Instruments

Basic Optics

Rays of Light

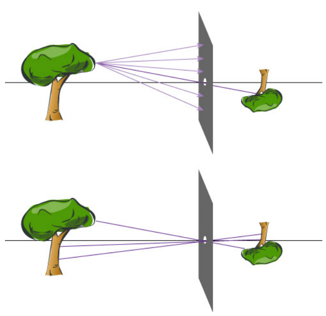


Fig. 1 A pinhole will project an inverted image on a plane.

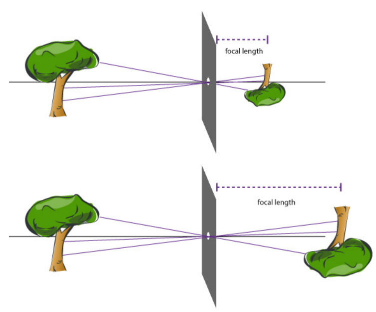


Fig. 2 The image will be in focus everywhere. It's size changes based on the position of the focal plane.

The pin-hole camera allows a small amount of light to pass through an opening. However, because the whole is small, very little light passes, which makes measurements difficult. If the hole's diameter is increased, then the image becomes blurred.

Converging Lens

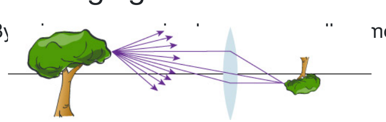


Fig. 3

By [illegible] more light to pass through the hole, which increases our 'photon count.' A consequence of using a lens however, is that now the focal length, F, is fixed.

Images

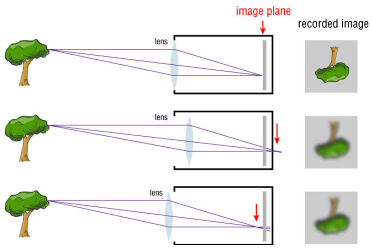


Fig. 4 Changing the position of the screen will result in a blurry image.

Light from stars

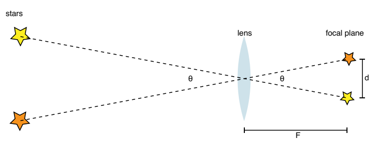


Fig. 5 Two stars separated by an angle θ in the sky, will create images separated by a distance d on the detection screen.

Waves of light

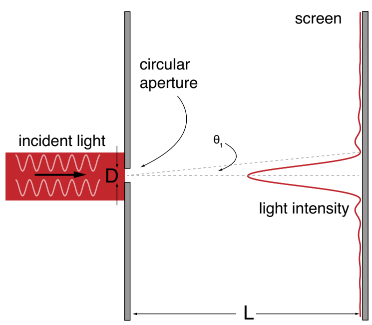


Fig. 6

Coherent, mono-chromatic light passing through a circular aperture will be diffracted.

Airy Disc

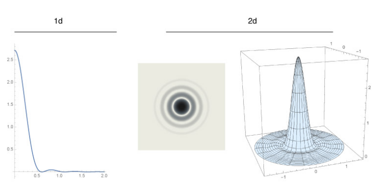


Fig. 7

There is a limit

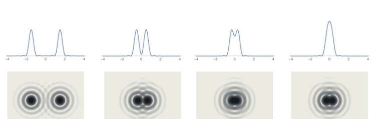


Fig. 8 Two point sources getting closer.

Unresolved: if the central maximum falls inside the location of the first minimum.

Unresolved point sources

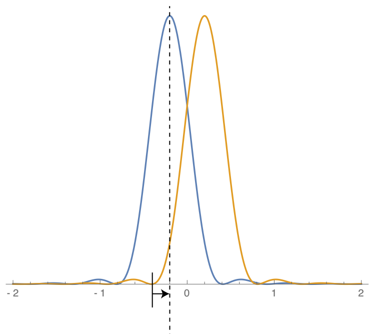


Fig. 9

Rayleigh Criterion

$$\theta_{\text{min}} = 1.22\frac{\lambda}{D}$$

Basic Imaging Systems

The eye

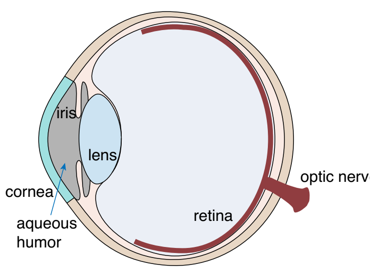


Fig. 10 The human eye

Nature has made many different eyeballs. Most operate on the principles of lenses we've just looked at.

