Astronomy 211
Fall 2013

CCD Calibrations and Noise Considerations

Some material adapted from Simon Tulloch smt@ing.iac.es

Defects in a CCD

Cosmetically perfect CCD’s are incredibly expensive, so… we have defects.

The first kind of defect is a ‘dark column’. Their locations are identified from flat field exposures.

Flat field exposure of an EEV42-80 CCD

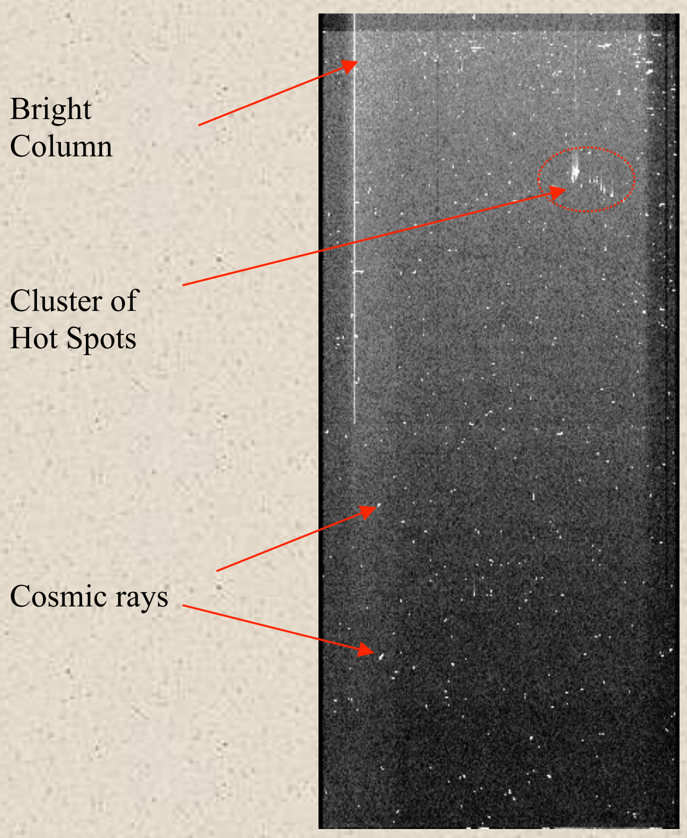
Dark columns are caused by ‘traps’ that block the vertical transfer of charge during image readout. The CCD shown at left has at least 7 dark columns, some grouped together in adjacent clusters.

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 – they usually flat out.

Image Defects

There are three other common image defect types : **cosmic rays, bright columns and hot spots**.



900s dark exposure of an EEV42-80 CCD

Bright columns are also caused by traps . Electrons contained in such traps can leak out during readout causing a vertical streak.These usually flat out.

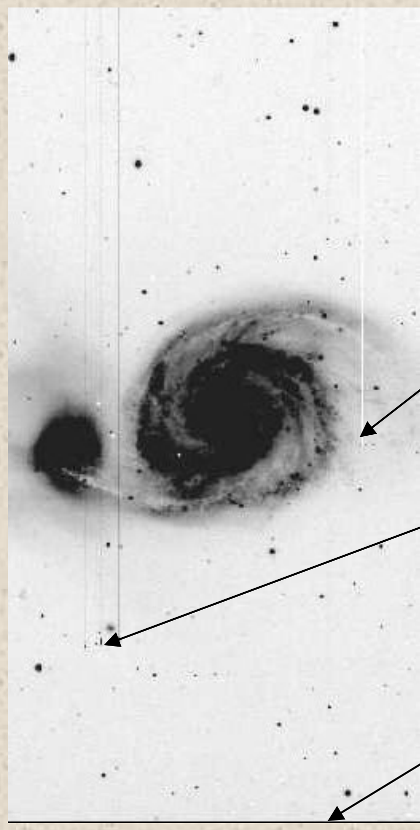
Hot spots are pixels with higher than normal dark current. Their brightness increases linearly with exposure times. These usually flat out

Cosmic rays are unavoidable. Charged particles from space or from radioactive traces in the material of the camera can cause ionization in the silicon. The electrons produced are indistinguishable from photo-generated electrons. Approximately 2 cosmic rays per cm^2 per minute will be seen. A typical event will be spread over a few adjacent pixels and contain several thousand electrons.

Cure: Dithering and subsequent median filtering.

