Use of a CCD Camera

1   Introduction

The charge-coupled device (CCD) is the detector of choice in many research applications in observational astronomy. The high sensitivity of the CCD, the linearity of its response to incident light, and the efficiency with which the digitized data can be manipulated make the CCD an ideal tool for accurate scientific measurement in astronomy.

In this practical, you will use a CCD camera to take a number of images in the laboratory in order to discover the basic principles of its use. The aims of this practical are:

- to introduce the CCD as an astronomical detector;

- to familiarize the student with the software used to control the SBIG CCD cameras which are used on the Meade telescopes;

- to teach the student the image corrections required to produce a scientifically useful CCD image.

2   The CCD

The principle, properties and operation of the CCD are described in references 1 and 2, given below. The following description is intended as a summary for the purposes of this experiment, but you are encouraged to refer to the Foreword and parts of Chapter 1 of Buil (ref. 1), or Chapters 1, 2 and 4 of Howell (ref. 2) for a more complete introduction.

2.1   The operation of a CCD

The light-sensitive area in a CCD consists of a two-dimensional array of metallic electrodes which is insulated from a semiconducting silicon wafer by a layer of silicon oxide. The application of a voltage to the electrodes creates an array of voltage "wells" within the silicon substrate. A photon falling onto the CCD may penetrate into the silicon and free an electron by the photoelectric effect, which then becomes trapped within a local voltage well.

The number of electrons produced in each well is proportional to the number of incident photons in a given *integration* time, during which the CCD is exposed to light. In this way, an optical image is transformed into an electronic image in the substrate of the chip. The individual voltage wells are referred to as *pixels* (after "*pic*ture *el*ements") because of the imaging function of the CCD.

Following integration, the number of electrons in each individual pixel is counted by a process of transferring the electrons from one pixel to another along the rows and columns of the array (rather like an electronic "bucket-brigade"), to a point where the charge in each pixel can be measured, or "read out." Each charge "packet" is measured as a voltage, which is converted into a number of *counts*, or analogue-to-digital units (ADU). The number of electrons per ADU is known as the system *gain*.

2.2 Other properties of a CCD

Q.1: Describe three of the principal advantages of the CCD over the photographic emulsion. (Refer to the foreword and section 1.7 of Buil, and chapter 1 of Howell)

The typical size of a CCD pixel is in the range 10–30 μm, which compares with a spatial resolution of about 5 μm for a good photographic emulsion. For a given telescope/camera combination, therefore, the CCD generally has poorer spatial resolution. Also, the size of the light-collecting area compares unfavourably with a photographic plate. The CCD used in this experiment has 375×242 rectangular pixels of size 23×27 μm. This gives a collecting area of 8.63 mm $\times 6.53$ mm, which translates to about 11.7×8.8 arcminutes on the sky when used with a Meade 10-inch telescope operating at $f/10$.

3 Using the CCD camera

In practice, there are a number of factors which must be taken into account in making corrections to a raw CCD image. The most important of these are:

- the contribution of thermal electrons, or dark current;
- pixel-to-pixel sensitivity variations;
- non-uniform illumination of the chip due to vignetting, dust, *etc.*

In this practical, you will obtain and reduce CCD images of a photographic slide in order to discover the basic principles of operating the CCD; you will take a number of exposures to investigate the above effects, and then apply image corrections to the raw image data.

3.1 The lab-bench CCD setup

For this experiment, the CCD camera is mounted on an optical bench. A demonstrator or technician should make sure that the equipment is correctly set up before you begin. DO NOT adjust any part of the equipment yourself, except for those adjustments described below which are required in order to carry out the experiment. In particular, *never* disconnect the CCD camera head from its CPU box, and do not fiddle with the controls of the power supply. If you are not sure about which parts of the equipment you may safely adjust, ask a demonstrator.

