ES431 ASTRONOMY LAB: Session I – CCD Characterization

Name:...Student Id:..........................Date:...................

Session Plan

A Understanding the working of a CCD

B Characterization of the IIST KAF0401E CCD in the SBIG ST-7XE Camera

1. Read Noise
2. Dark Current
3. Linearity
4. Gain
5. Charge Transfer Efficiency

C Analysing data using IRAF (This part can be done after the sessions on IRAF Tutorials)

Note: Show all steps to the faculty present. Create a folder with the date of your laboratory session and store the images there.

1 Introduction

The CCD-detector (Charge-Coupled Device) was invented more than 40 years back in 1969 by Boyle and Smith at Bell Labs in New Jersey, the same laboratory where the transistor was invented. The CCD was originally intended for use as computer memory. It was in 1970 that it was first used in astronomy. Since then the CCD has dominated detection in the infrared, optical and X-ray wavelengths in astronomy as well as in other fields. The CCD is an array of tiny light-sensitive squares called 'pixels' arranged in a checkerboard pattern. The basic functioning of the CCD device depends on four sequential operations

1. Conversion of incident photons to electron-hole pair - *photoelectric effect*.
2. Trapping and accumulation of electrons in the potential wells produced by the array of electrodes called gates on the CCD over the desired exposure time.
3. Transfer of the stored charges from pixel to pixel for the read-out procedure - like a *conveyor belt*.
4. Accurate read-out of the accumulated charge (over the desired exposure time) for each pixel.

In the 'no-signal' condition, the CCD electronics produces a small positive reading for each pixel. This electronic signature is termed as the 'bias' level and can be determined by taking a zero exposure (in our case 0.12s is the shortest exposure). Several (atleast five) bias frames should be obtained to remove random read-out noise, while preserving any spatially coherent noise and pixel-to-pixel bias levels. A mean bias frame must be subtracted from each exposed frame as the first step in all procedures involved. Unfortunately, not all pixels are electronically equivalent, and substantial gradients and patterns can exist in the bias frame.

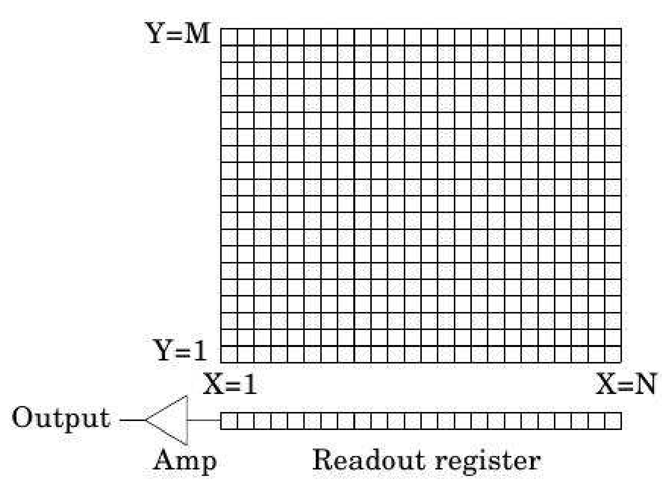

Figure 1: Schematic of a CCD showing the pixels and the readout mechanism

The charge transfer is a two-step process. First, a row is shifted to the Y=0 position (called a parallel transfer). Next, all the charges in the row are transferred sequentially to the X=0 position and read out (called a serial transfer). The electromechanical shutter covers the CCD during the readout to prevent streaking across the image. Hence, a new exposure cannot be started before the previous image is read out. The CCD is cooled with a solid state thermoelectric cooler. The cooler transfers heat out of the CCD and dissipates it into a heat sink, which is part of the mechanical housing. This heat is then dumped into the air using a heat exchanger and a small fan. The eciency of the cooling (and hence the lowest operating temperature) depends on the ambient temperature.

