

How Telescopes Work.

1. *Why do we need telescopes?*

There are two main reasons for needing telescopes:

- Mirrors are much cheaper, per unit area, than detectors. So if you want to gather a lot of radiation, it makes sense to build a big mirror to gather all the radiation into a small spot, and put a detector there. Note that this is now always true. The MWA and LOFAR radio telescope designs use dipoles as detectors, and don't have any mirrors/dishes/reflectors. Some gamma-ray detectors similarly lack a mirror.
- Directionality: telescopes sort out the radiation coming from different directions, and deposit it into different parts of the detector.

2. *How do you focus the light?*

Radio telescopes use chicken-wire or metal sheeting. X-ray telescopes use mirrors, but the X-rays must bounce off the mirrors at an extreme angle, or they would pass straight through.

Optical telescopes can use either mirrors or lenses. Both have advantages:

Lenses:

- Don't need their surfaces to be as smooth. If part of the surface of a mirror is out of alignment by an angle θ , the rays that bounce off it will be deflected by an angle of 2θ (because angle of reflection equals angle of incidence). An imperfection in a lens shape has a much smaller effect. This is why most historic telescopes were refractors, and why most cheap amateur telescopes are refractors.
- If the lens surfaces are correctly treated, very little light is lost passing through a lens. Basically light is reflected whenever the refractive index jumps abruptly, as at an air-glass interface. By coating the surface with one or more thin films with refractive indices intermediate between air and glass, reflection can be greatly reduced. Most mirrors, on the other hand, lose up to 20% of the light that falls on them, particularly in the UV. Recent protected silver mirror coatings can, however, reduce this.

Mirrors:

- Can be supported from behind. Lenses, on the other hand, can only be supported around the edges. This is a big problem for large lenses, especially as most of the weight is in the middle.
- Reflect all wavelengths of light by the same amount. The refractive index of glass, in contrast, is a function of wavelength. This means that different colours of light are brought to a focus in different places: so called "chromatic aberration". It is, however, possible to get around this to some extent by making lenses out of combinations of glass with different optical properties, such that the aberrations cancel to some extent.

Essentially all modern research telescopes use mirrors for at least their primary and secondary focussing elements. But lenses, sometimes very big ones, are also used as field correctors, and in instruments.

3. ***Focal Stations.***

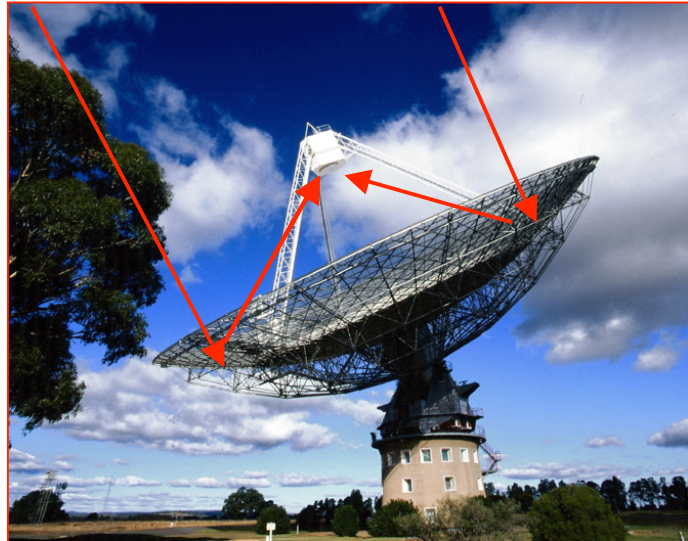
The purpose of a telescope is to bring the light to a focus somewhere. There are many possible locations for this purpose, each with its own advantages and disadvantages.

