Activity 1: Introduction to CCDs

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In this activity the basic principles of CCD imaging is explained.

What is a CCD?

Charge Coupled Devices (CCDs) were invented in the 1970s and originally found application as memory devices. Their light sensitive properties were quickly exploited for imaging applications and they produced a major revolution in Astronomy. They improved the light gathering power of telescopes by almost two orders of magnitude. Nowadays an amateur astronomer with a CCD camera and a 15 cm telescope can collect as much light as an astronomer of the 1960s equipped with a photographic plate and a 1m telescope.

CCDs work by converting light into a pattern of electronic charge in a silicon chip. This pattern of charge is converted into a video waveform, digitised and stored as an image file on a computer.

Photoelectric Effect

The effect is fundamental to the operation of a CCD. Atoms in a silicon crystal have electrons arranged in discrete energy bands. The lower energy band is called the Valence Band, the upper band is the Conduction Band. Most of the electrons occupy the Valence band but can be excited into the conduction band by heating or by the absorption of a photon. The energy required for this transition is 1.26 electron volts. Once in the conduction band the electron is free to move about in the lattice of the silicon crystal. It leaves behind a ‘hole’ in the valence band, which acts like a positively charged carrier. In the absence of an external electric field the hole and electron will quickly re-combine and be lost. In a CCD an electric field is introduced to sweep these charge carriers apart and prevent recombination.

Increasing energy

Thermally generated electrons are indistinguishable from photo-generated electrons. They constitute a noise source known as ‘Dark Current’ and it is important that CCDs are kept cold to reduce their number.

CCD Analogy

A common analogy for the operation of a CCD is as follows:

An number of buckets (Pixels) are distributed across a field (Focal Plane of a telescope) in a square array. The buckets are placed on top of a series of parallel conveyor belts and collect rain (photons) across the field. The conveyor belts are initially stationary, while the rain slowly fills the buckets (During the course of the exposure). Once the rain stops (The camera shutter closes) the conveyor belts start turning and transfer the buckets of rain, one by one, to a measuring cylinder (Electronic Amplifier) at the corner of the field (the corner of the CCD).

The animation in the following slides demonstrates how the conveyor belts work.
Exposure finished, buckets now contain samples of rain.

Conveyor belt starts turning and transfers buckets. Rain collected on the vertical conveyor is tipped into buckets on the horizontal conveyor.

Vertical conveyor stops. Horizontal conveyor starts up and tips each bucket into the measuring cylinder.
After each bucket has been measured, the measuring cylinder is emptied, ready for the next bucket load.
Structure of a CCD

The image area of the CCD is positioned at the focal plane of the telescope. An image then builds up that consists of a pattern of electric charge. As the end of the exposure this pattern is then transferred, pixel at a time, by way of the serial register to the on-chip amplifier. Electrical connections are made to the outside world via a series of bond pads and thin gold wires positioned around the chip periphery.

Quantum Efficiency Comparison

The graph below compares the quantum of efficiency of a thick frontside illuminated CCD and a thin backside illuminated CCD.
**Image Defects in a CCD 1.**

Unless one pays a huge amount it is generally difficult to obtain a CCD free of image defects. The first kind of defect is a 'dark column'. Their locations are identified from flat field exposures. Dark columns are caused by 'traps' that block the vertical transfer of charge during image readout. The CCD shown at left has at least 7 dark columns, some grouped together in adjacent clusters. Traps can be caused by crystal boundaries in the silicon of the CCD or by manufacturing defects. Although they spoil the chip cosmetically, dark columns are not a big problem for astronomers. This chip has 2048 image columns so 7 bad columns represents a tiny loss of data.

**Image Defects in a CCD 2.**

There are three other common image defect types: Cosmic rays, Bright columns and Hot spots. Their locations are shown in the image below which is a lengthy exposure taken in the dark (a 'Dark Frame'). Bright columns are also caused by traps. Electrons contained in such traps can leak out during readout causing a vertical streak. Hot spots are pixels with higher than normal dark current. Their brightness increases linearly with exposure times. Cosmic rays are unavoidable. Charged particles from space or from radioactive traces in the material of the camera can cause ionisation in the silicon. The electrons produced are indistinguishable from photo-generated electrons. Approximately 2 cosmic rays per cm² per minute will be seen. A typical event will be spread over a few adjacent pixels and contain several thousand electrons. Sometimes one can light-emitting defects which are hot spots that act as tiny LEDs and cause a halo of light on the chip.

**Image Defects in a CCD 3.**

Some defects can arise from the processing electronics. This negative image has a bright line in the first image row. Dark column

Hot spots and bright columns

Bright first image row caused by incorrect operation of signal processing electronics.
Biases, Flat Fields and Dark Frames 1.

These are three types of calibration exposures that must be taken with a scientific CCD camera, generally before and after each observing session. They are stored alongside the science images and combined with them during image processing. These calibration exposures allow us to compensate for certain imperfections in the CCD. As much care must be exercised in obtaining these images as for the actual scientific exposures. Applying low quality flat fields and bias frames to scientific data can degrade rather than improve its quality.

