# Compact Medium-Resolution Spectrograph for Alt-Azimuth Mounted Cassegrain Telescopes: Optical Design And Performance Analysis

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## ABSTRACT

Alt-azimuth mounted telescopes with Cassegrain focus are widely adopted by astronomers due to their affordability and versatility. However, the limited clearance between the telescope and mount precludes coupling with standard commercial spectrographs. To address this, we designed and constructed a novel compact, medium-resolution spectrograph optimized for integration with existing alt-azimuth mounted telescopes at minimal cost. The instrument employs a 1200 grooves/mm diffraction grating (50 mm × 50 mm) and a slit aperture (0.008 mm × 6 mm). Optical performance was validated through ray-tracing simulations in Zemax OpticStudio 2025 R2, which demonstrated effective spectral dispersion and sharp image formation on the CCD plane. The optical design closely aligns with theoretical predictions and successfully resolves and focuses RGB spectral lines at 700 nm, 550 nm, and 400 nm respectively. Aberration analysis reveals negligible higher-order effects, including coma, astigmatism, field curvature, distortion, and chromatic aberration, with only minor spherical aberration observed across the field. Overall, the system exhibits excellent optical performance and high image quality, fully validating the design optimizations performed in Zemax OpticStudio and enabling accessible spectroscopy for a broad range of astronomical applications.

**Keywords:** Slit Spectrograph, Alt-Azimuth mount, Optical Design, Zemax OpticStudio, Astronomy Instrumentation

## 1. INTRODUCTION

Spectrographs are fundamental instruments in observational astronomy. By analyzing the spectrum, we can determine the physical and chemical composition of celestial bodies for various research purposes. Astronomical spectrographs are typically mounted at the eyepiece of the telescope. However, Cassegrain telescopes with Alt-Azimuth mounts, which are comparatively inexpensive and widely used by astronomers, do not allow a commercially available spectrograph to be mounted at the eyepiece due to the limited gap between the telescope and the mount, as shown in figure 1 [1]. To resolve this issue, we designed a compact, medium-resolution spectrograph capable of mounting onto a CPC 1100 telescope located at the Department of Physics, University of Colombo. The spectrograph is designed with flexibility to allow compatibility with other Alt-Azimuth telescopes in the CPC series.

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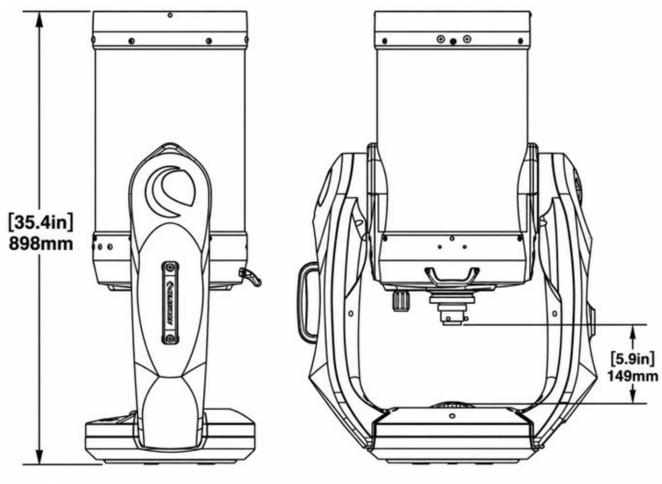


Figure 1. 2D view of CPC 1100 (Celestron, 2022)

The incoming light from the eye piece is directed to the spectrograph through a variable slit. The slit allows a very narrow beam of light. The collimator lens makes the light from the slit, parallel and directs the beam to the diffraction grating. The diffraction grating disperse the light beam into its constituent wavelengths and the splitted light is focused by a convex lens and detected by the CCD camera [4]. The purpose of this novel inclusion of concave lens is to increase the beam size of the collimator as shown in the figure 2 and hence increase the resolving power of the spectrograph.

