

# Optical Telescopes and their use in Astronomy

## **Brief history**

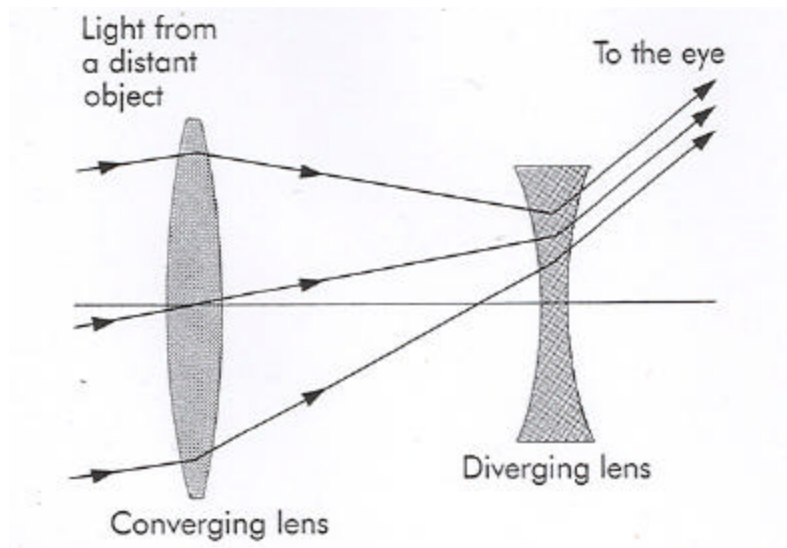
**Roger Bacon** (1214-1294): spectacles for correction of long sight

**Giambattista Della Porta** (1535-1615): camera obscura

**Leonard Digges** (1520-1559): long focal lens + concave mirror -- Also invent the theodolite (1550)

**Hans Lippershey** (1570-1619): two lenses telescope (1608)

**Galileo Galilei** (1564-1642) heard about the telescope and reproduced the effect creating his own design = **Galileo refractor**



Long focal length converging lens + shorter focal length diverging lens placed before the focus  $\Rightarrow$  upright images

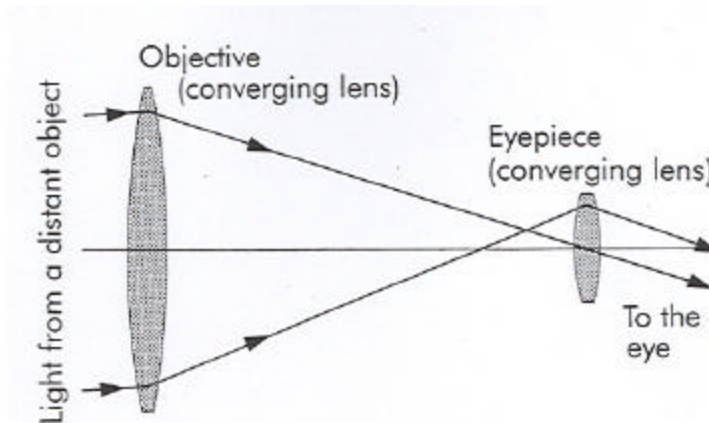
Magnification:  $30\times$

Discoveries:

1. Craters on the moon
2. planets  $\neq$  point sources
3. 4 largest satellites of Jupiter
4. Phases of Venus + angular size variations  $\Rightarrow$  argument in favor of heliocentric system

Early 17<sup>th</sup> century: difficult to produce short focal length diverging lenses with deep concave surfaces

**Astronomical refractor:** long focal length converging lens (**objective**) + short focal length converging lens (**eyepiece**) placed after focus  $\Rightarrow$  upside down image



Problems:

1. Aberrations: Spherical + chromatic
2. Poor quality of glass: debris from furnace + bubbles of air
3. Poorly polished  $\Rightarrow$  not correct shape

$\Rightarrow$  Saturn's ring not observed until Huygens (1629-1695) 40 years after the invention of telescope

4. Small **FOV** (field of view)  $\Rightarrow$  difficult to find object
5. No mountings  $\Rightarrow$  difficult to track

One neat trick: to reduce aberrations = focal length of lens must be long compared to diameter  $\Rightarrow$  high **focal ratio**  $f/D$

Implications:

- Terrestrial telescope  $\Rightarrow$  retractable
- Astronomical telescope  $\Rightarrow f = 3-5$  m

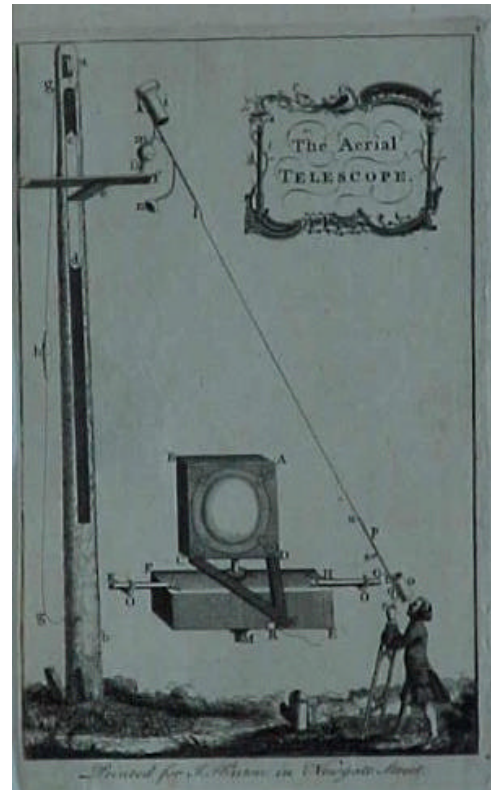
One excessive ex. = **aerial telescope**

**Johannes Hevelius** (1611-1687):  $f = 60$ m

Lens mounted on tube on top of mast + objective mounted on other tube connected by taut line

Eye-piece held in hand by observer moving around the mast to point in different directions

