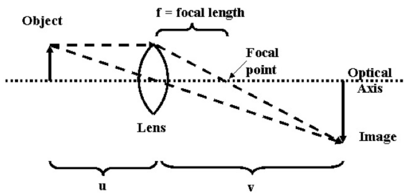
Telescopes

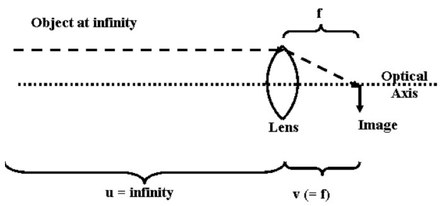
Review of Geometrical Optics

- The lens equation describes the formation of images:

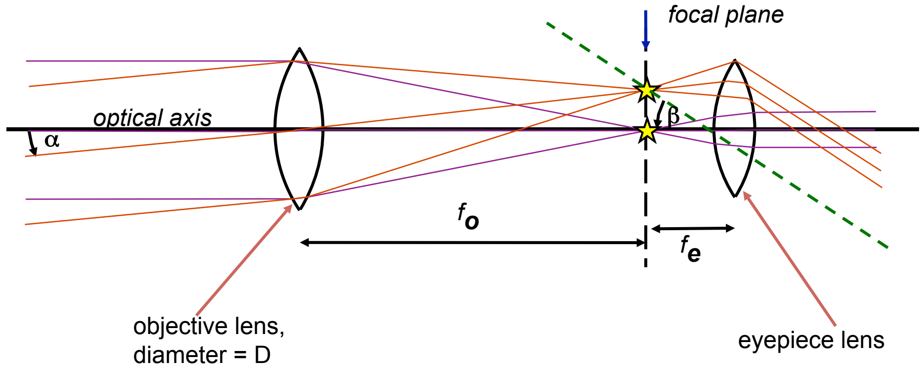
  1/u + 1/v = 1/f



- Astronomical sources are at infinity, therefore images are formed in the focal plane



A Basic Refracting Telescope



Angular magnification = $\dfrac{\beta}{\alpha} = \dfrac{\mathbf{f_o}}{\mathbf{f}_e}$

NB – the image is inverted!

Key Parameters

D = diameter of telescope f = focal length λ = wavelength

- **Light collecting power** scales with D^2
  - How quickly does the telescope collect photons?
- **Resolving power** scales with λ/D
  - How much fine detail can you see in the images obtained?
- **Plate scale** scales with 1/f
  - What angle does 1mm in the focal plane subtend on the sky?
- **F-ratio** (or speed) scales with f/D
  - How much does the optics spread out light in an image?
- **Field of view** scales (in general) with F-ratio
  - How large a patch of sky can the telescope view in one shot?
- **Ettendue** scales with D^2 and field of view
  - How quickly can a telescope complete a wide area survey?
- **Throughput**
  - How efficiently do the lenses/mirrors transmit/reflect light?
- **Large telescopes collect light fast at good resolution over (generally) small fields of view**

Light Collecting Power

- Eye can see up to 6th mag (maybe 4th in cities)
- Telescope has larger collecting area (aperture)
- Increasing collecting area increases detected flux: $\frac{f_T}{f_E} = \frac{D_T^2}{D_E^2}$
- So, if a star seen with the naked eye (aperture D_E = 1mm) is of magnitude m_E=6, using a telescope of aperture D_T = 1000mm will make the star appear to be of magnitude:

