HOW TO BUILD A

TELESCOPE

G. Carboni, March 1996
English version revised by David P. Adam

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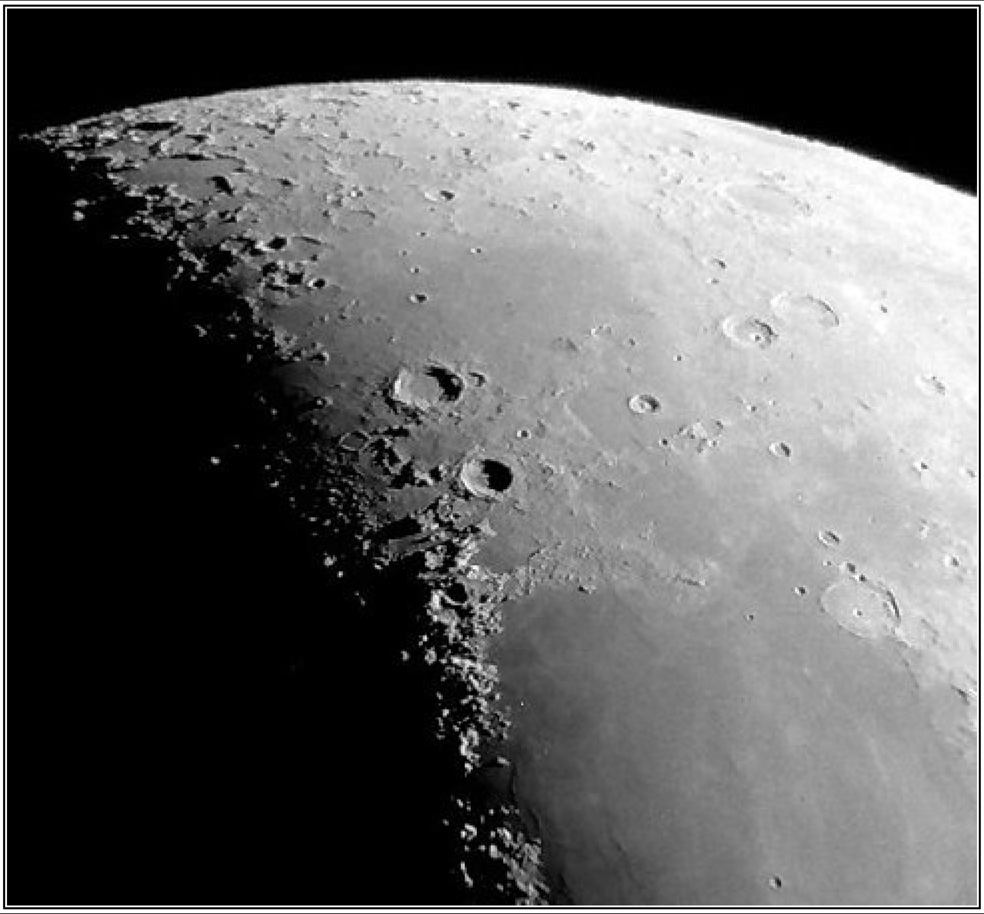

INTRODUCTION

We describe below how to construct two telescopes. The first one is simpler to build, but is important for understanding the solutions adopted in the second one, which is perfected and optimized for astronomical observations.

THE FIRST TELESCOPE

As we said, you can build this first simple instrument without difficulty while allowing you to learn the structure and operation of telescopes in general. Although it is simple, it can reveal the craters of the Moon and the satellites of Jupiter. It is also very useful for demonstrating lens aberrations. You really need to build this telescope as a necessary step towards understanding the solutions employed in the second and improved telescope model. In the section "From Lenses to Optical Instruments", you saw how a telescope works; here we simply remind you that the objective lens produces an image of the object observed, and this image is magnified by the eyepiece.