How defects appear on an image

M51



Dark column

Hot spots and bright columns

Bright first image row caused by incorrect operation of signal processing electronics.

Calibration Frames

These are required to extract the best information from science frames!

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.
- Take MANY (they're cheap!) and then average them, rejecting the minimum and maximum values.
- Noise in the bias is reduced by $1/\sqrt{N}$ for N frames.

Flat Fields

- Some pixels are more/less sensitive than others.
- Dust in optics.
- Take image of evenly illuminated extended source (spot in dome, or twilight sky); divide into science frames (after processing). use a well-exposed flat with >10000 counts/pixel → noise/pix <0.01 x signal → ~no noise added to the calculation

Dark Frames.

- Professional CCDs are usually liquid nitrogen cooled (<100K) so dark current is negligible.
- Take several darks the same duration as longest image, and combine to eliminate cosmic rays.

Example of a Dark and a Flat

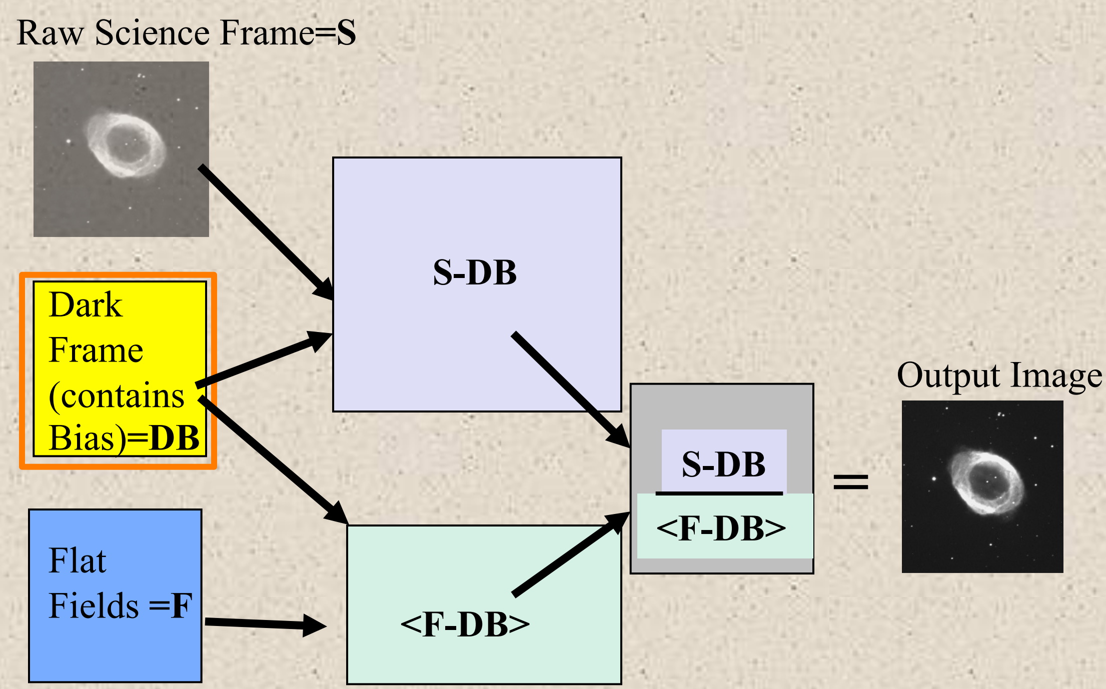
A dark frame and a flat field from the same EEV42-80 CCD are shown below. The dark frame shows a number of bright defects on the chip. The flat field shows a criss-cross patterning on the chip created during manufacture and a slight loss of sensitivity in two corners of the image. Some dust spots are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

