# ASTR:4850 - Characterizing CCD Cameras

## 1 Equipment List

- Orion StarShoot G3 Deep Space Imaging Camera
- Computer with Orion Camera Studio, DS9, and Python

## 2 Introduction

Charge-coupled devices (CCDs) are extremely sensitive and accurate photon detectors, but there are limitations on their performance. In this lab, you will learn about some of those limitations and measure the performance of the Orion StarShoot CCD cameras.

A CCD can make accurate, but not perfect, measurements of the charge accumulated in each CCD pixel. One important limitation is the noise associated with the electronics that amplifies and digitizes the charge signal in the CCD readout. Even if the exact same charge is placed in a given pixel in two different images, this noise will produce fluctuations in the number of ADU (analog to digital units) recorded. We can measure the noise by taking repeated images with the same amount of charge in each pixel. Since the amount of charge in a pixel depends on the amount of light entering that pixel, the easiest way to get the same amount of charge is to have no light enter the pixel. Thus, for these images, we block any light from entering the camera by simply not opening the shutter.

Because the analog to digital converter (ADC) in the CCD reports only positive values, while the noise fluctuations can be positive or negative, a constant offset, called a 'bias', is added to the ADC value. Images obtained with no light entering the camera and with the minimum possible exposure length are called 'bias' frames. The CCD noise is the fluctuation in the ADU counts around the bias value.

Even in the absence of light, charge will accumulate in each pixel. This is because the CCD is at a temperature above absolute zero and thermal fluctuations in the silicon can release electrons. This accumulation of charge is called 'dark current'. Dark current depends on the CCD temperature (as you will find out for yourself). Typically when taking astronomical images, one takes dark frames with the same exposure and at the same CCD temperature used in imaging the astronomical target so that the dark current contribution to the target frames can be subtracted. The use of dark and bias frames is discussed further in the 'Signal to noise' lab.

## 3 Equipment Description

You will use a StarShoot G3 Deep Space Monochrome Imaging Camera made by Orion Telescopes and Binoculars for this lab. One of the links above under "Reading" leads to the manual for the camera. You can also find it on the Orion web site (https://www.telescope.com). Note that we use the monochrome version of the camera.

Another link is the data sheet for the CCD (charge coupled device) image sensor contained inside the camera. A good instrumentalist enjoys reading sensor data sheets. Some highlights of the ICX419ALL data sheet are the number of pixels, the physical size of the pixels, the relative response as a function of wavelength, and the discussion of "cruel condition".

The software we will use to control the camera and retrieve images from it is called Orion Camera Studio. We also use ASCOM drivers that interface to the camera. ASCOM stands for the Astronomy Common Object Model. Camera Studio and the ASCOM drivers for the StarShoot should be installed on the computers in Room 655 Van Allen Hall. Download and look over the Camera Studio manual; you will need to know how to run Camera Studio to do this lab and a few other labs. For this lab, we will use SAOImage DS9, an astronomical imaging and data visualization application, to look at our images. This software should also be on the computers in room 665.

When we start using telescopes on the roof and elsewhere for astronomical observations and measurements, each lab team will need to have the software installed on a laptop computer. You can either use the computer on your bench or load the software onto your own laptop. Camera Studio only runs on Windows. DS9 and Python, which will be using in later labs, runs on Windows, Macs, and Linux. All the software that we use is publicly available.

# 4 Setting up the Camera

First, you need to set up the equipment. Remember to record what you do in your lab notebook. Your notebook is used to record data and analysis results, but also to record each step of what you did so that you (or someone else) can recreate what you did at a later time. You will find yourself frequently referring back to your lab notebook to figure out what you have done when you need to write the lab report.

- Get the camera and install the 1.25-in nosepiece adapter. While you are doing this, take a moment to enjoy the pleasure of seeing the CCD chip itself which is a rectangular device, several millimeters on a side. The CCD is protected by a thin piece of glass. Indicate in your lab notebook if you were gratified to see this amazing marvel of technology.

- The camera has connectors for a USB cable, a 12 V power supply, and an autoguider. The autoguider connector looks like a phone jack and we won't be using it for this lab. Connect a USB cable to the camera and then to the computer. Plug in the +12V power supply and then plug it into the camera.

- Start up Orion Camera Studio on the computer. This would be a good time to read section 3 of the StarShoot manual.

