CCD Calibration I: System Corrections

Best Observing Season: any

Level: Intermediate

Learning Goals: The student will determine a CCD camera's system corrections

Terminology: blooming, CCD, charge transfer efficiency, correlated double sampling, dark count, dynamic range, gain, linear response, quantum efficiency, readout noise, system throughput

Software: MaxIm.

Archive Image Directory: none

Archive Images List: none

References: Buil, Christian. 1991, CCD Astronomy, (Willmann-Bell, Inc., Richmond, Va.).

Note: This laboratory needs to be done in the Astronomical Laboratory (655) room. See your instructor for details.

Background and Theory

The term "CCD" means Charge-Coupled Device. The CCD is a solid state sensor consisting of a wafer of silicon crystal. When the silicon wafer is exposed to light, the photoelectric effect liberates electrons from the silicon bonds. These free electrons are collected and deposited in potential wells in the silicon wafer. When the exposure is completed, the potential wells are "emptied" into a register. The computer counts the number of electrons liberated from each pixel (small square area) of the silicon wafer. The number of electrons liberated is proportional to the number of photons that entered the pixel during the exposure.

Even though CCD cameras and chips are mass-manufactured, every CCD camera is unique. While the manufacturer is able to indicate ranges in which your CCD camera's operation will fall, it is always wise to check the camera yourself, to find out the exact response of your camera over the entire range of possible conditions. There are many properties of a chip which should be thoroughly examined before you attempt to do any imaging. The procedures described in this lab can be carried out before or after the installation of the camera on the telescope. In some cases, a slight modification may be required, but both situations are covered here. The material described below can also be found on Apogee Instruments web page called 'CCD University' (at www.ccd.com).

Quantum Efficiency

The typical CCD sensor responds differently to different wavelengths. This is known as the Quantum Efficiency of the chip. This is most noticeable when comparing the response in red and blue filters. The average CCD camera is much more sensitive to the longer wavelengths (red and infrared >600nm) than to shorter, bluer wavelengths (<500 nm). As a result, the exposure times for blue objects must be longer than those for red objects in order to achieve the same response from the chip. Typical QE ranges in the wavelength range 400-800 nm vary from 30% to 85% for modern CCD sensors.

Blooming and Anti-blooming

Blooming occurs when a CCD chip is overexposed. The overexposure causes so many free electrons to be produced that they overflow from the wells where they were trapped, and move into neighboring wells. The image at right is a picture of Jupiter which was intentionally overexposed to image the moons. This blooming can be irritating, if the target object lies above or below a particularly bright object.

There are two ways to avoid this problem. The first is to make a modification to the chip itself. This entails making 'gutters' between rows of readable pixels, so that the electrons can overflow into the gutter, and be carried off of the image. This method, however, causes a loss of 30% of the pixel area. This reduces both sensitivity and well depth, as well as the resolution! The quantum efficiency is also reduced, by nearly a factor of 2 in most cases. A second solution (the more common method for astronomical purposes) is to reduce the exposure time of your image, and take multiple exposures. These exposures can then be 'stacked', or added together with image processing software, to get an image with the required signal to noise ratio. Note that the signal to noise of multiple stacked images is the same as one image of the equivalent exposure time. Stacking images avoids the blooming problem, but can still overexpose the bright objects in the field. The main disadvantage of this method is the readoff time of the chip. Taking many images is a much longer process than taking one long image (more about this later). However, many times this is not really an issue, especially for small private telescopes where the observing time is allotted at the discretion of the owner!

Binning

A CCD camera is a digital device, separated into pixels, each of which collects light, and liberates electrons. The number of electrons in each pixel is read off systematically by the computer, and later this number is converted into a grayscale (ADU, or Analog to Digital Unit) count, and displayed as part of an image. The read-off is accomplished in two steps. First, a row of pixels is shifted downward into a horizontal register. Then, this register is shifted sideways into an output amplifier. This process is depicted in the schematic at right.

Reading off each pixel individually is the method to use when you wish to maximize resolution. However, image acquisition is slower (this is not a trivial consideration during operations such as focusing), and the sensitivity is not as great as in a binned system. Binning combines squares of pixels, and reads them off as one large 'super pixel'. This decreases read-off time, increases sensitivity, and also decreases image size (1×1 images are 4 times as large as 2×2 images).

