CCD - Laboratory Evaluation

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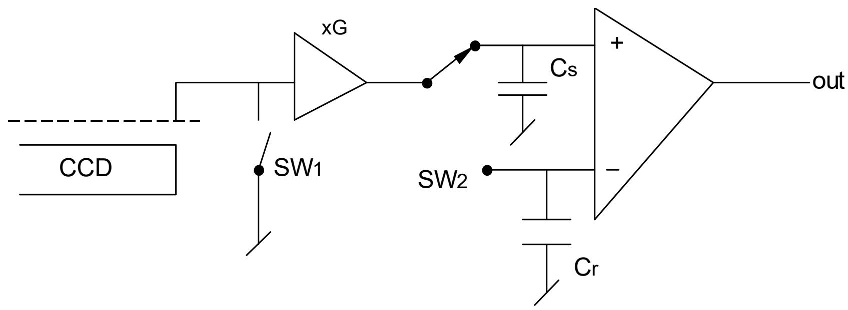
The photographic plate was the detector of choice for astronomical imaging for nearly a century. However, none have been used on major telescopes for the past seversl decades. The current detector of choice is the charge coupled device (CCD). The advantages of the CCD include:

- greater quantum efficiency
- lower noise
- more uniform calibration
- inherent digital nature (for analysis/storage)

CCDs were developed by the military and the television industry as light-weight high-sensitivity cameras. They are the heart of modern digital cameras and phone cameras.

Before using any apparatus on a telescope it is important to understand its basic operating principles. If possible it is also a good idea to practice using it in the laboratory environment. (The dark, late-night, and windy conditions in the dome are less conducive to clear thought than a comfortable air-conditioned laboratory.) The basic operating principals of CCD's are described in Astrophysical Techniques by C.R. Kitchin. Most of that section is devoted to charge transfer using a three phase chip. Unfortunately the text is vague on questions of measuring device characteristics.

Consider the following structure:



The electrons are moved to the output well by driving the previous gates more negative in the clocking pattern discussed in our lectures. This charge develops a voltage, $V_o = N_e\, e/C_o$, where C_o is the output capacitance associated with the output well, N_e is the number of electrons in the well, and e is the charge on an electron. This voltage is sensed by the output amplifier and sampled by an electronic circuit that holds the amplified voltage constant, the amplified voltage charges a capacitor, C_s to a voltage $G\, V_o$. Switch SW_1 is then closed to drain the charge from the output well (called resetting the well) and at the same time Switch SW2 is closed and a second voltage reading is taken, amplified and stored in a second capacitor, C_r. The electronics then convert the voltage difference between C_s and C_r into a digital signal for storage and display. The technique of making two measurements in quick succession and then differencing them is very common in modern scientific measurements. In the present case it is called double correlated sampling. In other instances it is called chopping, beam switching, synchronous demodulation and lock-in detection. By using this technique one is relatively insensitive to long term electronics drift in the various amplifiers. If the amplifier drifts over a period of seconds, it will have very little effect on the reading (which occurs on a timescale of microseconds). Of course if it varies over a couple of microseconds, all bets are off. As usually happens, folks work hard on the amplifier drift until it is slow enough and small enough that it does not constitute a significant source of noise.

What has been described so far is a one-dimensional transfer. But because images are two-dimensional a second layer of charge transfer is needed. In the case of our chip, the entire image is shifted down by one line all at once (called a parallel transfer) then the bottom-most line is shifted out to the right to the output well (called a serial transfer). Remember the terms up, down, left and right only have meaning for a particular orientation of the camera and are used here only to give the reader a mental picture of what's going on.

Many parameters are needed to describe the various functions of a CCD chip. Kitchin points out that the charge transfer efficiency, CTE, is an important characteristic of a CCD chip. If the CTE is too small then the image is blurred out as it is transferred to the output well; a bright star looks like a comet with a very straight tail. There are four other CCD characteristics which are also extremely important to the user of CCD's in astronomical applications: dark current, read noise, linearity and quantum efficiency. Each of these is described below.