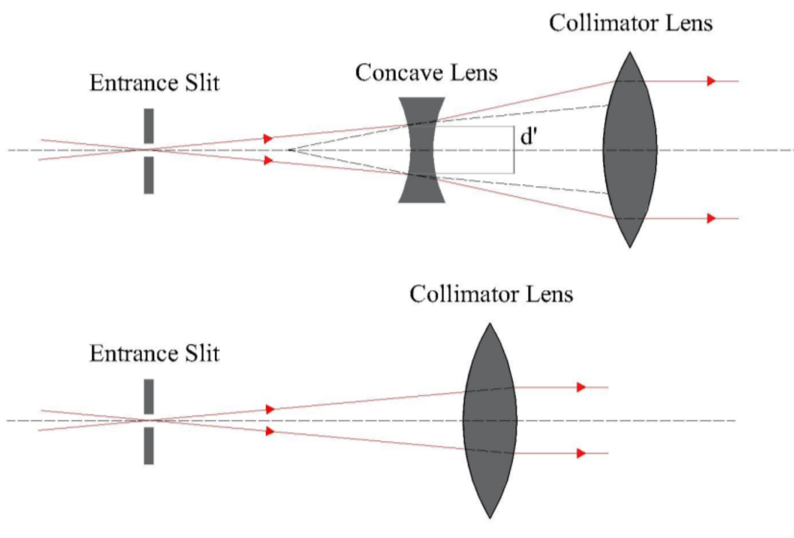


Figure 2. The inclusion of concave lens to increase the light cone fallen on the collimator lens

By measuring the outer diameter effective focal length of the CPC 1100 we approached to design the spectrograph that can be mounted with the eye piece of the telescope and be placed on top of it as shown in the figure 3. The optical components; slit, collimator lens, focusing lens and the diffraction grating were chosen according to the theoretical calculations done based on the measurements.

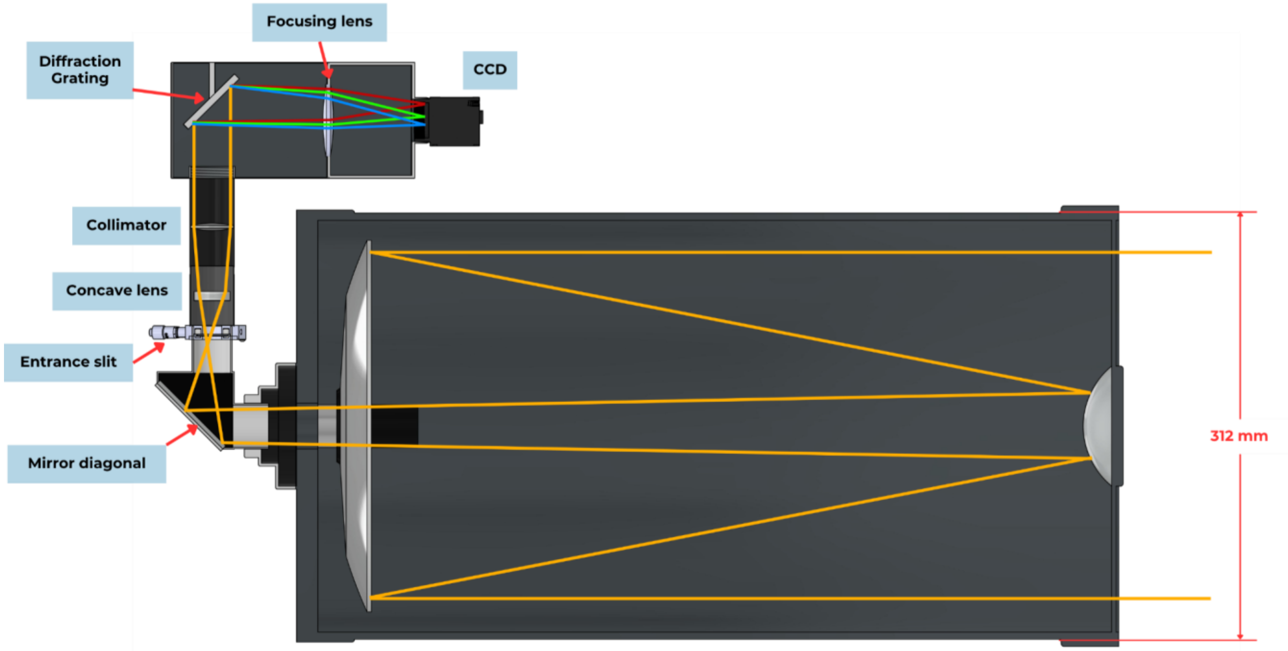


Figure 3.Illustrated Optical Layout of the Spectrograph

## 2. OBJECTIVES

This design presents a universal spectrograph for the CPC alt-azimuth series of telescopes with apertures of 8″, 9.25″, and 11″. The spectrograph was initially developed as a mountable system for the 11″ CPC telescope. A key feature of this instrument is its adjustable optical mechanism, which allows variable lens alignment, making the spectrograph novel, versatile, and compatible with the entire CPC telescope series.