Prime Focus:

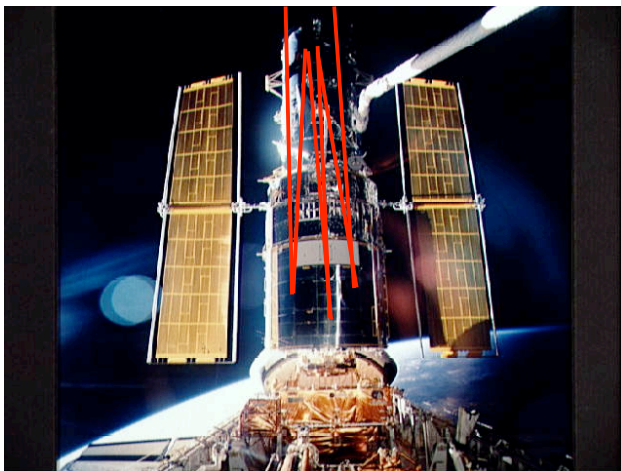
The light bounces off the primary mirror and is brought straight to a focus, high up on some support structure.

It is simple, and because only one reflection is involved, minimal light is lost. It can also give a very wide field of view.

The disadvantage is that you have to have the detector and instrument high up on a wobbly support structure, blocking some of the light as it comes down to the primary mirror. You cannot have large instruments here, they are hard to access for maintenance, and they wobble and shake a lot, making them unstable.



Cassegrain Focus:



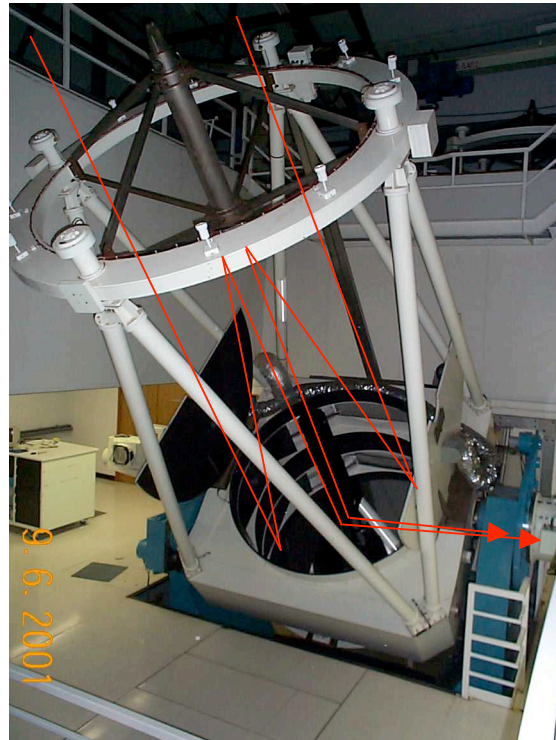
The radiation bounces off a secondary mirror (suspended high), and passes through a hole in the middle of the primary mirror. Detectors and instruments are placed down here behind the primary.

The instruments are much more accessible, and don't block the light and hence can be bigger. But there is an extra reflection to lose some light. And the instruments still have to move around with the telescope, though they are not in such a wobbly location.

The field of view is often smaller, unless you have a large secondary mirror (which blocks more light) and a large hole in the middle of the primary mirror.

Nasmyth Focus:

The light bounces off a 45-degree tertiary mirror just above the primary mirror. It then goes through a hole in the middle of the hinge. The instrument sits out here. The instrument is extremely accessible. It may have to rotate, but otherwise isn't being swung around across the sky, so it can be much more stable. But there is yet another reflection to lose light, and the field of view is more restricted in general.
Only works on alt-azimuth telescopes.

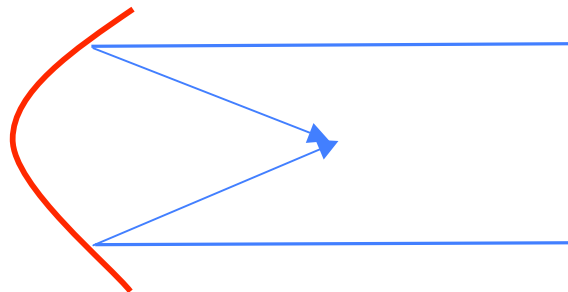


An even more stable focus is the **Coude Focus**. Here the light goes through the hinge, as for the Nasmyth focus, but then bounces off another two mirrors and goes through the hinge in the other axis. This means that the light can be sent to the same place regardless of where the telescope is pointing. You can thus build extremely large and stable instruments, such as echelle spectrographs here. The price you pay is 6 or more reflections, each of them costing you light.

