The Charge-Coupled Device

I. Introduction to the CCD

The purpose of this lab is to measure the critical operating parameters of the charge-coupled device (CCD) at the SFSU Observatory. The CCD itself is built around an interface between two slabs of silicon, each doped with different impurities (see Figure 1). The bulk of the device is a p-type semiconductor, where the majority charge carriers are holes. A thin (1µ) layer of n-type material (where the electrons are the primary charge carriers) is sandwiched between the p-type layer and a very thin layer of insulating material (usually silicon dioxide).

As in a diode, electrons from the n-type layer diffuse across the p-n interface and combine with holes in the nearby p-type material. As the electrons drift across the junction, a net positive charge is left on the n-type side; similarly, a net negative charge builds up on the p-type side of the junction. In between, the material is depleted of charge carriers by the electron/hole recombination and is thus called the “depletion layer”. The junction then resembles a charged capacitor, with regions of positive and negative charge separated by an insulating layer. As the charge builds up on either side of the junction, the electric field grows and eventually halts the diffusion across the boundary.

On the other side of the n-type layer, opposite the p-n junction, the negative charge carriers remain more or less unaffected. As a result, the electrostatic potential reaches a maximum somewhere within the n-type layer (Figure 2). This potential maximum serves as a potential energy well for electrons. When photons strike the semiconductor, electrons are raised into the conduction band, creating electron-hole pairs. If the interaction occurs sufficiently close to the n-type layer, these electrons will quickly be trapped in the potential well, which is called the channel. The ability of the CCD to trap and store photoelectrons is the key to its utility as a light detector.

Two-dimensional imaging: the pixel

In order to record a two-dimensional image, the CCD needs additional apparatus to hold each trapped charge at the position of the incident photon. Charge is localized by a grid of electrodes placed across the CCD’s surface. Parallel lines of heavily-doped p-type material, called channel stops, isolate narrow (5-30µ) columns near the surface of the n-type material. Within each column, a series of metal electrodes, called gates, are attached to the insulator at the surface of the CCD. In a standard mode of operation, these electrodes are maintained at a positive potential relative the channel stops. The positive bias on the gates deepens the potential well within the channel and provides a barrier to charge diffusion from column to column.

In each series of three neighboring gates, the central gate is biased higher than its neighbors. This combination of gates and channel stops isolates the potential maximum in both dimensions, creating a picture element, or pixel. The structure of each pixel is shown in Figure 3. When photons strike a pixel, the resulting photoelectron is trapped in the local well and is prevented from moving by the potential barriers on all sides. The number of electrons accumulated in each
pixel thus records the number of photons that arrived at each position on the CCD. All that remains to create an image is to measure the charge in each pixel.

**Reading out the pixels**

In the simplest case, the charge in each CCD pixel is measured by a single circuit at the corner of the pixel array. After an exposure is completed, charge is shifted from pixel to pixel along each column of the CCD. The shifting of charge during readout gives rise to the name charge-coupled device. The shift is accomplished by raising and lowering the gate potentials in sequence as shown in Figure 4. At the end of each column, the charge on the last pixel is dumped onto a single row of pixels, called the serial line. For each parallel shift along the columns, charge shifts along the full length of the serial line, perpendicular to the columns. If there are $N$ columns in the array, there must be $N$ shifts along the serial line for every single shift along the columns. The speed of the readout is thus limited in part by the capacitance of each pixel in the serial line.

At the output of the serial line, the charge of each arriving pixel is dumped onto a capacitor, and the resulting voltage across the capacitor (microvolts) is detected and amplified. This stage introduces noise, called readout noise. The readout noise in research-quality CCDs is usually in the range $5-10\text{e-}$ per pixel. The amplified voltage (and of course the accompanying noise) forms the analog signal at the output of the CCD.

**Analog to Digital Conversion**

The final step is to convert this analog signal to a digital value that can then be stored in a computer. The quality of the analog-to-digital (ADC) converter determines the dynamic range of the system. An ADC with 2 bits can distinguish $2^2=4$ levels, an 8-bit ADC stores 256 levels, and a 16-bit ADC can cover the range $0 – 65536$. Because the potential wells that form each CCD pixel can often store up to several hundred thousand electrons, the range of the ADC is usually scaled by a number greater than one to cover the full range of the CCD. This factor relating the number of electrons in the well to the number of analog-to-digital units (ADU) is called the gain. For a 16-bit ADC and a well depth of roughly $200,000\text{e-}$, a typical value of the gain would be around 3.

Note, however, that by increasing the gain above unity, we have increased the noise. The smallest detectable signal is now, say, three electrons rather than one. In most CCDs, the readout noise is substantially larger than this digitization noise. However, in high-end CCDs with very low read noise, digitization noise can be the limiting factor. On the other end of the spectrum, less expensive systems with fewer bits in the ADC require higher gain to cover the well depth, resulting in larger digitization noise. Again, the digitization noise can dominate. For a given CCD and ADC, the choice of gain thus involves a balance between the measurable signal range and the resolution.
Summary: figures of merit

The ability of a CCD to provide precise, accurate measurements of faint photon fluxes thus boils down to a few critical parameters. Here I list some specific figures of merit in no particular order. We will measure a few of these quantities to characterize the SBIG ST-10XME CCD camera used at the SFSU Observatory.