Used by **Cassini** (1625-1712) to find new satellites of Saturn and its ring



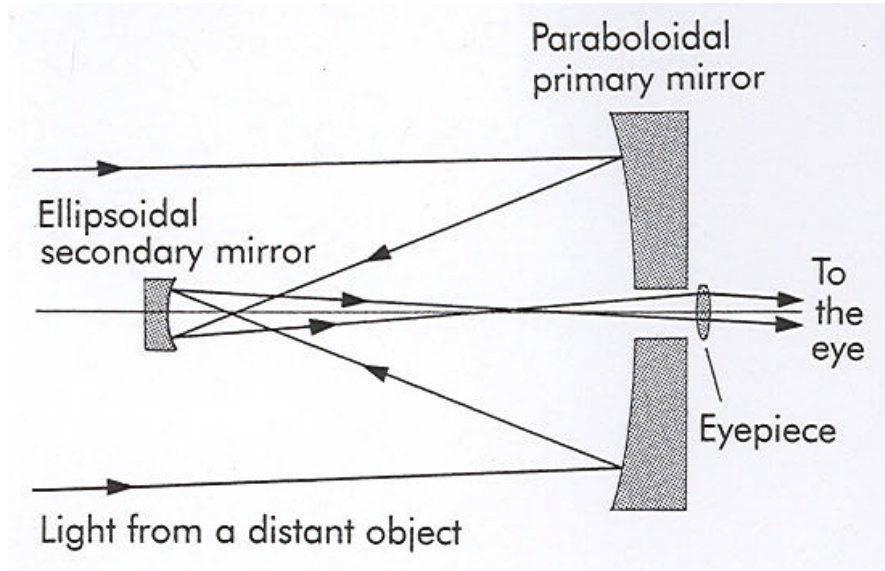
Mid 17<sup>th</sup> century: used of reflector to avoid achromatic aberration

Using paraboloid  $\Rightarrow$  eliminates spherical aberration

**Jones Gregory** (1638-1675) invented the **Gregorian telescope** (1663): paraboloid mirror for objective (**primary mirror**) + **secondary mirror** (ellipsoid) placed after focus

The light emerges through a small hole in center of the primary mirror

Observation through eyepiece made of lenses



Disadvantages: Small FOV + difficult in construction  $\Rightarrow$  no astronomical observations

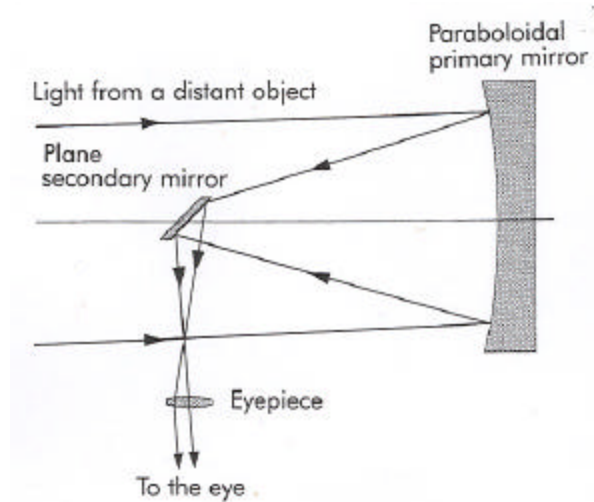
**Isaac Newton** (1642-1727)

Invent **Newtonian telescope** five years after Gregory

Parabolic primary + 45° flat mirror

$\Rightarrow$  focus on the side of telescope

Diameter = 25mm

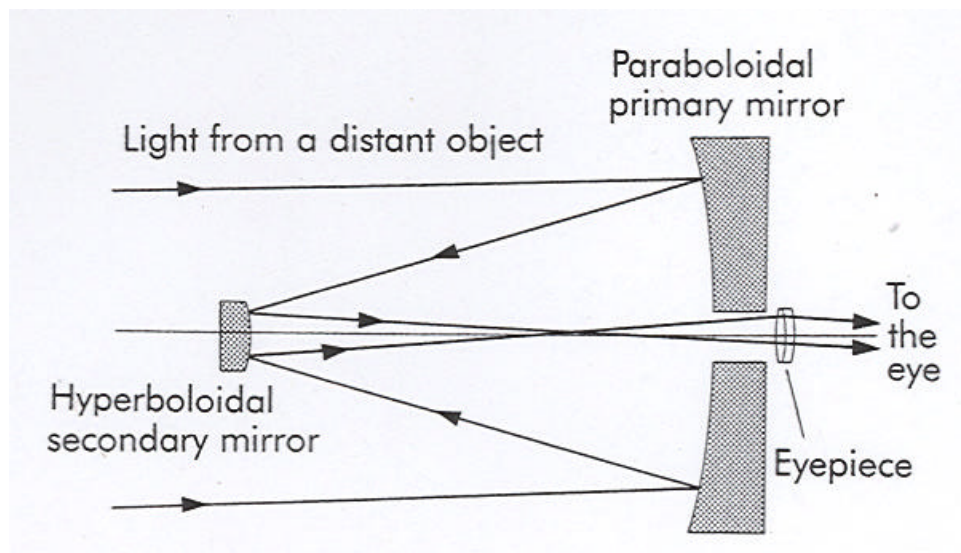


Problems:

- Bad coating = metal + alloy (75% copper + 25% tin + zinc + arsenic)  $\Rightarrow$  reflectivity 60% + tarnish quickly
- Aperture 1 inch maximum
- 2 mirrors  $\Rightarrow$  few more light than observed by eye
- Magnification  $25\times$   $\Rightarrow$  light spread over 600 times area  $\Rightarrow$  only brighter object can be observed