Fibres: an alternative to all of these is to use fibre optics. Bring the light to focus wherever you like, and have one end of a fibre-optic cable waiting for it there. The light will pass down the cable and can end up wherever you like – usually some nice stable temperature-controlled room below the floor of the dome.

4. Field of View.

The correct shape for a primary mirror that brings all the light coming straight down the optical axis to a focus at a point is a parabola.



Unfortunately, light that comes in at an angle is not brought to a focus. So you get nice images of whatever you are pointing directly at, but objects even a tiny distance away look crap. This may not be a problem for radio telescopes with only a single receiver, or telescope dedicated to spectroscopy of single objects. But for most applications it is a big problem.

The normal response is to change the shape of the primary mirror slightly. This degrades the quality of the image from on-axis light, but improves it for light coming in at a small angle. By distorting the secondary mirror, or adding a corrector lens or two, you may be able to get OK images over quite a wide field.

The widest field is obtained by Schmidt telescopes. These actually have a spherical primary mirror. Because it is a sphere, it is easy to make, and reflects light coming in from all directions in the same way. But unless heavily corrected, it gives truly appalling images everywhere. And the focal plane is a sphere, so you need detectors which can handle this. A Schmidt telescope puts a huge corrector lens in front of the primary mirror, to give acceptable images over an immense field. The picture shows the UK Schmidt telescope at Siding Spring.



More common is the Richey-Chretien design, which combines particularly shaped primaries and secondaries to give a reasonably large field of view with reasonable images.

