Instrumental (CMOS) Characterization and Atmospheric Extinction Calculation using GIT

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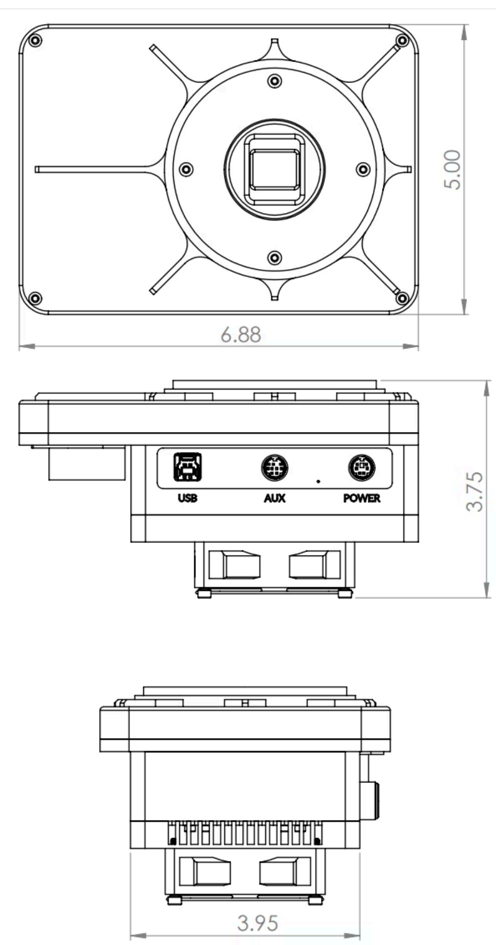
Image source: Growth India

CMOS Imaging Principles and Application

The Complementary Metal-Oxide-Semiconductor (CMOS) sensor **(SBIG STC 428 FW)** is an advanced detector for astronomical photometry and imaging.

- Converts incident photons into measurable electronic charge with on-chip amplification.
- Offers low noise, high speed readout, and excellent dynamic range.
- Essential for precise measurement of celestial object brightness with reduced power consumption.

The values we obtained differed from those reported in *data sheet*. This variation is precisely why we performed the CMOS characterization.



Source: **SBIG STC 428 FW Datasheet**[1]

Part I: CMOS Characterization

Key Parameters for Detector Calibration

Gain

Conversion factor from electrons (e^-) to Analog-to-Digital Units (ADU).

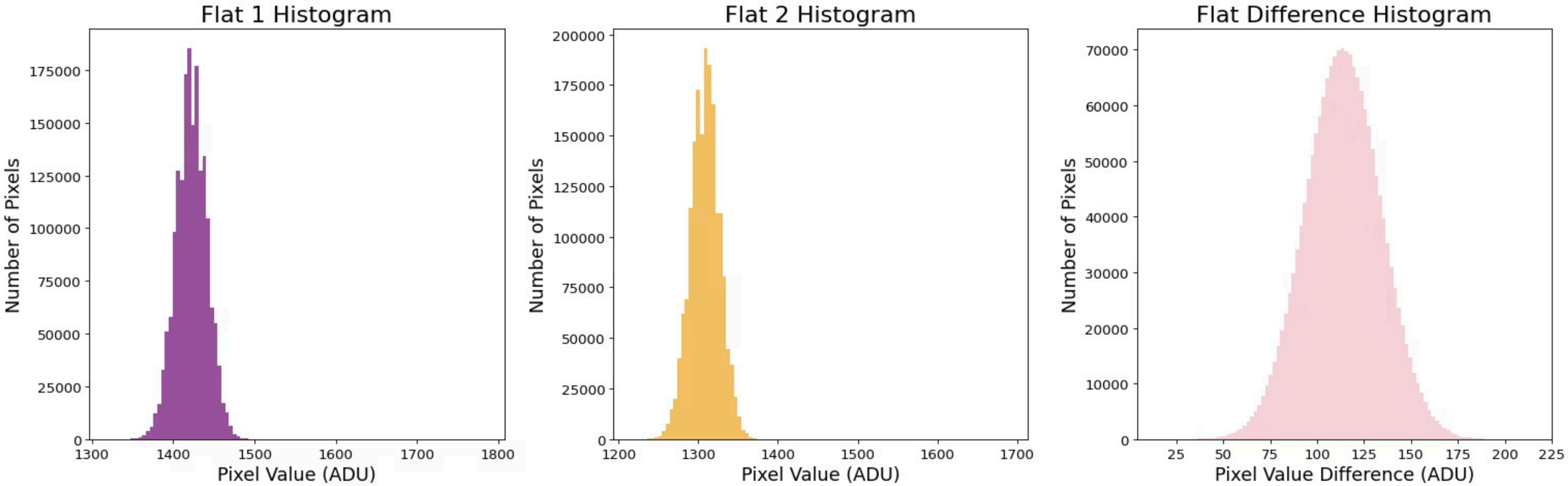
Dark Current

Thermal generation of charge in the absence of light; corrected via dark frames.

Readout Noise

Electronic noise introduced during charge transfer and measurement.

Histograms of Calibration Frames



Part I: CMOS Characterization

Gain determination methods

Mean Variance Method

Gain is measured by linear fitting a line to a scatter plot of noise variance vs signal mean from paired flats.

