OBSERVATIONAL ASTRONOMY

AUTUMN 2023

Lecture 2

Vitaly Neustroev

Telescopes

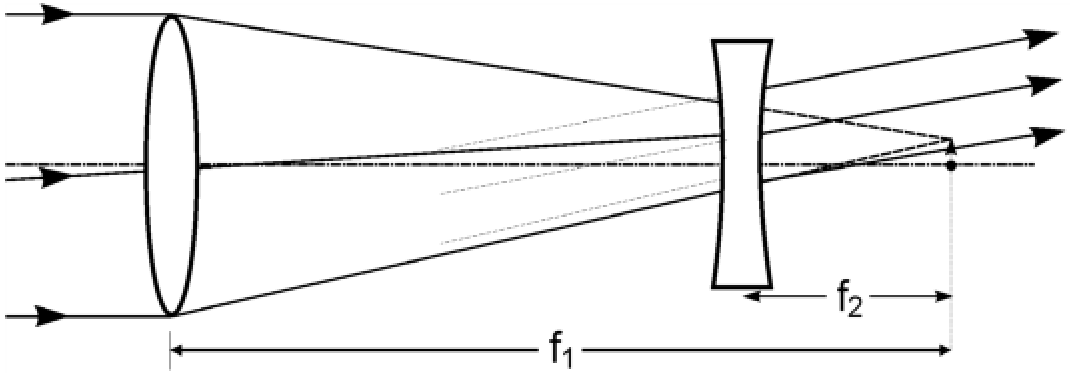
- See how radiation is brought to a focal plane
- Basic technique is reflection off curved surfaces
- Different techniques and materials at different frequency or wavelength.

Telescopes

- Historical introduction
- General principles
- Diffraction and Spatial resolution
- Aberrations in reflecting telescopes
- Optical configuration
- Telescope configurations
- Optical Telescopes
- Segmented mirror telescopes
- Adaptive optics
- New large telescopes
- Problems of Extremely large telescopes
- Radio Telescopes
- Atmospheric transparency
- Infra-Red Telescopes
- UV Telescopes
- X-ray telescopes
- Gamma-ray telescopes

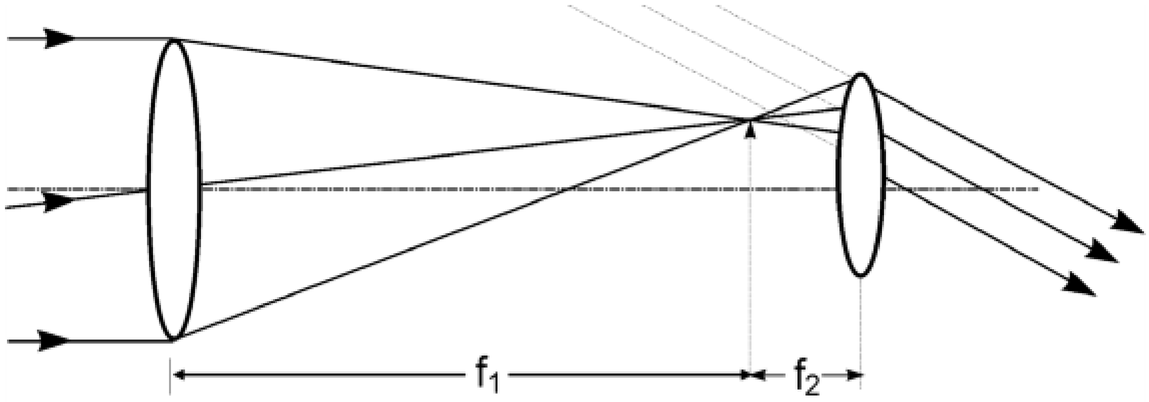
Historical introduction

In July of 1609, Galileo Galilei developed the first astronomical optical telescope. His telescope is formed by the combination of a concave and a convex lens, today known as the Galileo telescope system. The front convex lens is called an objective because it is close to the object being viewed and the rear concave lens is called an eyepiece because it is closest to the observer's eye.



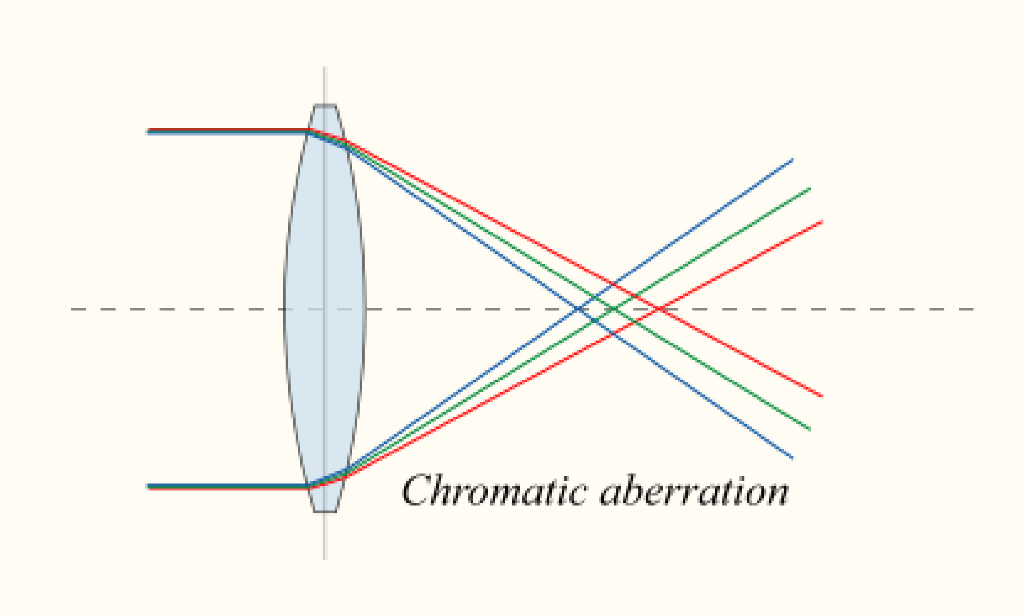
Historical introduction

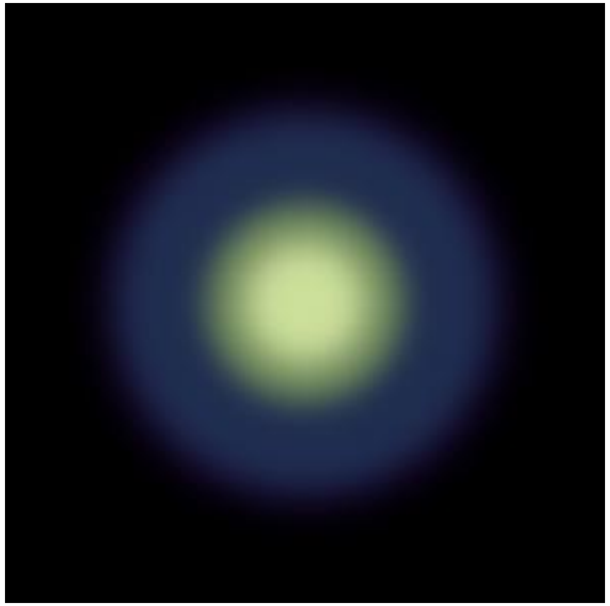
In 1611, Johannes Kepler invented another type of longer telescope comprising two convex lenses, known as the Kepler telescope system. The Kepler telescope forms an upside down image, but with a slightly larger field of view.



Kepler's telescope and Chromatic Aberration

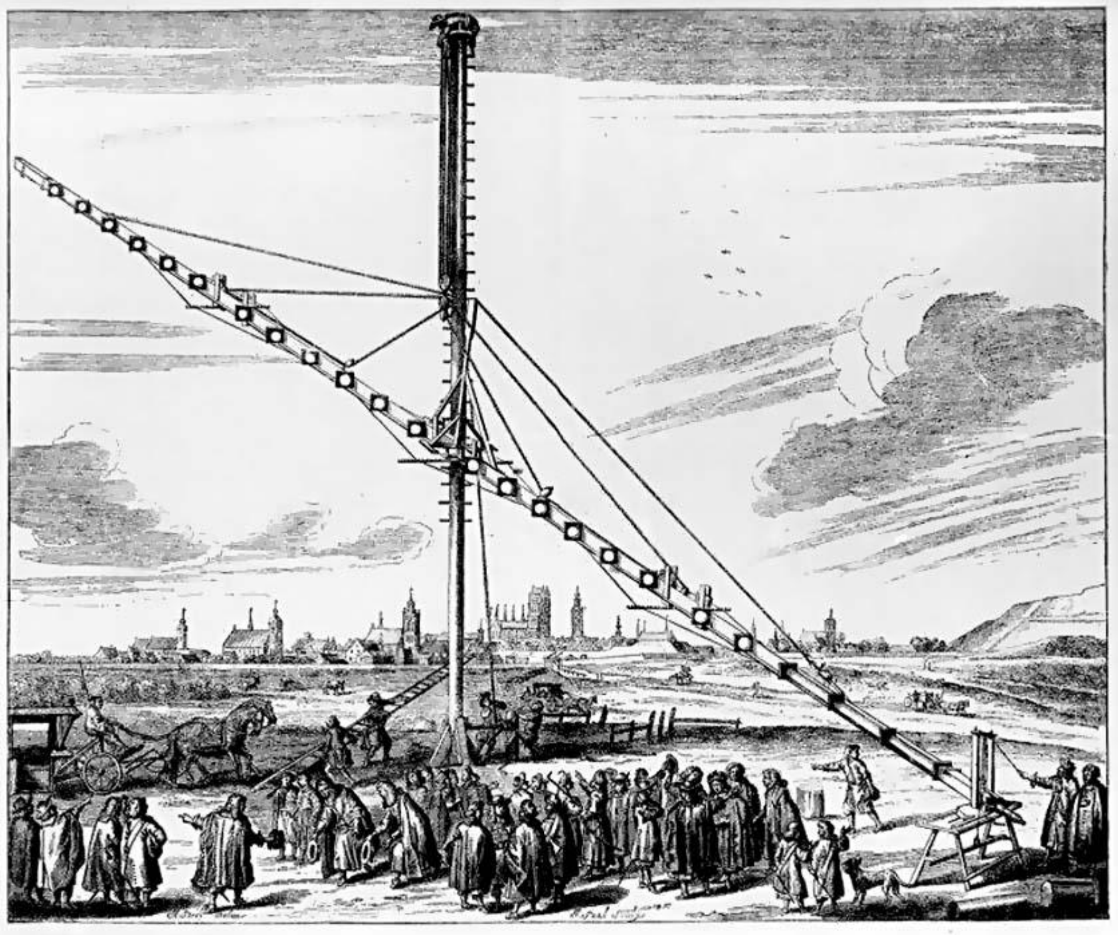
The sharpness of the image in Kepler's telescope is limited by the chromatic aberration introduced by the non-uniform refractive properties of the objective lens



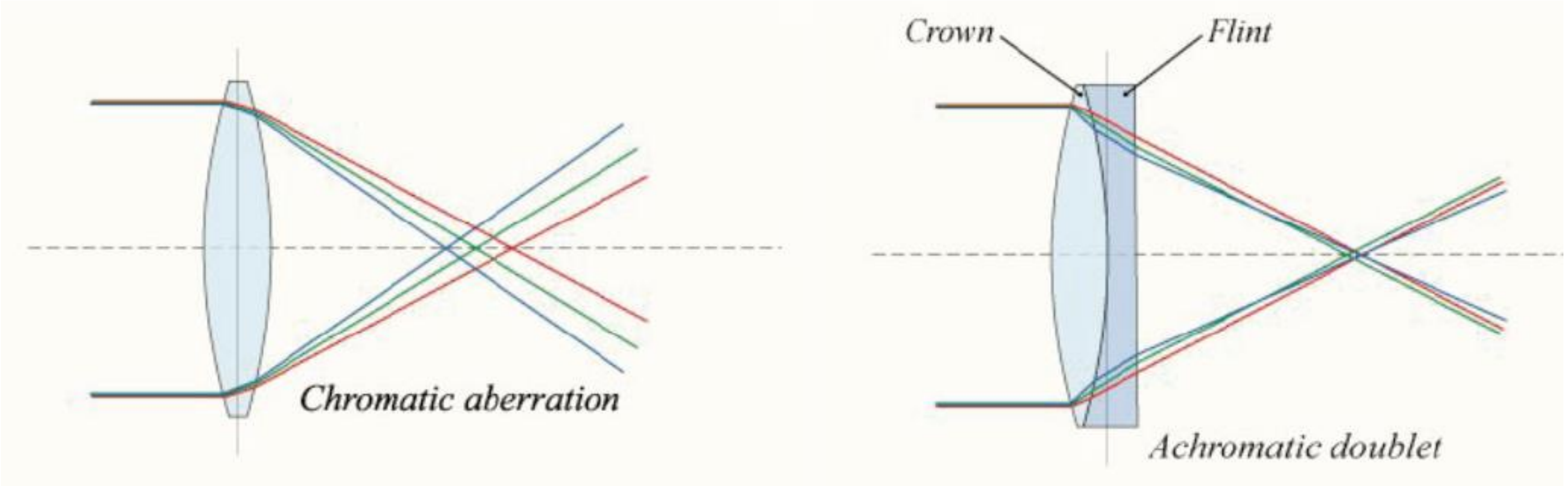


Kepler's telescope and Chromatic Aberration

The only way to overcome this limitation was to create objectives with very long focal lengths.

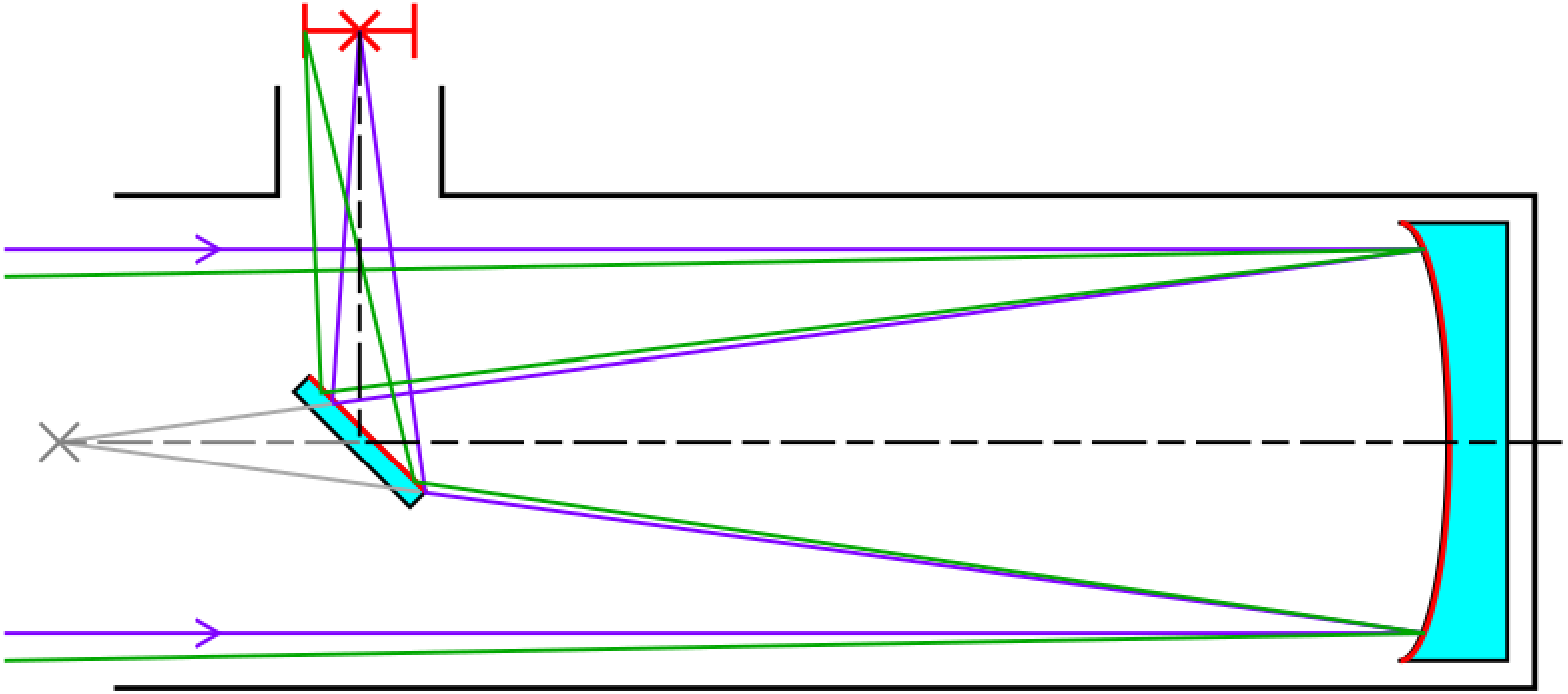


Chromatic Aberration: possible solution



Historical introduction

In 1668, Sir Isaac Newton invented and built the first reflecting telescope. The telescope uses a concave primary mirror and a flat diagonal secondary mirror.



Historical introduction

Advantages of the Newtonian design:

- They are free of chromatic aberration found in refracting telescopes.
- Newtonian telescopes are usually less expensive for any given aperture than comparable quality telescopes of other types.
- Since there is only one surface that needs to be ground and polished into a complex shape, overall fabrication is far simpler than other telescope designs.
- A short focal ratio can be more easily obtained, leading to wider field of view.
- The eyepiece is located at the top end of the telescope. Combined with short f-ratios this can allow for a much more compact mounting system, reducing cost and adding to portability.