You will use a CCD camera manufactured by the Santa Barbara Instrument Group. The camera is controlled with a program running under Windows. Part of the purpose of this experiment is that you become familiar with the basic operation of the control software so that you can handle the equipment with confidence when using the CCD on a telescope on a clear night.

3.2 Running the control program

The optical bench consists of a light source, a slide holder for 35mm slides, and the CCD camera head with a lens attached to project the slide image onto the CCD. The voltage

for the light source is preset to 2.5–3V in order to provide sufficient illumination for the slides.

Before starting the exercise, you should create a new folder for saving images on the data disk used to store SBIG CCD data. Open `My Computer` on the desktop (by double-clicking on the icon) and then open the network data drive 'Win-apps on Uriel'. Open the `sbig` directory, then `ccd` and select `File` ↦ `New` ↦ `Folder`. Rename the new folder with a unique identifier, like your initials.

Then start the CCD-control program by double-clicking the `SkyPro` icon on the Windows desktop. To connect to the CCD camera, select the `Camera` pull-down menu, and then `Link` ↦ `Establish`. When the connection is made, the status bar at the bottom of the screen should indicate the camera model (in this case, ST6), the baud rate for data transfer (57k), and temperature information. If you have trouble establishing the link to the camera, consult a demonstrator.

Now try out a test exposure, just to check everything is working.

N.B. Whenever you take an image during this practical, you should switch off all the room lights (including the desk lamp); you may switch them on again between frames if you wish, or use the table lamp (in order to read the script!).

Work through the following steps:

1. First remove the camera lens cap and check the camera aperture is set to $f/2$. Then select `Camera` ↦ `Take Exposure` to take a trial exposure. Set the exposure time to 0.1 seconds; set the exposure mode to `Grab`, the `Frame Mode` to light frame only, and automatic background and range (which means that the contrast and brightness of the displayed image will be automatically adjusted). The resolution should always be set to 'high'.

   Click on `OK`. The camera should then expose, digitize and download an image to the PC while displaying status boxes to show you how things are progressing. It does not matter if the resulting image appears out of focus — do not attempt to refocus the lens; the focussing procedure is described later on in the script.

2. Try out one or two tools on the test image: choose the `Select Panel` from the `View` menu, and select the (+) zoom function. With this selected, the left mouse button zooms into the image; the right mouse button restores it to normal display.

3. The (x, y) pixel position of the cursor, measured from $(1, 1)$ at the top left of the image, is displayed at the left of the status bar. You can also see (in brackets) the number of counts in the pixel at the cursor position shown (re-select the 'normal' cursor from the `Select Panel` to see where you're pointing). The pixels become saturated (filled) with electrons above about 50000 counts for this CCD; in general, one would not expose an image so long that the brightest parts become saturated.

4. You can save the image by selecting `File` ↦ `Save As ...`, or by clicking on the floppy-disk icon on the toolbar. You will need to give a name for the file in which to save the data, making sure you save it in the folder you created above: *e.g.*, if your folder name is `abc`, navigate back up the directory tree on the right to `ccd\abc`, and save the test image as `test.st6`.

4 Dark current and cooling

Even in complete darkness, a signal is detected in a CCD exposure. This is known as the dark current, and the strength of the signal depends on the integration time and the temperature of the CCD.

Q.2 What causes the dark current in a CCD?

In order to correct an image for the effect of the dark current, we must subtract from the original image an exposure obtained at the same temperature and for the same integration time, but in darkness. This is called the "dark frame."

4.1 Taking dark frames

The CCD camera head contains a two-stage thermoelectric cooler which cools the chip to about $-42°$ C below the ambient temperature. In order to illustrate the effect of temperature on dark current, you will take two dark exposures of the CCD at different temperatures.

Replace the camera lens cap at this stage to keep out any stray light. Take the following steps, keeping the room lights off during exposures:

1. To set the temperature of the chip, select `Camera` $\mapsto$ `Temperature` and switch the temperature regulation on. Set the temperature first of all to $+10°$ C, or to a degree or two less than the ambient temperature if the room is already cooler than $10°$ C.

