# OBSERVATIONAL ASTRONOMY

FALL 2025

Lecture 2

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# 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

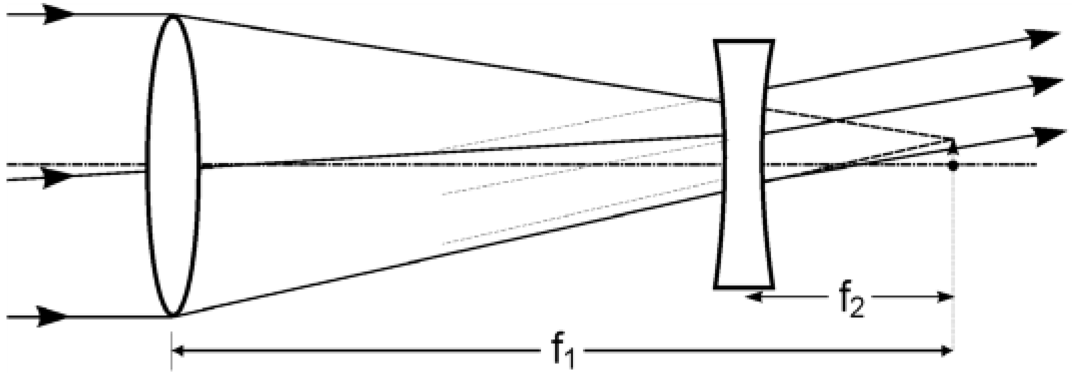


- Historical introduction
- General principles
- Diffraction and Spatial resolution
- Aberrations in reflecting telescopes
- Optical configuration
- Telescope configurations
- Optical Telescopes
- Segmented mirror telescopes
- Adaptive optics
- New large telescopes
- Problems of Extremely large telescopes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

# Historical introduction (1)



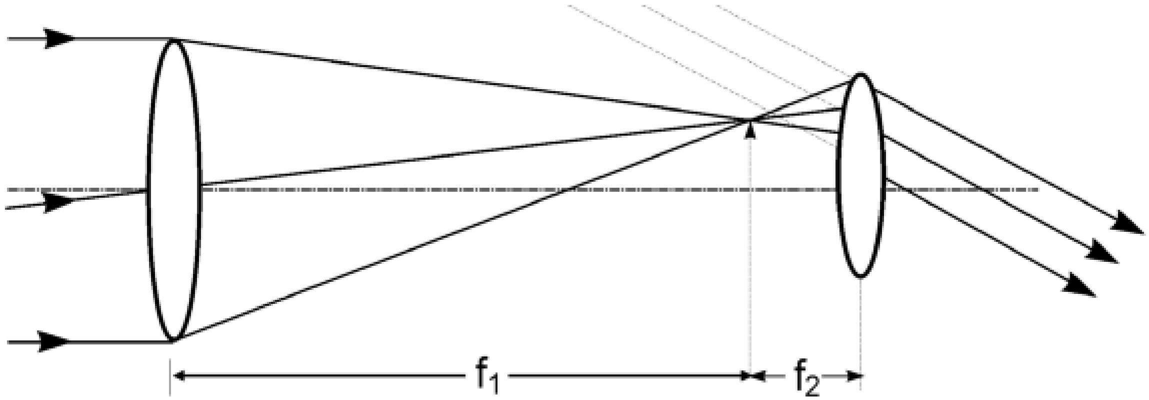
In July of 1609, Galileo Galilei developed the first astronomical optical telescope. His telescope is formed by the combination of a concave and a convex lens, today known as the Galileo telescope system. The front convex lens is called an objective because it is close to the object being viewed and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



# Historical introduction (2)



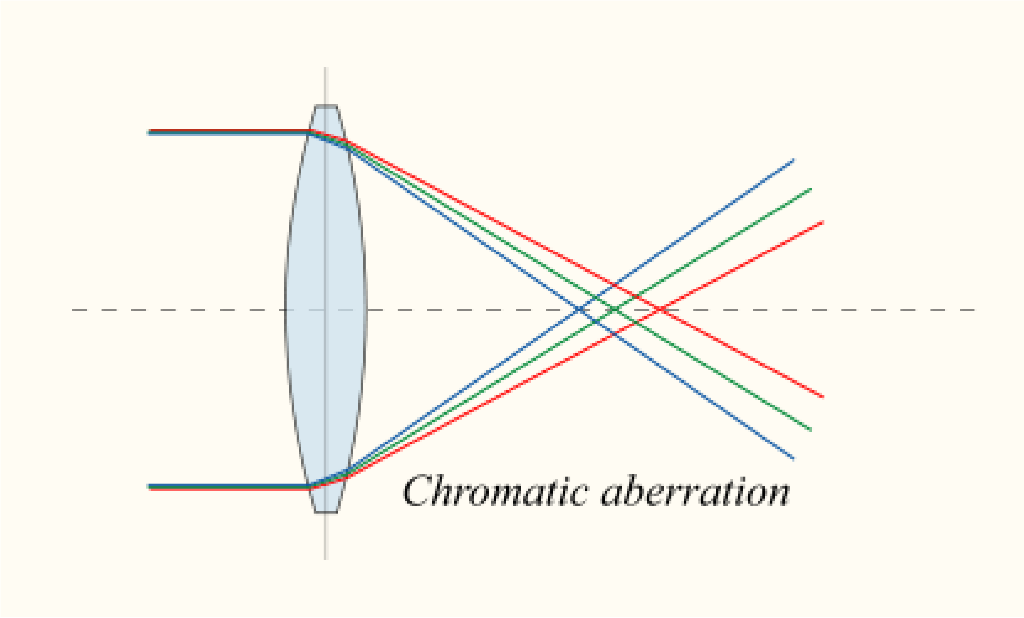
In 1611, Johannes Kepler invented another type of longer telescope comprising two convex lenses, known as the Kepler telescope system. The Kepler telescope forms an upside down image, but with a slightly larger field of view.

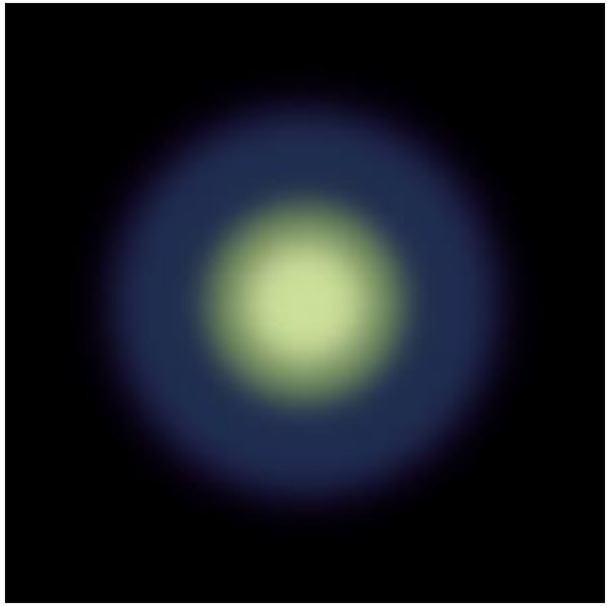


# Kepler's telescope and Chromatic Aberration (1)



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

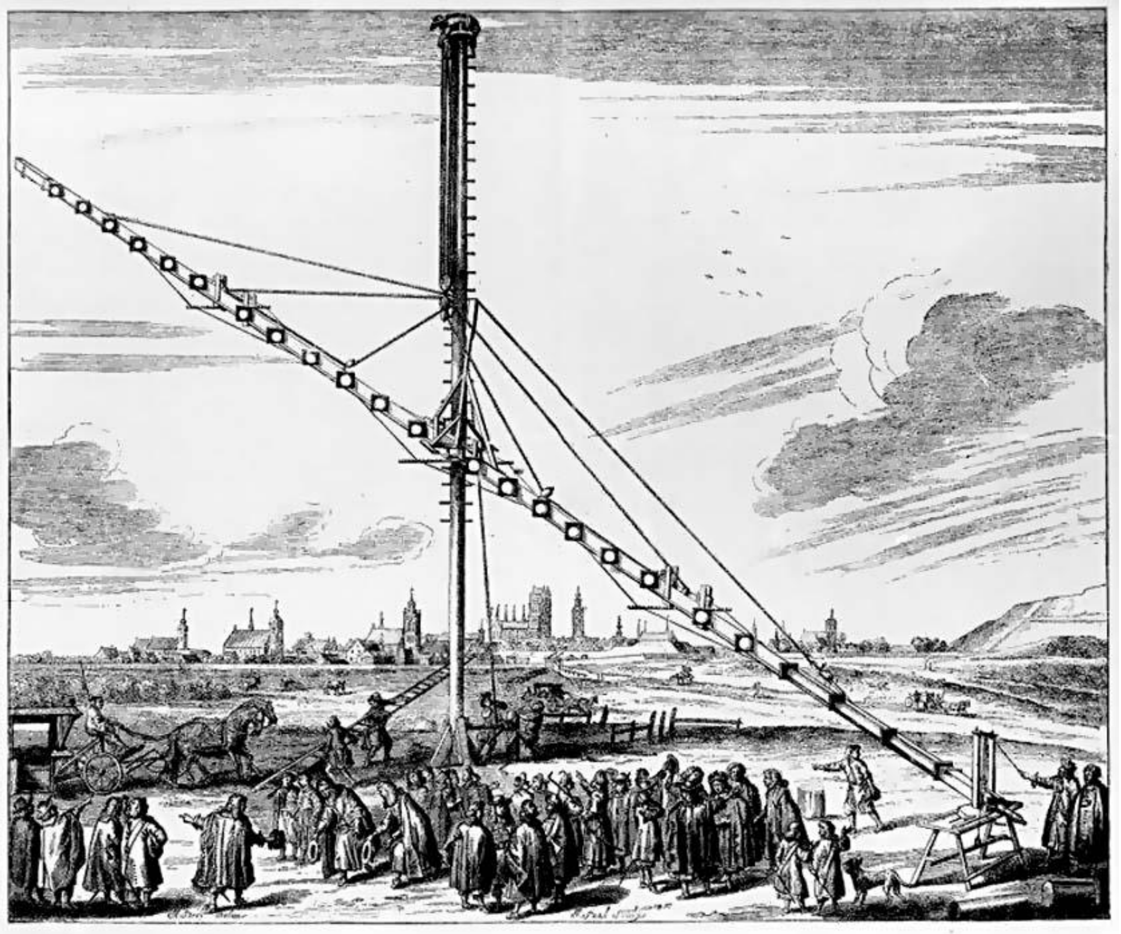


# Kepler's telescope and Chromatic Aberration (2)

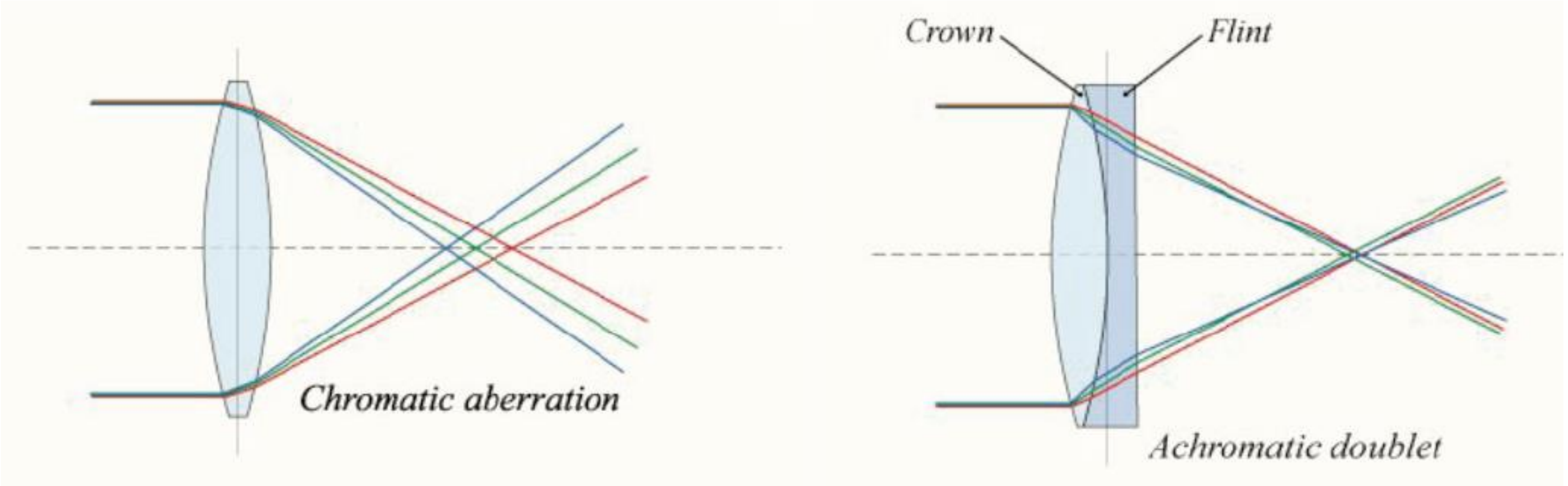


The only way to overcome this limitation was to create objectives with very long focal lengths.