$$m_T - m_E = -2.5 \log \frac{f_T}{f_E} = -5 \log_{10} \frac{D_T}{D_E}$$

$$m_T = m_E - 5 \log_{10} \frac{D_T}{D_E} = 6 - 5 \log_{10} 1000 = -9$$

Light Collecting Power

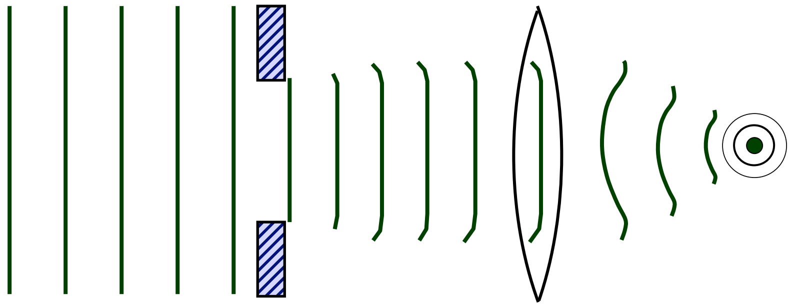
- Magnification by a telescope: $m_T = m_E - 5 \log_{10} \frac{D_T}{D_E}$
- Turning the previous argument around, if m_E(lim) is the faintest star detectable with the human eye, then the faintest star by the Eye+Telescope is:

$$m_T(lim) = m_E(lim) + 5 \log_{10} \frac{D_T}{D_E}$$

- So a human eye can see 21^{st} magnitude stars through a 1m class telescope
- Other detectors can also integrate longer than the human eye, which can extend the limit to fainter magnitudes!

Resolving Power

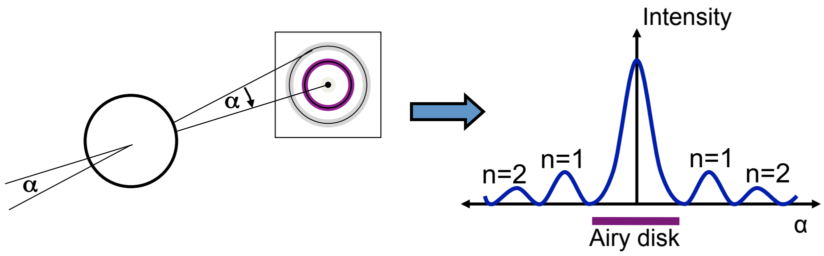
Diffraction by a Circular Aperture



Diffraction places a fundamental limit on our ability to distinguish two closely spaced objects (eg stars). Only 84% of the light is concentrated in the central spot, the rest falls in surrounding rings.

Resolving Power

Huygens Principle



- The constructive and destructive interference patterns are described according to Huygen's Principle
- For a telescope with diameter D and light with wavelength l, minima occur at positions given by:

$$\sin \alpha_n = \frac{m_n \lambda}{D}$$

Resolving Power

Airy Disk

- n is the number or order of the minimum
- m is the numerical factor for any given n (found by integrating over the light pattern)
- Because α is small, we may write:

$$\alpha_n = \frac{m_n \lambda}{D}$$

n	m
1	1.22
2	2.23
3	3.24

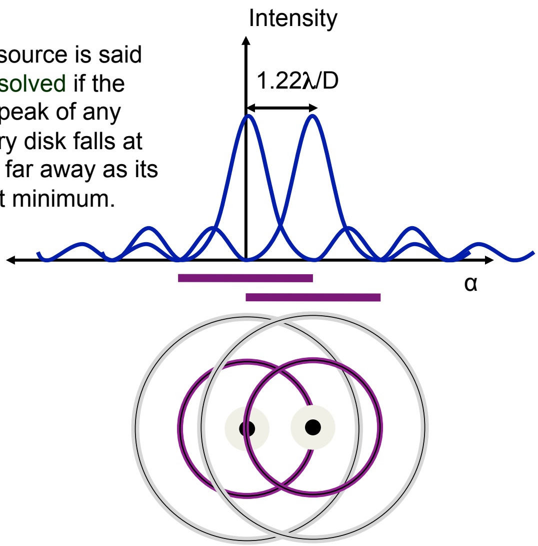
- The light contained within the radius (84% of the total) defined by the first minimum is called the Airy disk, where