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

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

Monitors Method

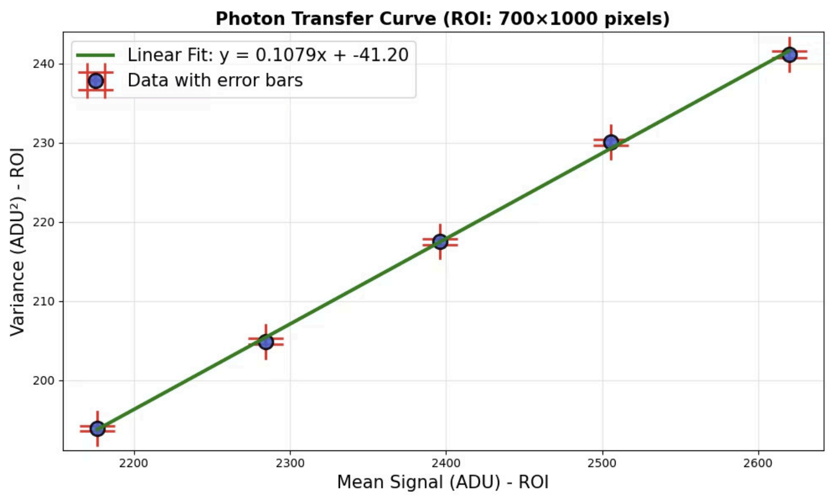
The Monitors Method calculates gain from **multiple independent measurements** using pairs of flat and bias frames, then take the mean and standard deviation.

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

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

Gain results

Results of Mean Variance Method



$$\text{Gain} = 9.26 \pm 0.14\ e^{-}/ADU$$

Results of Monitors Method

Bias Statistics (ROI with σ-clipping):

Bias_1 mean: 241.06 ADU

Bias_2 mean: 241.06 ADU

$\sigma^2_{(\text{diff\_bias})} = 0.93\ \text{ADU}^2$

Flat statistics chosen pair wise

$$\text{Gain} = 9.94 \pm 0.06\ e^{-}/\text{ADU}$$

Read Noise

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

$$\Delta(\text{Read noise}) = \frac{G\,\sigma(B_1 - B_2)}{\sqrt{2}} \sqrt{\left(\frac{\Delta G}{G}\right)^2 + \left(\frac{\Delta\sigma(B_1 - B_2)}{\sigma(B_1 - B_2)}\right)^2}$$

