The Life of an Astronomical Photon

Image Calibration

http://www.astro.yale.edu/mgeha/teaching.php
http://astronomy.nmsu.edu/holtz/a535/ay535notes/node8.html
Chromey Chapters 8 & 9
http://www.physics.upenn.edu/~garyb/#courses (see Astr 503 notes)
The Life of an Astronomical Photon

Object \xrightarrow{\text{convolution}} X \xrightarrow{} \text{Image}

PSF

\text{= point spread function}
Nyquist Sampling

under sampled

one ccd pixel

over sampled
Nyquist Sampling

Nyquist Thm: To accurately reproduce an analog signal, need to digitally sample at twice the "frequency" of the signal.
The Charge-Coupled Device (CCD)

There is a minimum threshold frequency before a photoelectron is produced.

For Silicon, the minimum energy is $E_c = 1.26$ eV which is equal to a wavelength of 1 micron.

In the infrared, various different substances are used, including HgCdTe, InSb, and PtSi which have min wvl closer to 2-3 microns.

The maximum energy (minimum wavelength) is set by the thickness of the detector. High energy photons are absorbed before reaching valence band. For most CCDs, the maximum energy photon detected is in near UV.
An astronomical photon passes through the atmosphere, telescope optics and camera optics, and is converted into an electron by the CCD. The CCD electronics converts this analog signal into a digital image.

An analog-to-digital circuit converts electrons into a digital signal (typically 8-bit or 16-bit). We measure the signal in the output image in **Analog-to-Digital Units (ADU)**.
Output voltage from a given pixel is converted to a digital number (ADUs – analog-to-digital units)

A/D (ADC, analog-to-digital converter) performs the conversion of output voltage signal to a digital number

Digitization circuits are complicated and not included in a CCD chip, “off-chip” circuit.

Digital output values can only be integer numbers with digital bits:

- 8 bits: \(2^8 = 256\)
- 10 bits: \(2^{10} = 1024\)
- 14 bits: \(2^{14} = 16383\)
- 16 bits: \(2^{16} = 65535\)

Ultimate readout speed depends on how fast the process of pixel examination and A/D conversion can take place

At a readout rate of 50 \(\mu s/\text{pixel}\) (~ 20 kHz), how long does it take over to read out a 2048 by 2048 CCD?
Dark Energy Survey Camera:
62 CCD’s; 570 megapixels
CCD Data Reduction

This number is in ADU.

The goal of data reduction is to convert ADU into a meaningful flux unit (e.g., photons/sec/pixel)
The Analog-to-Digital Converter converts electrons in each pixel into a digital signal.

-- The Gain (G) is the number of electrons combined to generate one ADU.

\[
\text{Gain} = \frac{N_{\text{electrons}}}{\text{ADU}}
\]

-- One ADU = \( N_{\text{electrons}} / G \), where \( N_{\text{electrons}} \) = number of electrons arriving at amplifier

-- Normally, G is set as a positive number larger than 1.

-- The dynamic range of a CCD is limited by the number of digital bits of the output.
CCD Data Reduction: Analog-to-Digital Units and Gain

An Example: HST ACS

The ACS imager on HST produces a 16-bit output, allowing $2^{16} = 65536$ values.

Each pixel can physically hold a maximum of 85000e-.

What gain setting (e-/ADU) allows us to use the full ADU range?
The ACS imager on HST produces a 16-bit output, allowing $2^{16} = 65536$ values. Each pixel can physically hold a maximum of $85000e^-$. 

What gain setting ($e^-$/ADU) allows us to use the full ADU range?

**ANSWER:** gain $= 85000 e^- / 65536 = 1.3 e^-$/ADU
CCD Data Reduction: Full Well Depth and Linearity

**Full Well Depth:** The maximum charge that can be held by a pixel

**Linearity:** How consistently a CCD responds to light over its full well depth.

- The physically larger a pixel, the more charge it can hold
- A pixel is ‘saturated’ when it has reached its maximum charge
- A CCD pixel full well-depth is typical ~100,000 electrons
- A CCD will become non-linear as it reaches ~80% of full well depth
Data Reduction

- **Bad columns**: fixed by averaging signal on either side
- **Out-of-focus dust**: fixed by flat field
- **Bias Structure**: fixed by bias subtraction
- **Saturated star blooming**
CCD Data Reduction

Just as the atmosphere and the telescope optics affect the incoming astronomical signal, the CCD and readout electronics add noise and systematic effects into the data.

- Quantum Efficiency
- Full well depth and Linearity
- Read noise
- Dark Current
- Charge transfer inefficiency
- Cosmetic defects
- Fringing

For more details see:
http://astronomy.nmsu.edu/holtz/a535.fall11/ay535notes/node7.html
CCD Data Reduction: Dark Current

Even though CCDs are cooled, thermal motion librate electrons which are then counted as a (spurious) photon detection. This is called dark current.

