Observational Astrophysics
5. Introduction to Telescopes

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1 Introduction

Telescopes are used to collect the light from distant objects and direct it to a recording device. The images of the distant objects will many times be magnified. A telescope should be able to obtain high-quality data from the object but also be able to point towards it and follow its apparent movement in the sky (what is called tracking). For obtaining the high-quality data, there is a drive to design telescopes that maximize collecting area and throughput (in the wavelengths of interest).

Telescopes are usually made of several optical elements (e.g., mirrors, lenses, prisms, gratings, etc) held in place with proper alignment by a mechanical structure. A telescope made of lenses is called a refractor or dioptric telescope. One that relies on mirrors is called a reflector or catoptric telescope (lenses can be involved as correcting elements). In cases that combine mirrors and lenses as important light gathering parts, the telescope is called a catadioptric telescope. There is also the special case of "grazing incidence" telescopes, used for collecting photons of high energy (e.g. X-rays).

2 Read these texts

About some fundamental design definitions and common aberrations, it is enough to read pages 106-111 of Chapter 4 from the book "The design and construction of large optical telescopes" (Bely 2003)[1].

For the types of telescope foci see Sections 3.4.1 and 3.4.2 of Lawrence (2013)[2] and pages 16-20 of the book "Telescopes and Techniques" by Kitchin (2012)[3].

And for different designs see pages 84-89 of the book "Astrophysical Techniques" by Kitchin (2020)[4].

[1] See https://link.springer.com/book/10.1007%2Fb97612.

[2] https://link.springer.com/book/10.1007/978-3-642-39835-3

[3] https://link.springer.com/book/10.1007%2F978-1-4614-4891-4

[4] https://www.google.com.br/books/edition/Astrophysical_Techniques_Sixth_Edition/fU3BAQAAQBAJ?hl=en&gbpv=0

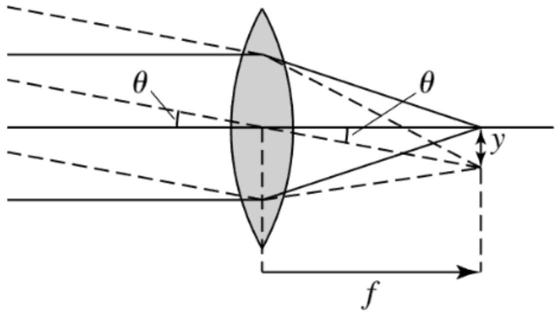

Figure 1: Plate scale. Credit: Fig 6.6 from Carroll & Ostlie (2017), see a preview in `https://www.google.com.br/books/edition/An_Introduction_to_Modern_Astrophysics/PYOwDwAAQBAJ?hl=en&gbpv=0`.

3 Summary of concepts

- Telescope mount is the mechanical structure of the telescope. It can be of several types related to how it moves to point to an astronomical object and track it through the sky: 1) The equatorial mount has an axis that is parallel to Earth's rotation axis; 2) The altitude-azimuth (alt-az) mount has the two axis of motion parallel and perpendicular to the surface of Earth; 3) Fixed altitude mounts rotate only in azimuth (have a fixed angle with the surface and rotate around an axis that is perpendicular to the Earth's surface); 4) Fixed mounts, which just look at one position (like the zenith, for example).
- In a telescope, the first optical element that collects light is called the primary. The second one is called the secondary, and so on.
- Aperture stop is the diameter of the element of the optical system that determines the amount of light that is collected. Usually this is the boundaries of the primary mirror or lens, but it can be a separated diaphragm that limits the aperture size.
- Field stop is the diameter of another element that obstructs the field and determines the (angular) size that can be imaged. This can be, for example, the edges of the detector.
- Entrance pupil is the image of the aperture stop formed by a part of the optical system preceding it. For most modern professional telescopes, there is no imaging element that precedes the aperture stop. In these cases, the entrance pupil is the aperture stop.
- Exit pupil is the image of the aperture stop as seen through the optical system.
- Elements positioned between the primary aperture and the detector can obstruct part of the rays that are entering from the edges of the aperture. These can be other lenses, mirrors, or baffles, either in the telescope itself or in the instrument. As a result, the power of the light can decrease gradually towards the edges of the field. This effect is known as vignetting.
- If a source of angular size θ projects an image of physical size y (see Fig. 1), we can relate these quantities by $y = f \tan\theta$. If the angle is small, this becomes $y = f\theta$ (the angle in radians). If we want to know how a small increase in θ reflects in y, $d\theta/dy = 1/f$, where

$d\theta/dy$ is known as the plate scale or image scale (sometimes p). This is usually expressed not in radians but in arcsec, so $p = 206265\text{''}/f$. And more often in arcsec/pixel, so one would still express the size f in terms of the pixel scale of the detector.