Simple reflecting telescopes

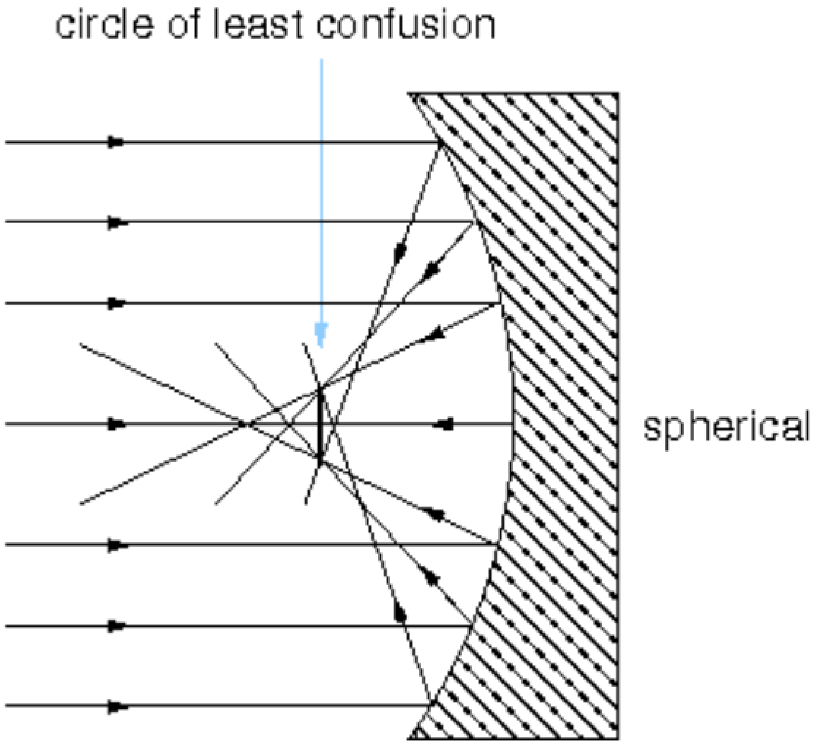
At wavelengths from Radio to UltraViolet, most telescopes are **simple dishes** made of

wire mesh (low frequency radio);
metal plates (high frequency radio);
glass covered with a deposit of

gold (infra-red);
silver (optical and near-infrared) or
aluminium (optical and UV).

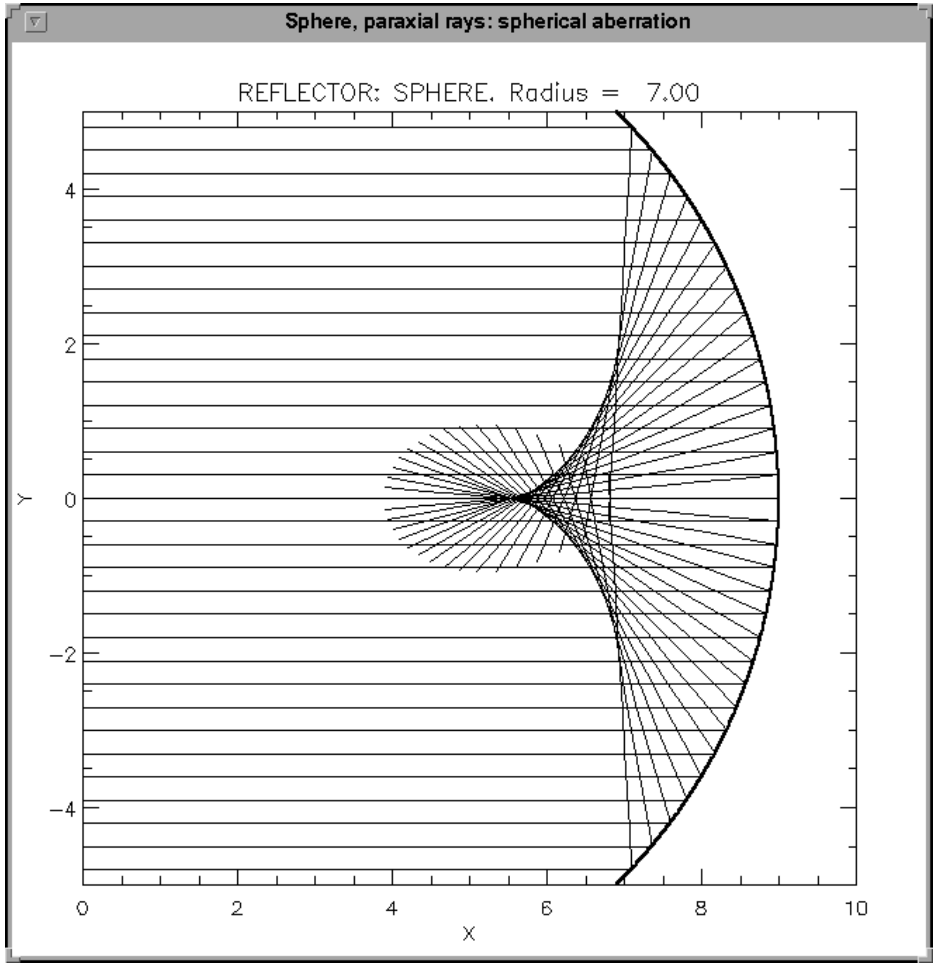
Often there are overcoatings to enhance reflectivity and protect the reflecting surface.

Simple reflecting telescopes



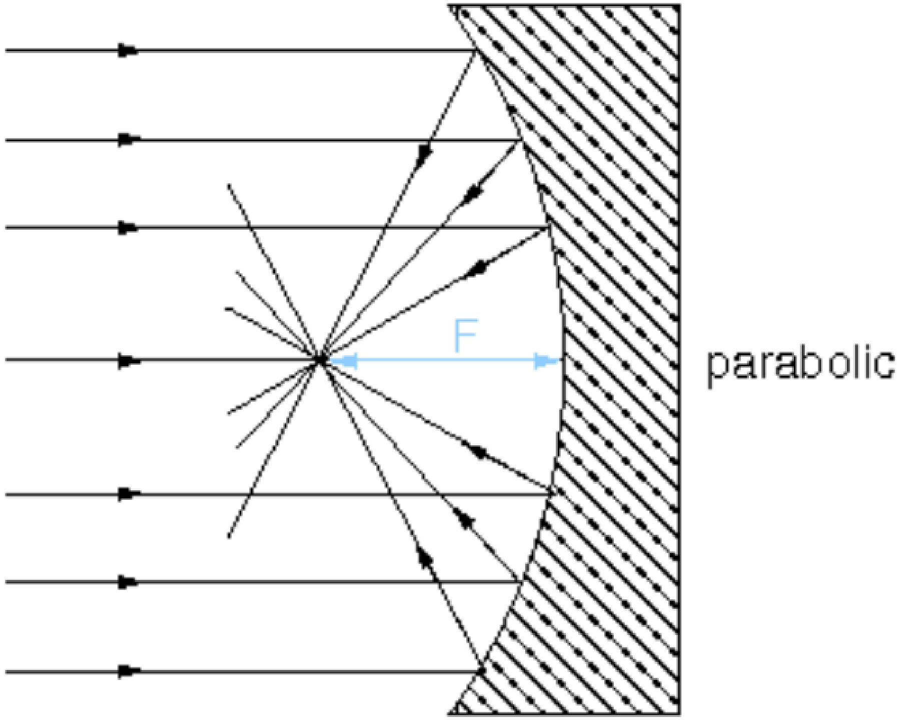
Spherical surface suffers from spherical aberration – rays hitting the outside of the dish come to focus at a different point on the optical axis from those hitting the centre.

Simple reflecting telescopes



Spherical surface suffers from spherical aberration – rays hitting the outside of the dish come to focus at a different point on the optical axis from those hitting the centre.

Simple reflecting telescopes



Paraboloidal reflector brings all rays to focus at the same point on the optical axis, and eliminates spherical aberration.

Most telescopes at radio, IR, optical and UV wavelengths are based upon paraboloidal reflectors

Diffraction and Spatial resolution

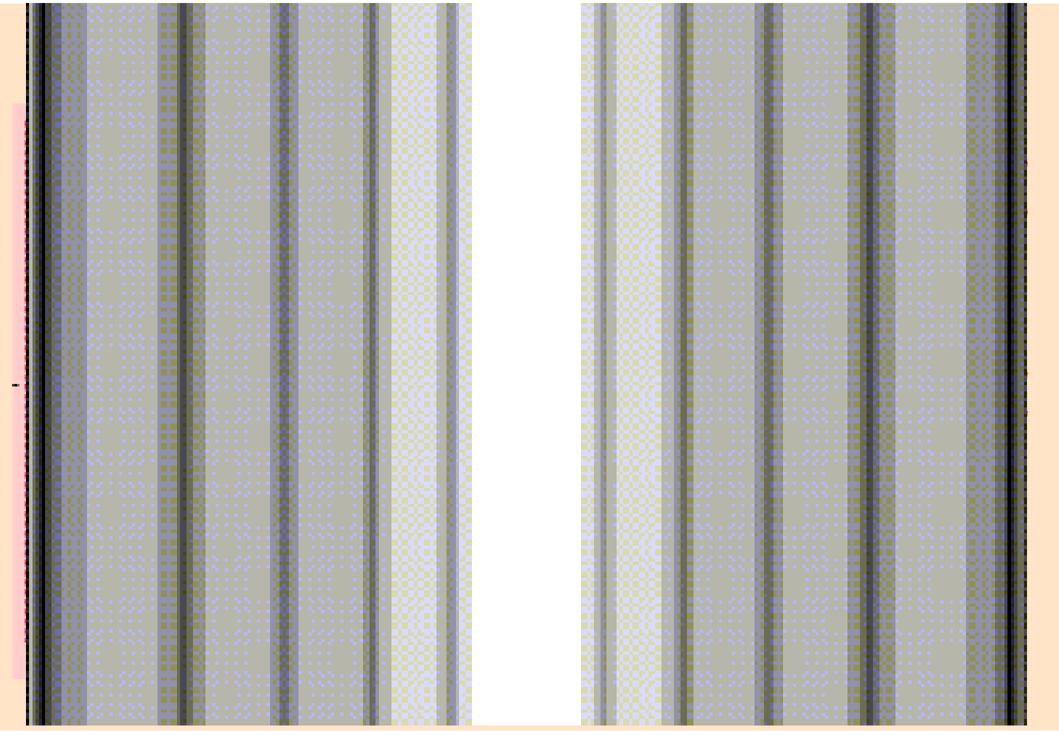
- All astronomical observations at wavelengths from mid-frequency radio to X-ray use telescopes, which are a means of bringing a parallel beam of light from a distant source to a focus.
  The majority of telescopes have a circular aperture.

Diffraction problem for a circular aperture of telescopes

- Diffraction places fundamental limit on angular resolution of telescopes.

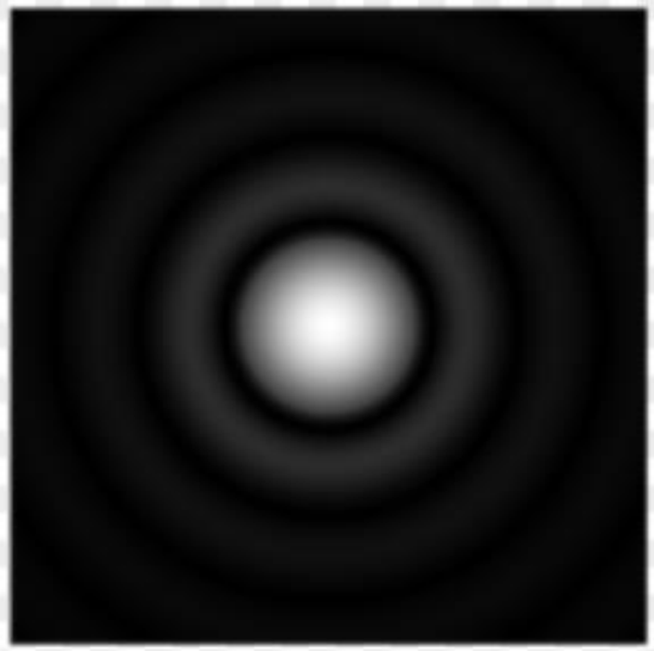
- Diffraction through a single slit (due to the wave nature light):
  the waves from secondary sources within the slit interfere.

Image of a narrow slit:



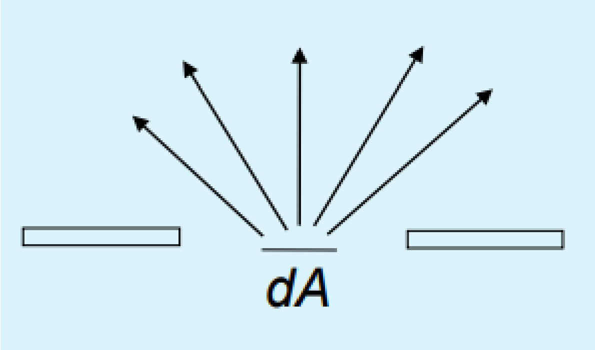
Diffraction problem for a circular aperture of telescopes

- The interference pattern on the screen behind the circular aperture of a finite size is created similarly to the slit:
  the waves from different secondary sources in the apperture interfere.
  The resulting pattern is a set of co-centric circular bright and dark bands with the highest peak in the center.



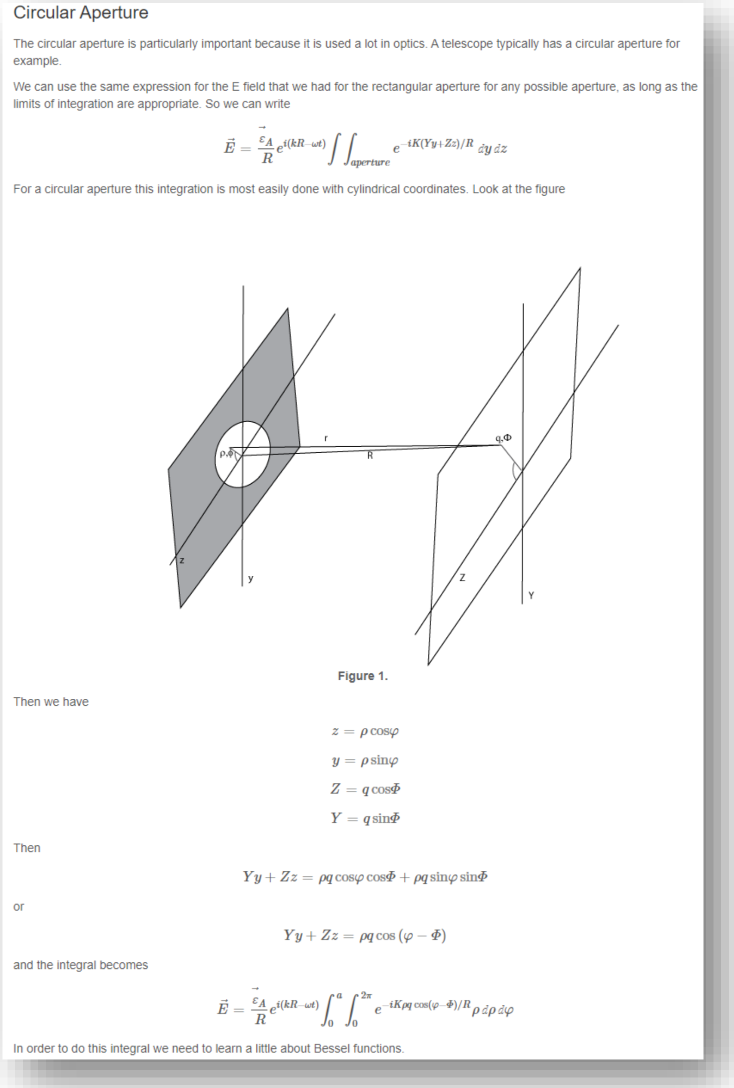
Diffraction and Spatial resolution

- An approach for diffraction by a circular aperture:
  - Take an element of area dA which radiates in all directions. We then need to sum all contributions, over all such elements, at some angle θ.



- Analytical expression for diffraction pattern obtained, for example, in the Kitchin book or here: http://cnx.org/content/m13097/latest/

http://cnx.org/content/m13097/latest/



Circular Aperture

The circular aperture is particularly important because it is used a lot in optics. A telescope typically has a circular aperture for example.

We can use the same expression for the E field that we had for the rectangular aperture for any possible aperture, as long as the limits of integration are appropriate. So we can write

$$\vec{E} = \frac{\vec{\varepsilon}_A}{R} e^{i(kR-\omega t)} \int\int_{aperture} e^{-iK(Yy+Zz)/R}\, dy\, dz$$

For a circular aperture this integration is most easily done with cylindrical coordinates. Look at the figure

Figure 1.

