Topics in Observational Astrophysics

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Lecture 6

• Current large telescopes
• Future extremely large telescopes
• Space telescopes (0.1 to 30μm)
• Photometric accuracy and signal to noise ratio
• Far-IR and radio astronomy

Current large telescopes

Keck, 2x10m, Hawaii
Subaru, 8.2m, Hawaii
Gemini, 2x8.2m, Hawaii and Chile
VLT, 4x8.2m, Chile
Current large telescopes

- LBT, 2x8.4m, Arizona
- GTC, 10.4m, Canary Islands
- HET, 10m, Texas
- SALT, 9.2m, South Africa

Future Extremely Large Telescopes (ELTs), 0.3 - 30μm.

- ELT, 39m, Chile
- GMT, 7x8.4m, Chile
- TMT, 30m, Hawaii?
Folded 3 mirror anastigmat

M1 is elliptical and is made of 798 hexagonal segments, each is 1.45m across the corners.

M4 is a flat adaptive mirror with 5316 actuators.

M5 is a fast tip/tilt flat mirror

ELT optical design

ELT optical design
ELT M4 adaptive mirror

- Mirror is made of 6 petals.
- Petals are 1.9mm thick.
- Each petal is coupled to a group of 32 actuator “bricks”.
- Each brick has 28 actuators.

Mirror surface
Stroke ~120μm
Frequency range 1-1000 Hz

Space Observatories (0.3 – 30um)

1. Hubble Space Telescope (HST), D=2.4m, 0.1 – 2.5μm
2. Spitzer (now a warm mission), 3.6 & 4.5μm camera, D=0.85m
3. James Webb Space Telescope (JWST), D=6.5m, 0.6 – 28μm, will launch in March 2021.
4. WFIRST, D=2.4m, will launch around 2025.
Other space missions (optical/IR)

1. GAIA, astrometric mission.
2. Kepler, exoplanet transit search, 0.4 – 0.9um, 0.95m.
3. WISE, D=0.4m, 3.4, 4.6, 12 and 22um filters.
4. TESS, exoplanet transit search, 0.6 – 1.0um, 4×0.1m telescopes.
5. CHEOPS, D=0.32m, 0.4 – 1.1um, exoplanet transit studies. Launched in Dec 2019.

6. Euclid, 1.2m, 0.55 – 2.0um, science: dark energy and cosmic acceleration, will launch June 2022.
7. PLATO, exoplanet transit search, 0.4 – 0.7um, 0.95m. 32×0.12m telescopes. Will launch 2026.
8. ARIEL, exoplanet transit spectroscopy, D~1m, 2-8μm, will launch in 2028.

Photometric accuracy

- The telescope + instrument feeds the light from some source that we are interested in on to a detector where it will illuminate a patch of pixels.
- The patch of pixels will correspond to some area on the sky and some passband (i.e. the range of wavelengths of the light).
- In addition to the light from the source of interest (the signal) in the same patch of pixels we will also detect an unwanted background illumination which will increase the error (noise) in our measurement.
- The background can be due to the sky or detector dark current or speckles from a nearby star or thermal radiation from within the telescope and/or instrument etc.
We need to measure the background on its own so we can subtract it off. We therefore take 2 measurements: one of the source plus the background and one of just the background on its own.

The first measurement is \([Q+B_1]\) and the second is \([B_2]\) where \(B_1\) and \(B_2\) are the contributions from the background and \(Q\) is the signal from the source.

To begin with let’s assume that the exposure time, \(T\), is the same for both measurements and that \(B_1 = B_2 = B\). To estimate \(Q\) we just take the difference of the 2 measurements

\[
Q_{est} = [Q + B] - [B] = Q
\]
The error in this estimate is the error of the 2 measurements added in quadrature. Assume the measurements are made in photon counts which obey Poisson statistics such that for \( N \) photons

\[
\text{error} = \sqrt{N}
\]

The error in our estimate of \( Q \) is therefore

\[
\sqrt{\left(\sqrt{Q+B}\right)^2 + \left(\sqrt{B}\right)^2} = \sqrt{Q + 2B}
\]

The signal-to-noise ratio (SNR), \( Z \), is then given by

\[
\frac{S}{N} = Z = \frac{Q}{\sqrt{Q + 2B}}
\]

Introduce the photon rates \( R_Q \) from the source and \( R_B \) from the background such that in exposure time \( T \) we have

\[
Q = R_Q T, \quad B = R_B T
\]

The expression for \( Z \) can then be written as

\[
Z = \frac{R_Q T}{\sqrt{R_Q T + 2R_B T}}
\]

\[
Z = \sqrt{T} \frac{R_Q}{\sqrt{R_Q + 2R_B}}
\]