**Cassegrain 1672:**

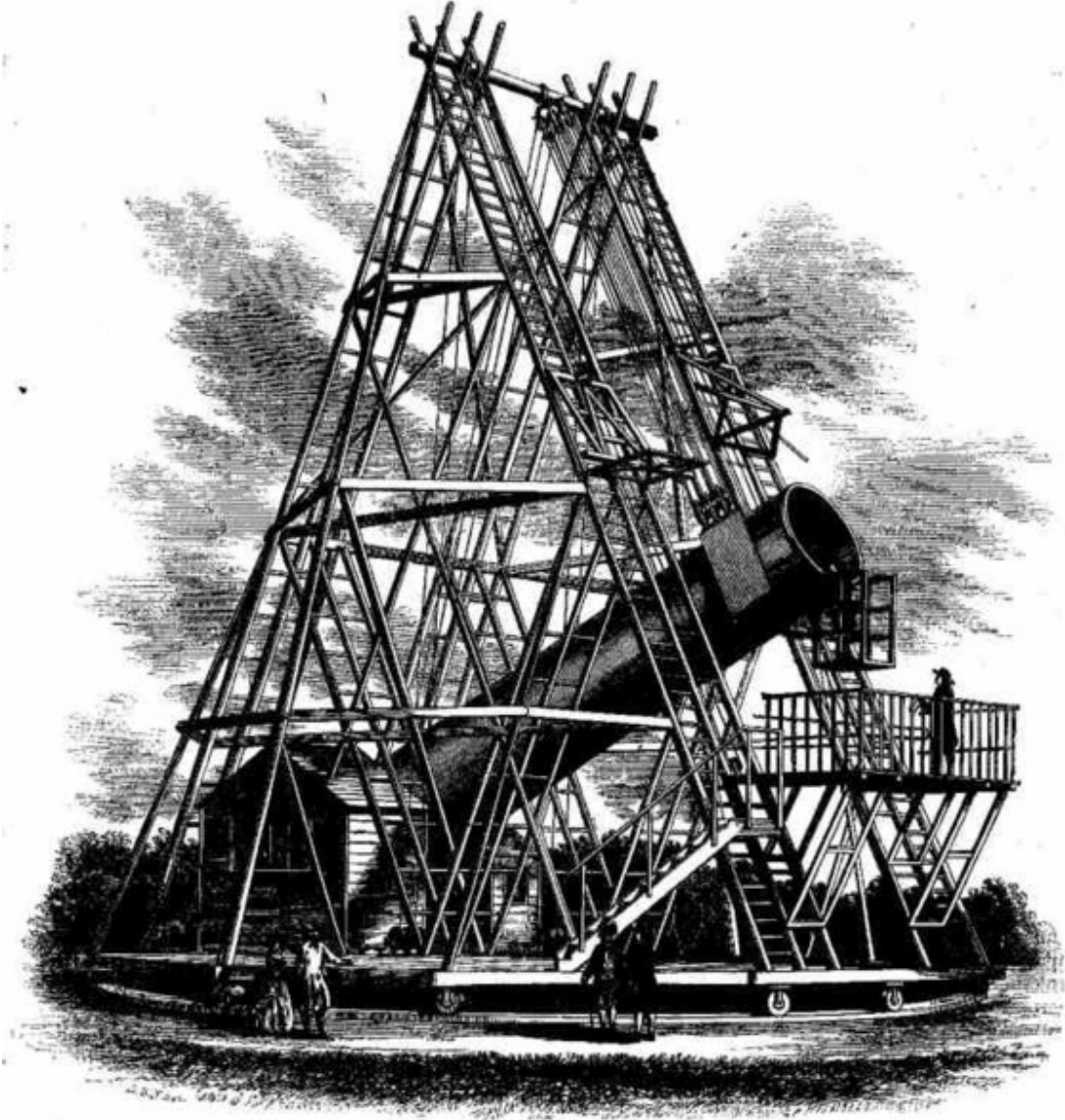
- Secondary = convex hyperboloid
- Mirror placed before focus  $\Rightarrow$  telephoto property = focal length much greater than physical length
- Huge economic gain:
  - Short tube = thinner material
  - Mounting + drive smaller



FOV bigger than Gregorian but more difficult to build  $\Rightarrow$  Gregorian more popular at the time

Early 1720, first correctly shaped parabolic primaries by *John Hadley* (1682-1744) also invent the sextant (1730)

*William Herschel* (1738-1822) used telescope without a secondary  $\Rightarrow$  **off-axis telescope**



Cumbersome 1.26m telescope with  $f/9.5$

Early 18<sup>th</sup> century – refractor + reflector of bad quality

In 1729, *Chester Moor Hall* (1703-1771) invent **achromatic lens**

*John Dollond* (1706-1761) produces high quality achromatic lenses using crown glass + flint

Invention of **Doublet**: two simple lenses attached together made of glasses with different refractive indices and different amounts of dispersion  $\Rightarrow$  better image than a simple lens.  
 $\Rightarrow$  **achromat**: optimized to reduce chromatic aberration + reducing spherical + other optical aberrations

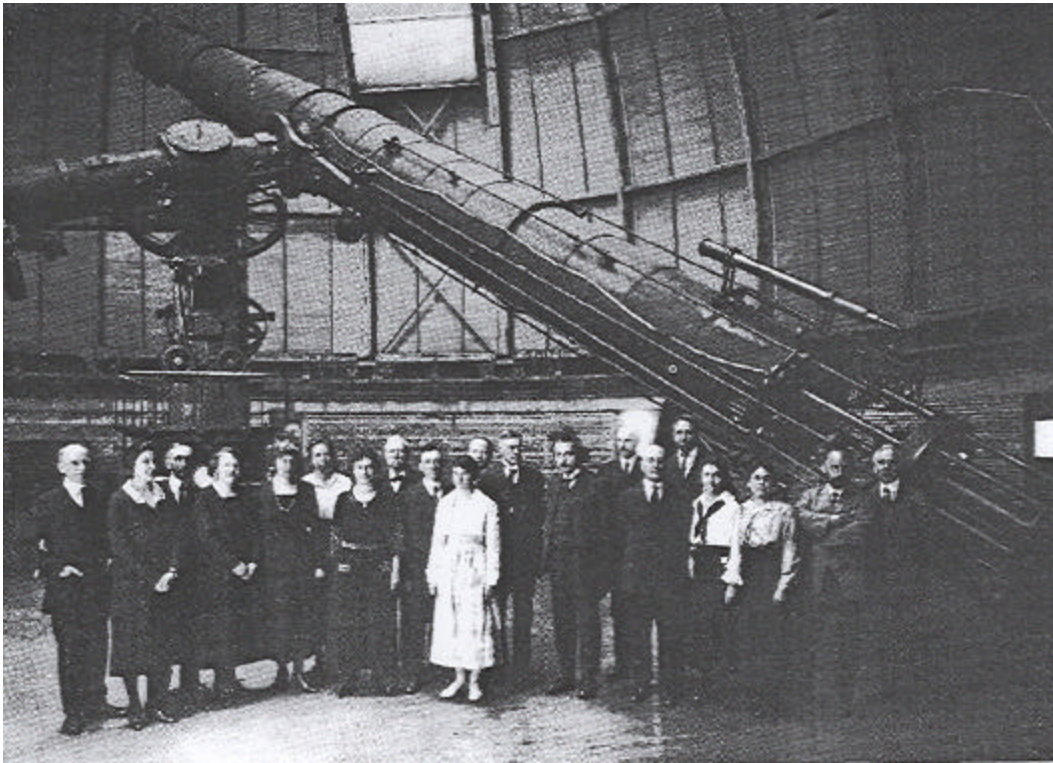
From mid 18<sup>th</sup> century refractors develop rapidly