Then we have

$$z = \rho \cos\varphi$$

$$y = \rho \sin\varphi$$

$$Z = q \cos\Phi$$

$$Y = q \sin\Phi$$

Then

$$Yy + Zz = \rho q \cos\varphi \cos\Phi + \rho q \sin\varphi \sin\Phi$$

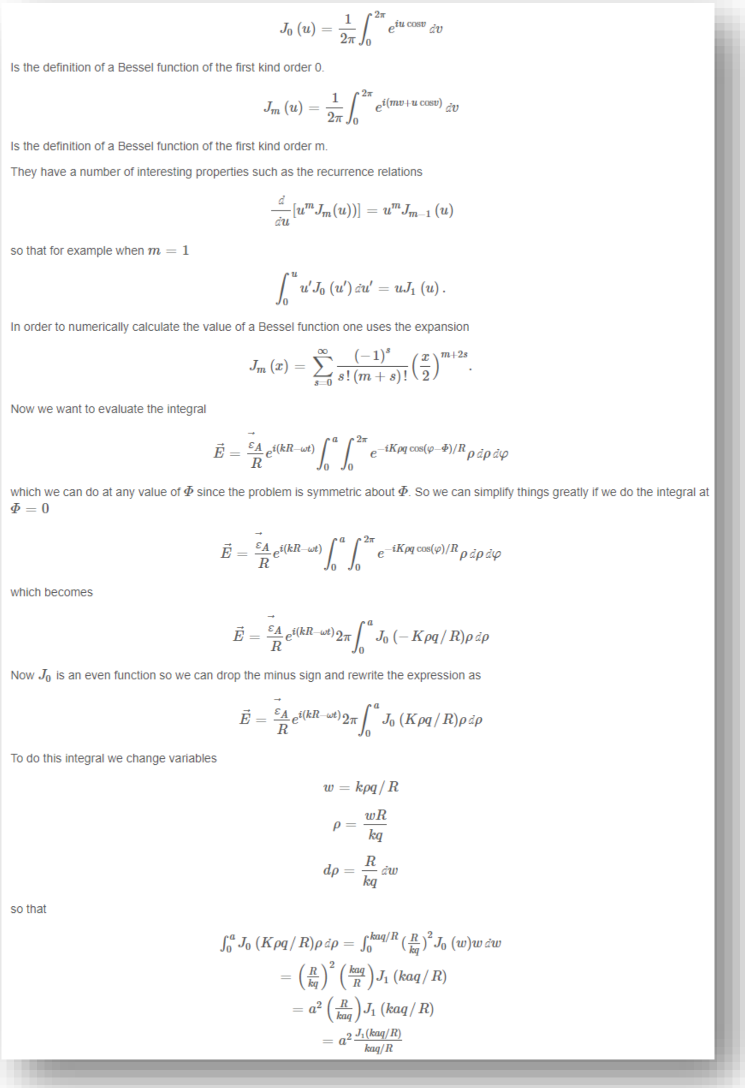
or

$$Yy + Zz = \rho q \cos(\varphi - \Phi)$$

and the integral becomes

$$\vec{E} = \frac{\vec{\varepsilon}_A}{R} e^{i(kR-\omega t)} \int_0^a \int_0^{2\pi} e^{-iK\rho q \cos(\varphi-\Phi)/R} \rho\, d\rho\, d\varphi$$

In order to do this integral we need to learn a little about Bessel functions.



$$J_0(u) = \frac{1}{2\pi} \int_0^{2\pi} e^{iu \cos v}\, dv$$

Is the definition of a Bessel function of the first kind order 0.

$$J_m(u) = \frac{1}{2\pi} \int_0^{2\pi} e^{i(mv + u \cos v)}\, dv$$

Is the definition of a Bessel function of the first kind order m.

They have a number of interesting properties such as the recurrence relations

$$\frac{d}{du}[u^m J_m(u))] = u^m J_{m-1}(u)$$

so that for example when $m = 1$

$$\int_0^u u' J_0(u')\, du' = u J_1(u).$$

In order to numerically calculate the value of a Bessel function one uses the expansion

$$J_m(x) = \sum_{s=0}^{\infty} \frac{(-1)^s}{s!\,(m+s)!} \left(\frac{x}{2}\right)^{m+2s}.$$

Now we want to evaluate the integral

$$\vec{E} = \frac{\vec{\varepsilon}_A}{R} e^{i(kR-\omega t)} \int_0^a \int_0^{2\pi} e^{-iK\rho q \cos(\varphi-\Phi)/R} \rho\, d\rho\, d\varphi$$

which we can do at any value of Φ since the problem is symmetric about Φ. So we can simplify things greatly if we do the integral at $\Phi = 0$

$$\vec{E} = \frac{\vec{\varepsilon}_A}{R} e^{i(kR-\omega t)} \int_0^a \int_0^{2\pi} e^{-iK\rho q \cos(\varphi)/R} \rho\, d\rho\, d\varphi$$

which becomes

$$\vec{E} = \frac{\vec{\varepsilon}_A}{R} e^{i(kR-\omega t)} 2\pi \int_0^a J_0(-K\rho q/R) \rho\, d\rho$$

Now J_0 is an even function so we can drop the minus sign and rewrite the expression as

$$\vec{E} = \frac{\vec{\varepsilon}_A}{R} e^{i(kR-\omega t)} 2\pi \int_0^a J_0(K\rho q/R) \rho\, d\rho$$

To do this integral we change variables

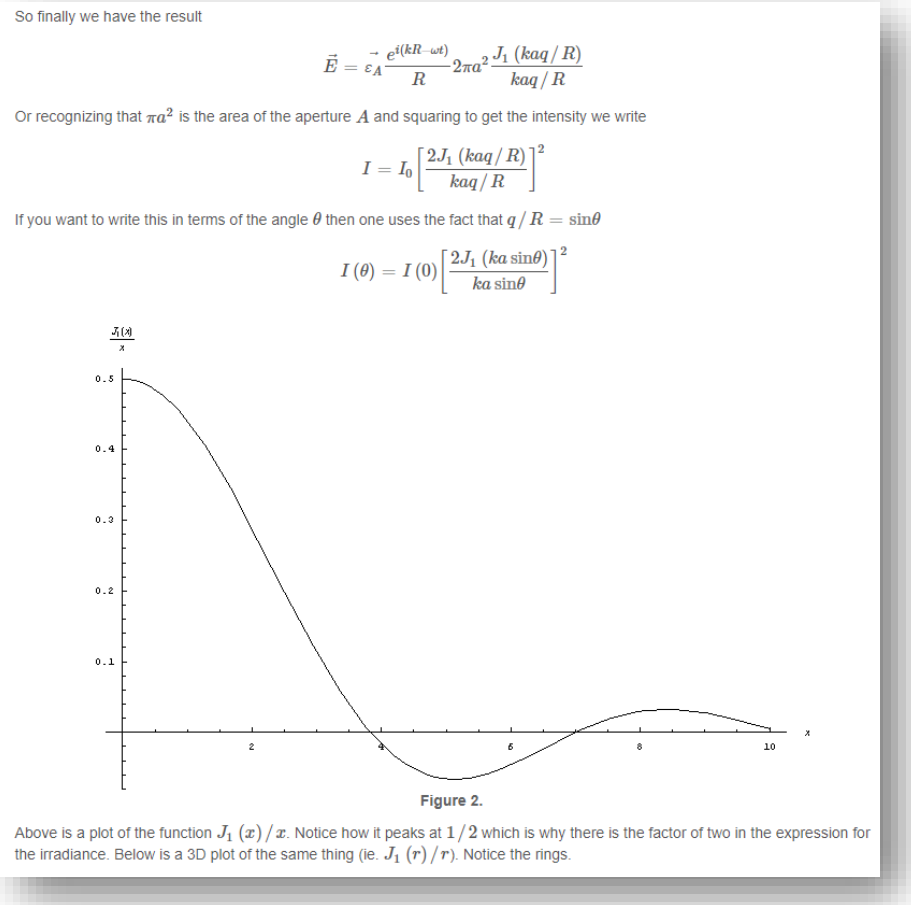
$$w = k\rho q/R$$

$$\rho = \frac{wR}{kq}$$

$$d\rho = \frac{R}{kq}\, dw$$

so that

$$\begin{aligned} \textstyle\int_0^a J_0(K\rho q/R)\rho\, d\rho &= \textstyle\int_0^{kaq/R} \left(\frac{R}{kq}\right)^2 J_0(w) w\, dw \\ &= \left(\frac{R}{kq}\right)^2 \left(\frac{kaq}{R}\right) J_1(kaq/R) \\ &= a^2 \left(\frac{R}{kaq}\right) J_1(kaq/R) \\ &= a^2 \frac{J_1(kaq/R)}{kaq/R} \end{aligned}$$



So finally we have the result

$$\vec{E} = \vec{\varepsilon}_A \frac{e^{i(kR-\omega t)}}{R} 2\pi a^2 \frac{J_1(kaq/R)}{kaq/R}$$

Or recognizing that πa^2 is the area of the aperture A and squaring to get the intensity we write

$$I = I_0 \left[\frac{2J_1(kaq/R)}{kaq/R}\right]^2$$

If you want to write this in terms of the angle θ then one uses the fact that $q/R = \sin\theta$

$$I(\theta) = I(0) \left[\frac{2J_1(ka \sin\theta)}{ka \sin\theta}\right]^2$$

Figure 2.

Above is a plot of the function $J_1(x)/x$. Notice how it peaks at $1/2$ which is why there is the factor of two in the expression for the irradiance. Below is a 3D plot of the same thing (ie. $J_1(r)/r$). Notice the rings.

Diffraction and Spatial resolution

Answer is (first derived in 1835 by Airy):

$$I_{\vartheta} \propto [J_1(2m)/m]^2$$

where $m = (\pi\, r \sin\theta \;/\; \lambda)$,

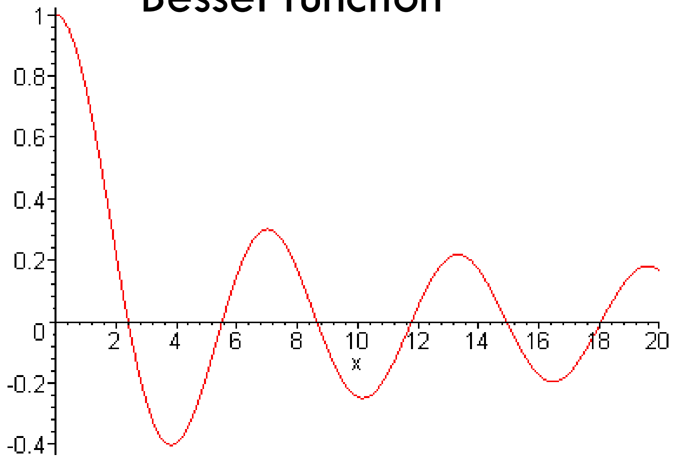
ϑ is the angle to the normal from the aperture,

r is the radius of the aperture,

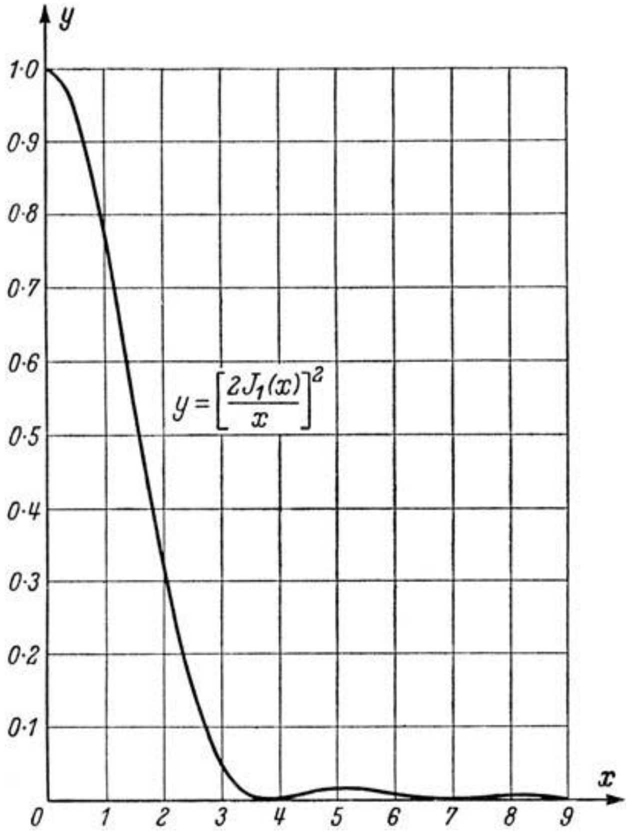
J_1 is a Bessel function of the 1st kind and 1st order.

Diffraction and Spatial resolution

Bessel function



Diffraction of a circular aperture with normalized intensity



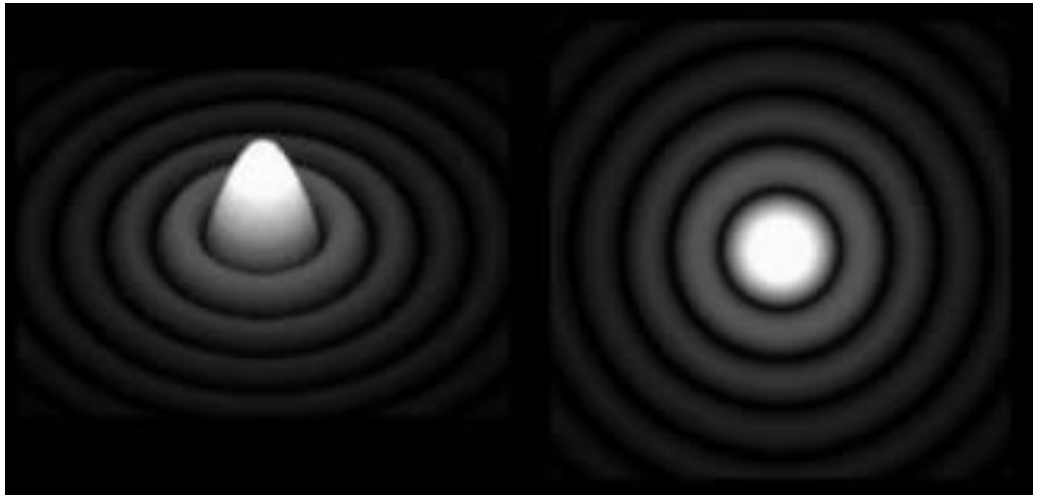
The first zero of the Intensity function occurs at $m = 1.916$, or for small ϑ:

$$\vartheta \cong 1.22\,\lambda / D \text{ (radians)}$$

$D = 2r$ is the diameter of the aperture

Diffraction and Spatial resolution

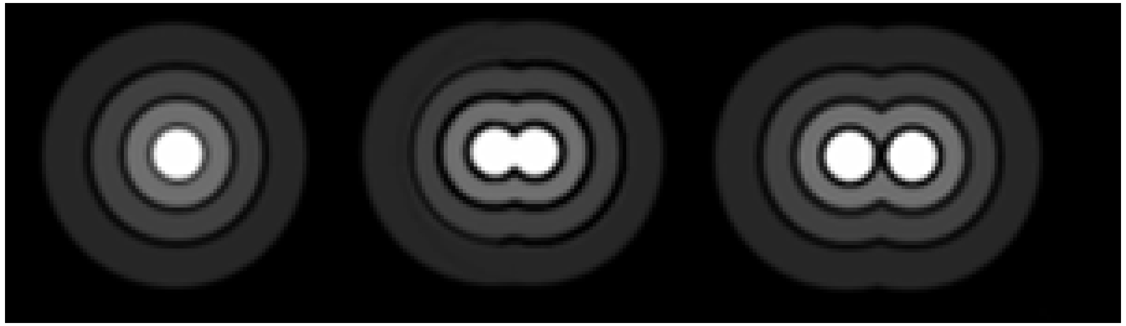
- Airy pattern:



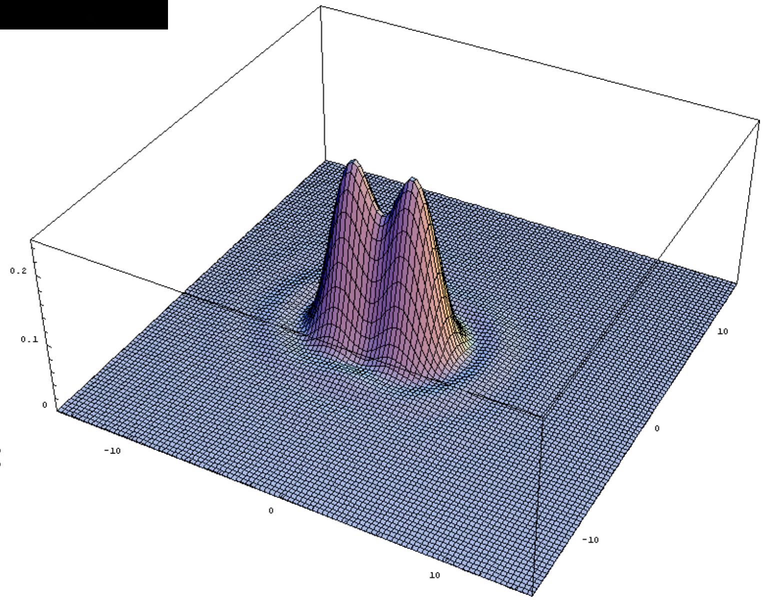
- The 1st maximum is roughly 1.75% of the central intensity, the 2nd – 0.42%.
- 84% of the light arrives within the central peak called the **Airy disk**.

Effect of diffraction on image resolution

- Two distant point sources through a circular aperture:



- **The Rayleigh criterion:** two sources are just resolved if the centre of the 1st Airy pattern is superimposed on the 1st dark ring of the 2nd pattern.