Bias Frames
A bias frame is an exposure of zero duration taken with the camera shutter closed. It represents the zero point or base-line signal from the CCD. Rather than being completely flat and featureless the bias frame may contain some structure. Any bright image defects in the CCD will of course show up, there may also be slight gradients in the image caused by limitations in the signal processing electronics of the camera. It is normal to take about 5 bias frames before a night’s observing. These are then combined using an image processing algorithm that averages the images, pixel by pixel, rejecting any pixel values that are appreciably different from the other 4. This can happen if a pixel in one bias frame is affected by a cosmic ray event. It is unlikely that the same pixel in the other 4 frames would be similarly affected so the resultant ‘master bias’ should be uncontaminated by cosmic rays. Taking a number of biases and then averaging them also reduces the amount of noise in the bias images. Averaging 5 frames will reduce the amount of read noise (electronic noise from the CCD amplifier) in the image by the square-root of 5.

Biases, Flat Fields and Dark Frames 2.

Flat Fields
Some pixels in a CCD will be more sensitive than others. In addition there may be dust spots on the surface of the chip or coloured filters mounted in front of the camera. A star focused onto one part of a chip may therefore produce a lower signal than another star of the same brightness. These variations in sensitivity are called flat-field errors and need to be subtracted from the science image. The way to do this is to take a ‘flat-field’ image: an image in which the CCD is evenly illuminated with light. Dividing the science image, pixel by pixel, by a flat-field image will remove these sensitivity variations very effectively.

Since some of these variations are caused by shadowing from dust spots, it is important that the flat fields are taken shortly before or after the science exposures; the dust may move around! As with biases, it is normal to take several flat-field frames and average them to produce a ‘Master’. A flat field is taken by pointing the telescope at an extended, evenly illuminated source. The twilight sky or the inside of the telescope dome are the usual choices. An exposure time is chosen that gives pixel values about halfway to their saturation level: i.e. a medium-level exposure.

Dark Frames.
Dark current is generally absent from professional cameras since they are operated cold using liquid nitrogen as a coolant. Amateur systems running at higher temperatures will have some dark current and its effect must be minimised by obtaining ‘dark frames’ at the beginning of the observing run. These are exposures with the same duration as the science frames but taken with the camera shutter closed. There are later subtracted from the science frames. Again, it is normal to take several dark frames and combine them to form a ‘Master’, using a technique that rejects cosmic ray features.

Biases, Flat Fields and Dark Frames 3.

A dark frame and a flat field from the same EEV42-80 CCD are shown below. The dark frame shows a number of bright defects on the chip. The flat field shows a criss-cross patterning on the chip created during manufacture and a slight loss of sensitivity in two corners of the image. Some dust spots are also visible.

Biases, Flat Fields and Dark Frames 4.

If there is significant dark current present, the various calibration and science frames are combined by the following series of subtractions and divisions:

1. Subtract the dark frame from each science image.
2. Divide each dark-subtracted image by the flat field.
3. Combine the flat-field images and divide each resulting image by this combined flat field.
4. Finally, combine all the bias images and divide each image by the master bias.
**Dark Frames and Flat Fields 5**

In the absence of dark current, the process is slightly simpler:

- Bias Image
- Flat Field Image
- Science Frame
- Flat-Bias Science Frame
- Output Image

**Good Observing Procedure**

- Take 3-5 exposures of each object in each filter
- Move telescope slightly between exposures.
- Allows you to get rid of cosmic rays and avoid bad pixels

**Photometric Calibration**

- Vega has magnitude zero in every filter
- What is magnitude of your asteroid?
- Calibration Procedure:
  - observe Vega
  - observe asteroid
  - \( m_s - m_l = 2.5 \log_{10} \left( \frac{f_s}{f_l} \right) \)

\[ m_{ast} - m_{vego} = 2.5 \log_{10} \left( \frac{f_{vego}}{f_{ast}} \right) \]

**Zeropoint Calibration**

- \( m_{ast} - m_{vego} = 2.5 \log_{10} \left( \frac{f_{vego}}{f_{ast}} \right) \)
- \( m_{ast} = ZP - 2.5 \log_{10}(f_{ast}) \)
- \( ZP = 2.5 \log_{10}(f_{vego}) \)
Effect of Atmosphere

- The equations on the previous slide work if
  - you measure flux of both objects with the exact same aperture
  - you observe both objects through the same amount of air/atmosphere

Effect of Atmosphere

- Zenith Distance

<table>
<thead>
<tr>
<th>Zenith Distance</th>
<th>Sec Z (airmass)</th>
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<tbody>
<tr>
<td>0°</td>
<td>1</td>
</tr>
<tr>
<td>60°</td>
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<tr>
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</tr>
<tr>
<td>78°</td>
<td>5</td>
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</tbody>
</table>

Don’t go higher than 2!!!

Wavelength Dependence of Atmosphere Absorption

http://www.britastro.org/vss/ccd_photometry.htm

Solving for Airmass Term

- If you observe your standard star (Vega) and object (asteroid) at different airmasses, you have to account for atmospheric absorption when solving photometric equation.

\[ m = ZP - 2.5 \log_{10}(\text{flux}) + c \times X \]

where \( X \) is airmass and \( c \) is coefficient
Complete Photometric Equation

- If you observe your standard star (Vega) and object (asteroid) at different airmasses, you have to account for atmospheric absorption when solving photometric equation.

\[ m = c_1 - 2.5 \log_{10}(\text{flux}) + c_2 X + c_3 (V-R) + c_4 (V-R)X \]

where:
- \( c_1 = ZP \)
- \( c_2 = \text{airmass term} \)
- \( c_3 = \text{color term} \)
- \( V-R = \text{VR} \)

- Observe many standard stars at many different airmasses to solve the equation accurately