*Joseph von Fraunhofer* (1787 - 1826) produces very high quality lenses

End of 19<sup>th</sup>  $\Rightarrow$  Culmination of refractor era = **Yerkes 1m telescope**

Limits of concept:

- Lens several inches thick
- Very heavy
- Absorption of light
- Supported only to the edge  $\Rightarrow$  lens change form under own weight



Einstein visit to the Yerkes 1m telescope

Advantages of reflectors:

- Larger diameter  $\Rightarrow$  superior in gathering light
- Can be supported from the back
- Only surface has to be high quality

**William Parson (1800-1867)**: with 1.8m telescope (1845) discover spiral arms in galaxies

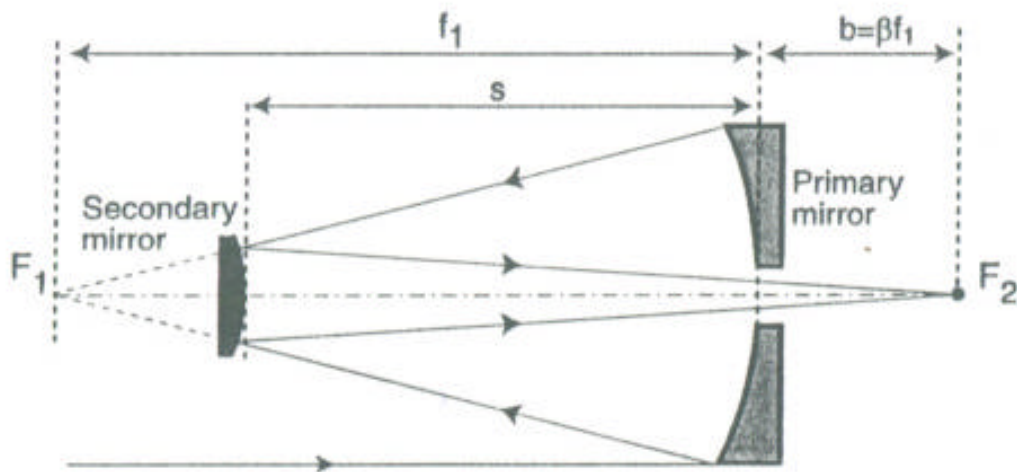
Problem of speculum mirrors = repolishing changes curve of telescope

Later part of 19<sup>th</sup> century, uses of metal coating on glass:

- Very high reflectivity  $\sim$  95% or more
- Removing old coating does not affect shape
- First coating = Silver  $\Rightarrow$  tarnish rapidly (a few weeks)
- Aluminum coating replace Silver  $\Rightarrow$  evaporated on to the glass while inside vacuum chamber
- Aluminum oxide, but first coated is transparent and seal surface from further oxidation
- Recoating only every year

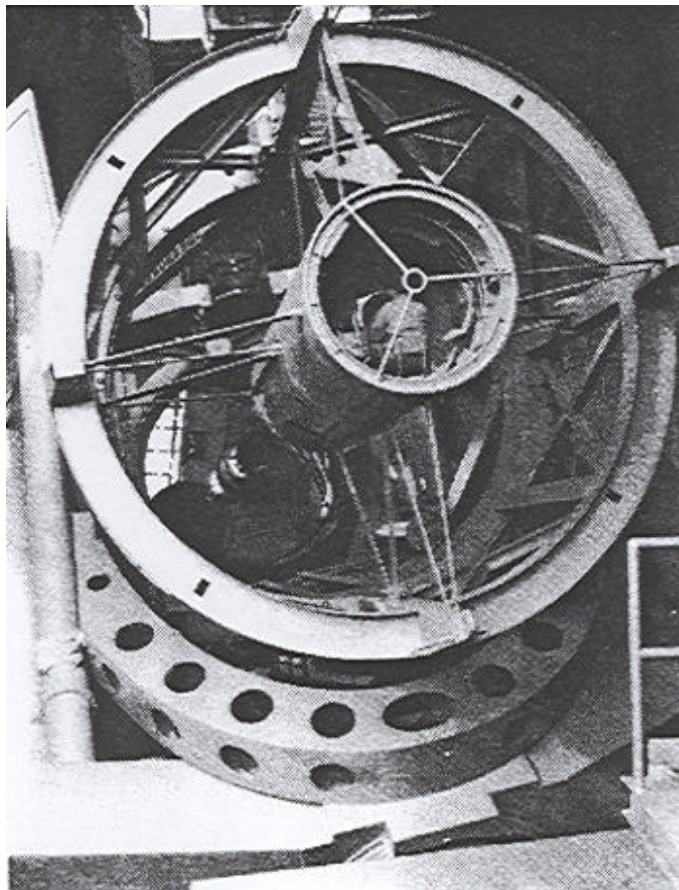
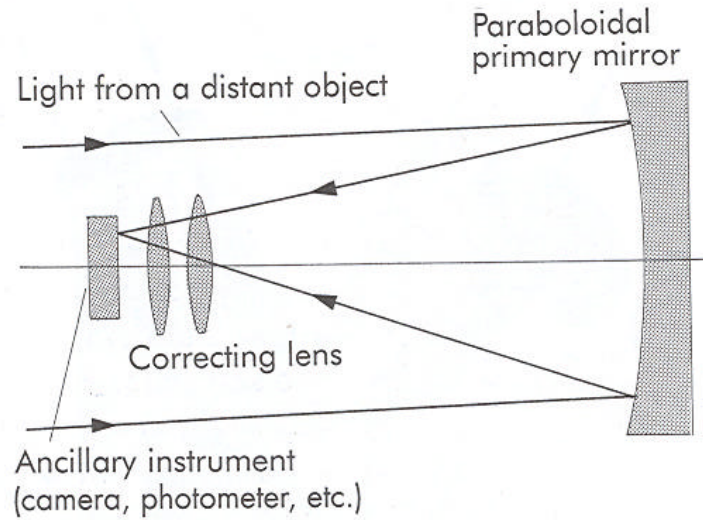
Modern design: **Ritchey-Chrétien** – primary and secondary = hyperboloid