Dark Frame

Flat Field

Calibrations Needed for CCD Images

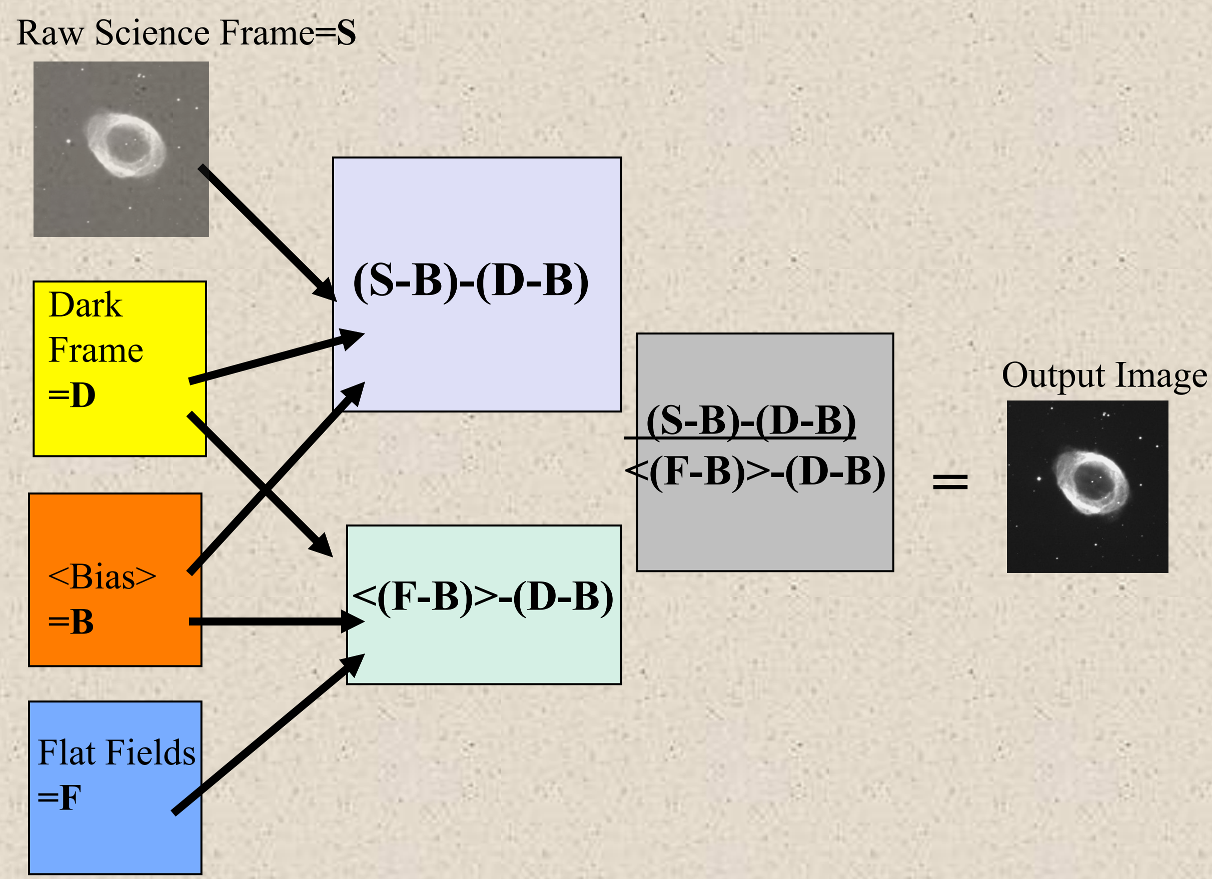
If there is significant dark current, as in our CCD, this is how the image arithmetic proceeds:



The dark frame must be the same exposure as the object image.