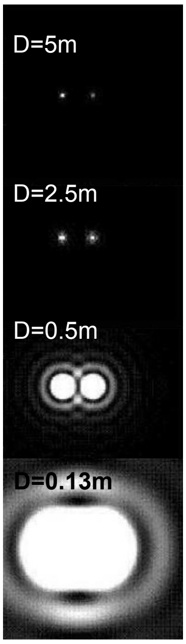
$$\alpha = \frac{1.22\lambda}{D}$$

Resolving Power

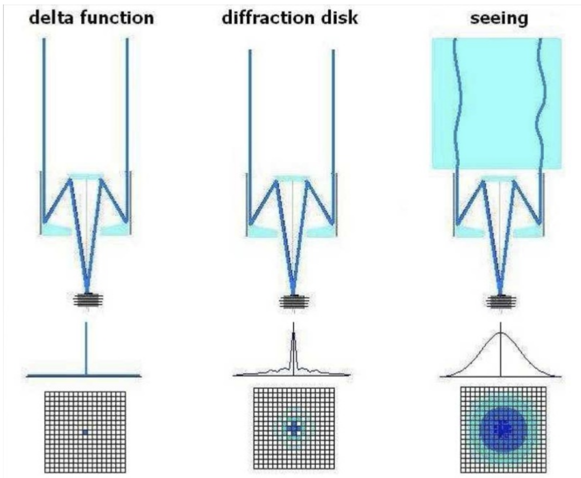
Rayleigh Criterion

A point source is said to be resolved if the closest peak of any other Airy disk falls at least as far away as its own first minimum.





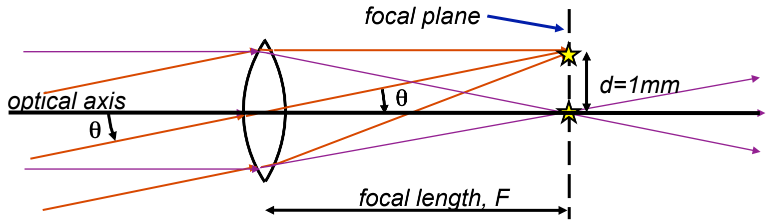
Geometry … waves … atmosphere



Geometrical Optics Wave Optics Real Atmosphere

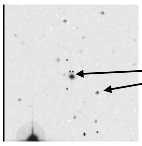
Plate Scale $\theta = \frac{1\ (\mathrm{mm})}{F\ (\mathrm{mm})} \mathrm{radians}$

- What angle does 1mm at the focal plane subtend on the sky?



- For the UK Schmidt telescope, F=3074 mm, thus, its plate scale is:

$$\theta = \frac{1\ (\mathrm{mm})}{3074\ (\mathrm{mm})} \mathrm{rad} = 3.25 \times 10^{-4} \mathrm{rad} = 67.2\ \mathrm{arcsec/mm}$$



Distance between these two stars is 2mm, i.e. 134.4 arcsec

Focal Ratio and “Speed”

- F-ratio = $\dfrac{\text{focal length}}{\text{diameter}} = \dfrac{f}{D}$
- Often written as “f/f-ratio” i.e. f/8 is an f-ratio of 8, i.e. the focal length is 8x the lens (or mirror) diameter

- If, whilst keeping D fixed you double the focal length then:
  - the F-ratio doubles
  - the plate scale halves (angle subtended by 1mm at focal plane halves)
- The light from an extended object is spread out over an area 4x larger in the focal plane
- A given photon flux per unit area of the focal plane therefore takes 4x longer to accumulate
- Telescopes with larger/smaller F-ratios are therefore said to be “slower”/”faster”
- However the total amount of light gathered is determined only by D

Field of View (FoV)

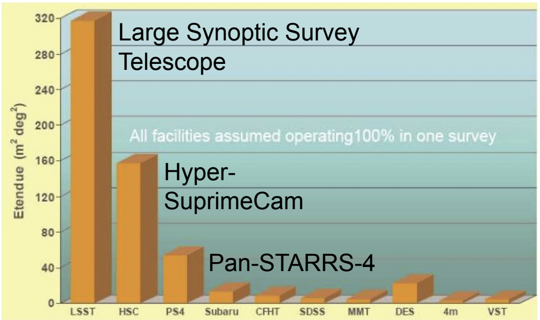
- Defined as the angular size of the patch of sky observable by a telescope
- Depends on the plate scale and the size of the detector

