Astronomical Detectors

Detector Basics

The purpose of any detector is to record the light collected by the telescope. All detectors transform the incident radiation into a some other form to create a permanent record, such as particles (photographic plates), molecules (eyes), or electrons (CCDs).

There are eight important properties by which to gauge the utility of a detector:
1. Quantum Efficiency and Spectral Response
2. Temporal Response and Resolution
3. Dynamic Range
4. Linearity and Stability
5. Noise
6. Spatial Resolution and Field of View
7. Ease of Conversion to Digital Signal
8. Spectral Resolution

Quantum Efficiency (QE) and Spectral Response

Quantum efficiency is defined as the percentage (or fraction) of incident photons that are detected \[\text{QE} = \frac{\text{# photons detected}}{\text{# incident photons}}\]

• Ideally you want QE=100%.
• No detector is efficient at all wavelengths, but rather has a QE that varies with wavelength. The spectral response is the dependence of QE upon wavelength.
Quantum Efficiency (QE) and Spectral Response

QE curve for Chandra HRC-I detector

Temporal Response

How quickly can you take images, and how long do you have to wait?

- What is the shortest integration possible?
  - Time variability
- How long can you integrate?
  - Faint sources (related to dynamic range and detector noise properties)
- How quickly can you take consecutive images (readout time)?
  - Time variability
  - Observing efficiency

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Image courtesy Nick Raines and Steve Eikenberry

This lecture draws upon the lecture notes of Steve Majewski (www.astro.virginia.edu/class/majewski/astr313), and C. S. J. Pun (www.physics.hku.uk/~phys2022). Several slides are taken, with permission, directly from the last of these sources.
**Dynamic Range**

Can I look at bright and faint things at the same time?

Dynamic range = largest possible signal / smallest possible signal

- The dynamic range is relevant because it tells you for a single image the range of object brightnesses you can observe.
- A related quantity for digital detectors is the full well depth (capacity), which tells you how many detections your detector can record before saturation.

Concrete example: CCD

- # of detections is an integer (so min=1)
- Assume full well depth = 2^16 (65,536) counts

Dynamic range = 65,536/1 = 65536

In magnitudes, this is 12.04 mag of dynamic range.

**Linearity**

2 + 2 = 5?

- Ideally, you want the response of your detector to be linearly proportional to the number of photons (1 photon → 1 detection).
- Human eyes and photographic plates highly nonlinear
- CCDs and most other modern detectors are nearly linear
  - In some cases, must still apply a "linearity correction".

**Stability**

Will it count the same tomorrow as today?

- How reliable is your photometry? Is the efficiency of your detector stable in time?
  - Sensitivity of photographic plates degrades with time, especially in high humidity.
  - Sensitivity of detectors on satellites can degrade with time due to hard radiation and cosmic rays.

**Noise**

It is a sad fact of life that detectors introduce additional noise into observations...

- Types of noise:
  - Poisson noise (shot noise): Goes as N\(^{-1/2}\), where N is the number of photons. For an ideal detector this is the only source of noise. Two components that contribute to the Poisson noise are (1) source photons, and (2) background sky photons.
  - Read noise (RN): Some detectors, like CCDs, generate additional noise when the signal is read out.
  - Noise in electronics: self-explanatory

- Noise components add in quadrature, so
  - Total noise = \[ N + RN + \text{dark noise} + \text{electronic noise} \]^1/2

For research instruments, Poisson and read noise are usually the dominant sources of noise.
Angular Resolution and Field of View

- Angular resolution
  - Recall that the image scale (in arcsec/mm) is determined by the design of the telescope
  - Two pixels are required to resolve an object
  - Consequently, for a detector the angular resolution = image scale • 2 • pixel size

- Field of view
  - FOV = image scale • Npix • pixel size

- Want the resolution to be well-matched to the telescope.
  - If the detector resolution is worse than the seeing, you're sacrificing performance.
  - If the detector resolution is much better than the seeing, you're sacrificing field of view.

Ease of Conversion to Digital Signal

For quantitative analysis, you want to convert your data into a digital format.
- Eye: out of luck (try theory)
- Photographic plates: densitometer
- CCDs and other modern detectors: direct digital output

Spectral Resolution

Spectral resolution is a moot point for current optical and infrared detectors, but at some wavelengths (particularly high energies like X-rays and Gamma rays) the detectors return energy information for the individual photons. In these cases it is relevant to quantify the precision of this energy information.
Types of Radiation Detectors

- Chemical
  - Human Eye
  - Photographic plates
- Electronic
  - Electron emission
  - Photomultiplier tube
  - Photocell
  - Photovoltaic cell
    - [solar collector, near-infrared InSb detectors]
  - Pyroelectric cell
  - Thermocouple
  - Resistance
    - Bolometer
    - Photoconductive cell
      - [NIR HgCdTe detectors]
  - Charge
    - Charge Coupled Device (CCD)
      - Cooper pairs (excess quasiparticles)
    - Superconducting Tunnel Junction (STJ)
- Thermal detectors respond to temperature rise due to absorption of radiant energy. [Example: bolometer]
- Quantum detectors respond to incident photons. [Examples: photographic plate, CCD]