focusing the eye

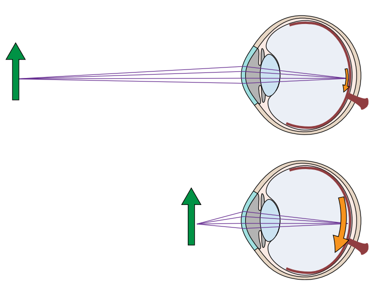


Fig. 11 Focusing the eye

Focusing on objects: We cannot adjust the position of the lens with respect to the retina. So, the muscles around the eye change the shape of the lens, which then changes its focal length.

A Basic Telescope

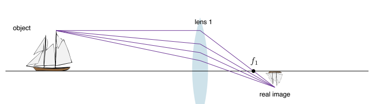


Fig. 12

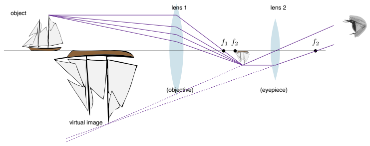


Fig. 13

Magnification:

$$M = \frac{f_1}{f_2} = \frac{f_{\text{objective}}}{f_{\text{eyepiece}}} \quad (1)$$

Aberrations

Lenses aren't perfect.

Chromatic Aberration

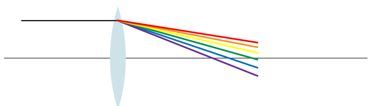


Fig. 14 Chromatic Aberrations

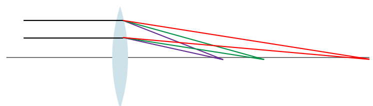


Fig. 15 Different Colors with have different focal points

Since different colors will refract at different angles, the focal point will be slightly different for different wavelengths. This leads to **Chromatic Aberration.**

Spherical Aberration

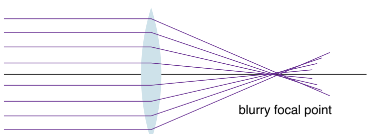


Fig. 16 Spherical Aberrations

Earlier, our thin lens approximation ignored the fact that the thickness of the lens changed as a function of distance away from the central axis.

This leads to rays having slightly different focal points depending on where they are incident on the lens. The further the rays are away from the central axis, the worse the **Spherical Aberration** effect is.

Fixing aberrations

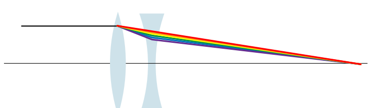


Fig. 17 Fixing Aberrations

Fortunately, by using a multi lens setup, we can correct these aberrations. For example, to correct the chromatic aberration caused by a converging lens we can insert a diverging lens after the converging lens to refocus the different colors back to the same point.