To bin or not to bin is an issue you will have to decide for yourself. If you are in a location such as Iowa, where the atmospheric seeing is on average poorer than your pixel resolution, then binning is for you- no question about it. If, however, you are in a location with good atmospheric conditions, you will have to weigh the options. You may decide to bin for some projects, and not for others.

System Gain

The number of electrons represented by each ADU count is called the system gain. A gain of 2.5 electrons/ ADU indicates that each count or gray level represents 2.5 electrons.

In general, a lower gain is better. However, this is only true as long as the total well depth (number of electrons that a pixel can hold) of the pixels can be represented. For example, suppose that each pixel in the chip can hold 85,000 electrons. A gain of 1.0 with this system would be low, but would also allow only 65,536/1.0 electrons to be counted. (2^{16}=65,536) Some loss of well depth is not the disaster that it may seem, as cameras used in amateur astronomy are generally capable of only 13 bit performance due to the occupation of the lower bits by 'noise' (uncertainty associated with each conversion to ADU). High gains result in higher digitization noise. System gains are designed to be a compromise between the extremes of high digitization noise, and loss of well depth.

Correlated Double Sampling

Correlated double sampling is a method used to 'clear' the readout pixel location before reading the next pixel value from it. The pixel is not actually cleared, but instead is flooded with electrons to a reference value. The pixel charge is then transferred in, and read out. The value assigned to this pixel is the difference between the reference charge and the readout charge. This method provides the best representation of the actual charge accumulated in the pixel.

Readout noise

There are two types of readout noise. The first type is due to the non-repeatability of the readout. The same charge in the same pixel will not always give exactly the same ADU count. This noise is intrinsic, and in most cases is very small. The second type of noise is the product of unwanted random signals from the sensor, the electronics, and the environment, which gets digitized along with the image pixel charge. Every analog to digital conversion circuit shows a distribution around an ideal conversion value. The sensor is the major contributor to noise.

Dark count

All CCD cameras will liberate electrons over time. These electrons will collect in the pixels of the CCD camera. This process is extremely temperature dependent, and is the reason for cooling the CCD camera. The dark count is usually expressed as the number of electrons per unit time at a given temperature, and so is sometimes called the dark current.

Corrections for the dark count can be made in the post-processing of the image, but the error in this method increases with increasing dark count. Thus the ideal method is to minimize the dark count present in the imaging system.

System Throughput

The system throughput is a description of the system speed. However, the definition of this term varies with manufacturer. Some manufacturers use it to represent the data rate to the computer's memory, ignoring display or digitization time. Others may include the digitization, but not the display time. The important issue is the length of time between the close of the shutter and the appearance of the image on your screen. If this time is very long, focusing becomes quite tedious, and the number of images that can be fit into a given observing night drops considerably. Also, as the transfer time from the CCD grows, so does the dark count. This can cause a gradient in the dark count from the top to the bottom of the image.

Dynamic Range

The dynamic range is a measure of how much signal it is possible to collect above the readout noise. This is sometimes represented as a decibel scale. For example, a system with a well depth of 85,000 electrons and a readout noise of 12 electrons would have a dynamic range = 20 log 85,000/12, or 77dB. The higher the number, the better.

Charge Transfer Efficiency

As the charge in each pixel is transferred through the system, some loss occurs. The percent of electrons left behind is indicated by the charge transfer efficiency. The charge transfer efficiency is sensor dependent, and can be degraded by a poorly designed camera. **The ideal efficiency is 0 (no electrons left behind).** For example, if 10 electron out of 85,000 are transferred to the amplifier, the charge transfer efficiency is (85,000-10)/85,000, or 0.99988.

Procedure

Testing the linearity of the response

This test determines how the sensor responds to varying light levels over the well depth. A CCD sensor should respond in a linear fashion all of the way up to the maximum well depth. For example, if a 1-second exposure produces 1000 electrons, a 5-second exposure should produce 5,000 electrons, and a 10-second exposure should produce 10,000 electrons. This linearity cuts off when the well is full, as it simply can not hold any more electrons. At this point, the image has become overexposed, and blooming may occur.

The results of this test will be somewhat contaminated by the contribution of the dark current (recall that this grows with exposure time), but with an adequately cooled camera and relatively short (<5 seconds) exposure times, this should be a significant contribution.