On-axis image degraded but off-axis image improved  $\Rightarrow$  increased FOV (10 arcminutes)



**Primary focus telescopes:**

- Eliminate light loss from secondary
- Bigger FOV
- Instrument difficult to access (4m telescope observer on cage at primary focus)

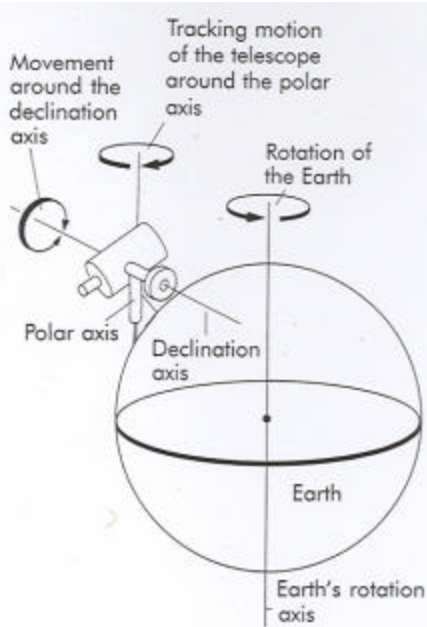


Cage at the primary focus of the Mount Palomar 5m telescope

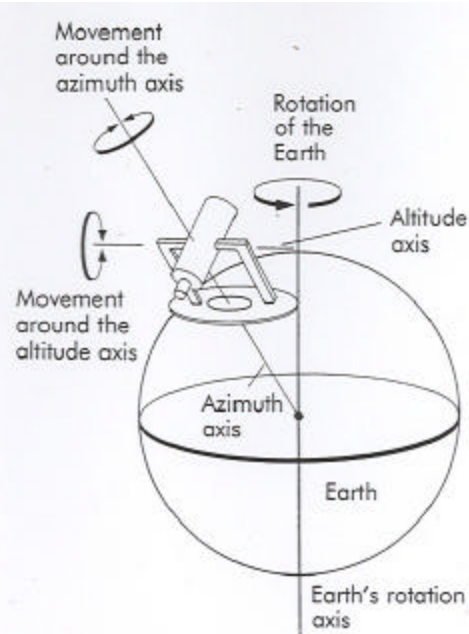
## Special Mountings

⇒ They allow pointing and tracking

### Equatorial mount



### Alt-azimuth mount



Equatorial mounting – need to be aligned with Earth rotation axe – focus is changing with position due to weight of instrument (must be as light as possible)

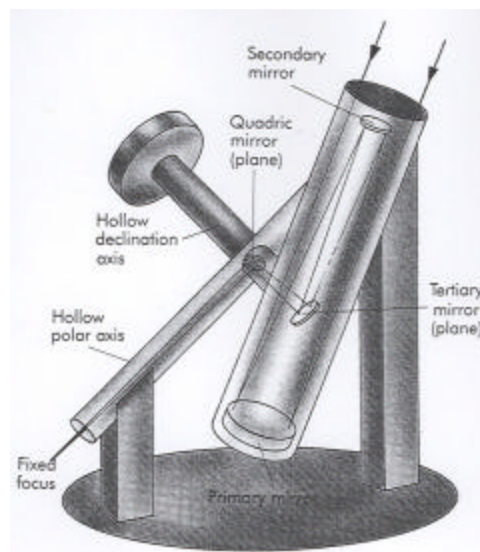
Alt-azimuth mounting is easier to build (no alignment needed) for very large mirror telescope – but do not allow to observe at zenith

**Coudé Focus** = fixed focus

Avoid the problem of changing focus  
⇒ instruments can be heavier

Used for échelle spectroscopy (very high resolution spectroscopy), where stability of focus and instrument is fundamental