Mean Variance Method

$$\text{Read Noise} = 6.32 \pm 0.10\ e^{-} RMS$$

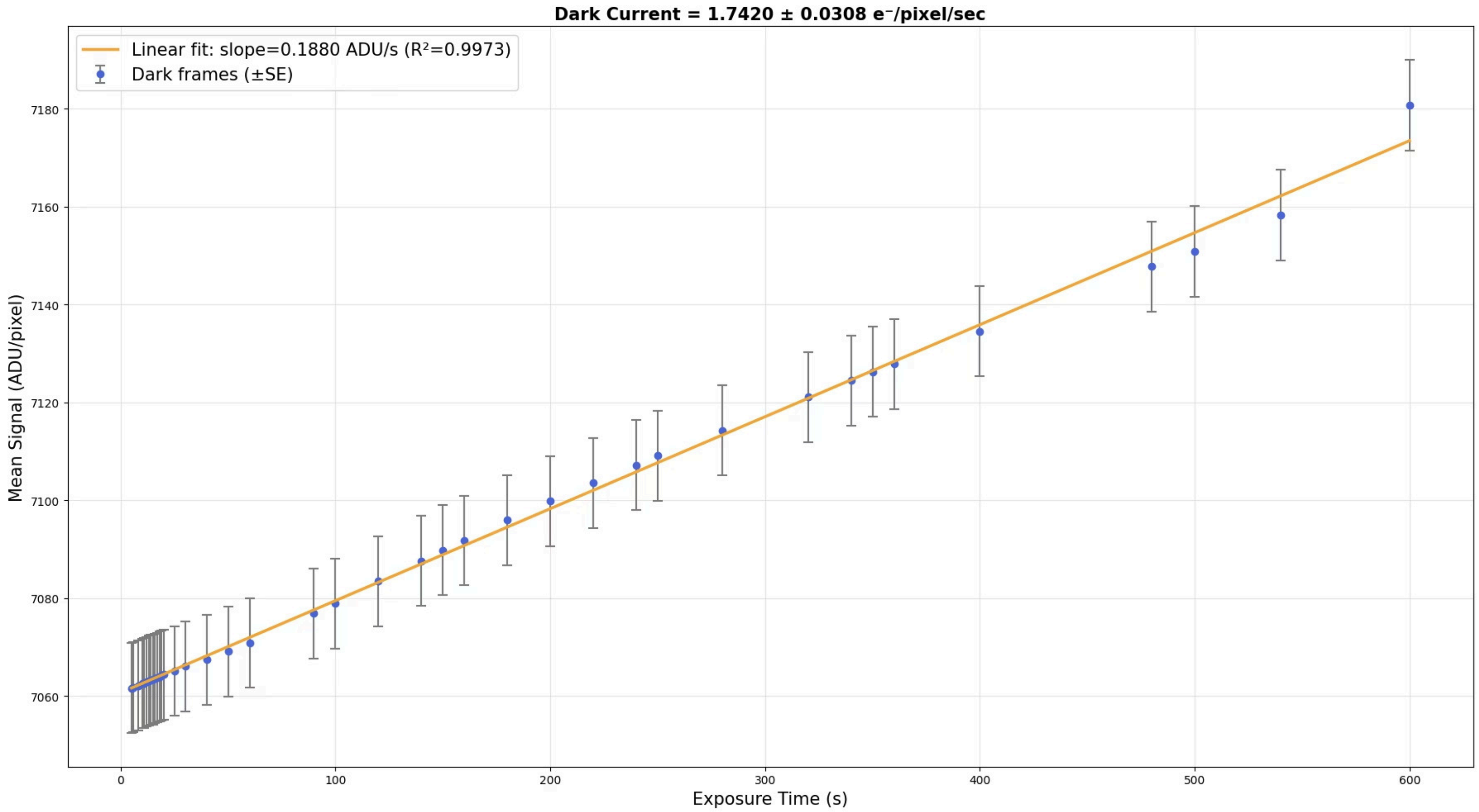
Monitors Method

$$\text{Read Noise} = 6.78 \pm 0.04\ e^{-} RMS$$

Dark Current

$$\text{Dark Current} = gain \times slope$$

$$\delta(\text{Dark Current}) = \text{Dark Current} \times \sqrt{\left(\frac{\delta\text{Gain}}{\text{Gain}}\right)^2 + \left(\frac{\delta\text{Slope}}{\text{Slope}}\right)^2}$$

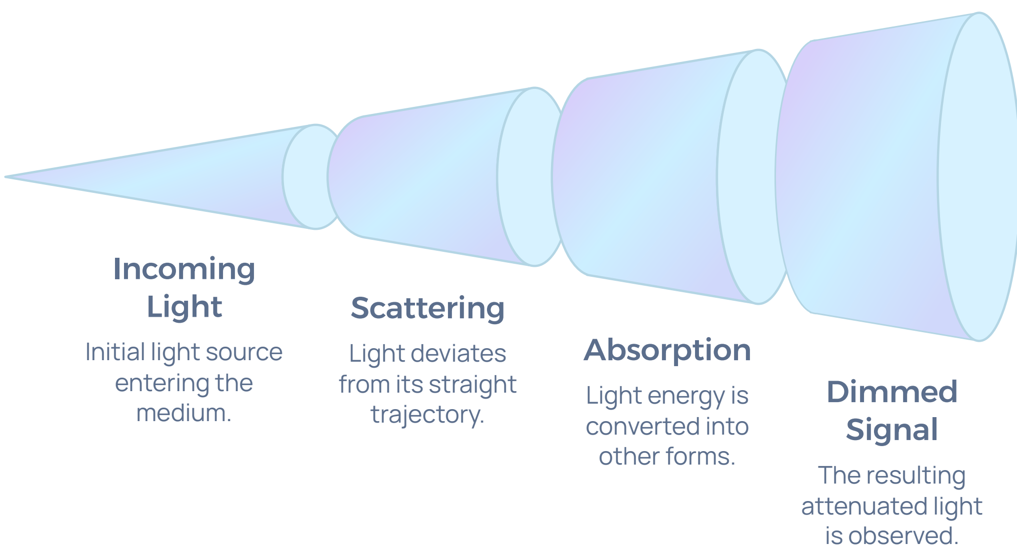


$$\text{Dark Current} = 1.74 \pm 0.03\ e^{-}/\text{pixel}/\text{sec}$$

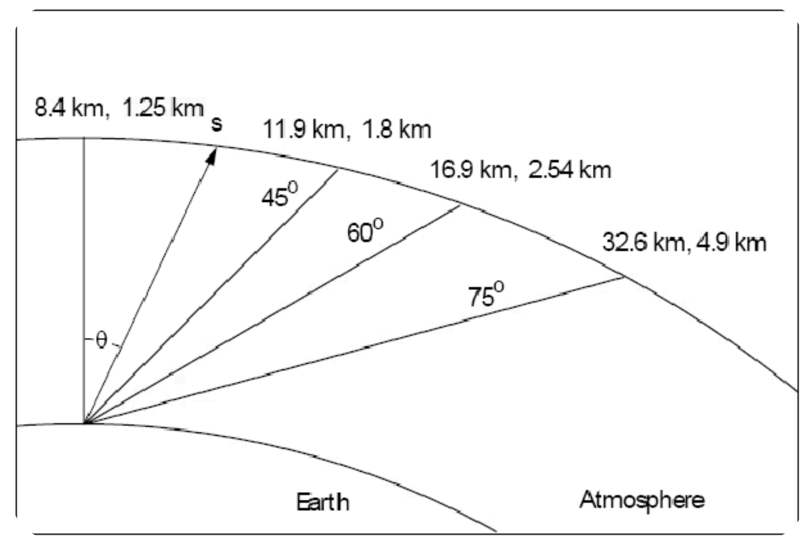
Impact of Earth’s Atmosphere

Atmospheric extinction is the dimming of light as it passes through the atmosphere.
A correction is required for accurate photometry.

Attenuation of source light due to atmosphere



Airmass variation with zenith angle



Undeger, Cagatay. (2009). Modeling daytime and night illumination.

This effect is wavelength-dependent and varies with atmospheric conditions and the observer's zenith angle.