Calibrations Needed for CCD Images

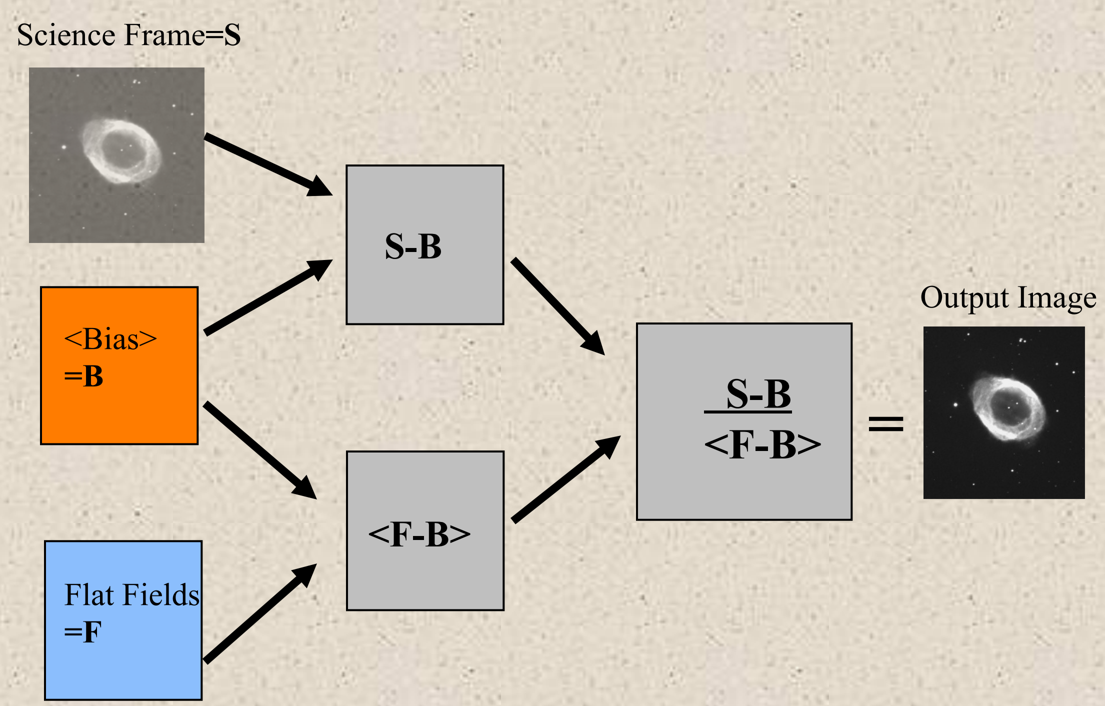
If there is significant dark current, as in our CCD, and dark and many bias frames are taken separately, this is how the arithmetic proceeds:



If the dark frame exposure is longer than the object frame, it must be bias-subtracted first, then scaled to the proper time.

Calibrations Needed for CCD Images

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



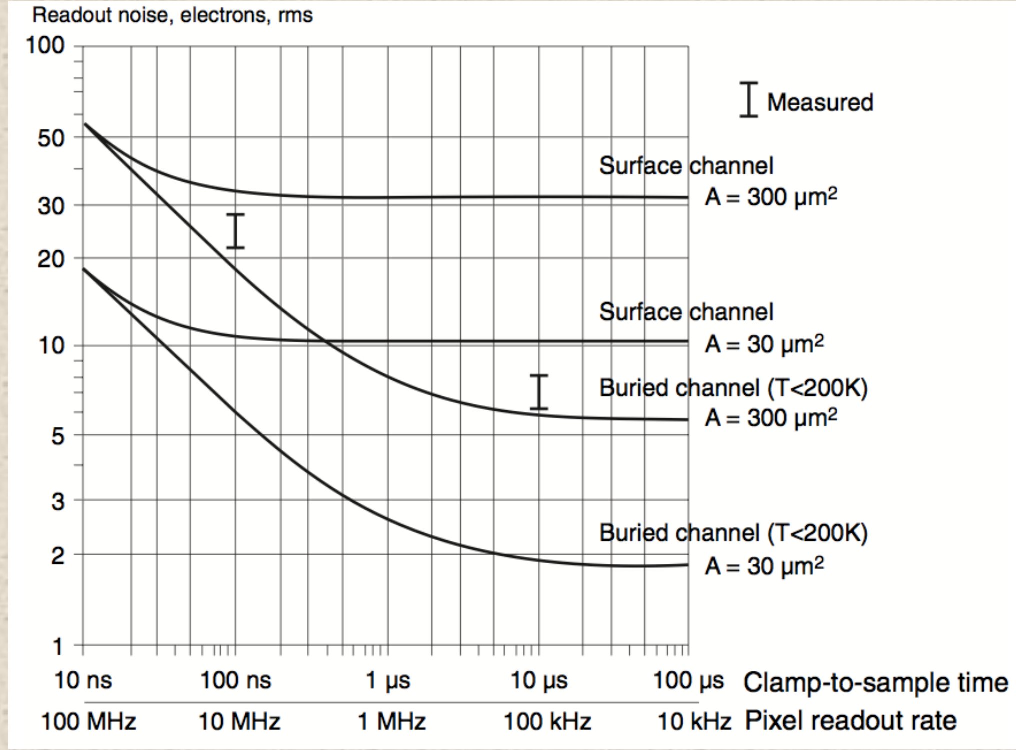
Sources of Noise in a CCD

1. READ NOISE.

• Fundamental limit on the performance of a CCD caused by electronic noise in the CCD output: there is not perfect repeatability each time charge is dumped & digitized
  - conversions of same pixel with same charge won't always yield exactly same result from ADC.
  - injection of unwanted random signals by sensor &electronics gets digitized along with pixel charge.
  - in addition, every A/D conversion circuit will show a about an ideal conversion value.

