Lab-1: Properties of CCDs and Astronomical Images

1 Introduction

In this lab, you will measure characteristic properties of the observing equipment used at Stone Edge Observatory (SEO). Starting from a SEO observation of an astronomical object, you will find the data used to calibrate the observation, and characterize the properties of both. *Your data is always only as good as your calibration!*

1.1 Lab Overview

In this lab, you will download data from SEO, find the calibration frames used to go from the raw to calibrated image, and characterize the data in all the files.

1.2 CCD Cameras

Charge-coupled devices (CCDs) are the sensors of choice for optical, infrared, and X-ray astronomy. At its heart, a CCD detector converts incoming photons to electrons. A big advantage of CCDs is that the response is nearly linear over most of the dynamic range, i.e. the ratio of electrons to incoming photons is nearly constant:

$$N_{\text{electrons}} \propto (Flux) \times (\Delta t) \tag{1}$$

where Δt is the exposure time. (In contrast, photographic plates have an approximately logarithmic response.) These electrons are read out and digitized into *counts* using an analog-to-digital converter (ADC). To infer the flux of photons from the observed object from the measured counts requires a series of calibration steps. Most of these are based on additional calibration data, which is provided on the SEO website and automatically used in the SEO reduction pipeline to convert *Raw* to *Calibrated* images.

In this section, we describe the following properties of CCD cameras, which are important for understanding the calibration steps.

1.2.1 Gain

The gain, which is set by the electronics of the camera, expresses the conversion of electrons into counts by the ADC:

$$Gain \equiv G = \frac{N_{\text{electrons}}}{N_{\text{counts}}} \tag{2}$$

The units of G are electrons per count, typical values for the gain are $\sim$1-3.

1.2.2 Bias Level

Every true CCD camera as an electronic offset level applied to it, the so-called bias. Hence, even if there is no signal, the counts measured in a bias frame (an exposure of 0 seconds duration) are greater than 0.

1.2.3 Dark Current

In cameras that are not cooled to $\sim$100degC, electrons can spontaneously tunnel into the conduction band even when there is no incoming light, mimicking a signal. The number of electrons is proportional to the time over which the data is integrated, i.e., the exposure time. The dark current is measured in units of electrons per pixel per second.

1.2.4 Dead Pixels

Pixels without a response, i.e., even with large incoming photon flux, no electrons are excited into the conduction band.

1.2.5 Hot Pixels

Pixels with large dark current. These pixels will saturate even for short exposure times. For dead pixels and hot pixels, the linear relation between counts and photons is broken. It is not possible to recover information from these pixels, and they should be removed from the analysis. This can be done with a bad pixel map (or mask), an image of the same dimensions as the CCD, where good pixels have a value of 1 and bad pixels have a value of 0.

1.2.6 Read Noise

The process of measuring the number of electrons in a pixel and converting them to counts is not perfect, it generates random noise. Read noise is measured in electrons per pixel.

1.3 Calibration Data for Imaging

1.3.1 Bias Frames

A bias frame is an exposure of 0 seconds duration (and a closed shutter). They are used to measure the bias level of every pixel.

1.3.2 Dark Frames

Dark frames are taken with the same exposure time (and CCD temperature) as the science exposures, but with a closed shutter, i.e. no signal. They are used to measure the dark current of each pixel, and to identify hot pixels.

1.3.3 Flat fields

Exposures of evenly illuminated surfaces, such as the twilight sky (sky flats) or illuminated parts of the dome (dome flats). Flat fields are used to measure, and correct for, the relative sensitivity of the CCD pixels to each other.

2 Data and Observations

We will start by looking at archival data from the SEO database. To do this, we fill follow these basic steps: a) find an image in the SEO database , b) characterize the properties of the image, before and after calibration, c) characterize the properties of the calibration frames, and d) make a plan for future observations with SEO later in the week.

2.1 SEO Observations

For step (a), follow these steps:

1. Go to the SEO FITS viewer website: *https://stars.uchicago.edu/fitsview25/*.
2. Find a recent observation (i.e, past ∼3-months) that looks interesting to you.
3. Download both the *Raw* and *Flux Calibrated* image, which will be noted in the *Pipe Step* button. The raw and calibrated FITS file should say *RAW* and *FCAL* in the name, meaning that the processing pipeline has calibrated this observation (i.e., correcting for bias, dark, flat fielding).
4. In the FITS header, find the names of the files used for the: bias, dark, and flat-fielding. Download these FITS files.