# Chromatic Aberration: possible solution

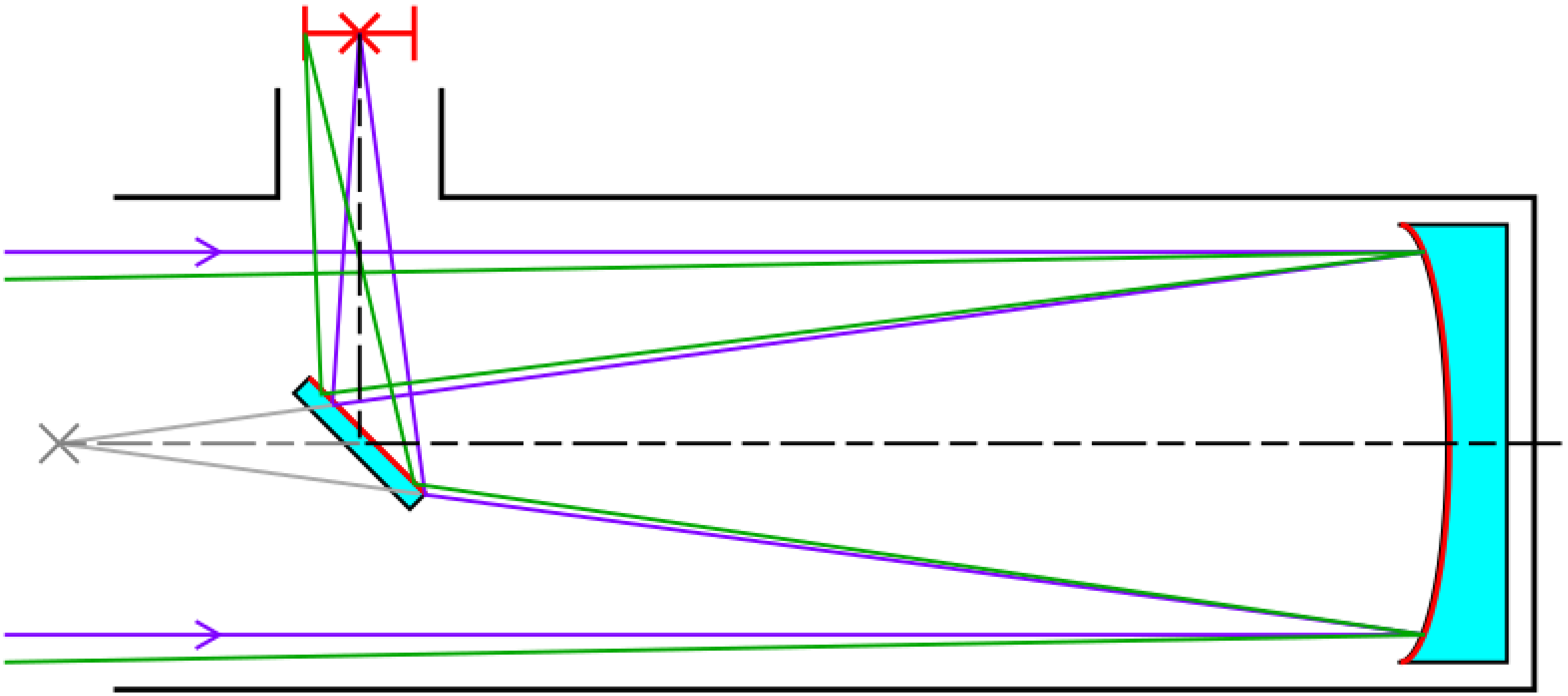




# Historical introduction (3)



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.



# 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);

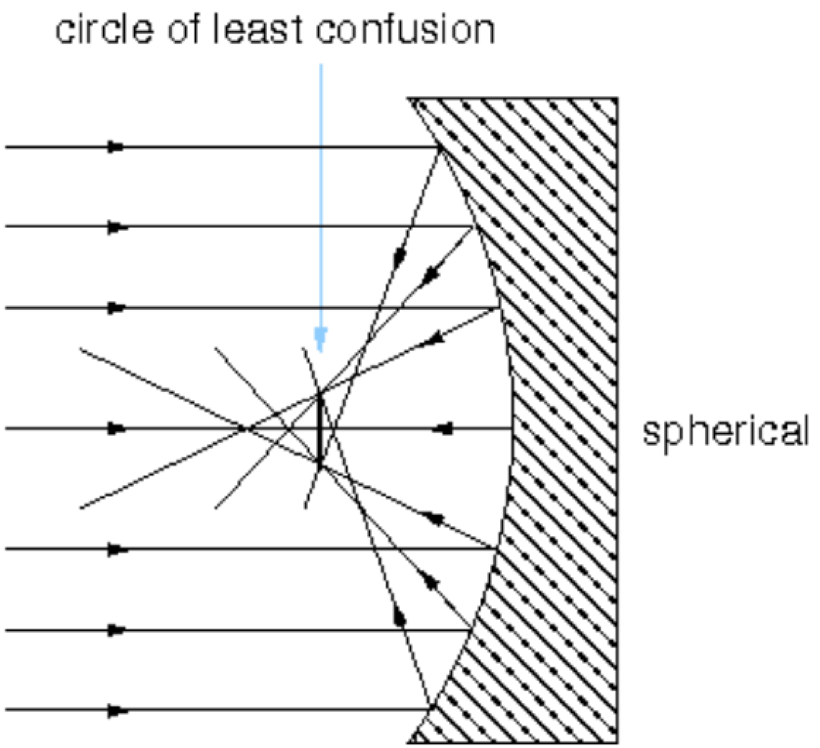
glass covered with a deposit of

- 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.

# Spherical Aberration (1)

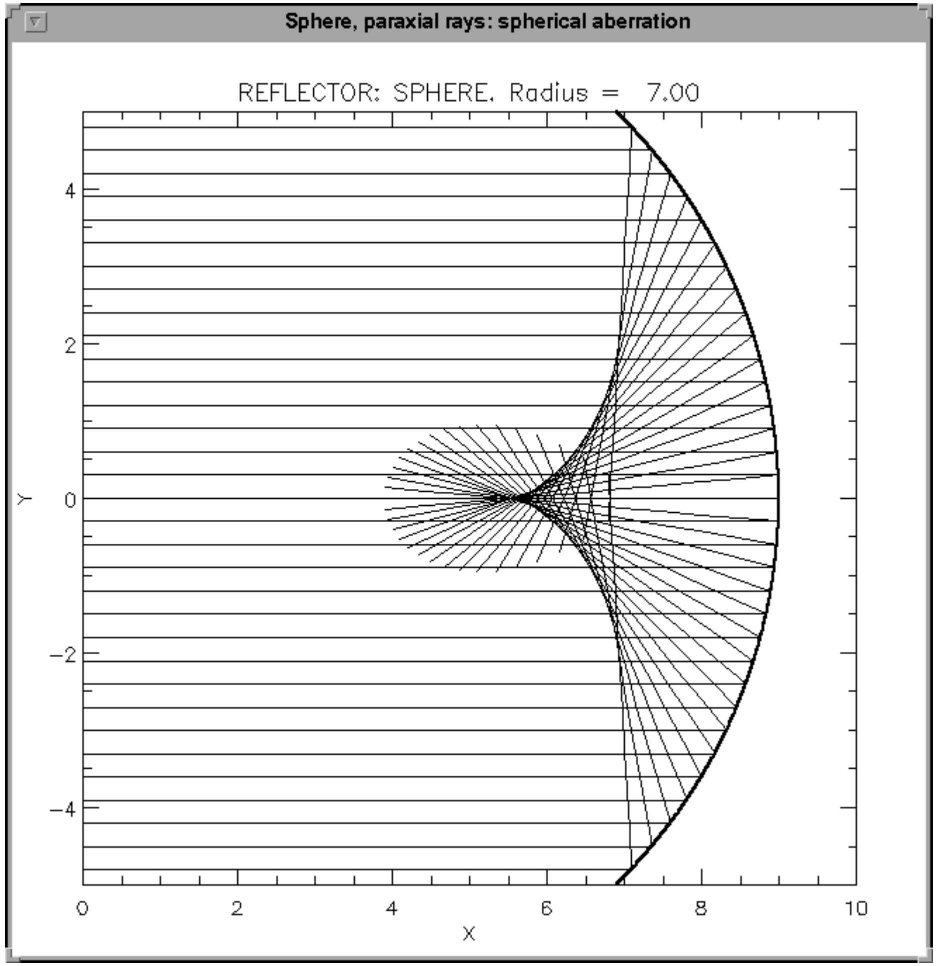





Spherical surface suffers from spherical aberration – rays hitting the outside of the dish come to focus at a different point on the optical axis from those hitting the centre.

# Spherical Aberration (2)



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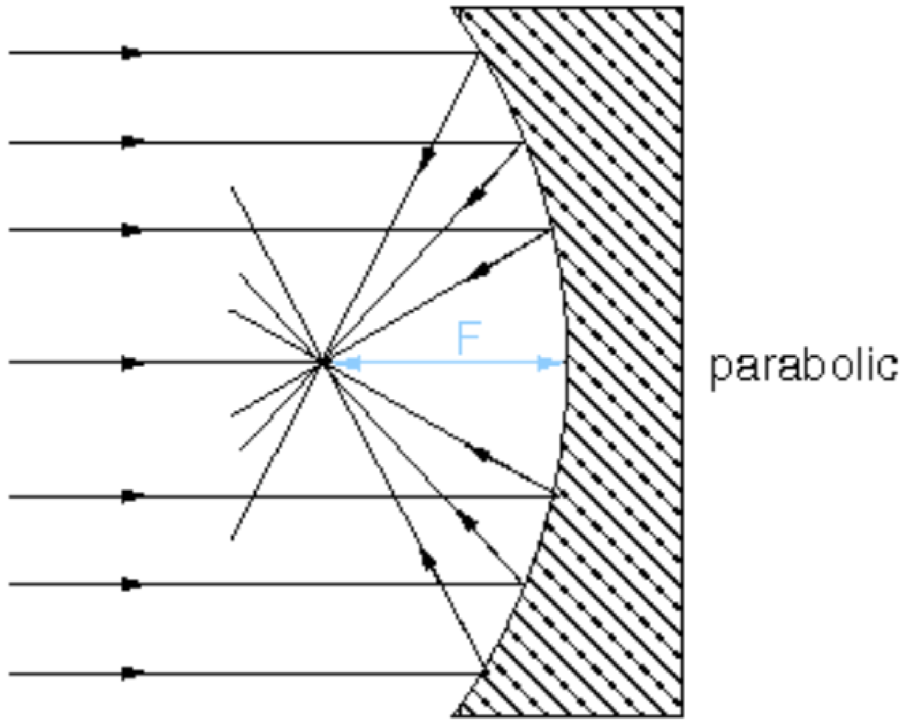
# Paraboloidal reflector






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

# A circular aperture of telescopes



- 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.

