The CCD Camera

The CCD is very good at the most difficult astronomical imaging problem: imaging small, faint objects. The CCD detector has several advantages over film: greater speed, quantitative accuracy, ability to increase contrast and subtract sky background with a few keystrokes, the ability to co-add multiple images without tedious dark room operations, wider spectral range, and instant examination of the images at the telescope for quality. CCD technology is in use at all modern astronomical research facilities, including the Macalester Observatory.

CCD Camera Operation

The basic function of the CCD detector is to convert an incoming photon of light to an electron which is stored in the detector until it is read out, thus producing data which your computer can display as an image. It doesn't have to be displayed as an image. It could just as well be displayed as a spreadsheet with groups of numbers in each cell representing the number of electrons produced at each pixel. These numbers are displayed by your computer as shades of gray for each pixel site on your screen, thus producing the image you see. How this is accomplished is eloquently described in a paper by James Janesick and Tom Elliott of the Jet Propulsion Laboratory ("History and Advancements of Large Area Array Scientific CCD Imagers", James Janesick, Tom Elliott; Jet Propulsion Laboratory, California Institute of Technology, CCD Advanced Development Group):

Imagine an array of buckets covering a field. After a rainstorm, the buckets are sent by conveyor belts to a metering station where the amount of water in each bucket is measured. Then a computer would take these data and display a picture of how much rain fell on each part of the field. In a CCD the "raindrops" are photons, the "buckets" the pixels, the "conveyor belts" the CCD shift registers and the "metering system" an on-chip amplifier.

Technically speaking the CCD must perform four tasks in generating an image. These functions are 1) charge generation, 2) charge collection, 3) charge transfer, and 4) charge detection. The first operation relies on a physical process known as the photoelectric effect - when photons or particles strikes certain materials free electrons are liberated. Thus, a photon from an astronomical source enters a CCD and dislodges an electron. In the second step the photoelectrons are collected in the nearest discrete collecting sites or "pixels". The collection sites are defined by an array of electrodes, called gates, formed on the CCD. The third operation, charge transfer, is accomplished by manipulating the voltage on the gates in a systematic way so the signal electrons move down the vertical registers from one pixel to the next in a conveyor-belt like fashion. At the end of each column is a horizontal register of pixels. This register collects a line at a time and then transports the charge packets in a serial manner to an on-chip amplifier. The final operating step, charge detection, is when individual charge packets are converted to an output voltage. The voltage for each pixel can be amplified off-chip and digitally encoded and stored in a computer to be reconstructed and displayed on a television monitor."

The simplest everyday analog is the digital camera: these operate in very much the same way as the CCD imaging cameras used by astronomers. The key difference is that a digital camera operates at the normal range of temperatures we experience (say, from freezing up to 90°F or so), but that CCD cameras are cooled well below freezing. The reasoning is very simple: in everyday experience we are usually dealing with very bright objects that we can see with our eyes. Most astronomical objects, on the other hand, are very very faint. Since digital imaging systems have intrinsic noise levels that depend on temperature (due to the kinetic motions in atoms), the lower the temperature of the camera, the more sensitive it is to very faint differences in light levels. Thus, a common digital camera mounted on a telescope would not be effective at collecting information about astronomical objects; dedicated, cooled (and sealed) CCD arrays are used for this purpose.

Basic CCD Image Properties

Most CCD imaging systems produce images compatible with the "FITS" (Flexible Image Transport System) format. The wavelength region that a CCD is sensitive to is part of its design; some are effective at short wavelengths (bluer light) while others are more effective at red wavelengths (longer wavelengths). We can isolate particular regions of the electromagnetic spectrum that fall on a CCD by introducing a *filter* in the system; a blue filter, for example, absorbs longer-wavelength photons and allows primarily blue light (shorter wavelengths) to fall on the CCD. This is an important technique used by astronomers to study astronomical objects.