- According to Rayleigh criterion, the minimum resolvable angular separation or angular limit of resolution is given by:

$$\vartheta \cong 1.22\,\lambda / D \text{ (radians)}$$

- λ is wavelength and D is the diameter of the aperture

Diffraction and Spatial resolution

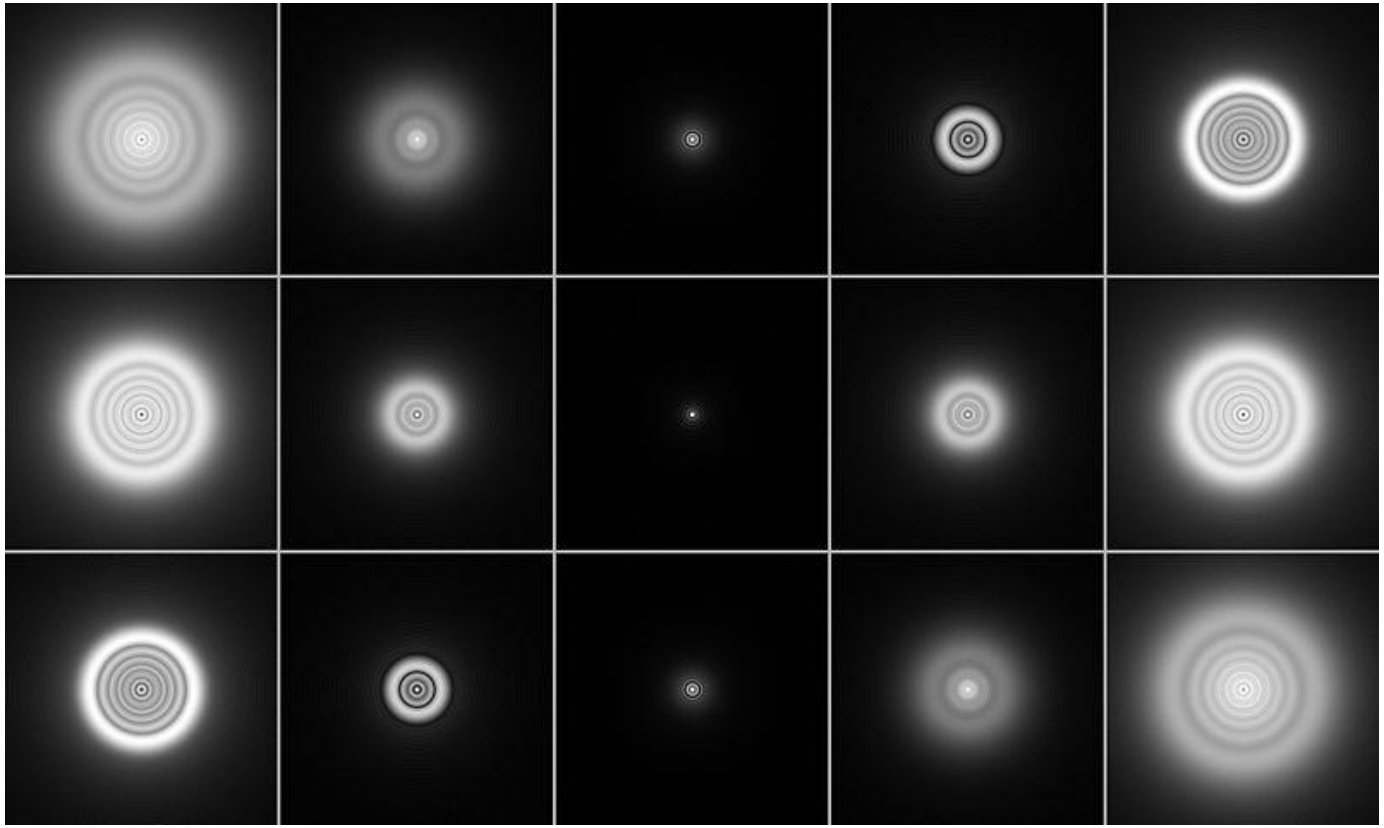
- The **fundamental** limit to the spatial resolution of a circular aperture telescope is set by the size of the Airy diffraction pattern, but **in practice** the resolution is often worse than that, particularly at wavelengths shorter than 10 μm (100000 Å).
- Causes are:
  - Distortion of the wavefront by the atmosphere (seeing);
  - Imperfections in manufacture or support of the reflecting surface;
  - Aberrations.

Aberrations in reflecting telescopes

- **Spherical aberration** – caused by different parts of the mirror bringing rays to focus at different points on the optical axis.
- **Coma** – teardrop or comet shaped aberration proportional to the square of the distance of the image off axis.
- **Astigmatism** – cylindrical wavefront distortion resulting in an ellipticity of the image which is orthogonal on different sides of focus. Can occur on-axis if the mirror is stressed, off axis it results from magnification at the secondary (i.e. if final focal length **>>** primary focal length) and is proportional to the square of the distance of the image off axis.
- **Curvature of the field of the image**

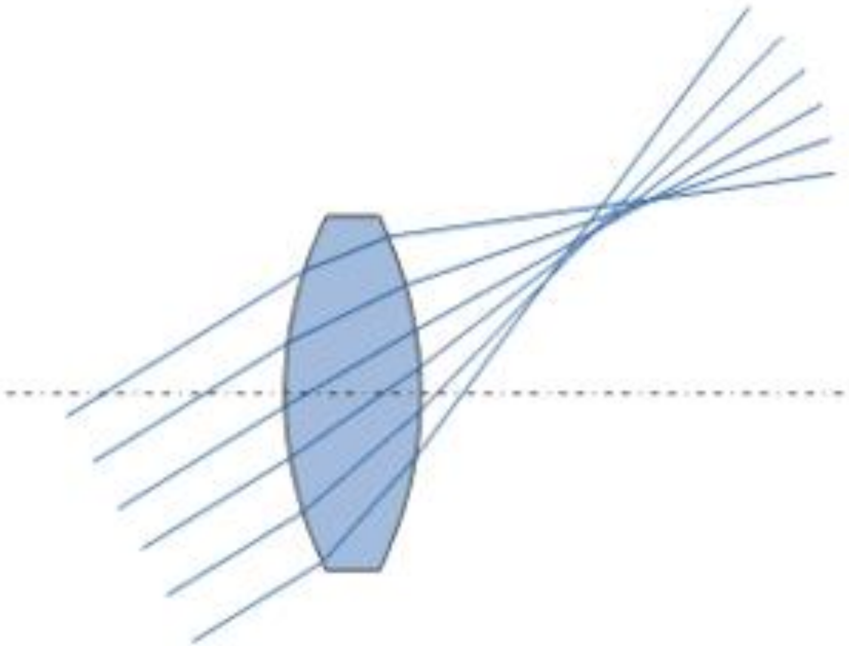
Aberrations in reflecting telescopes

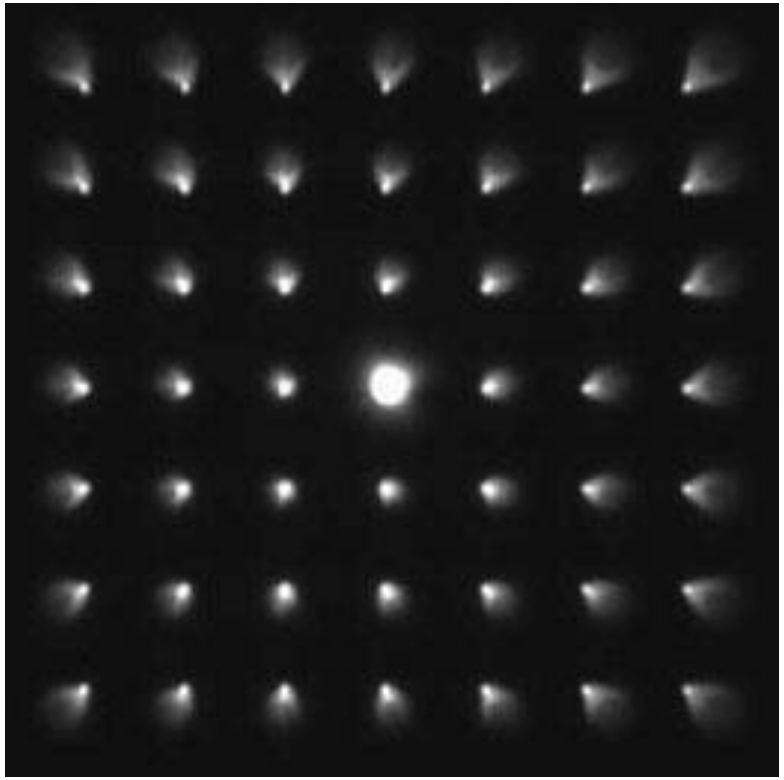
- **Spherical aberration** – caused by different parts of the mirror bringing rays to focus at different points on the optical axis.



Aberrations in reflecting telescopes

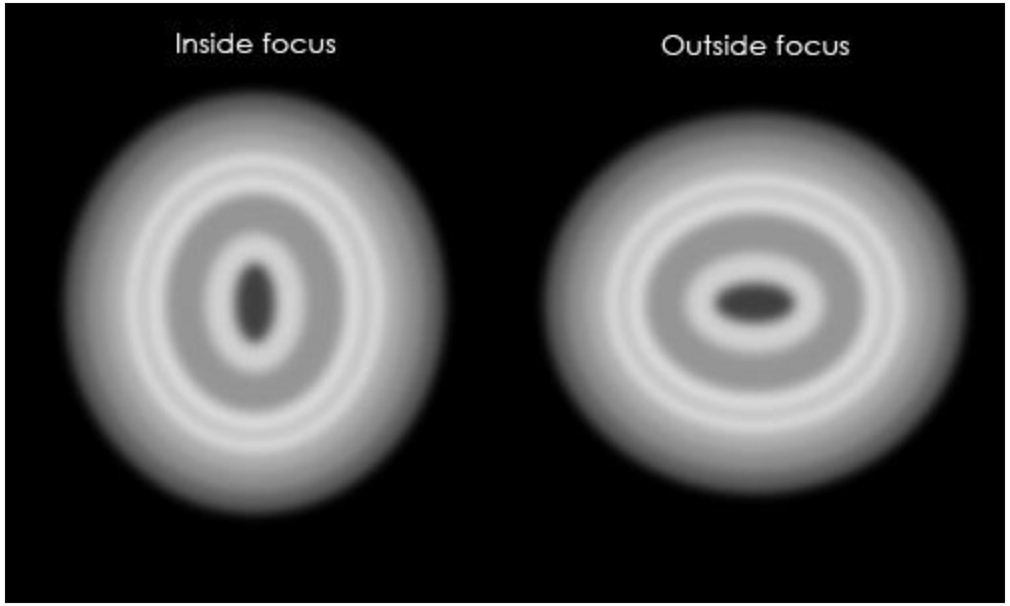
- **Coma** – teardrop or comet shaped aberration proportional to the square of the distance of the image off axis.





Aberrations in reflecting telescopes

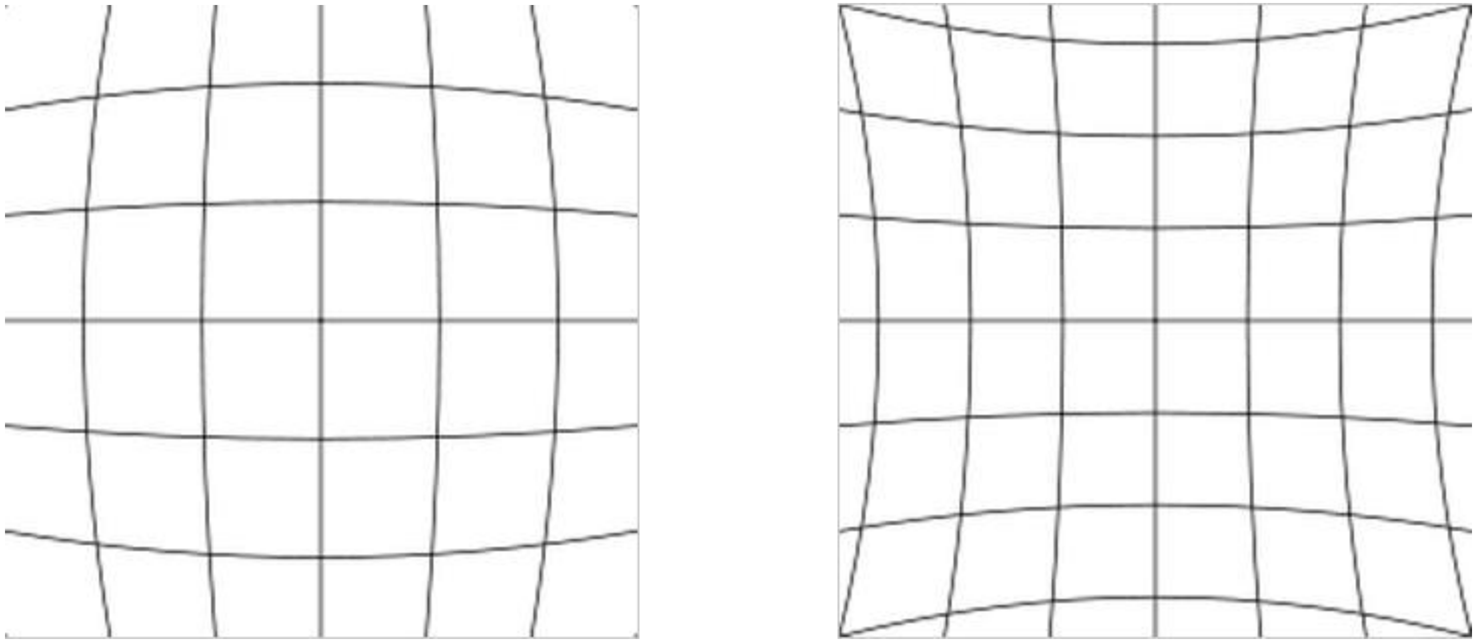
- **Astigmatism** – cylindrical wavefront distortion resulting in an ellipticity of the image which is orthogonal on different sides of focus. Can occur on-axis if the mirror is stressed, off axis it results from magnification at the secondary (i.e. if final focal length >> primary focal length) and is proportional to the square of the distance of the image off axis.



Aberrations in reflecting telescopes

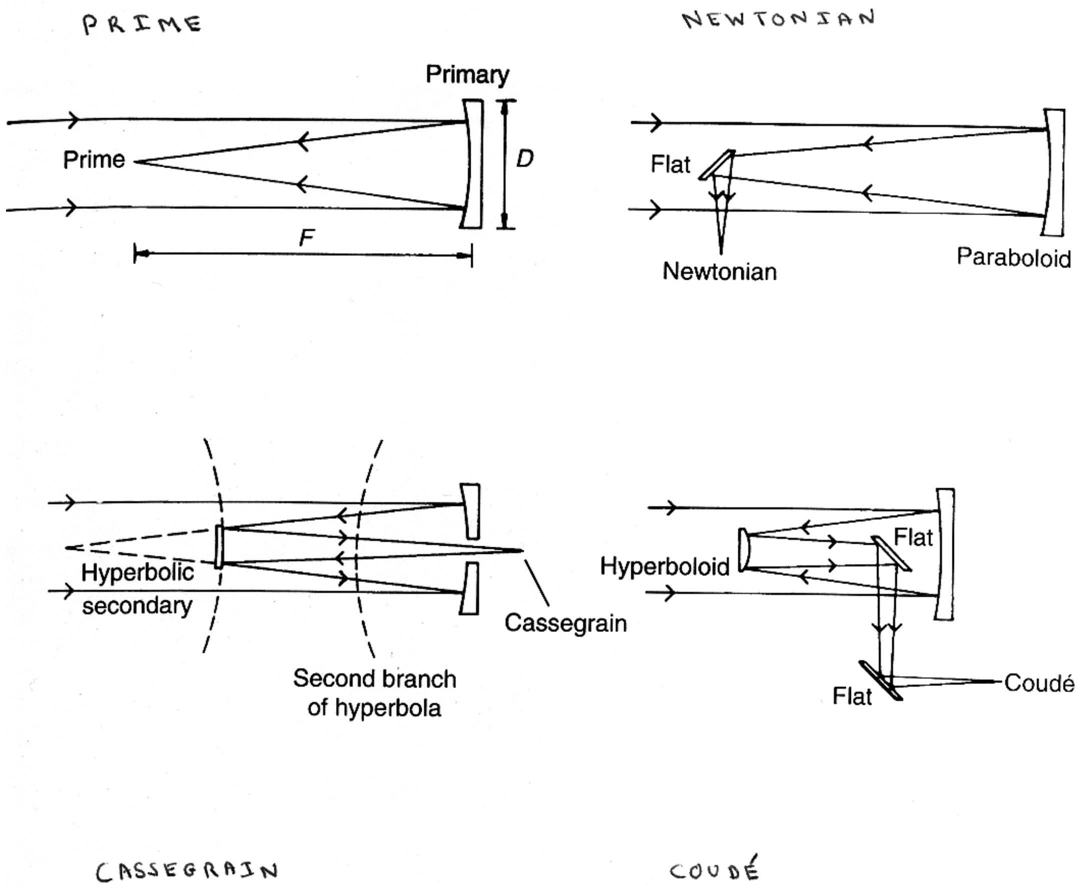
- **Curvature of the field of the image –**

  Barrel and Pincushion distortions of the image



Optical configuration

Here “optical” does not mean wavelength, but the way the system is configured to accept rays of radiation.

