

AY 105 Lab Experiment #6: CCD Characteristics II: Image Analysis

Purpose:

In this lab, you will continue investigating the properties of CCDs that you started in Experiment #5. The CCD enables measurement of both the number of photons and the position where they hit, giving spatial information. Placing a CCD at the focus of a telescope or behind a camera lens allows it to detect and record images, i.e. pictures.

This lab is designed to give you experience in characterizing a two-dimensional CCD detector plus amplifier in terms of read noise, bias, dark current, system gain, bad pixels, linearity/saturation, and flat fields.

As we have only one experimental setup, both groups will work together on acquiring data during the first lab period. The second may be spent on data “reduction”; these steps are outlined below in italics.

Background:

A charge coupled device or “CCD” is an array of millions of pixels each sensitive to photons. Photons enter the CCD and are absorbed by a silicon layer. This absorption excites an electron from the silicon’s valence band to its conduction band in a process known as the photoelectric effect. These “photo-electrons” are then captured and stored by applying a positive voltage to the pixel to hold the electrons in a potential well. The varying number of electrons stored in each pixel produces different voltages across the pixel that is measured (by a fast voltmeter) and the voltage converted to a digital number (DN) that is presented as “counts” or ADUs (analog-to-digital units).

The ability to detect a signal depends on the relative strengths of the signal and overall noise present on the detector. For our purposes, noise will be quoted as the standard deviation of a signal. There are several types of noise in a CCD. Shot noise is noise that is associated with events that occur with constant arrival rates. (i.e. the photons collected by the telescope and the electrons detected by the CCD). Shot noise follows Poisson statistics, and it can be estimated by the signal in the units of the events recorded at the detector. Note that the events themselves are quantized in electrons (not ADU!). However, as discussed in lecture, the readout electronics that convert electrons detected at the CCD to digital numbers (DN or ADU) that are stored in the image by way of the gain present additional noise sources. Specifically, the read noise is the average error contributed to a pixel value by the amplifier used to measure the number of electrons contained in the pixel. Thus there is noise associated with the signal that arrives on the detector and noise associated with the detection of that signal.

To make effective use of a CCD, its noise sources must be understood and calibrated.

Equipment:

- Black box containing diffuser, filter, and test pattern
- Apogee Alta CCD Camera (borrowed from COO engineer Anna Moore)
- Maxim analysis software (on right-side PC)

Setup:

We will be using a science grade CCD detector that was recently used on the Antarctica plateau. It is an Apogee Alta detector that runs under the Maxim software, installed on the right-side PC in the lab. To see a brief description of its duties as one of the “Gattini” test cameras click here: <http://mcba11.phys.unsw.edu.au/~plato/gattini.html> OR <http://spacefellowship.com/news/art12078/camera-at-south-pole-to-determine-if-its-night-sky-is-ideal-for-new-telescope.html> .

(Note that you may have to type in the part of the url beyond the line break.)

CCD detectors are very sensitive to light. To achieve accurate and reproducible results, a change is required in the experimental methods generally used thus far, where optics and detectors were used in the open. To reduce as much as possible the stray light reaching the CCD, in this lab the detector is located on top of a (more or less) light-tight enclosure, and is mounted in a “down-looking” fashion, (perhaps with duct tape, in Ay105 fashion).

The detector is cooled by a thermoelectric cooler (TEC), which takes about 5 minutes to cool the CCD to a stable equilibrium. Thus, the first thing you should do is to start up the CCD control software and make sure the CCD is cooling.

The Maxim program has two windows: a small window with several tabs and a larger display window where your images will appear. Check to see that the camera itself has the power cable connected, and that the transformer is plugged in (if the fan is running, all is well here). Also verify that the camera is connected to the PC; to initialize the camera operation, go to the Setup tab and click Connect. Then, set an initial temperature of -20 C (on one of the tabs). At any time the software displays numbers like -20 / 75 %. This is a reading of the CCD temperature in C, and the percentage of the total available cooling power that is being applied to the CCD. After you set a new temperature, you will see these numbers change a lot, and you may notice that the approach to the set temperature is under-damped. It oscillates about the set temperature for a while before settling down, and takes about 5 minutes to fully settle.