Mirrors

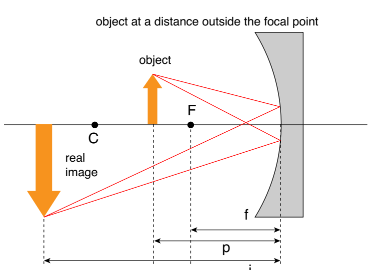


Fig. 18 A mirror ray diagram

Some Real Instruments

Galileo's Telescope

Fig. 19 Galileo's Telescope

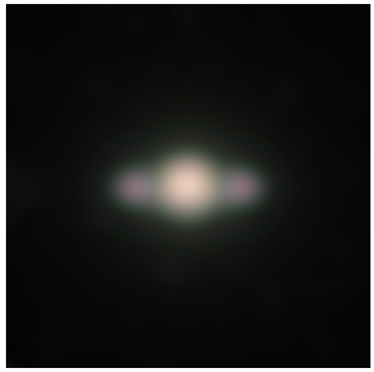


Fig. 20 Saturn as viewed through Galileo's telescope

https://www.astromatic.net/2009/05/23/see-saturn-as-galileo-did

Galileo's Telescope

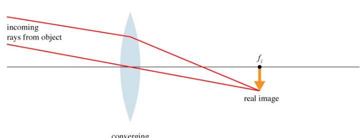


Fig. 21

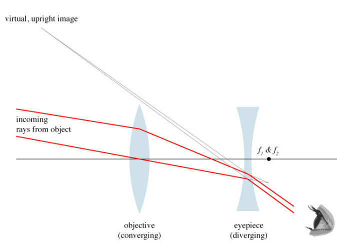


Fig. 22

Keplerian Optics

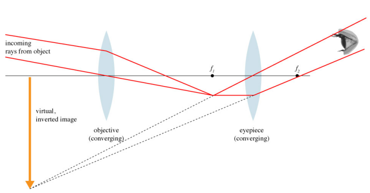


Fig. 23

Fig. 24 Yerkes Observatory 40 inch Refractor Telescope (It is the largest refracting telescope used for astronomical research.) Williams Bay, Wisconsin, US

https://commons.wikimedia.org/wiki/File:Yerkes_40_inch_Refractor_Telescope-2006.jpg

Fig. 25 The Great Paris Exhibition Telescope of 1900, with an objective lens of 1.25 m (49 in) in diameter, was the largest refracting telescope ever constructed. It was built as the centerpiece of the Paris Universal Exhibition of 1900. 200 ft long. Too big to use.

By Unknown - Le panorama (Paris, 1900)., Public Domain, https://commons.wikimedia.org/w/index.php?curid=20083299

A reflecting Telescope

Fig. 26 A reflecting Telescope

Newton's Telescope

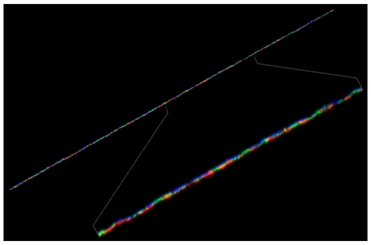
Fig. 27 A replica of the Newton - Wickins telescope, Newton's third reflecting telescope that was presented to the Royal Society in 1766 after being restored by Thomas Heath. It is described as the better of the instruments Newton built

By User:Solipsist (Andrew Dunn) - www.andrewdunnphoto.com, CC BY-SA 2.0, https://commons.wikimedia.org/w/index.php?curid=513483

Where should we put these telescopes?

Early telescopes could be placed near where people lived, since there were not a lot of lights to get in the way. Now, we usually put telescope as far away from people as possible.

Astronomical seeing



As light passes through the atmosphere, small variations in air density, usually caused by temperature fluctuations will disturb the incoming waves. There is turbulent mixing of air throughout much of the atmosphere (but not everywhere)

Fig. 28 Scintillation of a star, over time

http://spaceweathergallery.com/indiv_upload.php?upload_id=124490

Fig. 29 Moon Seeing Effect

Fig. 30 Mountain in the atmosphere

Detectors

We can classify most of the standard astronomical instruments as either imaging cameras or spectrometers. Either way, we need to collect photons. That used to be done with chemical film, but we use digital methods. They have a much greater **quantum efficiency**, which means that it requires fewer photons to trigger a detection by a pixel.

- Photographic Plate: 1%
- Human Eye: 10%
- CCD: 80-90%

Charge-coupled Device: CCD

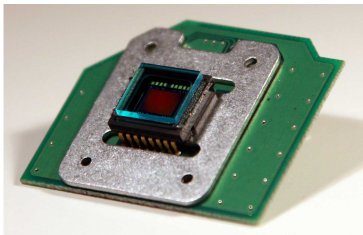


Fig. 31 A CCD device

Other Wavelengths

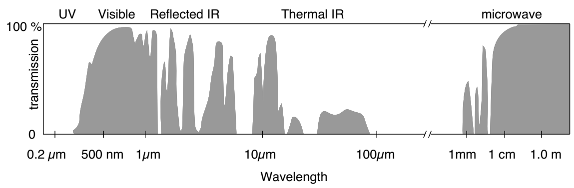


Fig. 32 The transparency of the atmosphere

Adapted from
https://earthobservatory.nasa.gov/Features/RemoteSensing/remote_04.php

Radio Telescopes

Fig. 33 Clouds linger at twilight over the Karl G. Jansky Very Large Array in its most compact configuration.

