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 you need to acquire. Some of the calibration data can be taken during the day-time, a few types of calibration data have to be taken at night-time, under the same conditions as your science data.

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

Due to the poor weather at SEO, we will look at archival data from the SEO database. To do this, we fill follow these basic steps: a) find an image in the SEO , b) characterize the properties of the image, before and after calibration, c) characterize the properties of the calibration frames, and d) schedule a future observation of this object in the SEO queue.

2.1 SEO Observations

For step (a), follow these steps:

1. Go to the SEO FITS viewer website: *https://stars.uchicago.edu/fitsview22/*.
2. Find a recent observation (i.e, past ∼2-3-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? 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:

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. **Raw and Calibrated Image:** Choose a region of the image where there are one (or several) obvious astronomical objects. How does the point spread function (PSF) vary between the Raw and Calibrated image? Can you fit a Gaussian to the PSF and measure the full-width at half-maximum, what size is the object in each?

7. **Raw and Calibrated Image:** How does the zero point compare between the Raw and Calibrated image? Was there an offset that you measured in the previous Gaussian fit?

8. **Raw and Calibrated Image:** Pick a seemingly blank-sky region of the image, such that whatever you are measuring seems to be due to atmospheric emission (i.e., sky brightness). How does the zero point compare here between the raw and calibrated image? Is one obviously closer to zero than the other? What is the standard deviation of signal in this "blank-sky region" for each the Raw and Calibrated image in this same area? What is the fractional change of sky brightness in the Calibrated image?

4 SEO Queue and Future Observations

For your object, submit a queue observation for your object at the SEO queue webpage[1]. Based on your data, choose a reasonable exposure time such that the camera doesn't saturate for any of the g, r, and i bands (use the same exposure time for all bands). Have one person from your lab group contact Amanda Pagul via email[2] or Slack, and ask for an account.

Include a note in your report, for what you submitted to the queue and how you choose your exposures.

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.

[1] https://queue.stoneedgeobservatory.com
[2] apagul@uchicago.edu