To achieve this universality, a custom optical hub was designed to mount the star diagonal, bending the incoming light by 90° within a maximum available space of 124 mm, which corresponds to the minimum back-focus clearance common to all three telescope models, as shown in the figure 4. The distance between the entrance slit and the diffraction grating is kept fixed. A carefully designed combination of concave and convex collimator lenses enables multiple alignment configurations, producing a well-collimated (parallel) beam incident on the diffraction grating. Each configuration results in different collimated beam diameters.

According to Equation (1), the spectral resolution depends on the number of illuminated grating grooves; therefore, varying the beam size directly enables resolution control, complemented further by the use of an adjustable slit. This flexible lens-based collimation approach allows a single spectrograph design to adapt to different CPC telescope apertures, thereby realizing a truly universal spectrograph for the CPC series.

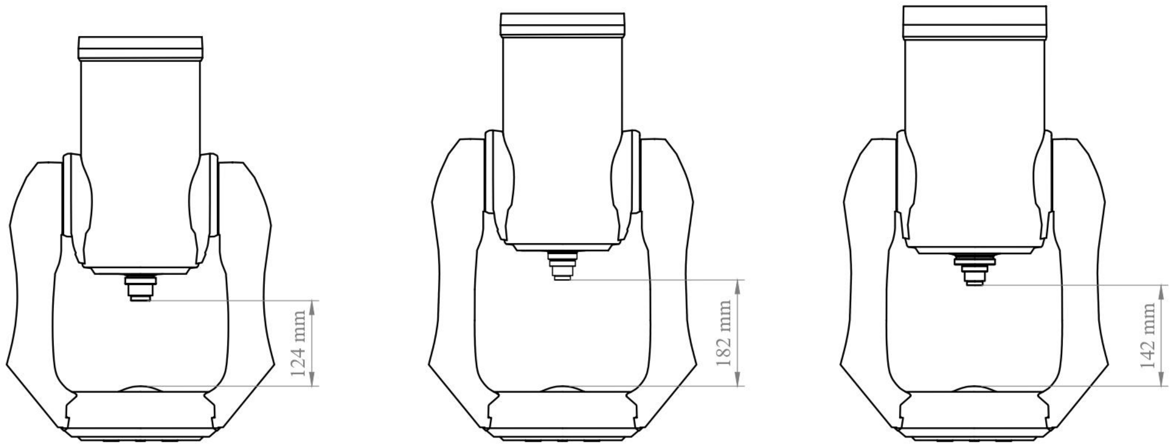


Figure 4. Entire CPC series telescope models with the limited gaps between the telescope and the mount

This configuration allows systematic control of beam divergence, pupil size, and grating illumination without modifying the grating or collimator optics.

### 2.1 Motivation for Pre-Collimator Beam Expansion

The theoretical resolving power of a diffraction grating spectrograph is given by [3] when the number of illuminated grooves increased the resolution, R will be increased.

$$R = m \times N \tag{1}$$

Where, m is the diffraction order and N is the number of coherently illuminated grooves. For a plane grating,

$$N = \frac{D}{d} \tag{3}$$

With, D being the diameter of the collimated beam incident on the grating and d the groove spacing.

## 3. OPTICAL DESIGN

The lens dimensions and optical parameters, including focal length, were calculated with reference to the outer diameter of the telescope's optical tube (312 mm) to ensure proper mounting of the spectrograph on the telescope barrel. The placement of the slit from the central axis was determined by locating the focal point of the primary mirror after reflection from the mirror diagonal. Therefore the slit distance from the central axis, was 62.9 mm.

However, the measured light cone incident on the collimator was 10.7 mm which is too small. To increase the size of the light cone, a concave lens was introduced. A concave lens with a focal length of 25 mm and a diameter of 25 mm was selected, as it ideally matched our requirements. The approach enlarges the cone diameter to 24.95 mm theoretically.