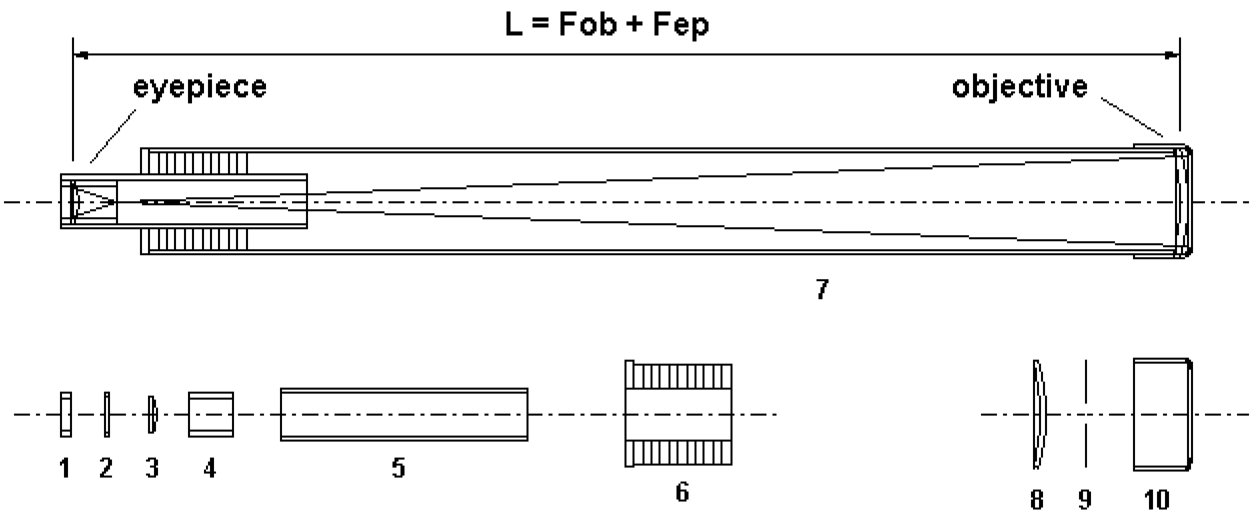

Fig. 1 - Section of the first telescope

Figure 1 shows our first telescope, which is made using easy-to-find materials. The components of this instruments are:

1. ring to secure the eyepiece lens from behind
2. ring for centering the eyepiece lens
3. eyepiece: lens with focal length of 20-50 mm. You can buy one in an optical or photographic shop, or you can get one free by using the lens of a disposable camera.
4. ring to secure the eyepiece lens from the front
5. a cardboard tube for the eyepiece. You can use the tube from a roll of plastic food wrap or paper towels. You can also use short sections of this tube to make rings 1, 2, and 4 which you need to hold the eyepiece lens in place
6. coupling between the eyepiece tube and the main tube. This is a hollow cylinder with an outer diameter that fits snugly into the end of the main tube and an inner diameter that provides a snug but movable fit to the outside of the eyepiece tube. You can make the coupling using several plywood disks glued together or using a polystyrene cylinder with a hole bored through it. If you use polystyrene, you will need to add an opaque covering at each end.
7. main tube. Use a cardboard or plastic tube about as long as the focal length of the objective lens and with an outside diameter of 50-60 mm about. Suitable sources include map mailing tubes and core tubes for carpets, drawing paper, or wrapping paper.
8. objective lens. You can use a common eyeglass lens with a focal length of 500-1000 mm. You can buy it in a optical shop. Ask the optician to reduce the lens diameter in order to fit it precisely into the tube cap
9. diaphragm. Cut it from a black card, then open a hole of about 15 mm in diameter in the center of the disk
10. Cap of the tube. If you buy a tube for drawing sheets, you should have a cap which will be useful for retaining the objective and the diaphragm. Otherwise, you can made it with a disk of cardboard. Make a series of radial cuts around the edge of the disk to make a set of tabs, Moisten the tabs; then place the tube cap on one end of the principal tube and bend the tabs around the outside of the tube. Glue the tabs together where they overlap, but be careful not to glue the cap to the principal tube yet. When the glue is dry, slip the cap off and cut in the cap a hole a few mm less in diameter than the outside diameter of principal tube.