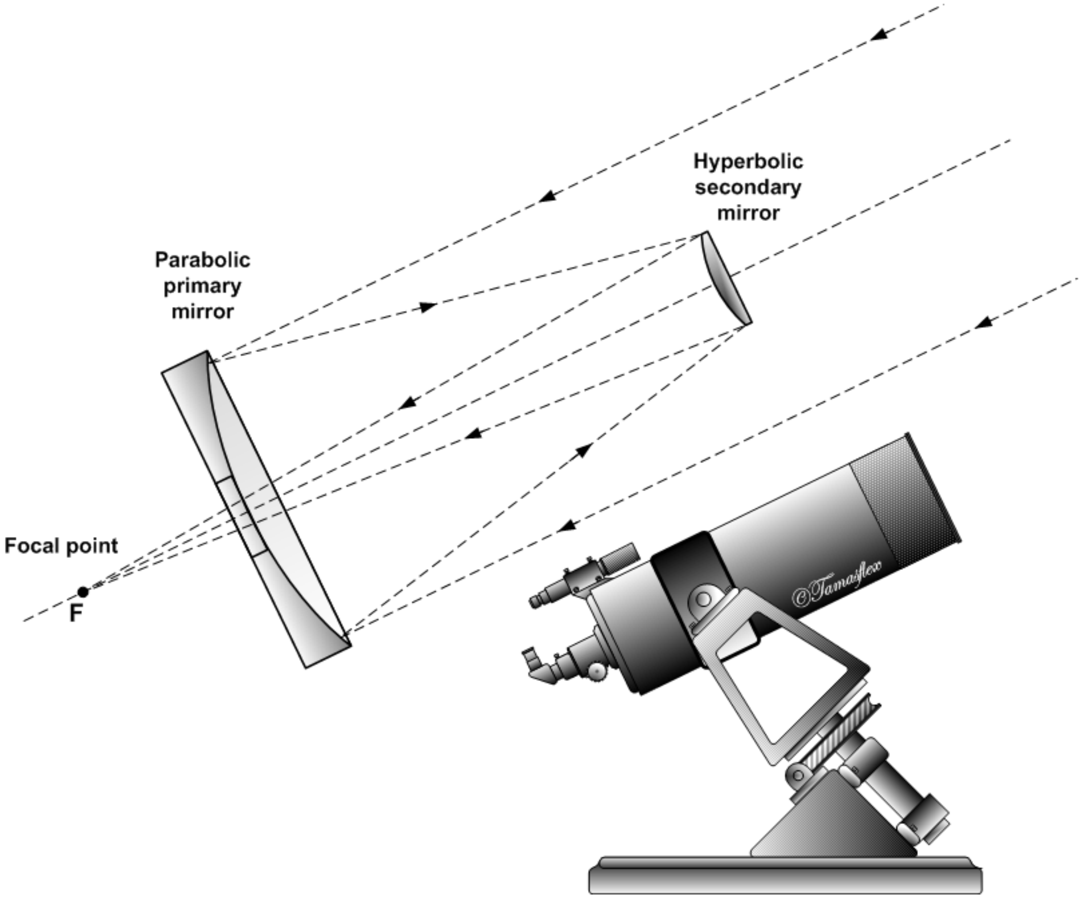


Optical configuration

- **Prime Focus –** detector or receiver is at the focus of the paraboloidal reflector
- **Cassegrain –** a convex hyperboloidal secondary mirror or reflector is used to bring the rays to a focus below a hole in the primary.
- **Gregorian –** the secondary is now a concave elliptical mirror or reflector above the primary focus. **Disadvantage** is less compact than Cassegrain.
- **Nasmyth –** like Cassegrain except that a folding flat is added above or below the primary

Optical configuration

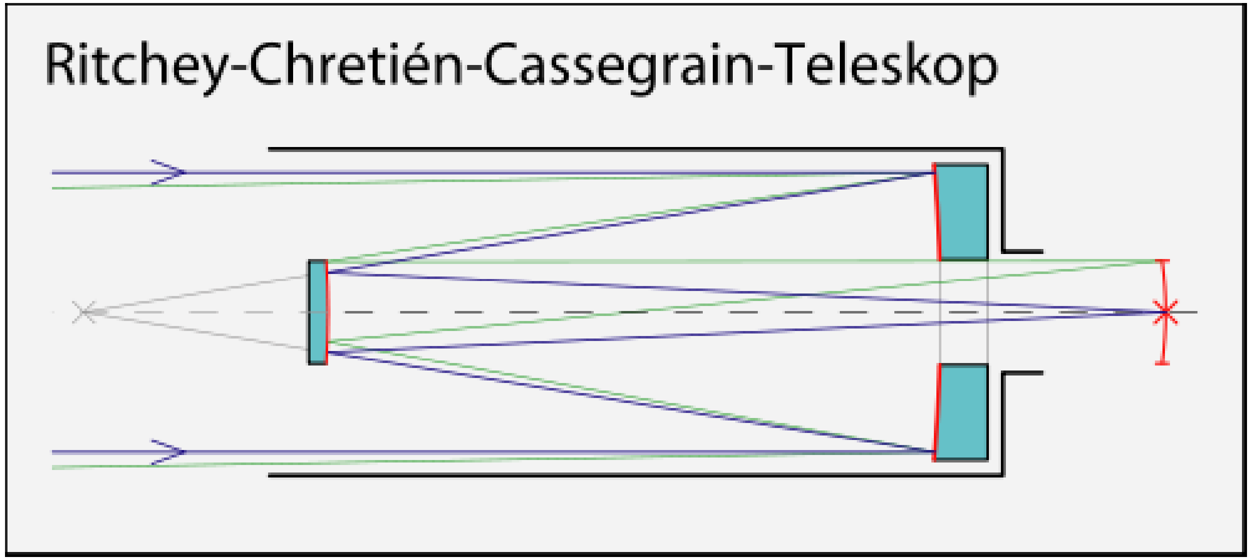
Schematic of Cassegrain optical telescope



Optical configuration

Schematic of Ritchey–Chrétien telescope

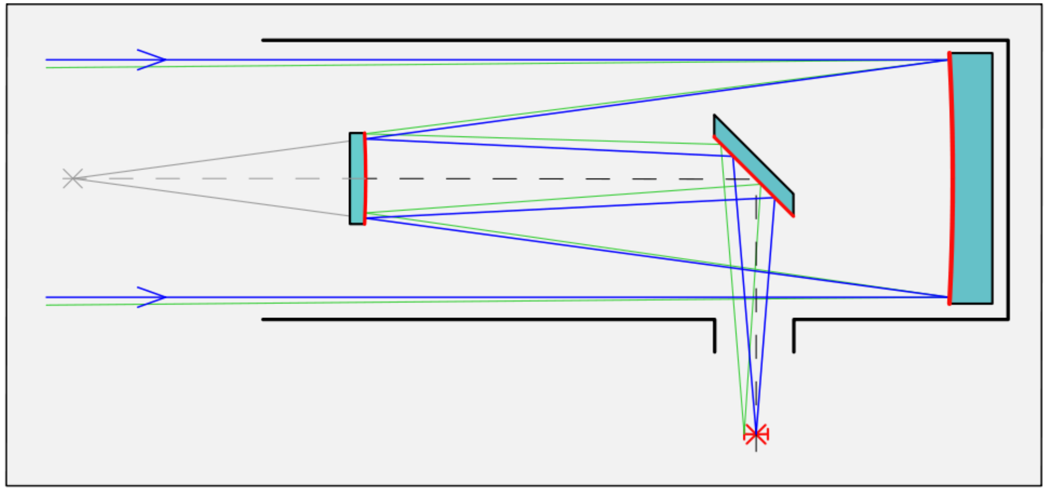
- ☐ Both mirrors, a primary and a secondary, are hyperbolic.
- ☐ Designed to eliminate coma, thus providing a large field of view compared to a more conventional configuration.
- ☐ But more expensive.



Optical configuration

Schematic of Nasmyth telescope

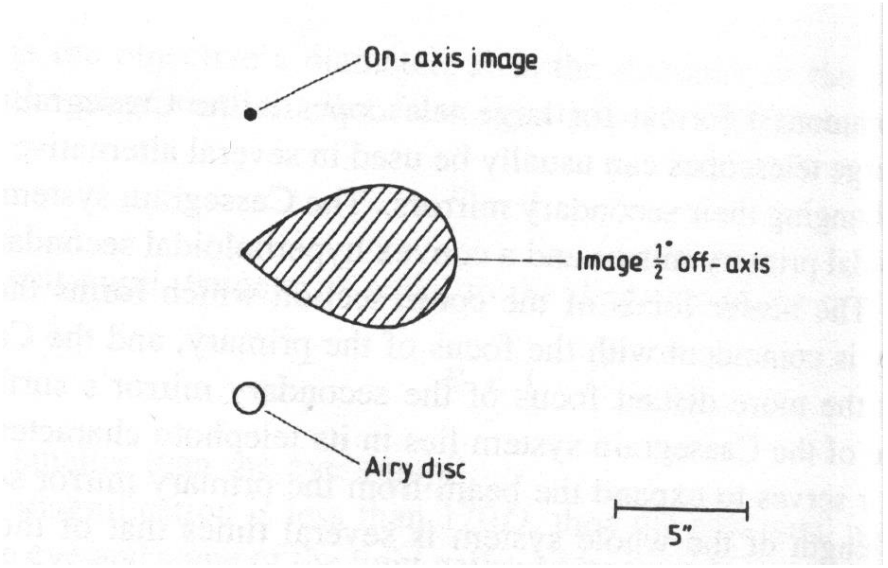
- There is no hole in the primary mirror.
- The eyepiece or instrument does not need to move with the telescope. This has significant advantages for heavy instruments typically used at research observatories.
- Most modern research telescopes can be configured into a Nasmyth telescope.



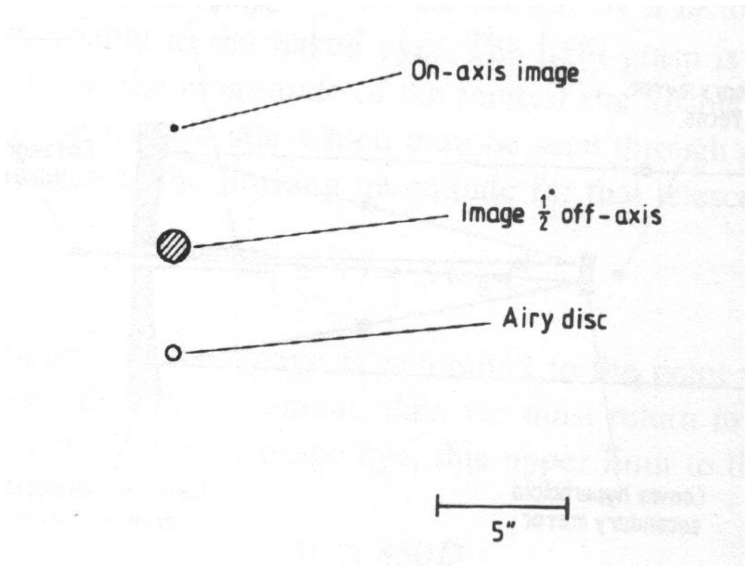
Aberrations in reflecting telescopes

- **Cassegrain** system with paraboloidal primary provides perfect images on-axis, but off-axis coma restricts the useful field of view.
- **Ritchey-Chrétien** optical system where the primary is deepened into a hyperboloid, and a stronger hyperboloid is used as the secondary, allows the coma and astigmatism to be balanced over a wider field

Wide Field telescopes



Cassegrain optics with paraboloidal primary



Ritchey-Chrétien optics with hyperboloidal primary

Image quality on- and off-axis

Optical configuration

- **Radio telescopes** are most commonly prime focus, occasionally Cassegrain, Gregorian or Nasmyth.
- **Optical telescopes** are most commonly Cassegrain of different types, mostly Ritchey-Chrétien, often configurable with interchangeable top end.

Examples of Cassegrain radio antennas

The 14 m Radio Telescope at Metsähovi

Examples of Cassegrain radio antennas

The 32m Radio Telescope at Cambridge

Examples of Cassegrain radio antennas

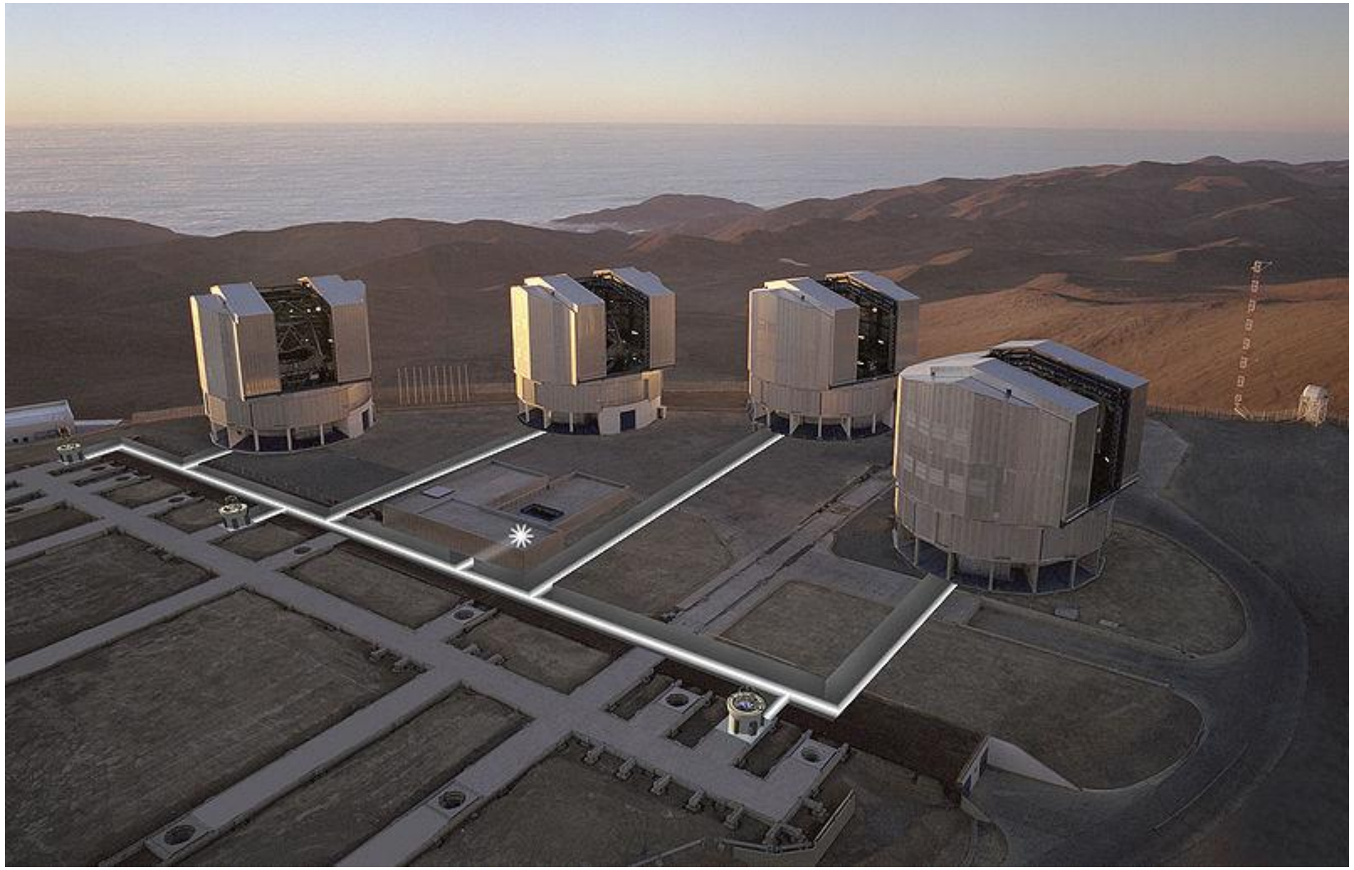
The 70 meter dish at Jet Propulsion Laboratory (JPL) Goldstone antenna complex.

Examples of large Ritchey–Chrétien telescopes

Hubble Space Telescope (2.4-m)

Examples of large Ritchey–Chrétien telescopes

The four 8.2-m telescopes comprising the Very Large Telescope in Chile



Examples of large Ritchey–Chrétien telescopes

The 10.4 m Gran Telescopio Canarias at Roque de los Muchachos Observatory

Examples of large Ritchey–Chrétien telescopes

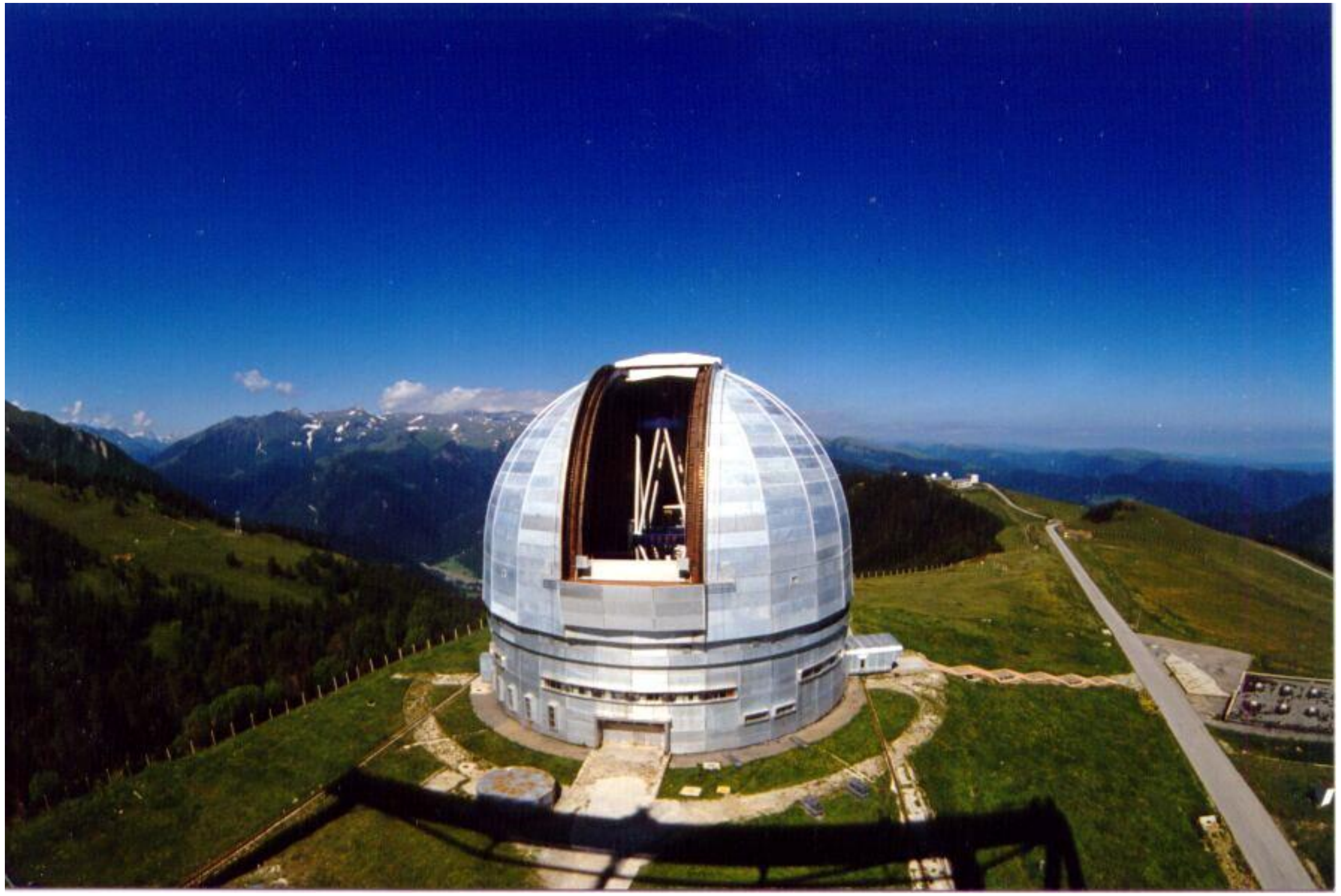
The Nordic Optical Telescope (2.5-m)