- Spherical aberration happens for spherical mirrors or lenses that do not bring parallel rays (like the ones from a distance source) to the same focus (see Fig. 2 and the top row of the spot diagram of Fig. 3).
- Coma is a property of telescopes using parabolic mirrors and for sources imaged off-axis (i.e., where the rays do not arrive parallel to the optical axis). In this case, different parts of the optical element focus the rays in different regions, with the effect being larger the farther away from the axis (see Fig. 4 and center row of the spot diagram of Fig. 3).
- Astigmatism happens when the two perpendicular axis of the optical system create images at different foci (see Fig. 5 and bottom row of the spot diagram of Fig. 3)
- Field distortion appears because of differential transverse magnification for different distances of the image away from the optical axis (see Fig. 6). The plate scale is not constant but varies with direction, usually in a symmetric way. This can be corrected during data processing.
- Field curvature happens when different parts of the image are brought to focus not on a plane but on a curved surface. The problem is not a serious problem for imaging elements that are spherical. One of the alternatives to deal with this problem is the use of curved detectors (see e.g. Swain et al. 2004; Gregory et al. 2015)[5].
- Chromatic aberration is a problem suffered by lenses, as the focal length varies for different wavelengths. The effect can be reduced with the combined use of two lenses of different sizes and glass types.
- Focal plane tilt is one other type of aberration. This means that the focal plane is not perpendicular to the optical axis. It can happen by construction or some flaw in construction.
- The first telescopes were refractors. In the mid-seventeenth century it was suggested that mirrors could be used to avoid chromatic aberration and that with a paraboloidal shape of the primary, spherical aberration could be eliminated.
- A Gregorian telescope (Fig. 7) uses a parabolic mirror as the primary and an ellipsoidal mirror as the secondary, but placed after the focus of the primary. This design was first proposed by the Scottish astronomer and mathematician James Gregory[6] (Simpson 1992)[7] in his book *Optica Promota* (Gregory 1663)[8] but successfully built only a few years later[9].
- A Newtonian telescope (Fig. 8) has a parabolic primary and a flat mirror as the secondary. The secondary is set at 45 degrees to the axis of the telescope so that the focus is positioned at the the side of the telescope. This telescope was first built by Isaac Newton[10] in 1668.

[5] `https://ui.adsabs.harvard.edu/abs/2004SPIE.5301..109S/abstract` and `https://ui.adsabs.harvard.edu/abs/2015ApOpt..54.3072G/abstract`

[6] See `https://mathshistory.st-andrews.ac.uk/Biographies/Gregory/` for a biography.

[7] `https://ui.adsabs.harvard.edu/abs/1992JHA....23...77S/abstract`

[8] See here for a translation of the book: `http://www.17centurymaths.com/contents/contentsGregory.htm`.

[9] By Robert Hooke, English scientist, who was also the first person to view micro-organisms through a microscope, see `https://mathshistory.st-andrews.ac.uk/Biographies/Hooke/`.

[10] We mentioned Newton before, so here only the link to his biography: `https://mathshistory.st-andrews.ac.uk/Biographies/Newton/`.