- Go to the "Camera Control" tab and click on connect. Note that you can pull the tab out of the main window if you like. The CCD temperature should start updating. Since you don't have cooling turned on, it should read about room temperature (about 22 C). We don't really need the cooler for this lab, but let's practice using it anyway so it is in your camera turn on procedure in your lab notebook. Click on "Cooler

On". The Power should jump to 100%. If it doesn't check your +12V supply and connection. Let the cooler run a few minutes and record the lowest temperature that you read. Then set the target temperature 1 or 2C above that and click the "Set" button. Watch the temperature for a while and see how if fluctuates. Record your findings.

- Now we'll try capturing an image. Since the camera isn't yet attached to a telescope or a lens, this part is really about learning how to run the software and adjust the exposure. Check on the Camera Control tab that the Offset and Gain are at their default values of 127 and 185, respectively. Now move to the "Capture" tab. Click on the "Single" button. The Status box should read "Exposing", then "Downloading", then go back to "Idle". You should see a display in the image window and also in the "Histogram" window. In the "Histogram" window, select "Low" on the drop down box on the right. Look at the values for "Black" and "White". If they are above 50,000 or so, it means that the CCD is saturating. (How many ) In this case, decrease the exposure time. The minimum exposure time is 0.010 seconds. Decrease the exposure time until the value for "White" in the "Histogram" window is below 45,000 indicating that the CCD is not saturating. Each time you adjust the exposure, you need to click Single again. If adjust the exposure while taking multiple images by clicking "Loop", the exposure won't be updated until you stop the loop. The other values in the "Capture" tab should be at their default values of Type=Light, Bin=1x1, Subframe, Auto dark, and New buffer should not be checked. Depending on the brightness of the room, you may need to partially cover the camera aperture; cloth, sheets of paper, or your hand work for this.

In this lab, we will only be taking images in which no light enters the camera. The StarShoot cameras do not have a shutter, so we must cover their aperture manually. You can either put a cover directly on the camera or on the telescope (if the camera is attached to a telescope). In either case, make sure that the cover seals tightly. It is worthwhile to check that your dark images don't change between having the room lights on versus off.

It is important to take all of your images with the same settings. In Camera Studio, go to the 'Camera Control' tab and check that Offset = 127, Gain = 185, and 'Fast Readout' is not checked.

To take dark frames, go to the Capture tab and set 'Type' to 'Dark'. The program will then prompt you to cover the camera. Make sure that 'Bin' is set to '1x1' and adjust 'Exposure(s)' to the desired value. Then click the 'Single' button. For bias frames, the procedure is the same with the 'Type' set to 'Bias'. The exposure time is then set to 1 millisecond and can't be adjusted. Record the necessary procedures in your lab notebook.

We will also vary the CCD temperature. In Camera Studio, go to 'Camera Control' and record the starting 'CCD Temperature' value. Click on 'Cooler On', adjust 'Target' to the temperature that you wish to reach, then press the 'Set' button. The thermoelectric cooler (TEC) in the camera can only produce a temperature differential of about 10 C. Watch the 'Power' number in the 'Camera Control' tab, this is the percentage of the maximum possible power supplied to the TEC, 100% means that the TEC is at max power all the time. To get a stable temperature, the duty cycle must drop below 100%. That way the

TEC can compensate for small temperature fluctuations (this isn't so important in the lab, where the room temperature is constant, but is a major concern when outside). If the TEC duty cycle does not drop below 100% after a few minutes, increase the setpoint temperature gradually until it does drop below 100%. Record the CCD temperature and the Power value. Comparing to the starting temperature, calculate **the maximum temperature difference** you can achieve with your camera.

# 5 Data Taking

Now we are ready to take a bunch of bias and dark frames at a range of temperatures. For an efficient use of your time, I suggest taking the required data in this sequence: (1) set a target temperature and wait for it to stabilize, (2) take a set of biases, (3) take darks at a range of exposure times, and (4) repeat steps 1-3 at a different temperature. More details are provided in the following subsections.

## 5.1 Bias vs. Temperature

All electronics are temperature sensitive. When using a CCD for astronomical imaging, it is important to maintain the CCD at a constant temperature and to take all calibration frames (bias, dark, and flat) at the same temperature as the astronomical images. To illustrate this point, let's look at some bias frames from the StarShoot camera at a range of temperatures and look at how the image changes with temperature.