The spectrograph is mounted on optical bench at Coudé focus



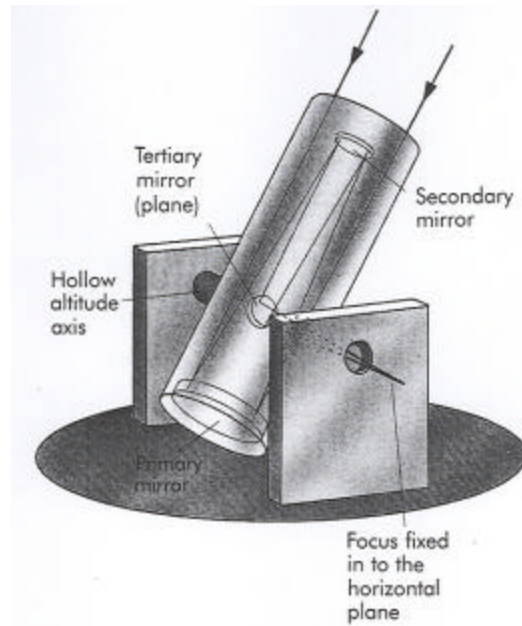
For Alt-azimuth mount

### Nasmyth focus

Focus is horizontal

- Easier access to focus
- Heavier instruments
- Multiple instruments

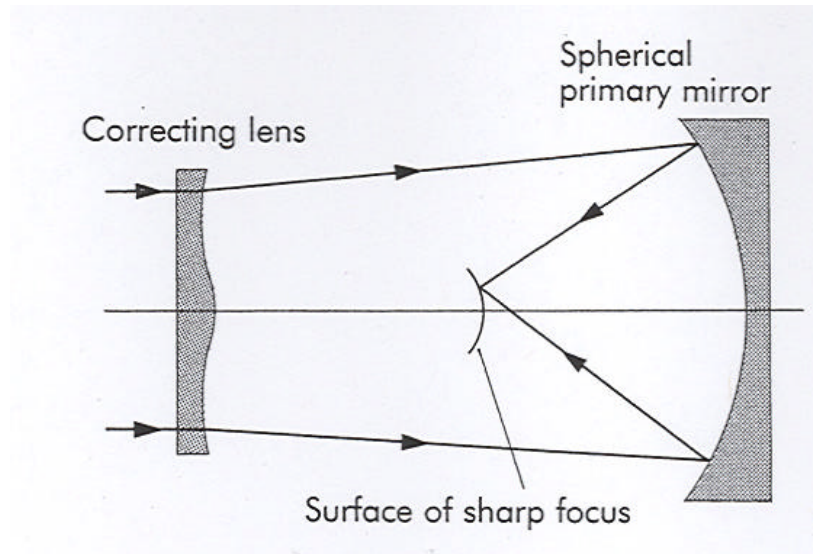
But FOV rotating  $\Rightarrow$  need a special system to compensate rotation



### Schmidt Camera (1930)

- Very wide field FOV --  $6^\circ - 10^\circ$
- $\Rightarrow$  used to do surveys
- One Schmidt camera in the north and Another in the south can cover the all sky very rapidly

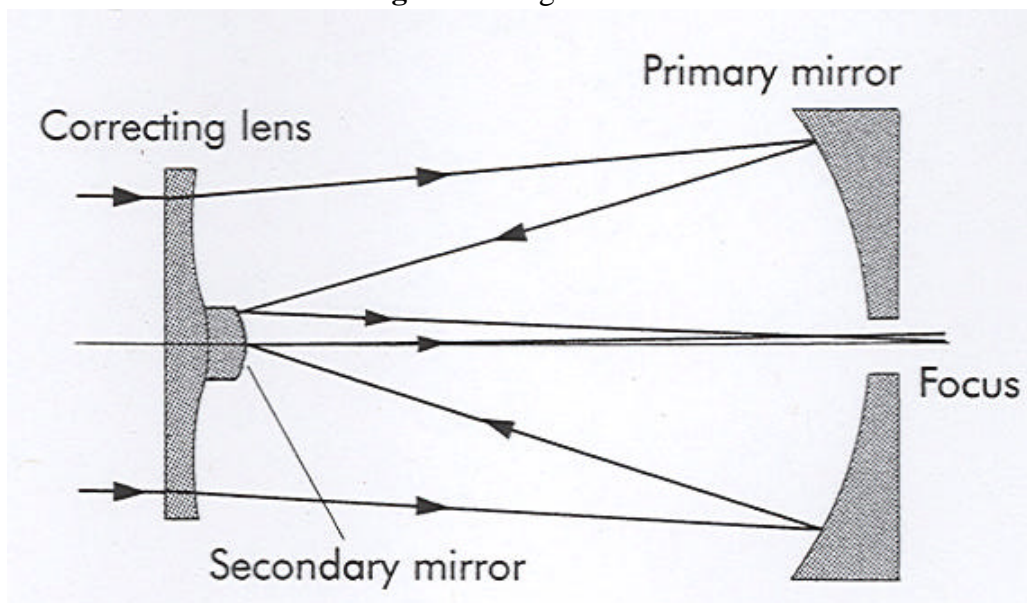




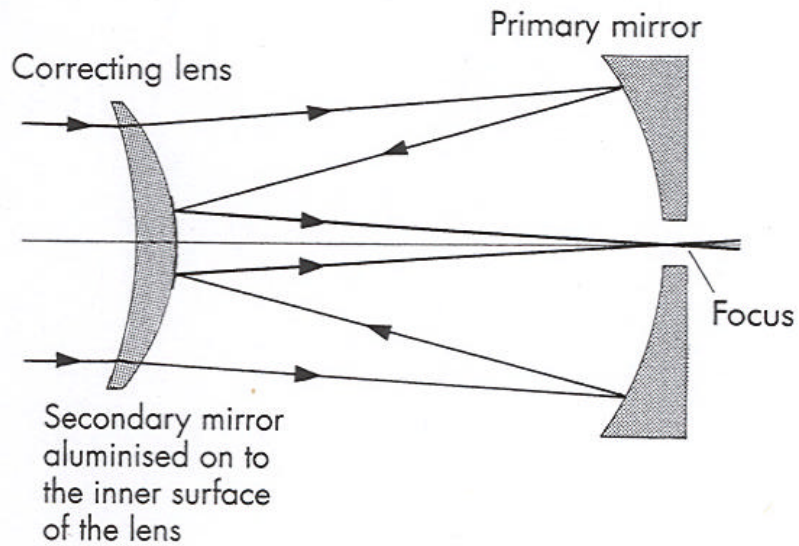
Problems:

- Focus out of reach
- Focus not a plane  $\Rightarrow$  photographic plate is bended
- $f \approx 2 \times D$
- Use a lens  $\Rightarrow$  **catadioptric** (refractor = **dioptric**)
- $D$  larger than useful aperture
- Spherical aberration corrected by lens

Modern version: **Schmidt—Cassegrain**  $\Rightarrow$  light reflected to back of instrument