- A Cassegrain telescope (Fig. 9) has a design similar to the Gregorian one. In the Cassegrain version, it has the same parabolic primary but the ellipsoidal concave secondary is replaced by a convex hyperboloidal mirror. The secondary is now also placed before the focus of the primary. The design appeared in 1672 proposed by a French called Cassegrain[11].
- A Herschelian telescope (Fig. 10) uses one single mirror that is tilted so that the focus, where the observer is positioned, can be outside the light path. William Herschel[12] developed such a telescope, without a secondary mirror, in order to eliminate light losses. The original Herschel design was affected by spherical aberration, coma and astigmatism. Modern versions use asymmetrical mirrors to minimize such issues.
- A Ritchey–Chrétien telescope (like the VLT) is a variant of the Cassegrain design where the parabolic primary is substituted by a hyperbolic mirror. This design completely eliminates the coma. The design was developed in the early 1910s by American astronomer George Willis Ritchey[13] and French astronomer Henri Chrétien[14].
- Field rotation: if the telescope has a alt-az mount, it can not accompany the rotation of the sky, keeping a fixed orientation. In that sense, if the telescope is tracking a source for a certain amount of time, the field being observed will rotate. Field rotation also happens for a coudé configuration. When the field of view is not large, it is possible to introduce an optical element called "derotator" to compensate for field rotation. If the field of view is large (than about 1 arcmin), the size of the derotator becomes to big to be practical.

4 Infrared telescopes

In comparison to observations in the optical, there are a few additional challenges when operating in the infrared. The main problem is the need to beat up the thermal background (both from sky and from the surrounding objects; including the telescope and instrument themselves). We will come back to the topic of infrared observations in more details later.

[11] Whose identity was uncertain until 1997, when some new findings led to the conclusion that his name was Laurent Cassegrain, see Baranne & Launay (1997) in `https://ui.adsabs.harvard.edu/abs/1997JOpt...28..158B/abstract`. He was a priest from the town of Chartres, France. The design was not published under Cassegrain name, but mentioned by Claude Estienne in the French Journal des Sçavans (in an edition that I could not find) after he read about Newton's telescope (Newton 1672), see `https://gallica.bnf.fr/ark:/12148/bpt6k56524t/f17.item`, page 58, for the original text in French about Newton's telescope. Estienne considered Cassegrain's design superior. Some controversy ensued when Newton and Huygens accused Cassegrain of badly copying the design of Gregory (Huygens 1672), see page 98 in the previous link, and see also `https://link.springer.com/referenceworkentry/10.1007/978-0-387-30400-7_242`. In any case, nowadays the Cassegrain design is widely used and actually any kind of telescope where the observations are made behind the mirror is said to have a Cassegrain focus.

[12] William Herschel was a German astronomer. He discovered the planet Uranus. Between 1785 and 1789 he constructed the 40-foot telescope, with about 1.2m in diameter and 40 foot (12 meters) long. For a biography, see `https://mathshistory.st-andrews.ac.uk/Biographies/Herschel_William/`.

[13] See `https://link.springer.com/referenceworkentry/10.1007/978-0-387-30400-7_1172`.

[14] See page 148 of `https://archive.org/details/isbn_9780415060424/page/148/mode/2up` and an obituary in `https://ieeexplore.ieee.org/document/7267409` (Journal of the SMPTE 1956).

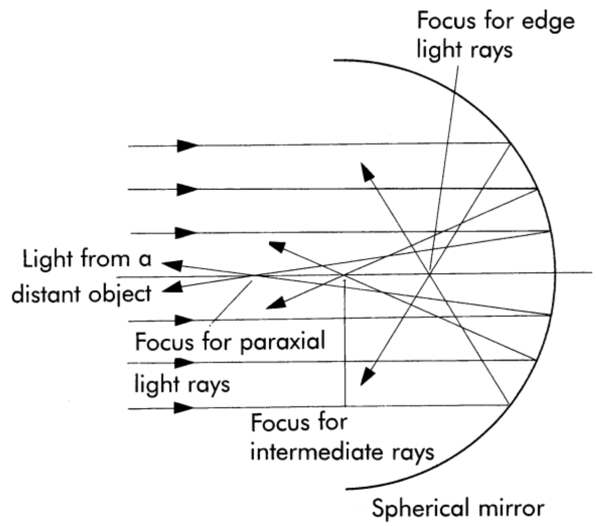

Figure 2: Spherical aberration in a mirror. Credit: Fig. 1.4 from Kitchin (2012).