Considering the beam diameter and the length at the outer surface of the optical tube, a collimator lens with a focal length of 75 mm and a diameter of 30 mm was selected using the lens calculations.

A diffraction grating with 1200 grooves/mm and dimensions of 50 × 50 mm was selected to achieve maximum spectral resolution. To ensure a compact spectrograph design, a focusing lens with a diameter of 30 mm and focal length of 50 mm was selected to project the spectrum onto the CCD.

The optical system consists of the following components:

1. Entrance Slit: VA100 adjustable (variable slit width, 0.0 - 6.0 mm)
2. Concave lens: 25 mm Dia. x -25 mm FL, VIS 0° Coated, Double-Concave Lens
3. Collimator lens: 30 mm Dia. x 75 mm FL, Double-Convex Lens
4. Diffraction Grating: 1200 Grooves, 50 mm Square, 500 nm Ruled Diffraction Grating
5. Focusing lens: 30 mm Dia. x 50 mm FL Uncoated, Double-Convex Lens
6. CDD/ Photo detector

## 4. OPTICAL SIMULATION

### 3.1 System Overview

The optical design of the spectrograph was modelled in Zemax OpticStudio 2025 R2 [5] with three wavelengths: 400 nm, 550 nm, and 700 nm, representing the blue, green, and red extremes of the visible band. The entrance slit and diffraction grating were modeled with real material properties and precise dimensions. All lenses were selected from the Zemax lens library to match the exact specifications of the calculated physical setup, with a slit opening of 0.008 mm × 6 mm. The full system layout is shown in figure 5.

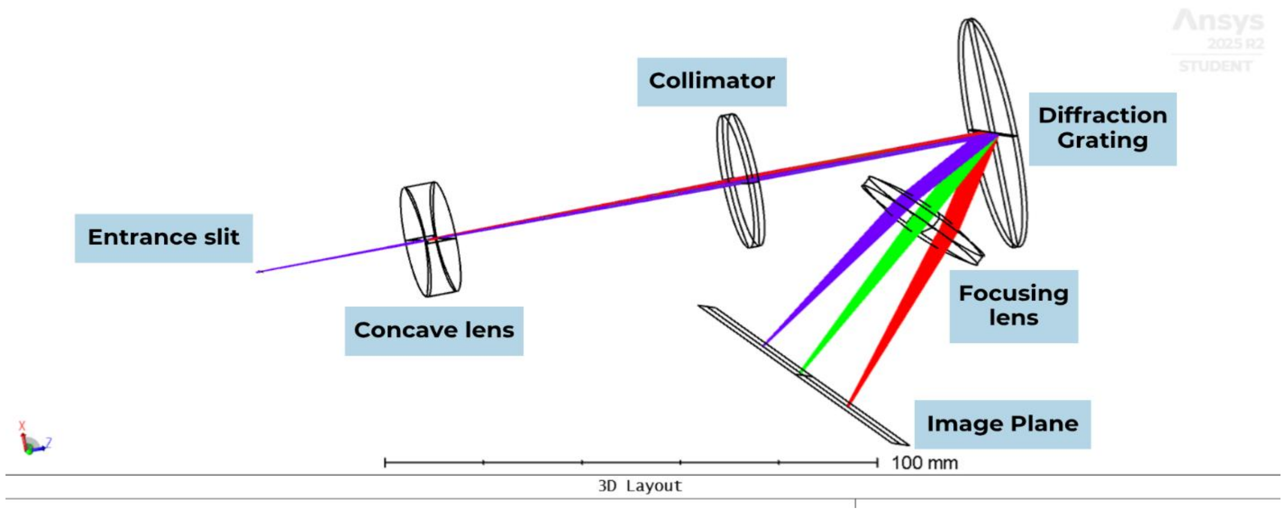


Figure 5. 3D ray trace layout showing wavelength-dependent diffraction by the grating. Blue, green, and red ray bundles correspond to 0.400 µm, 0.550 µm, and 0.700 µm respectively