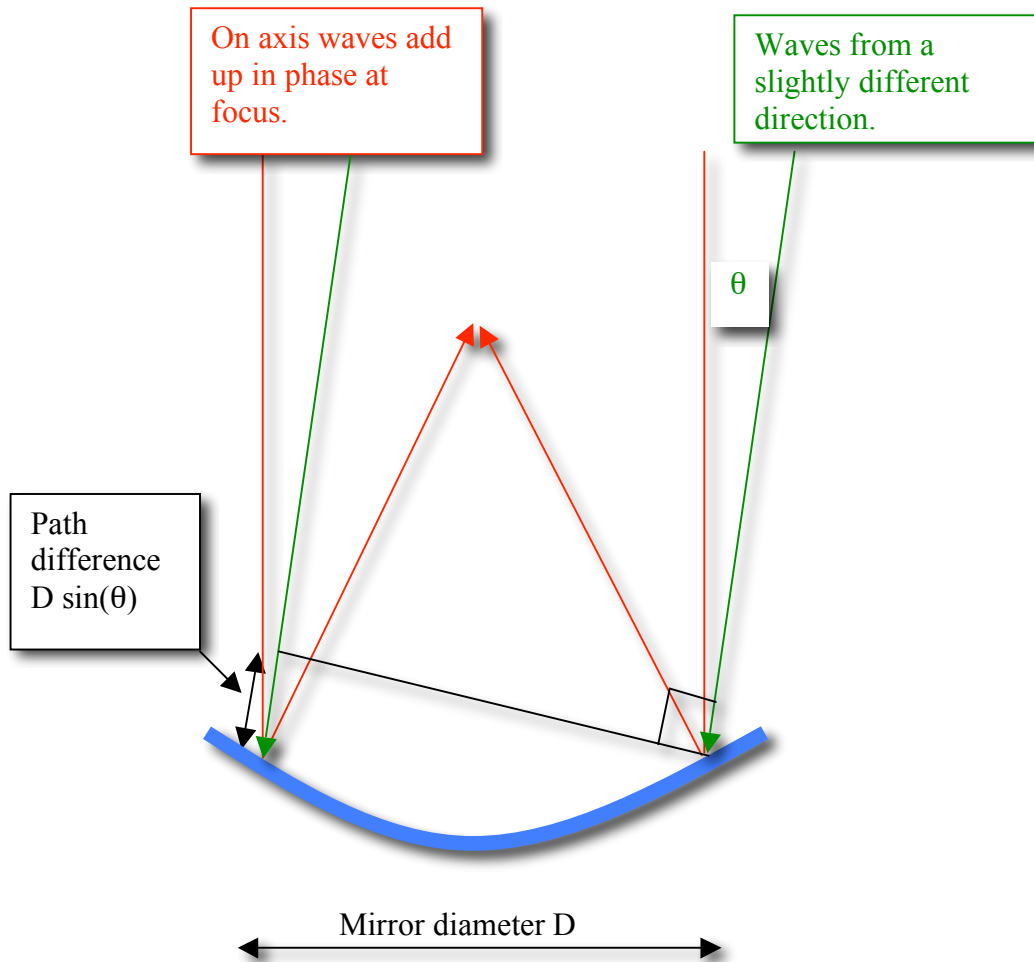
5. Diffraction Limit

So far, we've treated light as a particle: bouncing it off surfaces and tracing rays. But quantum mechanics tells us that light also behaves like a wave. This has one crucial consequence for telescopes: it imposes a fundamental limit on how accurately we can pin down where the light is coming from.

Consider how a telescope works from a wave perspective, using Huygens principle. A plane-wave of light arrives at the front of the telescope. From each point on this wave, according to Huygens principle, electromagnetic waves spread out in every direction. In most directions they destructively interfere. But at the focus, waves arriving everywhere should constructively interfere, and give a strong signal.

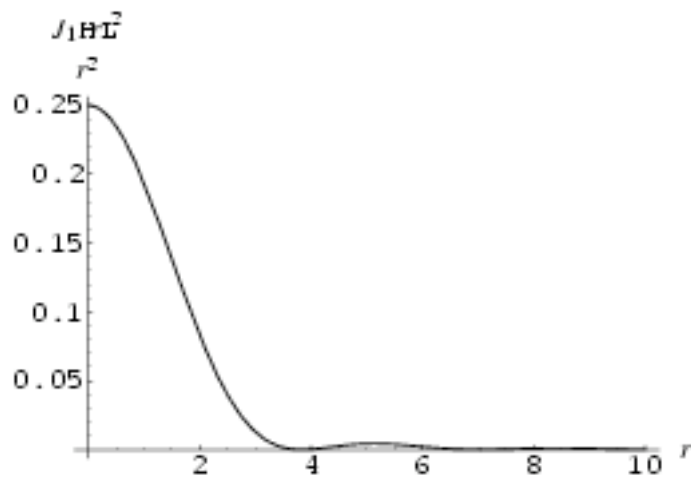
In an ideal telescope, light coming from one source would give a strong signal at one delta-function location in the focal plane. But consider a location slightly to the side of this in the focal plane. The light from one side of the telescope has to travel a slightly shorter distance to get here, while the light from the other side has to travel slightly further. This means that these waves no longer add up perfectly in phase. But you can move a small way and still get some constructive interference.

As the figure shows, if light from a given direction adds up perfectly in phase, light coming from an angle θ away will have an extreme phase difference (for light hitting opposite ends of the mirror) of $D \sin(\theta)$, where D is the diameter of the primary mirror.



So the waves will start cancelling when $D \sin(\theta) \sim \lambda/2$. Where λ is the wavelength of the light. If θ is smaller than this angle, you will still pick up some signal, even though the rays are not coming in on axis.