Examples of large Ritchey–Chrétien telescopes

The two 10-m telescopes of the Keck Observatory

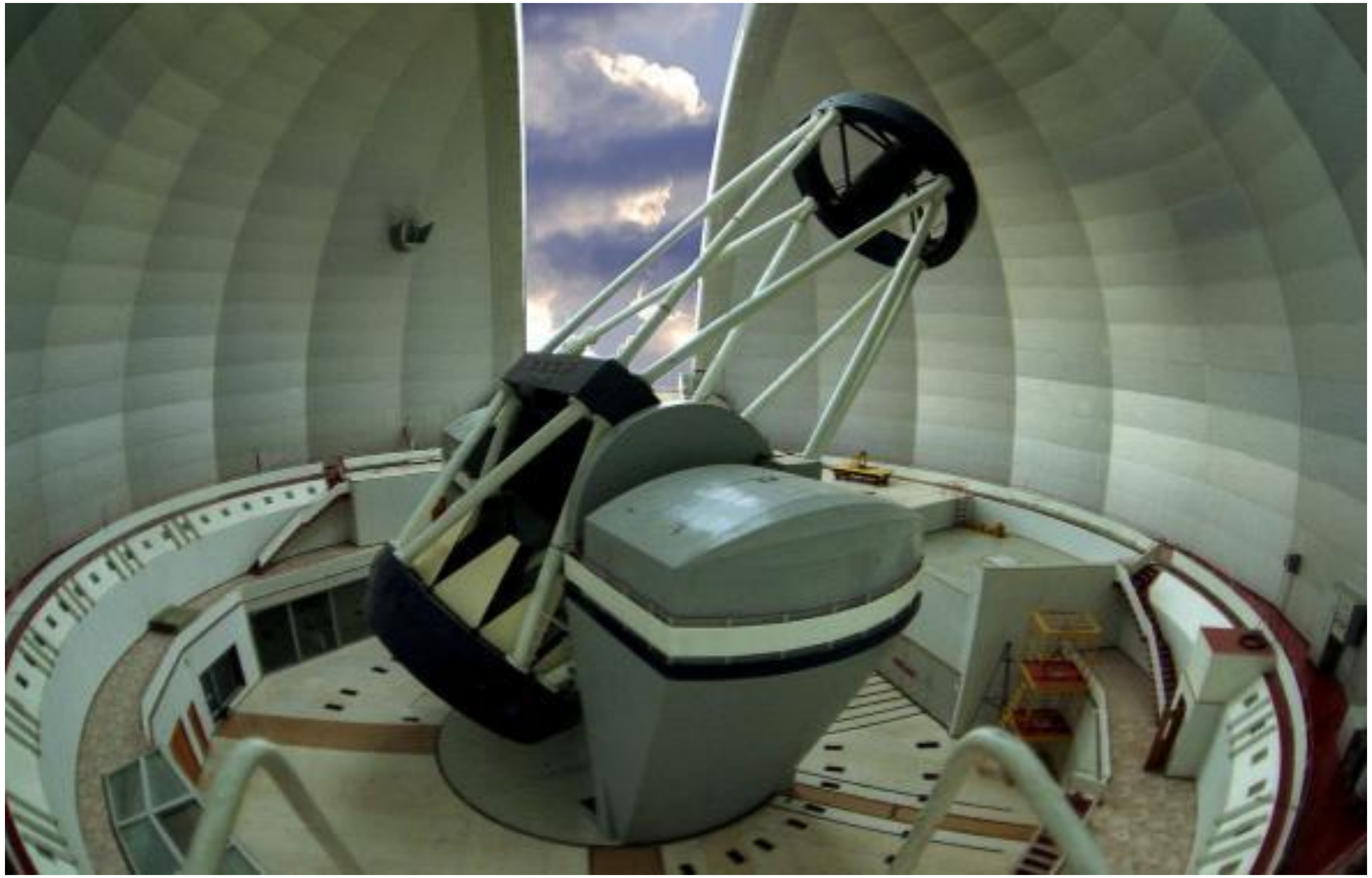
Examples of Nasmyth telescopes

The 6-m alt/az mounted telescope (Russia)



Examples of Nasmyth telescopes

The 6-m alt/az mounted telescope (Russia)



Examples of Nasmyth telescopes

The 6-m alt/az mounted telescope (Russia)

Infra-red telescopes

- Basic principles as for optical telescopes, but the differ in a number of ways. Basic driver for design is that the background comes predominantly from the telescope not from the sky:
  - Choose high, cold sites (e.g. South Pole, Hawaii)
  - Minimize the mechanical structure, telescope structure radiates so that the less are it presents to the detector the better.
  - Low emissivity coatings (gold or silver rather than aluminum) on mirrors.
  - Use rapid beam switching (e.g. with chopping secondary) to subtract of background contribution.
  - Use long focal length, cold baffles and undersized secondary mirror to avoid background radiation reaching the detector.

Ultra-violet telescopes

- Ultra-violet radiation at $\lambda < 3100$ Å is absorbed by the atmosphere. Ultra-violet telescopes must be in space, but their design is otherwise similar to optical telescopes.
- The Hubble Space Telescope is the premier ultra-violet telescope.

Telescope mountings

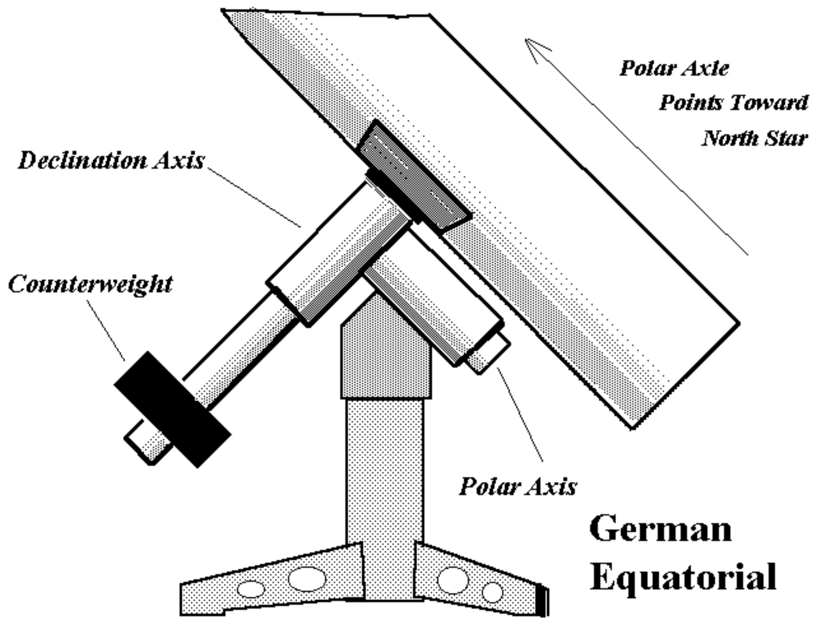
Practical telescope configurations

- Mechanical mounting

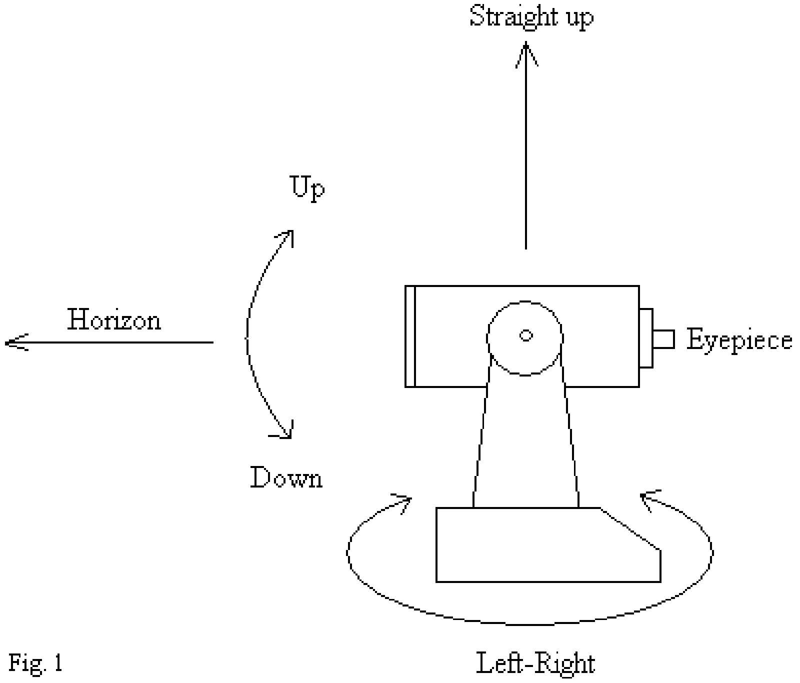
  In the past optical telescopes were mounted in an *equatorial* configuration, where one axis points at the north or south pole, and the other axis was horizontal and perpendicular to the polar axis. In this configuration the telescope needs to be driven at a constant angular velocity about the polar axis to compensate for the rotation of the earth and track a source.

Practical telescope configurations

An equatorial mounting



An alt-azimuth mounting



Practical telescope configurations

All large radio telescopes, and most modern optical and infrared telescopes are mounted in an *altitude-azimuth* configuration. Here the axes are vertical and horizontal, which is mechanically simpler and cheaper to construct. To track a source across the sky, both axes need to be driven at variable angular velocity, but with modern computers this is possible and cheap compared with the difference in the mechanical cost.

Maintaining figure and alignment

- In order to maintain the image quality at the limit set by diffraction (or the atmosphere) it is important to:
  - maintain the paraboloidal figure of the primary reflector
  - maintain the alignment of the optical axes of the primary, secondary and any tertiary reflector with power (i.e. non-flat)
  - maintain the relative orientation of the reflectors, i.e they must not tilt with respect to each other.

If you do not do this you get aberrations (coma and astigmatism)

Homologous deformation

- Any telescope designed to operate at a wavelength λ should have its surface manufactured to a tolerance of λ/20 to maintain diffraction limited performance.
- It should maintain this accuracy as its orientation changes, i.e. as it tracks a source across the sky.
- Mechanically this is possible for small steerable dishes (10 metres diameter or less) but difficult for larger structures.

Homologous deformation (radio telescopes)

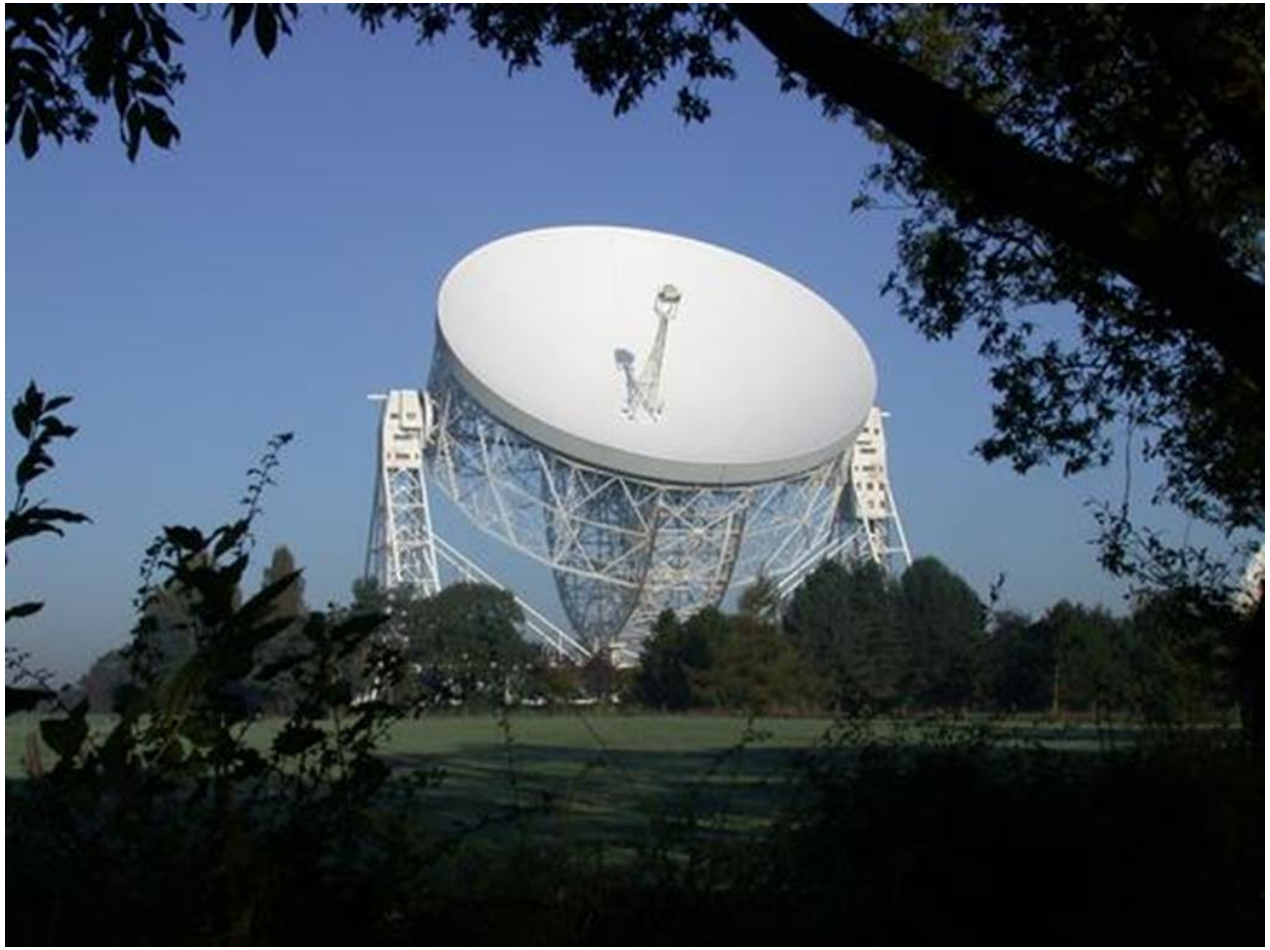
- Strictly what is required is not thats its figure should not change with orientation, but that its figure should remain a paraboloid of rotation.
- Large radio telescopes are designed to deform but to remain paraboloids.
- The Effelsberg 100 metre diameter steerable dish deforms by up to 6cm, but remains a paraboloid to < 0.4 mm, so it performs to specification at wavelengths as short as 1cm

Radio telescope performance

- Radio telescope performance in terms of maintaining the figure is usually limited by thermal expansion effects and by wind. For this reason many modern high-frequency radio telescopes are not made from steel or aluminium, but from more exotic materials such as Carbon Fibre or other composite materials.

Radio Telescopes

Lovell telescope at Jodrell bank



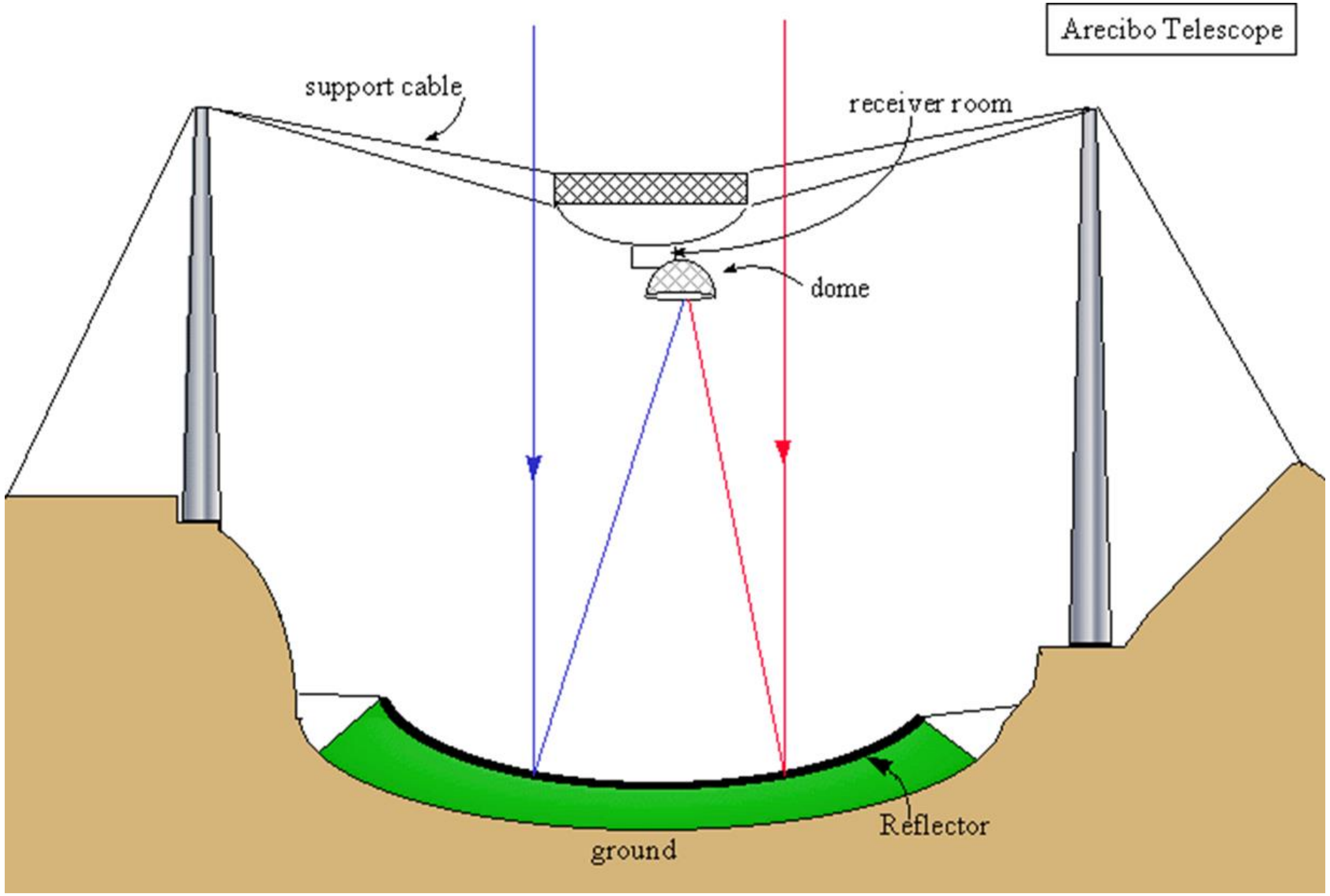
Parkes Radio telescope, Australia

64-m diameter parabolic dish

Above a modern photo, to the right in 1969. What is the difference?