2. Once the temperature (indicated at the bottom of the screen) has settled down to within a degree or so of $+10°$ C, `Grab` a dark frame with a 10-second exposure.

3. Once the image has been displayed, save the file as `dark1.st6` (if you saved the test image above, all further files should automatically be saved in your new folder). The image should appear peppered with bright pixels.

4. Reset the temperature setpoint to $-30°$ C. When the chip has cooled to within a degree of this temperature, take another 10-second exposure and save the image as `dark2.st6`.

5. Finally, take a second 10-second exposure at $-30°$ C and save the image as `dark3.st6`.

N.B.: To make sure you have enough time to complete the acquisition of the full set of image and flat-field frames, you should probably carry out the analysis in section 4.2 below only after completing sections 5 and 6.

4.2 Investigating the dark current

You will now measure the dark current in the dark frames obtained above.

In the first instance, the counts in two dark frames obtained at different temperatures will be compared. The results will be used to consider the implications for astronomical use of the CCD.

Then the repeatability of the dark counts will be investigated: in each dark frame, you may note that the dark current from one pixel to another is rather variable. In order

to see whether this is a random effect or whether certain pixels are prone to filling with thermal electrons, we shall compare the two dark frames obtained at the same temperature.

Carry out the following:

1. Open the first dark frame, `dark1.st6`, and zoom 2 or 3 times into the top left corner of the image, so you can see the individual pixels clearly. Record the (x, y) positions and counts of several (at least 3 or 4 of each) bright and dark (black) pixels within the image.

2. Open the second dark frame, `dark2.st6`, zoom exactly the same part of this image, and record the counts in the same pixels.

3. In the same way, record the counts in the same pixels in the third dark frame, `dark3.st6`.

Q.3 Compare the results for `dark1` and `dark2`. The measured counts have a zero-level (or "bias offset") of about 100 counts.

(*a*) Obtain the average of the dark counts for each frame, and then subtract the bias offset. By what factor has the dark current been reduced between the two frames?

(*b*) What would be the longest exposures possible at (*i*) the temperature used for `dark1` and (*ii*) $-30°$ C if the dark current in the darkest pixels you recorded were required to be less than about 5000 counts? (Convert your figures first to a dark-count *rate*).

(*c*) What do you conclude about the importance of cooling for the astronomical use of CCDs? (Hint: think about the typical exposure times required for astronomical imaging.)

Q.4 Compare the results obtained for `dark2` and `dark3`:

(*a*) Does the dark current vary randomly between exposures and from one pixel to another; or is it relatively constant for a given pixel?

(*b*) What do you conclude about the usefulness of subtracting a dark frame from an image of a real source? How would the exposure time used for the real source matter?

5 The object frame

With the chip now cooled to a suitable operating temperature ($-30°$ C), you are ready to take an image of a slide, which we will call the object frame. Use the slide of the galaxy Centaurus A, marked with the label 'CCD Expt'. Insert it in the slide holder, with the grey side facing the camera. Remove the camera lens cap and turn the room lights off for these exposures.

5.1 Checking the focus

The slide holder should be set up for you so that the image is in focus within the range of the camera lens. It will be instructive to carry out the procedure for determining the best focus since this is often necessary for astronomical use of the CCD.

In focus mode, a small portion of the CCD image can be updated rapidly in order to observe the effects of fine focus adjustments. This greatly speeds up the process of finding the best focus, rather than repeatedly exposing full frames.

1. Select the `Focus` exposure mode in the `Take Exposure` dialogue box, and set the following parameters:

Exposure time:	0.1s	Background and Range:	Automatic
Frame mode:	Automatic dark-frame	Update:	Continuous
Frame size:	Spot		

2. Click `OK` to start the exposure. The `Spot` frame size means that the focus routine will readout a small region of the chip around the brightest part of the image. The image is updated every few seconds, and you can slowly adjust the camera lens focus until the image becomes clearer.