For your lab report, you will want to:

1. Describe the object you choose, i.e., What is it? A planet, a galaxy, a nebula, etc.?
2. Describe basic properties of the observations, e.g.., When were they taken? What filter bands were used? How long was the exposure?
3. In a Table, give the directory location and names of each file that you used.
4. Make a Figure (or Figures) that shows images for each of these files: a) Raw image, b) Calibrated image, c) Bias frame, d) Dark frame, e) Flat-field.

3 Data Analysis

For each of the observations above, characterize the basic statistical properties of the images and include the below information in your lab report:

1. For each image, measure the mean, median, standard deviation, maximum, and minimum value of the images. Put these values in a table, and describe the basic properties of each, i.e., why they do (or don't) make sense given the nature of each (e.g., why are the calibrated units different than the raw image? How do the mean and standard deviation of the bias compare to the other images?

2. **Bias frame:** The standard deviation of the bias frame is a measure of the read noise in units of counts. Does the standard deviation match the width of the distribution in the histogram? Why doesn't it? What might be a better way to estimate the read noise (i.e., rather than a straight standard deviation)?

3. **Dark frame:** Plot a histogram of the counts. Can you identify any hot pixels? From the histogram, what cut would you use to reject them? And what fraction of pixels gets rejected?

4. **Dark frame:** What is the dark current in electrons per pixel per second? What temperature was your dark frame taken at? Was the bias frame taken at the same temperature, and how would that affect this measurement?

5. **Flat field:** Plot a histogram of counts in the flat field? Describe its statistical properties, and relate features in the image to what you see? What does the flat field have to say quantitatively about the variation of sensitivity or efficiency across the raw image?

6. **Calibrated Image:** Choose a region of the image where there are one (or several) obvious astronomical objects. Can you fit a Gaussian to the point spread function (PSF) and measure the full-width at half-maximum (FWHM)? What is your measured FWHM in pixels? and arcseconds?

4 New SEO Observations

To gain experience with real-time observations with SEO, you are going to take an image of an object from the *Messier catalog.* The Messier catalog includes some of the most visually impressive objects in the sky. There were originally selected in the 18th century as a set of relatively bright, extended, non-stellar objects. There are 110 Messier objects in total, and includes 39 galaxies, 29 globular clusters, 27 open clusters, 6 diffuse nebulae, 4 planetary nebulae, and 1 supernova remanent. You can find a full list of Messier objects at *https://en.wikipedia.org/wiki/Messier_object.*

Preparing for your SEO observations:

1. *Join Itzamna:* Make sure you are in join the **itzamna** channel on the SEO Slack. Ask your TAs, Brad, or Marc to be invited.

2. *Pick an object:* Look through the list of Messier objects, and find one that is interesting to you and observable from SEO in the next week. Feel free to use itzamna channel to find objects and plot their visibility.

3. *Schedule a time:* Make sure to check out the SEO calendar [1]. Pick a date and time that would be convenient for your group to observe your targets and reserve time on the calendar. Ideally, you would schedule a zoom session amongst your lab group to jointly participate and follow along with remote observing.

4. *Itzamna observing instructions:* For detailed observing instructions, review and follow the steps in the *SEO Cheat Sheet* [2]

5. *Take SEO images:* Take *gri* filter measurements of your object (i.e., one observation per filter, three observations total). You will likely want to take 30 or 120 second exposures, though it will depend on the object's magnitude. You might want to take an initial short exposure (e.g., 10 or 30-sec), to see how it looks before deciding.

6. *Download your data:* You will likely have to wait 1-day for your images to be processed. You can check on the processing state and eventually download your data from *https://stars.uchicago.edu/fitsview24.*

For your lab report, you will want to:

1. Describe the object you choose, i.e., What is it? A planet, a galaxy, a nebula, etc.?

2. Describe basic properties of the observations, e.g.., When were they taken? How long was the exposure?

[1] https://github.com/bradfordbenson/ASTR21200_2025/wiki/Stone-Edge-Observatory

[2] https://github.com/bradfordbenson/ASTR21200_2025/blob/main/Labs/ASTR21200_SEO_Cheat_Sheet.pdf

3. Make a Figure (or Figures) that shows the RGB image of your object. To make a RGB image, you are going to make a composite image from your *gri* filter measurements. Using these filters, *i* is your reddest color and *g* is your bluest color. To make an RGB image, you can use whatever software you prefer, but either ds9[3] or python[4] are good options, with tutorials linked to the footnotes.