• In any case the result is an "uncertainty" = **readnoise**, specified in electrons (e^-) per pixel.

• Can be reduced at the expense of increased read out time.
• Good CCDs have a readout noise of a few electrons per pixel.



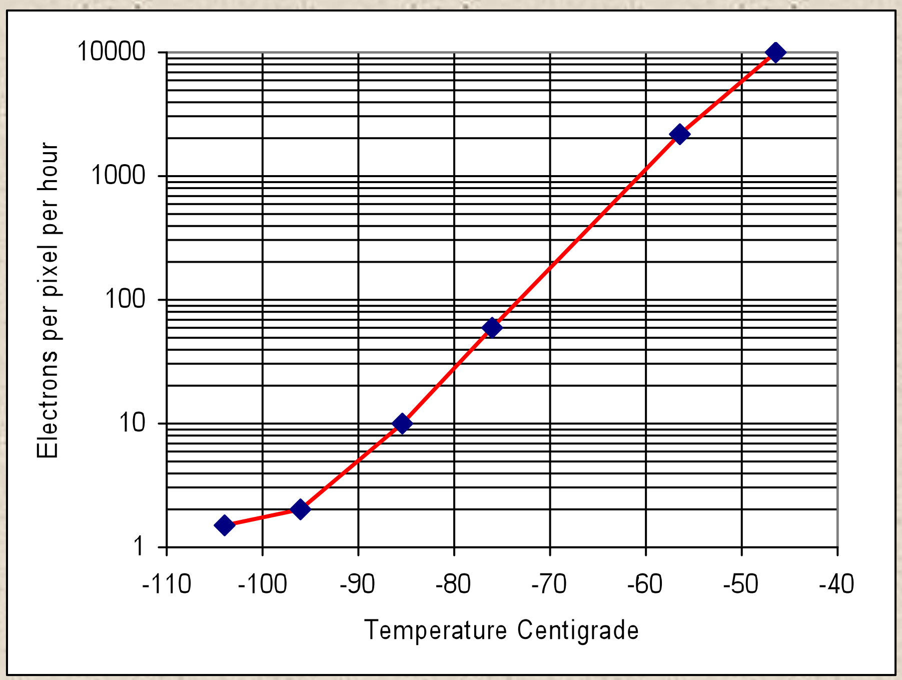
www.springer.com/ cda/ content/ document/ cda_downloaddocument/ 55_918to932.pdf?SGWID=0-0-45-359899-p81055696

Sources of Noise in a CCD

2. **DARK CURRENT**.

- Caused by thermally generated electrons in the CCD. Minimized by cooling the CCD.

Electrons can be generated in a pixel either by thermal motion of the silicon atoms or by the absorption of photons. Electrons produced by these two effects are indistinguishable. Dark current is analogous to the fogging that can occur with photographic emulsion if the camera leaks light.



Sources of Noise in a CCD

3. PHOTON NOISE.

Also called 'Shot Noise,' due to the fact that the CCD detects photons, which arrive in an unpredictable fashion described by Poisson statistics. This unpredictability causes noise.

Back to "rain in bucket" analogy:

- rain drops arrive discretely, independently and randomly (i.e., *Poisson*)
  → *CCD astronomy: small pixels collecting very low flux* → Poisson statistics
  → Root Mean Square uncertainty (RMS noise) in photons/sec/pix = RMS photon flux

- For example, if a star is imaged onto a pixel with average 10 e^- /s and we observe 1s
  → uncertainty of brightness measurement = $\sqrt{10}$ = 3.2 e^- = *photon noise, shot noise*

- Increasing exposure to100 s → photon noise = 10 electrons, but S/N→10
  The S/N will increase as $\sqrt{t}$. Astronomy wants maximum S/N!