The amount of dark current is proportional to the exposure time.
CCD Data Reduction: Read Noise

Readout noise is Johnson (thermal) noise in the on-chip amplifier and A/D circuit.

Readout noise is quantified in terms of number of electrons. Typically 3-5 electrons per pixel for modern CCDs.

Readout electronics will give a finite signal when there are no photoelectrons, this is a measure of the voltage in each pixel. This is called the bias level.

Can reduce readout noise by reading out array slower.

Note: Dark current adds to the signal. Read noise adds to the noise in the signal.
CCD Data Reduction: Charge Transfer Efficiency (CTE)

When pixels are nearly empty, charge can be trapped by impurities in the silicon. Faint images have tails in vertical (read-out) direction.

This is a particular problem for HST, but can be characterized and corrected:

Modern CCDs can have CTE per transfer of 99.999995%, after 2000 transfers only 0.1% of charge is lost.
At longer (redder) wavelengths, light can interfere with itself, creating fringing pattern. Mostly a problem in very thinned CCDs.
## CCD Data Reduction

### DECam Characteristics

#### Main Characteristics of Focal Plane

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field of View</td>
<td>3 square degree (2.2 degree field of view)</td>
</tr>
<tr>
<td>Pixel scale</td>
<td>0.2637 arcsec/pixel (center), 0.2626 arcsec/pixel (edge)</td>
</tr>
<tr>
<td>Detector</td>
<td>62, 2048x4096 pixel red-sensitive science CCDs from LBNL, 520 megapixels total (570 Mpix including guide and focus CCDs)</td>
</tr>
<tr>
<td>Read-out noise</td>
<td>7e-</td>
</tr>
<tr>
<td>Read-out time</td>
<td>20 seconds</td>
</tr>
<tr>
<td>Dark-current</td>
<td>~&lt;25 e-/pixel/hr (spec)</td>
</tr>
<tr>
<td>QE</td>
<td>60% at 0.4 μm, 90% at 0.9 μm</td>
</tr>
<tr>
<td>Dynamical range</td>
<td>16 bit</td>
</tr>
<tr>
<td>Inter-CCD Gaps</td>
<td>3.0 mm (201 pixels) along long edge (e.g., between S4 and N4); 2.3 mm (153 pixels) along short edge (e.g., between N4 and N5)</td>
</tr>
<tr>
<td>Cosmetics</td>
<td>Good to excellent. On average, each CCD has 0.05% bad pixels and the worst CCD has 0.39% bad pixels.</td>
</tr>
<tr>
<td>Filters</td>
<td>6 filters now available (ugrizY)</td>
</tr>
<tr>
<td>Gain</td>
<td>4.5 e-/ADU (typical, provisional 2012-Nov)</td>
</tr>
<tr>
<td>Non linearity, &lt; 1%</td>
<td>For normal observing, keep level below 100,000 e-, 22,000 ADU</td>
</tr>
<tr>
<td>(provisional/conservative)</td>
<td></td>
</tr>
<tr>
<td>Raw data format</td>
<td>FITS (with extensions), 1 GB/file, ~600 Mbyte/file compressed</td>
</tr>
<tr>
<td>Instrument F ratio</td>
<td>f/2.7</td>
</tr>
<tr>
<td>Available filters</td>
<td>u g r i z Y</td>
</tr>
</tbody>
</table>
**DESCRIPTION**

The F9000 represents the next step in the evolution of the Alta line of cameras with faster readout speeds. The Alta F9000 uses a very large format 9-megapixel full frame sensor with anti-blooming gates, ideal for applications requiring large field of view, such as astrophotography, sky surveys and radiology. All Alta systems are backed by a 2 year warranty on the camera and lifetime warranty on the CCD chamber integrity.

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**CCD SPECIFICATIONS**

<table>
<thead>
<tr>
<th>Description</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCD</td>
<td>Kodak KAF-09000</td>
</tr>
<tr>
<td>Array Size (pixels)</td>
<td>3056 x 3056</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>12 x 12 microns</td>
</tr>
<tr>
<td>Imaging Area</td>
<td>36.7 x 36.7mm (1345mm²)</td>
</tr>
<tr>
<td>Imaging Diagonal</td>
<td>51.9mm</td>
</tr>
<tr>
<td>Linear Full Well (typical)</td>
<td>110K electrons</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>84dB</td>
</tr>
<tr>
<td>QE at 400nm</td>
<td>37%</td>
</tr>
<tr>
<td>Peak QE (550nm)</td>
<td>64%</td>
</tr>
<tr>
<td>Anti-blooming</td>
<td>&gt;100X</td>
</tr>
</tbody>
</table>

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**CCD SENSITIVITY**

![CCD Sensitivity Graph]

Imaging area of CCD

36.7 x 36.7mm
CCD Data Reduction

Typically, we remove instrument signatures in reverse order from which they were introduced.