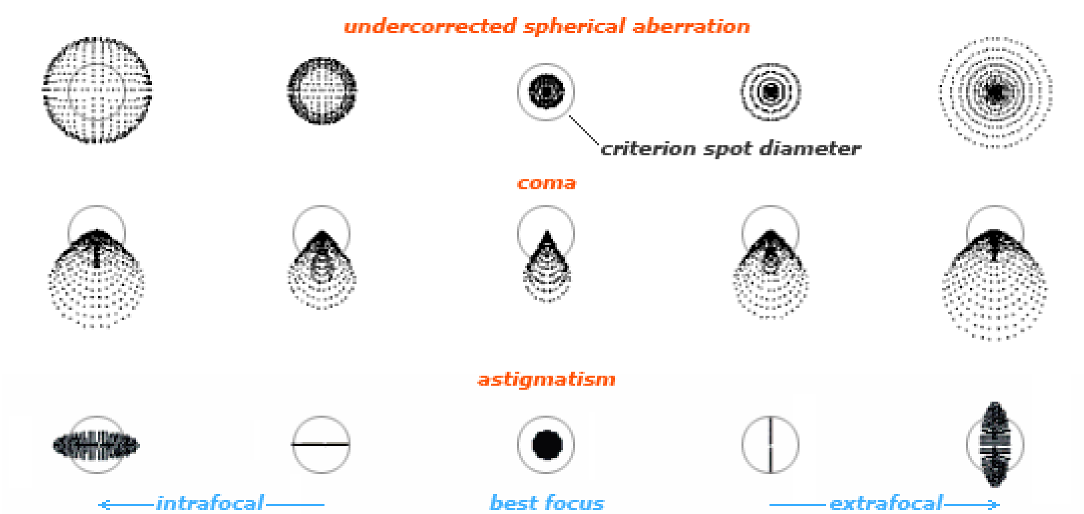

Figure 3: Spot diagram showing spherical aberration, coma, and astigmatism, at various positions before and after the best focus. Credit: 2014 Bruce MacEvoy in `https://www.handprint.com/ASTRO/ae4.html`, under Creative Commons 3.0 (may be freely reproduced without changes).

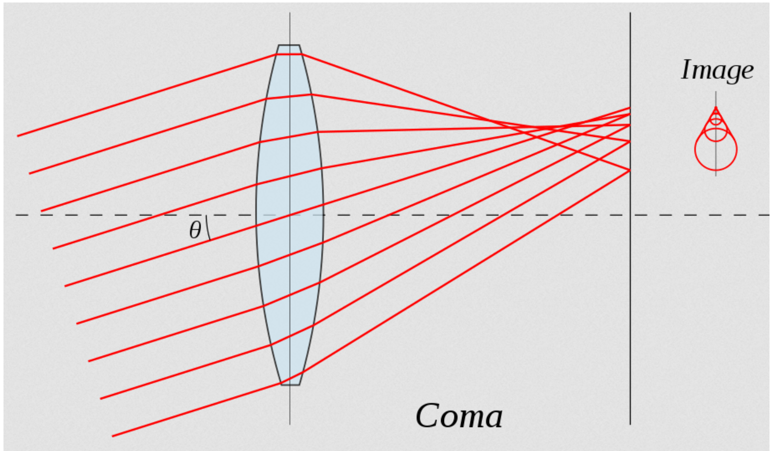

Figure 4: Coma in a lens. Credit: Wikipedia in `https://commons.wikimedia.org/wiki/File:Lens-coma.svg`.