- Example:
  - The Canada France Hawaii Telescope (CFHT) has a primary mirror of D=3.58m, and a focal length of f=13.62m
  - The f-ratio is: 13.62/3.58 = 3.8
  - The plate scale is: ϑ = 1/13.62m = 7.34×10^{-5}rad/mm = 15 arcsec/mm
  - Mega-Cam is a camera containing detectors (CCD chips) that span a roughly square 24cm x 24cm region of the focal plane
  - The field of view is: FoV = 24cm x 15arcsec/mm = ~1degree

  - What would the FoV of Mega-Cam be if it was mounted on a telescope with the same mirror size as CFHT, but an f-ratio of f/8?

Etendue

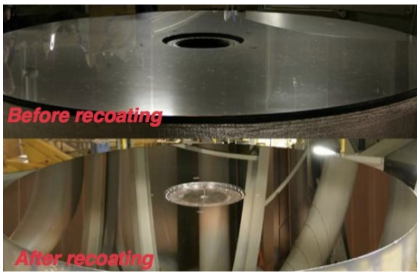
- Etendue is a figure of merit for wide-field imaging surveys
- It quantifies the pace at which a survey can observe the sky
- Etendue = collecting area x field of view



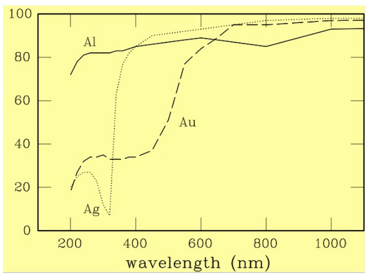
- What is the etendue of CFHT/Mega-Cam?

Throughput

- Mirrors need to be cleaned frequently
  - CO_2 “snow” used to blow off dust
  - Sometimes wet clean with detergents
- Mirrors also need to be re-coated every few years

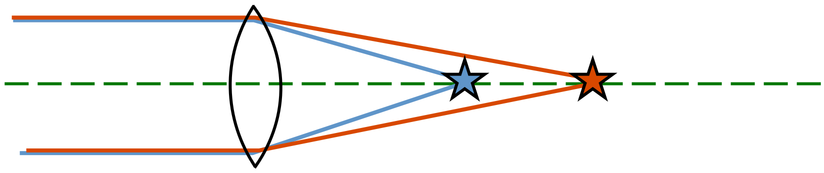


- Choice of coating affects reflectivity of mirror:
  - UV: Aluminium
  - Optical: Silver
  - IR: Gold

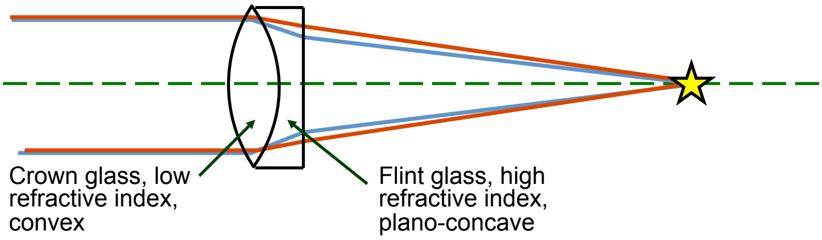


Chromatic Aberration

- The focal length of a lens is a function of wavelength:



- A compound lens can correct the problem to some extent:

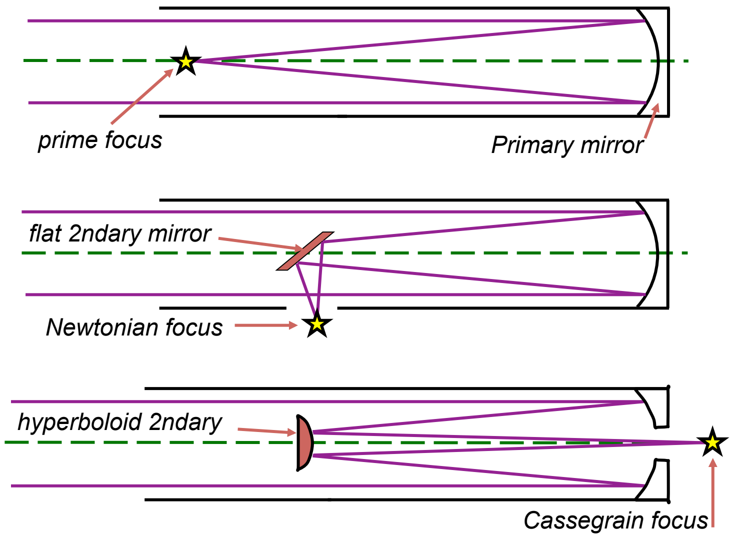


Limitations on Refractor Size

- Increasing lens size creates problems:
  - Lenses have to be supported around the edge
  - Light grasp propto d^2; mass propto d^3
  - Flexure (bending) of the lens causes optical aberrations
- Largest refractor ever built was the Yerkes telescope (D=1m)

Yerkes refractor in 1895

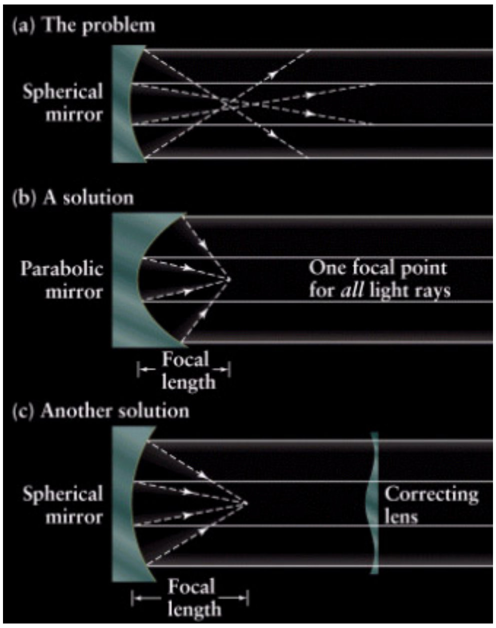
Reflecting Telescopes



Benefits of Reflectors

- Aperture not limited to ~1m because mirrors can be supported across their back side
- Do not suffer chromatic aberration because reflection is independent of wavelength
- Contain fewer optical surfaces than refractors and therefore are optically more efficient
- Largest optical telescopes are reflectors
  - Keck telescopes have primary mirrors with D=10m
  - Note humans opposite!

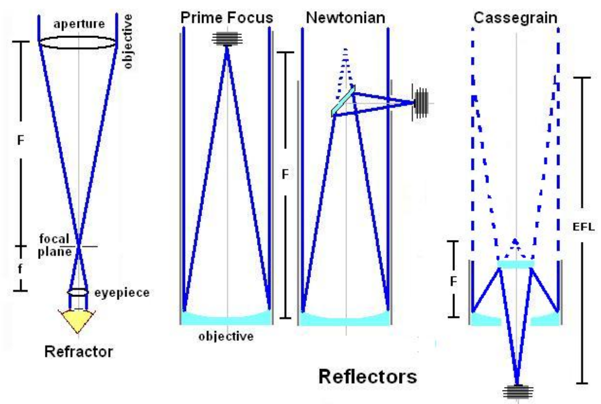
Spherical Aberration



- Spherical mirrors don't focus parallel beams to a point
- Most modern telescopes solve this problem with a parabolic primary mirror
- But parabolic mirrors have a smaller field of view, suffer coma and low f-ratios
- Another solution is to use a correcting lens
- Wide field of view survey telescopes use this option (e.g. Schmidt telescopes)

Refractors and reflectors

Effective focal length depends on focal lengths of primary and secondary and their separation



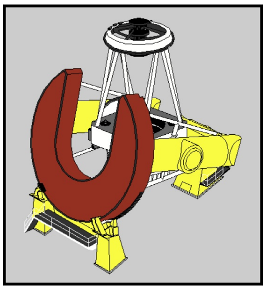
At fixed f-ratio, a Cassegrain telescope is more compact because of the hyperbolic (magnifying) secondary

