CHAPTER IV

INSTRUMENTATION: OPTICAL TELESCOPE

Outline:

⊙ *Main Function of Telescope*

⊙ *Types of Telescope and Optical Design*

⊙ *Optical Parameters of Telescope*

- *Light gathering power*
- *Magnification*
- *Resolving power*
- *Limiting magnitude*
- *Image scale*
- *Apparent and actual field of view*

IV.1 Main Function of Telescope

An optical telescope provides two important functions:

(1) to allow collection of energy over a larger area so that faint objects can be detected and measured with greater accuracy

(2) to allow higher angular resolution to be achieved so that positional measurements can be made more accurately and so that more spatial detail and information of extended objects can be recorded.

IV.2 Types of Telescope and Optical Design

Since its invention, the telescope system has been improved progressively. Its development has been controlled by a variety of factors. At the beginning of telescope application, the eye and brain was the only way of recording and interpreting the images that the optics formed; consequently, the aim of early telescope design was to provide the sharpest images for visual inspection. The first form of the telescope was the **refractor** which uses lenses to produce the images. For the simplest of refracting systems, the telescope has the defect of the image position being dependent on the wavelength of light. This defect is known as *chromatic aberration* (see **Figure 4.1**).

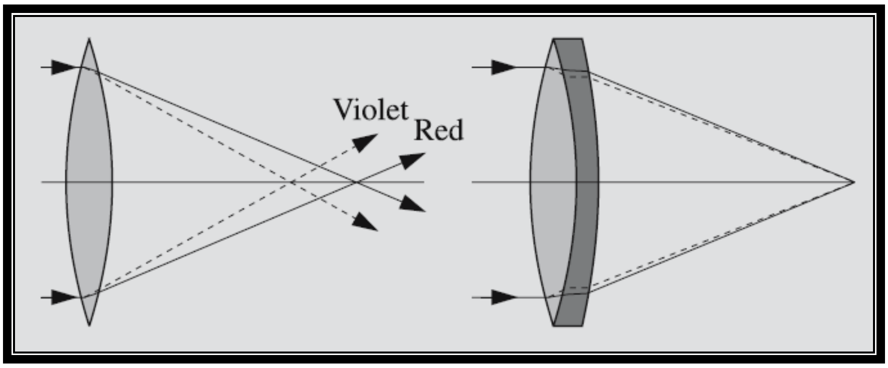

Figure 4.1 Chromatic aberration. Light rays of different colours are refracted to different focal points (*left*). The aberration can be corrected with an achromatic lens consisting of two parts (*right*)

Many people, including Sir Isaac Newton, thought that this defect, which is inherent in simple lens systems, could not be overcome and indeed Newton himself introduced the alternative method of forming optical images by using a curved mirror. **Reflectors**, by their nature, do not suffer from chromatic aberration. In the very largest telescopes, the observer can sit with his instruments in a special cage at the *primary focus* (**Figure 4.2**) without eclipsing too much of the incoming light. In smaller telescopes, this is not possible, and the image must be inspected from outside the telescope. In modern telescopes instruments are remotely controlled, and the observer must stay away from the telescope to reduce thermal turbulence. Interest in refracting systems was aroused again when it was discovered by Dolland in 1760 that the effect of chromatic aberration could be reduced considerably by the use of a compound lens system.

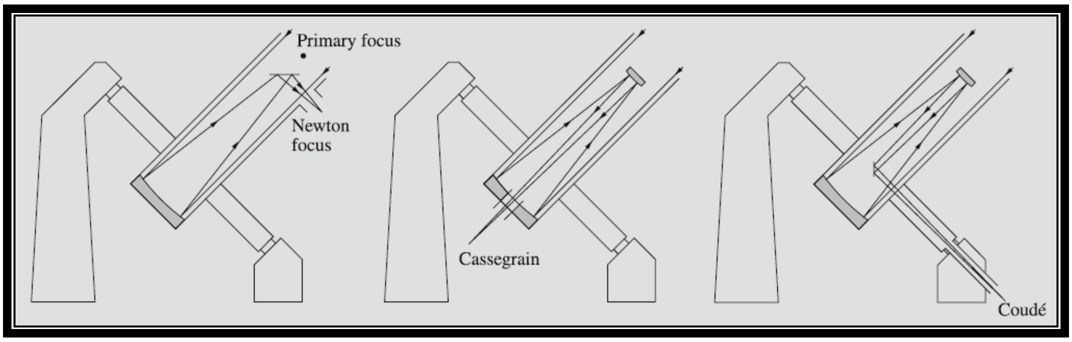

Figure 4.2 Different locations of the focus in reflectors: primary focus, Newton focus, Cassegrain focus and Coudé focus.

