Instrumental Characterization and Atmospheric Extinction Estimation using GROWTH-India Telescope

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Abstract

This report presents a detailed study and analysis of the CMOS sensor characterization and estimation of atmospheric extinction coefficient at the GIT observatory in Hanle.

The first part of the report focuses on the characterization of the CMOS sensor onboard the GIT Telescope. We determine the detector gain, dark current and related noise properties using bias, dark, and flat-field calibration frames. Further, the gain is estimated using two different methods - Mean Variance, Monitor method, both yielding consistent results.

The second part of the report deals with the calculation of the atmospheric extinction coefficient, which has been estimated using photometry of the NGC 1039 open cluster, observed at different altitudes. Instrumental magnitude obtained from calibrated photometry are plotted against air mass to get extinction slopes. The extinction coefficients obtained exhibit a clear decreasing trend when plotted against wavelength, being inline with the results obtained in Stalin et al. (2008, Reference 1). A detailed analysis of the observations and sources of error is also included.

All analysis scripts along with the raw and calibrated data has been made available on this GitHub repository.

Contents

1 Introduction

1.1 Instrumental Characterization

It is immensely essential to perform characterization of CMOS/ CCD detectors in order to ensure the reliability of observations and data captured. There are two major factors that strongly affect the quality of astronomical data obtained - the first being the atmospheric conditions and the other being instruments used to capture the data. Even a slight change in any of these could significantly alter measurements. The one factor that is fully within our control is the performance of the instruments. Hence, it is critically important to ensure that we do proper characterization of the detectors, i.e., obtain the properties inherent to the detector, such as gain, readout noise, dark current, etc.

1.2 Atmospheric Extinction Estimation

The second aim of our project is to calculate the atmospheric extinction. In simple terms, extinction results in reduced intensity of light reaching us. Now, extinction is caused by scattering effects, primarily Rayleigh scattering, and aerosol scattering, as well as due to molecular absorption. Here, we aim to parametrize and fit the linear relation between instrumental magnitude (magnitude of target, as observed through the telescope, GIT here), plotted against the air mass.

1.3 Growth India Telescope

The Growth India Telescope (GIT) is a 70 cm, F/6.5 telescope located at Hanle, at an altitude of about 4500 m. The site offers exceptional low-water-vapour conditions and dark skies, enabling stable photometric observations. GIT is mounted on an Alt-Azimuth mount and provides automated pointing and scheduling.

2 Theory

2.1 CMOS Characterization

2.1.1 CCD vs CMOS

- **CCD -** transport charge from pixel to pixel and convert it to voltage at output nodes, with limited conversion points across the sensor
- **CMOS -** have each pixel equipped with its own charge-to-voltage conversion amplifier

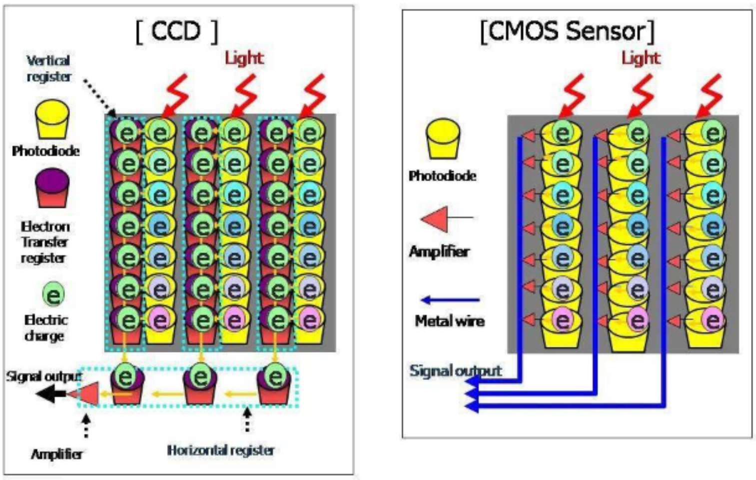

Figure 2.1: Side-by-side comparison of CCD and CMOS, Source: https://www.nevsemi.com/

2.1.2 Standard Calibration Frames

There are three calibration frames required here:

- **Bias** - Zero exposure frames. They record the electronic offset that occur during readout.
- **Flat field** - Uniformly illuminated (light sky or a dome). They're used to correct vignetting and other optical defects
- **Dark** - Frames taken with closed shutter, with a finite exposure time. They are very important to estimate the dark current

2.1.3 Gain, Readout Noise & Dark Current

- **Gain** — the amplification factor that determines how the sensor's electrical signal is converted to digital values, measured in electrons per ADU (analog-to-digital unit).