### 3.2 Spot Diagram

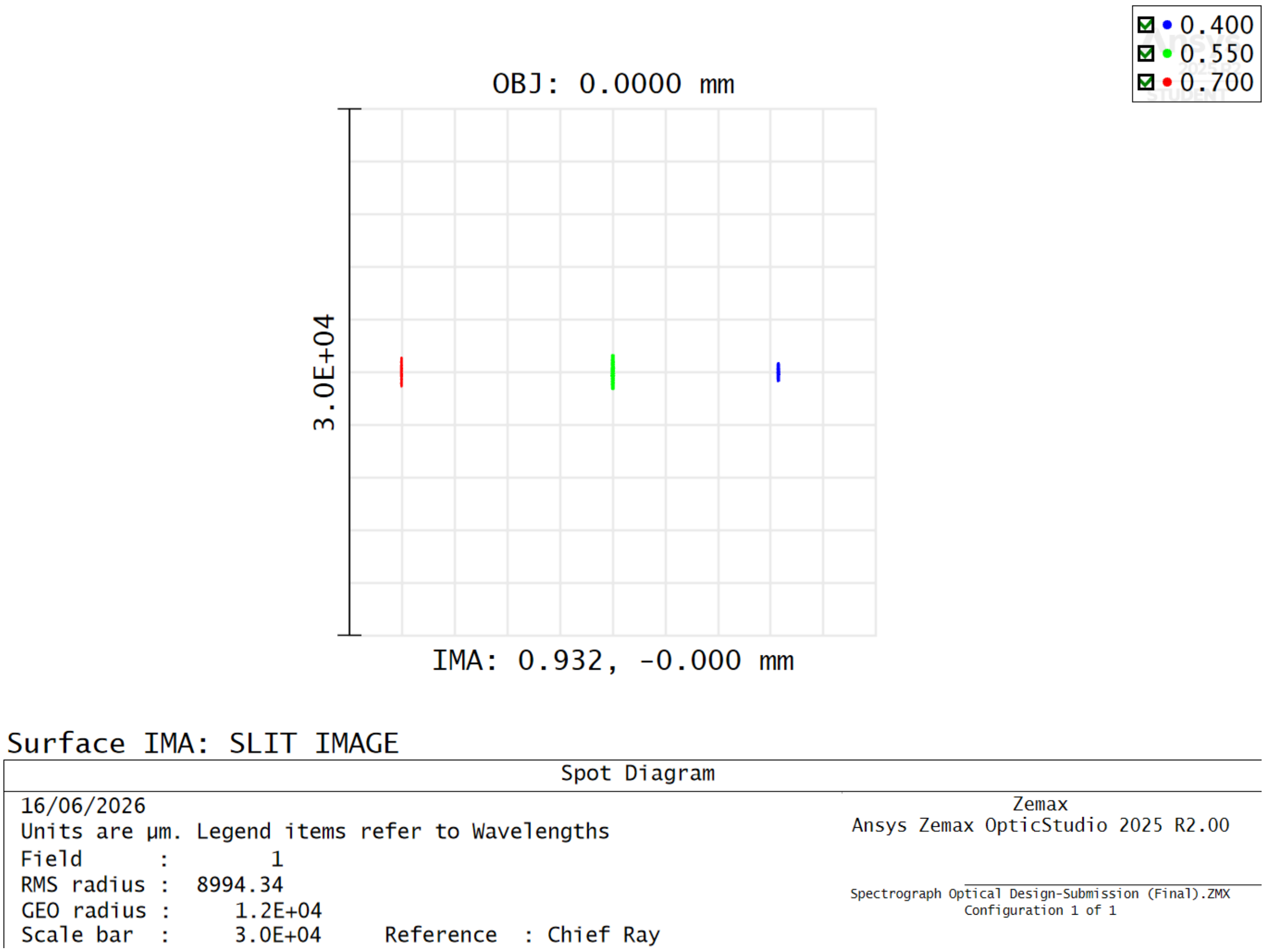


Figure 6. Spot Diagram [Three wavelength spots: 0.400 µm (red), 0.550 µm (green), 0.700 µm (blue)]

The spot diagram at the image plane is shown in figure 6. Three wavelengths are displayed: 0.400 µm (red), 0.550 µm (green), and 0.700 µm (blue), corresponding to the blue, green, and red extremes of the design bandpass. The three spot groups are well-separated in the horizontal (spectral) direction. The separation confirms that the grating effectively disperses the visible spectrum and that the optical alignment is correct.