Solving this for \( T \) we get

\[
T = \frac{Z^2 \left( R_Q + 2R_B \right)}{R_Q^2} \approx \frac{2Z^2 R_B}{R_Q^2}
\]

So far we have ignored readout noise. This result is valid in the background-limited regime (i.e. when readout noise is negligible) which is usually the case for real astronomical observations.
Optimising the signal-to-noise ratio (1) increase $Q$

- Build a bigger telescope
- Use a more efficient detector
- Use more efficient optics
- Use longer integration times (if photon-noise limited)

Optimising the signal-to-noise ratio (2) decrease $B$

- Use a detector with the lowest intrinsic background (dark current) and cool the detector.
- Sharpen the image so there's less sky background mixed up with the source signal.
- Design the optics to concentrate the light into the minimum number of detector pixels
- Cool the instrument (IR)
- Cool the telescope (IR) (not so easy)
- Baffle out unwanted light

How to optimise the S/N ratio

If we include readout noise, the error in our estimate of $Q$ becomes

$$
\sqrt{\left(\sqrt{Q + B}\right)^2 + \left(\sqrt{B}\right)^2 + 2nr^2} = \sqrt{Q + 2(B + nr^2)}
$$

where $n$ is the number of pixels in the patch and $r$ is the rms readnoise per pixel. The signal-to-noise ratio, $Z$, is then given by

$$
\frac{S}{N} = Z = \frac{Q}{\sqrt{Q + 2(B + nr^2)}}
$$

We will be in the readnoise-limited regime when $B < nr^2$ which occurs for short exposure times. Eventually if we expose long enough, sufficient background is collected to put us in the background-limited regime.
The effect of systematic errors

Now let’s assume $B_1 \neq B_2$ but instead $B_2 = fB_1 = fB$ where $f \sim 1$ but is not equal to one. This is a systematic error which could be for any of the following reasons:

- The two measurements were made at different times and the background was varying.
- The two measurements were made simultaneously but through different optical paths in the instrument/telescope.
- The two measurements were made simultaneously but the background varies spatially (has structure).

Ignoring readnoise we now have

$$Q_{est} = [Q + B] \pm \sqrt{Q + B} - [fB] \pm \sqrt{fB}$$

And the fractional error is

$$\frac{Q_{est} - Q}{Q} = \frac{1}{Z} = \frac{(1-f)B \pm \sqrt{Q + B} \pm \sqrt{fB}}{Q}$$

$$\frac{1}{Z} = \frac{(1-f)R_B}{R_Q} \pm \frac{\sqrt{R_Q + R_B}}{R_Q \sqrt{T}} \pm \frac{\sqrt{fR_B}}{R_Q \sqrt{T}}$$

As $T \rightarrow \infty$ the second and third terms on the RHS vanish so that the final signal-to-noise ratio is

$$Z = \frac{R_Q}{(1-f)R_B}$$

For example for $f=0.99$ and $R_B/R_Q=100$ then $Z=1$!

When there are systematic errors the SNR doesn’t keep on improving as the exposure time gets longer – it eventually hits an upper limit. This is unlike the result we got earlier where

$$Z \propto \sqrt{T}$$
Far-IR Astronomy

- 30um to ~300um (or up to 450um by some definitions)
- Herschel Space Observatory (3.5m), Spitzer Space Telescope (0.85m), IRAS, and Infrared Space Observatory. Also the airborne SOFIA telescope (2.5m).
- Proposed missions: Origins Space Telescope (5.9m, NASA) and SPICA (2.5m ESA/JAXA)

![Diagram showing atmospheric bands and wavelengths for Far-IR astronomy.](attachment:far-ir_diagram.png)

Plot is for a wet site at sea level. This edge is better at a high dry site.
Radio Astronomy

- From 300um to 30m (a very big range)
- SKA, VLA, ALMA, Arecibo, Jodrell Bank, Greenbank, FAST.
- Large parabolic dishes used collect and focus flux
- Interferometers can be built from many single telescopes. Directional sensitivity (image sharpness) is $\sim \lambda/D$ where $D$ is the longest baseline in the array of telescopes. Image quality is improved by having good baseline coverage.
- Phased arrays are made up of individual omnidirectional antennas. Directional sensitivity comes from processing the data.
CMB Astronomy

- 100μm to 10mm (3000 – 30 GHz)
- Precision measurements can be made from space
- Planck’s 52 High Frequency Instrument (HFI) detectors are bolometers which are cooled down to 0.1K. A bolometer is a heat absorbing element attached to a resistor which produces a large resistance change for a small temperature change.
- The 22 detectors for it’s Low Frequency Instrument (LFI) are high electron mobility transistors which are cooled to 20K. These convert the tiny voltage fluctuations from the electromagnetic radiation into large current variations.