You should be able to cover a range of at least 10 C using the cooler (in the winter, you may open the windows in order to go even cooler.). Set at least four different temperatures within the temperature range that the cooler can achieve. You should have determined this range in the previous section. For the qualitative analysis in § 6.1, consider linear spacing of the temperatures (e.g., 14, 16, 18 C). Give the CCD a few minutes to come to the set temperature after changing the temperature and remember to record your procedure, conditions and file name for each frame, etc. Save each of these frames. Use appropriate file names (e.g., 'bias_18C.fits').

## 5.2 Biases at constant temperature

To measure the readout noise of the StarShoot, we take a number of bias frames at a constant temperature. In Camera Studio, set the camera temperature to the room temperature (e.g., 18 C). Record the camera temperature. Take about 10 bias frames. Save the frames in FITS format. Include the word 'bias', the temperature, and the sequence number in the file name (e.g., bias_18C_001.fits). The sequence number is necessary because you will take a number of bias frames at the same temperature. Remember to record the directory where you are saving your files.

### 5.3 Dark current vs. Time

Now we will take frames to measure the dark current versus exposure time and more bias frames.

Set the camera temperature to the same temperature that you used for the bias frames in the previous section. Take dark frames with exposure times of 60, 120, 180, 240, and 300 seconds. Save each frame in FITS format. Later you will need to know the exposure time and temperature for each frame, so you need to record this and/or encode it in the file name. Include the word 'dark', the temperature, and the exposure time in the file name (e.g., 'dark_18C_240s_001.fits').

### 5.4 Dark Current & Bias vs. Temperature

Now we will take frames to measure the dark current versus temperature.

Take dark frames with a constant exposure times (240 seconds) at a range of temperatures. Take a bias frame after each dark frame so that the bias is taken at the same temperature. You should be able to cover a range of at least 10 C using the cooler (in the winter, you may open the windows in order to go even cooler.). Similar to § 5.1, set at least four different temperatures within that range and consider linear spacing of the temperatures. Remember to record your procedure, conditions and file name for each frame, etc. Save each of these frames (at the minimum, one dark frame and one bias frame per temperature, for four temperatures covering the full temperature range that the cooler can achieve). Use appropriate file names (e.g., 'dark_18C_240s.fits').

### 5.5 System Shutdown

Once you have collected all of the data needed to carry out the analysis in § 6, turn off the camera cooler and press the 'Disconnect' button, then disconnect the USB cable from the camera.

## 6 Analysis

### 6.1 Bias Pattern vs. Temperature

You can use DS9 to closely inspect the bias frames you took at a range of temperatures in § 5.1. To be able to observe the changes in the bias pattern, make sure all of the images are displayed at the same contrast level (i.e., black and white pixels correspond to the same ADU values). The following procedure works well in DS9:

- Open DS9, load the bias frame at the highest temperature. Click 'File' on the top menu and select 'Open' in the dropdown to open a window to select the file).
- Click 'Scale' button in the middle ribbon, then click 'zscale' and 'linear'.
- Click 'Scale' on the top menu, then select 'Scale Parameters' at the bottom of the dropdown menu. Record the Low and High Limits (these were automatically determined by the 'zscale' function). We will use these limits for all of the bias frames.

- Now let's open the next bias frame. Click on 'Frame' on the top menu, select 'New Frame'. A blank frame will open. Go to 'File - Open' to select the next bias frame. Goto 'Scale' - 'Scale Parameters', set the Limits to the low and high values you recorded in the previous step. Click on 'Apply' to apply the changes.
- Repeat the previous step for all of the remaining bias frames so that all of the frames are loaded and displayed at the same contrast level.
- To loop through the loaded frames, click on 'frame' in the middle ribbon, and use the 'prev' and 'next' buttons.

The image should be mostly dark shades of gray. There may be a few white dots: these pixels produce large amounts of charge even in the absence of light ('hot' pixels). Notice the patterns in the image (ignoring the white dots). Are there vertical or horizontal striations? If you zoom in, what do you see? Now turn off cooling and repeatedly grab bias frames as the CCD heats up. Does the pattern change with temperature? What you are seeing is the effect of temperature on the electronics in the CCD and its readout. Write down your observations and explain how the patterns that you see related to the structure of the CCD. Note that the CCD is not a square. Thus, by looking at the CCD images and the datasheet, you should be able to figure out how the CCD is read out and how that corresponds to the axes of your images.

