Optics Laboratory

The Eye and Telescopes

1. OBJECTIVES

- Investigating how the eye physically works (imaging, accommodation, myopia and hyperopia) by means of simple lens models.
- Study of the essential optics underlying telescopes and recreation of some types of telescopes.

2. THEORY

The eye is a natural optical device that allows us to see objects if their image is formed on the retina. To improve direct vision, we have developed optical instruments, which help us to observe small objects or very distant ones with a level of detail that cannot be achieved with the naked eye. Here we study how the eye works and the functioning of telescopes.

2.1 The eye

In the simplest case, we can consider the eye as a positive lens (which summarizes the performance of both the cornea and the lens), with the retina being the screen where images are formed (see Fig. 1).

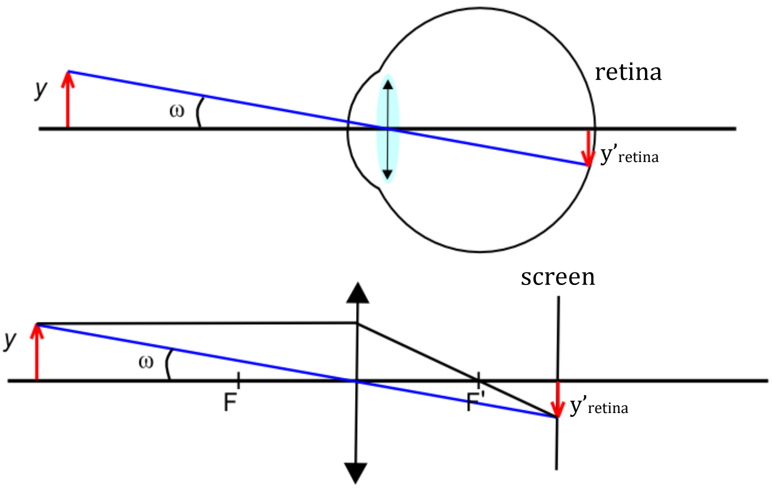

Figure 1. Imaging process in a human eye (top) and simulation of the process with a single positive lens (bottom), substituting the retina by a flat screen.

The eye can see objects located at different distances, thus, the eye can form clear images of objects at different distances without modifying its size as its lens has the capability to varying its focal length. An emmetropic eye can focus on the retina the image of far distant objects $(s = -\infty)$ without accommodation. When an eye is affected by ametropia (ametropic eye), it cannot focus the image on the retinal plane. In the case of myopia, the image of far distant objects is formed before the retina while in case of hyperopia, the image appears behind the retina. In both cases it can be used googles with adequate focal lengths to obtain focused images in the retina.

2.2 Visual magnification

The visual or angular magnification of an optical instrument is defined as the ratio between the image sizes in the retina with and without the instrument. This is equivalent to the ratio of the tangents of the angles under which the eye sees the object with and without instrument, respectively, as seen in Fig. 2

$$M = \frac{y'_{\text{with}}}{y'_{\text{without}}} = \frac{\tan \omega_{\text{with}}}{\tan \omega_{\text{without}}}, \tag{1}$$

In Eq. (1), y'_{with} and y'_{without} denote, respectively, observation with and without the instrument (the same holds for the angles ω_{with} and ω_{without}).

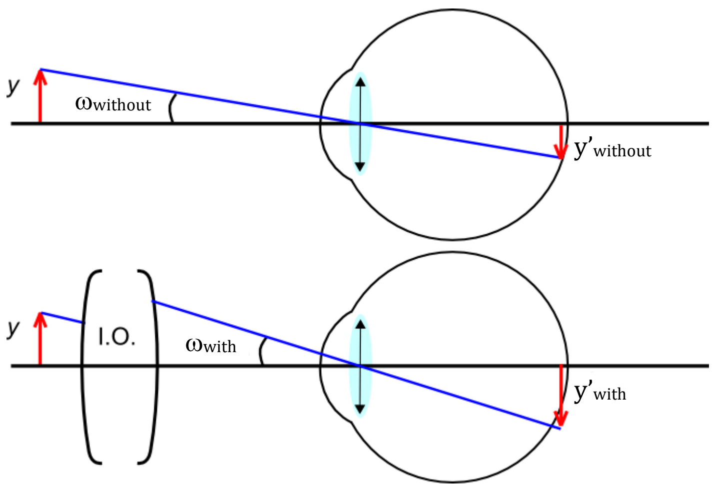

Figure 2. Observation without instrument (the size of object and image are denoted, respectively, by y and y'_{without}) and with instrument (y and y'_{with}).

