CCD imaging and reductions

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Part-I: An introduction to charge-coupled devices
Astronomical imaging and detectors

• The first detectors: the human eye

• Photographic plates
  • First objective, permanent record of astronomical phenomena
  • Long exposure times possible; faint objects can be detected
  • Large format: many surveys carried out as recently as the 1990s
  • BUT quantum efficiency is very low, around 1% (most of the photons lost)!
  • Photographic plates do not respond linearly to the amount of incident light.
Photoelectric detectors

- Photomultiplier tubes (1950-1990s)
  - more sensitive (30% quantum efficiency)
  - Extremely stable broad band devices which made possible the first highly accurate photometric systems
  - Flux calibration of photomultiplier based systems still more accurate than modern array imaging detectors!
  - BUT only a single element detector! (leading to applications specialised in the study of single objects, variable stars...)

[Diagram of Photomultiplier Tube (PMT)]
**Charge coupled devices**

- Since the late 1980s CCD arrays have been the detector of choice for astronomy
- Deep counts, gravitational arcs
- Incoming photons produce free electrons in semiconducting material.
  - This charge is then ‘shuffled’ to the output electrodes by applying electrical pulses
- The output signal is converted from electron units to digital units by amplifiers with a conversion factor or gain, “g” (measured in electrons per analogue-to-digital unit).
- Gain is simply a multiplicative factor.
- Pixel ADU value\times gain=number\ of\ electrons.

\[
\sigma(x) = \sigma(y) / g^2
\]
How CCDs work (II)

- Reading out a CCD can take time, especially for the largest arrays with many pixels.
- One way around this is to use many amplifiers in parallel but you have to be careful to not increase the *read noise*.
- In *drift scanning* CCDs are read out continuously (for example like the SDSS camera); no read-out time but integration time is fixed!
- Shuffling charge on CCDs can be a way to account for atmospheric seeing -- see the orthogonal charge transfer chips used in the Pann Starrs project.
The great advantage of CCD cameras...

- Extremely good quantum efficiency at redder wavebands -- almost 100%!
- Limiting magnitudes increased by four to five magnitudes!
- Sensitivity of telescopes is now limited by light collecting area and not the detector area.

- Detectors are linear over a very wide flux range making calibrations easier
- Output is digital!
CCDs and CCD mosaics
The next generation of large mosaic detectors...
Some problems with CCD detectors

- Poor blue (4500A) response
  - **Megacam** (Canada-France Hawaii Telescope) is one of the few wide-field detectors with good u* response
  - Different CCD manufacturing techniques can help solve this problem

- It’s hard to make large *monolithic* CCD detectors (but this can be solved by making mosaics from ‘buttable’ detectors).

- **Charge transfer efficiency** between wells is not 100% and degrades over time especially in space-based detectors; this can cause a problems when attempting to measure shapes to galaxies (see Massey et al. COSMOS papers).

- Cryogenic cooling (normally liquid nitrogen is used) is necessary to reduce dark current

- Reading out CCDs can take time!
What can go wrong...

- Diffraction spike/megaprime secondary mirror
- Cosmic ray hits in megacam-u* image
- Charge transfer bleeding in STIS detector
Characterising CCD detectors

- **Quantum efficiency (QE):** what percentage of incident photons produce a measurable signal. Can be as high as 90% in visible wavelengths for the best detectors today.

- **Dynamic range/full well capacity/saturation level.** Around $10^5 e^-$. At the saturation level, object fluxes ‘peg’ or wrap around.
  - It’s important to choose an exposure time short enough so that objects of interest are not saturated! (But long enough so you are sky-noise limited).

- **Resolution/pixel size:** for the images to be properly sampled, there must be at least twice the number of resolution elements as the size of the point spread function psf; otherwise the images are said to be *undersampled*. 
Sources of noise in CCD observations

- **Dark current**
  - Even in the absence of illumination, CCDs produced a residual or ‘dark’ current. Typical values of around $10 / e^- \text{ hr}$

- **Readout noise**
  - This is electronic amplifier noise, usually quoted in electrons. Does not depend on exposure time

- **Sky noise**
  - The night sky is not dark. Sky background increases at longer and longer wavelengths

- In order to avoid being dominated by read noise, CCD exposures should be long enough to accumulate enough counts in the sky background -> sky noise dominated
Sky background

Moonlight is blue, so better to observe in redder bandpasses near the full moon.

At longer wavelengths airglow lines cause significant variations in sky brightness.
Optical point spread function ("PSF").

- Astronomical images are a convolution of the astronomical signal and the telescope "point spread function".
- For ground-based telescopes, in long exposures, the effect of the atmosphere broadens out or smears the light profile.
- The amount of this broadening is parameterized by the "Full width at half maximum", which is the width at half maximum of a Gaussian fit to the light profile.
- Note that this function isn’t really a Gaussian and that significant amount of signal can be found in the object wings.
- The best optical observatories have a "seeing" of around 0.6”-0.7”
- Many factors contribute to the seeing -- sources of heat in the telescope for
The CCD equation

- Read noise follows a Gaussian or normal distribution

- Shot noise follows a Poissonian distribution (counting statistics)

\[ P_n = \frac{m^n e^{-m}}{n!} \]
\[ \sigma = \sqrt{m} \]

\[ N = \sqrt{S_* + S_S + t \cdot dc + R^2} \]