Part II: Atmospheric Extinction coefficient calculation

Extinction Coefficient and Airmass

The Extinction Equation (Bouguer's Relation)

$$\boxed{m(\lambda, Z) = m_0(\lambda) + 1.086 \cdot k_\lambda \cdot \sec(Z)}$$

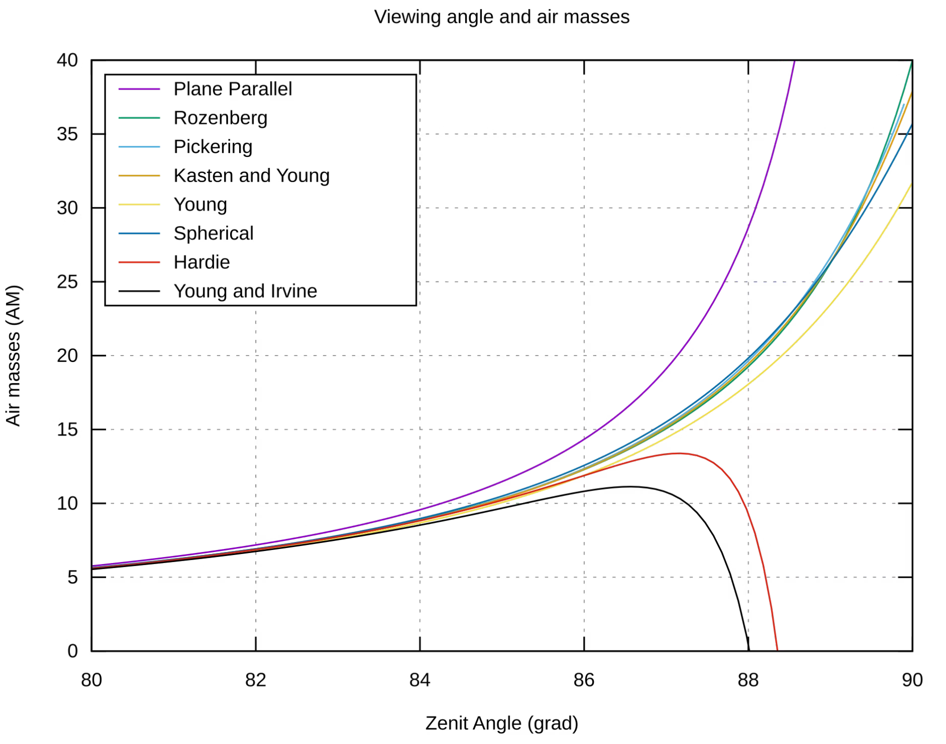
$k_\lambda = \text{Extinction Coefficient}$

$m(\lambda, z) = \text{Observed Magnitude}$

$sec(Z) = \text{Airmass in Atmosphere}$

$Z = \text{Zenith Angle} = 90^\circ - \text{Altitude}$

Equation Reference : Stalin et. al



By Amishaa - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=127852654

Extinction coefficient results from Stalin et al. (2008)

Table 1. The calculated and measured values of the extinction coefficients in mag/airmass at Hanle

Filter	$\lambda_{0\AA}$	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

NOTE: The paper has data for UBVRI filters, however, GIT operates with UGRIZ (SDSS) filters

Part II: Atmospheric Extinction coefficient calculation

Processing Pipeline

Target Selection

Select a dense region in the sky with a large number of stars, like a star cluster with a culmination point at high altitude

Data Acquisition

Take exposures of the targets uniformly spaced in airmass

Plotting Magnitude Variation

Plot observed magnitude vs. airmass for each filter band.

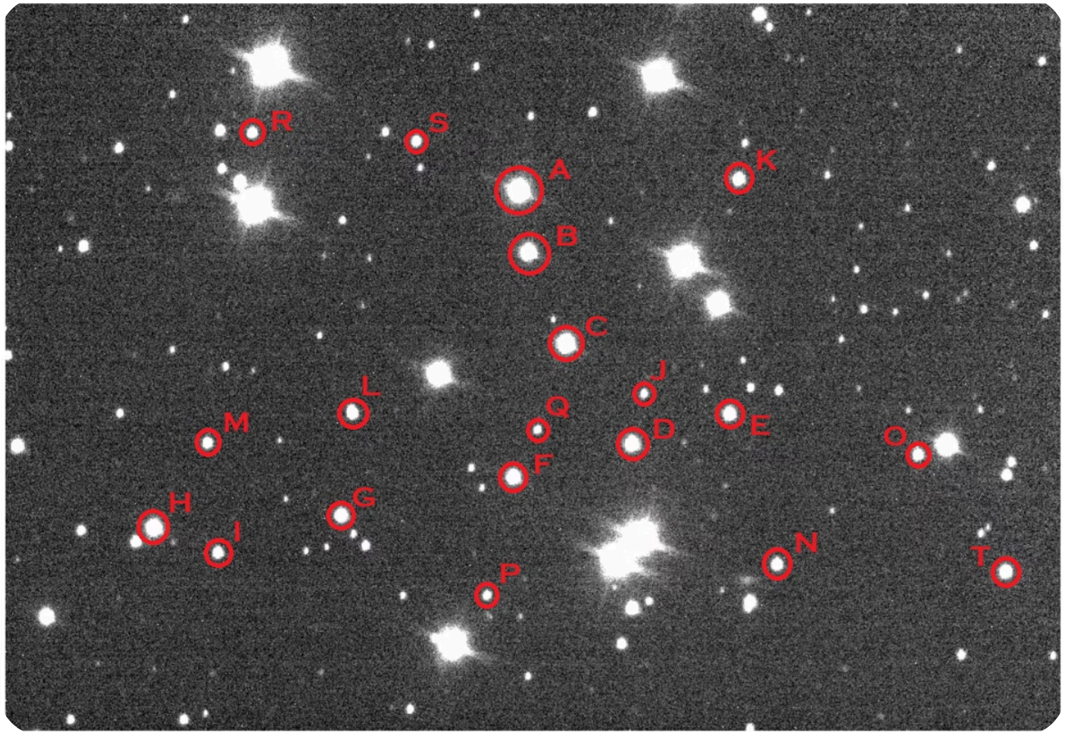
Extinction Coefficient Calculation

The slope of the linear fit determines the atmospheric extinction coefficient (k_λ)