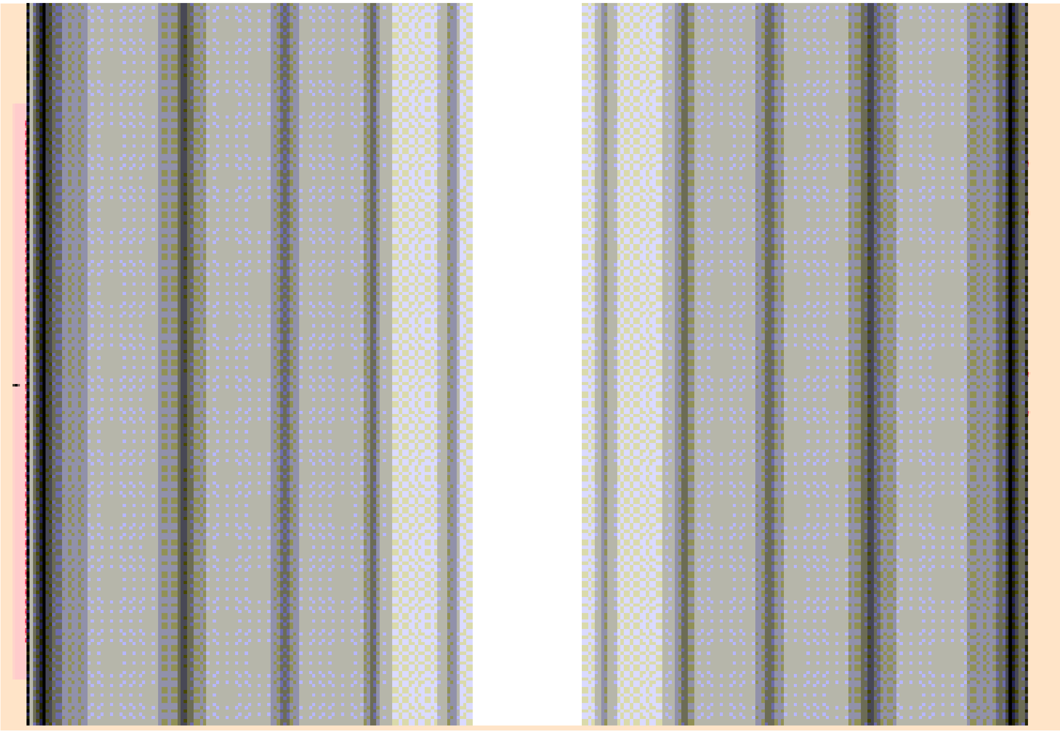
# Diffraction through a single slit



- 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.

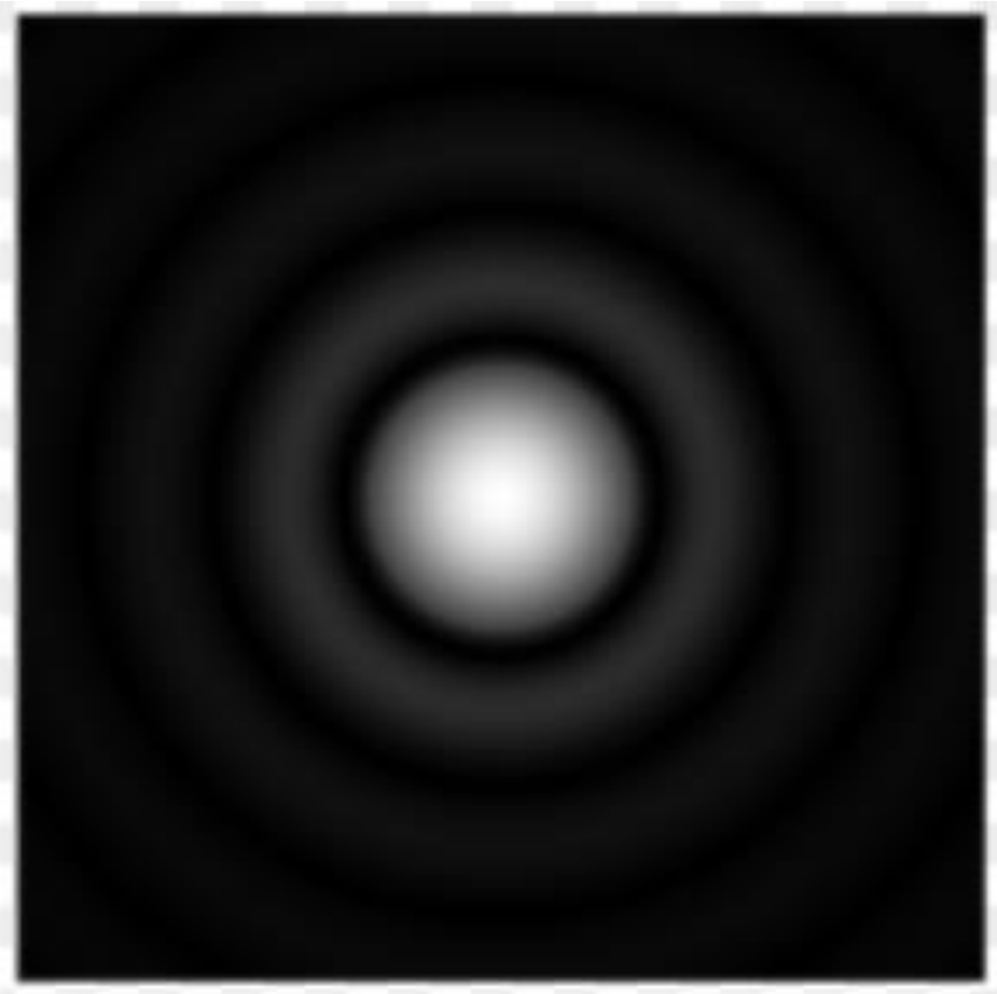
Image of a narrow slit:



# Diffraction problem for a circular aperture



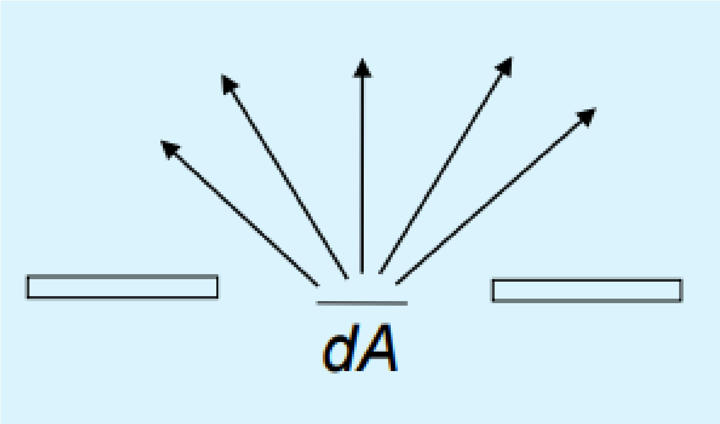
- The interference pattern on the screen behind the circular aperture of a finite size is created similarly to the slit: the waves from different secondary sources in the apperture interfere.
- The resulting pattern is a set of co-centric circular bright and dark bands with the highest peak in the center.



# Diffraction and Spatial resolution (1)



- 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 "Astrophysical techniques"

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

Does not work anymore



## 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

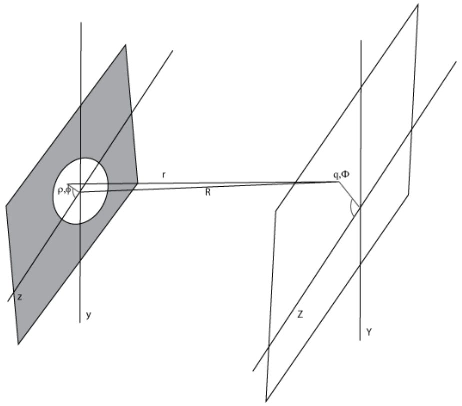



**Figure 1.**

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 $\Phi$ since the problem is symmetric about $\Phi$. 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

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

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 $\pi a^2$ 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 $\theta$ then one uses the fact that $q/R = \sin\theta$

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

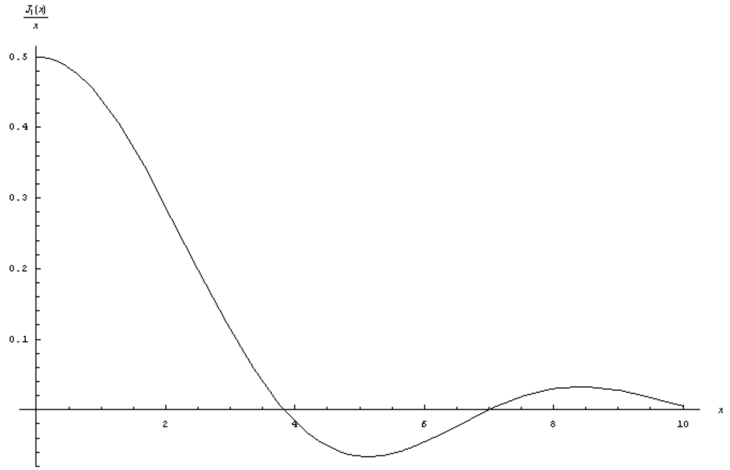



**Figure 2.**

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 (2)