1.1 Read Noise

Read noise comes from the electronics used to 'read' the CCD. Two factors contribute to this noise - (1) The charge collected within each pixel is measured as a voltage which is converted into an output Digital Number (DN). Each pixel's charge is sensed and amplified by an output low noise amplifier which is directly built into the CCD chip and hence termed as 'on-chip' amplifier (2) passage of the signal through the amplifier and the analog-to-digital convertor. The electronics itself introduces spurious electrons generating unwanted fluctuations in the output signal. Hence, read-out noise is defined as the mean error contributed to the pixel by the amplifier and the A-D convertor. The read noise is the ultimate noise floor for the CCD.

1.2 Dark Current

Random motions of atoms at normal room temperature within the silicon lattice will give rise to continuous stream of electron-hole pair in the absence of incident light. These electrons get trapped in the potential wells and hence masquerade as signal when the CCD is read-out.This contribution is called dark current, and it is a strong function of temperature. 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. Dark current is usually given as the number of thermal electron generated per pixel per second.

The dark current is proportional to the exposure time. The typical dark current seen in CCDs is 2 electons per pixel per second. This looks to be a small value but the scenario changes when the exposure time increases. For instance, a 15 min exposure will give rise to an additional 1800 thermal electrons per pixel. The contribution of these additional electrons cannot be uniquely removed from the astronomical signal after read-out. The dark current sets an inherent noise floor for a CCD. The dark current signal can be removed from the science frames. However, the dark noise follows a Possion distribution - if the number of electrons from dark current is N_d then the uncertainty is $\sqrt{N_d}$. The fluctuation in the dark current is a noise term that cannot be corrected for.

1.3 Linearity

An useful feature of the CCDs are that if operated properly, they are linear detectors over a large dynamic range – the output voltage signal is proportional to the incident number of photons falling on the CCD to very high accuracy, often better than 0.1% of the signal. This property makes it possible to calibrate observations of very faint objects by using shorter exposures on much brighter photoelectric standard stars. 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.

1.4 Gain

The gain of a CCD is set by the output electronics and determines how the amount of charge collected in each pixel will be assigned to a digital number in the output image. The output voltage from a given pixel is converted to a digital number during readout. The amount of voltage needed (which translates into the number of collected electrons orreceived photons) to produce 1 count (also called an analog-to-digital unit, ADU) is called the **gain** of the CCD. A typical gain might be 10 electrons/count, which means that for every 10 electrons collected within a photosite, that pixel will produce, on average, 1 count.

The relation between the number of detected electrons N_e and the number of ADU N_A is

$$N_e = g \times N_A \tag{1}$$

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

$$\langle N_e \rangle = g \times \langle N_A \rangle \tag{2}$$

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

$$\sigma_e^2 = \langle (N_e^2) \rangle - (\langle N_e \rangle)^2 = \langle (g N_A^2) \rangle - \langle g N_A \rangle^2 = g^2 (\langle (N_A^2) \rangle - (\langle N_A \rangle)^2) = g^2 \sigma_A^2 \tag{3}$$

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:

$$\frac{\sigma_A^2}{\langle N_A \rangle} = \frac{g \sigma_e^2}{g^2 \langle N_e \rangle} = \frac{\langle N_e \rangle}{g \langle N_e \rangle} = \frac{1}{g} \tag{4}$$

Thus a plot of the variance in ADU vs. the mean pixel value in ADU gives a straight line with slope 1/g.

1.5 Charge Transfer Efficiency

The Charge Transfer Efficiency (CTE) is a measure of the fraction of charge which is successfully transfered for each pixel transfer.The transfer of charge from one pixel to the next is never perfect. Modern CCDs are remarkably good. In shifting the charge one pixel to the next, good CCDs transfer 99.999% of the original charge.

2 Characterizing IIST-CCD

2.1 Getting started

First connect the the USB cable to the portable computer (operating system should be Windows). Then connect power lines to the camera and switch the power on (there is a switch in the adapter). The CCD operating software, CCDOPS can now be started. Click on Establish Comm Link to establish a communication link between the computer and the camera. Once the COM link is established, click on Camera Setup (or Ctrl-U), and choose a setpoint temperature. Once you type in the setpoint, set the temperature control to active, and hit ENTER.Watch the temperature (the quantity displayed as a percentage is the cooling eciency) on the bottom right, and wait until the setpoint temperature is reached. To take an exposure, click on the Grab icon. Type in the exposure time (units are seconds), select whether to take an exposure, dark frame or both, and then click OK. Once the exposure is completed, the CCD is read and the image is shown on the screen. To save the image, click on File and select Save. Choose the format to save the image (you should use FITS format), type in the lename (using meaningful le-names which have information on the nature of exposure and exposure time can save eort later) after selecting a suitable directory, and then click OK.