Other relevant parts of the software menu that you may find useful are the following:

File - Settings: Change to Unsigned Number Format?

File - Setup Header: Change variables that are written to the fits header.

View - CCD Control Window:

Setup: Connect, Cooler On, Warm Up, Disconnect

Focus: Used to continually display images

Sequence: Save a batch of images

Settings: define a subframe or binning

Expose: Type=Light, Bias, Dark
Set exposure time and delay

View - Screen Stretch Window:

View - Information Window:

Also note that there is a known bug in the software display: if an image is taken such that the window is saturated ($65535 \text{ ADU} = [2^{16} - 1]$ where our ADC is 16-bit), you must close all the image windows then expose again. If you do not, the successive images will appear to be saturated, even if the CCD is covered properly. Please note this, in case you run into any mystery behavior as you acquire data.

Once the detector is cooling, look inside at the layout of the optics inside this “black box” and sketch/explain this in your lab notebook. You may remove the red screws on the top and lift the handle to reveal the diffuser / filter / test pattern located inside the enclosure. Check to make sure that the test pattern is in the final slot (extreme right). When finished, replace the cover and tighten the red screws with your fingers. You may also unscrew the other cover below the CCD and look at the camera lens, then up towards the CCD. Also note the configuration of the cables, the serial and power cables to the CCD camera as described above. Include these in your sketch.

This CCD does not have a shutter, but instead operates in “frame-transfer” mode, taking about 4 ms to transfer. The minimum integration time is 1 millisecond.

You will note that we use a special high-end light source for our setup - a flashlight with black tape over it and a small hole punched in.

Measurements:

You will use the PC to initiate CCD exposures from several milliseconds to several minutes of integration time, read out the serial CCD data and display it, and save the “good” exposures in FITS format for analysis. The exposure time (and other parameters, none of which are critical for this lab) can be set by clicking on the Exposure tab in the control window.

Explore the information content in the various window tabs if you like, but you already know everything you need to know for this lab. Try taking a short exposure. There is a red/green slider at the top of this window that allows you to control the dynamic range in the image display. The white is a histogram of the pixel values that will help you set the red and green sliders. Change the integration time and take another. The program saves each image in an internal temporary buffer. As you will want to save images for later analysis, find the pull-down on the display window that allows you to save images of interest to disk – either by default as part of an image readout/save, or individually after you have examined them. Images saved in FITS format have a “.fit” extension.

An important piece of advice is that you should be sure to keep a log of the images you take, i.e. image number and the integration time, subject, any relevant notes, etc. Part of this lab, as in real life, is figuring out which data is worth saving and how to keep track of it and its salient parameters and content.

“Science” Exposures:

These first exposures you are obtaining are images of the test target. Try to get several thousand, even 10,000 ADU. Among other things, this will tell you whether everything is working inside the enclosure. You may need to adjust the focus of the Nikon camera lens. As above, you can access the lens by removing the four red screws on the front cover. Rotate the lens only a small amount from its original position (pre-class testing showed that this new camera / mount system does not

yield well-focused images with the lens all the way at one end of its range of motions). Replace the cover each time before taking another exposure (the CCD is very sensitive!). Out of focus is good enough for our purposes, however. When happy, save one or more of your "science" images to disk.

CCD Cosmetics:

Always remember when observing with a new array to examine your images. When taking the data frames below, change the display/contrast and zoom in/out as necessary.

What do you notice about individual pixels in the array? What is wrong with them when they are "too faint" or "too bright" relative to their neighbors? Are the same pixels always poorly behaved, or do they come and go? In every detector array, a small percentage of pixels are bad in some way. Some are pixels that do not respond to light at all. Others may seem to have too much response because either they respond in a nonlinear way and/or they may have extreme dark current. It is important to identify these bad pixels on the chip and mask their aberrant values so they do not contribute the image you may be trying to quantify. More on these issues below.