Answer is (first derived in 1835 by Airy):

$$I_\theta \propto [\, J_1(2m)/m\,]^2$$

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

$\lambda$ is wavelength

$\theta$ is the angle to the normal from the aperture,

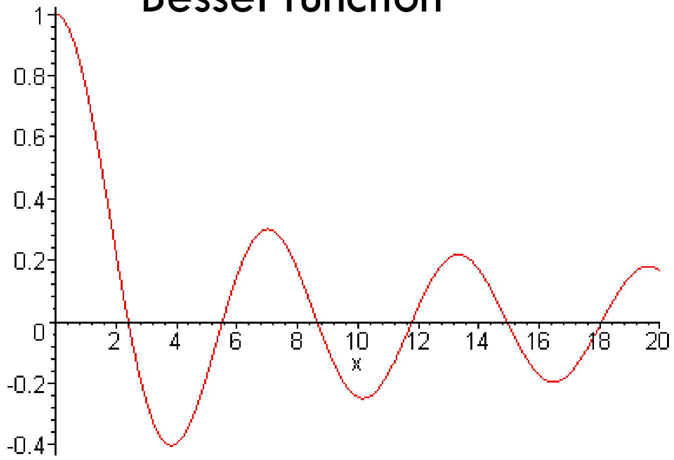
$r$ is the radius of the aperture,

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

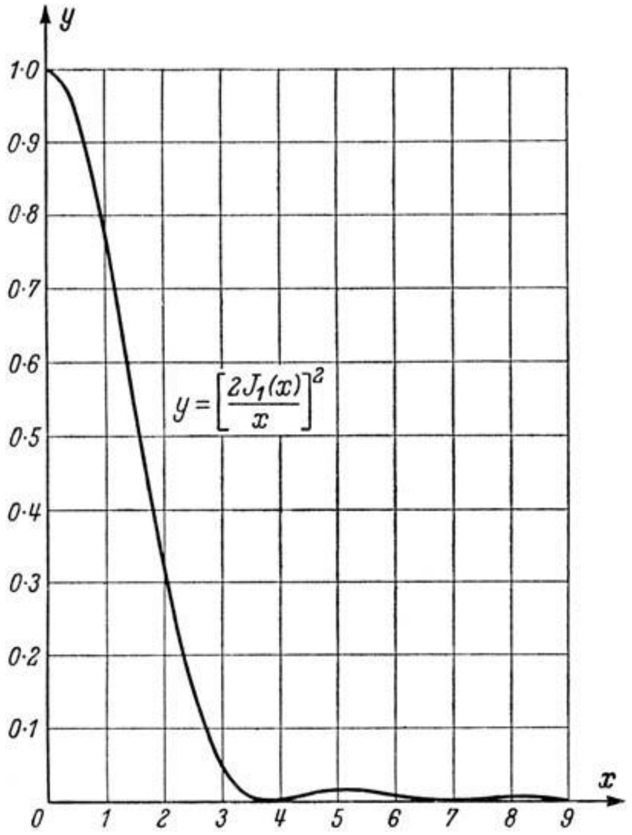
# Diffraction and Spatial resolution (3)



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 $\theta$:

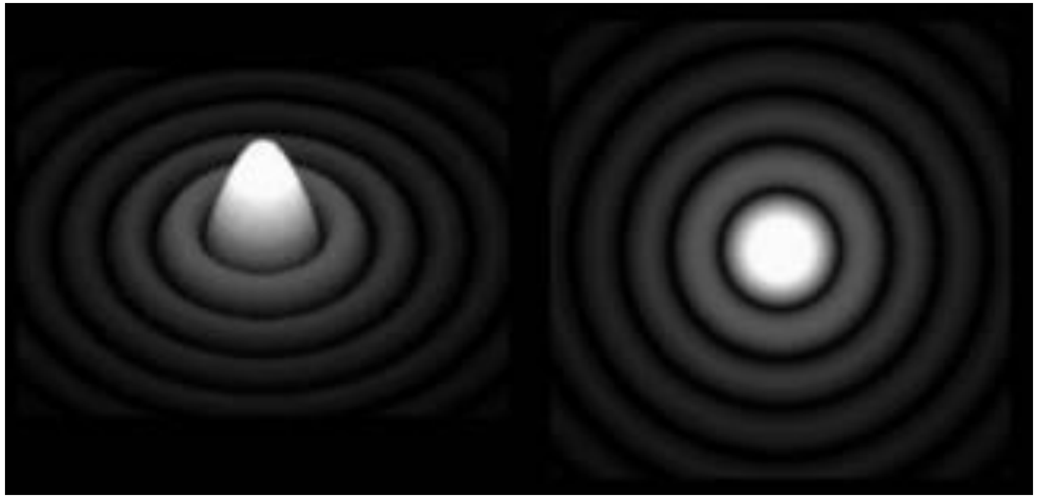
$$\theta \cong 1.22\,\lambda / D \text{ (radians)}$$

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

# Airy pattern



- Airy pattern:

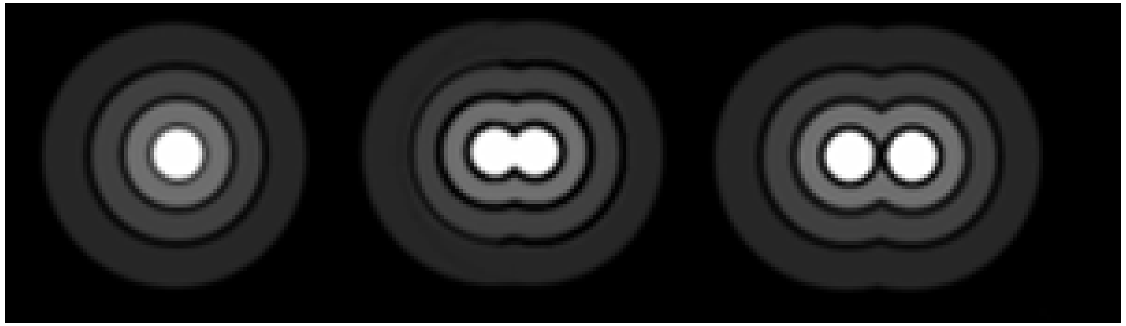


- The 1st maximum is roughly 1.75% of the central intensity, the 2nd – 0.42%.
- 84% of the light arrives within the central peak called the **Airy disk**.

# Effect of diffraction on image resolution



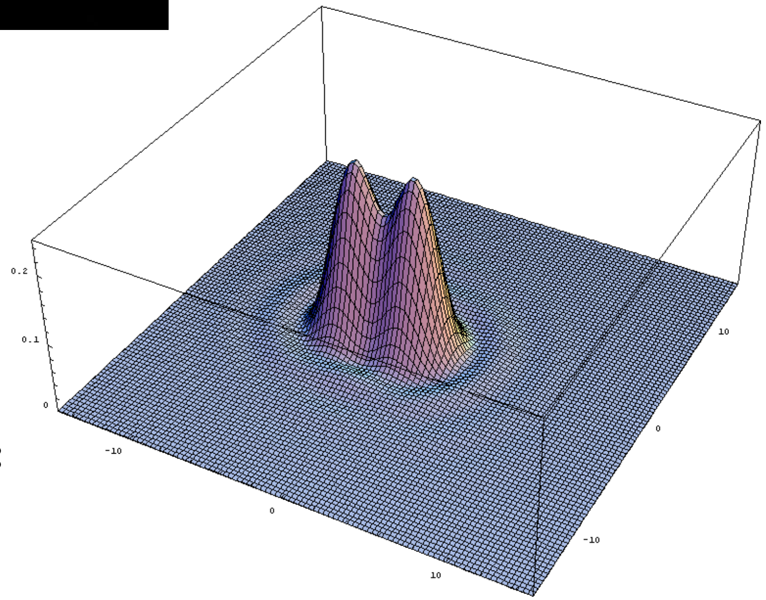
- Two distant point sources through a circular aperture:



- **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:

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

$\lambda$ is wavelength and $D$ is the diameter of the aperture



# Diffraction and Spatial resolution (4)



- 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**

# Spherical aberration



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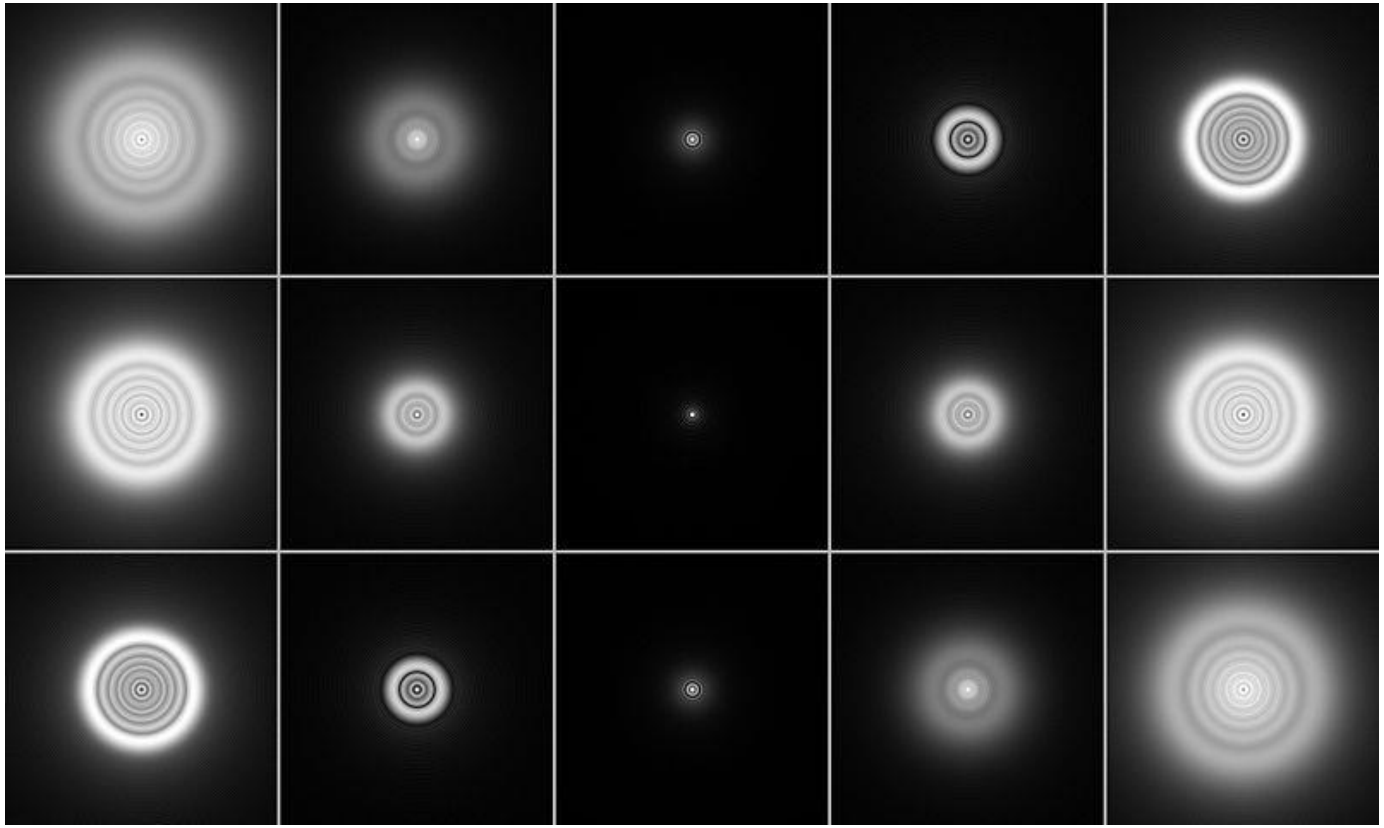

# Coma



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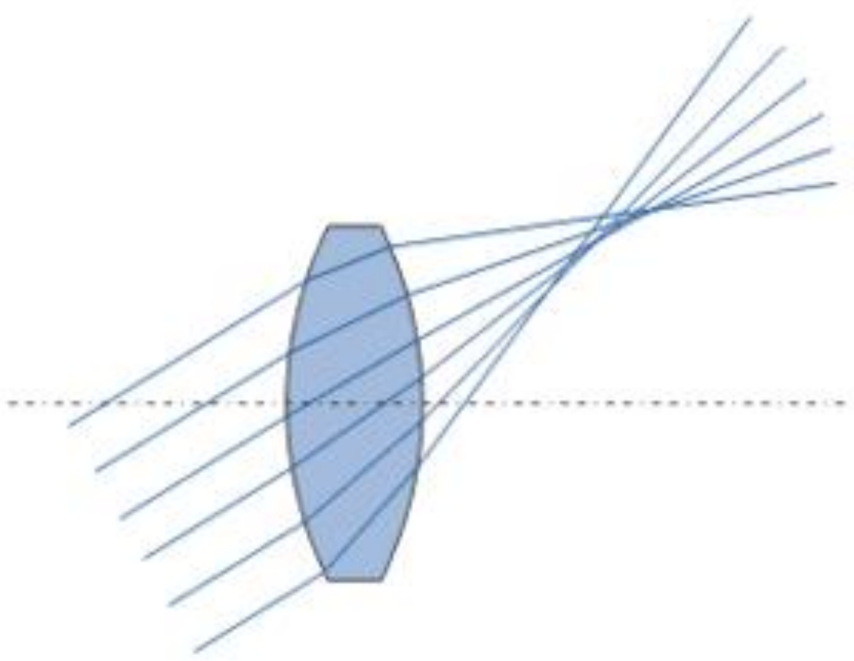