  - **Mean–Variance (Photon Transfer) Method** This method uses two uniformly illuminated flat frames. The variance of their difference increases linearly with the mean signal, and the slope of this linear relation gives the gain.

$$G = \frac{1}{\text{slope of Var}(F_1 - F_2) \text{ vs. mean}(F)}$$

  - **Monitor Method** This method uses only two flats and two bias frames. It compares the combined means of flats and biases with the variance of their differences.

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

  - **Uncertainty in Gain:**

$$\delta G = \frac{\delta m}{m^2}$$

    where m is the fitted slope obtained from the photon-transfer curve (Refer figure 5.2).

- **Readout Noise** — noise generated during the conversion of accumulated charge into a voltage and its digitisation into ADU values.

  - Read Noise:

$$RN = G \times \frac{\sigma(B_1 - B_2)}{\sqrt{2}}$$

  - Uncertainty in Read Noise:

$$\delta RN = RN\sqrt{\left(\frac{\delta G}{G}\right)^2 + \left(\frac{\delta \sigma}{\sigma}\right)^2}$$

- **Dark Current** — thermal electrons generated within the sensor irrespective of incoming light; increases linearly with exposure time.

  - Dark Current:

$$I_{\text{dark}} = m \cdot G$$

  - Uncertainty in Dark Current:

$$\delta I_{\text{dark}} = I_{\text{dark}}\sqrt{\left(\frac{\delta G}{G}\right)^2 + \left(\frac{\delta m}{m}\right)^2}$$

2.2 Atmospheric Extinction

Atmospheric extinction refers to the attenuation of starlight as it passes through the atmosphere due to scattering and absorption. Since this attenuation depends on wavelength and observing altitude, it is necessary to measure extinction coefficients to correct observed magnitudes. In this part, extinction is calculated using photometry of the open cluster NGC 1039 observed at multiple altitudes.

2.2.1 Air Mass

- In simple terms, air mass refers to the amount of atmosphere traversed by the incoming light. Usually, it is defined relative to the zenith.
  - **Simple sec Z Approximation** For small to moderate zenith angles, the atmosphere can be approximated as plane–parallel. The airmass is then:

    $$X \approx \sec Z$$

    where Z is the zenith angle.
  - **Note: We have used this simplistic expression for air mass in our analysis for atmospheric extinction**

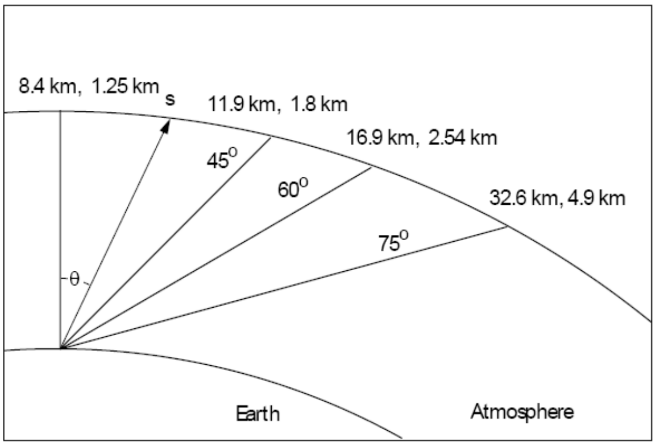

Figure 2.2: Different optical paths; Source: Undeger, Cagatay. (2009). Modeling daytime and night illumination.

  - **More Accurate Airmass Expression** At large zenith angles, the curvature of the atmosphere becomes important, and sec Z diverges. A more realistic model, commonly used in photometry, is the Kasten–Young formula:

    $$X = \frac{1}{\cos Z + 0.50572(96.07995^\circ - Z)^{-1.6364}}$$

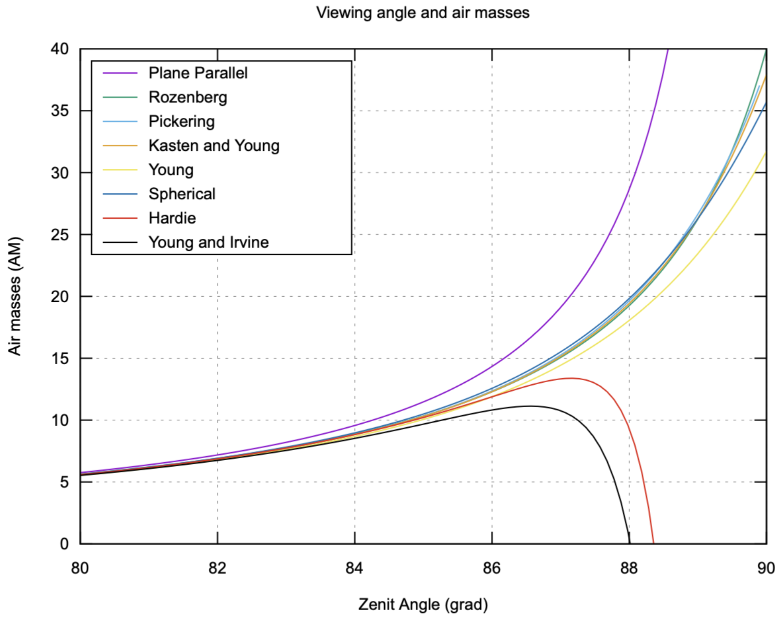

Figure 2.3: Different methods of estimating air mass; Source: Wikipedia

- **Uncertainty in Airmass** The uncertainty mainly comes from the propagated error in the altitude/zenith-angle measurement:

$$\delta X = \left| \frac{dX}{dZ} \right| \delta Z$$

2.2.2 Bouguer's Equation

The atmospheric extinction relation used in this work follows the formulation given in C. S. Stalin et al. (2008), derived from the long-term photometric monitoring of the Hanle site. The observed magnitude at a given wavelength decreases linearly with increasing airmass, and is expressed as:

$$m(\lambda, z) = m_0(\lambda) + 1.086\, k_\lambda \sec z$$

- $m(\lambda, z)$ is the observed magnitude at wavelength λ and zenith angle z and $m_0(\lambda)$ is the magnitude the star would have outside the Earth's atmosphere, and $\sec z$ is the air mass
- k_λ is the first-order extinction coefficient (magnitudes per airmass) - This is what we need to estimate.
- The factor 1.086 converts exponential attenuation (optical depth) into magnitudes since $2.5 \log_{10}(e) = 1.086$.

3 Targets & Data Acquisition

3.1 Targets

3.1.1 CMOS Sensor Characterization

- **Target:** Bias (5 frames), Dark (40 frames), and Flat frames (5 frames)
- **Exposure Times:**
  - Bias frames: $\sim 10^{-3}$ s
  - Dark frames: 5 s, 10 s, 20 s, 30 s, 60 s, 120 s, 300 s, 600 s, 900 s
  - Flat frames: 5 s in U filter

3.1.2 Atmospheric Extinction Calculation

- **Target:** NGC 1039 (Open Cluster)
- **Exposure Sets:**
  - U, G, R, I, Z filters (sdss ugriz)
  - 8 exposures per filter
  - Altitude range: 30° to 76° (corresponding to a wide airmass range)
- **Science Frames:** ugriz frames of NGC 1039 acquired at multiple airmasses for extinction measurement
- **Stars Used:** 20 stars (labeled A–T) selected for aperture photometry

All these data were stored as FITS or WCS.FITS files and processed using Python (Astropy, Photutils libraries).