CCD Image Analysis Tools

In this course you will use two major analysis packages for optical images: *IRAF* and *IDL*. See the Moodle course website for links to the websites for each package; *IRAF* is generally the most commonly-used package for optical astronomy. It has built-in tutorial packages that you are strongly encouraged to complete.

Using CCD Images

The CCD camera is designed to measure the intensity of light from faint astronomical sources with precision and accuracy. However, the raw data that a CCD provides contains information from multiple sources: the background level of the detector itself (a "bias" level), the noise due to atomic motions that depend on temperature and are proportional to the exposure length (the "dark" current), and the signatures of any cosmetic defects on the camera (e.g., dust). To arrive at a "finished" CCD image, we must correct our raw images for each of these effects.

First, imagine that we allow the CCD camera to take an exposure but keep the shutter closed. Thus, we do not expose the image to the sky at all. We might expect to see a perfectly black image, representing zero signal. However, we in fact find that each pixel has some signal in it; this is the intrinsic background noise in the detector. This type of image is called a bias frame; an example might appear as follows:

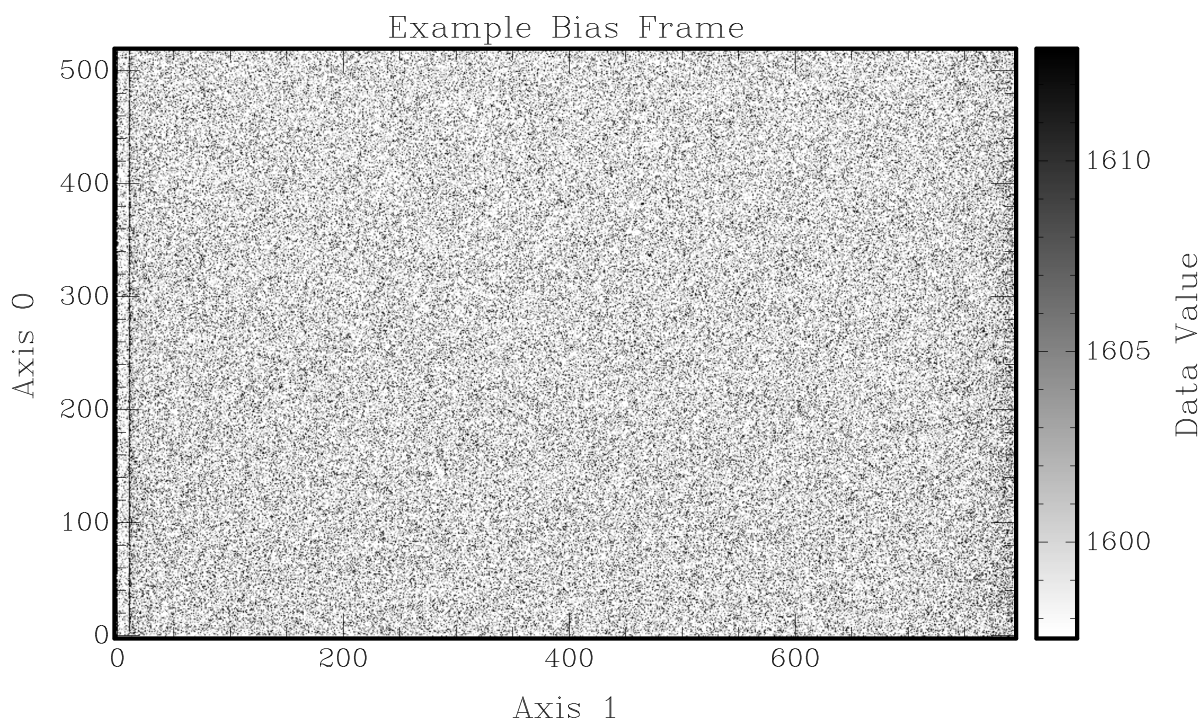


Figure 1: A zero-length image from a CCD camera. Note that each pixel does contain a measurable signal (here, roughly 1600 counts per pixel). This represents the intrinsic background level of this particular CCD chip.