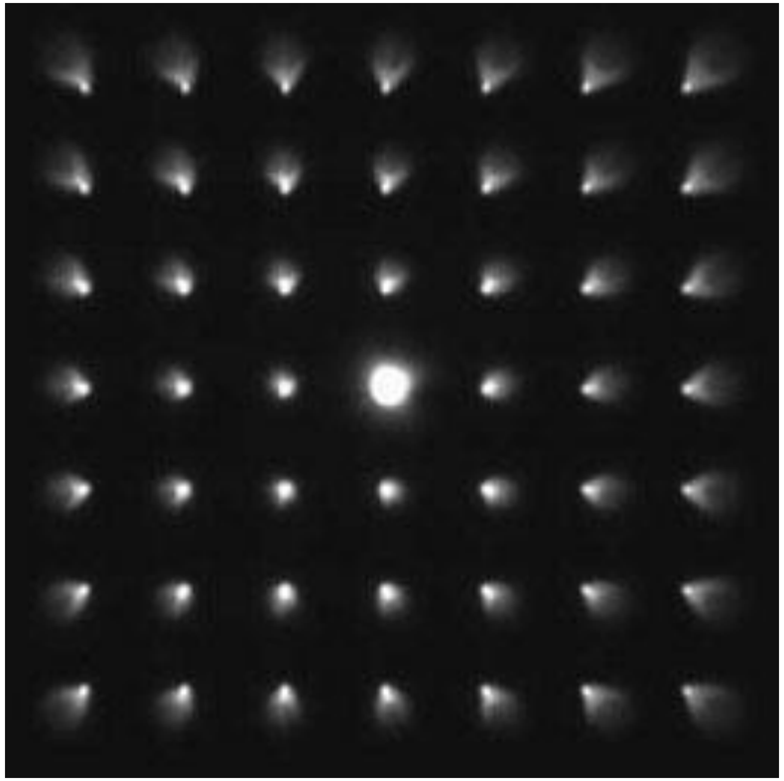

# Astigmatism



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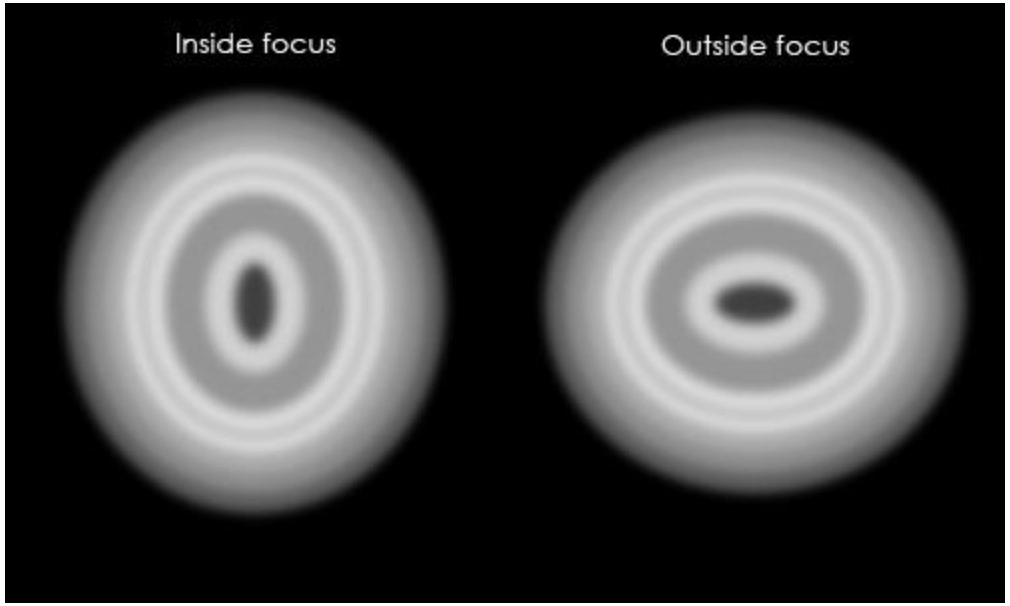
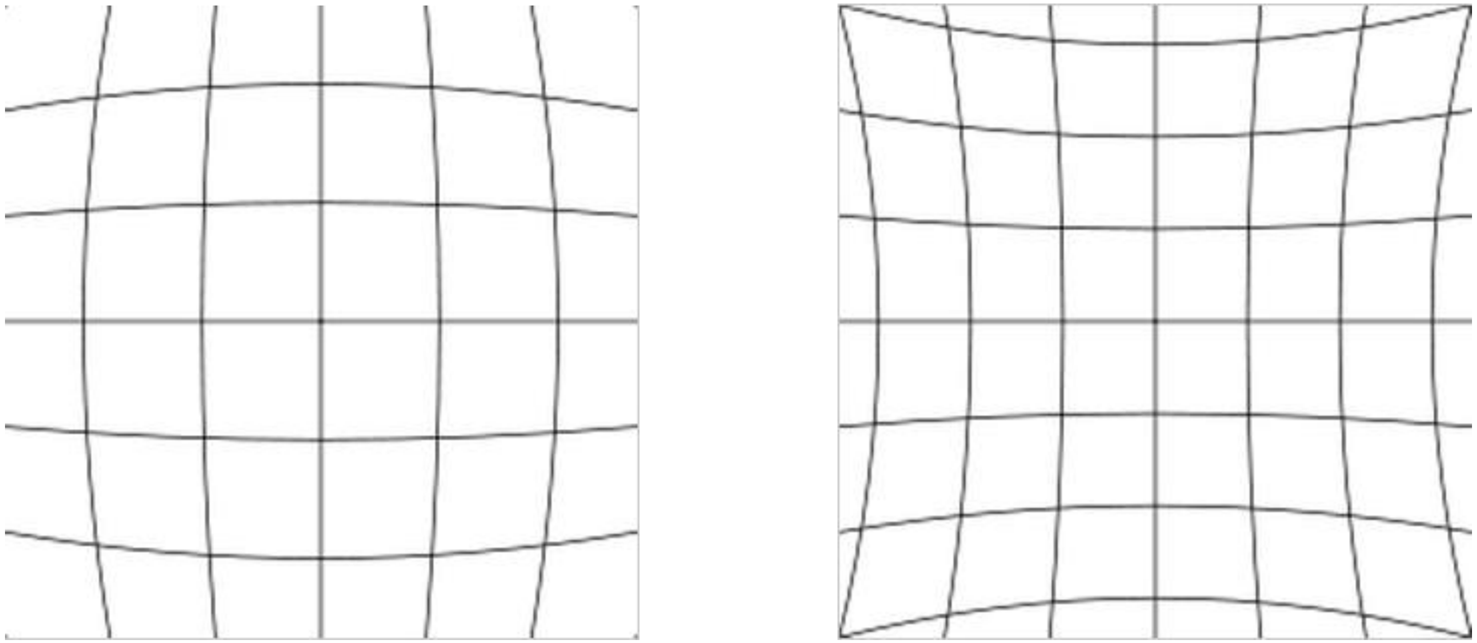


# Curvature of the image field



- Curvature of the field of the image –

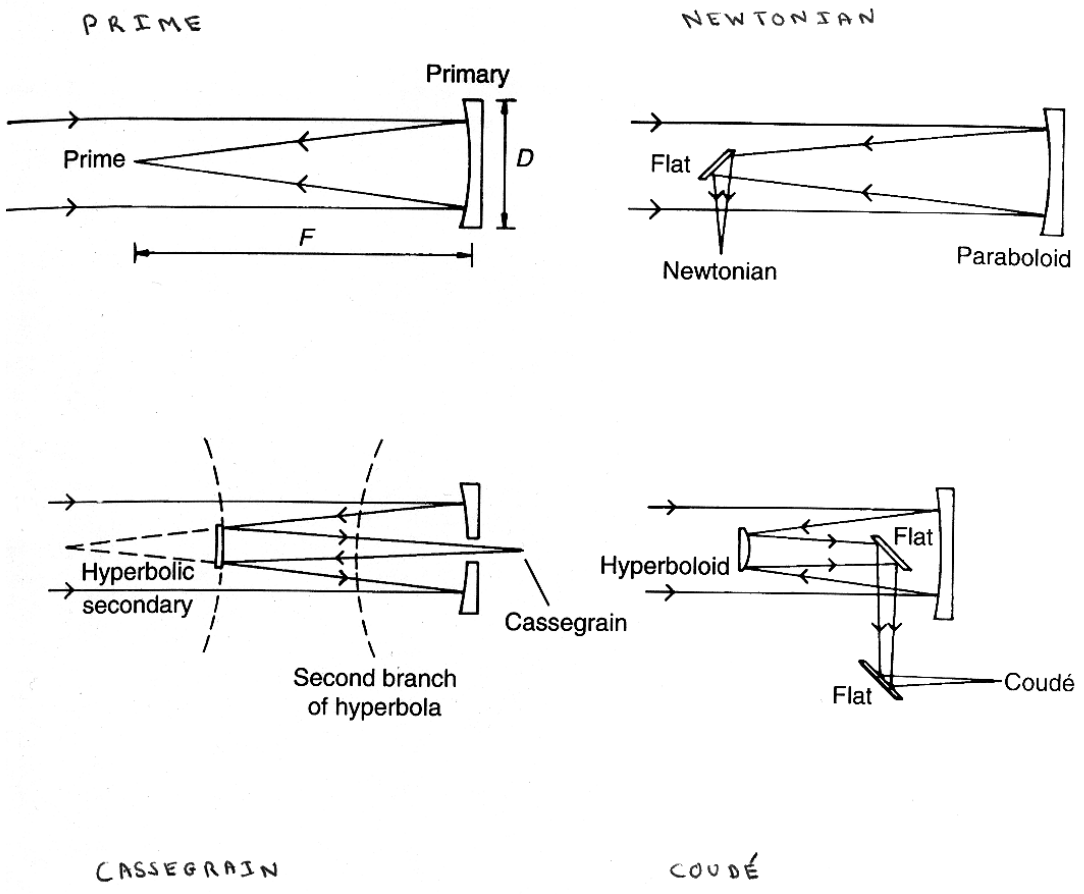
  Barrel and Pincushion distortions of the image