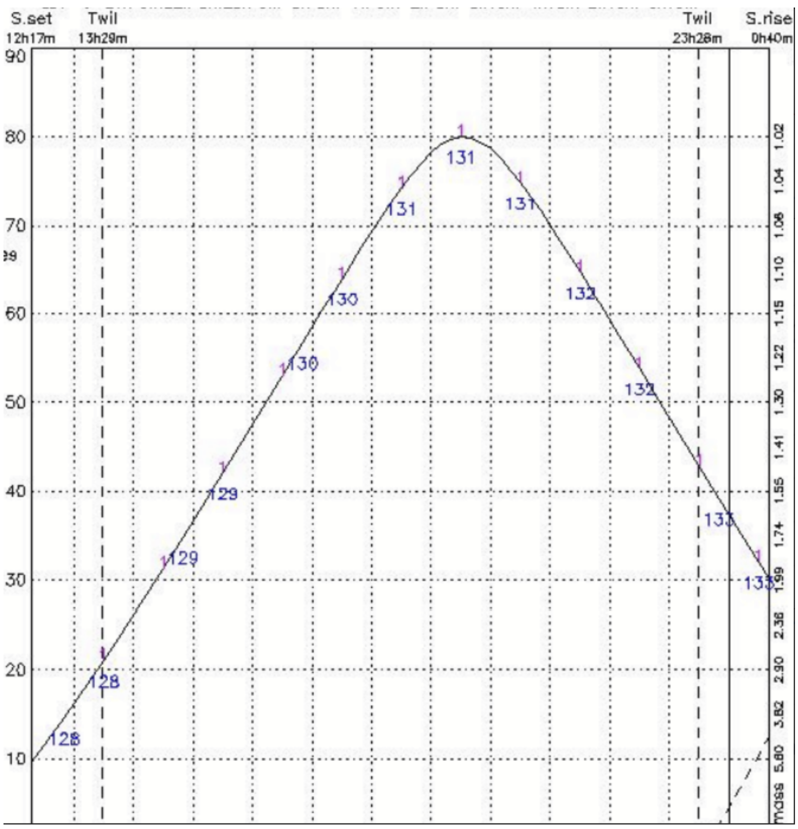

Figure 3.1: Euphemeris Plot, showing the altitude variation of the target

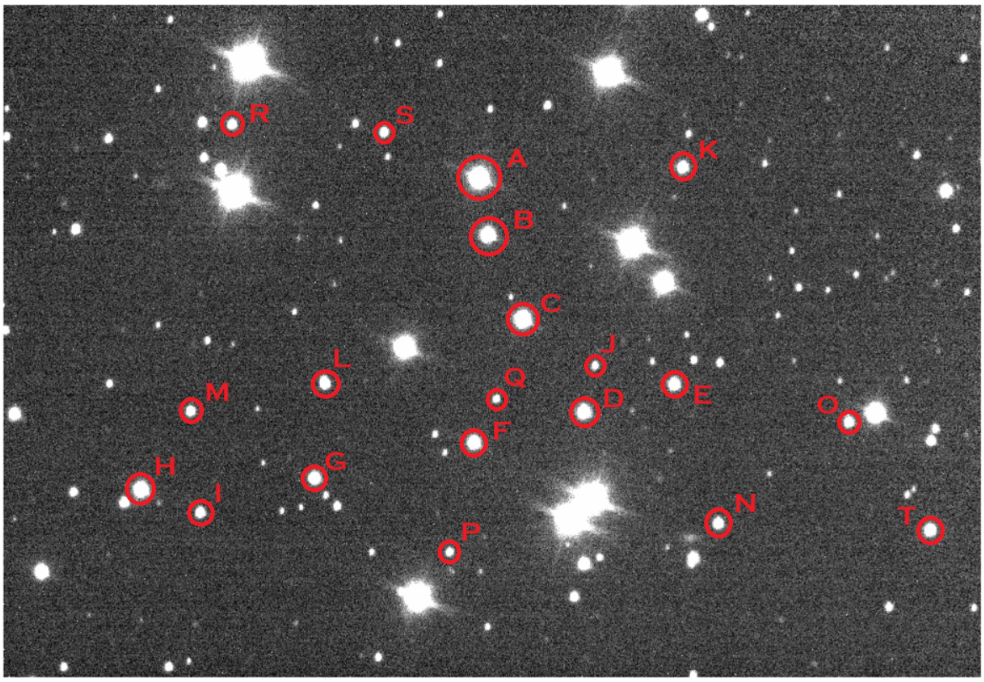

Figure 3.2: g-band Image of the selected 20 stars (A - Z) for aperture photometry (on DS9)

4 Methods

Calibrated data, analysis code, and processed outputs are available on this GitHub repository.

4.1 CMOS Detector Characterization

- All calibration FITS files (bias, flat, dark) were read using Astropy with header-safe loading; a central 700×1000 ROI was extracted and cleaned using iterative 3σ-clipping.
- Master bias was created via median combination; flat pairs were selected only when their mean values agreed within 1%.
- Variance and noise measurements were computed from difference frames ($F_1 - F_2$, $B_1 - B_2$, dark pairs) to remove fixed-pattern structure.
- Gain was obtained using both the Mean–Variance and Monitor methods by computing ROI means/variances for all flat and bias pairs; read noise was extracted from bias-pair differences and scaled by the measured gain.
- Dark current was obtained by fitting mean dark-signal versus exposure time and converting the slope to electrons using the gain.

4.2 Aperture Photometry and Atmospheric Extinction

- WCS information was used to convert catalog star coordinates to pixel positions; circular aperture photometry with annular background subtraction was performed on all selected stars across all ugriz frames.
- Airmass was computed from the target altitude; instrumental magnitudes were plotted against airmass and fit with a straight line to obtain extinction slopes per star and per filter, and the final extinction coefficients were computed using inverse-variance weighting:

$$k = \frac{\sum_i \frac{k_i}{\sigma_i^2}}{\sum_i \frac{1}{\sigma_i^2}}, \qquad \sigma_k = \left(\sum_i \frac{1}{\sigma_i^2} \right)^{-1/2}.$$

5 Results

5.1 Detector Characterization

Table 5.1: Detector parameters (Low Gain mode).

Quantity	Mean–Variance Method	Monitors Method
Gain (e^-/ADU)	9.26 ± 0.14	9.94 ± 0.06
Read Noise (e^- RMS)	6.32 ± 0.10	6.78 ± 0.04
Dark Current (e^-/pix/s)	1.74 ± 0.03	1.87 ± 0.02