We can take many of these images and combine them in order to get a very good idea of the intrinsic background level of the image.

Now, imagine that we do the same exercise, but let the camera collect data for a longer period of time. Again, we keep the shutter closed and do not allow any light to enter the CCD. We might expect to see the same thing as in a zero-length or a very short exposure.

In fact, we see something quite different: the average level in each pixel is the same but the noise (i.e., the strength of variations in pixel values across the image) is higher. This is caused by the thermal motions of atoms; since temperature is related to kinetic energy, the higher the temperature, the more likely that one atom in the detector will be bumped by another atom sufficiently violently so as to discharge an electron. If we were observing an astronomical source, the CCD would have no way to determine if this electron is due to the noise in the detector or due to an astronomical source. However, since we kept our shutter closed; we know the origin.

Astronomers creatively term these longer exposures with the shutter closed “dark frames”. Note that the average pixel levels in the dark frame and in the bias frame should in theory be equal. This means that the bias level is in fact included in the dark frames (actually, the bias level is included in any image that the CCD acquires); since both effects are artifacts that we wish to eliminate, we can get rid of both by simply subtracting the dark frame from every image; more on this later.

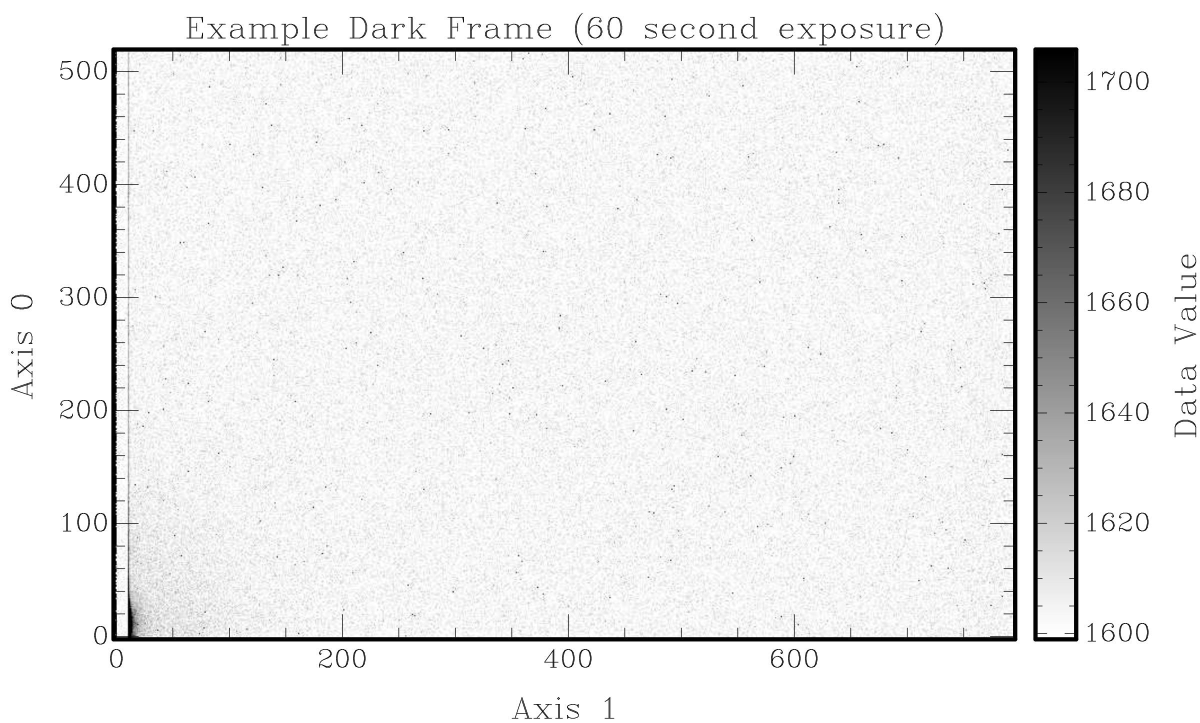


Figure 2: A 60 second dark image from a CCD camera. Note that each pixel again contains a measurable signal; the average level should be very close to the average level in a bias frame (of zero length exposure time). However, the variation between pixels is higher in a dark frame; this noise increases as the length of the exposure increases. Note that the scale of this image is slightly different than the scale shown for the Bias Frame in Figure 1.