Measuring Quantum Efficiency: Flat Field Exposures:

Each pixel in a CCD has a different sensitivity to photons. The fraction of photons hitting a pixel that result in a photoelectron is called the Quantum Efficiency (QE) of the pixel. The typical QE for CCD pixels nowadays is well above 99%. Last week we looked at the QE as a function of wavelength in both coarse fashion (the green and red laser) and detailed (the computer program including fringing effects as well as the overall QE behavior of silicon. Here, you will determine the QE for each pixel and correct the "science" CCD images for these pixel-to-pixel differences.

A flat-field exposure is made by shining a uniform smear of light on the CCD. Ideally, every pixel receives the same amount of light. The resulting flat-field image has different numbers of counts in each pixel because of their differing QE. The ratio of counts in neighboring pixels is equal to the ratio of their QE.

For example, if one pixel has 10,000 counts and the neighboring pixel has 11,000 counts, the second pixel has a QE that is 10% higher. All images of the night sky must be corrected for the differing QE of the pixels by dividing the image by a flat-field image, thereby "dividing out" the QE variations. Ideally, a master flat-field image is the average of many flat-field images, so that the Poisson variations (square-root of the number of photons) is minimized.

Remove the test pattern from inside the enclosure, turn on the high quality lamp, and take several well-exposed "flat field" exposures using just the opal glass diffuser. The same exposure times as from your well-exposed "science" images should be sufficient. What large-scale features do you see in the images? These images also reveal the pixel-to-pixel variation in the gain of the CCD to uniform

illumination. Once you find an appropriate integration time, take a number of identical exposures and save them to disk. Ten or eleven is a good number.

Note that in real life there are several methods for obtaining flat fields. One is, like this, an exposure of an “internal” lamp illuminating the instrument optical path; these types of flat fields are often used for spectra, especially at high dispersion. The second is an “external” lamp illuminating the telescope dome. Along these lines, the generally preferable way to obtain flats is by taking images of the sky immediately after sunset, when the sky is still bright but before the stars begin to be visible, or similarly near sunrise. Such “sky flats” are truer flats than “dome flats”, since the illumination by a lamp can be a non-uniform lighting source and, furthermore, generally has a different color than the night sky.

Later (perhaps using IMCOMBINE in IRAF) average the flats you obtained together to produce a file (e.g. flat.fits). Sample a sub-image consisting of 100 x 100 pixels near the center of the flat.fits image. Compute the mean count level and the standard deviation (perhaps using IMSTAT in IRAF). Make a histogram of the sub-image (IMHIST in IRAF). From these three efforts, then compute the variation in the QE as a fraction of the typical QE. Note that you can't figure out the mean QE itself, only its variation. Does QE vary across the detector by 0.1%, 1%, 10%, or by how much from pixel to pixel?

In examining the full image histogram you may see obvious outliers from the distribution. Pixels that deviate significantly are bad. You can assign a cutoff value (ADU level), below which the pixels you see are not part of the bulk distribution. Copy your averaged flat.fits frame to another frame that you will modify. You can modify pixel values which lie within some range of values, and set them to another value (e.g. using IMREPLACE in IRAF). In this way you can manipulate pixel values so that all your “good” pixels have values equal to 1 (ADU), and all your “bad” pixels have values equal to 0 (ADU). Here, pixels that have values below the main distribution are ones that are minimally responsive (if at all) to light. Construct a mask of these bad or “dead” pixels.

Bias and Dark Frames:

The bias and dark current are measures of the CCD output with no light input. Bias images are images taken with a total integration time of 0 seconds (or whatever the minimum exposure time is of the system, perhaps 0.1 sec). Dark current images also are taken without any light input but have exposure times greater than zero.

Bias frames are used measure the read noise that is introduced into the system each time the chip is read out by the electronics. For a constant signal level on the detector, the value that the readout electronics assigns to each pixel is not exactly the same. Some of this noise is strictly due to readout of the electronics. The read noise is always present and in the same capacity, independent of exposure time.

Take a bias image and display it. What do you see? Just by looking at this image, can you identify imperfections in the CCD? Is so, what are they? How will these imperfections

affect your results? Why are the counts larger than zero if the exposure time was zero? Now take several biases, justifying your choice for how many.