If the CCD camera is already attached to the telescope, you will want to take flats of longer and longer exposure times. Flats are images of an out-of-focus, evenly illuminated source, such as a white piece of paper inside the dome.

1. Begin taking flats at the shortest exposure time for which you see no vignetting (about 0.1 seconds).

2. Increase the exposure time by regular intervals (every 0.1 seconds or so) until you overexpose the image. Most image display programs will allow you to check the ADU count by clicking on the image. The image is overexposed if the ADU counts exceed the well depth.

3. Examine each flat. You will want to find the mean of a region of the image (say 100×100 pixels), and also find the root mean square (RMS) noise in that region. Many programs will do this for you. For example, the Information window in *MaxIm* will tell you the mean ADU count and RMS noise of any portion of the image that you put a box around. Check the instructions for your software to find out how to average the ADU count in a region of an image. Make sure that you use the **same** area in each image!

4. Plot the mean vs. exposure time for all of the flats that you took. Fit a line to it using a program such as *Mathcad* or *Graphical Analysis*. The ideal sensor is perfectly linear.

If the camera is not attached to the telescope,

1. Place the camera upright in a room with no windows and a stable light source. A fluorescent light will work. Position the light so that it casts indirect light on the ceiling above the camera.

2. Place a piece of plain white paper over the camera opening.

3. Take exposures with the camera in even increments until the camera saturates. (i.e. 0.1 sec, 0.2 sec, 0.3 sec, etc.) Begin with the shortest exposure just long enough to eliminate the problem of vignetting (imaging the shutter as it opens). To determine whether the camera has saturated, measure the ADU counts of the image. When the ADU count exceeds the well depth, you have saturated the camera.

4. Examine each image. You will want to find the mean of a region of the image (say 100×100 pixels), and also find the root mean square (RMS) noise in that region. Many programs will do this for you. For example, the Information window in *MaxIm* will tell you the mean ADU count and RMS noise of any portion of the image that you put a box around. Check the instructions for your software to find out how to average the ADU count in a region of an image. Make sure that you use the **same** area in each image!

5. Plot the mean counts on the Y axis and the time on the X axis. The counts can be converted to electrons by multiplying by the gain of the system. The line should be reasonably straight throughout the well depth of the sensor.

Determining the dark count

Dark count is a function of the CCD characteristics and the temperature of the CCD. The dark count will double with a rise of 5-6 degrees C.

1. Place the camera in a very dark room (or cover it with lots of dark cloth) to prevent the shutter from leaking light onto the sensor.

2. Take a 60-second exposure with the shutter closed at a temperature of -5° C.

3. Determine the mean value of the pixels within an area on the image (say 100×100 pixels).

4. Take a bias frame and again determine the mean value. The dark count then becomes: (Dark - Bias)/ 60*system gain. The units of the dark count are electrons/second.

Note: It may seem like a good idea to lower the temperature of your camera below the recommended operating temperature in order to lower the dark current. Be aware that the recommended temperature is usually determined by other factors, such as the freezing threshold of the materials in the camera, or the ability of the case to withstand extreme gradients between the ambient and internal temperatures.

Determining the system gain

The signal variance method of determining system gain in electrons per ADU is the most difficult of the tests discussed here, but can be repeated by anyone who follows the procedure outlined. This method is one where multiple exposures are taken with increasing light. Standard deviation and mean count data is collected for each image. The standard deviation numbers are each squared, then plotted with the net mean (mean - bias) numbers. The slope of the line represents the gain of the system. The test setup is very much like that discussed for the linearity test above.

If your camera is not attached to the telescope:

1. Set up the conditions as you did for the linearity test. The light will probably have to be brighter.

2. Stack several sheets (8-10) of plain white paper over the camera.

3. Take a bias frame. Record the mean and standard deviation from the cursor box positioned in the middle of the frame.

4. Remove a sheet of paper. Take a 0.1 second exposure.

5. Record the mean and standard deviation from the cursor box positioned in the middle of the frame.

6. Repeat steps 4-5 until the paper is gone or the image saturates.

7. Create 2 more columns next to the data you've recorded. In one column record the variance (square of the standard deviation) of the data you recorded earlier. In the other column, subtract the bias mean from each mean you recorded.