Arecibo radio telescope, Puerto Rico

Arecibo radio telescope, Puerto Rico

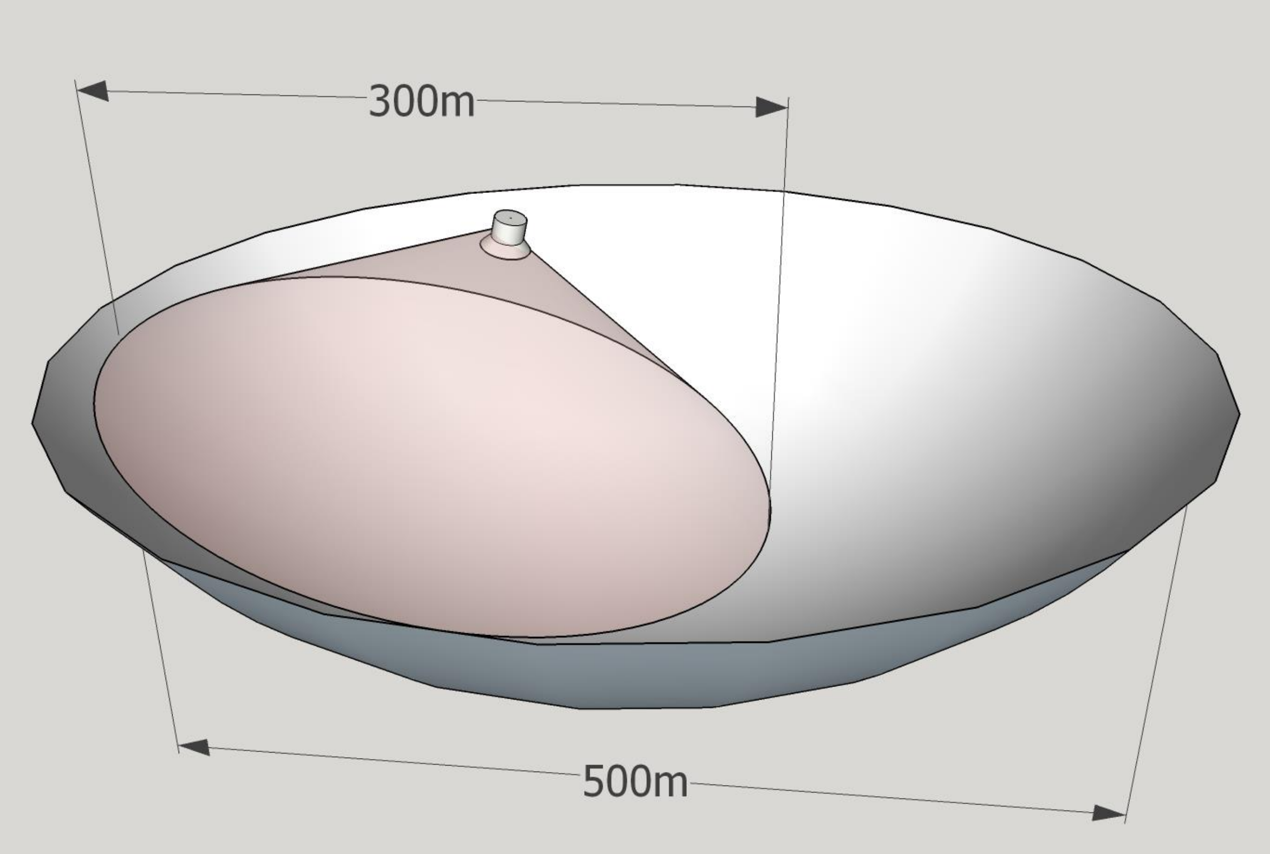


A new king of radio-astronomy – FAST (China)

Five-hundred-meter Aperture Spherical Telescope (FAST)

FAST (China)

- Diameter: 500 m
- Illuminated diameter 300 m

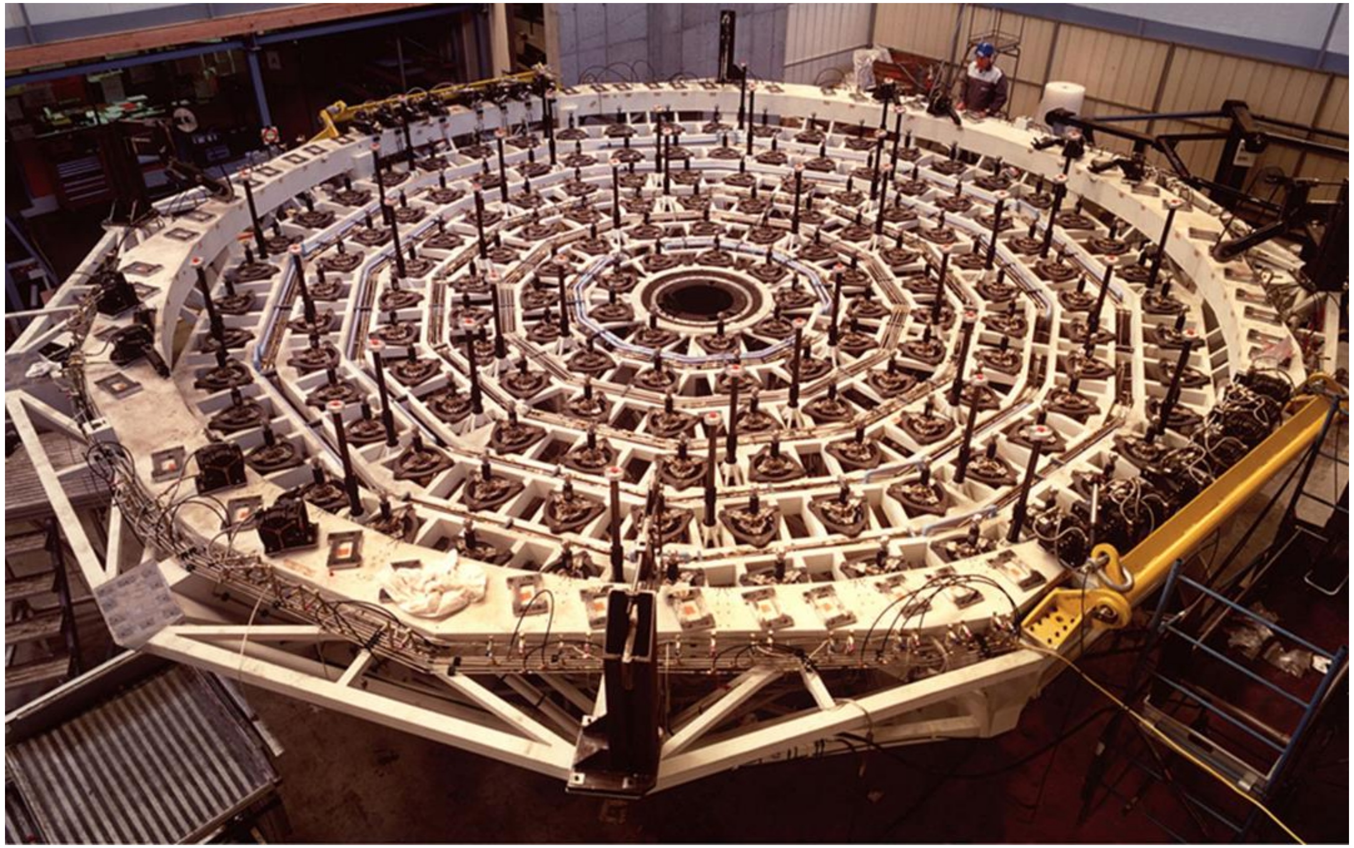


Optical telescopes - active mirror support

- In an optical telescope the primary reflector is usually a zero expansion glass surface coated with a reflecting metal. In small telescopes this can be rigid and maintain its structure.
- In larger telescopes the deformations are modelled as a function of telescope attitude, and a series of pneumatic or hydraulic actuators are used to apply the correct force at each point on the mirror to make sure the shape is maintained.

Optical telescopes - active mirror support

The VLT primary mirror support, showing 150 actuators arranged in six concentric rings.

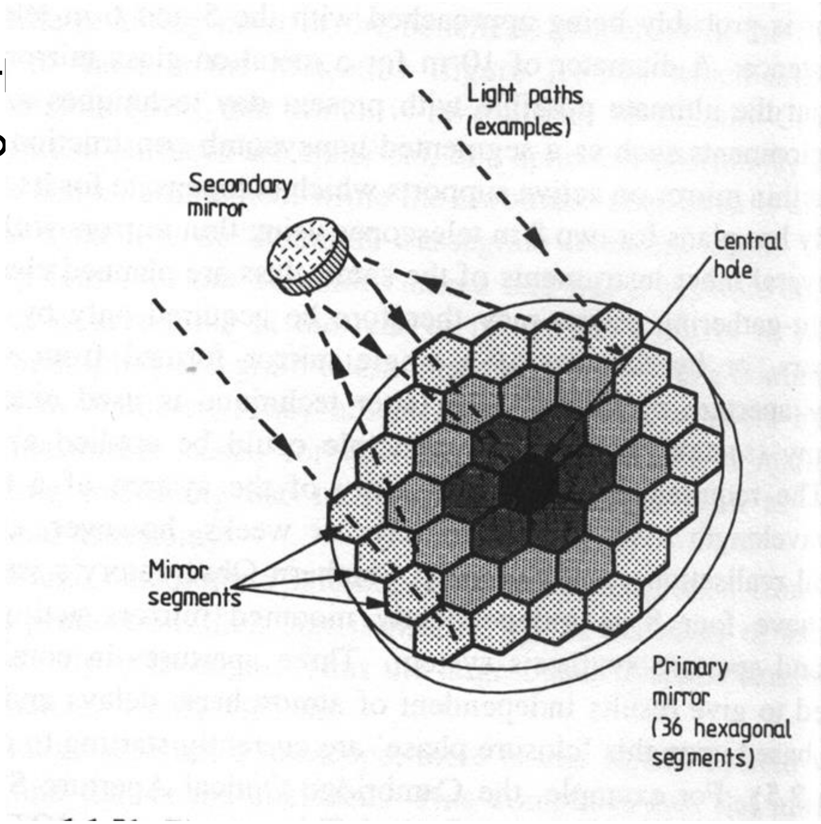


Optical telescopes - active mirror support

- In smaller telescopes, primary mirror cell is *semi-active*, in that the actuators correct the tilt and translation of the primary mirror, but they do not alter its figure.
- In larger telescopes, such as the Gemini 8 metre and the VLTs, there are more actuators (of the same type), the mirror is a meniscus, and the actuators have sufficient force to correct the figure.

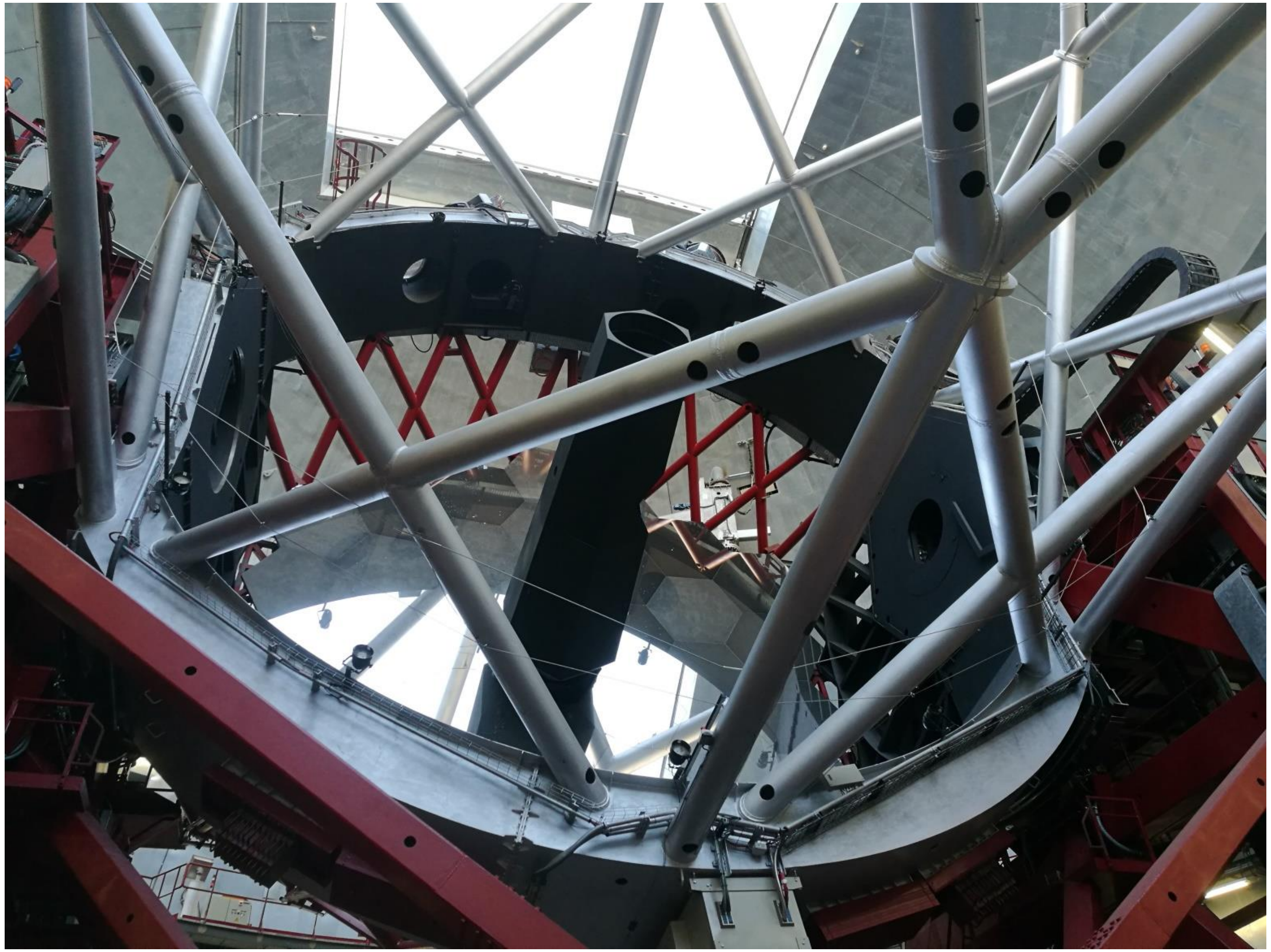
Segmented mirror telescopes

- In the Keck and GranTeCan (GTC) telescopes, instead of a single monolit mirror, the mirror is built up of hexago segments, which can be controlled accurately to bring their light to the same focus *at the same phase*. These telescopes are Cassegrain altitude-azimuth designs.