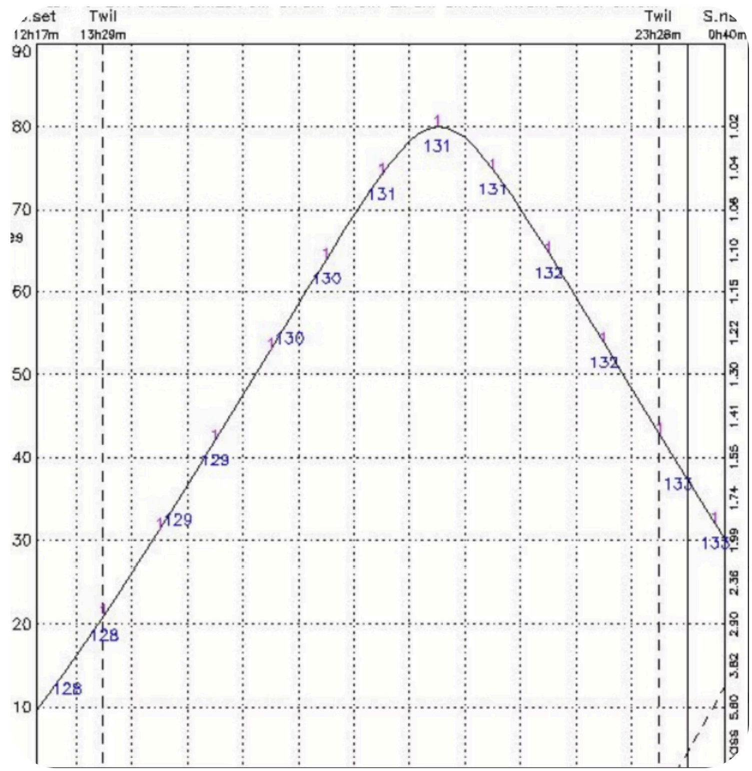
Part II: Atmospheric Extinction coefficient calculation