If all CCD imagers operated perfectly, then one dark image of a given exposure length would appear exactly the same as the next. While the actual behavior of most modern CCDs is very close to this ideal, they are not perfect. Multiple factors can lead to unpredictable variations in individual pixels (which astronomers term "hot pixels"). For that reason, it is good form to acquire several dark frames of a given length and average them together; software can isolate pixels that vary between each exposure and eliminate them (a technique called "outlier rejection"), giving a more accurate representation of the dark (and bias) levels for a given integration time.

The final image artifact we need to consider is how efficiently each pixel responds to light that falls on it. A perfect CCD would have all pixels responding exactly the same way to a given amount of light. However, cosmetic effects (e.g., dust that falls on the chip) can produce artifacts that decrease the sensitivity of one or (very often) more pixels. While such effects sound discouraging, we can in fact easily rid ourselves of these bothersome artifacts. The technique is simple: uniformly illuminate the entire CCD with light. Any variations we see must be due to artifacts in the CCD itself; if we have an image of these variations, we can use it to remove the artifacts from any science images we wish to work on. These images are called "flat fields", because the purpose is to create a "flat" field of view in the CCD. Usually such flat field images use a lamp or the twilight sky to flood the camera with a uniform source of light; an example flat field might look like the following:

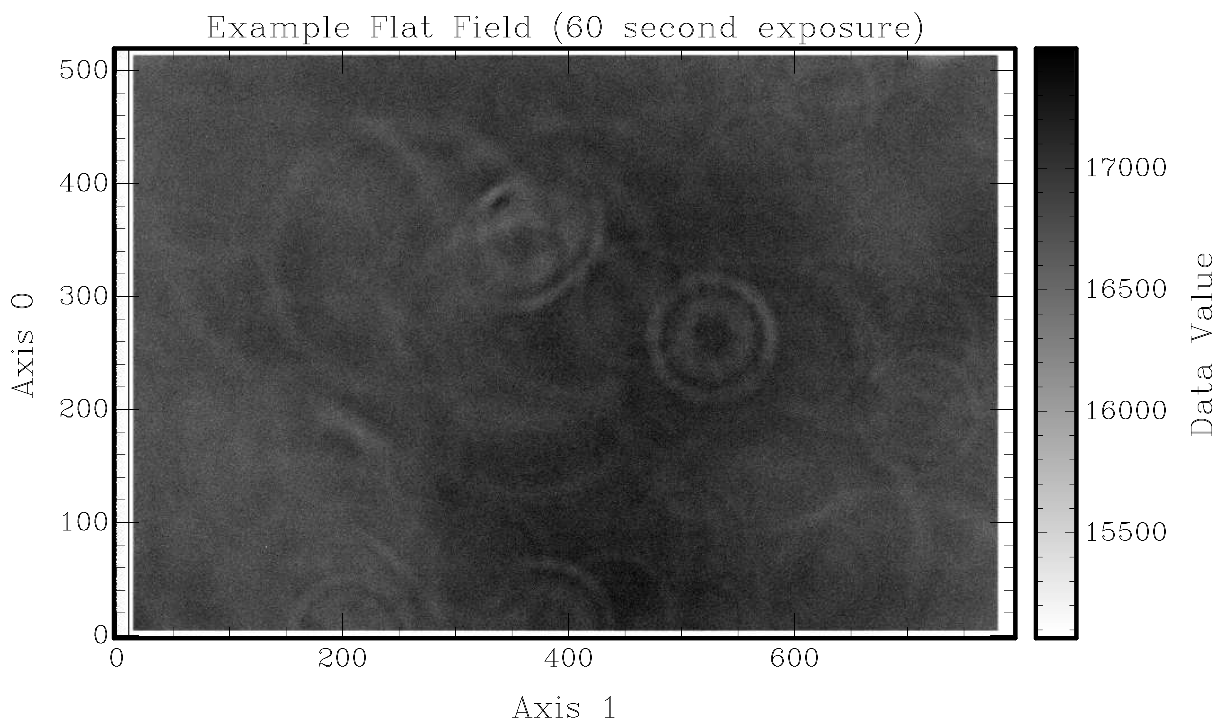


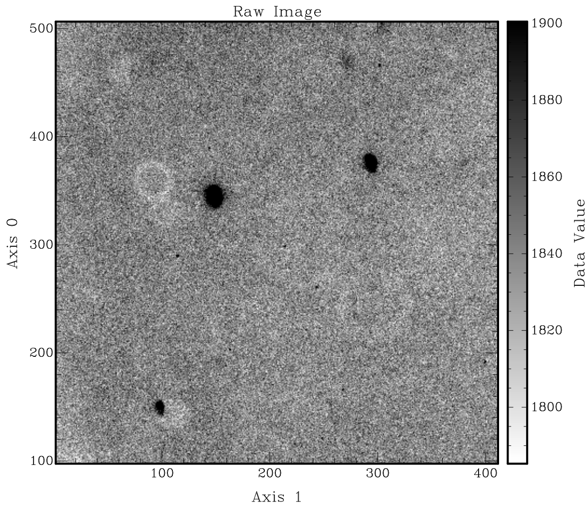
Figure 3: A 60 second flat field image from a CCD camera. Note that the scale of the image is now much higher than the scale shown for the bias and dark frames in Figures 1 and 2. This is because the telescope was pointed at the twilight sky, flooding the camera with photons that uniformly illuminate the CCD. This allows us to isolate cosmetic artifacts in the detector; many are present on this particular CCD.