A telescope has to be mounted on a steady support to prevent its shaking, and it must be smoothly rotated during observations. There are two principal types of mounting, *equatorial* and *azimuthal* (**Figure 4.3**). In the equatorial mounting, one of the axes is directed towards the celestial pole. It is called the *polar axis* or *hour axis*. The other one, the *declination axis*, is perpendicular to it. Since the hour axis is parallel to the axis of the Earth, the apparent rotation of the sky can be compensated for by turning the telescope around this axis at a constant rate. The declination axis is the main technical problem of the equatorial mounting. When the telescope is pointing to the south its weight causes a force perpendicular to the axis. When the telescope is tracking an object and turns westward, the bearings must take an increasing load parallel with the declination axis.

In the azimuthal mounting, one of the axes is vertical, the other one horizontal. This mounting is easier to construct than the equatorial mounting and is more stable for very large telescopes. In order to follow the rotation of the sky, the telescope must be turned around both of the axes with changing velocities. The field of view will also rotate; this rotation must be compensated for when the telescope is used for photography. If an object goes close to the zenith, its azimuth will change 180◦ in a very short time. Therefore, around the zenith there is a small region where observations with an azimuthal telescope are not possible.

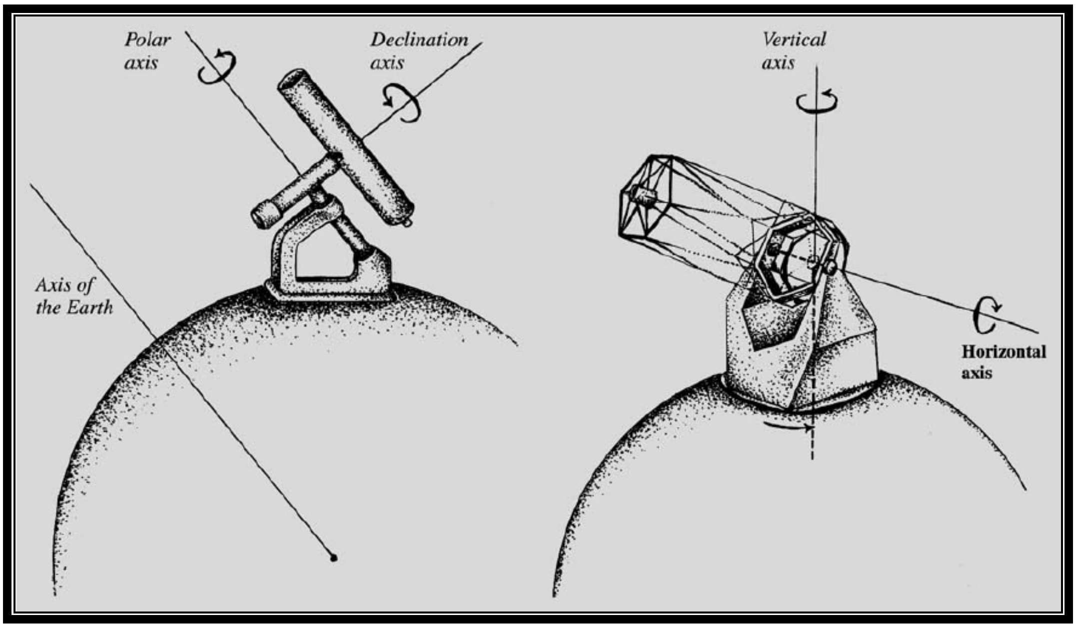

Figure 4.3 The equatorial mounting (*left*) and the azimuthal mounting (*right*).

4.3 Optical Parameters of Telescope

4.3.1 Light-gathering power

We can think of light from a star as a steady stream of photons striking the ground with a certain number of photons per unit area per second. If we look straight at a star, we will see only the photons that directly strike our eyes. If we can somehow collect photons over an area much larger than our eye, and concentrate them on the eye, then the eye will receive more photons per second than the unaided eye. A telescope provides us with a large collecting area to intercept as much of the beam of incoming photons as possible, and then has the optics to focus those photons on the eye, or a camera, or onto some detectors.