The Human Eye

- A thin convex lens
- Focal length ~ 14mm (near vision) – 17mm (far vision)
- Aperture ~ 2 – 8mm
- Dynamic range: 100,000:1
- Photon sensor on the retina: cones (photopic vision) in daylight, rods (scotopic vision) at night
- QE: ~ 3% (cone) – 10% (rod)
- Cones: 6-7 million
- Rods: 100 million

Photographic Plates

Photography was invented in 1840s, but use in astronomy only started to become popular in around 1900.

- Micron size crystals of soluble silver halide salts (such as silver bromide, AgBr) are suspended in a gelatin emulsion on a glass plate
- When a photon strikes, the silver ion can then combine with the electron to produce a silver atom.
- The free silver produced in the exposed silver halide makes up the latent image
- The latent image is later amplified in the developing process. The deposit of silver produces a dark area in the film.

- Advantages of photographic plates
  - Nonlinear and not completely stable medium
  - Low QE (~4%)
  - Not easy to convert to digital output
  - Angular resolution and field of view

- Disadvantages of photographic plates
  - Nonlinear and not completely stable medium
  - Low QE (~4%)

Electronic Detector Basics: Photoelectric Effect

- Physical basis for most detectors in astronomy
- Photons of sufficient energy hitting surface of metal releases electrons (photoelectrons)
- Energy of released electrons depends on intensity of light (particle nature of light).
- There is a minimum frequency of light before any photo-electrons can be emitted from a particular metal

$$KE_e = E_{photon} - W = hf - W = h(v - v_{min})$$

where $KE_e$ is the KE of photoelectron, $E_{photon}$ is photon energy, $W$ is the work function of the metal, $h$ is Planck’s constant, $v$ is the photon frequency, and $v_{min}$ is the minimum photon frequency of the metal.
Types of Radiation Detectors

Photomultiplier Tube

- Combines photoelectric effect with amplification of electric signal.
- 1. Photon comes in.
- 2. Photoelectric effect generates electron.
- 3. Electrons, like photons, when moving with sufficient KE, not only release electrons from metals, but there is also amplification, with more electrons coming out of the metal than entering.
- 4. Signal recorded.

- Good QE (30%)
- Linear
- Low Noise

Spitzer IRAC InSb Detector

- Photovoltaic
- Incident photons generate voltage difference across a p-n junction
- Indium Antimonide (InSb)
- Used in near-infrared

- Other applications:
  - Medical Imaging
  - Missile Guidance
  - Infrared Microscopy
  - Solar Panels

- Fast read out

Photoconductive

- Incident photons increase electrical conductivity, or equivalently decrease resistance (large changes in photons generate current)

- Mercury Cadmium Telluride (HgCdTe)
- Used in near-infrared

Bolometer

- Heating of material by incident light changes resistance of material.
- Differences from photoconductor is that this is a thermal rather than photoelectric effect.

- Widely used at submillimeter and microwave wavelengths.
- Each bolometer is equivalent to a single pixel.

Courtesy Nick Raines and Steve Eikenberry
Types of Radiation Detectors

Charge Coupled Device (CCD)

A CCD is a two-dimensional quantum detector that outputs a digital image. (We'll talk about the details shortly).

- Photovoltaic effect: photons captured as charge.
- Detector consists of an array of “pixels” (picture elements) laid out in rows and columns.
- Charge filled pixels are manipulated to move the charge to the output and into a control computer.
- QE can be ~90%, and response is reasonably linear.

Limited number of pixels, so must often make a tradeoff between resolution and FOV.

Comparison of Various Optical Detectors

<table>
<thead>
<tr>
<th>Detector</th>
<th>QE</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eye</td>
<td>10%</td>
<td>Quick reset between images</td>
<td>Fixed integration time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large dynamic range (100,000:1)</td>
<td>Nonlinearity</td>
</tr>
<tr>
<td>Photographic</td>
<td>4%</td>
<td>Good angular resolution &amp; FOV</td>
<td>Nonlinearity, Stability issues, Low QE, Conversion to Digital</td>
</tr>
<tr>
<td>Plate</td>
<td></td>
<td>No electronic noise</td>
<td></td>
</tr>
<tr>
<td>Photomultiplier</td>
<td>50%</td>
<td>Decent QE, Linear</td>
<td>Angular resolution/FOV</td>
</tr>
<tr>
<td>Tube</td>
<td></td>
<td>Digital</td>
<td></td>
</tr>
<tr>
<td>CCD</td>
<td>~90%</td>
<td>High QE even wide wavelength range, Large dynamic range, Linear, Digital</td>
<td>Somewhat limited FOV, Readout can be slow</td>
</tr>
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