Quantum Efficiency: the fraction of incident photons detected by the system at each wavelength. Some photons are reflected from the surface of the CCD and never detected; others are absorbed far from the channel and never make their way to the potential well. In the optical region, each photon generates one electron/hole pair. On the blue side of the spectrum, the quantum efficiency is limited by absorption in the surface structures, and a typical CCD records few photons below about 360nm. The band-gap of silicon (roughly 1.14eV depending on the doping), defines the long-wavelength cutoff at approximately 1100nm. In between these limits the quantum efficiency depends on the details of the device, whether it is illuminated from the front or the back, and whether it is coated with thin films to reduce reflection. Typical values are given in Figure 5.

Linearity: a useful feature of CCDs is the linear relation between the number of measured electrons and the number of incident photons over a wide range of signal levels. This feature distinguishes the CCD from earlier astronomical detectors such as the photographic plate. However, at large signal levels, the linearity breaks down. If the ADC covers the full well of the CCD, this non-linearity is often measurable.

Saturation: at high signal levels, either the potential well fills up or the limit of the ADC is reached. This level defines the upper end of the measurable signal range; beyond this level, no change will be registered in the detector. Note that if the potential well fills up, charge can diffuse along the columns defined by the channel stops. Thus saturated objects “bleed” charge along columns.

Read Noise: noise produced by the readout amplifier. Even at zero signal level, the readout produces fluctuations at the level of a few electrons r.m.s. up to a hundred electrons or so.

Dark Current: electron/hole pairs are constantly generated as thermal fluctuations raise electrons across the band gap. These electrons can be trapped in the channels and therefore masquerade as signal. This contribution is called dark current, and it is a strong function of temperature (Figure 6). At room temperature, the dark current can saturate the detector in a few seconds and thus limits the CCD’s utility severely. CCDs used to detect faint signals must be cooled to reduce the dark current to acceptable levels. Although the mean dark current can be measured and subtracted, the noise simply adds to the total noise and usually dominates at room temperature.

Cosmetics: perfect CCDs are difficult to produce and are therefore expensive. Most arrays include at least one defective column and several defective pixels. The pixels can be bad for various reasons: “dead” pixels register little or no charge, “hot” pixels are always saturated or
nearly so. Bad pixels can also fall somewhere in between, and are usually characterized by a non-linear response.

**Format:** the more pixels, the better. A typical format in scientific CCDs is 2048 x 2048 pixels. Cutting edge mosaic cameras available at large observatories now combine up to thirty six 2048 x 4096 CCDs.

**Charge Transfer Efficiency:** the transfer of charge from one pixel to the next is never perfect. Modern CCDs are remarkably good, though: in shifting the charge one pixel, good CCDs transfer 99.9999% of the original charge. Note that this efficiency retains 99.8% of the charge after transferring across 2048 columns.
In this lab, we will measure the critical operating parameters of the SBIG CCD used in the SFSU Observatory. We will take the measurements in the observatory and process them in the computer lab. Our goal is to measure the dark current, read noise, gain, and linearity of the CCD.

Definitions

**Bias exposure**: readout of the CCD after reset. Zero integration time; the shutter remains closed.

**Dark exposure**: readout of the CCD after reset and non-zero integration time (shutter closed).

**Normal exposure**: readout of the CCD after reset and non-zero integration time (shutter open).

**Dark Current**

We measure the temperature dependence of the dark current by taking several 60-second dark exposures at various temperatures. The mean contribution from dark current alone is simply the mean value of the difference between the dark exposure and the bias exposure. We will approximate the bias with a zero-second dark. Note that the minimum exposure time on this camera is 0.12 seconds, so this is not exact, but it should be close (how close?).

1. Turn on the CCD camera. Turn the cooler on and set the temperature set point to roughly room temperature. Let the temperature settle and then take a 60-second dark exposure.
2. Take a 0-second dark (i.e. our approximation to a bias exposure).
3. Turn down the set point temperature in intervals of 4 or 5 degrees Celsius. Take dark exposures at each temperature.

**Analysis**: plot the mean dark count rate (above the bias level) vs. temperature. Which pseudo-bias exposures give the best approximation to the true bias? Eventually, we want the dark current in electrons rather than counts (ADU). For this, though, we need the gain, which we measure later.

**Read Noise**

If all pixels were electronically equivalent, the readout noise could be estimated by measuring the variance of the ensemble of pixel values in a single bias exposure. It is worth measuring this variance as a first guess at the read noise (use `imexamine` and `imstat` in IRAF when you get to the analysis section).

