Indian Institute of Technology Bombay

Instrument Characterization and Atmospheric Extinction Coefficient Calculation

Project Report

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1 Abstract

This project focuses on the characterization of the CMOS detector used in the GROWTH telescope and the determination of the atmospheric extinction coefficient at the observation site. Accurate photometric measurements require detailed knowledge of the detector's response and the effects of atmospheric absorption on incoming stellar light.

The instrument characterization involved measuring key parameters such as gain, read noise, and dark current of the SBIG STC-428 FW CMOS sensor using calibration frames (bias, dark, and flat fields). The gain was determined from the variance–mean relation, read noise from the bias distribution, and dark current from the slope of mean signal versus exposure time.

To quantify atmospheric extinction, images of a selected stellar cluster were obtained at multiple altitudes (airmasses). The observed magnitude variation with airmass (secZ) was analyzed to fit the Bouguer's relation and obtain the extinction coefficient.

Together, these measurements enable reliable photometric calibration and improved accuracy in flux estimation for astronomical observations using the GROWTH telescope setup.

2 Instrument Characterization

2.1 Introduction

The instrument characterization aims to determine the key performance parameters of the imaging system used for astronomical observations. The observations were carried out using the GROWTH-India telescope, which employed its backup CMOS sensor (SBIG STC-428FW [1]) as its imaging detector. Characterizing the instrument involves measuring quantities such as gain, read noise, and dark current, which define the detector's response to incident light and its intrinsic noise properties. Understanding these parameters is essential for accurate photometric calibration and for assessing the quality and reliability of the data obtained from the telescope.

2.2 Calibration Parameters [3]

2.2.1 Input Data for Calibration

There are three types of calibration images required to characterize a imaging detector -

- **Bias frames** : They are captured with the shutter closed and an exposure time of zero seconds. They include contributions from read noise.
- **Dark frames** : They are taken with the shutter closed but with a finite exposure time to measure the thermally generated electrons that accumulate during an exposure. They primarily capture the dark current signature of the detector.
- **Flat-field frames** : Flat-field images are acquired under evenly distributed illumination, from a uniformly lit source. They compensate for issues like dust motes on optical surfaces, uneven pixel sensitivity, and vignetting.

2.2.2 Gain

It represents the conversion factor between the number of photoelectrons generated in a pixel and the corresponding digital output value, expressed in electrons per ADU (e^-/ADU). It indicates how efficiently the sensor converts charge to a digital signal, affecting both sensitivity and dynamic range.
Gain can be calculated using two methods:

1. **Mean Variance Method** -
   The mean–variance method calculates the detector gain by analyzing the relationship between the signal level and the corresponding noise variance. A series of flat-field frames with varying illumination levels are taken, and for each level, paired flats are used to compute the mean signal and noise variance after bias subtraction. When the variance is plotted against the mean signal, the points follow a linear trend in the detector's linear response regime.

$$Gain = \frac{1}{m}$$

$$Error : \Delta g = \frac{\delta m}{m^2}$$

The slope of this linear fit provides a direct measure of the detector gain. This approach effectively captures how efficiently the detector converts photoelectrons into digital counts, while the quality of the linearity also reveals the sensor's response stability and saturation limits.

2. **Monitors Method -**
The monitors method calculates gain by taking several independent measurements using multiple pairs of flat and bias frames. For each pair, the difference image removes fixed-pattern noise, while the mean signal and variance provide an individual estimate of gain. This process is repeated for all frame pairs to obtain a set of gain values.

The final gain is taken as the average of these individual measurements, and the scatter among them gives the uncertainty. This method is advantageous because it relies on multiple independent estimates, reducing statistical noise and providing a more robust measure of the detector's performance.

$$Gain = \frac{(\overline{F_1} + \overline{F_2}) - (\overline{B_1} + \overline{B_2})}{\sigma^2_{(\overline{F_1} - \overline{F_2})} - \sigma^2_{(\overline{B_1} - \overline{B_2})}}$$

$$Error : \sigma_G = \frac{N}{D}\sqrt{(\frac{\sigma_N}{N})^2 + (\frac{\sigma_D}{D})^2}$$

