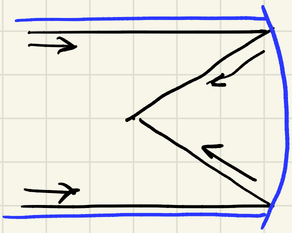
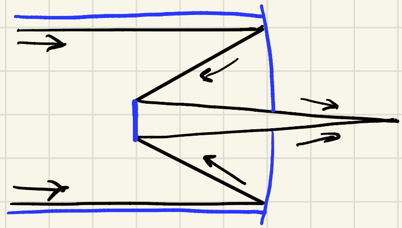
Telescopes

Sources: Chromey Ch. 5-6, Schroeder Ch 6-9 (requst)

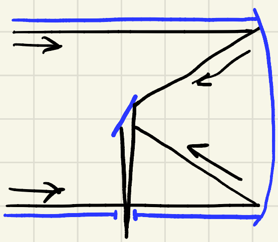
Telescope designs:



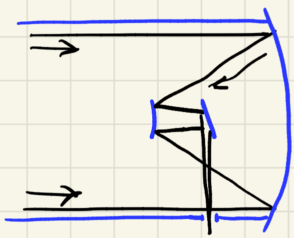
Prime focus



Cassegrain focus



Newtonian Focus



Nasmyth focus

Prime:

Pros: simple, minimal light loss

Cons: instrument blocks mirror → use when instrument $\ll$ mirror, usually $D > 3.5$m. Bad large-field image quality.

Newtonian

Pros: easier access to focus than prime, still not much light loss

Cons: large-field image quality still bad, long focal length need big tube, mostly used for small amateur scopes

Cassegrain
Pros: shorter than a Newtonian of same focal length,
focus is conveniently located
Con: optics are more complex (pros are worth this)

Nasmyth:
Pros: can mount heavy instruments
Cons: longer than the cassegrain

KPNO 4m has prime and cassegrain focus.
Magellan are nasmyth and cassegrain.

<u>Telescope mounts</u>: (see Chromey 6.1)

AltAz mount:
simpler construction, rapid rotation at zenith, rotation of focal plane

Equatorial mount:
larger mount, tracks on one axis, difficulty pointing N rather than zenith, no rotation of focal plane

Image Quality

Aberrations (Chromey 5.5)

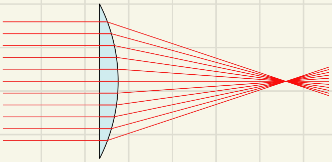
chromatic aberrations: a lens will refract light of different wavelengths differently. This causes light with different λ to focus at different places. Usually correct with compound lenses.

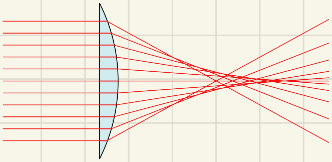
In an ideal telescope, all incoming rays from an incoming planar wavefront should focus to the same point and straight lines on the sky should produce straight lines in the image.

Some aberrations can occur even in monochromatic light.

spherical aberration:
(Chromey 5.5.4)

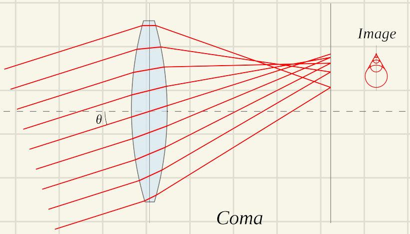
when light rays at different places on a mirror/lens are focused to different distances.





comatic aberration:
(Chromey 5.5.5)

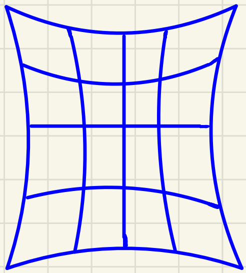
when light rays are focused to different positions in a plane parallel to the mirror/lens



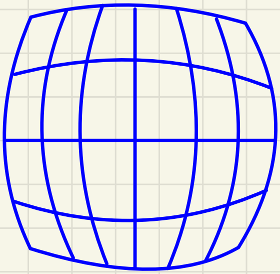
astigmatism: when the orientation of different planes in the
(chromey 5.5.6) incoming wavefront have different foci.