GTC telescope

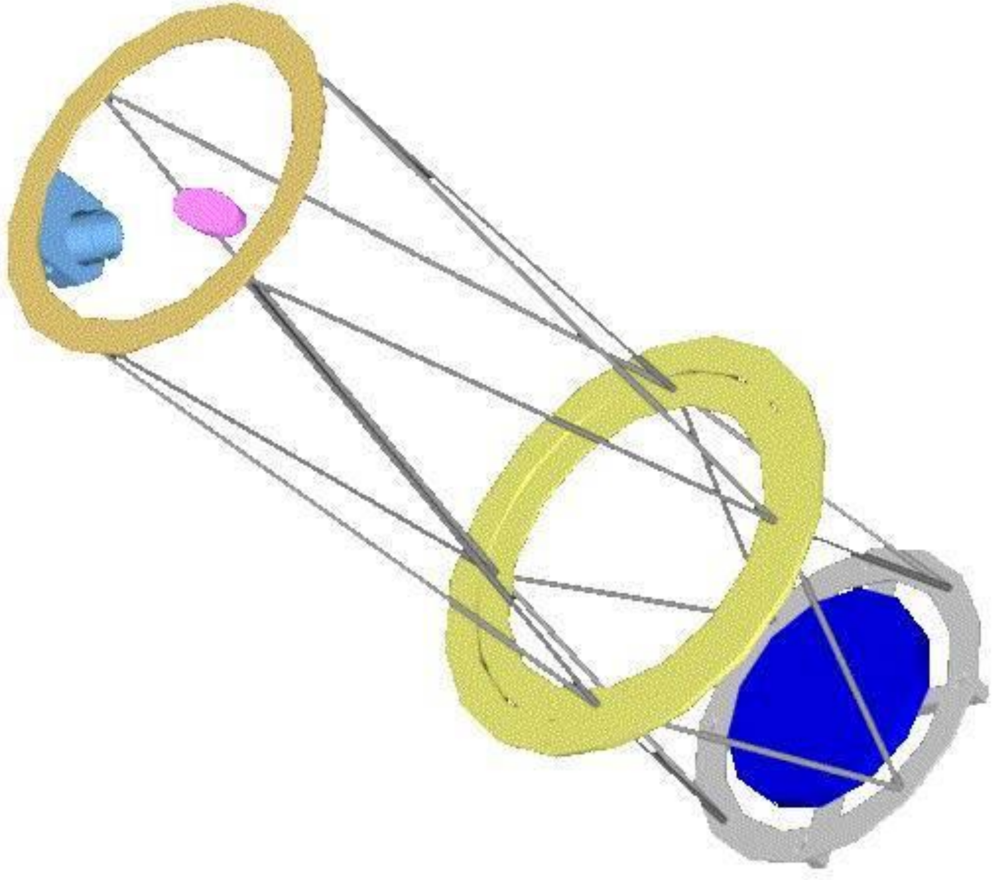
Segments are kept aligned and in phase by electromechanical support and feedback system



The Serrurier Truss

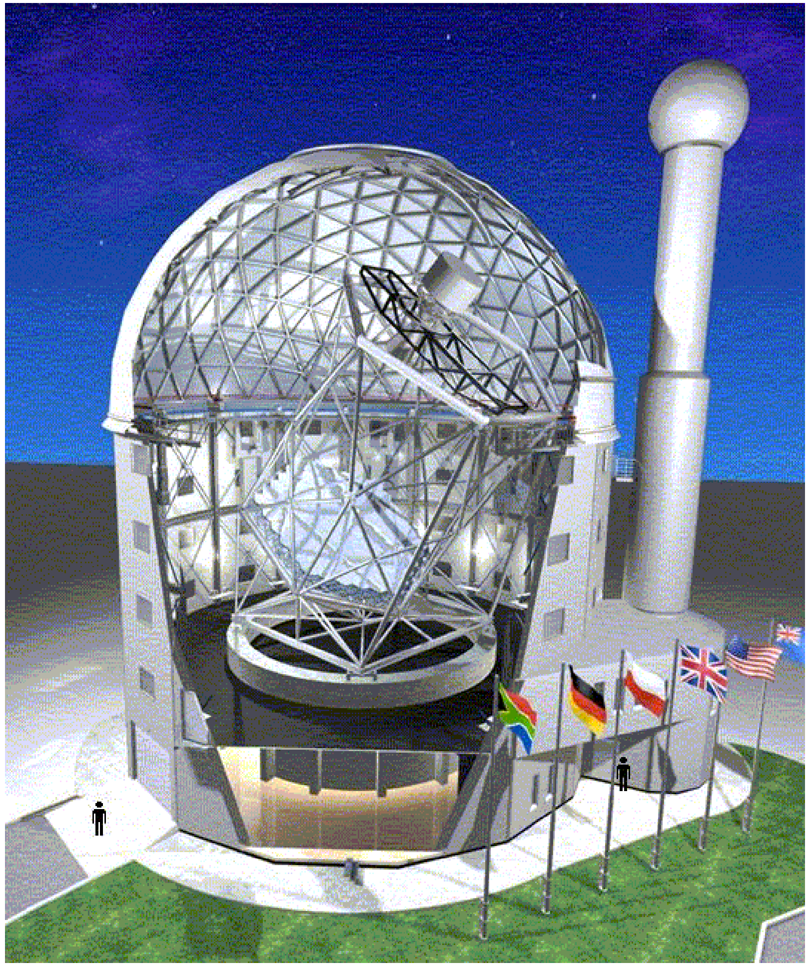
- It is very important to keep the optical axes of the paraboloidal and/or hyperboloidal primary and secondary mirrors precisely aligned, otherwise you get coma even on-axis.
- The Serrurier truss is an open “tube” structure designed so that at any orientation the flexure of primary and secondary mirrors is identical, maintaining the alignment.
- This design allows a relative rotation of primary and secondary mirrors, which can in turn be corrected by pneumatic and/or electromechanical actuators.

The Serrurier Truss



Southern African Large Telescope

- Azimuth only tracking.
- Prime focus top end moves Arecibo style.
- Limited sky area and tracking time.
- Limited field of view.
- Cheaper to engineer as flexure as you tip is not a problem.

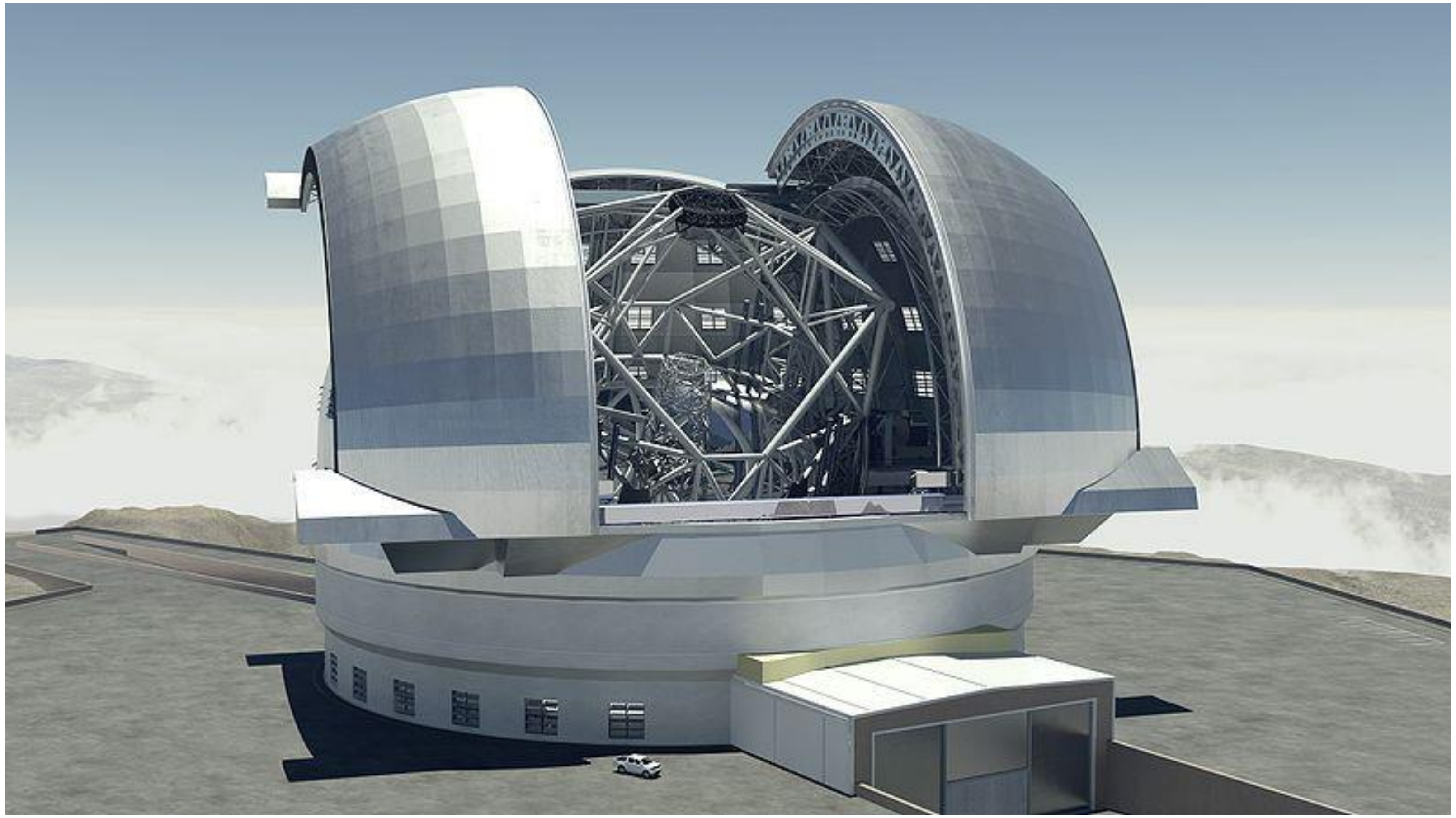


New Large Telescopes

- Current state of the art in optical/near infra-red telescopes is:
  - 8.2 metre monilithic meniscus mirror
  - 10 metre equivalent mirror with hexagonal segments.
- Various proposals for larger 20-100 metre aperture telescopes.
- The European Extremely Large Telescope (ELT) is already under construction.
- International 30 metre telescope (TMT) is preparing to start construction.

The European Extremely Large Telescope

- Diameter: 39 m (798 hexagonal 1.4 m mirror segments).



The European Extremely Large Telescope

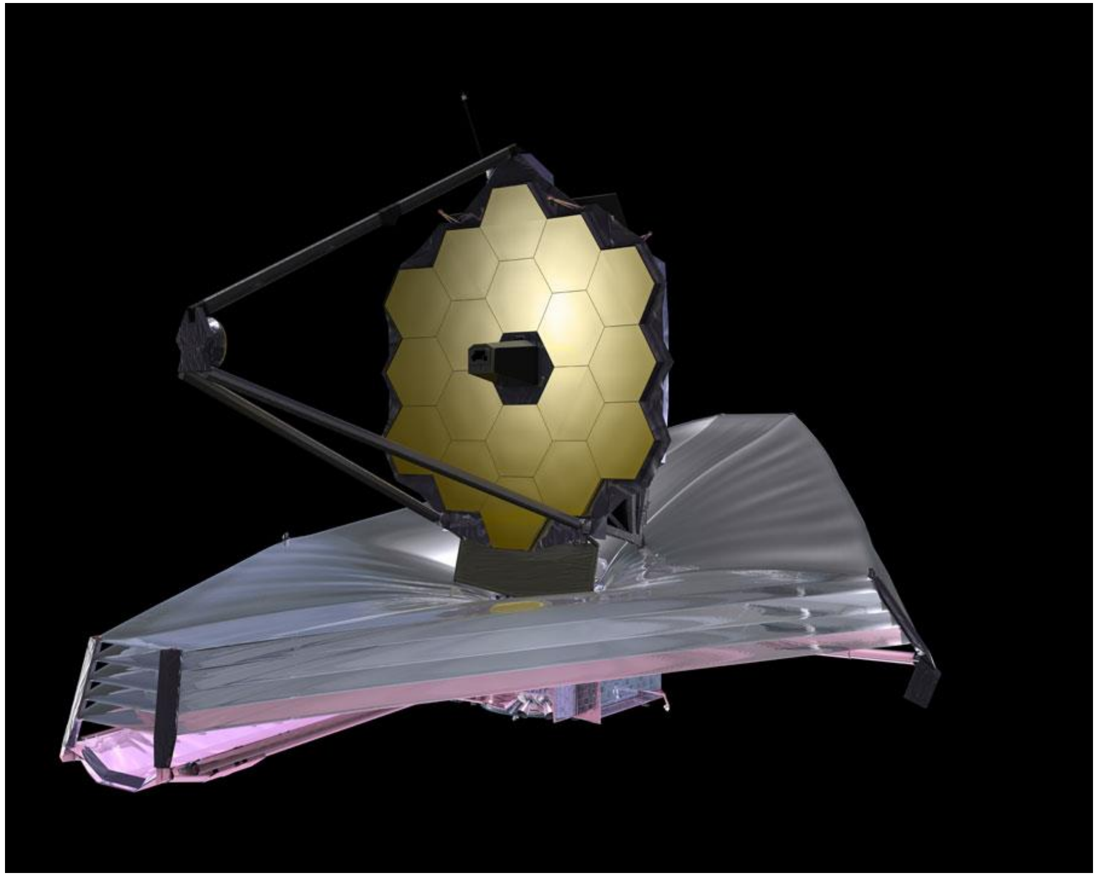
- Current state (3 September 2023, 7:00 CEST)
- 2028 (planned): Technical first light of the ELT

International 30 metre telescope (TMT)

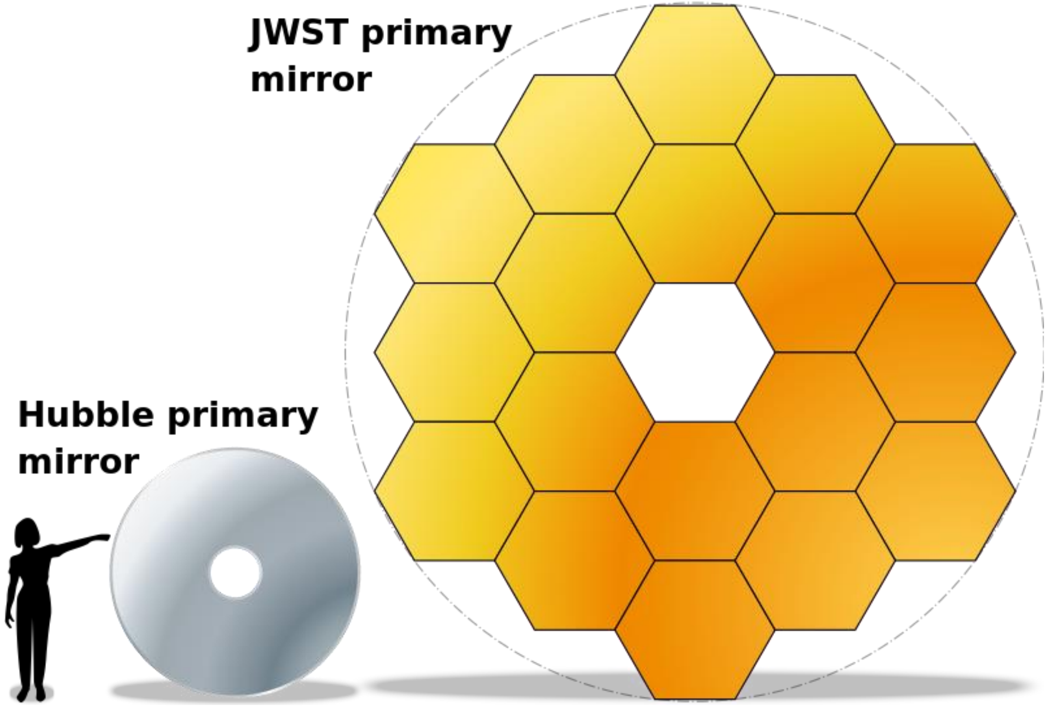
Problems of Extremely large telescopes

- Need light stiff structures, composite materials, e.g. Silicon Carbide for mirror segments.
- Large downward looking secondary is a huge problem, carbon fibre structures.
- Control loop to keep segments aligned is heavily nested hierarchical control at hundreds of Hz, beyond the scope of current hardware.
- Wind distortion a severe problem.
- Adaptive mirrors up to a metre across may be required.
- Need Multi-Conjugate Adaptive optics with laser guide stars (see next lectures).
- Huge data rates.

James Webb Space Telescope

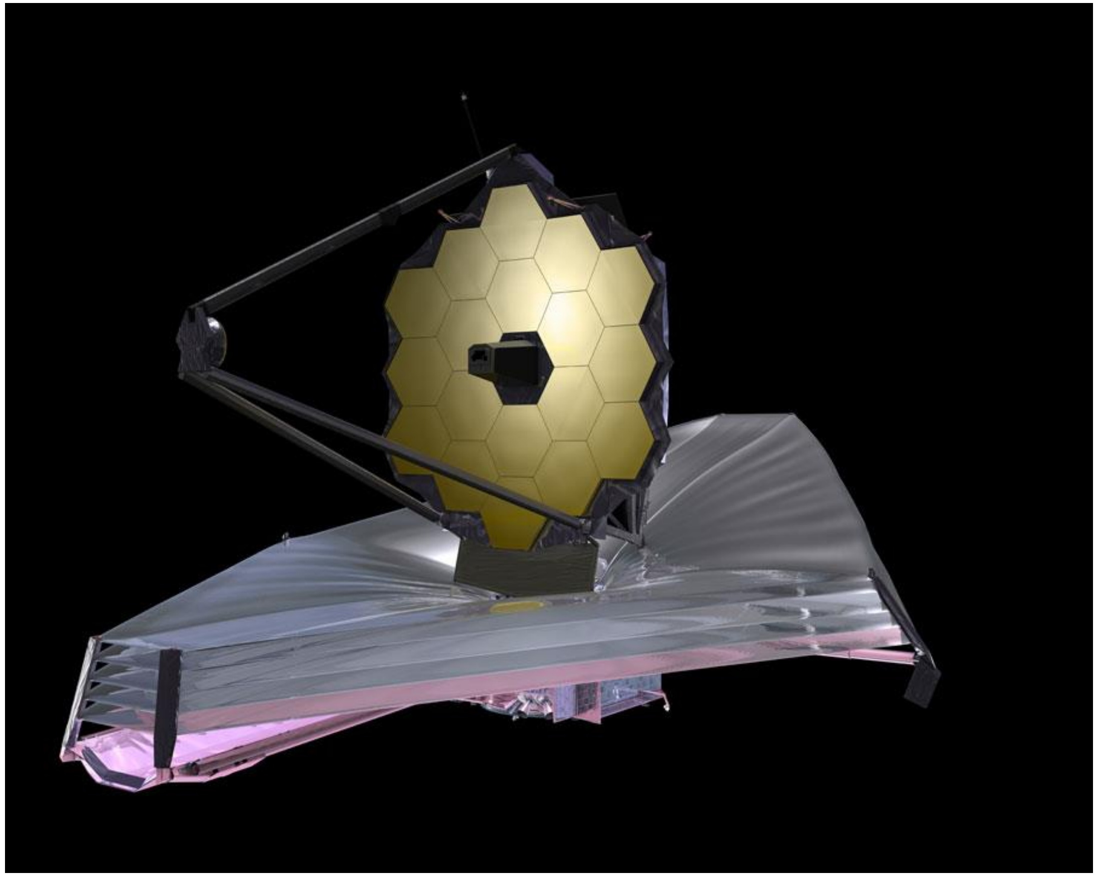


Primary mirror consists of 18 hexagonal mirror segments, which combined create a 6.5-m diameter mirror.



JWST observes from long-wavelength visible light through mid-infrared (0.6–28.3 μm).
The telescope must be kept extremely cold, below 50 K.

James Webb Space Telescope



- JWST's optical design is a three-mirror anastigmat (Korsch telescope).
- Homework: Plot a scheme and explain differences with the classical Cassegrain telescope. What are the advantages?