2.2.3 Read Noise

It is the random noise introduced by the electronics during the signal readout process, measured in electrons (e^-). It sets the lower limit of detectable signal, and a lower read noise allows detection of fainter sources.
Read noise can be calculated as:

$$ReadNoise = \frac{Gain \times \sigma(B_1 - B_2)}{\sqrt{2}}$$

$$\Delta(\text{Read Noise}) = (\text{Read Noise}) \times \sqrt{(\frac{\Delta G}{G})^2 + (\frac{\Delta\sigma_{(B_1 - B_2)}}{\sigma_{(B_1 - B_2)}})^2}$$

2.2.4 Dark Current

It is the unwanted signal generated in the absence of light due to thermal excitation of electrons within the sensor, measured in electrons per pixel per second (e^-/pix/s). It increases with temperature and contributes to background noise in long exposures.
Dark current can be determined by taking a series of dark frames at different exposure times and plotting the mean signal against exposure time — the slope of this linear relation gives the dark current in electrons per pixel per second.

$$\text{Dark Current} = \text{Gain} \times \text{Slope}$$

$$\Delta(\text{Dark Current} = \text{Dark Current} \times \sqrt{(\frac{\sigma_{Gain}}{Gain})^2 + (\frac{\sigma_{Slope}}{Slope})^2}$$

2.3 Results

2.3.1 Mean Variance Method

- Figure 1 shows the plot obtained for calculating gain using the first method.

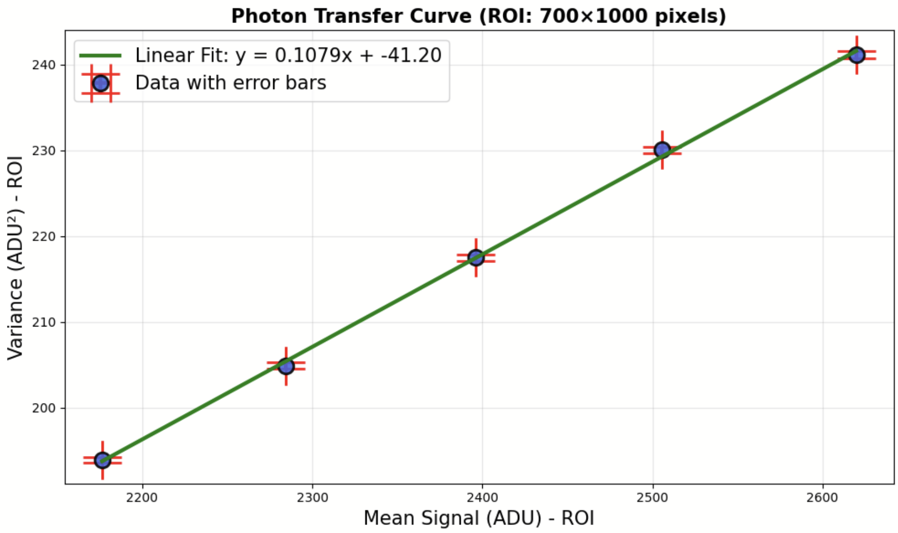

Figure 1: Mean vs Variance plot

- Obtained values of Gain and Read noise are -

$$\underline{\textbf{Gain}} = 9.26 \pm 0.14 \quad e^-/ADU$$
$$\underline{\textbf{Read Noise}} = 6.32 \pm 0.10 \quad RMS$$

2.3.2 Monitors Method

- In monitor's method, we use pairs of flat and bias frames to calculate gain and read noise. The histograms obtained for flat frames are shown in Figure 2