Distortions: when parallel lines on the sky are not parallel in the image:

pincushion



barrel

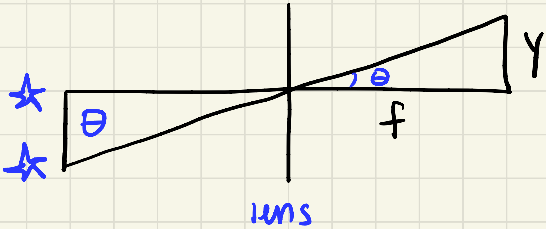


specifications of a telescope:

Plate scales: (chromey 5.3.2)

What aspects of a telescope determine the platescale? That is, the mapping of the sky to the camera, in arcsec/mm?

How many arcseconds does a pixel correspond to?



$$S = \frac{\theta}{y} = \frac{1}{f}$$

in radians

plate scale

$\tan\theta = y/f$
for small angles, $\tan\theta \approx \theta$

to express the plate scale in arcsec/mm, let $y = 1$mm:

$$S = \frac{206265}{f} \quad [\text{arcsec/mm}]$$

Focal ratio:

$$R = f/D$$

f → focal length

D → aperture diameter

WIRO has a focal ratio of 27, usually written as f/27. Larger R is "slow", smaller R is "fast".

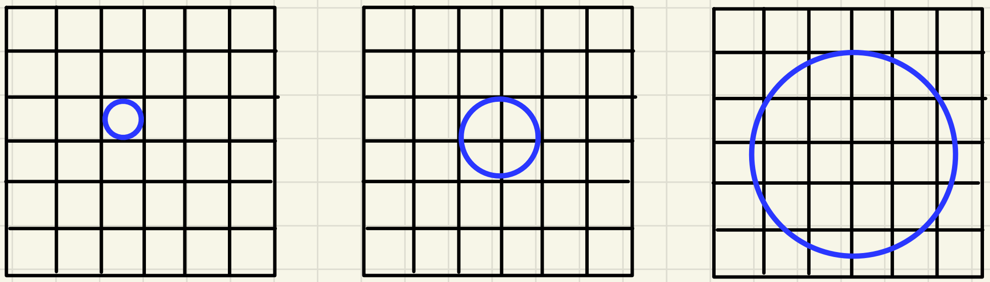
z.B. WIYN at KPNO is an f/6.29 3.5m telescope. What is its platescale?

$$R = f/D \Rightarrow f = R \cdot D = 6.29 \cdot 3.5\text{m} = 22\text{m}$$

$$S = \frac{206265}{f} = \frac{206265}{22\text{m} \cdot 1000\text{mm/m}} = 9.37 \text{ arcsec/mm}$$

- f is always the effective focal length, which can be achieved with a complex optical path. WIYN doesn't have a 22m length!

- the combination of plate scale and detector pixel size need to be carefully chosen so that the data (e.g. star images) are sufficiently well sampled.
- the Nyquist criterion (nyquist sampling) specifies that there need to be two detector elements per resolution element.
- z.B. the full width at half-maximum (FWHM) of the seeing disk (the Point spread function or PSF) is 1 arcsec, then you want to have 0.5 arcsec/pixel or better.



undersampled

- poor image definition for point sources
- poor separation for close sources
- can dither to try to recover shape info

Nyquist or critically sampled

- adequate image reconstruction and source separation

oversampled

- may allow superior image reconstruction and definition, but also leads to more noise (it's per pixel) and larger flux uncertainty
- smaller FOV

Field of view (FOV) is pixel size multiplied by number of pixels.

2. B. Suppose you are observing at WIYN (3.5m, $f/6.29$) and the seeing is 0.8" at best. What pixel size, in microns, should your detector have in order to achieve Nyquist sampled data?

Need to get pixels with $p = 0.8''/2 = 0.4''$

$R = f/D \Rightarrow f = 6.29 \cdot 3.5\,m \cdot 10^6\,\mu m/m = 22 \times 10^6\,\mu m$