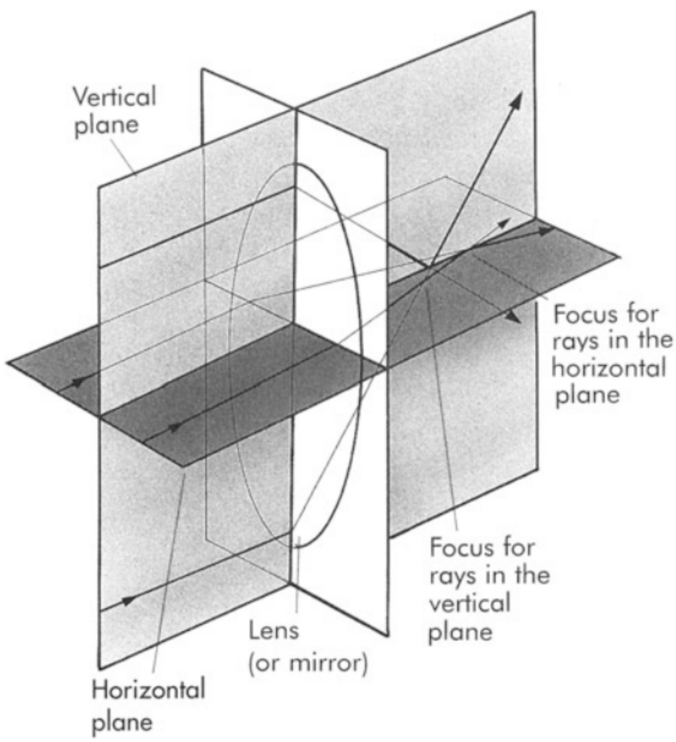

Figure 5: Astigmatism in a lens. Credit: Fig. 2.12 from Kitchin (2012).

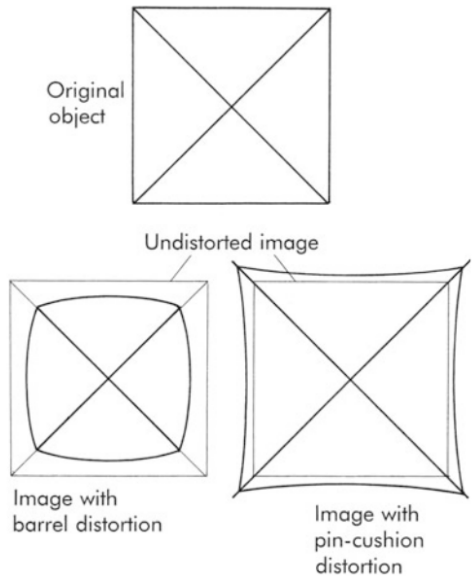

Figure 6: Field distortion. Credit: Fig. 2.14 from Kitchin (2012).

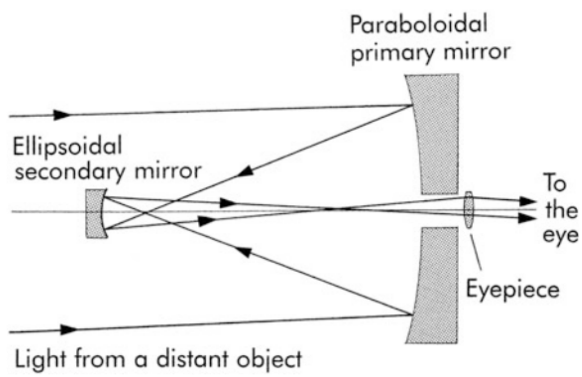

Figure 7: Gregorian telescope. Credit: Fig. 1.9 of Kitchin (2012).

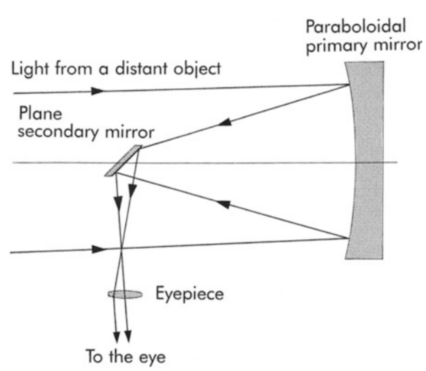

Figure 8: Newtonian telescope. Credit: Fig. 1.10 of Kitchin (2012).

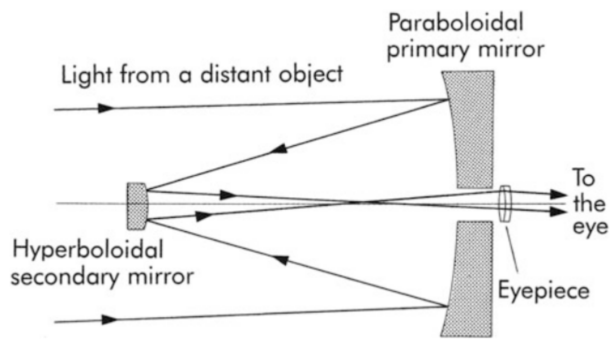

Figure 9: Cassegrain telescope. Credit: Fig. 1.11 of Kitchin (2012).