1. **Bias level:** A CCD pixel has a non-zero ADU level simply by being read out.

2. **Dark Current:** Thermal motion can create electrons which cannot be distinguished from photon generated electrons.

3. **Flat fielding:** There are sensitivity differences between individual pixels

4. **Bad pixel or cosmic ray rejection:** Need to account for dead pixels, cosmic rays or saturated stars

5. **Image Registration/Shifting:** Individual science frames may have small spatial shifts.

6. **Sky Subtraction:** To determine true flux of an object, need to subtract background light from the sky.

For each of these steps, it is important to understand whether the correction is **additive or multiplicative**.
CCD Data Reduction: Bias Frame

Readout electronics will give a finite signal when there are no photoelectrons, this is a measure of the voltage in each pixel. This is called the bias level.

A bias frame is constructed by reading out the CCD with zero (t=0 second) exposure.

In addition to an overall level, the bias frame can occasionally show 2D fixed pattern noise.

The bias is the signal present in every pixel before exposure. Remove by subtracting the bias from every frame.

To create bias frame, take a series of zero level exposures and combine.
Stacking Images: Median vs. Mean

When combining three or more images, best to use the median rather than the mean. Improves bad pixel rejection.

Mean = The arithmetic average of a set of numbers
Median = The value for which half numbers are above and half are below.

For some set of numbers:

3, 3, 4, 5, 82

\[
\text{mean} = \frac{(3+3+4+5+82)}{5} = 19.4
\]

\[
\text{median} = 4
\]
CCD Data Reduction:  Image Stacking

A single bias image contains two types of noise

1. Cosmic Rays, hot pixels
2. Read Noise

Read Noise is noise inherent converting the number of electrons to a digital number.

If the ‘true’ value of the pixel is 100 e-, each measurement will have an error of $\sqrt{100}$.

Combing a series of repeat measurements reduces both types of noise:

1. Cosmic Rays removed by median combine
2. Read Noise is reduced by $N^{1/2}$ the number of frames combined.
A single bias image contains two types of noise

1. Cosmic Rays, hot pixels
2. Read Noise

Read Noise is noise inherent converting the number of electrons to a digital number.

If the ‘true’ value of the pixel is 100 e-, each measurement will have an error of $\sqrt{100}$.

Combing a series of repeat measurements reduces both types of noise:

1. Cosmic Rays removed by median combine
2. Read Noise is reduced by $N^{1/2}$ the number of frames combined.

The combined bias image is much smoother (or less grainy) in general. The noise is lower in the combined image so that you can see a slightly hot column more clearly in the combined image.
A single bias frame will have a mean equal to the bias level and width equal to the Read Noise.

The combined bias will also have mean equal to the bias level, and width equal to Read Noise / sqrt(N).
CCD Data Reduction: Bias Frame

Step #1: The (combined) bias frame is subtracted from every image.
Even though CCDs are cooled, thermal motion can librate electrons which are then counted as a (spurious) photon detection. This is called dark current.

The amount of dark current is proportional to the exposure time.

Take a series of ‘dark’ exposures with same exposure time as expected science exposures.

**Step #2:** Subtract the (combined, bias subtracted) dark frame from each science exposure. Need to match (or scale to) the exposure time.
CCD Data Reduction

Typically, we remove instrument signatures in reverse order from which they were introduced.

1. **Bias level:** A CCD pixel has a non-zero ADU level simply by being read out.

2. **Dark Current:** Thermal motion can create electrons which cannot be distinguished from photon generated electrons.

3. **Flat fielding:** There are sensitivity differences between individual pixels.

4. **Bad pixel or cosmic ray rejection:** Need to account for dead pixels, cosmic rays or saturated stars.

5. **Image Registration/Shifting:** Individual science frames may have small spatial shifts.

6. **Sky Subtraction:** To determine true flux of an object, need to subtract background light from the sky.

For each of these steps, it is important to understand whether the correction is **additive or multiplicative.**
CCD Data Reduction: Flat Fields

- Throughput loss to dust on optics
- Possible vingetting of field
- Intrinsic pixel-to-pixel sensitivity variations

Differences in the sensitivity are a multiplicative correction.

Ideally, we want uniform sensitivity throughputs across whole CCD.

- Flat fielding corrects for varying throughput as a function of position in the field.

Raw Science frame includes:
  - Throughput loss to dust on optics
  - Possible vingetting of field
  - Intrinsic pixel-to-pixel sensitivity variations
Suppose we observe an object which has intrinsic count rate of 100 ADU.