5.1.1 Plots

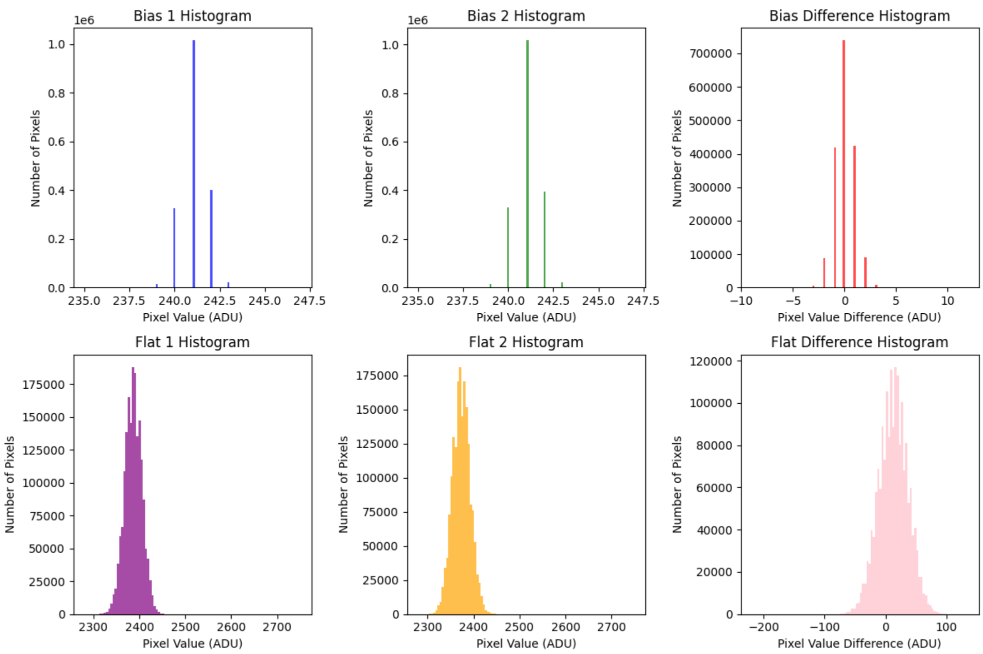

Figure 5.1: Histograms of 2 flat frames, along with their differences

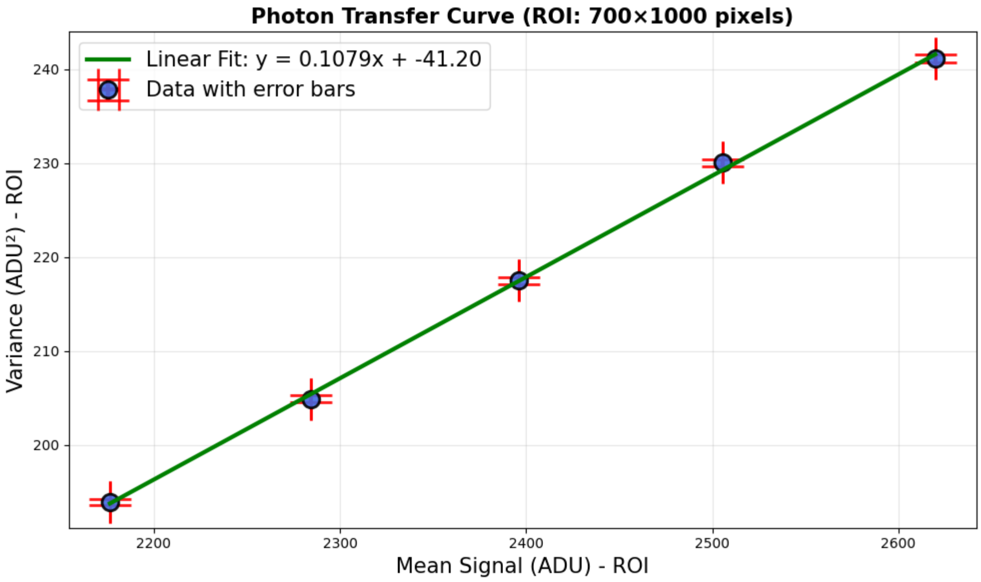

Figure 5.2: Photon Transfer Curve

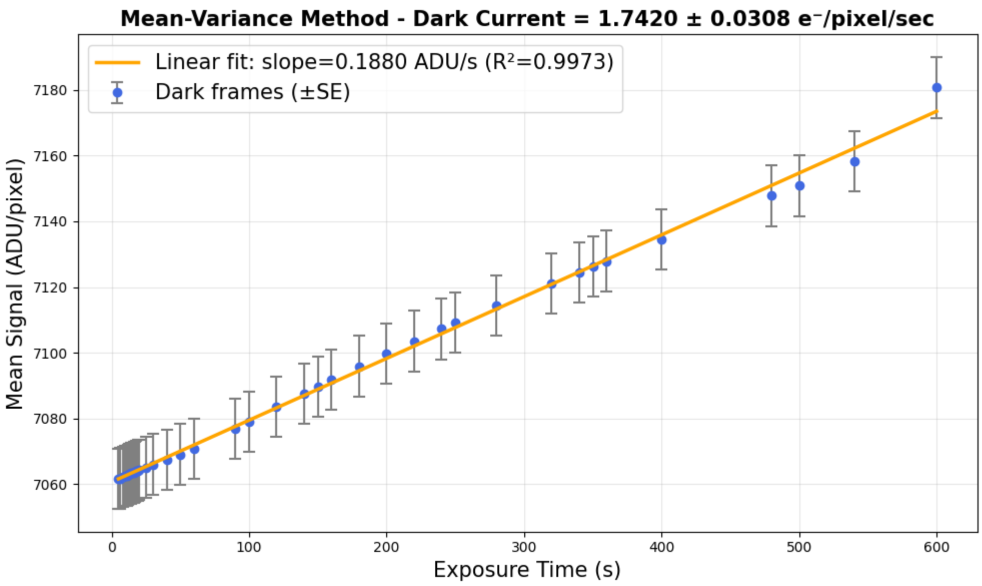

Figure 5.3: Mean Variance method - Dark Current Estimation

5.1.2 Observations

- We see that the gain, read noise and dark current values obtained using both the methods are very consistent
- The photon-transfer (variance–mean) curve shows a well-defined linear region
- The measured gain ($\sim$ 9.3–9.9 e^-/ADU) is significantly higher than the value provided in the datasheet (5.5 e^-/ADU) The datasheet value is much lower (Reference: 2).

5.1.3 Sources of Error

1. Intrinsic sensor noise - including read noise, shot noise (Poisson distributed noise). These are some fundamental limiations in CMOS image sensors