Unfortunately, not all pixels are electronically equivalent, and substantial gradients and patterns can exist in the bias frame. These gradients inflate the variance in the frame above the variance contributed by the read noise alone. To measure the read noise alone, we need to subtract one bias exposure from another. Because the bias pattern is usually fixed, the resulting frame should
be free of patterns and gradients, but will include random noise that scales with $\sigma_r$, the readout noise (how?). Eventually, we want to know the readout noise in electrons, but for that we need the gain, which we measure in the next step.

1. Take a large number of bias exposures (say 40-50) when the CCD reaches is minimum operating temperature. By combining these biases, we reduce the noise in our estimate of the bias for each pixel.
2. Note the appearance of the bias frames and any obvious variations as they come in.

**Analysis:** Form the difference of any two bias exposures and measure the standard deviation in ADU using `imexamine` and `imstat`. Derive the read noise in ADU (including the uncertainty). Combine all bias frames into a single, low-noise bias frame. This is your best estimate of the bias offset in each pixel. (How can we use this frame to measure the read noise in individual frames?)

**Linearity**

Next, we will open up the telescope and point it at a uniformly illuminated wall. Exposures of this uniform source tell us how each pixel responds to the same incident flux (these exposures are called flat-fields). We will start by exposing just enough that the count rate is well above the bias level (try five seconds or so with the wall lights at maximum). After that, we will increase the exposure slowly and therefore increase the count level. We will repeat this process until we saturate the detector. In a perfectly linear detector, increasing the exposure by some factor should increase the counts by the same factor (within the uncertainties, of course). Any systematic departure from this trend indicates non-linearity in the system. If we ignore this non-linearity, we will introduce systematic errors in the measured fluxes of bright sources.

This technique relies on the stability of the light source. In order to monitor the stability and account for any changes in illumination, we will repeat the 5-second exposure after each of the longer exposures. For example, a typical series of exposure times (in seconds) would be 2, 5, 4, 5, 6, 5, 8, 5, 10, 5, 12, 5, 14, 5, etc until the CCD saturates.

**Procedure:**

1. Take a large number of exposures of the wall using the same exposure time. Set the exposure time so that the count level is roughly midway between zero and saturation. We will combine these into a low-noise flat-field image.
2. Take a series of exposures of varying exposure time under more-or-less uniform illumination. Increase the exposure time for each exposure until the chip saturates. Between each of these exposures, repeat the original (short) exposure as described above.

The mean pixel value in each of the frames (after bias and dark subtraction) should increase linearly with the exposure time. In a real CCD, it will not, especially when the count rate approaches saturation.
**Analysis:** For each exposure time, calculate the ratio of the mean pixel value to the expected mean pixel value. For a linear detector, we expect the mean pixel value to simply scale with the exposure time. Plot this ratio as a function of the measured mean pixel value \((i.e. \text{the ratio measured counts / expected counts vs. measured counts})\). Be sure to include uncertainties on both axes. This is our measure of the linearity of the detector. Are the uncertainties in the measurements to detect non-linearity with confidence? How would you state your confidence in your detection or non-detection?

**Gain**

The same exposures used to determine the linearity can be used to estimate the gain. Recall that the relation between the number of detected electrons \(N_e\) and the number of ADU \(N_A\) is

\[ N_e = g N_A \]

This relationship defines the gain, \(g\). Their expectation values are then simply related by

\[ \langle N_e \rangle = g \langle N_A \rangle \]

The variance in the two count values are then related as follows:

\[ \sigma_e^2 = \langle N_e^2 \rangle - \langle N_e \rangle^2 = \langle (gN_A)^2 \rangle - \langle gN_A \rangle^2 = g^2 \langle N_A^2 \rangle - \langle N_A \rangle^2 = g^2 \sigma_A^2 \]

Because we can measure only ADU, not electrons, it is useful to form the ratio of the variance in ADU to the mean pixel count in ADU. This ratio is then

\[ \frac{\sigma_A^2}{\langle N_A \rangle} = \frac{g \sigma_e^2}{g^2 \langle N_e \rangle} = \frac{\langle N_e \rangle}{g \langle N_e \rangle} = \frac{1}{g} \]

Where the last step invokes Poisson statistics: \(\sigma_e^2 = \langle N_e \rangle\). Thus a plot of the variance in ADU vs. the mean pixel value in ADU gives a straight line with slope \(1/g\). Note that the relationship between the variance and the mean in ADU is not what is expected from Poisson statistics. It is the photons (and therefore the generated photoelectrons) that follow Poisson statistics, not the scaled quantity ADU.

**Analysis:**

1. Measure the mean and the variance in each of the frames used to determine the linearity.
2. Plot the mean vs. the variance and measure the slope of the line. The slope is the inverse gain of the CCD.
3. Finally, go back to the earlier parts of the lab and re-compute the read noise and dark current in electrons.
Figure 1 (from the tutorial published by Scientific Imaging Technologies, Inc., available at http://www.site-inc.com/tutorial.htm)

Figure 2
Figure 3

Side view ↑
Top view ↓
Figure 4
Figure 5