CCD Cameras are very useful devices used for high resolution imaging. They are particularly useful in Astronomy, where scientists have taken advantage of the CCD’s, or charge coupled devices, extreme sensitivity to light. This aspect of the device has many practical applications including laboratory research where detection of low light levels is needed. Images taken by a CCD need to be corrected for certain factors, including dark noise, readout noise, and saturation, among others. This can be done through collection of dark frames and flat fields, which can be subtracted from an image using image data reduction software. Basic CCD theory and operation, CCDOps and IRAF software usage, and calibration imaging will be discussed in this essay.
CCD Camera Operation and Theory: A Basic Introduction

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Introduction

A CCD, or charged coupled device, is a device used in digital photography that converts an optical image into electrical signal. CCD chips can detect faint amounts of light and are capable of producing high resolution images needed in scientific research and applications thereof. CCDs are particularly useful in astronomical imagery due to their great sensitivity to light. In theory, CCDs are linear-producing accurate images, transmitting the value they detect in a 1:1 ratio. This is usually not the case. Various factors, such as dark noise, readout noise, saturation, along with the fact that each pixel on a CCD is unique and varies from its neighbors, require that in-depth testing, analysis, and data reduction be implemented when using a CCD for any type of scientific imagery. Other variables, including the effects of a lens before a CCD and shutter speed of the camera being used, along with others, must be taken into consideration and dealt with accordingly in order to obtain a true image. There are various methods of testing for the above factors, a few of which will be described, along with the appropriate data reduction procedure.

Basic Theory of a CCD

The CCD is a special integrated circuit consisting of a flat, two dimensional array of small light detectors referred to as pixels. The CCD chip is an array of Metal-Oxide-Semiconductor capacitors (MOS capacitors), each capacitor represents a pixel. Each pixel acts like a bucket for electrons. A CCD chip acquires data as light or electrical charge. During an exposure, each pixel fills up with electrons in proportion to the amount of light that enters it. The CCD takes this optical or electronic input and converts it into an electronic signal. The electronic signal is then processed by some other equipment and/or software to either produce an image or to give the user valuable information.

Practical Applications of the CCD Camera

As stated, CCD cameras are useful in scientific imagery, especially in astronomy, where, with the help of a telescope, they allow for high resolution images of stars, galaxies, and other
celestial bodies that human eye cannot detect. CCD cameras can also be used in a laboratory to image in finer detail than a regular camera. The fact that CCDs are extremely sensitive to light makes them useful in experimentation where faint light detection is needed.

For example, the 8-inch shutter pictured below leaks about 1/10,000ths of incident light. Even in a dark room, the leaked light was imperceptible to experimenters. Though, a 10 second integration time CCD exposure can resolve all the details of the leaked light as shown in the picture. By applying IRAF image processing (to be described later), we removed extraneous lighting by subtracting a dark image from the signal image.

![8-inch shutter](image)

### Use of a CCD in a Controlled Environment

For the purposes of this essay and the description of CCD operation, functionality, test methods, and data reduction, it will be assumed that all CCD use is in a controlled environment such as an indoor laboratory or dark room. A procedure for operation in this type of environment will be described. Keep in mind that CCD usage in different situations call for other procedures than the ones described below, although many of the same principles still apply.

The CCD that was used for the actual data that will be represented is a product of SBIG, Santa Barbara Instrumentation Group. The model used was the ST-8300M/C.

<table>
<thead>
<tr>
<th>Table B. Specifications for the ST-8300</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CCD</strong></td>
</tr>
<tr>
<td>Pixel Array</td>
</tr>
<tr>
<td>Total Pixels</td>
</tr>
<tr>
<td>Pixel Size</td>
</tr>
<tr>
<td>Shutter Type</td>
</tr>
<tr>
<td>Exposure</td>
</tr>
<tr>
<td>Dimensions</td>
</tr>
</tbody>
</table>

When operating a CCD camera of these sorts, software must be used to acquire, view, and edit images. CCDOps is the software that was used in the acquisition of all images pictured. CCDOps is a free SBIG camera control software for Windows provided with the purchase of an SBIG camera. While simple to operate, CCDOps effectively controls all camera functions and is useful for basic image processing, although limitations may exist.
When further image processing and data reduction is necessary, many other useful programs exist, one of which is IRAF. IRAF stands for Image Reduction and Analysis Facility, and is a general purpose software system for the reduction and analysis of astronomical data. IRAF is written and supported by the IRAF programming group at the National Optical Astronomy Observatories (NOAO) in Tucson, Arizona. NOAO is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under cooperative agreement with the National Science Foundation. Basic IRAF operations will be explained in further detail later on in this report.