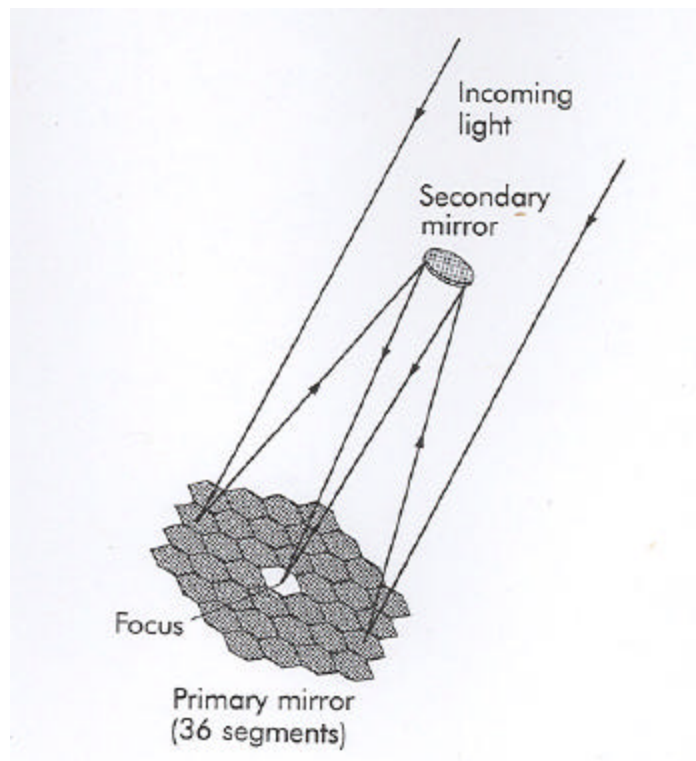


**Maksutov** – Primary mirror is spherical – aberration compensated by correcting lens  $\Rightarrow$  larger FOV + very cheap to build



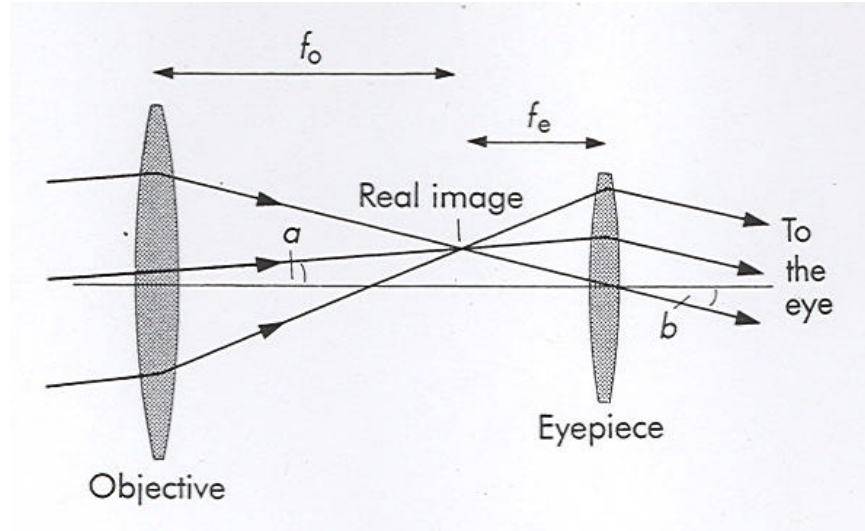
Muti mirror telescope – ex. Keck 10m telescope made of 36 2m mirrors

- Off-axis segments (difficult to shape)
- Active alignment of segments by computers



## Telescope optics

Principle: two lenses and/or mirrors are used in conjunction to magnified image  $\Rightarrow$  for point sources (stars) the image also looks brighter



- Object at infinite distance  $\Rightarrow$  parallel rays of light
- Focal point of objective = focal point of eyepiece

**Magnification:**  $M = \frac{b}{a} = \frac{f_o}{f_e}$

**Point source:** image of object smaller than detecting element of detector (pixel in CCD)

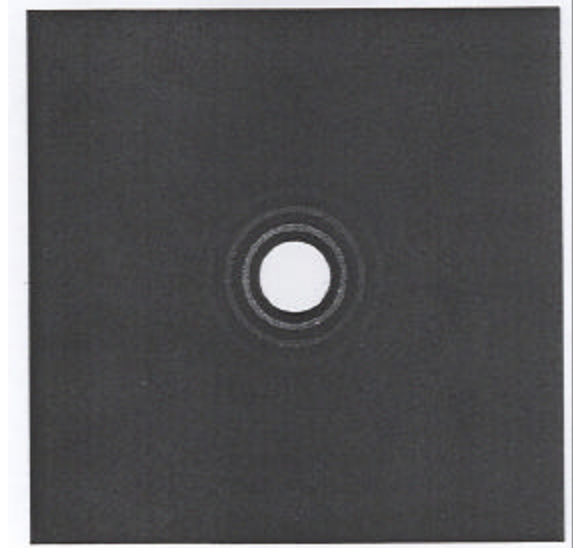
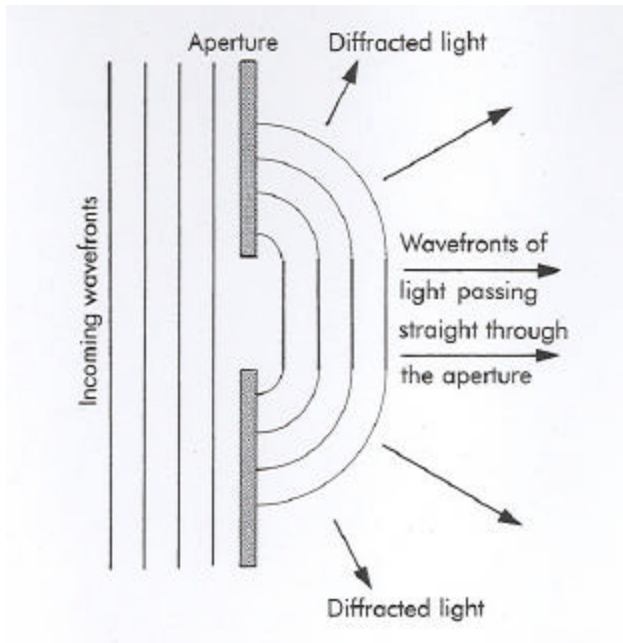
Increase in brightness = **light Grasp**

$$G = \frac{\text{collecting area}}{\text{pupil area}} = \frac{\mathbf{p}D^2/4}{\mathbf{p} \times (0.007)^2/4} \approx 20000D^2$$