Target - NGC 1039 Spiral Cluster

Selected 20 (A-T) stars for cluster method to determine atmospheric coefficient



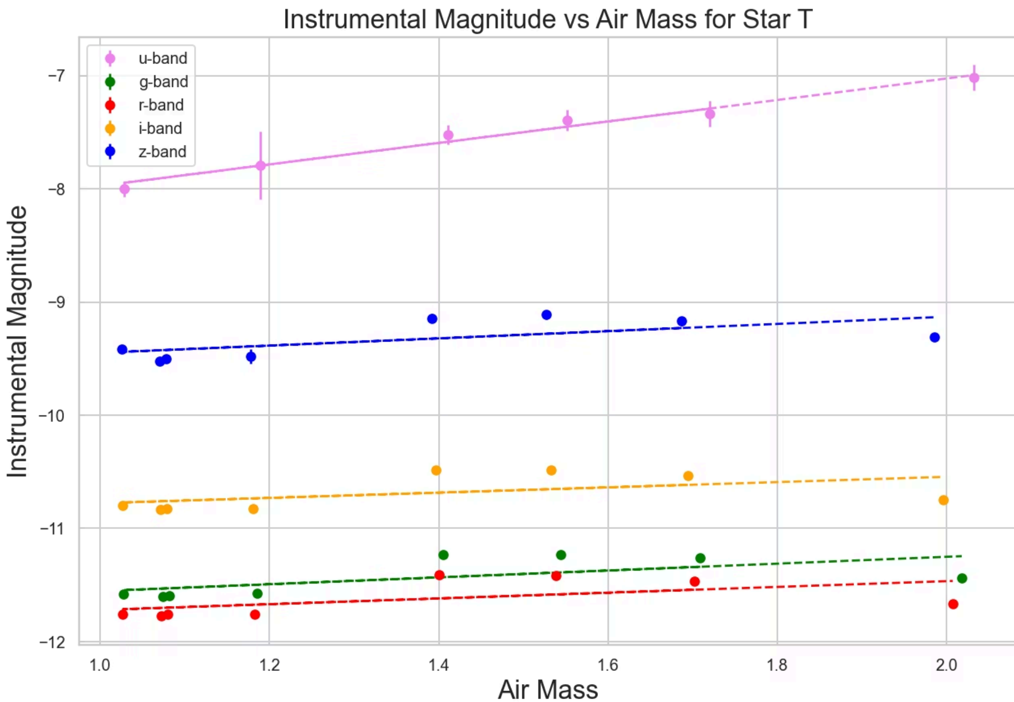
g-band Image of the star cluster

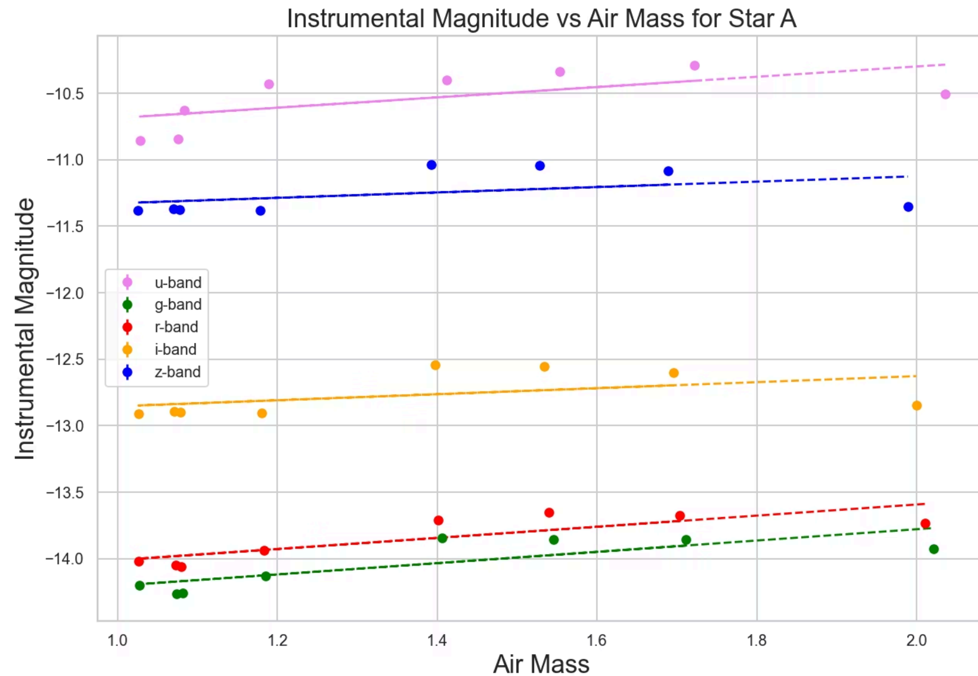


Altitude variation of the target

Part II: Atmospheric Extinction coefficient calculation

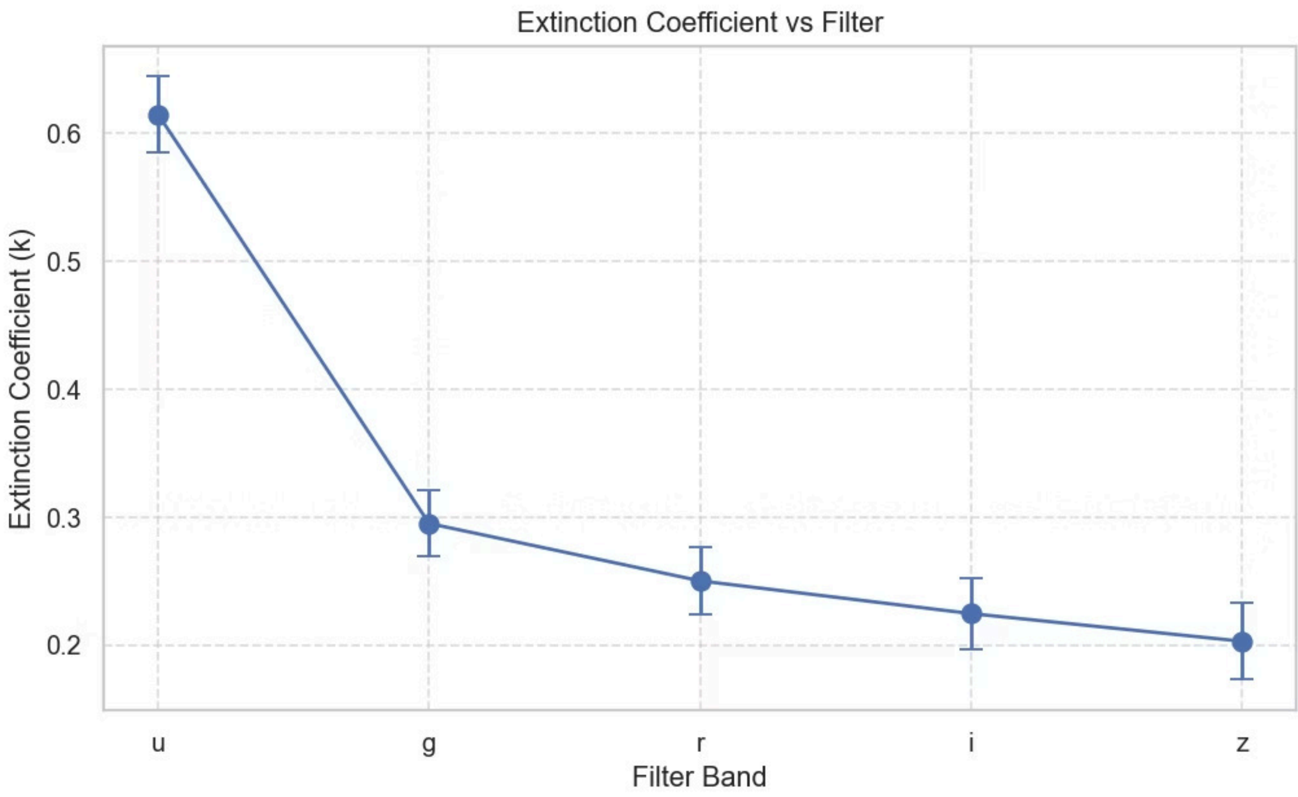
Extinction coefficient plots for UGRIZ filters