### 3.3 Optical Prescription

The full optical prescription of the spectrograph as modelled in Zemax OpticStudio 2025 R2 is given in Table 1. The OBJ surface represents the light source and the STO surface defines the entrance slit with an 8 µm wide rectangular aperture. The concave lens (f = −25 mm) acts as a pre-collimator to diverge and enlarge the beam to collimator. The convex lens of 30 mm diameter and 75 mm focal length serves as the collimator, producing a parallel beam incident on the diffraction grating. The diffraction grating (1200 lines/mm, m = 1) disperses the collimated beam angularly by wavelength. The convex focusing lens of 30 mm diameter and 50 mm focal length then focuses the dispersed beam onto the detector plane (IMA surface).

Table 1. Information on video and audio files that can accompany a manuscript submission.

| Surface | Type | Radius (mm) | Thickness (mm) | Role |
|---|---|---|---|---|
| OBJ | Standard | ∞ | 1.000 | Light source |
| STO | Standard | ∞ | 34.494 | Slit (8 µm) |
| 2 | Standard | -39.78 | 2.500 | Pre-Collimator |
| 3 | Standard | +39.78 | 61.506 | Pre-Collimator |
| 4 | Standard | +76.67 | 4.960 | Collimator |
| 5 | Standard | -76.67 | 50.000 | Collimator |
| 6 | DGrating | ∞ | -20.000 | 1200 lines/mm |
| 7 | Standard | -50.56 | -6.5500 | Focuser |
| 8 | Standard | -50.56 | -39.000 | Focuser |
| IMA | Standard | ∞ | — | Detector plane |

## 4. Aberration Analysis

The Seidel aberration diagram at $\lambda = 550$ nm is shown in figure 7.

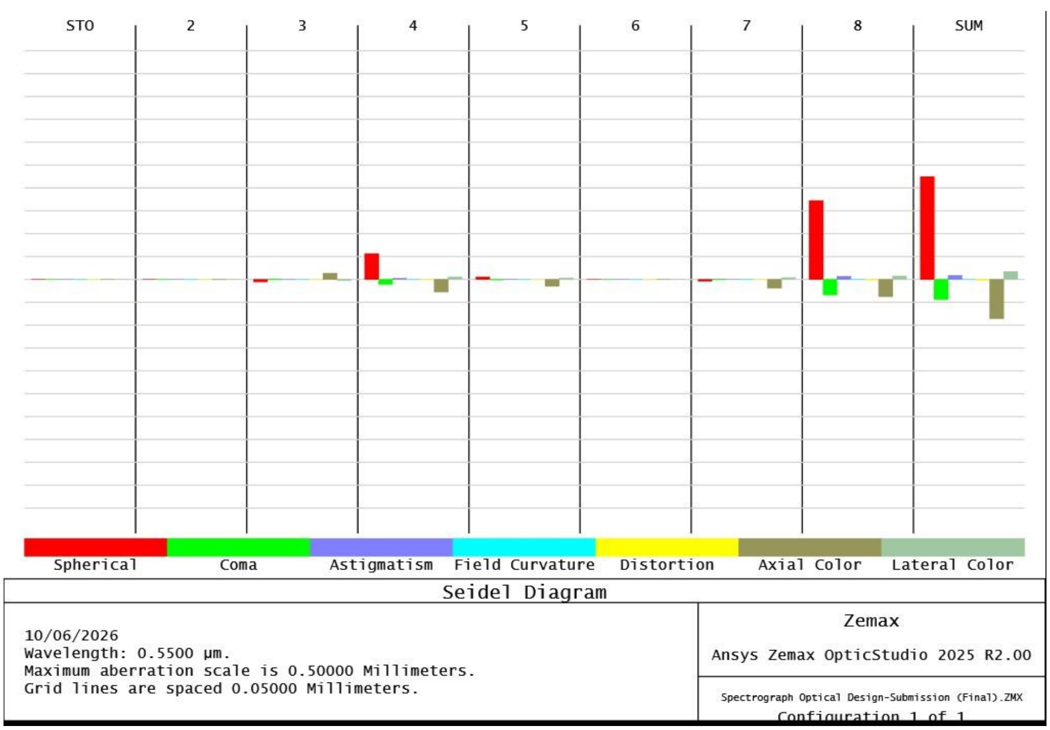


Figure 7. Seidel diagram (scale: 0.50 mm, grid: 0.05 mm)

Aberration analysis on each surface of the system showed very low optical errors. Minor spherical aberrations were observed at the surfaces of the collimator lens (surface no. 4) and the focusing lens (surface no. 8) , while coma, chromatic aberration, astigmatism, distortion, and field curvature were negligible.