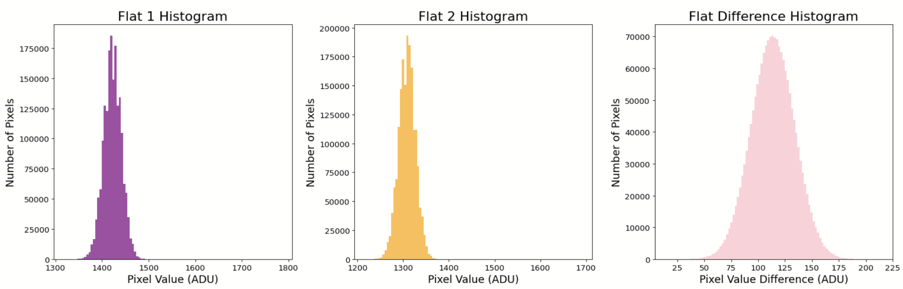

Figure 2: Histogram of Calibration Flat Frames

- Using this method, the obtained parameter values are-

$$\underline{\textbf{Gain}} = 9.94 \pm 0.06 \quad e^-/ADU$$
$$\underline{\textbf{Read Noise}} = 6.78 \pm 0.04 \quad RMS$$

2.3.3 Dark Current

- Dark is calculated using the slope obtained from the plot of Mean Signal vs Exposure Time, as shown in Figure 3

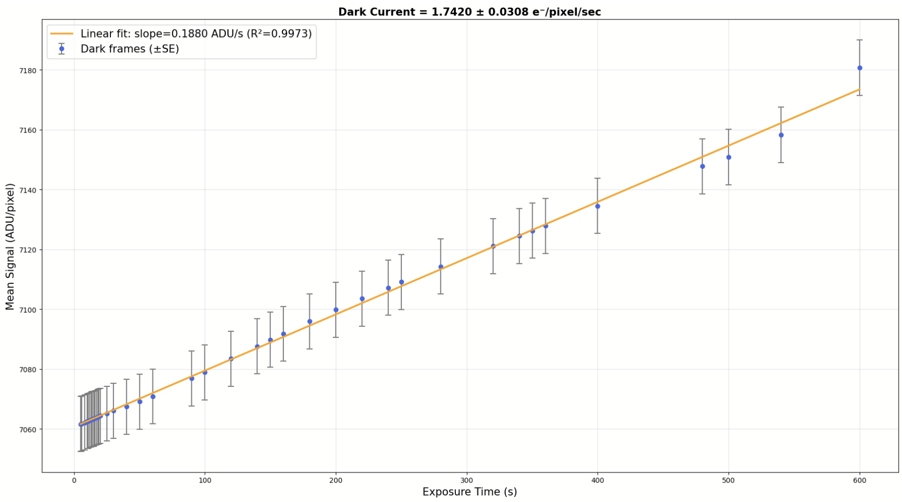

Figure 3: Mean Signal vs Exposure Time

$$\underline{\textbf{Dark Current}} = 1.74 \pm 0.03 \quad e^{-}/pixel \cdot sec$$

3 Atmospheric Extinction Coefficient Calculation

3.1 Introduction

The atmospheric extinction coefficient quantifies the attenuation of starlight as it passes through the Earth's atmosphere. This attenuation occurs due to scattering and absorption by air molecules, aerosols, and water vapor. By measuring the observed flux of standard stars at different altitudes (airmasses), one can determine how much light is lost per unit airmass and hence calculate the extinction coefficient. This coefficient is crucial for correcting observed stellar magnitudes to their true, above-atmosphere values and ensuring consistent photometric calibration across observations.

3.2 Theory

Bouguer's relation expresses the linear dependence between the observed instrumental magnitude of a star and the airmass. As light from a celestial source passes through the atmosphere, it experiences extinction proportional to the path length through the air. The relation is given by

$$m(\lambda, Z) = m_\circ(\lambda) + 1.086 \cdot k_\lambda \cdot sec(Z) \qquad [2]$$

here, Z is the zenith angle (90° - altitude), m(λ,z) is the instrumental magnitude of the star.

Plotting the instrumental magnitude against airmass thus yields a straight line whose slope directly gives the extinction coefficient.

A previous analysis done by Stalin et al [2] at the Indian Astronomical Observatory (IAO), Hanle near Growth India Telescope produced results as given in Figure 4.