8. All that remains is to plot the net signal on the Y axis and the SD2 data on the X axis. Draw a straight line through the data to make the best possible fit. To determine the slope, pick 2 points along the line. The slope will be (Ypoint 1 - Ypoint 2)/(Xpoint 1 - Xpoint 2). For example in this case, the two points might be net signal numbers of 10,000 and 100, and variance numbers of 2000 and 15. So (10,000-100)/(2,000-15) = 4.9 electrons per ADU (Analog to Digital Unit) or count.

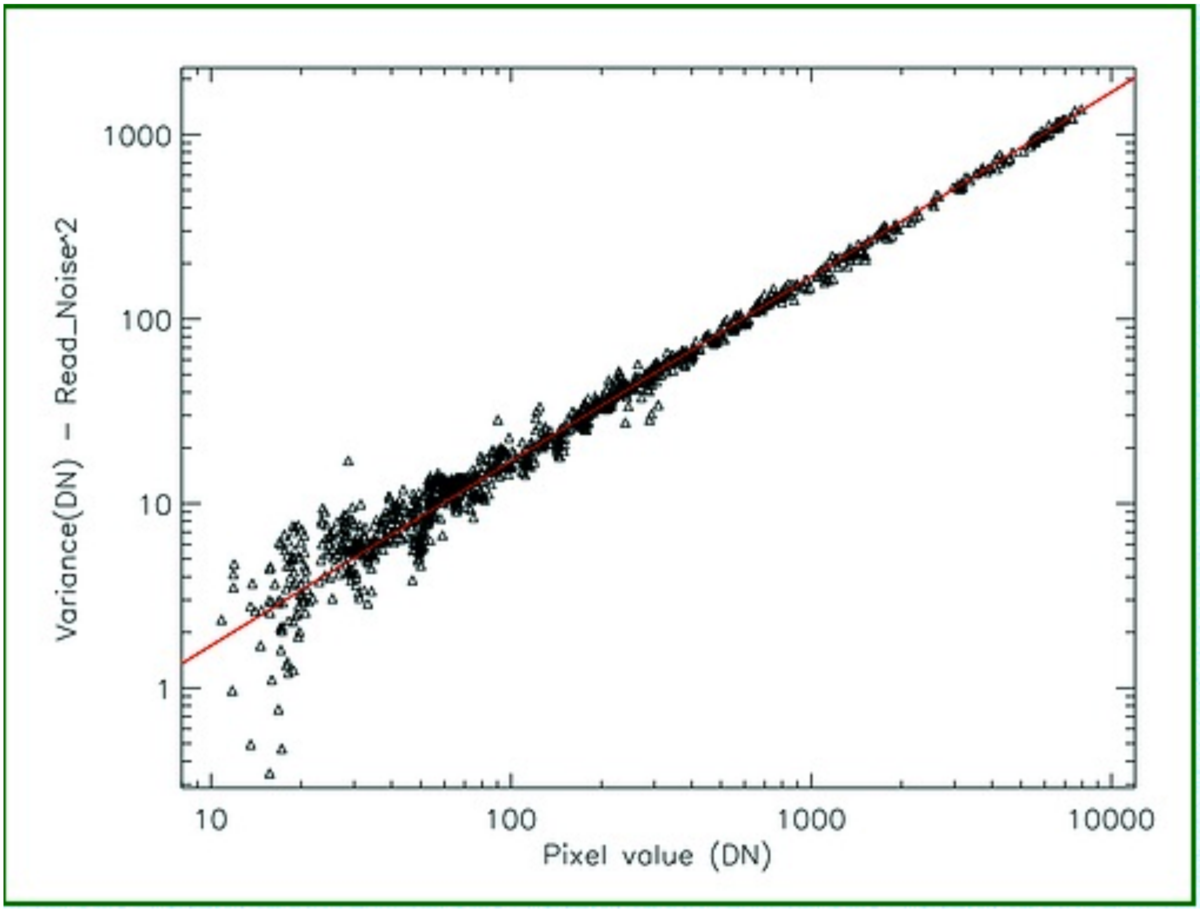

Fig.1 Variance vs. pixel count (ADU). This plot can be used to determine the system gain (elec/ADU).