: Wavefront Error Measurement Setup**.**

8 CONCLUSIONS AND RECOMMENDATIONS

An overview will be provided of the conclusion in this chapter that can be drawn based on the work in this thesis. Section 8.1 will discuss the conclusion of this thesis, while section 8.2 provides an overview of future work that can be done to improve the design.

8.1 Conclusions

In this thesis, an optical design has been presented that can achieve a ground sampling distance of 1m from an altitude of 600 km. The final design is the result of a concept study between two optical designs: an RC Cassegrain and a Korsch TMA.

The mission statement and some derived requirements, which are only applicable to the optical design, have been considered for designing a 1m GSD optical design layout. Specifications of optical design have been calculated by using optical first-order expressions.

Two alternative concepts have been evaluated after considering different optical configurations' pros and cons with respect to optical performance, Mass, manufacturing, AIT and cost. Trade-offs among concepts also have been evaluated and presented to choose two different concepts for further evaluation.

The RC Cassegrain has been selected as a candidate design for optical design as it meets all technical requirements. A detailed trade-off study has been done for the selection of two alternative concepts and weightage assigned to each of the parameters as per its critically. Based on the scoring of both designs, one design has been selected for further evaluation as a candidate optical design.

Performance analysis of RC Cassegrain optical design has been optimized and analysed and different optical performance indicators have been presented in compliance with technical requirements. Diffraction limited Optical MTF of 23% in the panchromatic band has been achieved with radiance transmission of 63% over spectral band 450nm – 800 nm. First order sensitive analysis of optical design has also been reported to find performance degradation of primary and secondary mirror de-centre and tilt.

The optical design has mainly two key requirements, MTF and wavefront error. The verification plan for these key requirements has been presented with the test setup and procedure to observe MTF and wavefront error separately.

8.2 Recommendations for Future Work

In this thesis, several aspects of optical design from scratch have been discussed and analysed. However, there remains a lot of work that can be done. In this section, several points are listed which will require additional research.

- The optical design needs to be athermalized for all types of temperature gradients which it will face in ground testing and in-orbit operation. Detailed athermalization techniques can be discussed with optomechanical engineers and can be analysed in optical design with required temperature gradients to achieve the required performance.
- High-resolution optical designs are usually very sensitive to manufacturing and alignment errors. First-order sensitivity analyses have been reported in Chapter 06, Section 6.2.5. Moreover, detailed tolerance analysis is required for more confidence in the optical design to be built. Detailed tolerance analysis will consist of optical elements simulated de-centre, tip/tilt and axial distances tolerances with multiple Monte Carlo analysis for confidence in the optical design.
- Optical analysis should also be devoted to stray light, an important issue for all telescopes.
- The prime sources of TID (total ionizing dose) in LEO are trapped electrons, trapped protons and solar protons. The radiation has the capability to damage materials by virtue of its ability to ionize atoms in the material. The energetic ions cause damage to materials by breaking and/or rearranging atomic bonds. In general, after exposure to sufficient total-dose radiation, the optical surfaces of mirrors and glasses become pale yellowish, which causes loss of transmission in optical elements. A detailed radiation analysis of the telescope will be performed to analyze the effect of total ionizing dose (TID) radiation on the mirrors and glasses surface at different orientations (nadir pointing, off-nadir pointing, deep space pointing and survival mode) of satellite modes of operation.

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