As with the dark frames, we want to assure that any transient variations in pixel sensitivity are accounted for by acquiring multiple flat fields and averaging them together. Note also that cosmetic effects can originate on different filters, so it is essential that flat field images are acquired for each filter that one will use throughout a given night.

How can the flat field images remove these artifacts? One might think that subtracting such a flat field image from a science image would do the trick, but in fact it will not; pixels with low relative sensitivity will be subtracted from one another, and the non-uniform appearance of the detector will remain. However, we can “normalize” the flat field image to achieve our goal: here, one divides the flat field image by the average pixel value; most pixels will then be very close to 1. Pixels with low relative sensitivity will have values less than 1, and those with higher than average sensitivity will have values greater than 1. If we then divide our science image by this normalized flat field, pixels with lower than average sensitivity will get a small positive correction to their values; those pixels with higher than average sensitivity will get a small negative correction. This serves to “flatten” the science image and to remove these cosmetic defects.

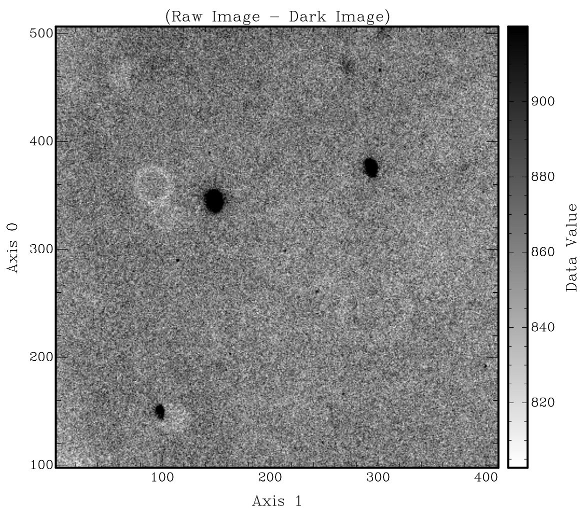
It is important to remember that the integration times of the science images and of the flat fields may well be very different (after all, the flat fields are looking at very bright objects, while the science images are of very faint ones). Therefore, we wish to acquire dark images of the same integration times as *any* of the images we will use: flat fields, objects, standard stars, etc. This is fairly straightforward with a cooled CCD imager; the temperature is regulated, so that one can simply plan out the observing sequence and acquire the necessary dark images at the beginning of the observing run (e.g., between executing flat fields and the beginning of science observations).

