Modern Observational/Instrumentation Techniques
Astronomy 500

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Coherent vs Incoherent

- Radio, Microwave, Sub-mm
- Single-mode optics
- Wave Statistics
- Time-domain spectroscopy

- Sub-mm, IR, optical, UV, x-ray, gamma-ray
- Multi-mode optics
- Poisson Statistics
- Dispersive or energy-resolved spectroscopy
Spatially resolved?

- Point source
  - we are measuring flux
  - \( E = A f_\nu \, dt \)
- Resolved source
  - We are measuring surface brightness
  - \( E = A \Omega I_\nu \)

Digital Detectors

- By far the most common detector for wavelengths 300nm<\( \lambda \)<1000nm is the CCD.
CCDs

1. Quantum efficiency is more than an order of magnitude better than photographic plates.

These are silicon fab-line devices and complicated to produce.

CCDs remain physically small compared to photographic plates, but they took over rapidly anyway.
CCDs: How do they work?

- Silicon semiconductors with "gate" structure to produce little potential corrals.

Photons → Electrons bumped into conduction band → Read out and amplify current → A/D convert to DN

`clock' parallel and serial registers
``CTE'' > 0.99999

CCD operation

- At room temperature, electrons in high-energy tail of the silicon spontaneously pop up into the conduction band: "dark current". Cooling the detectors reduced the dark current although at about -120°C the quantum efficiency starts to decrease.
- Therefore, CCDs usually are put into dewars with liquid nitrogen cold baths and heaters and the temperature is actively controlled to ~1°C.
- Readout speed is typically adjustable--faster readout gives higher readout noise per pixel.
CCDs cont.

- The potential corrals that define the pixels of the CCD start to flatten as e\(^-\) collect. This leads first to saturation, then to e\(^-\) spilling out along columns.
- The “inverse gain” is the number of e\(^-\) per final “count” post the A/D converter.
- One very important possibility for CCDs is to tune the response to be linear.

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- ``Counts” = ADU = DN

- DN is not the fundamental unit, the # of detected electrons is. The “Gain” is set by the electronics.

- Most A/D converters use 16 bits.
  - DN from: 0 to \((2^{16} - 1) = 65535\) for unsigned, long integers

- Signed integers are dumb: -32735 to +32735
  \(\pm(2^{15} - 1)\)
What gain do you want?

Example: a SITe 24µ-pixel CCD has pixel "wells" that hold ~350,000 e-

- 16-bit unsigned integer A/D saturates at 65525DN
- Would efficiently maximize dynamic range by matching these saturation levels:

\[
\frac{350,000}{65,535} = 5.3 \frac{e^-}{DN}
\]

- Note, this undersamples the readout noise and leads to "digitization" noise.

Signal-to-Noise (S/N)

- Signal=R\cdot t

\[\text{detected } e^-/\text{second}\]

- Consider the case where we count all the detected e- in a circular aperture with radius r.
• Noise Sources:

\[ \sqrt{R_s \cdot t} \quad \Rightarrow \quad \text{shot noise from source} \]

\[ \sqrt{R_{sky} \cdot t \cdot \pi r^2} \quad \Rightarrow \quad \text{shot noise from sky in aperture} \]

\[ \sqrt{RN^2 \cdot \pi r^2} \quad \Rightarrow \quad \text{readout noise in aperture} \]

\[ \sqrt{\left[ RN^2 + (0.5 \times \text{gain})^2 \right] \cdot \pi r^2} \quad \Rightarrow \quad \text{more general RN} \]

\[ \sqrt{\text{Dark} \cdot t \cdot \pi r^2} \quad \Rightarrow \quad \text{shot noise in dark current in aperture} \]

\[ R_s = e^-/\text{sec} \quad \text{from the source} \]

\[ R_{sky} = e^-/\text{sec/pixel} \quad \text{from the sky} \]

\[ RN = \text{read noise (as if } RN^2 e^- \text{ had been detected)} \]

\[ \text{Dark} = e^-/\text{second/pixel} \]