'Note: Error bars are present, albeit very small to physically see due to the y-axis scale

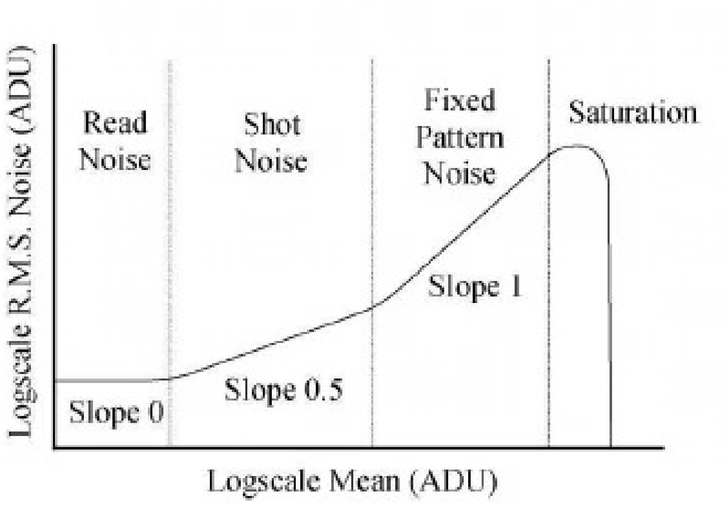
Variation of Extinction Coefficient Across Filters



Band	Average Extinction Coefficient	Error
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