- Total counts per pixel, electrons
- Astronomical Source
- Sky background
- Dark current
- Read noise
CCD Equation II

\[ \frac{S}{N} = \frac{S_\star}{\sqrt{S_\star + n_{\text{pix}} \cdot \left(1 + \frac{n_{\text{pix}}}{n_{\text{sky}}}\right) \cdot (S_S + t \cdot dc + R^2 + G^2 \sigma_f^2)}} \]

- In practice we estimate the flux in the sky from blank areas in the images in circular apertures; \(n_{\text{sky}} \gg n_{\text{pix}}\)
- Digitisation noise is also usually negligible
Estimating magnitude errors and limiting magnitudes

\[ \sigma \equiv \frac{N}{S} \]

\[ \sigma_{\text{mag}} \approx \frac{1.0857 \sqrt{S_{\star} + p}}{S_{\star}} = 1.0857 \left( \frac{1}{S/N} \right) \text{ [mag]} \]

• Note that this expression can underestimate the magnitude errors in real data because of correlated noise pixels produced by image resampling!

• The correction factor can be a factor of two or three.

• Normally this correction factor can be estimate by simulations (adding fake stars and galaxies of known magnitudes) and recovering them with sextractor.

• Another way is to put blank apertures at various locations around the image and measure the variance between them.
Some practical hints on how to answer the question “how long should I integrate for”

• Most observatories will offer “exposure time calculators” which will allow you to estimate how long to integrate to reach a given s/n

• However, if you have (or can get) real data taken with the same same instrumental setup it’s almost always better to use this, and to scale it up to your particular application.

• In practice, CCDs have finite “full well capacity” and the non-zero sky background means that integrating infinitely long is impractical (images would saturate on the sky). Also detectors have bad pixels / columns so it is in general better to take several shorter length exposures which are then dithered or offsetted on the sky and which can then be combined afterwards.

• It’s important (especially for wide-field instruments) to choose large enough dithers), so that bad pixels and other detector defects can be filled in.
Part-II: Reducing CCD observations
CCD calibration frames

- Raw images from CCD detectors are not immediately usable for scientific exploitation but are instead contaminated by several instrumental effects.

  - **Bias frame**: This is a fixed offset level applied to all data. There may be structure also in the bias. It can be measured by examining the “overscan” region of each CCD.

  - **Dark frame**: Even without any signal, there is a “dark current” of a few electrons. Ideally, one should take a dark frame of the same exposure time as real data.

  - **Flat field**: the pixel-to-pixel sensitivity of the detector is not constant. Flat-field is wavelength dependent.

  - **Fringe frame**: Thinned CCDs can produce interference fringes at longer wavelengths. The amplitude and separation of the fringes can be time-dependent.

Megacam data with badly removed fringe pattern
Typical CCD pre-reduction steps

- **Subtract bias or overscan**
  - Master bias can be computed from median of many frames. The “overscan” region can be used to compute the bias level

- **Subtract dark frame**
  - Master dark frame should be computed from many observations of several tens of minutes scaled up to the appropriate exposure time

- **Divide by twilight or dome flat-field (filter dependent)**
  - Dome flat-fields are almost always not flat enough for wide-field cameras
  - Make sure that there are enough counts in the flat-fields so they are effectively sky-noise limited.

- At each stage in the reductions you should verify that the noise per pixel in the individual frames decreases. It should approach the Poisson limit.

- If the reduction steps add noise then you are doing something wrong!
Other calibration frames you may need

- A **bad pixel mask** is computed from a single image and identifies where the stuck pixels, bad columns and cosmic rays and satellite trails are in each image.

- A **weight map** or **coverage map** which is computed from the normalised flat-field.

- The **weight map** is necessary to compute magnitude errors and detection thresholds correctly in a stacked image. Weight maps are less important for single detector cameras.

- Not all sections of the image will receive equal exposure time.

Megacam single image weight map (flat-field + bad pixel mask + cosmic ray mask)
FITS: the standard for astronomical images

- FITS = flexible image transport system

- FITS is an **architecture independent** way to store and transfer astronomical data

- Simplest FITS file consists of a primary header comprising of $n(36\times80)$ ASCII characters followed by binary data

- FITS files can also contain tables or spectra.

- In ‘multi-extension-FITS’ there are several extensions, which can be useful for mosaic camera data.

- **topcat, ds9, fv** can be used to manipulate and inspect fits tables

```plaintext
| KEYWORD = | NUMERIC_VALUE | / | COMMENT_STRING |
| KEYWORD = | LOGICAL_VALUE | / | COMMENT_STRING |
| KEYWORD = | STRING_VALUE  | / | COMMENT_STRING |
| COMMENT = | CHARACTER_STRING |
| HISTORY = | CHARACTER_STRING |
| END       |
```
Complete reduction step for CCD imaging data

- Carry out the pre-reductions described previously.
- If you have a series of images on the same part of the sky you will need to separately flux calibrate and astrometrically calibrate them.
- Images which are dithered around the sky will need to be re-aligned. For small detectors, a linear shifts are sufficient; for wide-field imaging detectors interpolation and reprojection will have to be carried out.
- Next the images need to be combined to produce a single image.
- The last step involves the extraction of catalogues.

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