Example:

Problem *Compare the light-gathering power of the naked eye, with a pupil diameter of 5 mm, to that of a 1 m diameter optical telescope.*

Answer *Let* d_1 *be the diameter of the pupil and* d_2 *be the diameter of the telescope. The collecting area is proportional to the square of the diameter. The ratio of areas is*

$$\left(\frac{d_2}{d_1}\right)^2 = \left(\frac{1.0\text{m}}{5.0\times10^{-3}\text{m}}\right)^2 = 4.0\times10^4$$

This is the ratio of luminosities that we can see with the naked eye and with the telescope. We can express this ratio as a magnitude difference (see equation (5.3) in Chapter V):

$$m_1 - m_2 = -2.5\log_{10}\left(\frac{b_1}{b_2}\right)$$
$$m_1 - m_2 = -2.5\log_{10}\left(\frac{d_2}{d_1}\right)^2$$
$$m_1 - m_2 = -11.5$$

This means that the faintest objects we can see with the telescope are 11.5 mag fainter than the faintest objects we can see with the naked eye. If the naked eye can see down to 6 mag, the telescopeaided eye can see down to 17.5 mag. This illustrates the great improvement in light-gathering power with the telescope.

4.3.2 Magnification

In order to make a visual inspection of the images which the telescope collector provides, some kind of eyepiece must be used. The effect of the use of an eyepiece is illustrated in a simplified way in **Figure 4.4**, where the virtual image is at a position on or beyond the near point of the eye (the actual final image is formed on the retina of the eye). Under this circumstance, it can be seen that the image produced by the collector lies inside the focus of the eyepiece. The figure illustrates that, with this simple eyepiece, the viewed image is inverted. The magnifying power, *m*, of the overall optical system is defined as the ratio of the angle subtended by the virtual image at the eye, αe, and the angle, αc, subtended by the object at the collector. Thus,

$$\mathbf{M} = \frac{\alpha_e}{\alpha_c} = \frac{f_c}{f_e} \quad ....(4.1)$$

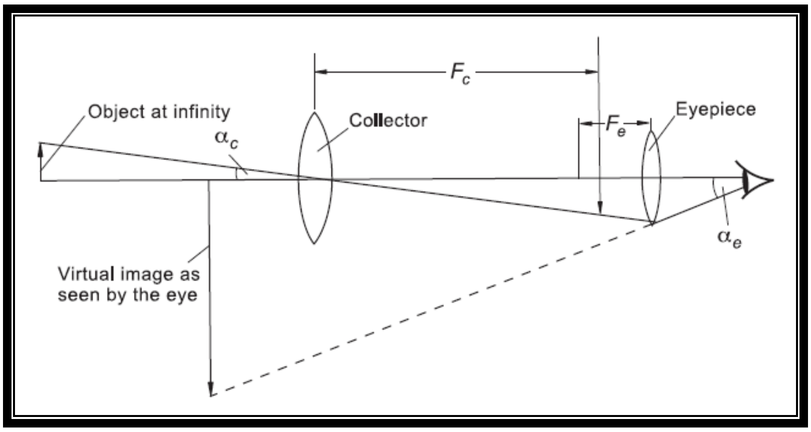

Figure 4.4 Visual use of a telescope. The collector is depicted as an objective.

Example:

Problem *What is magnification for a Meade 8" telescope (F_c = 2000 mm) when using eyepiece with focal length of 32 mm?*

Answer *We use equation (4.1) to obtain*

$$\mathbf{M} = \frac{f_c}{f_e} = \frac{2000\text{mm}}{32\text{mm}} = 62.5$$

There are both lower and upper limits to the magnification which can be usefully applied with any given telescope. The first consideration for a lower limit is that all the light which is collected by the telescope should be made available for viewing by the eye; the magnification must be sufficiently great to make the exit pupil equal to or smaller than the entrance pupil of the eye (see **Figure 4.5**). Thus, by using the definition of magnification given by equation (4.1), the lower limit of magnification can be conveniently approximated to

$$M \geq \frac{D}{2} \text{.........}(4.2)$$

where the diameter of the objective lens or mirror of the telescope, *D*, is expressed in mm.