Sources of Background noise

• Relic Radiation from Big Bang
• Integrated light from unresolved extended sources
• Thermal emission from dust
• Starlight scattered from dust
• Solar light scattered from dust (ZL)
• Line emission from galactic Nebulae
• Line emission from upper atmosphere (Airglow)
• Thermal from atmosphere
• Sun/moonlight scattered by atmosphere
• Manmade light scattered into the beam
• Thermal or scatter from the telescope/dome/instrument
S/N for object measured in aperture with radius $r$: $n_{\text{pix}} = \pi r^2$

Signal $\rightarrow R \cdot t$

Noise $\left\{ \begin{array}{l}
R \cdot t + R_{\text{sky}} \cdot t \cdot n_{\text{pix}} + \left( RN + \frac{\text{gain}}{2} \right) \cdot n_{\text{pix}} + \text{Dark} \cdot t \cdot n_{\text{pix}} \\
\sqrt{(R \cdot t)^2}
\end{array} \right.$

Noise from the dark current in aperture

Readnoise in aperture

Noise from sky $e^{-}$ in aperture

All the noise terms added in quadrature

*Note*: always calculate in $e^{-}$

**S/N Calculations**

- So, what do you do with this?
  - Demonstrate feasibility
  - Justify observing time requests
  - Get your observations right
  - Estimate limiting magnitudes for existing or new instruments
  - Discover problems with instruments, telescopes or observations
Side Issue: S/N $\leftrightarrow$ $\delta$mag

$m \pm \delta(m) = c_o - 2.5 \log(S \pm N)$

$= c_o - 2.5 \log\left[S\left(1 \pm \frac{N}{S}\right)\right]$

$= c_o - 2.5 \log(S) - 2.5 \log\left(1 \pm \frac{N}{S}\right)$

$= c_o - 2.5 \log(S) - 2.5 \log(1 \pm \frac{N}{S})$

$\delta(m) = 2.5 \log\left(1 \pm \frac{1}{S/N}\right)$

$= \frac{2.5}{2.3} \left[\frac{N}{S} - \frac{1}{2}\left(\frac{N}{S}\right)^2 + \frac{1}{3}\left(\frac{N}{S}\right)^3 - \ldots\right]$

$\approx 1.087\left(\frac{N}{S}\right)$

Note: in log +/- not symmetric

This is the basis of people referring to +/- 0.02mag error as “2%”

<table>
<thead>
<tr>
<th>S/N</th>
<th>$\delta$mag</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.44</td>
</tr>
<tr>
<td>10</td>
<td>0.10</td>
</tr>
<tr>
<td>100</td>
<td>0.01</td>
</tr>
</tbody>
</table>
How do you get values for some of these parameters?

• Dark Current: CCD@-120°C < 2e-/pix/hour
  Insb: ~2e-/pix/sec
• RN:                 CCD: 2 - 6 e-/pix
  Insb: 10 - 25 e-/pix
• R*: for a given source brightness, this can be calculated for any telescope and total system efficiency.
• In practice: *Go to the facility WWW site for everything!*

Source Count Rates

**Example: LRIS on Keck 1**
for a B=V=R=I=20mag object @ airmass=1

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>1470 e-/sec</td>
</tr>
<tr>
<td>V</td>
<td>1521 e-/sec</td>
</tr>
<tr>
<td>R</td>
<td>1890 e-/sec</td>
</tr>
<tr>
<td>I</td>
<td>1367 e-/sec</td>
</tr>
</tbody>
</table>

To calculate $R_*$ for a source of arbitrary brightness only requires this table and a bit of magnitude math.
Source Count Rates

\[ m_1 = c - 2.5 \log(I_1) \].............................(1)

\[ m_2 = c - 2.5 \log(I_2) \].............................(2)

\[ m_1 - m_2 = -2.5[\log(I_1) - \log(I_2)] \]..........(1) - (2)

\[ m_1 - m_2 = -2.5 \log\left(\frac{I_1}{I_2}\right) \]

\[ \frac{I_1}{I_2} = 10^{\left(\frac{m_1-m_2}{2.5}\right)} \]

Let \( I_2 \) be the intensity for the fiducial \( m=20 \) object

\[ I_1 = R_s (m_1) = I_{20} \cdot 10^{\left(\frac{m_1-20}{2.5}\right)} \]

\( R_{\text{sky}} \)

Signal from the sky background is present in every pixel of the aperture. Because each instrument generally has a different pixel scale, the sky brightness is usually tabulated for a site in units of \( \text{mag/arcsecond}^2 \).