This object will also have noise associated with it, but for moment, assume these variations are due to sensitivity variations only.

<table>
<thead>
<tr>
<th>raw science</th>
<th>flat correction</th>
<th>corrected science</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>1.11</td>
<td>100</td>
</tr>
<tr>
<td>95</td>
<td>1.05</td>
<td>100</td>
</tr>
<tr>
<td>100</td>
<td>1.00</td>
<td>100</td>
</tr>
<tr>
<td>110</td>
<td>0.91</td>
<td>100</td>
</tr>
</tbody>
</table>

\[
\text{raw science} \times \text{flat correction} = \text{corrected science}
\]
CCD Data Reduction: Flat Fields

To create a flat field, observe a source assumed to be spatially flat.

Dome Flat:
- Observe a white spot on side of dome
- Each pixel is assumed to be illuminated uniformly

Differences in ADU levels of output image show the *relative sensitivity* of each pixel.
Flat fielding

- Generally 3 types: dome flats, twilight flats, dark sky flats.
- Twilight flats: generally better than dome for large scale structure, but twilight is short!
- Sky flats: can use dark sky exposures to make the flats. Advantage that can match the color of the night sky perfectly. But generally count level is low (in optical) so hard to build up enough S/N. Usually the rule in ground-based IR.
Flats in the IR

- Flats are additionally complicated in the IR: background is intrinsically, spatially non-uniform ==> thermal radiation coming from the telescope and dome structures (esp. at longer IR wavelengths).

- Given this, how do you make a flat at all? Can beat the problem by observing the sky on the same pixels as your object ==> difference frame.

- Another possibility is dome flats with and without lights: subtract the two for your flat. Of course, this has the potential problems associated with dome flats: incorrect illumination and color mismatches. Take both this kind and sky flats.

- Remember!! Systematic errors are the most troublesome! Take images of the same object at several different field locations and empirically determine how well the measurements repeat. This is highly advised in the IR.
CCD Data Reduction: Flat Fields

Raw Science

Flat Field normalized to unity

Created by combining multiple bias/dark corrected images of the dome. Overall flux normalized to unity.

Science
CCD Data Reduction: Flat Fields
CCD Data Reduction: Flat Fields
CCD Data Reduction: Flat Fields
CCD Data Reduction: Flat Fields

**Raw Science**

**Flat Field** normalized to unity

**Science**

**Step #3:** Every science frame is multiplied by the normalized flat frame.
CCD Data Reduction

To summarize data reduction steps to far:

\[
\text{Science} = \frac{\text{(Raw Science - Bias - Dark)}}{\text{Flat}}
\]

Where:

\[
\text{Bias} = \text{median (many t=0 exposures)}
\]

\[
\text{Dark} = \text{median (dark image - Bias)}
\]

\[
\text{Flat} = \frac{\text{Median (dome flats - Bias - Dark)}}{\text{normalization}}
\]

normalization chosen such that \(\sum \text{Flat} = 1\)
CCD Data Reduction: Bad pixels and Bad Columns

Most CCDs have a few bad pixels or bad columns. These can’t be used for science.

There are several reasons for a column to be bad (ranging from electronic to mechanic)

Can ‘remove’ by replacing these pixels with average surrounding value.

*or* move the telescope for each exposure so all science targets ‘see’ good pixels.
CCD Data Reduction: Saturated Stars and Blooming

The image below shows an extended source with bright embedded stars. Due to the long exposure required to bring out the nebulosity, the stellar images are highly overexposed and create bloomed images.

The charge capacity of a CCD pixel is limited, when a pixel is full the charge starts to leak into adjacent pixels. This process is known as ‘Blooming’.

(The image is from a CCD mosaic and the black strip down the center is the space between adjacent detectors)
CCD Data Reduction: Saturated Stars and Blooming

Bright stars also show diffraction spikes which may or may not be saturated.
Cosmic Rays: High energy particles hit the CCD, liberates electrons causing a spot on the image.

High energy particle can either be genuine cosmic rays (exotic particle from exploding supernovae, black holes, etc.), or just the decay products of radioactive atoms present in the lenses near the CCD.

Cosmic rays are usually easy to recognize—much sharper than stars (particle hits just a couple of pixels).
CCD Data Reduction: Registering and Shifting Images

For a given science target, we usually take multiple, dithered frames.

1. Multiple frames helps with cosmic ray rejection.

2. Fill in regions lost by bad pixels.

3. If needed, improve sampling.

To create combined image, need to determine number of pixels to shift each image.
In all ground-based images, the sky itself is luminous. To determine true brightness of astronomical sources, we need to subtract off the sky.

Deviations from the true sky value are positive counts (stars and galaxies), approximate the sky by the mode of the distribution.
CCD Data Reduction

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