# Optical configurations of telescopes



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



# Optical configuration

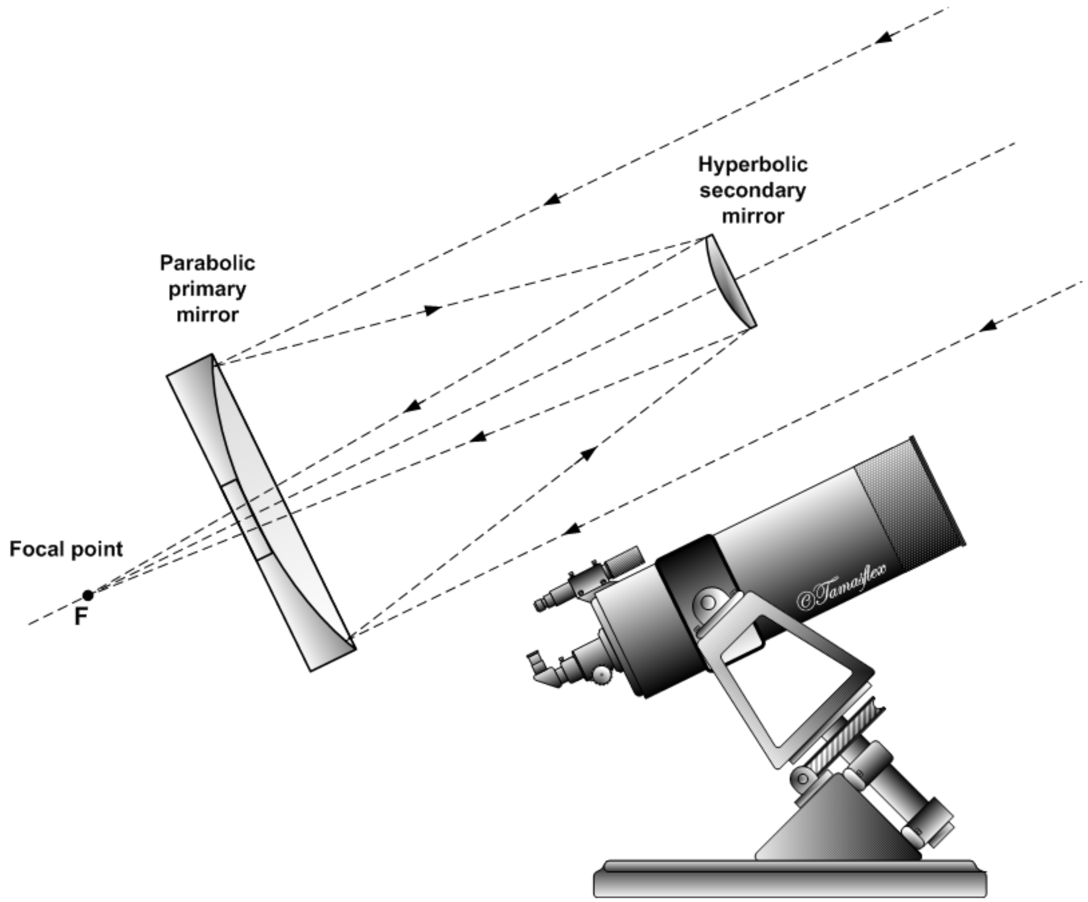


- **Prime Focus –** detector or receiver is at the focus of the paraboloidal reflector
- **Cassegrain –** a convex hyperboloidal secondary mirror or reflector is used to bring the rays to a focus below a hole in the primary.
- **Gregorian –** the secondary is now a concave elliptical mirror or reflector 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

# Cassegrain optical telescope



Schematic of Cassegrain optical telescope

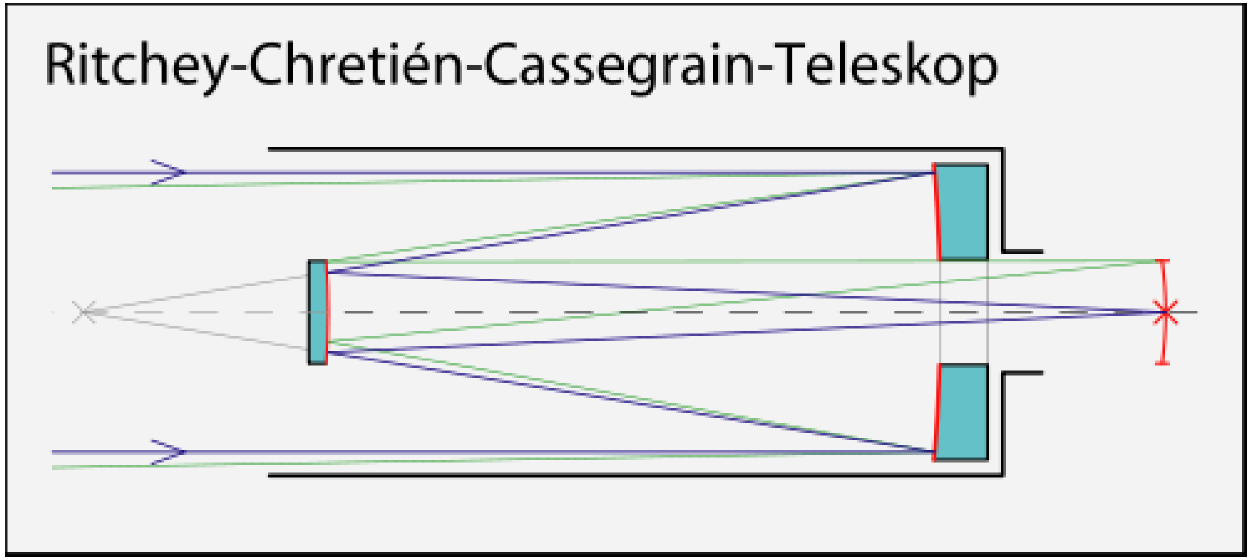


# Ritchey–Chrétien telescope



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.

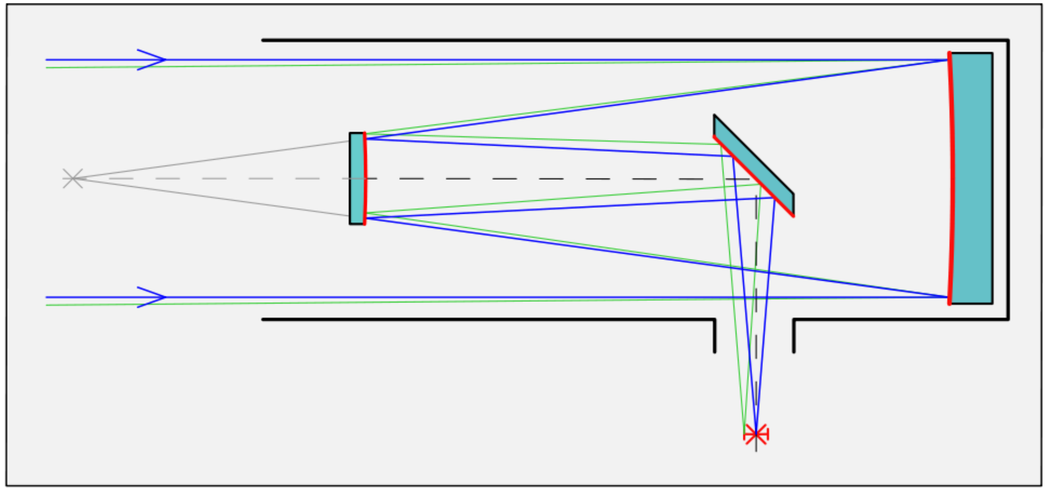


# Nasmyth telescope



Schematic of Nasmyth telescope

- No hole in the primary mirror is needed.
- 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.



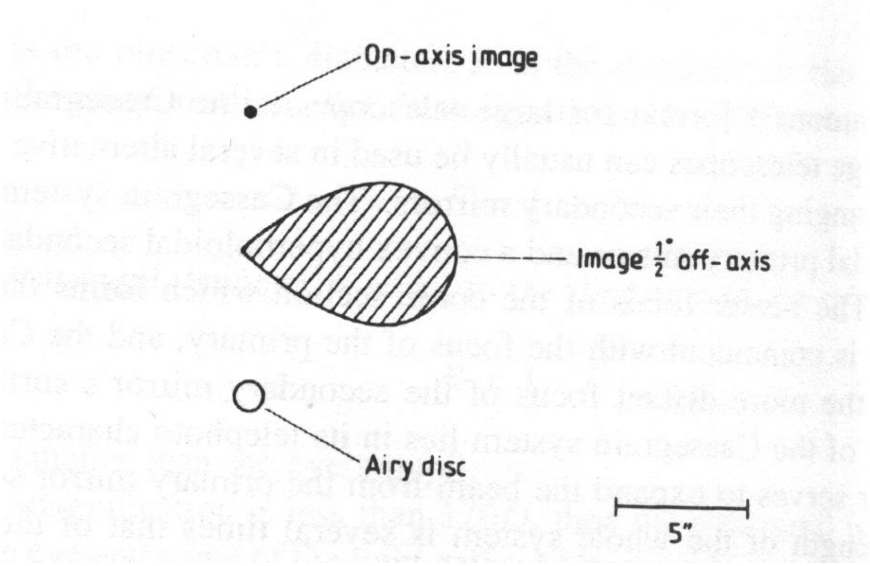
# Aberrations in reflecting telescopes

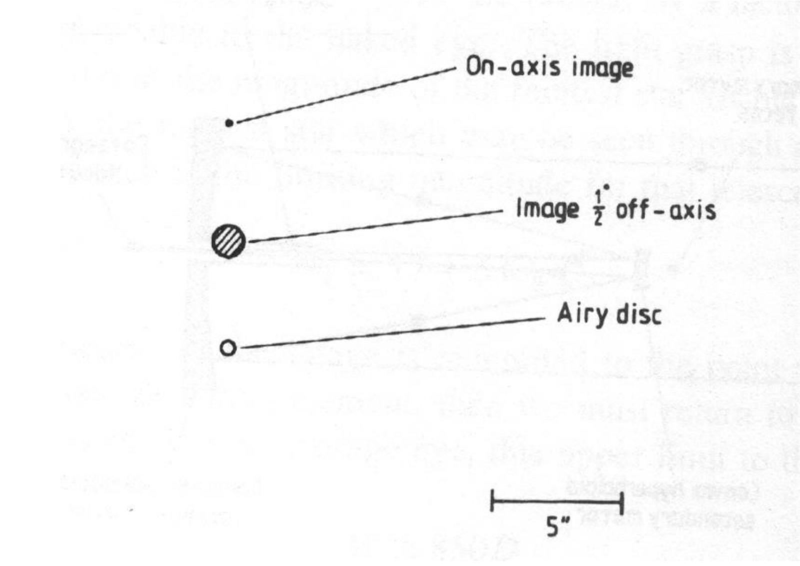


- **Cassegrain** system with paraboloidal primary provides perfect images on-axis, but off-axis coma restricts the useful field of view.
- **Ritchey-Chrétien** optical system
  [where the primary is deepened into a hyperboloid, and a stronger hyperboloid is used as the secondary] allows the coma and 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.
- **NIR, Optical, and UV 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