3. While this proceeds, adjust the focus of the camera lens in steady increments and observe what happens to the image; you'll need to allow a couple of seconds delay after each adjustment to give time for the image to update, so allow at least two updates between adjustments. Start with the lens fully in or out.

4. A fairly good indicator of the best focus position is when the value of the peak counts, displayed in the status bar, is a maximum. (It will vary a little anyway, even without any adjustment.) Once the best focus has been found, note down the peak counts and cancel the routine. Close the image window.

5. Finally, set the f-ratio of the camera lens to $f/16$. TAKE CARE NOT TO MOVE THE FOCUS! This adjustment is made to try and illustrate better the effects of flat-fielding on the images you will take in this exercise.

5.2 Taking the object frame

1. Select `Grab` and adjust the exposure parameters: set the exposure to be 5 seconds and set the frame mode to `Light frame only`.

2. Turn the room lights out and start the exposure.

3. Obtain a well-exposed image — aim for at least 10000 counts in the brightest part of the image, but make sure that the pixels are not saturated (*i.e.*, should be less than about 50000 counts). Adjust the exposure time if necessary and re-take the image.

   Make sure the image is full frame, *i.e.*, not just the part which was visible when focussing. If not, you might need to make sure you closed the image window used while focussing, and reset the exposure parameter `Frame size` to `Full`.

   Save the result as `image1.st6`.

4. Now obtain a dark-frame with *exactly the same exposure time* by setting the frame mode to be `Dark frame only`. Save this image as `idark.st6`.

6 The flat-field

A uniform illumination of the CCD would reveal that the sensitivity to light of each pixel differs from one to another. Also, when making astronomical observations, the

illumination of the CCD is never uniform because of optical vignetting by the lens or telescope, and because of the effect of dust on the front-window of the CCD chamber and on any filters, if used. Images obtained with the CCD must therefore be corrected for these effects.

These non-uniformities are quantified by obtaining an exposure of a bright, uniformly-illuminated source: the *flat-field*. The flat-field exposure must be obtained under conditions identical to those of the original image, *i.e.*, the same combination of telescope, filter, *etc.* The original image is then *divided* by this flat-field in order to remove the effects described above.

For astronomical direct images, the dusk or dawn twilit sky is often used for the flat-field, or a uniformly illuminated white screen inside the dome.

6.1 Taking the flat-field frame

In this experiment, your flat-field is conveniently provided by the background illumination used to project the slide image onto the CCD. The flat-field frame should be as well-exposed as possible in order to improve the noise characteristics of the final image; but it should not exceed about 50000 counts per pixel in any single exposure with this camera, when saturation effects may become noticeable.

In order to take the flat-field frame, remove the slide from the holder and replace it in its case. Then take the same series of exposures as for the object frame; use a 5-second exposure time to begin with. Obtain a well-exposed image without saturating the pixels.

When you have obtained a well-exposed flat-field frame, save it as `flat1.st6`, and save the corresponding dark frame as `fdark.st6`. If your flat-field exposure time is the same as that used for the object frame, you can use the same dark frame (`idark.st6`) instead of taking another.

Q.5 Note the non-uniformity of the flat-field by examining how the counts vary across the image:

(*a*) What is the *typical* variation from the centre to the edge of the illuminated part of the frame, expressed as a percentage of the maximum?

(*b*) What is the uniformity like on small (pixel-to-pixel) scales?

(*c*) Describe any other unusual features in the flat field, and their possible causes.

7 Reducing the data

We now have all the frames we need to illustrate the procedure of reducing the CCD data to produce a useful image.