## 6.2 Measuring the Read Noise

The read noise of the CCD causes the ADU recorded for each pixel to differ from the ADU value that should be produced given the charge deposited in the pixel. Using the bias frames, we can measure the read noise by calculating the mean and standard deviation of the pixel values (after removing hot and dead pixels). The standard deviation ($\sigma$) is a measure of the fluctuations of the data around the average value. It is the square root of the average of the squared deviations from the mean:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2}. \tag{1}$$

The standard deviation is often described as the RMS (or rms) since it is the square Root of the Mean of the Squared deviations.

We'll use python to calculate these statistics and plot a histogram of the pixel values in our bias frames. Bring up a copy of `histimage.py`, save it with a new file name (maybe `readnoise.py`), and edit it to load one of your bias frames taken in § 5.2. In calculating the statistics of a data set, one often prefers to discard outlier, e.g. pixels that have high values because they are saturated or 'hot' or pixels that have low values because they are damaged. Run `readnoise.py` and examine the histogram of your pixel values. Are there outliers? In the code, we set an allowed range for 'good' pixels values (between plow and phi) and then make a new array, imgcut, keeping only the values in that range. Adjust the values for plow and phi according to your histogram and record them. Then, run `readnoise.py` again and record the statistics of the pixel values of your image when keeping only the 'good' pixels.

The mean value reported is the bias value of the CCD. Record those. Examine the same image in DS9. Is the standard deviation dominated by systematic deviations between groups of pixels (say along columns or rows of the CCD) or do the fluctuations look random?

While inspecting the histograms, think about the following questions and implement your solution in your code:

- Do your histograms show large discontinuities between adjacent bins? What is the cause of this and how can you fix it?
- How would you do outlier rejection automatically without needing to plot and inspect a histogram?

For a better measurement of the noise of the CCD, we should remove the systematic variations across the chip and examine only the fluctuations within individual pixels. We can do this by looking at the difference between one bias frame and a master bias frame. The master bias can be built by taking the median or mean of many (∼10) bias frames taken at the same temperature (see § 5.2). You already have the tools to do this in Python. The code `darktime.py` has a section to make a master bias. Use code `diffimage.py` to load one of your bias frames and the master bias and calculated their difference. Add in code from `histimage.py` to make a histogram of the difference image and calculate the statistics. Note that you may want to remove outliers.

Edit the program to produce a histogram that covers only the difference values of interest in the bias frame. You are essentially trying to produce a plot similar to figure 3.8 (but with the constant removed) in the textbook using your own bias frames. You histogram should extend out to ± about 3 to 5 times the standard deviation. Print the histogram and paste it into your lab notebook. Record the mean and standard deviation of the differences. The standard deviation is a good estimate of the read noise. The gain for the ICX419ALL is 0.79 e-/ADU. Using the gain, convert your standard deviation values to electrons. Record the value in your lab notebook. *Are you impressed about how low the read noise is?* Record your findings in your lab notebook. You may want to repeat the exercise with a few other bias frames.

## 6.3 Dark Current vs. Time

We wish to measure how the average accumulated dark current in the CCD varies with exposure time. Load the python program `darktime.py` and have a look. Edit the file names to correspond to the names that you used in saving the dark frames. The array darkfile contains a list of the dark frames with different exposure times and the array time should contain the corresponding exposure times. *Are the exposure time and CCD temperature recorded in the FITS header? If so, can you utilize the header information in your code to avoid hardcoding these information?*

In the main loop, the program reads in a dark frame, subtracts off the bias frame, and then does some manipulation to get the pixel value differences into a properly shaped array so that we can calculated the statistics. The stuff after 'choose selection region' drops the pixels with the lowest and highest readings in order to weed out bad pixels. You can adjust the value of `f` which sets the fraction of pixels dropped on the low and high ends.

The program the plots an image of the bias-subtracted dark frame, plots a histogram, and calculates the statistics. Note that you can stretch out the plot windows to get better views of the plots (and make the labels not overlap). The program plots the mean pixel value as a vertical solid line and the median pixel value as a vertical dashed line. Explain what is the difference between mean and median in your lab notebook.

As you get to longer exposure times, you might see a second peak, a tail to high values, or an asymmetry in the distribution develop. We already know that some pixels look bad with very short exposures. In addition, there are pixels with unusually high leakage currents. These pixels become apparent when you use long exposure times. As you go to longer exposures, which provides a better estimate of the behavior of a typical pixel, the mean or the median? Explain in your lab notebook. You might want to put one or more plots into your lab notebook, particularly one with a long exposure time.