Later (e.g. using IMCOMBINE in IRAF) average together the bias frames and create a new file (e.g. bias.fits). Plot a histogram of the pixels. Is the histogram nearly Gaussian in shape? What is the mean count level (the bias level) in the CCD? What is the standard deviation of the counts in the bias image? You could also create a file sigma.fits by editing the parameters of IMCOMBINE. Now take the difference of just two bias frames and examine the mean and standard deviation in that histogram. Remember that the standard deviation about the mean for the difference frame will be $\sqrt{2}$ times the read noise, assuming that the noises in the two bias frames are the same. Why do observers need to determine the mean bias level? How many bias frames should you take in order to get a “good” determination of the bias?

The dark current in the CCD is a measure of the thermal agitation of the electronics in the CCD. That is, occasionally electrons will be expelled from the valence band due to the thermal energy due to the non-zero-temperature of the material. Once free, these non-photo-electrons are captured by the voltage difference in a CCD pixel and are indistinguishable from the photo-electrons freed by actual incoming photons. You will measure it by taking a series of dark exposures with different integration times up to 600 seconds. You may want to take more than one at each time for later averaging or medianing.

Later, combine the dark frames having the same integration time (e.g. using IMCOMBINE in IRAF). Examine an individual or your average file e.g. dark.fits and plot a histogram of the pixels. How different is this histogram from the bias histogram? What does this tell you about the dark current of the CCD? Answer: Plot the mean vs. exposure time. Fit a line to this plot, and calculate the slope. This slope (ADU/sec) is the dark current.

Given the histogram results from the zero-second bias image, estimate the lower limit (in counts/pixel/hr) of the dark current that could be measured with a dark image having an exposure time of 600 seconds. How does this value compare to your measurement?

As above when examining the flat field, in examining now the full image dark frame histogram, you may see obvious outliers from the distribution. Pixels that deviate significantly are bad. You can assign a cutoff value (ADU level), above (for the flat it was below) which the pixels you see are not part of the bulk distribution. Copy your averaged dark.fits frame to another frame that you will modify. You can modify pixel values which lie within some range of values, and set them to another value (e.g. using IMREPLACE in IRAF). In this way you can manipulate pixel values so that all your “good” pixels have values equal to 1 (ADU), and all your “bad” pixels have values equal to 0 (ADU). Here, pixels that have values below the main distribution are ones that are minimally responsive (if at all) to light. Construct a mask of these bad pixels with abnormally high values.

The overall bad pixel image is useful in order to identify where the problem parts of the array lie. By multiplying your two bad pixel masks together, you can make a mask that identifies both hot and dead pixels on the array. Since good pixels have values of 1 and bad pixels have values of 0, you can mask these bad pixels from any image you take while preserving the values of good pixels using image multiplication. How many bad pixels have you flagged? What percentage of the whole array is it? Examining your pixel mask image, are there any obvious clumps on the array where you will want to avoid?

The small elevation of the counts introduced by CCD dark current can be removed by simply subtracting from the science frame a dark frame of the same exposure time. Note that any such dark will also have the bias noise included in it. However, the noise introduced by the slightly larger signal (noise + signal) does not get removed by this subtraction. This noise can be minimized only by minimizing the dark current.

In addition to varying from pixel-to-pixel, the dark current is an exponential function of temperature. Therefore, CCD detectors are cooled so as to lower the dark current signal, thereby reducing the noise contributed by the dark current to the overall image.

From your exploration of the dark current with time, pick an integration time at which to explore the temperature dependency. Take another exposure at this time if desired. Now adjust the TEC temperature 3-5 degrees warmer and wait for the regulation cycle to settle; it is reported that moving the temperature by 3 degrees takes roughly 3 minutes. Take the same sequence of several exposures as before (2 should be enough) at this new temperature. Repeat to obtain a sequence at 3, 6, 9, 12...30 degrees warmer. You may need to shorten the exposure times at the highest temperatures to avoid saturating the detector. Also, you may wish to experiment concerning the speed with which the CCD cools vs the speed with which it warms when preparing to take these data.

From the (pairs) of exposures you should be able to determine the rate of dark current generation, and for one temperature (the one at which you took your bias frames) whether the dark current is generated at a constant rate. You should determine an average rate for pixels excluding any very "hot" pixels.