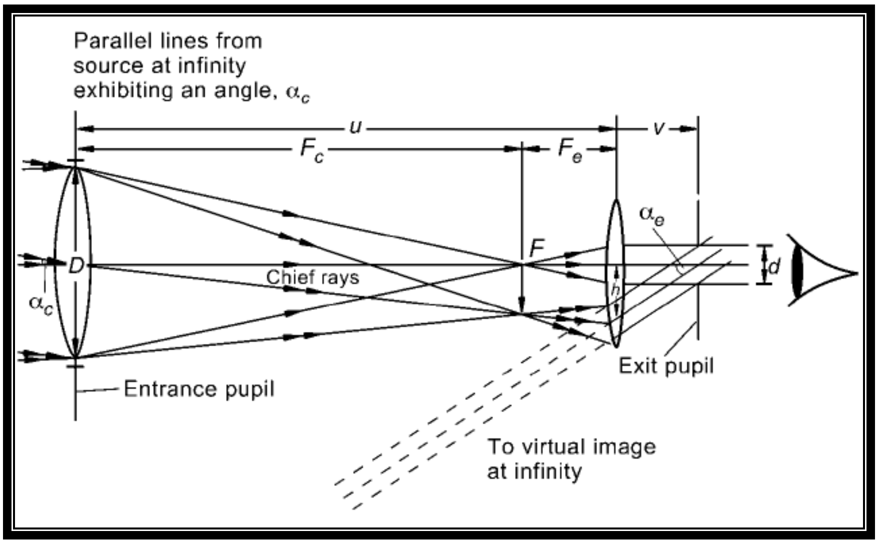

Figure 4.5 A schematic diagram of the astronomical telescope, illustrating the positions of the entrance and exit pupils.

The useful magnification of a telescope cannot be increased indefinitely. The upper limit is set by the impracticability of making eyepieces with extremely short focal lengths, by the quality of the optics of the collector and by the fact that the ability of the eye to record good images deteriorates when the beam that it accepts becomes too small. According to an empirical relation known as *Whittaker's rule*, deterioration of a viewed image sets in when the value of magnification exceeds the diameter of the telescope, *D*, expressed in mm. Using this rule, $m \leq D$. Magnifications greater than *D* (Whittaker's rule) can be used occasionally, especially with telescopes of small aperture. In fact, it has been found that in the case of double star observations with telescopes of small-to-medium aperture, the upper limit for magnification does not have a linear relationship with the telescope's diameter. According to *Lewis*, the upper limit is given by

$$M \leq 27.8\sqrt{D} \text{.........}(4.3)$$

4.3.3 Resolving power

We now look at resolving power. Resolution is the ability to separate the images of stars that are close together. It also allows us to discern the details in an extended object. One phenomenon that affects resolution is *diffraction*. Diffraction is the bending or spreading of waves when they strike a barrier or pass through an aperture. As they spread out, waves from different parts of the aperture or barrier interfere with one another, producing maxima and minima, as shown in **Figure 4.6**. As the aperture size, relative to the wavelength, increases, there are more waves to interfere, so the pattern is less spread out. Most of the power is in the *central maximum*, whose angular width $\Delta\theta$ (in radians) is related to the wavelength of the wave λ and the diameter of the aperture, D, by

$$\Delta\theta = 1.22\frac{\lambda}{D} \quad \text{.........(4.4)}$$

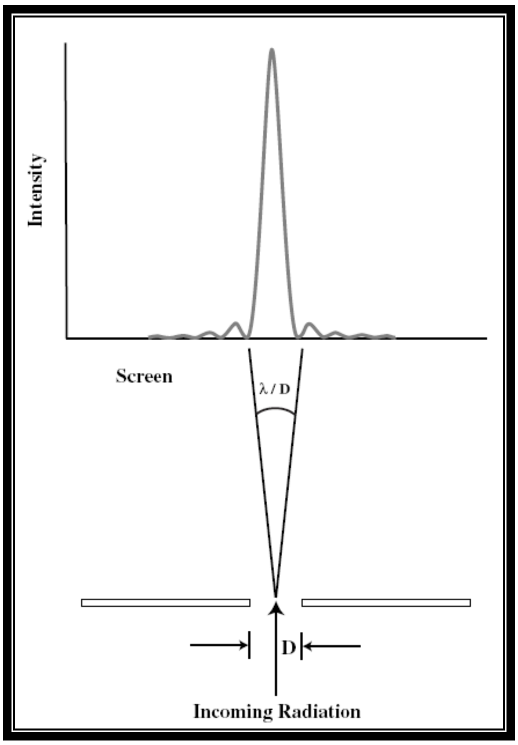

Figure 4.6 A light ray enters from the bottom, and passes through a slit of length *D*. Diffraction spreads the beam out and it falls on a screen.The intensity as a function of position on the screen is shown at the top. Most of the energy is in the main peak, whose angular width is approximately λ/D (in radians). Smaller peaks occur at larger angles.