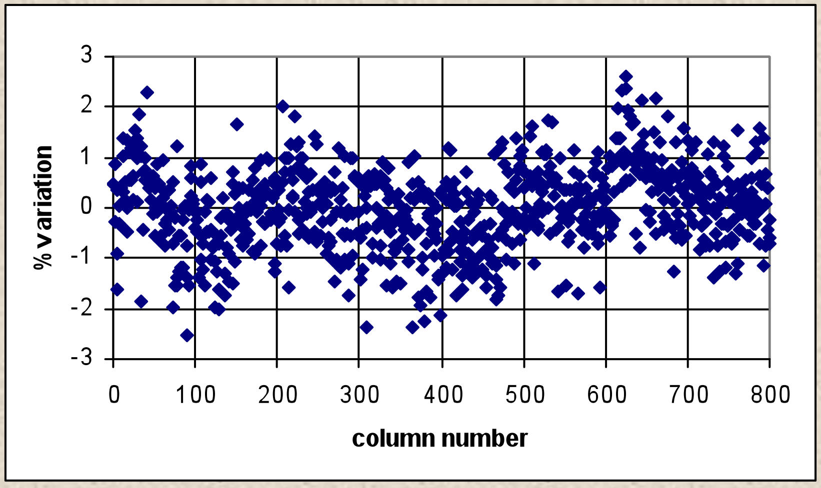
- Dark current also Poisson. If the mean dark current contribution to an image is 900 e^-/pix, the noise introduced into the measurement would be 30 electrons.

Sources of Noise in a CCD

4. PIXEL RESPONSE NON-UNIFORMITY.

Defects in the silicon and small manufacturing defects can cause some pixels to have a higher sensitivity than their neighbors. This noise source can be removed by ‘Flat Fielding,’ an image processing technique.

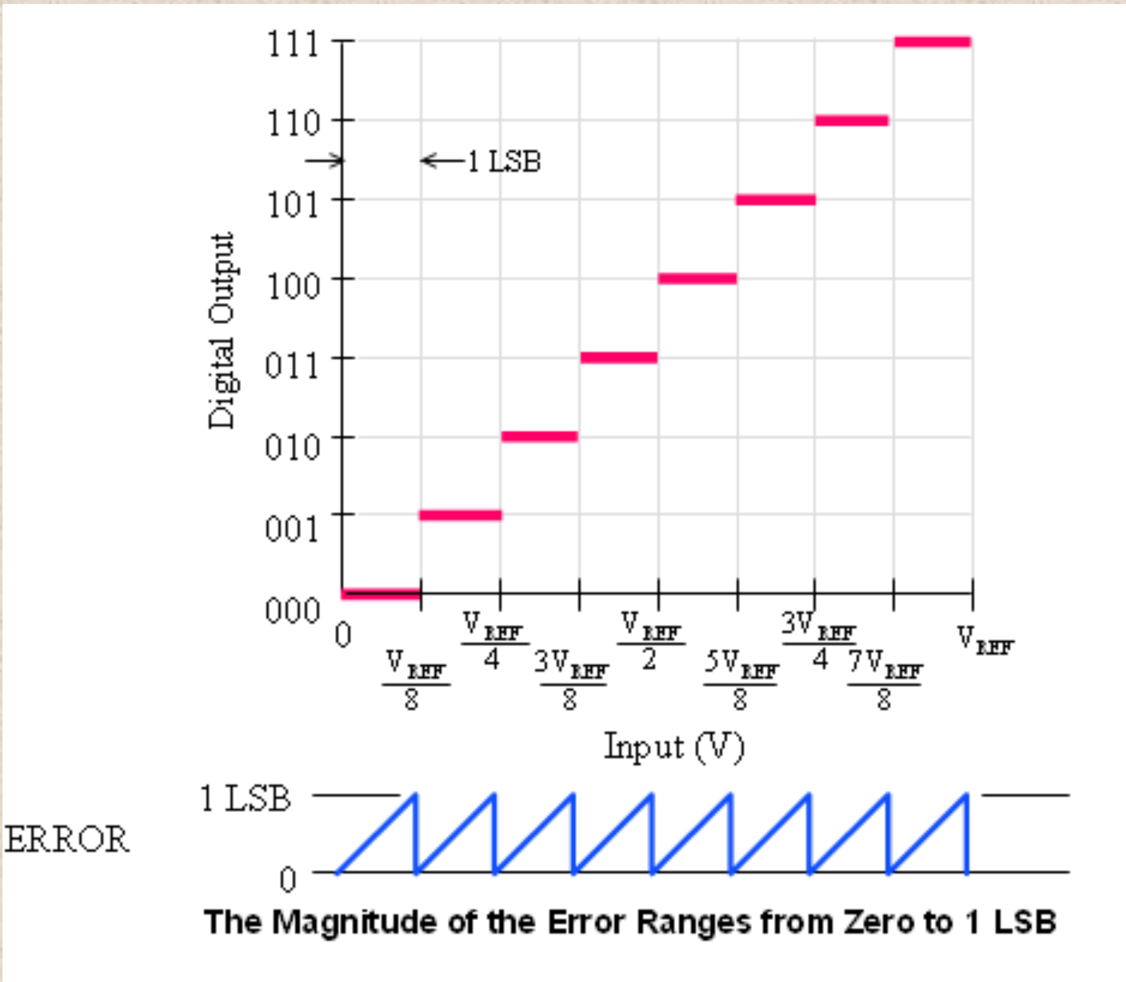
The graph below shows an EEV4280 CCD illuminated by blue light. The variations are as much as ±2%. Fortunately these variations are constant and are easily removed by dividing a science image, pixel by pixel, by a flat field image.