## 4. RESOLUTION ANALYSIS

The spectral resolution analysis follows Schroeder (2000) [2].

### 4.1 Grating Equation

The groove spacing of the 1200 lines/mm grating is 0.8333 μm. The diffraction angle β for each wavelength is obtained from the grating equation

$$m\lambda = d\,(\sin\beta + \sin\alpha) \qquad (3)$$

Where, m = 1 (first diffraction order) and the optimum incident angle is α = 42.5° (sin 42.5° = 0.6756). The calculation results for wavelengths of 400 nm, 550 nm, and 700 nm are presented in Table 2.

### 4.2 Angular Dispersion

The angular dispersion (A) is given by,

$$A = \frac{d\beta}{d\lambda} = \frac{m}{d.\cos\beta} \qquad (4)$$

### 4.3 Linear Dispersion

When the collimated light incidents on the disperser, the linear dispersion at the detector is,

$$\frac{dl}{d\lambda} = f_2 \times A \qquad (5)$$

Where, $f_2$ = 50 mm is the focal length of the camera optics following the dispersing element.

### 4.4 Anamorphic Magnification

The anamorphic factor (r) for a reflection grating, relates the projected slit width in the dispersion direction to the actual slit width is given by,

$$r = \frac{\cos\alpha}{\cos\beta} \qquad (6)$$

### 4.5 Projected Slit Width

The entrance slit of width w is reimaged onto the detector with transverse magnification $f_2/f_1$, further modified by the anamorphic magnification r in the dispersion direction

$$w' = r \times w \times \frac{f_2}{f_1} \qquad (7)$$

The projected slit w' = 3.93 µm is narrower than the physical slit (8 µm) due to both the demagnification ($f_2/f_1$ = 2/3) and the anamorphic compression (r = 0.737).

### 4.6 Limit of Resolution

The minimum resolvable wavelength interval is set by the projected slit width.

$$\Delta\lambda = \frac{w'}{(f_2 \times A)} \qquad (8)$$

### 4.7 Spectral Resolving Power

The spectral resolving power at the central wavelength is:

$$R = \frac{\lambda}{\Delta\lambda} \tag{9}$$

The resolving power varies across the bandpass from R = 6104 at 400 nm to R = 10681 at 700 nm, increasing toward longer wavelengths as cosβ increases. The per-wavelength performance is summarized in Table 2.

Table 2. Per- wavelength performance

| **λ (µm)** | **β (°)** | **r = cosα/cosβ** | **A (rad/nm)** | **dl/dλ (µm/nm)** | **w' (µm)** | **Δλ (nm)** | **R** |
|---|---|---|---|---|---|---|---|
| 0.400 | −11.28° | 0.7518 | 0.001224 | 61.18 | 4.01 | 0.0655 | 6104 |
| 0.550 | −0.89° | 0.7374 | 0.001200 | 60.01 | 3.93 | 0.0655 | 8392 |
| 0.700 | +9.46° | 0.7474 | 0.001217 | 60.83 | 3.98 | 0.0655 | 10681 |

## 5. CONCLUSION

A compact medium resolution grating spectrograph for visible wavelength spectroscopy (400 –700 nm) has been designed and characterised using Zemax OpticStudio 2025 R2. The instrument incorporates a concave as pre-collimator (f = −25 mm), a convex lens as collimator ($f_1$ = 75 mm), a 1200 lines/mm reflective diffraction grating at an incidence angle of α = 42.5°, and a convex focusing lens ($f_2$ = 50 mm). The corresponding resolving power at the central wavelength of λ = 550 nm is R = 8392, while the resolving power varies from 6104 at 400 nm to 10681 at 700 nm across the spectral band. The full 300 nm band is dispersed across 18 mm at the image plane. Seidel aberration analysis identifies dominant spherical aberration at the rear surface of the camera lens (Surface 10), acting exclusively in the spatial direction and leaving the spectral resolving power unaffected. Even though the theoretical resolving power (R) is 29400, the combination of the slit limits it to about 6000 – 11000.


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