Example:

Problem *Estimate the angular resolution of the eye for light of wavelength 550 nm.*

Answer *We use equation (4.2) and diameter D = 5 mm for pupil to obtain $\Delta\theta$. We convert from radians to arc seconds to convert the result to a convenient unit (1 rad = 206,265 arc sec).*

$$\Delta\theta = (1.22)(206{,}265)\frac{(5.5\times10^{-4}\,\mathrm{mm})}{(5\mathrm{mm})} = \frac{2000\mathrm{mm}}{32\mathrm{mm}} = 27.7\ \mathrm{arcsec}$$

4.3.4 Limiting magnitude

The amount of energy collected by any aperture is proportional to its area and, therefore, to the square of its diameter. In the case of the eye, the sensitive area responds to the energy which is accepted by the pupil and, accordingly, there is a limit to the strength of radiation that can be detected. For starlight, the limit of unaided eye detection is set at about sixth magnitude. By using a telescope, with its greatly increased aperture over the pupil of the eye, it should be possible to record stars which are much fainter than sixth magnitude.

If *me* and *mt* correspond to the magnitude of a star as seen by the naked eye and by the telescope, respectively, the apparent difference in magnitude can be obtained by using Pogson’s equation (see equation (5.3)). If a typical value of *d* = 8.0 mm is used and we also take into account the efficiency of the optical systems of telescope, the limiting magnitude of the telescope can be expressed as

$$m_{\mathrm{limit}} = 6 + 5\log_{10}\left(\frac{D}{10}\right) \quad \ldots\ldots\ldots(4.5)$$

where *D* is expressed in mm. Thus, in practice, the limiting magnitude for a 500 mm telescope is likely to be about 14·5. Some magnitude has been ‘lost’ due to the telescope’s imperfect transmission. Equation (4.5) is again not a hard and fast law, however, as each telescope must be treated individually and also the limiting magnitude will depend on the observer to some extent.

4.3.5 Image scale

The linear size of image formed in focal plane of the telescope represents angle subtend in the sky. This is known as the image scale of the telescope and formulated as

$$\textbf{Image scale}\left(''/\,\textbf{mm}\right) = \frac{\textbf{206,265('')}}{\textbf{f}_{\textbf{c}}\textbf{(mm)}} \quad \ldots\ldots\ldots(4.6)$$

According to equation (4.6), the image scale of Zeiss refractor (focal length of objective = 1,100 cm) at Bosscha Observatory is 18.72"/mm. This means for every mm of image formed in the telescope focal plane represents an angle of 18.72".

4.3.6 Apparent and actual field of view

Field of view (FOV) is the maximum angular size visible through optical system. Generally, as the magnification goes up, the FOV goes down (generally linearly). Eyepieces generally are characterized to have an *apparent field of view*, which is the maximum possible angle as viewed through the eyepiece alone. Typical eyepieces have field of view ranging from 40^0 to 65^0 or more. The intrinsic or apparent eyepiece FOV must then be divided by the magnification to get the actual field of view at the telescope. This can be written as

$$\begin{aligned}\textbf{Actual FOV} &= \frac{\textbf{Apparent FOV}}{\textbf{M}} \\ &= \frac{\textbf{Apparent FOV}}{\left(\textbf{f}_{\textbf{c}}/\textbf{f}_{\textbf{e}}\right)} \quad \ldots\ldots\ldots(4.7)\end{aligned}$$

Example:

<u>Problem</u> *Given a 25-mm focal length eyepiece with a 40 degree apparent FOV. If used on a telescope with a focal length of 2000 mm, what is actual field of view?*

<u>Answer</u> *We use equation (4.7) to obtain*

$$\textbf{Actual FOV} = \frac{\textbf{40}^{\textbf{0}}}{\left(\textbf{2000mm}/\textbf{25mm}\right)} = \frac{\textbf{40}^{\textbf{0}}}{\textbf{80}} = \textbf{0.5}^{\textbf{0}}$$

Astronomy Laboratory

Apparent FOV of Eyepieces

Procedure: Develop by your own

1. Choose one of telescope available in Earth and Space Laboratory. Try to determine the apparent field of view of eyepieces collection.

Lab Skills and Objectives

- **Be able to develop procedure of experiment**
- **Determine apparent field of view of eyepieces**