Credit: NRAO/AUI/NSF link

What about for EM radiation with frequencies and wavelengths not in the visible spectrum?

What if λ is really big?

$$\theta_{\text{min}} = 1.22\frac{\lambda}{D}$$

Example Problem #1:

When looking at 21 cm wavelengths, a 300 meter dish will have a diffraction limited resolution of what?

$$\theta = 1.22\frac{\lambda}{D} = 1.22 \times \frac{0.21 \text{ m}}{300 \text{ m}} = 0.000854 \text{ rad} = 2.94 \text{ min of arc}$$

Arecibo

Fig. 34

Credit: Author H. Schweiker/WIYN and NOAO/AURA/NSF link

Orbiting Astronomical Observatory

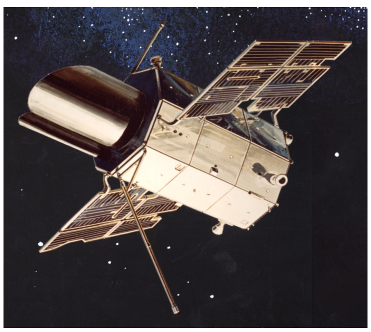


Fig. 35 The Orbiting Astronomical Observatory (OAO) satellites were a series of four American space observatories launched by NASA between 1966 and 1972, which provided the first high-quality observations of many objects in ultraviolet light.

Let's put a telescope above the atmosphere. There, instruments will be able to reach the diffraction limit mentioned above, rather than the seeing limit of ground based observatories.

Hubble

Fig. 36 The Hubble Space Telescope

Launched in 1990, the Hubble Space Telescope has taken many of the most recognizable space images.

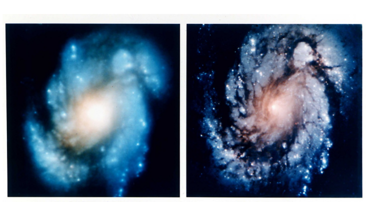


Fig. 37 Hubble before and after

It didn't work too well at first, and so a repair mission had to be sent. Astronauts fixed it.

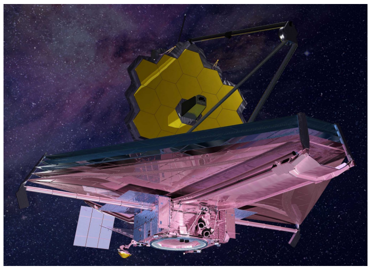


Fig. 38 The telescope that ate astronomy.

Fig. 39 Inspecting the mirrors on the James Webb Space Telescope

Credit: NASA/Chris Gunn - https://www.flickr.com/photos/nasawebbtelescope

Fig. 40 The primary mirror of NASA's James Webb Space Telescope, consisting of 18 hexagonal mirrors, looks like a giant puzzle piece standing in the massive clean room of NASA's Goddard Space Flight Center in Greenbelt, Maryland.

Image Credit: NASA/Chris Gunn - https://www.flickr.com/photos/nasawebbtelescope/30116152713/

Other improvements

1. Active Optics - mirrors that move.
2. Adaptive Optics - guide stars

Adaptive Optics

Fig. 41 An artificial star

Make a star using a laser.

The idea of adaptive optics has improved observing tremendously. If you create an artificial star using a laser, then you should know what is should look like. Simply adjust your optics in real-time to keep the laser-star looking good!

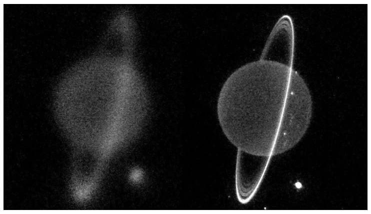


Fig. 42 Saturn without and with Adaptive Optics

Credit: Heidi B. Hammel and Imke De Pater/WMKO Keck