CCD Linearity and Saturation:

The number of counts is mostly linearly proportional to the number of photons that hit the pixel. But CCD response to light is linear only up to a certain light intensity. When a large amount of light is shined on the CCD, the number of counts is slightly less than it should have been, i.e. non-linear. When even more light is shined, the CCD will saturate: photons hitting the CCD no longer produce any counts. Using a light source, measure how the CCD becomes non-linear and eventually saturates involves shining uniform light on the CCD repeatedly with increasing exposure times, 1 sec, 2 sec, 4 sec, etc.

Calculate the mean number of counts as a function of exposure time. Plot the results and determine how linear the CCD is. At what count level does the linearity breakdown? Show in your plot the maximum counts that can be recorded by a 16-bit Analog-to-

Digital (A/D) converter. Remember that 16 bits represents 16 values of either 0 or 1 using base-2 to represent any number. What is the highest achievable number in a 16-bit A/D converter?

Gain:

The number of counts recorded in a pixel is proportional to the number of photo-electrons. The signal coming from the amplifier is digitized by an analog-to-digital (A-to-D) converter. This linear ratio of photo-electrons (i.e. detected photons) to recorded counts (i.e. ADU) is called the gain of the CCD. This is inversely related to the gain of the amplifier (the terminology is thus a bit unfortunate) with a lower gain for the amplifier meaning a smaller signal entering the A-to-D converter for a given number of electrons in the pixel and, thus, a large number of electrons per data unit. Conversely, a higher gain means fewer electrons per data unit. A larger system gain allows for a high dynamic range of linear data on the CCD, but at the expense of higher digitization noise. The gain can be set in many CCDs to achieve a suitable balance between the two.

With the data in hand you have enough information to determine the gain of the CCD. *Specifically, you can use average and sigma frames of your dark-subtracted flat fields. With a mean signal and sigma value for each different exposure time, you will plot the signal vs. sigma² for each exposure time and fit a line to these data points. The gain is the inverse slope of this line (e-/ADU).*

Remember that it is essential to work with differences of images. Further, the standard deviation of the pixel values in a flat field image about their mean has a contribution from both the read noise and the random arrival rate of photons. Photon arrival is a Poisson statistical process. Thus, if N photons are detected in an exposure of a certain length, then repeated such exposures will yield values with a standard deviation about their mean of \sqrt{N} . A larger gain means more electrons for a given number of data units and, thus, a larger pixel-to-pixel variation in the signal level.

To put all of the above together in a quantitative way, let g be the gain, s the average measured signal in data units, and N be the average number of electrons detected. Then $s = N/g$. Let r be the read noise measured in data units. The standard deviation of s or σ_s is the quadrature sum of the variation in N and the variation due to the read noise:

$$\begin{aligned}\sigma_s^2 &= (\sigma_N/g)^2 + r^2 \\ &= (\sqrt{N}/g)^2 + r^2 \\ &= N/g^2 + r^2 \\ &= s/g + r^2\end{aligned}$$

Solving for the gain yields

$$g = s/(\sigma_s^2 - r^2)$$

Again, it is necessary to measure σ_s from the difference of two flat-field images in order to suppress the effect of gradients on the standard deviations. The standard deviation of the difference image is $\sqrt{2}$ times σ_s .

A simple way to remember the gain calculation is to consider the “sum of the means” divided by the “variance of the differences”.

Data Analysis: You can use the second lab session or your own time to reduce your data. You can copy the data from the PC using “SSH Secure File Transfer” (see the instructor or TA if you have questions on how to use the software) over to an astro cluster machine, and use IRAF or IDL to perform the requested analysis. If you are not in a group with someone who has an astro account there is an ay105 account that can be utilized.

Final Science Image “Reduction”:

From your understanding of the CCD behavior and using the bias, dark, and flat field images you have taken, construct a corrected “reduced” image of the test pattern. Describe how you created the corrected image step by step. Why was it suggested that you take several images of each type rather than just a single image?

NOTE: This write-up borrows from similar CCD image data acquisition and analysis material in the U.C. Berkeley, U.T. Austin, and Rutgers astronomy curricula, but has been re-arranged and modified for the Caltech setup.