Sources of Noise in a CCD

Quantization "Noise" from the ADC

LSB= least significant bit



don't calculate; just be aware

http://www.national.com/AU/design/courses/175/print.htm

HOW THE VARIOUS NOISE SOURCES COMBINE

In general uncertainty ~ square root of signal.
Uncertainties add in quadrature:

Noise and S/N must ALWAYS be calculated in electrons (not counts):
electrons are Poisson; ADUs *are not!*

Total noise per pixel in raw frame: $\sqrt{\text{Signal} + \text{readnoise}^2 + \text{Dark}}$

If dark subtraction done: $\sqrt{\text{Signal} + 2(\text{readnoise}^2) + 2\text{Dark}}$

Note:
- *Signal includes object + sky*
- *Dark includes bias*
- *If no dark subtraction, then subtract average bias; assumed noiseless*

HOW THE VARIOUS NOISE SOURCES COMBINE

Signal-to-noise ratio per pixel

$$\frac{S}{N} \text{ per pixel} = \frac{N_*}{\sqrt{N_{*pix} + R^2 + D}}$$

where:

N_{*pix} = number of e^- in 1 pixel of the source
D = number of e^- in 1 pixel of dark
R = readnoise in e^-

Example: in a well-exposed flat S~10,000 counts
(assume g=1*, R=5, D=2)

What is S/N? $= \frac{10{,}000}{\sqrt{10{,}000 + 5^2 + 2}} = 99.87$

* *so that here, S has the same value in electrons as in ADU*

HOW THE VARIOUS NOISE SOURCES COMBINE

TOTAL Signal-to-noise ratio

$$\frac{S}{N}_{\text{tot}} = \frac{N_*}{\sqrt{N_* + n(R^2 + D)}}$$

where:

N_* = number of electrons in the *total* signal
D = number of electrons per pixel in dark
R = readnoise per pixel
n = number of pixels the measurement covers

Example: in a moderately-exposed star with N_*=5000
(assume g=1, D=, R=5, n=15 pixels)

What is S/N?

$$= \frac{5000}{\sqrt{5000 + 15(5^2 + 2)}} = 68.0$$

HOW THE VARIOUS NOISE SOURCES COMBINE

In general, $S/N \sim 1/\sigma$ where σ= standard deviation

$S/N=3 \rightarrow \sigma=0.33 \times$ signal (result is determined to ~33%)

$S/N=10 \rightarrow \sigma=0.10 \times$ signal (result is determined to ~10%)

$S/N=100 \rightarrow \sigma=0.01 \times$ signal (result is determined to ~1%)

NOISE IN LIMITING CASE OF BRIGHT OBJECT

$$\frac{S}{N} = \frac{N_*}{\sqrt{N_* + n(R^2 + D)}}$$

S/N limiting case: when $N_* >> R, D$ → $\frac{S}{N} = \frac{N_*}{\sqrt{N_*}} = \sqrt{N_*}$

S/N as a function of time:

$$\frac{S}{N}\text{(t) per pixel} = \frac{S_* t}{\sqrt{S_* t + R^2 + Dt)}}$$

Again, if $S_* t >> Dt + R^2$ → $\frac{S}{N}(t) = \sqrt{S_* t} \propto t^{1/2}$

Slower increase if condition not met.