$$\text{platescale} = \frac{206265}{22 \times 10^6} = 0.00937\ ''/\mu m$$

$$p = \frac{0.4''}{0.00937''/\mu m} = 42.2\,\mu m$$

What sized pixels will oversample the data? smaller

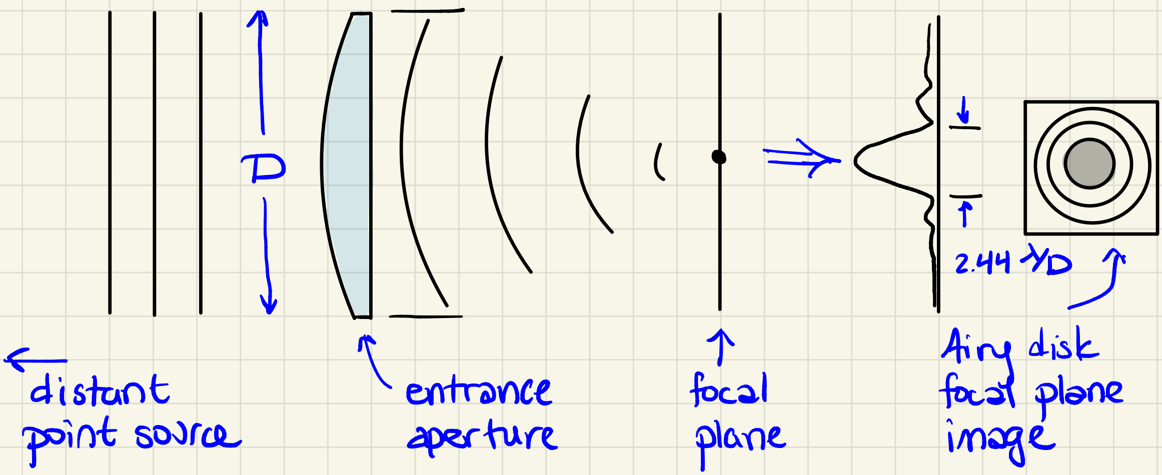
undersample? bigger

What would the FoV be for a 2048 x 2048 detector?

$\text{FoV} = p \cdot N_{pix} = 0.4'' \cdot 2048 = 819.2'' = 13.6'$

Angular Resolution (Chromey ch. 5.4)

There is a limit to the image quality you can achieve due to the wave nature of light.



The wavefront from distant astronomical sources will arrive perfectly planar and parallel at the telescope aperture.

They will encounter the entrance aperture of the telescope, usually the primary mirror or lens, with diameter D.

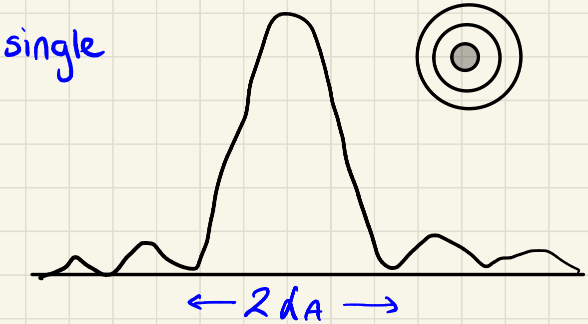
The calculation of how the planar wavefront interacts with this pupil is a problem first worked out by George Airy. Effectively, you will get a bullseye pattern, now called an Airy disk, which is the Fourier transform of a circular aperture.

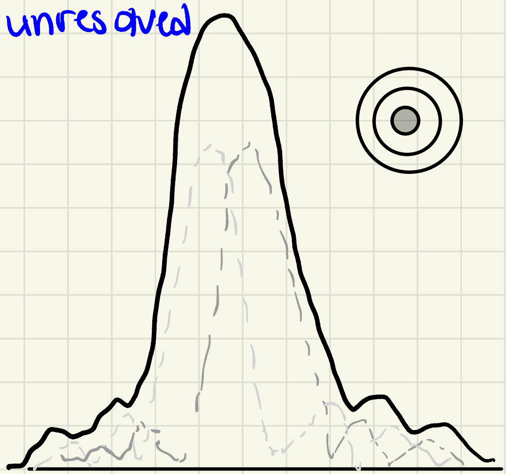
The size of this Airy disk is the diffraction limit of the telescope, and will be the minimum size of a point source.