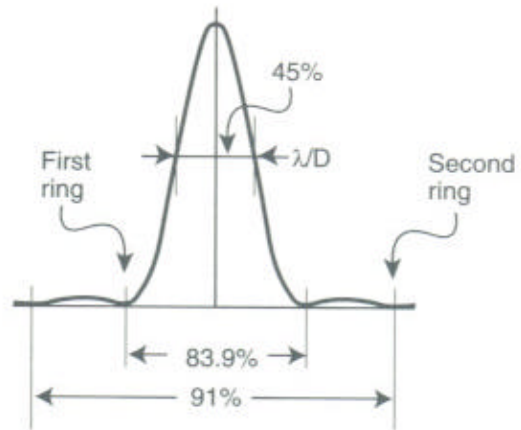
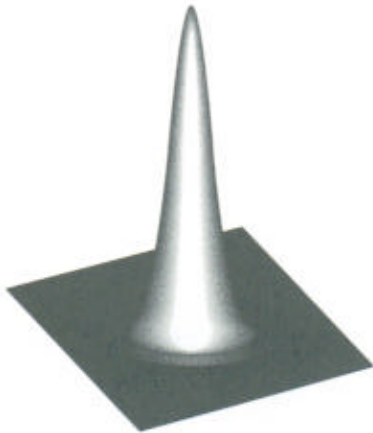
Where  $D$  = diameter of objective in meter

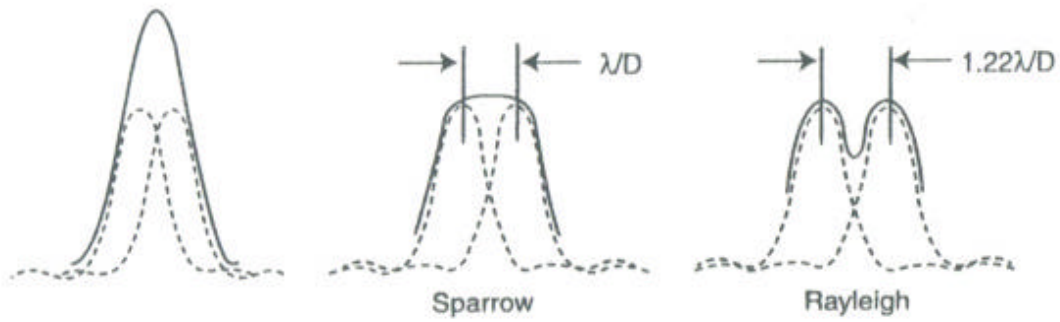
Limitations:

- diffraction at edge of aperture  $\Rightarrow$  points spread
- interference due to wave nature of light



**Airy disc**  $\Rightarrow$  diffraction limited image





**Angular resolution**  $A = \frac{1.22\lambda}{D}$

For visual  $\lambda = 500 \text{ nm} \Rightarrow A \approx \frac{0.13}{D} \text{ arcseconds}$

**Angular measures:**

$360^\circ = 2\pi \text{ radians} \Rightarrow 1 \text{ radian} \approx 57.2958^\circ \Rightarrow 1^\circ \approx 0.01745 \text{ radian}$

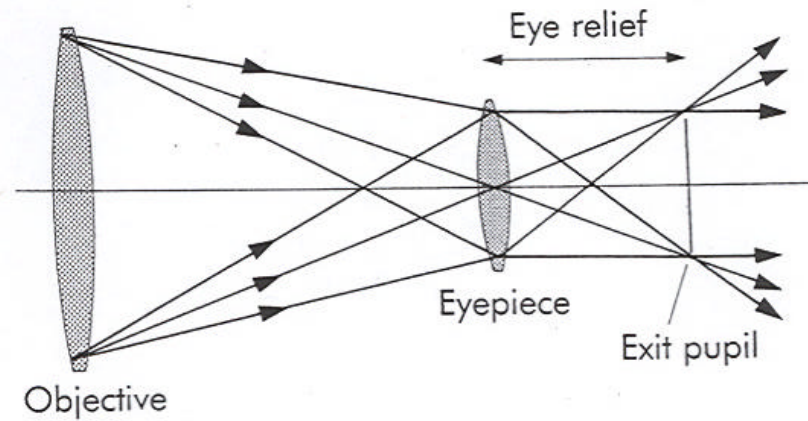
All sky =  $4\pi \text{ steradian} \approx 41269 \text{ square degrees}$

**Resolution of the eye:**  $0.3' - 0.5'$

In reality, resolution limited by atmosphere (seeing) – good sight  $\Rightarrow < 1''$

**Exit pupil:** image of objective produced by eyepiece

- ⇒ Point where emerging light has its smallest dimension
- ⇒ All light passes by the exit pupil
- ⇒ Best place where to place the eye (instrument)



$$D_{ep} = \frac{Df_e}{f_o + f_e} \approx \frac{Df_e}{f_o} = \frac{D}{M}, \text{ since } f_e \ll f_o$$

Minimum magnification for telescope used by eye:

$$0.007 > D_{eye} = \frac{D}{M} \Rightarrow M_{min} \approx 140D$$

Distance from eyepiece to exit pupil = **eye relief**  $\sim f_e$

⇒ Comfortable 6-10mm

**FOV of telescope:**  $FOV_{tel} = \frac{FOV_{eyepiece}}{M}$  where  $FOV_{eyepiece} \sim 30^\circ - 70^\circ$

**Extended object**  $\Rightarrow$  image larger than size of detector

$$\frac{\text{surf brightness trough tel.}}{\text{surf brightness to eye}} = \frac{G}{M^2}$$

$$\text{Since } G = \frac{D_o^2}{D_{eye}^2} \text{ and } M = \frac{D_o}{D_{ep}} \Rightarrow \frac{G}{M^2} = \frac{D_{ep}^2}{D_{eye}^2}$$

Minimum magnification  $\Rightarrow D_{ep} \approx D_{eye}$

Higher or lower magnifications  $\Rightarrow D_{ep} < D_{eye} \Rightarrow$  not all light reach the eye

Consequence: surface brightness of telescope, at best, no brighter than seen by naked eye and in practice will be fainter

Compensation due to eye structure: **cones** sensible to colors are more concentrated than **rods** which are not. Under low intensity light, rods become more sensible. Because light of extended object is spread by magnification a higher portion of it fall on rods  $\Rightarrow$  the object look brighter