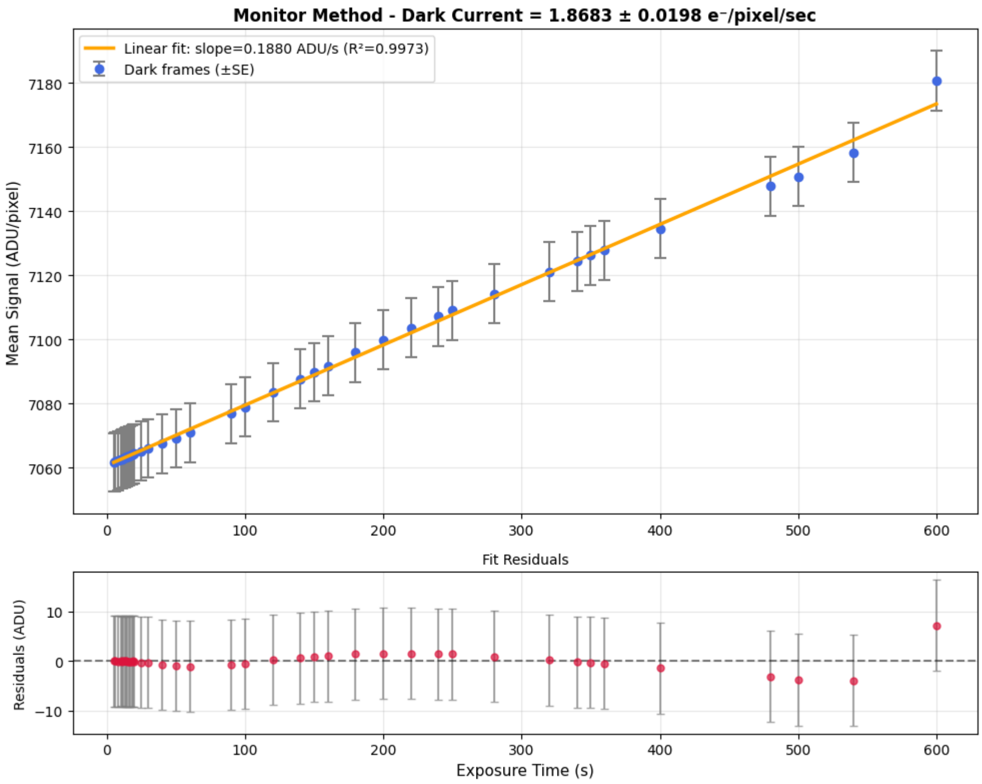

Figure 5.4: Monitor method - Dark Current Estimation

2. Vignetting and dust motes in flat fields - The flat field illumination is not perfectly uniform. This required to manually selection of flat pairs and rule-based ROI cropping
3. Hot and cold pixels in dark frames - These outlier pixels were excluded by doing σ clipping, with a threshold of 3 * σ (using the sigma_clip function from astropy library)
4. Temperature dependent dark current - This could also be a contributor to the error. The current method of estimation of dark current assumes constant thermal conditions.

5.2 Atmospheric Extinction

Table 5.2: First-order atmospheric extinction coefficients for the SDSS ugriz bands.