Filter	$\lambda_{0\mathring{A}}$	k_{Ray}	k_{aer}	k_{oz}	k_{sum}	Observed
U	3650	0.3307	0.0099	0.0008	0.3414	0.36 ± 0.07
B	4400	0.1522	0.0085	0.0005	0.1612	0.21 ± 0.04
V	5500	0.0610	0.0071	0.0262	0.0943	0.12 ± 0.04
R	7000	0.0229	0.0059	0.0036	0.0324	0.09 ± 0.04
I	8800	0.0091	0.0049	0.0000	0.0140	0.05 ± 0.03

Figure 4: Atmospheric Coefficient values obtained by Stalin et al [2] using UBVRI filters

3.3 Target Selection and Observations

The approach taken for calculating is extinction coefficient is to observe a large number of stars at varying altitudes, obtaining a linear fit for all the stars, and then taking a weighted average to find the final extinction coefficient.
The target selected for the purpose is the star field **NGC 1039 (Spiral Cluster)**. The cluster is located at the co-ordinates: RA $02^h43^m46.8^s$, Dec $+42°52'25.6''$. It was selected for the following reasons: -

- The cluster is composed of dense star field, as can be seen in Figure 5. From the obtained images, 20 stars (labelled A to T) were chosen for performing photometry and further calculations.

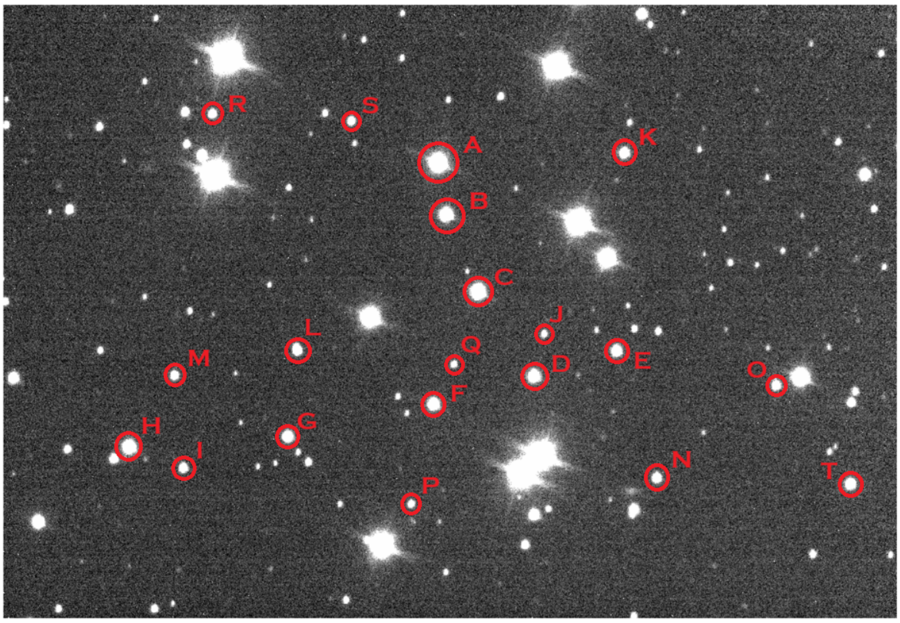

Figure 5: g-band image of star cluster Spiral Cluster (NGC1039) with labeled stars

- The altitude of the target varies from $\approx 30°$ to $\approx 80°$ in a single night (Figure 6) This provides us with distinct data points for the final plots, from which the extinction coefficients can be reliably derived.

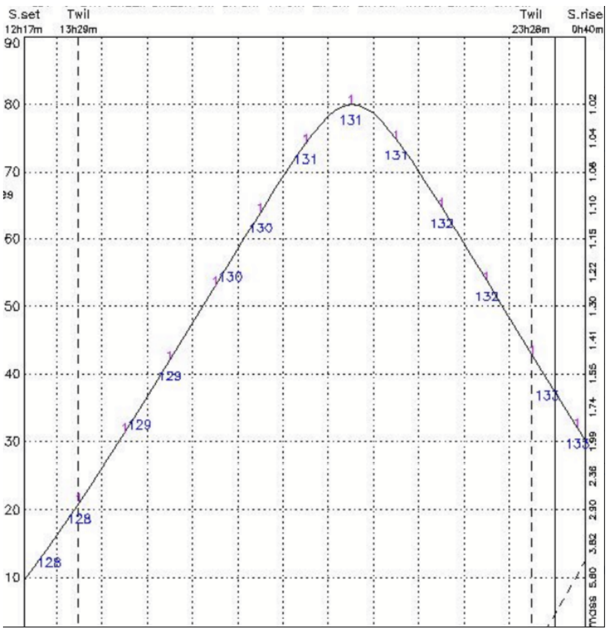

Figure 6: Altitude Varition of the Spiral Cluster in a single night

This cluster was observed overnight with images taken for an exposure time of 50 seconds for each image.

