

Detectors

1. Basics & Nomenclature

Modern astronomical detectors come in several varieties depending on wavelength and use case. The traditional detector introduced in the 1800s, the photographic plate, is too inefficient ($\sim 5\%$) and too inconvenient to convert into digital form to be of use today, though it continued to be used until about 2000. Here, we will not review the physics behind modern detectors except insofar as necessary to explain how to interpret data taken with them.

In the optical, out to about a micron, the most common detector in use is the *charge-coupled device* (CCD). Out to about $28\ \mu\text{m}$, the most common detectors are infrared detector arrays. Although CCD and infrared arrays are different technologies, both are semiconductor-based detectors that detect photons of energy higher than their band gap between their bound valence electron energies and their conduction band. Silicon is the best-developed CCD technology and has a band gap of $1.1\ \mu\text{m}$. Germanium CCDs could in principle extend this sensitivity to $1.8\ \mu\text{m}$, but their technology is not cost-effective today. HgCdTe (“MER-CAH-TEL”) infrared detectors have a band gap of that can be designed anywhere between $0.4\text{--}12\ \mu\text{m}$. Si:As detectors can extend to $28\ \mu\text{m}$ (and are for example used in the two redder WISE bands).

Each pixel of a CCD detects individual photons that hit it, each of which usually contributes one electron to the overall signal. For most hardware, the charge is *read out* at amplifiers along the side of the CCD, by transferring the charge from pixel to pixel to the edge of the CCD. At the last pixel the charge is converted to a digital signal by the amplifiers. CCDs may be readout by various numbers of amplifiers. Because of the finite temperature of the devices, some number of electrons are released even when there are no photons entering the device; this phenomenon is known as the *dark current*. To reduce the dark current, CCD detectors need to be cooled; variations in temperature can cause variations in the dark current.

Infrared detector arrays operate similarly, but the infrared-sensitive materials cannot today be used to support the circuits necessary for CCD operation. Instead, the infrared sensitive material is bonded to a silicon detector on which the read out occurs. These detectors are not CCDs but multiplexers, which are read directly out on each pixel. The charge can be read out nondestructively, allowing many reads on the same pixel. However, the read out is intrinsically noisier.

From this basic understanding, there results an interpretation of the digital numbers reported by a semiconductor device:

$$\text{DN} = \frac{n_e}{\text{Gain}} = \frac{n_p + \text{Dark}}{\text{Gain}} \quad (1)$$

where n_e is the number of electrons recorded by the device, n_p is the number of photons actually detected, i.e. which are converted to electrons (which will include all background photon sources). Gain represents the *gain*, the number of electrons per DN reported by the electronics. Dark

represents the dark current in units of electrons.

The noise in the DN is due primarily to two sources: Poisson noise around the mean n_e and *read noise* associated with the electronics. The read noise does not usually depend on the signal. Therefore:

$$\sigma_{\text{DN}}^2 = \frac{n_e}{\text{Gain}^2} + \text{Read Noise}^2 \quad (2)$$

The Poisson noise includes the “object” signal, the background signal, and the dark current contributions to the expected number of electrons n_e .

Over their usable dynamic range in number of electrons, CCD devices are remarkably but not perfectly linear. CCD devices are limited in their dynamic range by the number of electrons each pixel can store. If the number of electron approaches or exceed this limit, those electrons typically bleed to neighboring pixels; since the electronics is not isotropic, they typically bleed along the same direction the device is read out. They also may be limited by the dynamic range of their analog-to-digital converter, which is often 16-bits.

CCDs are also sensitive to cosmic rays and these will release electrons that contribute to the signal. A characteristic feature of a cosmic ray is that it will be a sharper feature than the atmosphere and optics allow. The exact nature of the cosmic ray distribution depends on altitude (with more reaching higher altitude and space detectors) and orientation of the detector relative to vertical (since underneath the atmosphere the cosmic rays will be directed preferentially downwards).

In the ultraviolet, other detectors are still in use. For example, GALEX uses a position sensitive proportional counter. These devices are essentially a crossed grid of wires under voltage inside a chamber filled with an inert gas that can be ionized by UV photons. When a UV photon causes a charge track, the voltage change is detected and recorded. Unlike CCDs, these detectors can detect individual photons.

In the X-rays, CCD detectors are now typically used. CCDs lose sensitivity in the UV due to absorption on their surfaces, but at energies > 120 eV (< 100 Å) they become sensitive again. Unlike in the UV and optical, X-ray photons can release many electrons. This fact, and that the photons much rarer, allows X-ray CCDs to be energy sensitive. At high count rates, they become complicated to analyze due to latency effects; for some period of time after a photon is detected subsequent photons cannot be.

In the low frequency radio, antennae of various sorts are generally used as detectors, and the signal is read out as a changing voltage. Radio detectors therefore preserve the phase information in the electromagnetic signal, unlike higher frequency instruments. This allows interferometry on very wide baselines to achieve very high angular resolution (low λ/D). In the higher frequency radio (sub-mm), superconductor-insulator-superconductor (SIS) devices are used, which are photon-sensing and so do not preserve the phase. In both regimes, feedhorns in the focal plane of the telescope are often used to match the focal plane to the antennae. In some configurations, antennae are used in arrays without any focusing element, and images are reconstructed through cross-correlating in

the resulting signals. Noise in radio instruments is often dominated by thermal noise due to the finite temperature of the receiver electronics.