2.3 Observation of far distant objects: Telescopes

Telescopes are instruments used to observe distant objects. Ideally, the object is assumed to be at infinity, so **without the instrument, an emmetropic eye observes without accommodation**. Additionally, when **the observation is made with the instrument**, i.e., with a telescope, for convenience, it is also desired that **the eye observes without accommodation**. Telescopes essentially consist of two optical elements: an objective and an eyepiece as illustrated in Fig. 3. They work under the principle that the angle ω subtended by the object at infinity (in practice, very far away) appears larger when observed through the telescope (see Fig. 2) giving rise to a subsequent apparent increase in the size of object. It can be shown that the visual magnification, in this case, is given by

$$M = \frac{y'_{\text{with}}}{y'_{\text{without}}} = \frac{\tan \omega_{\text{with}}}{\tan \omega_{\text{without}}} = -\frac{f'_o}{f'_e}, \quad (2)$$

where f'_o and f'_e denote, respectively, the back (or image) focal lengths of the objective and the eyepiece.

Depending on the optical phenomenon considered to build the objective and the eyepiece, there are refracting and reflecting telescopes (and mixtures). Among the former, the simplest models are the Keplerian and the Galilean telescopes. A Keplerian telescope consists of two positive lenses, which produce the increase in the apparent size of the observed object according to the ray diagram shown in Fig. 3. The Galilean telescope also consists of two lenses, although one is positive (objective) and the other negative (eyepiece), thus shortening the size of the device in the case of same magnification (same value, but opposite sign). Finally, the Newtonian telescope is a reflector telescope consisting of a primary concave mirror (objective) followed by a secondary flat (or convex) mirror, which redirects light towards the eyepiece. **In all telescopes, though, the distance between objective and eyepiece is equivalent to the sum of their focal lengths**, which makes the device to be afocal.

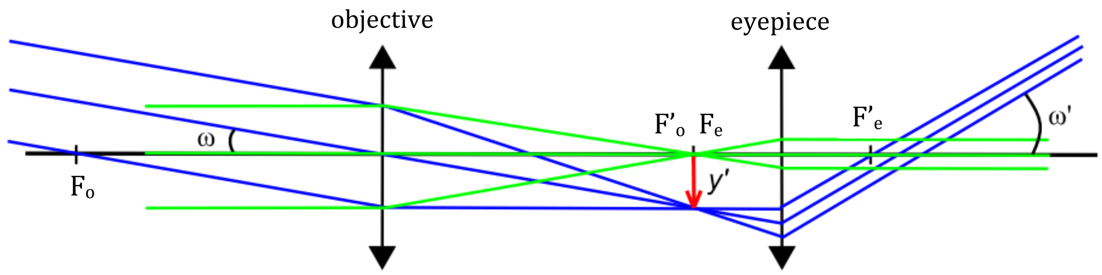

Figure 3. Ray diagram for a Keplerian telescope.

2.4 Beam expanders/reducers

Afocal optical systems are not only used to observe distant objects. They are also required as an essential part of different optical setups, for example, to modify (increase or decrease) the width of a light beam in order to accommodate irradiance conditions on a sample or the beam dimensions to the size of a detector. **The increase in the beam width in these cases is proportional to the inverse of the visual magnification**, as it can be seen from the green rays in the ray diagram displayed in Fig. 3. Note that angular magnification and linear magnification are going to be inverse one another.