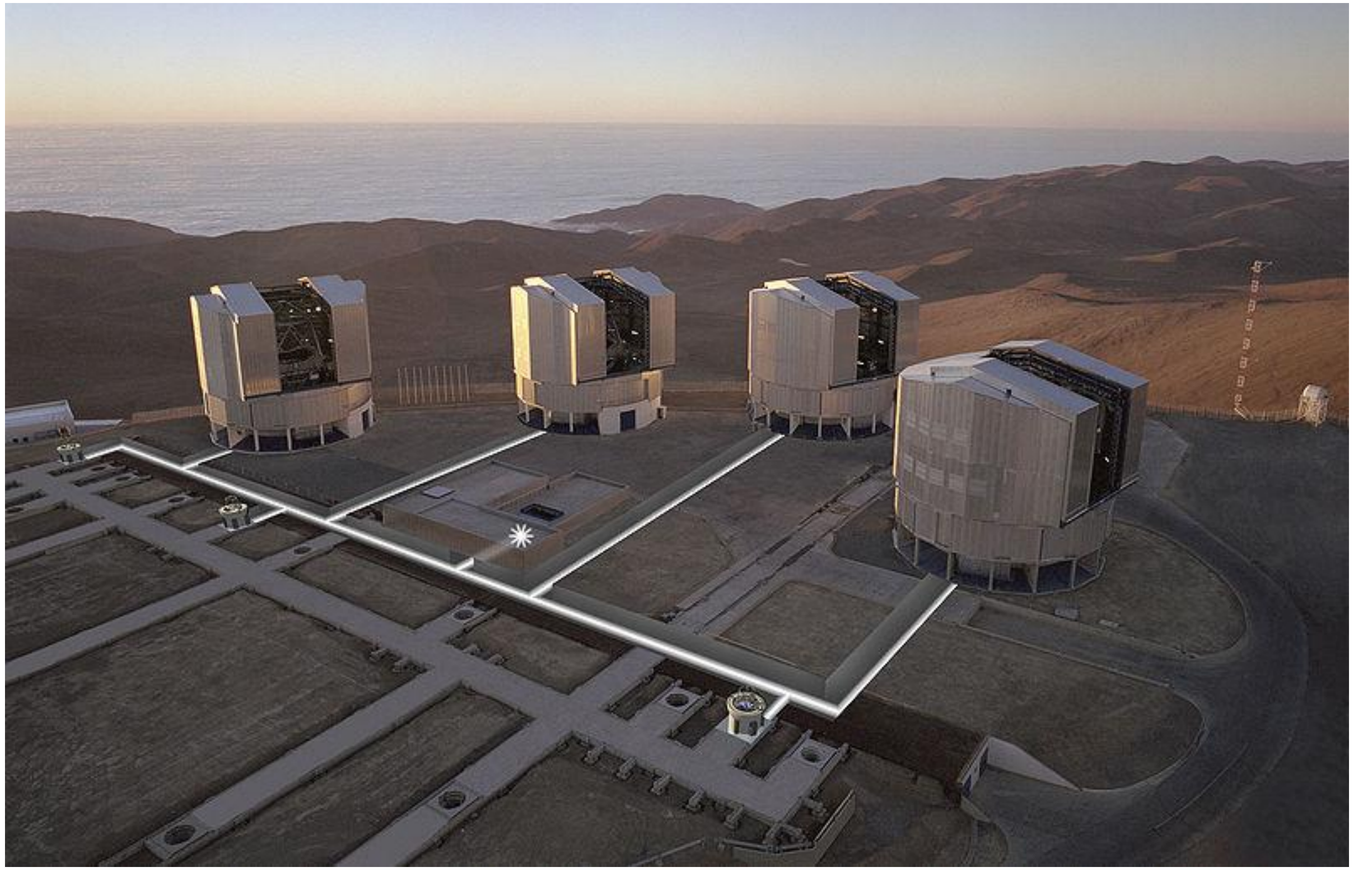


Hubble Space Telescope (2.4-m)

# 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 (2.56-m)

# Examples of large Ritchey–Chrétien telescopes

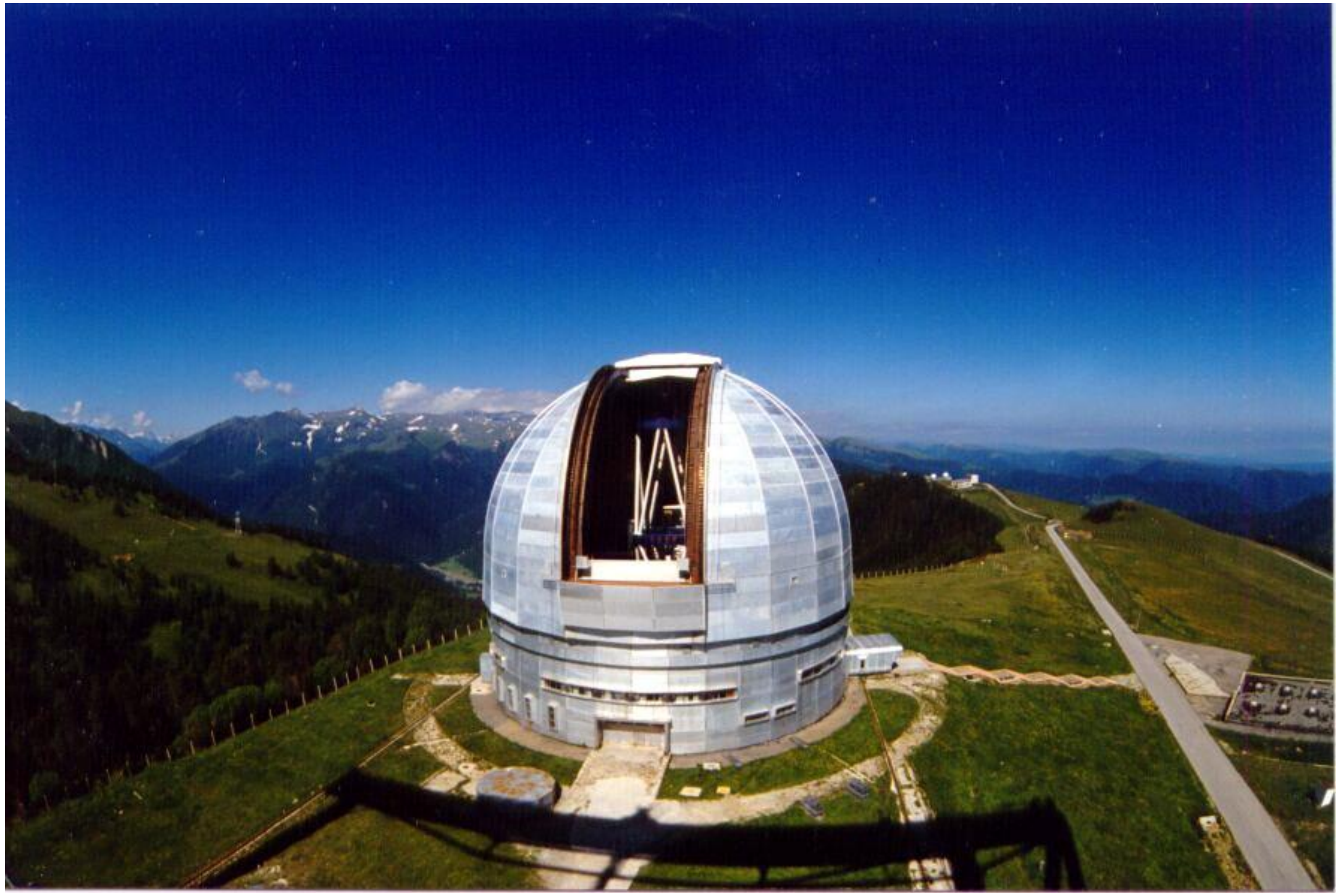


The two 10-m telescopes of the Keck Observatory

# Examples of Nasmyth telescopes



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



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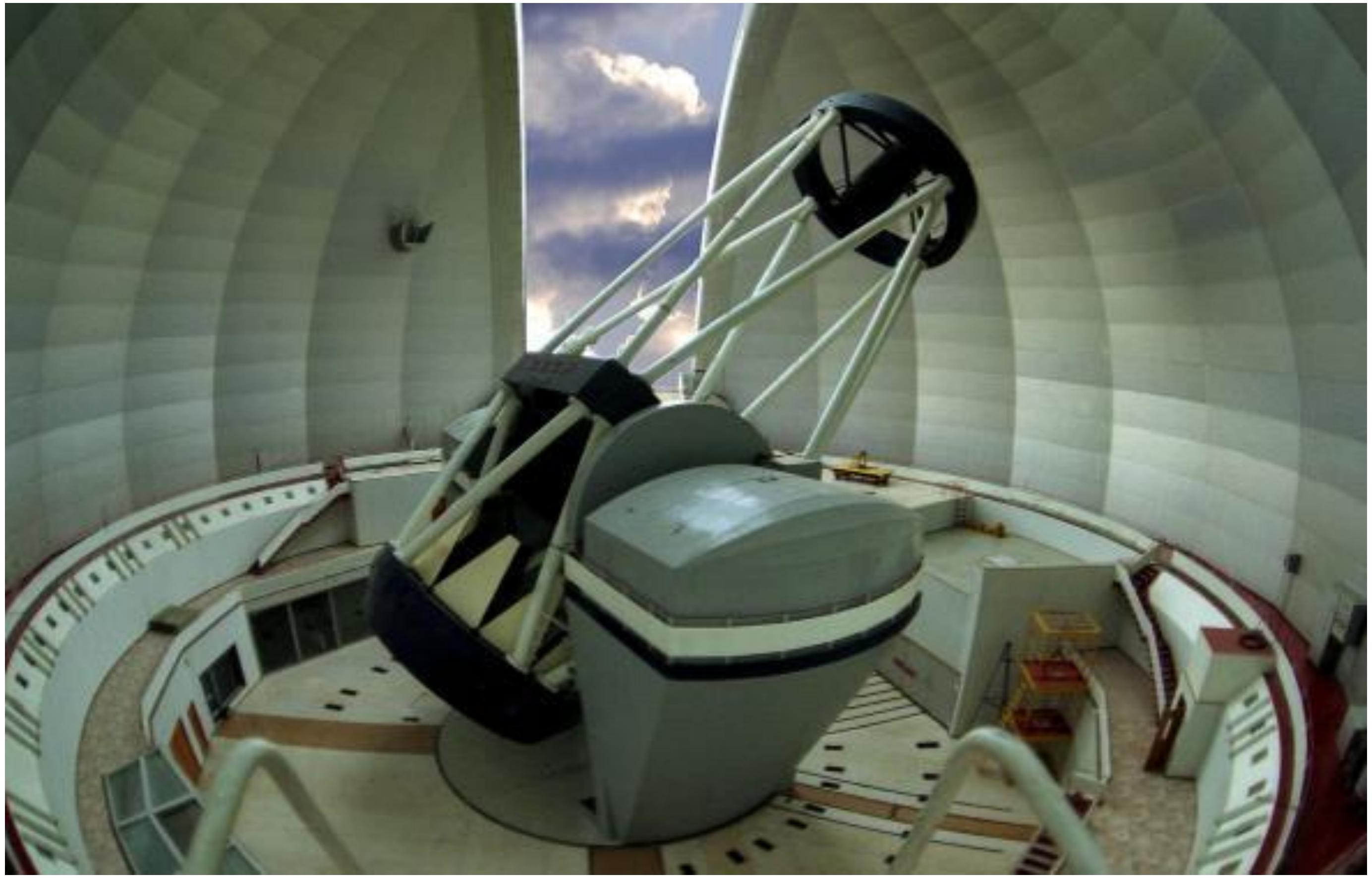


# Ultra-violet telescopes



- 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.