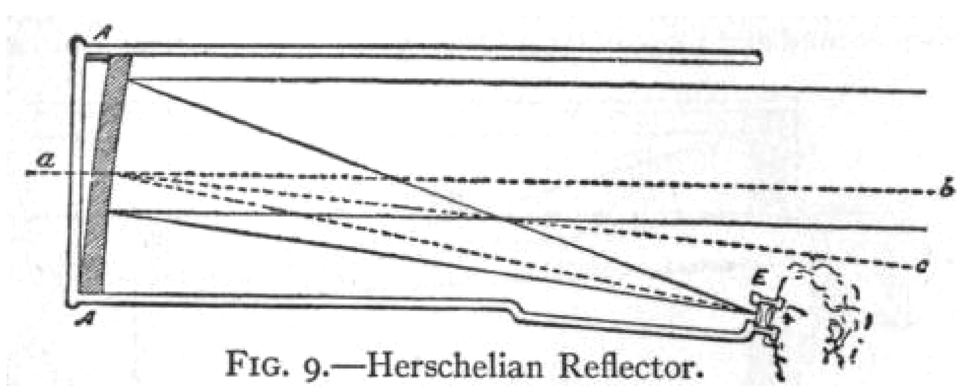

Figure 10: Herschelian telescope. Credit: Wikimedia commons https://commons.wikimedia.org/wiki/File:EB1911_Telescope_Fig._9.%E2%80%94Herschelian_Reflector.png.

5 Radio telescopes

Refractive lenses made of some types of plastics can be used at sub mm wavelengths. For radio waves, only reflection can be used. Parabolic metal dishes are usually used to collect and concentrate light. Imperfections in the mirror surface have to be small in comparison to the wavelength being observed. So it is much easier to make large radio dishes than mirrors for optical observations. For long wavelengths of the order of metres, one does not even need a full dish and a wire mesh is good enough. The radio receivers are usually placed either at the primary focus or at a Cassegrain focus.

If you are interested, you can find a short text about radio telescopes in Section 5.2.1 in the book "Observational Astrophysics" by Léna et al. (2012)[15].

6 High-energy telescopes

All X-ray observations have to be carried out from rockets or from space. At high energy, reflection is not so easy to obtain. For soft X-rays, it is possible with small angles of incidence. X-ray telescopes (Fig. 11) are made of nested tubes, where the photons that graze the side walls are reflected forwards towards the focus; they are called grazing incidence telescopes. For hard X-rays, the problems are worse and there is no attempt to focus. The challenges for gamma ray telescopes are even bigger. Direct detection of gamma rays is only possible from space, but indirect detection is possible from the ground by means of the Cherenkov air showers caused by gamma ray interaction with the atmosphere.

If you are interested in more details, you can find additional information in Sections 5.2.4 (X-ray telescopes) and 5.2.5 (Gamma ray telescopes) from the book by Léna et al. (2012), and Section 9.3.5 on air Cherenkov telescopes in the book "The principles of astronomical telescope design" by Cheng (2009)[16].

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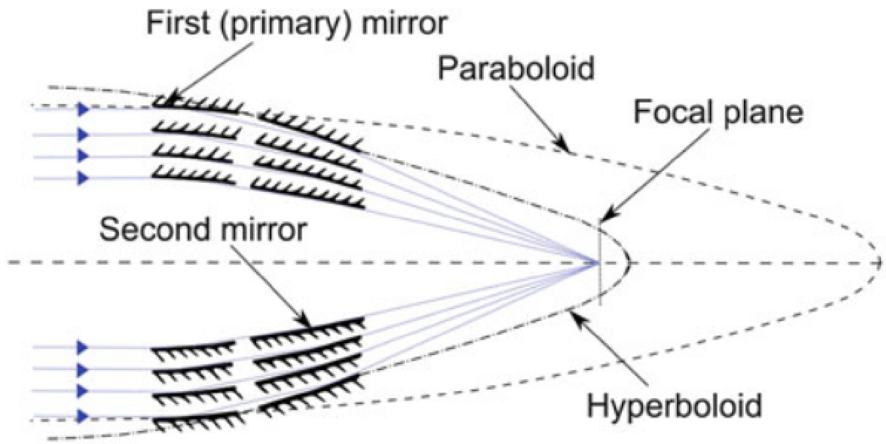

Figure 11: X-ray telescope layout. Credit: Fig. 3.10 from Lawrence (2013).

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