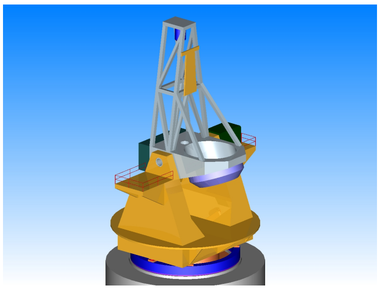
Cassegrain design lends itself to mounting heavy equipment more easily

But large effective focal length means plate scale is small and tends to limit field of view

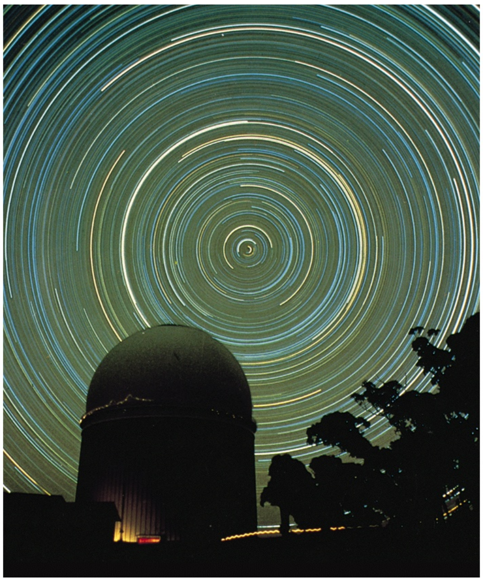
Telescope Mounts

- Telescopes must be free to move about two mutually perpendicular axes in order to cover the whole sky
- There are two main types:
  - Equatorial – one axis is aligned with the celestial poles so you need only track in one axis (i.e. in hour angle)
  - Altazimuth – telescope moves in (local) altitude and azimuth, so is simpler to design but has to be tracked in two axes





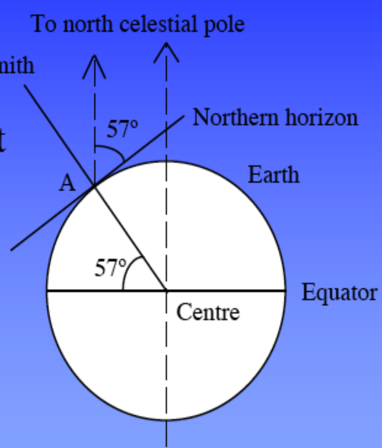
All through the night



- All stars revolve around the Pole relative to us
- Some stars don't set at all
- Some stars never rise, depending on where you are
  - e.g. Proxima Centauri at declination = –62º

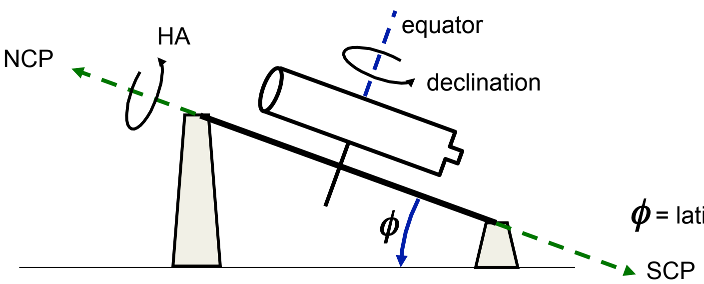
Pole Star above the Horizon

- The **latitude** of Aberdeen is the angle at the centre of the Earth shown in the diagram as 57°



- The **pole star** is the same angle above the northern horizon as your latitude. Sketch for Aberdeen