2.2 Read Noise

- Put the lens cap on the CCD to avoid leakage of stray light into the camera
- Take exposures of 0.5s, 1s and 3s. Take atleast five frames for each exposure time.
- Measure the standard deviation in several regions of the image.
- Check dependence of read noise on exposure time

2.3 Dark Current

Measurements can be done in two ways - (1) with lens cap on, or (2) with the option provided in the 'Grab' dialog. It is a frutiful exercise to do it both ways and compare and interpret the results obtained.

There are two aspects to the Dark Current measurements - (1) Dark Current as a function of exposure time, and (2) Dark Current as a funcion of operating temperature.

(1) As a function of exposure time: First take a bias frame. Then, take longer and longer exposures (e.g. 1 s, 2 s, 5 s, 10 s, etc.) until around 500 seconds. Measure the mean signal in each exposure and plot it as a function of time. The slope of the curve will give the dark current. Over the course of your exposures, you should take several bias frames to check whether the bias level is uctuating or not.

(2) As a function of operating temperature: The next step is to measure the dark current as a function of temperature. Choose an exposure time that will give you a reliable

estimate of the dark current (if you choose too short an exposure time, you will be dominated by read noise; if you choose too long an exposure time, you will end up spending a lot of time making the measurements). Set the operating temperature of the CCD through the camera setup dialog, and wait until the temperature is stable.Then, take a bias frame and a dark frame with the chosen exposure time. Repeat the procedure for dierent operating temperatures. You should have data for temperatures of 20, 15, 10, 5, 0,-5, and if possible -10 C. Plot the dark current as a function of temperature.

2.4 Linearity and Gain

The linearity can be tested by taking a series of exposures at a constant light level, which result in a wide range of DN values. 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. 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.

For this purpose use the set-up provided (which was built by Mr. Devesh Maurya as part of his project work). In this set-up light from a set of LEDs powered by a 9V battery is diffused through an aperture and translucent (tracing / butter) paper. Cover the entire set-up with a dark cloth to avoid leakage of stray light.

The data obtained can be used to estimate the gain and the conversion factor.

2.5 Charge Transfer Efficiency

The operational principle needs to be understood in order to measure the CTE. Suppose there are N charges in one pixel and zero in all the rest, then the distribution looks like

N	0	0	0	0	0	0	...

Then the distribution after one transfer is

Nϵ	Nα	0	0	0	0	0	...

where, α is the CTE and $\epsilon = 1 - \alpha$. The distributions after subsequent transfers would look like

Nϵ^2	2N$\epsilon\alpha$	Nα^2	0	0	0	0	...
Nϵ^3	3N$\epsilon^2\alpha$	3N$\epsilon\alpha^2$	Nα^3	0	0	0	...

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.

How do you get electrons only in one pixel to start with? Cosmic rays provide the answer. Cosmic ray hits cause electron distributions that are ideally suited for measurement of charge transfer efficiency. However, cosmic ray hits cause charge in more than one pixel so that this method gives a lower bound on α. Cosmic rays strike one or a few adjacent pixels and deposit several to many thousand electrons in them. If the charge transfer eciency is not perfect, the cosmic rays will blur out as the charge is transferred across the chip. Analyze one of the dark frames with many cosmic ray hits to get the charge transfer eciency. Do your analysis for several cosmic ray hits (at least five).

2.6 Shutting Down

To shut down the camera, select Shutdown in the Camera menu. This triggers an internal warm-up procedure in the camera, preventing rapid warming of the CCD chip. The chip is not likely to be harmed if it warms up suddenly, for example in a power failure. However, slow warm-up places less stress on the chip. Before you shut down the computer, copy your les onto a memory stick! You will be analyzing the data using IRAF in a dierent machine.