3.4 Results

After extracting the magnitudes and magnitudes for all star, we can plot the m vs sec(Z) curves for all stars in all the filters. The obtained curves for two of these stars(A and T) are given in Figure 7 and Figure 8.

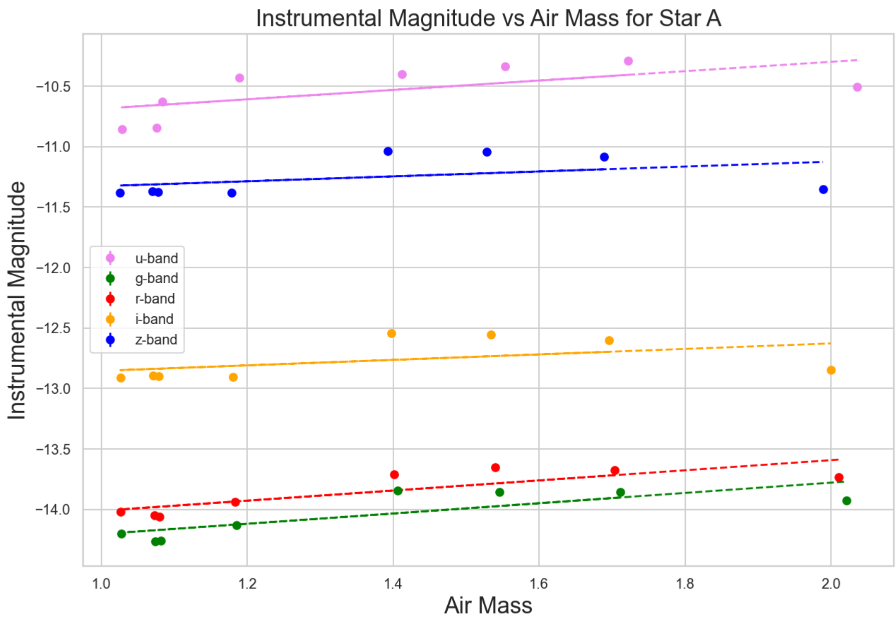

Figure 7: Instrumental Magnitude vs Airmass for star A

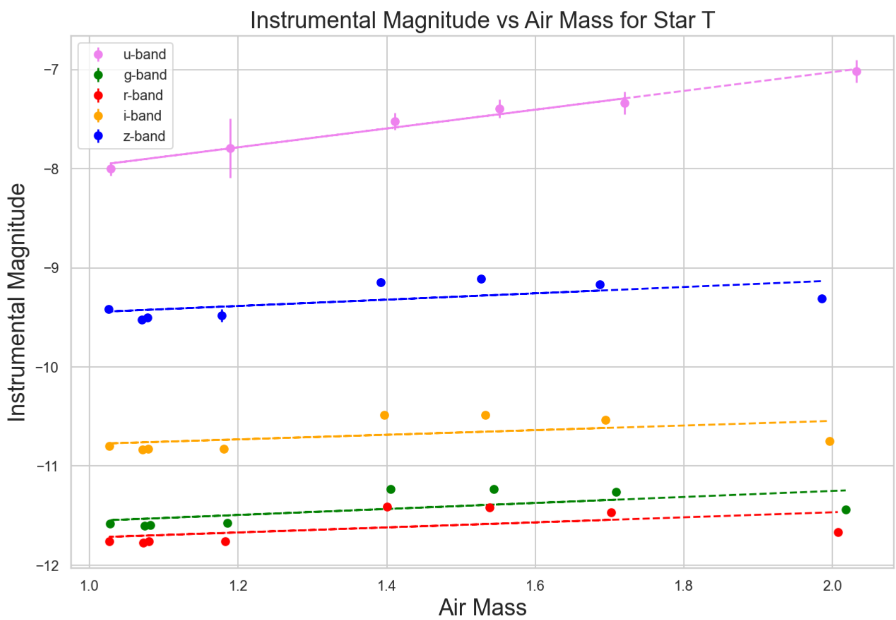

Figure 8: Instrumental Magnitude vs Airmass for star T

We can see that the slopes are different for different filters, and extinction coefficient falls as we go from filter u to z. This is also intuitive, since longer wavelengths would be less scattered by the atmosphere as compared to the shorter ones, resulting in them having a lower extinction coefficient.

The obtained coefficients are averaged using the given formula and are summarised in Table 1.

$$\overline{k} = \frac{\sum_i \frac{1}{\sigma_i^2} k_i}{\sum_i \frac{1}{\sigma_i^2}}$$

$$\sigma_k = \frac{1}{\sqrt{\sum_i \frac{1}{\sigma_i^2}}}$$

Filter	Extinction Coefficient
u	0.6149 ± 0.0299
g	0.2951 ± 0.0260
r	0.2502 ± 0.0266
i	0.2246 ± 0.0275
z	0.2030 ± 0.0299