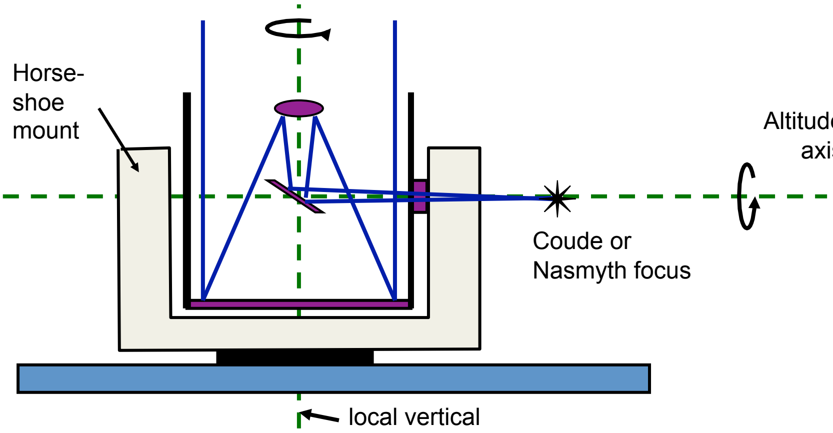
Equatorial mount



Only need to track in HA and there is no field rotation (direction of North in the focal plane is fixed).

But it is complex and expensive to build – especially for large telescopes.

Altazimuth mount



The design is simple, but it must track in both axes and the field rotates. The largest (8-10m) telescopes have alt-az mounts with Cassegrain and Coude/ Nasmyth foci

Telescope mounts

Equatorial mount

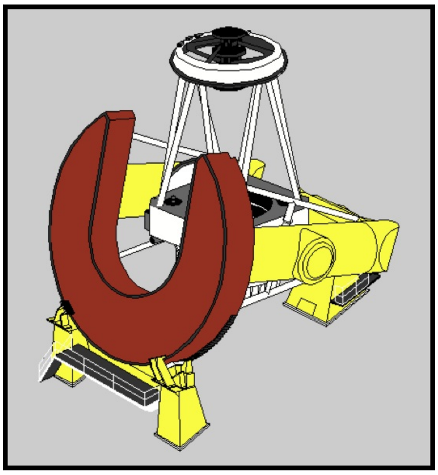
- Advantages:
  - Polar axis driven at constant rate
  - Dec axis stationary
  - Field of view doesn't rotate
  - Track in one dimension (simpler)
- Disadvantages
  - Telescope high off ground
  - Complex design
  - Large dome (expensive, prone to thermal currents)
  - Piers get in way (vignette the field of view)

Altazimuth mount

- Advantages
  - Compact construction
  - No obstructions
  - Smaller dome
  - Simple to design
- Disadvantages
  - Complex rotation, variable speed
  - Field of view rotates (can be corrected for)
  - Blind spot near zenith

4-5m Class Telescopes

Equatorial mount and multiple foci (Prime and Cassegrain)

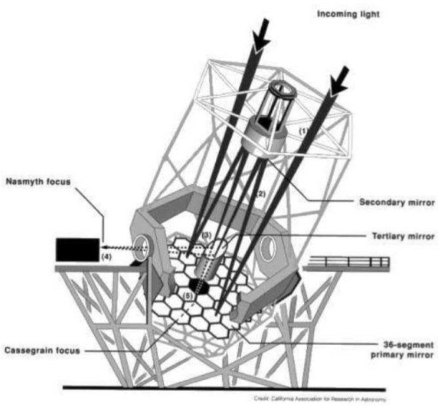


CFHT

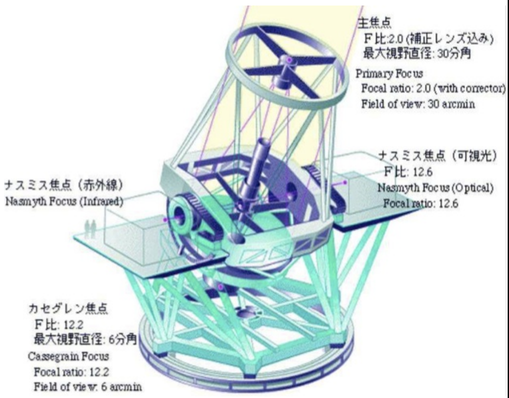
Hale

8-10m Class Telescopes

Alazimuth mount and multiple foci (including Naysmith and Coude)



Keck



Subaru