The sequence of operations we must carry out is to *subtract* the dark frames from the object and flat-field frames; then the dark-subtracted object frame is *divided* by the dark-subtracted flat-field frame. Thus, the corrected image I is obtained from

$$I = K\frac{O - D_O}{F - D_F},\tag{1}$$

where O is the object frame, F the flat-field, D_O and D_F are the respective dark frames for these, and the constant K is (usually) the mean count of the flat-field frame.

7.1 Dark frame subtraction

Open the images requiring dark subtraction, and their respective dark frames. Pull down the `Image` menu and select `Combine`. Choose the `Dark Subtract` function and select the names of the object frame and its dark frame as the source and operator images. Then click `OK` and the dark-subtracted image will be displayed. Follow the same procedure to carry out the dark subtraction on the flat-field image. Save the dark-subtracted images as `imaged.st6` and `flatd.st6`

It's unlikely that you will notice much difference in the images before and after dark-subtraction, since the dark count is actually quite low at $-30°$.

7.2 Flat-field division

To perform the flat-field division, select `Image` $\mapsto$ `Combine` and choose the `Flat Field` operation. Select the dark-subtracted image and flat-field frames as source and operator images, and click `OK`. The result is the final dark-subtracted , flat-fielded image. Save the final image as `imagef.st6`.

Place the raw image (`image1.st6`) and the final image side by side in the display window for comparison. Are any differences apparent? Select the `Blink Comparator` from the `Image` menu, and blink the raw object frame and the final image.

Q.6 (*a*) Describe any differences which you notice between the raw and final images.

(*b*) Summarise why you think flat-fielding would be important if (for example) you wished to use the CCD image to measure and compare the brightnesses of stars in different parts of the frame.

It is instructive to take a look at a real astronomical image frame and the improvement obtained by flat-fielding. Look at some of the images in the directory `ccd\examples`.

7.3 Obtaining and reducing more images

The above reduction process illustrates the complete procedure for correcting images for the effects of dark current and flat-field variations. If you have time to take some more images of other slides in the folder, or you wish to experiment further, then do so, and include any interesting results in your write-up.

Note the following:

- You should not need to refocus the camera lens. Adjust the exposure time if necessary to obtain a suitably exposed image.

- You have probably guessed that you can obtain a dark frame at the same time as the object frame in the `Grab` command; this ensures that the dark frame is of the same exposure and obtained at virtually the same temperature as the object frame. The dark frame is then automatically subtracted from the object frame before the image is downloaded to the PC and displayed. The image then only needs to be flat-fielded using the dark-subtracted flat-field already obtained.

When you have finished using the CCD, exit the program by selecting `Exit` from the `File` menu.

8   Writing up

Your write-up should include a descriptive account of the procedures followed in this practical, together with any background material you wish to include from references, and answers to the questions. Present a complete record of any measurements made from the images. There is no need to repeat how the control software is used, unless you wish to record for your own sake any points which you will find helpful in future. Make a note of any problems encountered and how you overcame them.

Obtain hard copies of some of your images for illustrating your write-up. In particular, illustrate one of the dark frames, the flat-field frame and any reduced images you wish to include. Inform the demonstrator of the directory where your images are stored. You will then be shown how to obtain hard copies of your images. If you do this the week following completion of the experiment, leave space in your write-up to paste in your images.

9   References and Background Reading

1. *CCD Astronomy: Construction and Use of an Astronomical CCD Camera*, Christian Buil (Willman-Bell, 1991).

2. *Handbook of CCD Astronomy*, Steve B. Howell (CUP, 2000)

3. *Model ST-6 Professional CCD Imaging Camera: Operating Manual* (Santa Barbara Instrument Group, 1993).

4. *CCD Astronomy* (Sky Publishing Corporation). Some useful articles can be found in the back issues of this publication which are held in the ULO library.

5. `http://www.ccd.com/ccdu.html` — Useful summary of properties of a CCD camera, from *Apogee Instruments Inc.*

6. `http://www.sbig.com/` — *SBIG Astronomical Instruments*' own homepage.