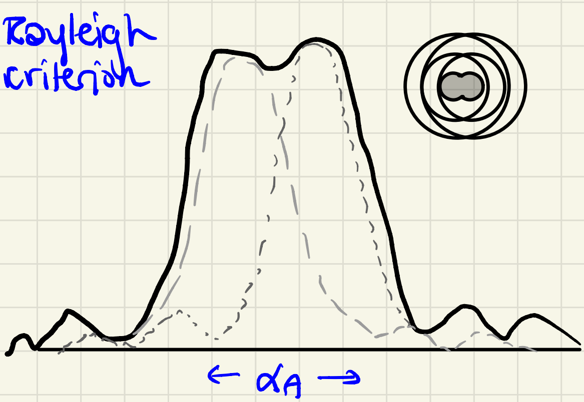
The angular radius of the first dark ring is

$$\alpha_A = \frac{1.22\lambda}{D} \text{ [radians]} = \frac{0.252\lambda}{D} \text{ [arcsec in } \mu m^{-1}\text{]}$$

The FWHM of the Airy disk is $0.9\,\alpha_A$. If two sources are two close, they may look like one. To resolve two sources, you need them to be separated by at least α_A, the angular radius of the central disk. This is called the Rayleigh Criterion. In this limiting resolution scenario, the maximum of one pattern coincides with the first dim minimum in the other.







Z.B. Find the angular resolution of the Hubble Space Telescope at 1200Å (about the bluest it can go). HST is a 2.5m.

$$\alpha[\text{radians}] = \frac{1.22 \cdot 1200\text{Å}}{2.5\text{m} \cdot \times 10^{10}\,\text{Å/m}} = 5.865\times10^{-6}\,\text{rad} \cdot \frac{206265''}{\text{radian}}$$

$\alpha = 0.012''$

HST is the best resolution you will get without adaptive optics or an interferometer.

Z.B. What is the best resolution you can get with Gemini/GMOS, an 8.1m that operates at 360–1030 nm?

$$\alpha[\text{radians}] = \frac{1.22 \cdot 360\,\text{nm}}{8.1\text{m} \cdot 10^{9}\,\text{nm/m}} = 5.422\times10^{-8}\,\text{rad}$$

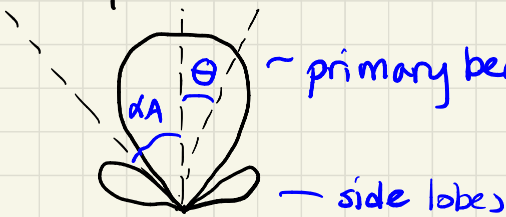
$\alpha = 0.011''$

Typical seeing at the Gemini N site is $\sim 0.75''$. So you can see that ground-based optical telescopes are not usually diffraction limited.

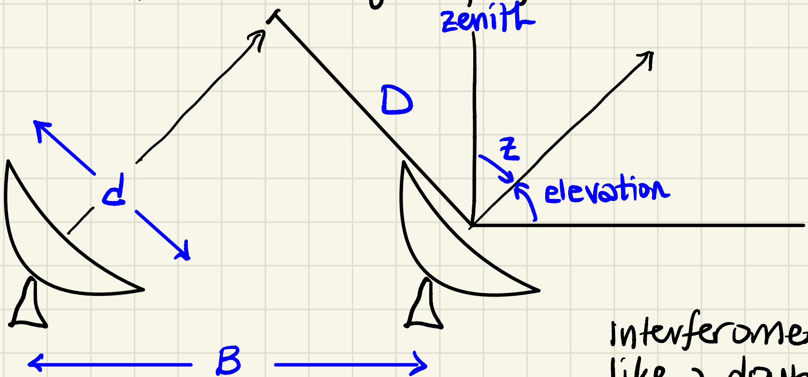
Interferometers:

In the radio, the field of view is given by the angular Airy disk size, so the power of a radio dish is:

The primary beam size is λ/d.



For interferometers, use the longest projected baseline as D.



Interferometers work like a double-slit experiment.

$$D = B \sin(\text{elevation}) = D\cos(z)$$

$$dA\,[\text{rad}] = \frac{1.22\lambda}{D\cos z}$$

z.B. The Very Long Baseline Array has a maximum baseline of 6156 km at a wavelength of 0.3cm. What is the resolution for a source observed at an airmass of 1.5?

$$x = 1/\cos z \Rightarrow \cos z = \frac{1}{x} = \frac{2}{3}$$

$$dA = \frac{1.22 \cdot 0.3\,\text{cm} \cdot 206265''}{6156\,\text{km} \cdot 10^5\,\text{cm/km} \cdot 2/3} = \boxed{0.18\,\text{mas}}$$