No detectors capture all of the photons hitting each pixel. The fraction of photons detected is known as the *quantum efficiency* of the device. It is a function of wavelength (most notably near the band gap). CCD and infrared devices have quantum efficiencies that are typically quite high, e.g. up to 95%.

2. Commentary

CCDs only became widely used in astronomy until the mid-1990s. Prior to that time most imaging and spectroscopy was performed with photographic plates. Photographic plates have only $\sim 5\%$ quantum efficiency typically, and obviously are harder to translate into digital results. However, they remained competitive for wide field imaging surprisingly long, because the high cost of CCDs kept them from being used to completely cover the focal planes of wide field telescopes.

3. Key References

- *Design and Construction of Large Telescopes*, Bely (2003)
- *Astrophysical Techniques*, Kitchin (2009)

4. Order-of-magnitude Exercises

1. Modern CCDs have read noise can be as low as 2 electrons, whereas infrared detectors often have read noise of ~ 20 electrons. How many independent reads would have to be performed of an infrared detector to beat down the read noise to compete with CCD read noise?
2. The cosmic X-ray background at 1 keV is about $3 \times 10^{-11} \text{ W m}^{-2} \text{ sr}^{-1}$ (Fabian & Barcons 1992). The Chandra X-ray telescope often takes exposures of $\sim 10^4$ s, and has a resolution of order an arcsec. What is the expected number of background photons within the a FWHM of a source that are contributed by this background for such an exposure?
3. What is the highest angular resolution that can be achieved by a ground-based interferometric radio experiment at ~ 1.6 GHz?

In interferometry, one can use aperture synthesis to create a larger baseline aperture than traditional telescopes by placing an array of multiple telescopes. The distance between any pair of two telescopes, the baseline, sets the diffraction limit for images produced by correlating the phase signal between the telescopes. The diffraction limit is $\theta \sim \frac{\lambda}{D}$ and the largest

possible distance we can separate two ground-based telescopes is of order the diameter of the Earth $D \sim 10^7$ meters. For 1.6 GHz light, we have an angular resolution of

$$\theta \sim \frac{3 \times 10^8}{(1.6 \times 10^9)(10^7)} \sim 2 \times 10^{-8} \text{ rad} \sim 4 \times 10^{-3} \text{ arcseconds.}$$

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5. Analytic Exercises

1. The detected electrons contributing to the noise include the object, background, and dark current signal. Write the fractional error in the object counts. Separate the terms involving the other sources of noise. For low object signal, how does the fractional error depend on signal? For high object signal, how does the fractional error depend on signal?

The noise N includes the Poisson noise in the object, sky, dark counts (n_{obj} , n_{sky} , and n_{dark}), added in quadrature with each other and the read noise N_{read} :

$$N = \sqrt{N_{\text{obj}}^2 + N_{\text{sky}}^2 + N_{\text{dark}}^2 + N_{\text{read}}^2} = \sqrt{n_{\text{obj}} + n_{\text{sky}} + n_{\text{dark}} + N_{\text{read}}^2} \quad (3)$$

The fractional error in the object counts is:

$$\frac{N}{n_{\text{obj}}} = \frac{\sqrt{n_{\text{obj}} + n_{\text{sky}} + n_{\text{dark}} + N_{\text{read}}^2}}{n_{\text{obj}}} = \sqrt{\frac{1}{n_{\text{obj}}} \left(1 + \frac{n_{\text{sky}} + n_{\text{dark}} + N_{\text{read}}^2}{n_{\text{obj}}} \right)} \quad (4)$$

Defining:

$$\sigma_{\text{other}}^2 = n_{\text{sky}} + n_{\text{dark}} + N_{\text{read}}^2, \quad (5)$$

we find that if $n_{\text{obj}} \gg \sigma_{\text{other}}^2$ (the object-dominated regime), then

$$\frac{N}{n_{\text{obj}}} \approx \frac{1}{\sqrt{n_{\text{obj}}}}. \quad (6)$$

If $n_{\text{obj}} \ll \sigma_{\text{other}}^2$ (the background-dominated regime), then

$$\frac{N}{n_{\text{obj}}} \approx \frac{\sigma_{\text{other}}}{n_{\text{obj}}}. \quad (7)$$

Therefore, for the faintest fluxes (below the background) the fractional errors are a stronger function of the flux than they are at brighter fluxes (above the background).

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2. The noise in a data set is determined by the Poisson noise in the expectation value of the signal. However, observationally we often only have access to one realization of the signal, and often the quoted errors are based on the Poisson noise in that signal. If we take multiple observations and combine them together weighting by the inverse variance estimated in this way, it leads to a bias. Ignoring any background contribution to the noise, estimate this bias as a function of n_e .

6. Numerics and Data Exercises

1. CCD images from SDSS are available as corrected frames. Those images are calibrated in physical units, and have the sky background subtracted. Read the documentation there, including the data model. Download a corrected frame in the r -band. Use the formulae in the documentation to translate the image into uncalibrated DN units with the sky background reinstated (the files have all the information necessary to do that). Is it all integers? Use the result to estimate the noise per pixel in a region without stars or galaxies. Can you independently estimate that noise from the distribution of flux values themselves, and do the estimates agree?

REFERENCES

- Bely, P. Y. 2003, The Design and Construction of Large Optical Telescopes
- Fabian, A. C., & Barcons, X. 1992, Annual Review of Astronomy and Astrophysics, 30, 429
- Kitchin, C. R. 2009, Astrophysical Techniques, Fifth Edition