Band	Extinction Coefficient k_λ	Uncertainty
u	0.615	0.030
g	0.295	0.026
r	0.250	0.027
i	0.225	0.028
z	0.203	0.030

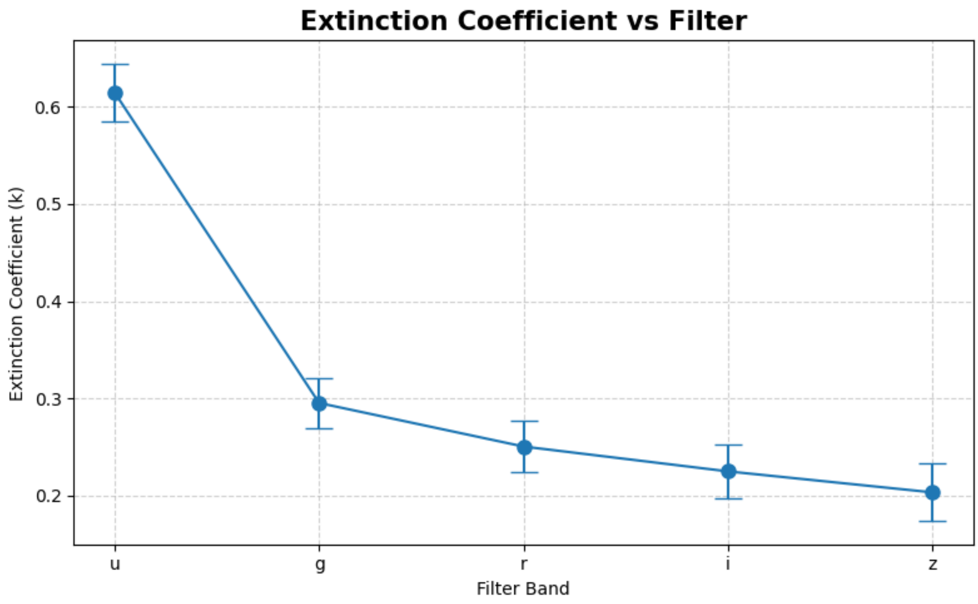

Figure 5.5: Extinction coefficient vs filter - Visible trend of decreasing coefficient values with increasing wavelength (u filter - smallest wavelength; z band - longest wavelength)

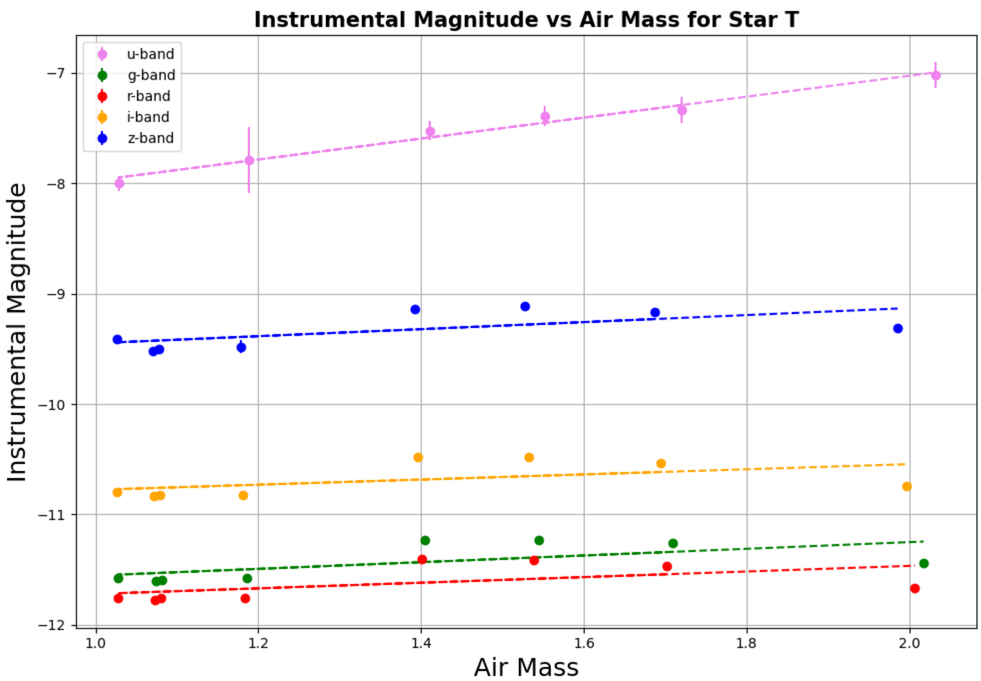

Figure 5.6: Instrumental Magnitude vs Airmass for star T

5.2.1 Plots

5.2.2 Observations

1. Extinction decreases systematically with increasing wavelength: $k_u > k_g > k_r > k_i > k_z$, matching the trends described in Stalin et al. 2008.