DARK CURRENT

In the absence of a photon signal, the wells in a CCD slowly accumulate thermally generated charges from the silicon chip. Cosmic rays passing through a pixel will deposit large amounts of charge in one or more adjacent pixels. However, cosmic ray hits are usually easy to spot, so we can ignore the "hit" pixels (and/or use other statistical tricks to replace the missing data from them). The problem with thermally generated charges is that they are stochastic in nature - they are not always the same. If the average number of thermally generated charges in an integration is N_d then the fluctuation in the number of charges is of order $(N_d)^{1/2}$. This uncertainty is noise. The thermal generation rate can be reduced by cooling the chip. That is why we go to the trouble of mounting the chip in a liquid nitrogen dewar. Also note that the **average** dark current is a constant (N_c is proportional to the exposure time) and can be subtracted from the measured signal. It is an offset and not a noise. However the **uncertainty** in the average cannot be predicted accruately and therefore cannot be "corrected for." It is a noise.

READ NOISE

In the absence of a photon signal and with the chip cooled to a low enough temperature that thermally generated charges are negligible, there is still noise in the system. It comes from the amplifier and the switch on the output well of the CCD, Sw_1. This read noise is the ultimate noise floor for the device. Some CCDs have been developed with read noises of less than one electron - more often than not they measure exactly how many electrons are in the output well.

LINEARITY

Is the signal reported by the electronics and the computer, DN, proportional to the total number of photons hitting the CCD? This can be tested by exposing the CCD for increasingly long times to a constant intensity and then plotting the reported DN as a function of exposure time.

BLOOMING

If the CCD is exposed to a very bright star, the well or wells in the star image are filled beyond their capacity. The excess charges will spill over into adjacent wells and the image size will expand. When the electronics attempt to move these full wells, the top few percent of the charge gets left behind and forms a trail behind the image. In extreme cases this trail will extend in both the vertical and horizontal directions. These effects come under the heading of blooming. You may sometimes see diagonal streaks coming out of the image in a pattern that looks like an "X". These spikes are due to diffraction by the supports that hold the telescope's secondary mirror and are not related to blooming.

CHARGE TRANSFER EFFICIENCY

The charges collected during the integration (exposure) are shifted to the output well by cycling the voltages on the CCD's electrodes. At each transfer from one well to the next a small fraction of the charge is "left behind." This results in blurred images and an uneven response across the area of the chip. The charge transfer efficiency (CTE) is the fraction of charge which is correctly transferred from one well to its neighbor. Since the charges from some wells must be transferred several hundred times the CTE must be very near one if the device is to be useful for actual observations. Typical values for the CTE are 99.99998%.

QUANTUM EFFICIENCY
In the presence of photons, charges are liberated and trapped in one of the wells (often called pixels on the chip), but some are lost in the sense that they fail to appear in one of the collection wells. The ratio of the number of electrons appearing in a collection well divided by the number of incident photons is the quantum efficiency (QE). Since the chip is not completely absorptive some photons are reflected, hence the quantum efficiency is less than 100%. Other limitations include the failure of a liberated electron to fall into one of the wells. The photon may be absorbed by an impurity which converts the photon's energy into heat instead of a liberated electron.

In the course of this laboratory you will learn to operate the camera. In addition you will measure the read noise, dark current, CTE (maybe?) and will determine the relation between the data number (DN; also sometimes called ADU) reported by the electronics and the number of electrons which were actually in the well. You will not measure the quantum efficiency - it requires an intensity-calibrated light source and well behaved optics.

