Observational Astrophysics
6. Active and Adaptive Optics

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1 Introduction

We talked a bit about geometrical optics and saw some drawings of aberrations, which make the focus of a telescope become not well defined. Well, even if we consider a perfect telescope, the image of a point source will not be a real point. This is because of diffraction, which happens because of the wave nature of light. There is a limit to the best size of the image of a point source, which is the diffraction limit. And since telescopes are usually not perfect, even achieving the diffraction limit can be challenging. Other effects, like atmospheric turbulence, can also degrade the quality of the image. Here, I'd like to summarize some of the technological developments that help astronomers to actually obtain diffraction limited images (in certain cases).

2 Read these texts

About diffraction effects, please read Sections 4.1.6 and 4.1.7 of the book "The design and construction of large optical telescopes" (Bely 2003)[1]. It is also interesting to read Section 4.2, for some words comparing telescope optical configurations with 1, 2, or 3 to 4 mirrors.

About active and adaptive optics, please read Sections 8.1 (The principles), 8.6 (Typical active optics systems), and 8.7 (Correction of seeing), of the same book, "The design and construction of large optical telescopes" (Bely 2003). But, for those really keen to see things in more detail, reading the whole Chapter 8 would be interesting. For a few different concepts of Adaptive Optics, read Section 6.3.5 of Léna et al. (2012)[2].

3 Summary of concepts

- The point spread function (PSF) describes the two-dimensional distribution of light in the focal plane of a telescope, when a point source is observed. The shape of the PSF can be quite complex, being affected by the shape of the aperture, by obstructions, irregularities of

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

[2] https://link.springer.com/book/10.1007%2F978-3-642-21815-6

the surfaces, dust, etc. Knowing how to evaluate the PSF is very important if you want to make the most out of your imaging system.

- For a perfect optical system[3] the PSF is given by the Airy[4] function or Airy pattern. That is a bright disk surrounded by alternating dark and bright rings.

- For photometric measurements, we will be interested in measuring the "encircled energy" within a given radius r from the center of the PSF. The encircled energy gives the fraction of the flux contained within that radius.

- Angular resolution is a quantity that expresses the ability of a system in distinguishing details in the image that it produces. If you think of two close-by point sources, it is clear that your ability to resolve the sources in the image will be connected to the size of the PSF. The usual criterion (the Rayleigh[5] criterion) says that we resolve the image when the peak of one PSF falls upon the first minimum of the other PSF. In that case, the angular resolution, in radians, is given by $\Delta\theta = 1.22\frac{\lambda}{D}$ (where D is the diameter of the aperture and λ is the wavelength).

- A system that achieves the resolution given by the Rayleigh criterion is said to be diffraction-limited. In practice, observations from the ground are usually seeing-limited.

- The Strehl[6] ratio is a measurement of the quality of the image formed by the optical system. It is the ratio between the peak intensity of the real point source image and the theoretical peak intensity in the perfect diffraction-limited case. Traditionally, one considers that a Strehl ratio greater than or equal to 0.8 means that diffraction limit was achieved.

- Active optics usually refers to a system that controls the shape of the primary mirror of a telescope, to compensate for errors induced by gravitational flexure, thermal effects, or oscillations induced by the wind. The shape of the mirror is controlled by a system of actuators that apply force to the rear side of the mirror. This system is also used to maintain the shape of a mirror made of smaller segments. This type of system was first implemented at ESO's 3.6m telescope in La Silla, named the "New Technology Telescope" (NTT) because of this.

- Adaptive optics usually refers to a system that corrects higher-frequency distortions of the image because of atmospheric turbulence. The corrections are computed by a system that monitors a nearby bright star in the field of view of the telescope. Such systems help telescopes to achieve diffraction-limited performance in near-infrared wavelengths. The adaptive optics systems needs a dedicated deformable mirror.

- Not always a suitable bright star is available for the adaptive optics. Because of this, some facilities are now equipped with a powerful laser, tuned to the Na D resonance line ($\lambda \sim 589.3$

[3]In geometrical optics terms, this would be a system where all rays of light that come from a given point in the object get together at the same point in the image. The object space is then perfectly reproduced in the image space.

[4]Named after Sir George Biddell Airy, an English mathematician and astronomer. The theory is deeloped in Airy (1835), see `https://archive.org/details/transactionsofca05camb/page/n305/mode/2up`. For a biography of Airy, see `https://mathshistory.st-andrews.ac.uk/Biographies/Airy/`.

[5]John William Strutt, the same Lord Rayleigh we discussed before.

[6]Named after the German physicist and mathematician Karl Wilhelm Andreas Strehl. See Strehl (1895, 1902) in `https://www.forgottenbooks.com/en/readbook/ZeitschriftfurInstrumentenkunde1895_11167983#369` (where only a few pages can be seen for free) and `https://www.slideshare.net/mikhailkonnik/strehl-1902` for the original works, in German. I could not find good biographical information in English.

nm), able to create a "laser-guide star", i.e., an artificial point source at about 90-100 km of altitude that can be used to monitor atmospheric turbulence.

- For a few different concepts of Adaptive Optics (MCAO, GLAO, MOAO, EXAO), see Section 6.3.5 of Léna et al. (2012).
- First order errors from atmospheric disturbance on the incoming light cause the image of the point source to move in the X-Y plane, what is called as tip-tilt fluctuation. This can affect in particular the guiding of the telescope (i.e., the capability of the telescope to follow the source). A tip-tilt correction system can be introduced to detect and correct this motion. The correction can be done with motion of the secondary mirror, or using a dedicated flat mirror at the pupil just in front of the focal plane. The mirror simply needs to tilt around the two axes, to keep the image centroid fixed. Even when using laser guide star for adaptive optics corrections, a natural guide star is needed for tip-tilt corrections.

4 Further reading

If you are interested in the theorey of diffraction, have a look at Born & Wolf (2013)[7].

You can read about the history of the development of active optics by ESO in Wilson (2003)[8]. More details about the history and concepts of active optics control systems can be found in Section 3.5 of Wilson (2013)[9].

More about adaptive optics can be found in the reviews by Davies & Kasper (2012)[10] and Guyon (2018)[11].

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[8] https://www.eso.org/sci/publications/messenger/archive/no.113-sep03/messenger-no113-2-9.pdf

[9] https://link.springer.com/book/10.1007/978-3-662-08488-5

[10] https://ui.adsabs.harvard.edu/abs/2012ARA%26A..50..305D/abstract

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