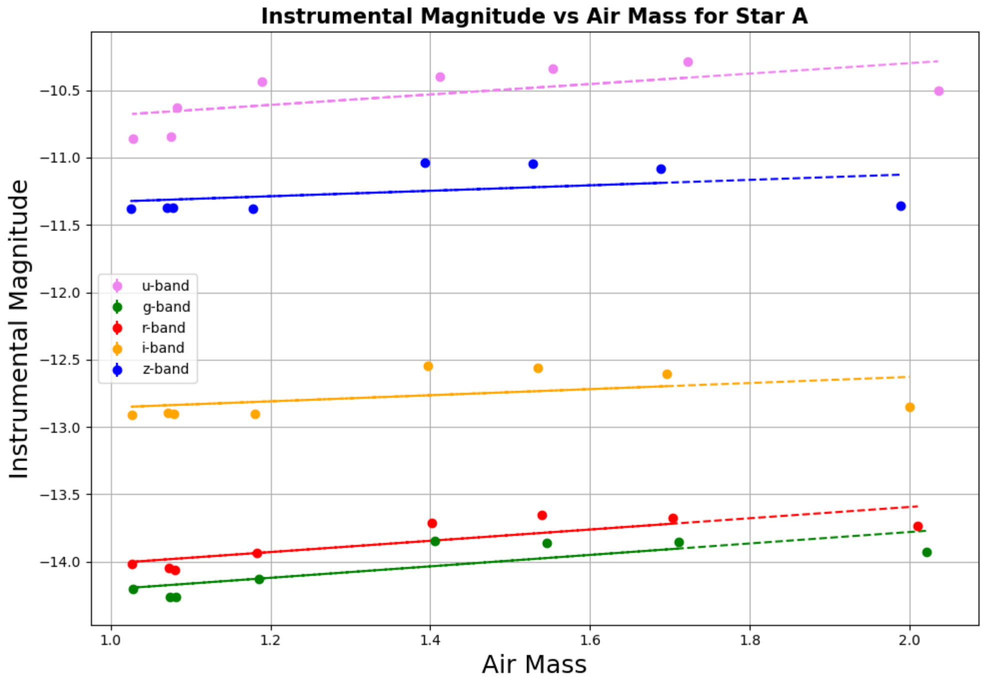

Figure 5.7: Instrumental Magnitude vs Airmass for star A

5.2.3 Sources of Error

We see that over the air mass of 1.4 (below the altitude of 45 degrees) (figure 5.8), the stars become noticeably fainter (the 3 data points located much higher than other points) - this could be attributed to:

1. Atmospheric seeing effects, Sky transparency changes (thin clouds/haze)
2. Real physical variations in atmospheric conditions (changing aerosol content, water vapor, temperature)
3. Variable airglow contributions to sky brightness

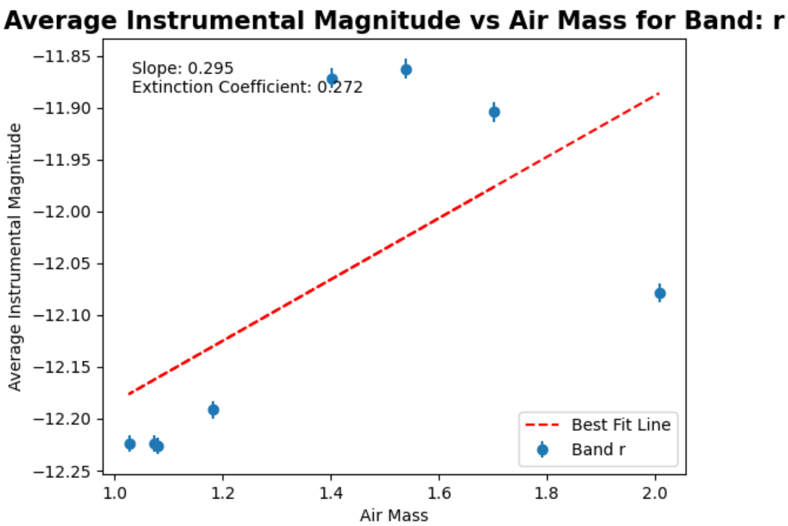

Figure 5.8: Fainter magnitudes for $< 45°$ Altitude stars

6 Conclusion

We successfully performed CMOS characterization and measured atmospheric extinction across the ugriz (sdss) bands from the observations of NGC 1039 cluster. The calculated extinction coefficients from the Bouguer's Equation, follow the expected wavelength dependence and overall agree with Stalin et al. (2008, Reference 1).

7 Biblography

1. Night sky at the Indian Astronomical Observatory during 2000 - 2008 - C. S. Stalin et al
2. Diffraction Limited, *SBIG STC-428 FW CMOS Camera Datasheet* (2024) - link
3. 2022, AAVSO Guide to CCD/CMOS Photometry with Monochrome Cameras, American Association of Variable Star Observers (AAVSO), AAVSO 185 Alewife Brook Parkway, Suite 410 Cambridge, MA 02138 - link