<table>
<thead>
<tr>
<th>Lunar age (days)</th>
<th>U</th>
<th>B</th>
<th>V</th>
<th>R</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>22.0</td>
<td>22.7</td>
<td>21.8</td>
<td>20.9</td>
<td>19.9</td>
</tr>
<tr>
<td>3</td>
<td>21.5</td>
<td>22.4</td>
<td>21.7</td>
<td>20.8</td>
<td>19.9</td>
</tr>
<tr>
<td>7</td>
<td>19.9</td>
<td>21.6</td>
<td>21.4</td>
<td>20.6</td>
<td>19.7</td>
</tr>
<tr>
<td>10</td>
<td>18.5</td>
<td>20.7</td>
<td>20.7</td>
<td>20.3</td>
<td>19.5</td>
</tr>
<tr>
<td>14</td>
<td>17.0</td>
<td>19.5</td>
<td>20.0</td>
<td>19.9</td>
<td>19.2</td>
</tr>
</tbody>
</table>
Scale = "/pix  
Area of 1 pixel = (Scale)$^2$

this is the ratio of flux/pix to flux/"  

In magnitudes:

$I_{pix} = I_nScale^2$

$I = $ Intensity $(e^-/sec)$

$-2.5\log(I_{pix}) = -2.5[\log(I_n) + \log(Scale^2)]$

$m_{pix} = m_n - 2.5\log(Scale^2)$  

(for LRIS-R : add 3.303mag)

and

$R_sky(m_{pix}) = R(m=20) \times 10^{(0.4-m_{pix})}$

Example, LRIS in the R - band:

$R_{sky} = 1890 \times 10^{(0.4-24.21)} = 39.1 \ e^-/pix/sec$

$\sqrt{R_{sky}} = 6.35 \ e^-/pix/sec = RN$ in just 1 second

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S/N - some limiting cases. Let's assume CCD with Dark=0, well sampled read noise.

$R_s\cdot t$

$[R_s \cdot t + R_{sky} \cdot t \cdot n_{pix} + (RN)^2 \cdot n_{pix}]^{1/2}$

Bright Sources: $(R_s t)^{1/2}$ dominates noise term

$S/N = \frac{R_s t}{\sqrt{R_s t}} = \sqrt{R_s/ t} \propto t^{1/2}$

Sky Limited $(\sqrt{R_{sky} t} > 3 \times RN)$: $S/N \propto \frac{R_s t}{\sqrt{n_{pix} R_{sky} t}} \propto \sqrt{t}$

Note: seeing comes in with $n_{pix}$ term
Read-noise-Limited

\[(3 \sqrt{R_{\text{skyn}}} t < RN) : \frac{R_t}{\sqrt{n_{\text{pix}}RN^2}} \propto t\]

\[S/N \sim \# \text{ of exposures}\]

Figure 2 shows the S/N vs exposure time for different FWHM values for the images. This assumes that you stick with the “optimum” aperture. Note the importance of image quality by comparing the exposure time at fixed S/N.
Figure 3: **Upper Panel:** The contribution of each noise source in \( \log(c^-) \) at fixed S/N over a range of magnitudes. **Lower panel** Exposure time vs mag.

Slope proportional to aperture
Zero point proportional to sky
What is ignored in this S/N eqn?

- Bias level/structure correction
- Flat-fielding errors
- Charge Transfer Efficiency (CTE) 0.99999/pixel transfer
- Non-linearity when approaching full well
- Scale changes in focal plane
- A zillion other potential problems