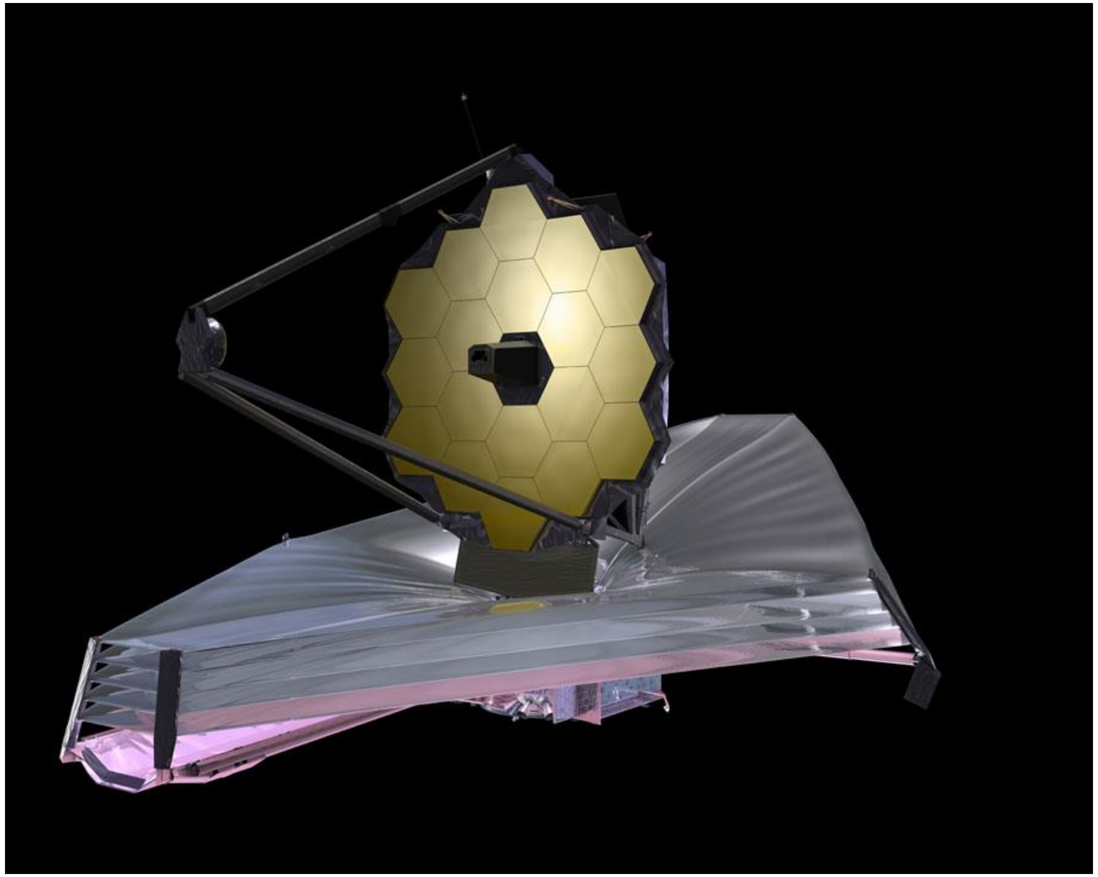
# Infra-red telescopes



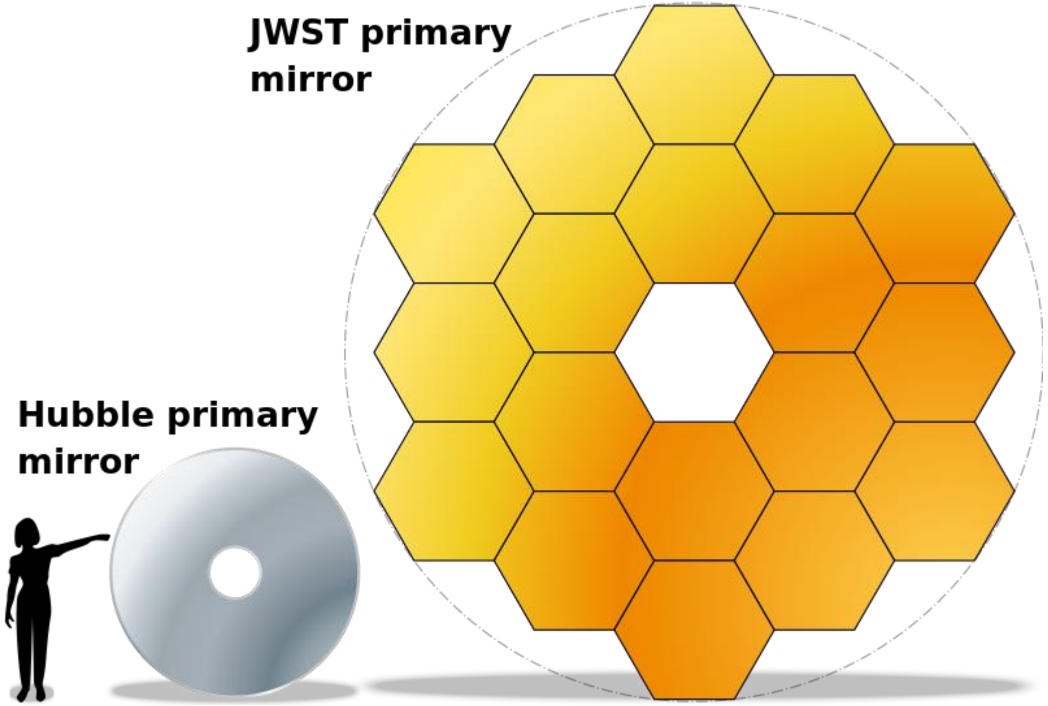
- Basic principles as for optical telescopes, but the differ in a number of ways. Basic driver for design is that the background comes predominantly from the telescope not from the sky:
  - Choose high, cold sites (e.g. South Pole, Hawaii)
  - Minimize the mechanical structure, telescope structure radiates 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.

# James Webb Space Telescope





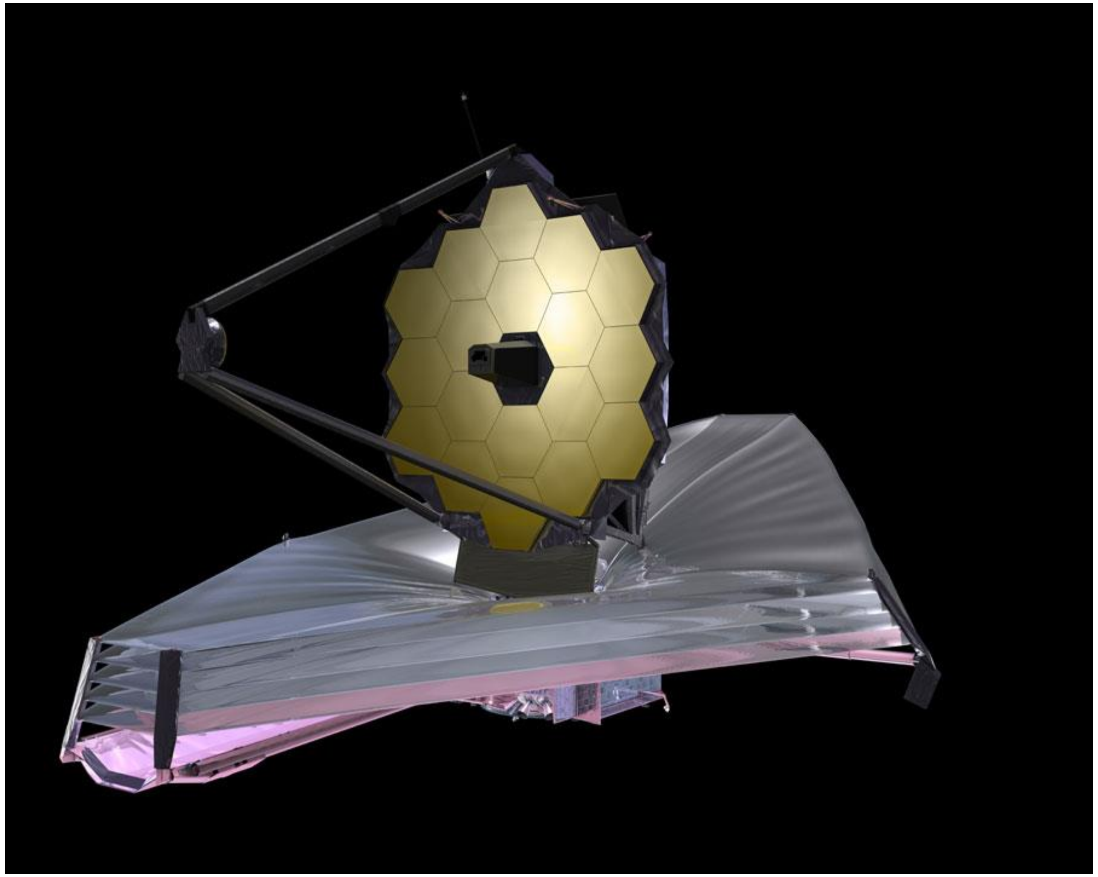
Primary mirror consists of 18 hexagonal mirror segments, which combined create a 6.5-m diameter mirror.




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?

# Telescope mountings

# Practical telescope configurations



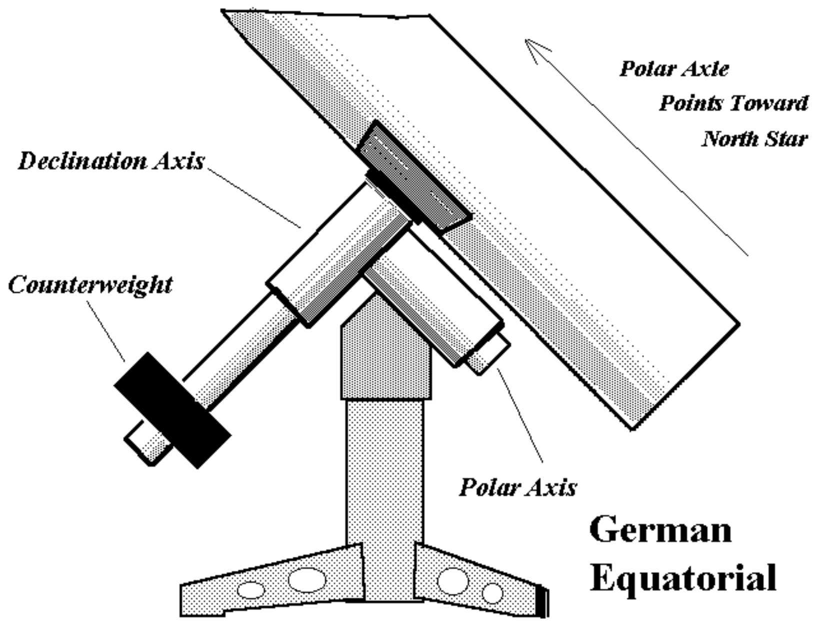
- Mechanical mounting

  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

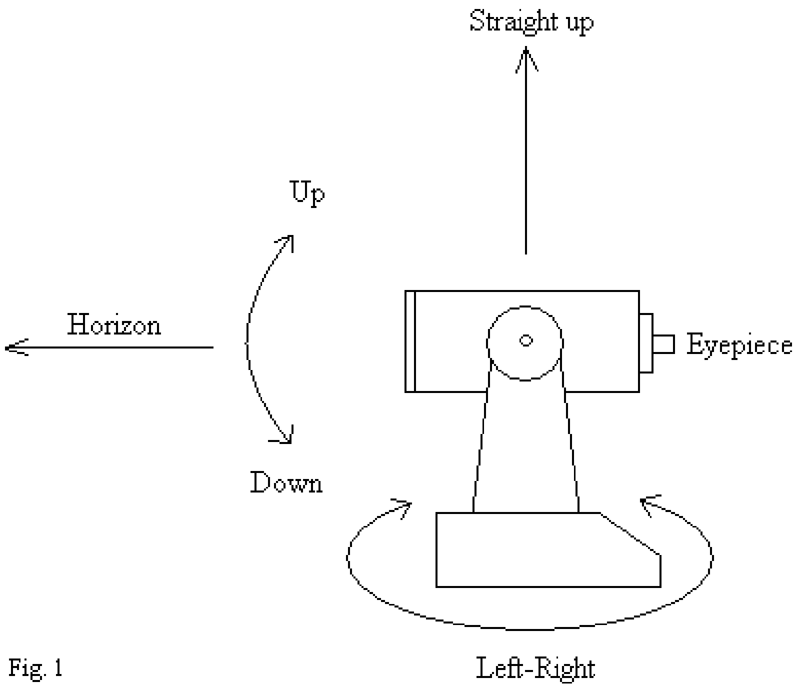



Fig. 1

# 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.