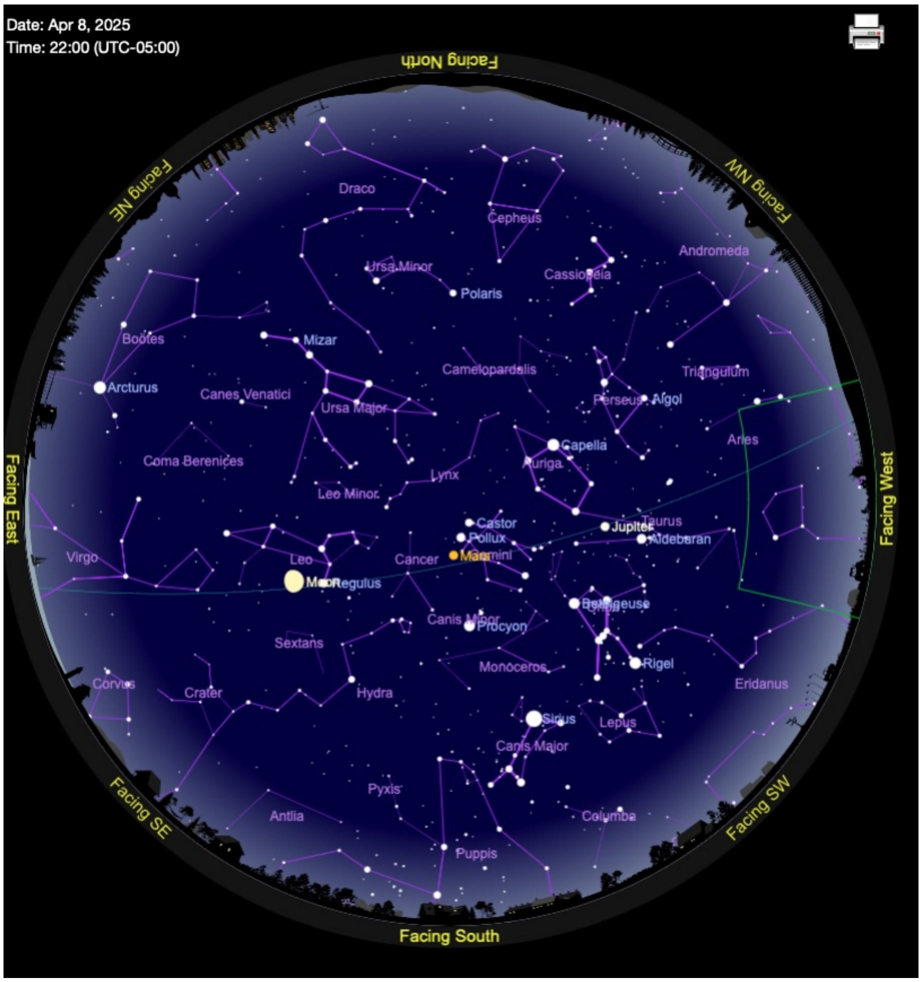

Figure 1: A star chart from Sonoma, CA on 10pm on April 8, 2025, taken from *https://skyandtelescope.org/interactive-sky-chart/*.

[3]https://astrobites.org/2011/03/09/how-to-use-sao-ds9-to-examine-astronomical-images/
[4]https://docs.astropy.org/en/stable/visualization/rgb.html

5 Lab Report

Prepare a *jupyter* notebook that documents your entire analysis for the lab. Make sure to explain your steps and conclusions; imagine writing a tutorial for another astronomy student, who is not taking the class. Use *markdown* boxes (which can also parse LaTeX). Note that you can also include figures (i.e., in png, jpg, etc. form) that are produced outside of the notebook (e.g. with ds9).

The explanations in the *jupyter* notebook will be what we read, but we might look at your code if we think you did something wrong. Make sure that the report is logical; each section should have a short introduction, then code with results and plots, then a conclusion. Make sure the section numbering follows this manual (e.g., Introduction, Data, Data Analysis, Conclusions). Once your notebook is finished, make sure to restart it and re-run all cells. Then save the notebook in pdf format, e.g., through the print menu.