After processing all the data files, the program then makes a plot of the statistic (mean or median) versus exposure time and does a linear fit. The program can be edited (e.g., uncomment either the line 'm = c_mean' or the line 'm = c_median' and also uncomment the appropriate plt.ylabel line) to use either the mean or the median. Which should you use? Record your choice and reasoning, put a copy of your plot in your lab notebook, and write down the fit parameters. *What do you expect for the intercept? Is your value reasonably close? Should you instead fit a linear relation with zero intercept? A correlation coefficient of* $r = 1$ *indicates a perfect linear relation. Do your data present a good linear relation? What is the unit of the slope? Convert the slope to electrons/pixel/second and record the value.* Now you have measured the mean dark current of the StarShoot camera at a given temperature.

## 6.4 Poison Noise from Dark Current

At first glance, dark current should not be a problem because we can always take a dark frame with the same exposure time as our image frames and subtract off the dark current. However, the generation of dark current is an inherently random process. Thus, if we take several dark frames with equal exposure, the accumulated charge in each pixel will fluctuate (*you can test this with your data*). Because it is Poisson noise, the standard deviation or rms of these fluctuations is equal to the square root of the number of *accumulated dark current electrons* ($N_{\rm dark}$):

$$\sigma(e^-/\text{pixel}) = \sqrt{N_{\rm dark}(e^-/\text{pixel})} \tag{2}$$

Using your best-fit value for the dark current ($e^-$/pixel/s) from the previous subsection, calculate and plot the expected noise from accumulated dark current electrons versus exposure time. In your write up, compare the readout noise versus the noise due to dark current; both should be in the unit of $e^-$/pixel. *At what exposure times does readout noise dominate? At what exposure time is the readout noise equal to the noise introduced by the dark current? At what exposure times do the dark current noise exceeds readout noise?* This exercise prepares us for signal-to-noise ratio estimates of sources detected in CCD images.

## 6.5 Dark Current versus Temperature

Now we wish to do the same sort of analysis as above, but looking at the dependence of dark current on temperature rather than time. Save `darktime.py` as `darktemp.py` and edit the program to read the set of frames that you took to measure the dark current versus temperature. Note that you should subtract the bias taken at the same temperature as the dark. Again look at using the mean versus the median. Make a plot of counts (mean or median) versus temperature. Then program in the ADU-to-electron conversions to make a plot of dark current in units of electrons/pixel/second (on the y-axis with a log scale) versus temperature (on the x-axis with a linear scale), similar to figure 3.6 in the textbook. We know that dark current exists because of the finite temperature of the detector and the Boltzmann distribution of electron energies. So we expect the following relation between dark current and temperature:

$$\mathrm{DC} = \mathrm{DC}_{\mathrm{max}} \exp\left(-\frac{E_g}{kT}\right), \tag{3}$$

where $\mathrm{DC}_{\mathrm{max}}$ and $E_g$ are the maximum dark current (which corresponds to infinite temperature) and the gap energy, $k$ is the Boltzmann constant and $T$ is the temperature in Kelvin. You can now determine $\mathrm{DC}_{\mathrm{max}}$ and $E_g$ with your measured DC as a function of $T$. You can do this using the `linregress` function if you manipulate your data a bit first to convert them into a linear relation between log(DC) and $1/kT$:

$$\log(\mathrm{DC}) = \log(\mathrm{DC}_{\mathrm{max}}) - \frac{E_g}{kT}, \tag{4}$$

Now plot log(DC) vs. 1/kT, fit a linear function to it and overplot the best-fit. Make sure to use e-/pix/s for the DC and convert the 1/kT to unit of $\mathrm{eV}^{-1}$. Report your best-fit values for $\log(\mathrm{DC}_{\mathrm{max}})$ and $E_g$ and their $1\sigma$ uncertainties. Include the plot and the best-fit values in your lab report. List $\mathrm{DC}_{\mathrm{max}}$ in the unit of dark current ($\mathrm{e}^-$/pix/s) and $E_g$ in eV. Interpret the physical meanings of your best-fit parameters. Based on your best-fit, calculate the decreasing factor of the dark current in the range of your target temperatures ($\sim$10 degrees between $\sim$15 and $\sim$25 C). Measure the same ratio directly from your data and see how they compare. This provides a good sanity check of your fitting result.