Basic CCDOps Usage

The following process describes operation of CCDOps from a Windows XP environment along with a few useful commands included in the program:

1. Install CCDOps onto a computer that runs Windows before connecting the camera to the computer.
   a. The process is simple and detailed instructions accompany the software package.
   b. Make sure that the proper drivers for specific camera are installed.
2. SBIG cameras come equipped with a USB cable that connects the camera to the computer.
   a. Plug the camera’s power supply into the wall and note that the internal fan comes on.
   b. Connect the USB to the computer and follow instructions provided in the manual and the “Found New Hardware Wizard” prompts.
3. Once CCDOps is installed and the camera is successfully connected to the computer, run CCDOps.
   a. The interface will display many commands, functions, and information concerning the camera in use.
      i. At first, the camera will not show up on the bottom panel of the display.
      ii. Click the Setup command in the Camera menu.
         1. The camera should automatically become connected.
            a. One can check the bottom right ribbon to verify that a connection has been established.
         2. Cooling is an option under Setup.
            a. A CCD should be cooled to approximately 30-35 degrees below the ambient temperature to reduce noise.
            b. One can select a temperature for the camera to reach but observe in the bottom right ribbon the percent capacity that is being used to cool camera.
            c. Once the temperature is reached, the percent capacity should be no more than 60-80 percent, and should never be operating at 100 percent.
            d. The fan should always be on.
b. *Grab* is the command used to collect an image.
   i. Options under *Grab* include *Integration time*, *Dark frame* (yes, no, only), *Special Processing*, *Exposure Delay*, and *Image Size*.
   ii. One can set the *Integration time* for the however long of exposure is required, but some cameras have limitations on how fast of exposure is possible.
      1. For example, the ST8300’s quickest exposure time is 0.1 seconds.
      2. The longest possible exposure time is 3600 seconds.
c. Under *Special Processing*, one can take a series of consecutive images using *Auto Grab*.
   i. This is useful when acquiring a set of dark frames at a certain integration time.
   ii. Another application is to observe changes in an image when one variable is adjusted.
d. Saving Images
   i. It is important to save all images with descriptive titles.
   ii. CCDOps requires that an image be saved before another image is taken or opened.
   iii. Images must be saved in *.fits* format to be compatible with IRAF.

These are just a few functions that CCDOps exhibits. The program also allows for a certain degree of image processing, mostly aesthetical.

**Dark Frames**

A dark frame is an image taken, theoretically, with no exposure to light. The shutter remains closed, but light may still leak in to a certain degree. In order to obtain a decent dark frame, it may be necessary to take one’s images in a so-called “dark room”. This is a room that is painted black, limiting reflection of light. Once all of the lights in a dark room are off, the amount of light that is present is essentially negligible. A problem that was presented was placement of the computer used to operate the camera. A computer, surprisingly, emits enough light to become an issue in CCD operation. For the acquisition of dark frames, this was easily fixed by covering the CCD itself with a black box that greatly reduced ambient light. Once the lights were off, this setup seemed to be appropriate for collection of dark frames.

As one can see, the image has a sort of “salt and
pepper” look to it. This is due to a few factors, one of which is the fact that some pixels are “hot pixels”. These exist because of an attribute of CCD sensors called dark current. A pixel in an ideal CCD, in the absence of light, would maintain a steady value. When exposed to light the pixel’s value would increase in response to the light but then as soon as the light went away the pixel would maintain its value again. In reality, CCD pixels suffer from the affects of dark current whereby the pixel’s value slowly increases, or brightens, over time. “Hot Pixels” are those where the dark current is higher than average.¹

In this five second exposure, there is noticeably more “light” than the first image, although both were taken under the same conditions, that is approximately 0°C, under a dark box, in the same dark room.

The existence of dark current can greatly alter an image, especially one of extended integration time. Cooling a CCD camera helps reduce the dark current. Using IRAF or another image processing software, dark frames can be “subtracted” from the real image to remove the effects that dark current has upon the image.

Another phenomenon evident in the above image is a brightening on the left of the image. This is referred to as readout glow and is caused by the electronics in the CCD. Each pixel must be digitized, or converted from analog to digital units. The readout glow in a buildup of light from a glow from the preamplifier structures in the upper-left hand corner of the CC. Read noise is another factor that affects a dark image. This is the noise in dark frames that have a zero time exposure.¹ A zero second exposure is referred to as a bias frame. The noise in a bias frame demonstrates the noise due to the electronics in the camera and the variance in pixels before these values can be altered by time.