Part III: Sources of Error

→ I - CMOS Sensor Noise

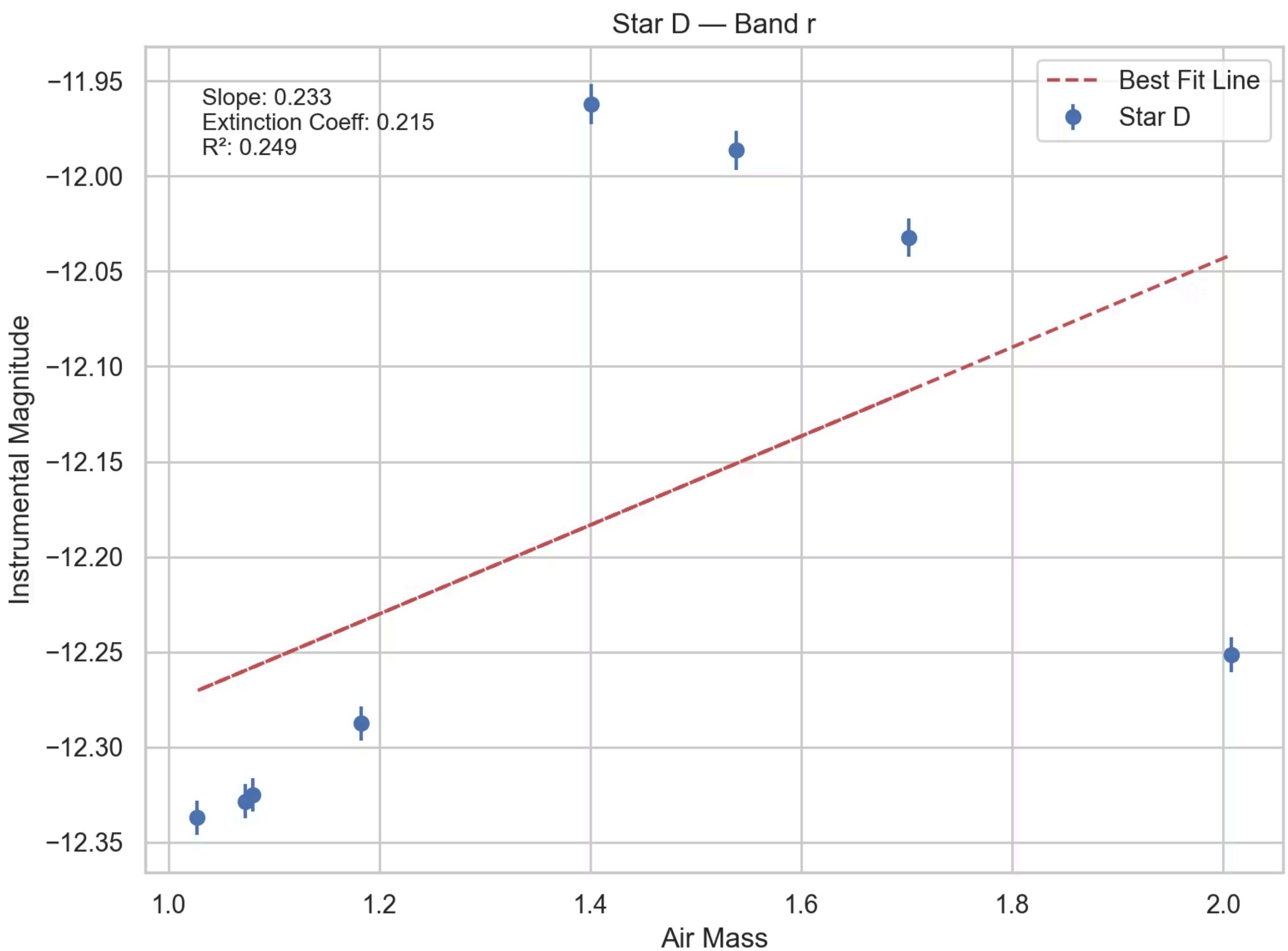


1. **Intrinsic sensor noise** (Read noise, shot noise, fixed pattern noise) - fundamental limitations in CMOS image sensors
2. **Vignetting and dust motes in flat fields** - spatial non-uniformity rejected by selecting central ROI (700×1000 pixels)
3. **Hot and cold pixels in dark frames** - outlier pixels rejected by 3σ sigma clipping
4. **Temperature-dependent dark current** - doubles every 5-8°C, requires temperature stability (±0.1°C)

Stewart, Graeme & Bates, Richard & Blue, A & Clark, A & Dhesi, S. & Maneuski, Dima & Marchal, Julien & Steadman, P & Tartoni, N & Turchetta, Renato. (2011). Comparison of a CCD and an APS for soft X-ray diffraction. Journal of Instrumentation. 6. C12062. 10.1088/1748-0221/6/12/C12062.

Part III: Sources of Error

→ II - Atmospheric conditions



We see that over the air mass of 1.4 (below the altitude of 45 degrees), the stars become noticeably fainter - 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

Challenges Faced

1. The first epoch of data we received had unusable images -
    - At one altitude, the dome failed to open, resulting in no visible stars.
    - At another altitude, a tracking issue caused all stars to appear as trails.
    - Two altitudes (77° and 78°) were too close to each other, effectively giving only a single data point instead of two distinct ones.
    - The u-band images were underexposed, leading to fields with nearly no stars in them.
2. In CMOS Characterization, we surprisingly got a high gain compared to the datasheet, which also resulted in increased dark current.

References

1. Stalin et al. (2008) https://arxiv.org/pdf/0809.1745
2. Benn, C.R., & Ellison, S.C., 1998, New Astronomy Review 42, 503
3. Determination of the STIS CCD Gain
4. CMOS Sensor (of GIT's secondary camera) Datasheet [1] - https://diffractionlimited.com/wp-content/uploads/2024/12/Diffraction-Data-Sheet-STC-428-FW.pdf
5. CMOS Characterization & Noise Reduction - https://isl.stanford.edu/~abbas/group/papers_and_pub/hui_thesis.pdf
6. Hayes, D. S., & Latham, D. W. (1975). *A rediscussion of the atmospheric extinction and the absolute spectral - energy distribution of Vega. The Astrophysical Journal*, 197, 593-601

GitHub Repo of raw & processed data, code and outputs:

ramanan849 / The_GARAMA_Project 2 ★

Atmospheric Extinction Coefficient Calculation and CMOS Characterization

ramanan849

GutHib

GitHub - ramanan849/The_GARAMA_Project: Atmospheric Extinction C...

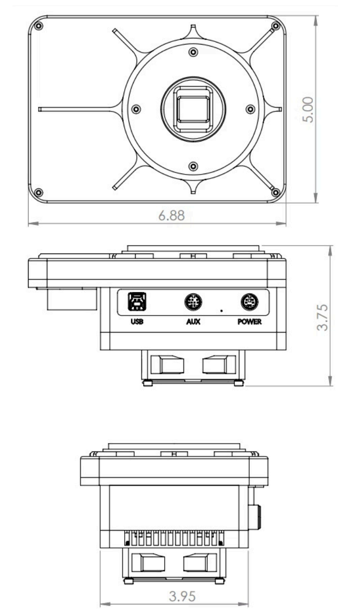
Atmospheric Extinction Coefficient Calculation and CMOS Characterization ramanan849/The_GARAMA_Project

Datasheet of CMOS Sensor

DIFFRACTION
ASTRONOMY + SCIENTIFIC IMAGING SOLUTIONS

SBIG® STC-428-Series

TECHNICAL SPECIFICATIONS	
A/D Converter	12-bit with High Gain / Low Gain modes
Binning Modes	1×1, 2×2
Computer Interface	USB 3.0 (USB 2.0 compatible)
Cooling Delta	Approximately 30°C
Dark Current	0.1 e-/p/s at -5°C
Exposure	0.001 – 3600 seconds
Filter Size	36mm / 1.25"
Filter Wheel Option	STC-428-FW includes 8-slot carousel
Imaging / Pixel Array	3208 x 2200 pixels
Imaging Sensor	Sony IMX428 CMOS sensor
OS Compatibility	Windows 10 or 11
Peak QE	78% typical
Pixel Size	4.5 x 4.5 µm
Power	12VDC, 4A max
Read Noise (Typical)	1.9 e- High Gain, 2.5 e- Med Gain, 5 e- Low Gain
Sensor Size	14.4 mm X 9.9 mm
Shutter	Global Shutter (electronic), Opaque Slot on Filter Wheel for Dark Frames, Optional Mechanical Dark Shutter
Temperature Regulation	Yes
SENSOR SPECIFICATIONS	
17.6 mm diagonal	80 dB dynamic range
Typical QE: • Red (635-700 nm) ~ 63% • Green (520-560 nm) ~ 78% • Blue (450-490 nm) ~ 75%	



Thank You!