This is a simplified argument. To get the true response you need to integrate the waves coming from all part of the mirror. This is actually equivalent (for small angles) to doing the 2D Fourier Transform of the telescope aperture. If you do this, you find that the signal in the focal plane follows an Airy Function, which looks like this (radial plot):

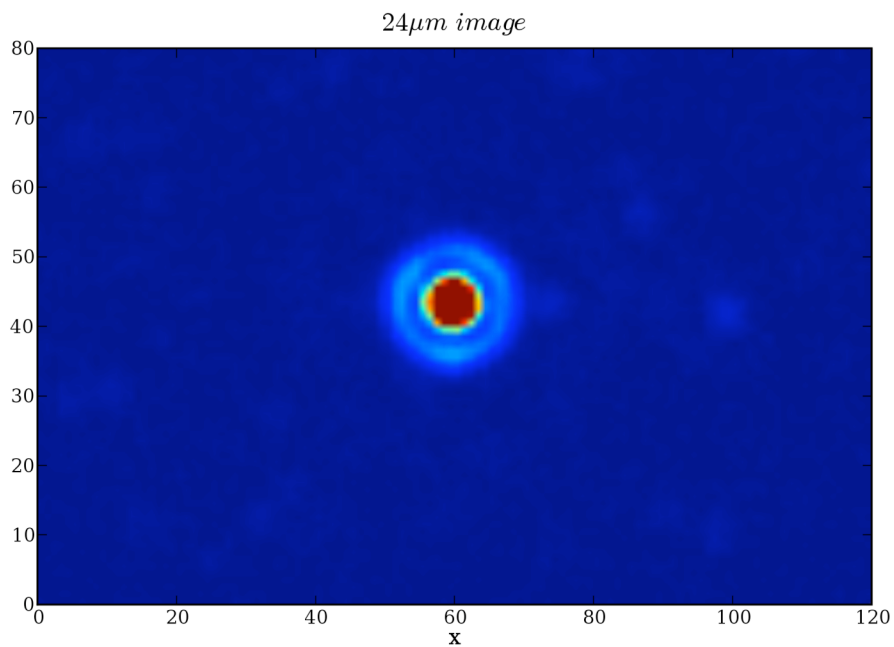


The intensity drops to a minimum at an angle:

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

It then rises again, producing a ring, then falls, rises again and so on, producing lower and lower rings further out.

Here's what it looks like in real data:



This is an image taken with the Spitzer Space Telescope at 24 microns. The target is actually just a dot. But you see it spread over several pixels, and a ring around it, due to this diffraction effect. In this case the second ring isn't really visible.

So what does this all mean? It imposes a fundamental limit on how sharp an image you can obtain with a telescope. Even if the optics were perfect, you cannot get an image that is sharper than the diffraction limit.

This is not normally a big issue for ground-based optical astronomy – you are normally limited by atmospheric seeing (of which more later) rather than diffraction. But for space telescopes and telescopes with good adaptive optics it imposes the limit. And at longer wavelengths, particularly in the radio, it is a really serious problem, because the long wavelengths mean that the diffraction limit is enormous.

What does it mean to have a diffraction limit? If two astronomical sources are closer together than this, they will appear as one blurred source. In principle it may still be possible to deblend them, by looking for marginal elongations of the image, but it's hard and requires very high quality data. It is also hard to work out the position of any object to much greater than the diffraction limit, though once again, with good quality data, it may be possible. It limits searches for planets, as their light tends to get drowned out in the outer parts of the Airy function of their (much brighter) star.

The pattern also applies the other way around – if you are looking at a given location on the sky, you will also receive signals (albeit weakened) from any sources that lie within the diffraction pattern. The Airy rings are called “sidebands” and can be a real curse. In one recent case, an astronomer thought that they had found a giant free-floating gas cloud, unassociated with any galaxies. But in fact they were picking up a nearby, well known galaxy in a side-band.

It also works for radio transmission: a signal from a radio disk doesn't only go in the direction you intended, but some fraction of the energy goes off into the side-bands. The US used this to great effect in the 1960's, by using satellites to detect the side-bands of the Kremlin's radio communication towers, and hence listen in to the Politbureau's communications.