Let us illustrate this procedure (science image minus dark image, divided by flat field image) by a set of example CCD frames:



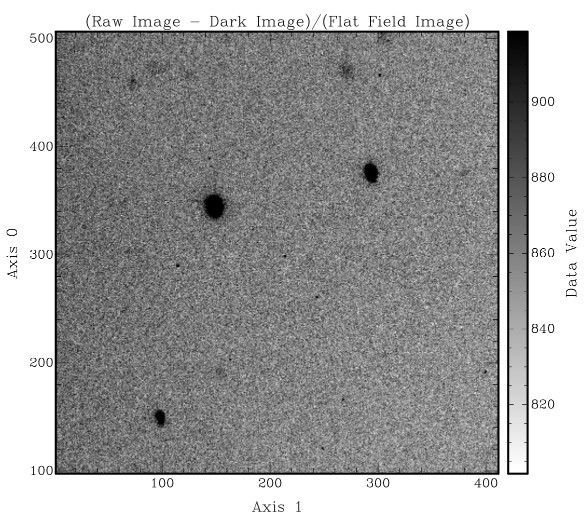
This raw CCD image contains instrumental noise and detector artifacts.

If we subtract a "dark frame" (shutter closed, same integration time) from this image, we can remove the instrumental bias level and (thermal) noise:



This modified CCD image contains detector artifacts; instrumental noise has been removed.

If we divide by a "flat field" image (uniformly illuminated image that is normalized to one), we can remove the remaining detector artifacts.



This modified CCD image is now ready for scientific use.

With careful planning, we can make our observing sessions extremely efficient. We begin by selecting our target objects and suitable integration times. If physically meaningful measurements of the brightness of these objects are needed, we also need to select nearby "standard stars" to observe. These objects have well-established, constant brightnesses that we can use to calibrate our data. Based on their brightnesses, we also select suitable integration times.

Our targets should be arranged in order of increasing Right Ascension, based on what time of the year and what time of the day/night we are observing. A simple way to ascertain what will be visible is to recall that the Right Ascension system is defined at 0 hours by the position of the Sun as it crosses the Celestial Equator on the Vernal Equinox (in late March). So, roughly speaking, 0 hours is overhead at noon in March, and 12 hours is overhead at midnight. Similarly, 12 hours is overhead at midnight in March, and 0 hours is overhead at midnight in September. We can then easily work forward or backward, with each month representing $\sim$2 hours of Right Ascension. For example, 2 hours is roughly overhead at midnight in October, 4 hours is roughly overhead at midnight in November, and so on.

We are now ready to begin observing; example workflows for the data acquisition and basic reductions might look like the following:

Basic steps to acquire CCD imaging data that is scientifically useful:

1. Flat field images: seek $\sim$20,000 counts per pixel in each filter to be used; acquire 5 such images for each filter
2. Dark images: acquire shutter-closed images of the same exposure time(s) as the science and flat field images; 5 such images for each exposure time
3. Science images: acquire data in chosen filter(s) and exposure time(s)
4. Note: bias images (zero or shortest possible exposure time) are not needed if dark frames are acquired, since the creation of dark images by definition contains the bias level

Basic steps to reducing CCD imaging data:

1. Average dark images for each exposure time (including outlier rejection)
2. Subtract dark frame from flat field and science images that have the same exposure time
3. Average (dark-subtracted) flat field images for each filter (including outlier rejection)
4. Calculate mean of central region of each flat field image; divide by this value
5. Divide science images by final flat field image for each filter