This bias frame taken by the ST-8300 looks similar to the five second exposure, but there are less hot pixels and the image is less noisy in general, as would be expected.

**Averaging Images**

Averaging is important when dealing with such high resolution images dependent on sensitive electronics. Every five second dark frame is not identical due to the fact that the electronics operate a little differently each time and pixels may exhibit some degree of variance. Some pixels may become saturated, that is too many
photons hit it and the signal can no longer increase. In order to obtain a more accurate dark frame, one should average a series of images. To do this, one must collect an odd number of images, preferably about 15-19, all at a certain integration time. Once the images are collected, IRAF can be used to obtain the mean value from the collection. Finding the mean is a little different from finding the average, but the mean value takes into account the fact that some values may be extremely off, as in the case of saturated pixels. Once an averaged, or mean, dark image is obtained, it is called a Master Frame and can be used again and again, being subtracted from actual images of the same integration time. But averaging is not only used for dark imaging; it is also useful when taking images of evenly distributed light, or flats.

**Flat Frames**

Flat frames, or flat fields, are images of evenly distributed light. A good light source to provide uniform distribution at a certain wavelength is an LED, or light emitting diode. Other light sources can be used as well, such as a halogen lamp. The light should be reflected off of a white surface aimed at by the CCD camera. It is difficult to acquire a perfect flat image because of the sensitivity of the CCD and shadows cast by a lens over the CCD. A good flat should portray how each pixel responds to light. Flats can be used to correct vignetting, or obstruction of light paths by parts of the instrument, as well as effects of dust particles on a lens. Flats can be averaged and subtracted from an image just like darks in order to remove the effects of vignetting and dust as well as the effects of a shutter from an image, particular one of fast exposure time. By taking a series of flats at different exposure times, subtracting out the appropriate darks, and combining the flats with IRAF, one can create a “shutter map” which can be useful in correcting shutter effects. This flat image exhibits some of these problems that must be corrected. A few dust particles are noticeable in the left side of the image. This image was not corrected for dark current, so there is a sort of fade-out observed. A shadow from the lens that was used is also portrayed on the bottom right corner of the image.

Flat fields are very useful, once obtained. They can be used to determine many characteristics unique to a CCD, such as how it responds to light with increasing exposure time. A good CCD will respond with “linearity”, that is, as exposure time increases, the value read by the electronics in the camera will increase proportionally. It is important to know whether or not a CCD is operating linearly.

![A flat frame taken by an SBIG camera with a Nikon lens](image-url)
Using Iraf

IRAF is a very good program for astronomical image processing. It can be challenging to learn, but it is very rewarding once mastered. For the purposes of this essay, only extremely basic IRAF commands needed to perform a few of the operations discussed will be covered. IRAF can be downloaded for free from the IRAF home page, or from other sources on the web. If IRAF is being run on a windows computer, Cygwin must be downloaded first. Cygwin is a Linux-type environment for Windows and can also be downloaded for free from the web. There are websites that have step-by-step instruction for how to correctly download and install Cygwin and IRAF. The command line for IRAF is similar to that of Cygwin/Linux but IRAF has many commands unique to the program that must be learned. Once IRAF is installed along with its appropriate packages and an image viewing software, such as DS9, IRAF can be used to view images and their histograms, analyze saturation points, pixel values, and image information, average series of images, and perform mathematical operations on images, including subtraction of Master Frames to remove imperfections, for a few.

To run IRAF, type “cl” in the directory containing the “login.cl” file. This will bring up the available packages and allow operation of the program.

To perform arithmetical operations on an image the command “Imarith” is used. “Imarith” is short for image arithmetic. If imarith acts on one image, it applies one arithmetic command to every pixel in that image. For example, multiplication by 1000 would be given by:

```
imarithmetic Picture1.fits * 1000 ProductPicture
```

Imarith can also combine two images on pixel-by-pixel bases via an arithmetic command. For example, in the shutter test, we removed the dark image from the signal image to isolate the transmitted light and divided by intensity to normalize. Its command can be given by:

```
imarithmetic Signal.fits - Dark.fits Transmitted.fits
imarithmetic Transmitted.fits / Intensity.fits PercentLeaked.fits
```

To learn more about any IRAF command type “help ’command’”.

Conclusion

The CCD, charged coupled device, is an amazing piece of technology that is very useful in science, particularly in Astronomy, as well as in everyday life. High resolution CCD images have allowed scientists to observe realms of the universe that the human eye had never seen. Using various means of imaging and data reduction, one can correct variances and imperfections exhibited by a CCD, and obtain a very accurate image.
References


Helpful Websites about CCDs


Helpful Websites about IRAF