MEASURING THE READ NOISE

1. Make a 9x 0.1-second dark exposures
2. Calculate the rms of the DN's in a pixel-wise manner (i.e. make a 2D array of the same size as the CCD, and please the RMS of the 9 measurements for each pixel in that pixel's location in the array). Place this in the "RMS array"
3. Look at the mean, RMS, and median values of the "RMS array". In theory, the mean (or median) is the average read noise of the CCD, in pixels. The RMS of the "RMS array" is the statistical spread in the average read noise (based on a single pixel), and the RMS divided by the square root of the number of pixels is the uncertainty in the average read noise (based on all the pixels).
4. Now, make a histogram of the distribution in "RMS array" values. Try to fit a Gaussian to the histogram - this should give a centroid (=mean) value, and a statistical spread (sigma). Compare the mean & uncertainty here to the estimates you made in #3. Do they differ? By how much? Why?
5. Do several longer (10x, 100x) snaps with 3 exposures at each exposure time and see if the read noise is a function of the exposure time.
6. How can you tell if there is a light leak into the camera? Check.

MEASURING DARK CURRENT

1. See #6 above!
2. Take a short dark exposure (0.2 seconds). This gives you a baseline for the electronic offsets etc. This baseline is called the bias level. You will measure bias levels many times over the course of the lab.
3. Do longer and longer exposures (increasing the time by 5x from one exposure to the next) until you see a noticeable increase in the image brightness or the exposure gets to be longer than 500 seconds. In the course of making the dark current, you should make several intermediate 0.1 sec exposures to see if the electronic offset is drifting.
4. Calculate dDN/dt. Do this by first just calculating the mean (or median) of each exposure. Then try by creating a histogram of the pixel value distributions and fitting it with a Gaussian to get the mean and sigma for each image. If you fit a line to the fitted values (including the mean AND uncertainties in each one) you can get the dark current (dDN/dt) and its uncertainty.

DETERMINING THE CONVERSION FROM DN's TO NUMBERS OF ELECTRONS

If the average number of electrons in a pixel following an integration is Ne then the variance in that number is $(N_e)^{1/2}$. In terms of DN's:

$$\text{Signal} = G\, N_e$$

$$\text{Noise} = G\, N_e^{1/2} .$$

Where G is the conversion factor from N_e to DN (in ADU per electron).

Therefore, if we subtract the bias level from the output signal and plot log(signal) vs. log(noise) then we should get a straight line with slope 1/2. However, at very low signal levels the system will be dominated by read noise, not root (N) noise. So the plot will flatten out at low signal levels at a value close to the read noise measured above. At high levels, saturation becomes an issue and the curve flattens again (there is no "noise" in a constant value of 65535 !). All together there are two noise terms we consider here:

$$\text{Read noise} = R_n = \text{constant}$$

$$\text{Photon noise} = G\, N_e^{1/2}$$

Remember, N_e is the number of signal electrons in a well. Note that these terms go as N_e to the 0, and 1/2 power of N_e. That provides the leverage needed to separate them from one another.

Setup the camera and do a number of exposures from 0.1 to 100 seconds under conditions that will fill the wells, resulting in DN's of 50,000 to 60,000 for a 100 second exposure with good uniform illumination. Take 3 images at each exposure time, and calculate the pixel-wise mean and RMS of each pixel (a "Mean array" and an "RMS array").

Plot the variance (RMS^2) versus the signal. There should be a linear range in the plot, where we have Variance = $G^2 N_e$ and Signal = $G N_e$, so the slope should be G. This is the gain (in ADU per electron - note that many people use $g = 1/G$ for the gain, in electrons per ADU). How does the gain you measure compare to the nominal gain for your CCD (which may be in the FITS header)? What is the uncertainty in your gain measurement? Are there any systematic effects evident in your data which could skew your result (gain and/or uncertainty)?

LINEARITY

The goal here is to make a series of exposures which result in a wide range of DN values ranging from 10 to 60,000. Be careful that the light level remains constant throughout the exposures. (Note: light from the monitor screen can significantly change the light level in the lab area!)

First find a light level/lens opening combination that gives about 2,000 DN's for a 10 second exposure. Next take a set of exposures of 1, 3, 10, 30, and 300 seconds. You may want to add a few values in-between to fill out the curve. Next reduce the light level by a 100x or so and repeat the sequence. You will have no way to accurately reduce the light level but you can shift the resulting curves up and down until they overlap or just present two curves, one for high and one for low light levels.

BLOOMING (optional - depends on getting a point source!)