3. EXPERIMENTAL METHOD

This practice is going to be developed with the aid of both the 2D Kit and the optical bench. For the simulation of the telescope in the bench, an object at infinity will be simulated with the aid of an auxiliary lens. All lenses are assumed to be thin, so the thin lens equation and any other relation for thin lenses is valid. Some focal lengths for the lenses to be used in the optical bench are annotated on their respective frames. Nonetheless, their values can be quickly checked using the autocollimation method and/or a ruler. However, according to what you have seen in the theory classes, could you estimate the position of the principal planes in the not so thin lenses of the 2D kit? Don't you think that maybe the principal planes are closer to the lens faces than to the center? Consider an index of 1.5, the lens radii can be estimated from the focal length.

In practice, the simulated eye will only have two fixed focal lengths, which will serve to simulate observation conditions with maximal accommodation and without accommodation. To this end, you will have to try two different lenses from the optical bench, accommodating them in front of the flat squared screen that plays the role of the retina (in order to obtain correct focus conditions on the simulated retina, it is important that the frame is attached to the correct fixing hole).

4. BIBLIOGRAPHY

[1] A. Ghatak, *Optics* (McGraw-Hill, 6th Ed., 2017).

[2] F. L. Pedrotti, L. M. Pedrotti and L. S. Pedrotti, *Introduction to Optics* (Pearson Int'l Edition, 2006).

[3] J. F. James, *An Introduction to Practical Laboratory Optics* (Cambridge University Press, 2014).

QUESTIONNAIRE

- **In this practice, <u>uncertainties are optional</u>.**
- **For an easier identification of the answers, please, specify in a visible place the number of the question responded (unless you have included explicitly the question).**

Recreation of an eye with the 2D kit

Warning: *To facilitate the experimental procedure when using the 2D kit, you can make marks on both the eye sheet and the squared paper available on your desk/whiteboard. It is only for personal use and should be removed once the experiments with the 2D kit are over.*

1. With the 2D kit, build an emmetropic eye using **lens 1** and determine its focal length.
2. Build a myopic eye using **lens 2** and determine its focal length. Justify why this lens should be used.
3. Find out which lens compensates myopia (nearsightedness) in point 2. Briefly justify your choice. Determine the focal length of the chosen lens, explaining the method selected for this purpose.

Recreation of telescopes and beam expanders with the 2D kit

4. Find theoretically the relation between visual magnification and beam-width magnification in a telescope. Hint: observe in Fig. 3 the relationship between the incoming and outgoing green ray bundles and the incoming and outgoing angles of the blue ray bundles.
5. Recreate a Keplerian-type telescope. Determine its visual magnification experimentally from its beam-width magnification and theoretically using Eq. (2). Write down which lenses you have used, indicating which one has been selected as the objective and which one is the eyepiece.
6. Recreate a Galilean-type telescope. Determine its visual magnification experimentally from its beam-width magnification and theoretically using Eq. (2). Write down which lenses you have used, indicating which one has been selected as the objective and which one is the eyepiece.
7. Recreate a Newtonian-type telescope. Determine its visual magnification experimentally from its beam-width magnification and theoretically using Eq. (2). Write down which lenses you have used.

Recreation of a telescope on the optical bench

Objective: Design a Kepler telescope using two available converging lenses to observe an object at infinity with the simulated eye observing without accommodation, so **that its visual magnification is the maximum possible**. Justify your choices. Answer the following questions:

1. Which lens acts as an objective? Indicate its focal length.

2. Which lens serves as an eyepiece? Indicate its focal length.

3. Indicate the separation between the objective and the eyepiece.

4. What lens serves as the cornea+crystalline lens? What is the separation between this lens and the screen?

5. Which lens is used to simulate the object at infinity?

6. Indicate the distance between the slide and the lens that takes it to infinity.

7. Calculate the visual magnification of the telescope according to expression (1).

8. Calculate the visual magnification of the telescope in terms of the objective and eyepiece focal lengths.

Additional Comments

9. If you have observed or thought about something else that has not been previously considered in any of the above points, you can add it here.