Table 1: Extinction Coefficients in ugriz filters

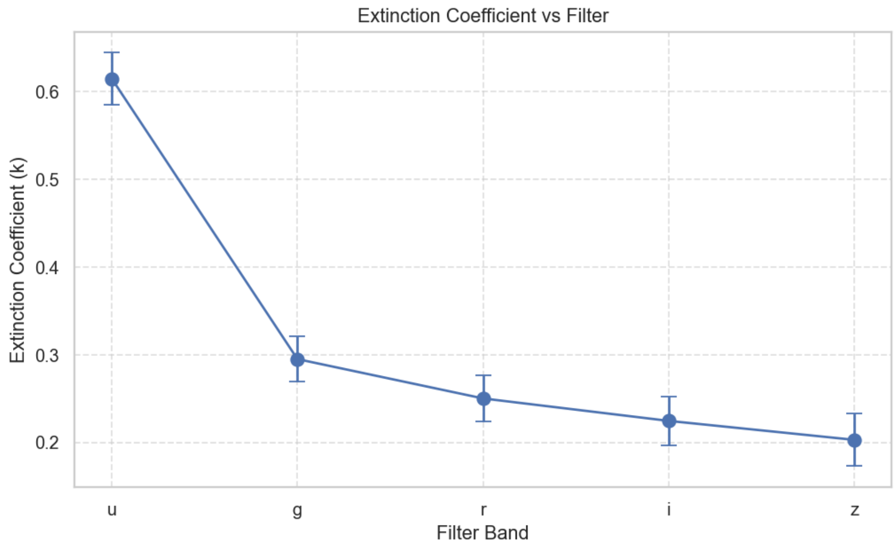

Figure 9: Variation of Extinction Coefficient over filters

From Figure 9, we can clearly see the decreasing trend of the extinction coefficients.

4 Conclusion

Through this study, the CMOS detector of the GROWTH telescope (SBIG STC-428 FW) was successfully characterized, and the atmospheric extinction coefficients were determined using photometric observations at varying altitudes.
Overall, the study provides a clear understanding of how instrumental characteristics and atmospheric conditions can influence photometric accuracy.

References

[1] Diffraction Limited. *SBIG STC-428 CMOS camera Datasheet*. 2024. URL: https://diffractionlimited.com/wp-content/uploads/2024/12/Diffraction-Data-Sheet-STC-428-FW.pdf.

[2] C. S. Stalin et al. "Night sky at the Indian Astronomical Observatory during 20002008". In: (2008). URL: https://arxiv.org/pdf/0809.1745.

[3] Hui Tian. *NOISE ANALYSIS IN CMOS IMAGE SENSORS*. 2000. URL: https://isl.stanford.edu/~abbas/group/papers_and_pub/hui_thesis.pdf.