Blooming is an important characteristic of a CCD chip if you are planning to measure a field of very faint object(s) that also contains a bright star. If the CCD blooms then charges from the over-exposed stellar image will interfere with measurements of the faint objects. The blooming performance of the chip can be determined by first making a short exposure of a "point source" which does not saturate the well at its core. Next one lengthens the exposures (by a factor of two or so each time) until the image of the point source beginning to bleed across the image. By what factor has the exposure exceeded the exposure needed to reach 65,000 DN? Along the way it is useful to keep track of the integrated signal just as in the linearity checks. Do you expect to find the same linear behavior with exposure time or not? The trailing streak is caused by poor charge transfer efficiency. Since the charge forming the streak is trailing the main charge, it lets you "see" which way charge is flowing (clocking).

CHARGE TRANSFER EFFICIENCY

This is the "Black Belt" part. **For the current course, it is also optional**, as the CCD CTE is so good that it is hard to measure the inefficiency (= 1-CTE) (!).

It is more difficult to determine the charge transfer efficiency, CTE than the previous quantities, but you can do it (maybe)! First it is important to understand what CTE is in an operational sense. If there are N electrons in pixel and zero in all the rest the distribution looks like and we make the substitutions α = CTE and ε = (1-CTE):

N	0	0	0	0	0	etc.

then the distribution after one transfer transfer is:

$N\varepsilon$	$N\alpha$	0	0	0	0	etc.

after another transfer transfer

$N\varepsilon^2$	$2N\varepsilon\alpha$	$N\alpha^2$	0	0	0	etc.

after another:

$N\varepsilon^3$	$3N\varepsilon^2\alpha$	$3N\varepsilon\alpha^2$	$N\alpha^3$

Notice every term is what was in the pixel previously times ε plus what was in the pixel to the left times α. This should remind you of Pascal's triangle and the binomial expansion. From there you can generalize to N transfers. The general value for the coefficients can be had from a math reference about the binomial expansion.

But how do we get electrons only in one pixel to begin with? Cosmic rays are the trick.

Cosmic rays strike one or a few adjacent pixels and deposit several to many thousand electrons in them. If the CTE is not perfect the cosmic rays will blur-out as the charge is transferred across the chip. To get a good dose of cosmic rays make a 300 second DARK exposure. When doing the cosmic ray method remember some of the initial cosmic ray charge may actually have gone into several pixels including the pixel which is "trailing" the main hit. Therefore, the derived CTE is a *lower limit* to the true CTE. (There is more "trailing charge" than just that left behind by the transfers, some was there from the initial hit.)

NOTE: One of the problems which plagues experimental equipment is that it often changes unpredictably from time to time. At the observatory we will track these changes by monitoring standard stars. This is difficult in the laboratory since an artificial standard source would also be subject to unpredictable changes. We can however monitor the zero level, the output when there is no light on the chip. This is most easily done by keeping track of the dark level for some constant exposure time. A one second dark should be a good value for this. In this way you should be able to detect changes in the system which might mask the real effects you are trying to observe. This is most critical in the measurement of the dark current since what we are trying to measure is inherently a small effect.

THE REPORT:

Your report should:

1. have a title and a date
2. a list of authors (It is assumed that the first author (you) did the analysis in the report and wrote the report and that listed co-authors helped in gathering the experimental data.)
3. describe the general objectives of the experiment
4. describe the setup (CCD and PC for control and display, light sources used, etc.)
5. contain a separate section on each of the measured characteristics (read noise, dark current etc.) (Each section should be complete in itself. It should state the objective of that section, the method used achieve the results, the results, and a brief summary. Graphs or drawings will help present the data clearly. If there is a set of data, it is best presented as a table.)
6. contain a conclusion section which might contain a table of the measured characteristics, any strange or otherwise remarkable results and perhaps suggestions on what might have been done to improve the quality of the results.

DO NOT LEAVE THE REPORT WRITING TO THE LAST MINUTE! A well written report is likely to take as long to write as it took to get the data. Don't worry about appearances too much, "It's the thought that counts."