The distance between objective and eyepiece lenses must be equal to the sum of their focal lengths. The eyepiece tube must stick out a few centimeters so you can move it to focus the telescope. Make the length of the principal tube short enough to allow you to grip the protruding part of the eyepiece tube with your fingers as you adjust the focus. The eyepiece tube must slide smoothly in its channel, but it should not be loose enough to fall out if you hold the telescope vertically. Paint the inside of the tubes with black opaque paint (matte finish) or India ink . Secure the cap of the main tube to keep it from pulling away from the tube.

HOW TO USE THE FIRST TELESCOPE

Do not use the diaphragm at first, but leave the objective at the greatest aperture. Point the

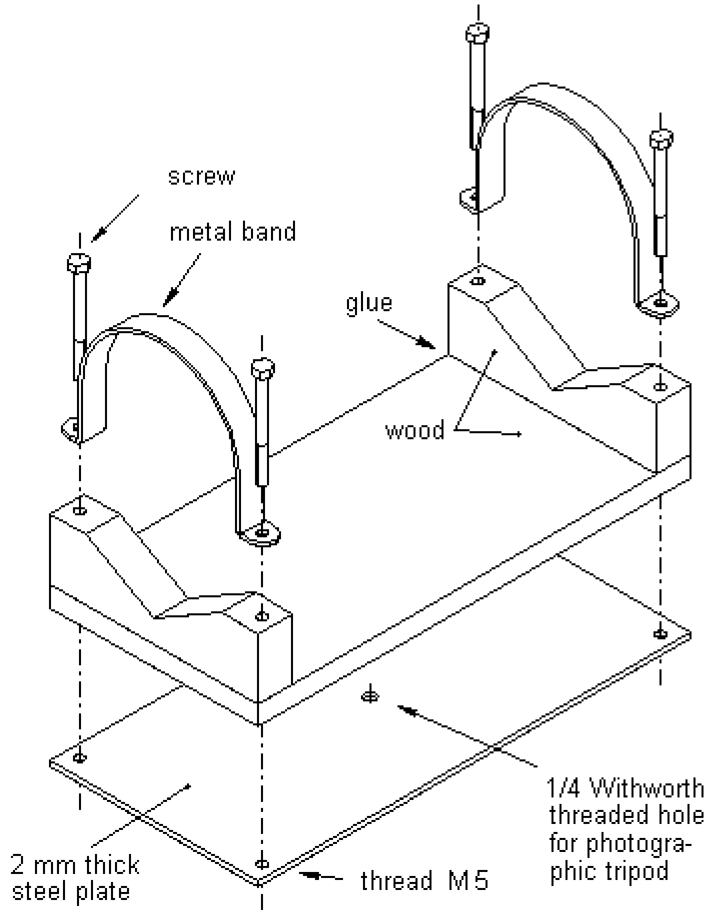

Fig. 2 - Telescope support

instrument towards a distant object. Move forward and backward the eyepiece tube until the image is as distinct as possible. You will soon realize that the image is of poor quality and is never distinct. This simple objective lens has many defects that produce the poor-quality image.

You can reduce some aberrations by decreasing the lens aperture. This is why we use a diaphragm on the objective. It is a round disk of black stiff paper with a 15-mm-diameter hole in the center. This diaphragm, placed in front the objective, reduces both the effects of the lens defects and the brightness of the image. As a consequence, you can only observe objects brightly illuminated by the Sun. To minimize the chromatic aberrations, you will need to replace the spectacle lens you used as the objective for your first telescope with an achromatic lens, as we shall see below.

THE TELESCOPE SUPPORT

As soon as you use your telescope, you will see that you cannot hold it steadily enough in your hands to maintain a stable image. You will need to build a support (fig. 2) to help you to point your instrument and keep it steady. You can mount this support on a photographic tripod by means of a 1/4 W threaded hole.

LENS ABERRATIONS

The first telescope will give you a good feel for lens aberrations (fig. 3). In this simple instrument, chromatic aberration is the most conspicuous. The aberrations can be greatly reduced by means of careful lens design. As it is not possible to limit all kinds of aberrations using only a single lens, objectives and eyepieces are created using multiple lenses. By selecting different types of glass for the various lenses and using appropriate surface curvatures and distances between lenses, it is possible to control in a satisfactory manner the aberration of the system. In general, the success of an objective or an eyepiece in correcting aberrations depends on the number of lenses used to make it.

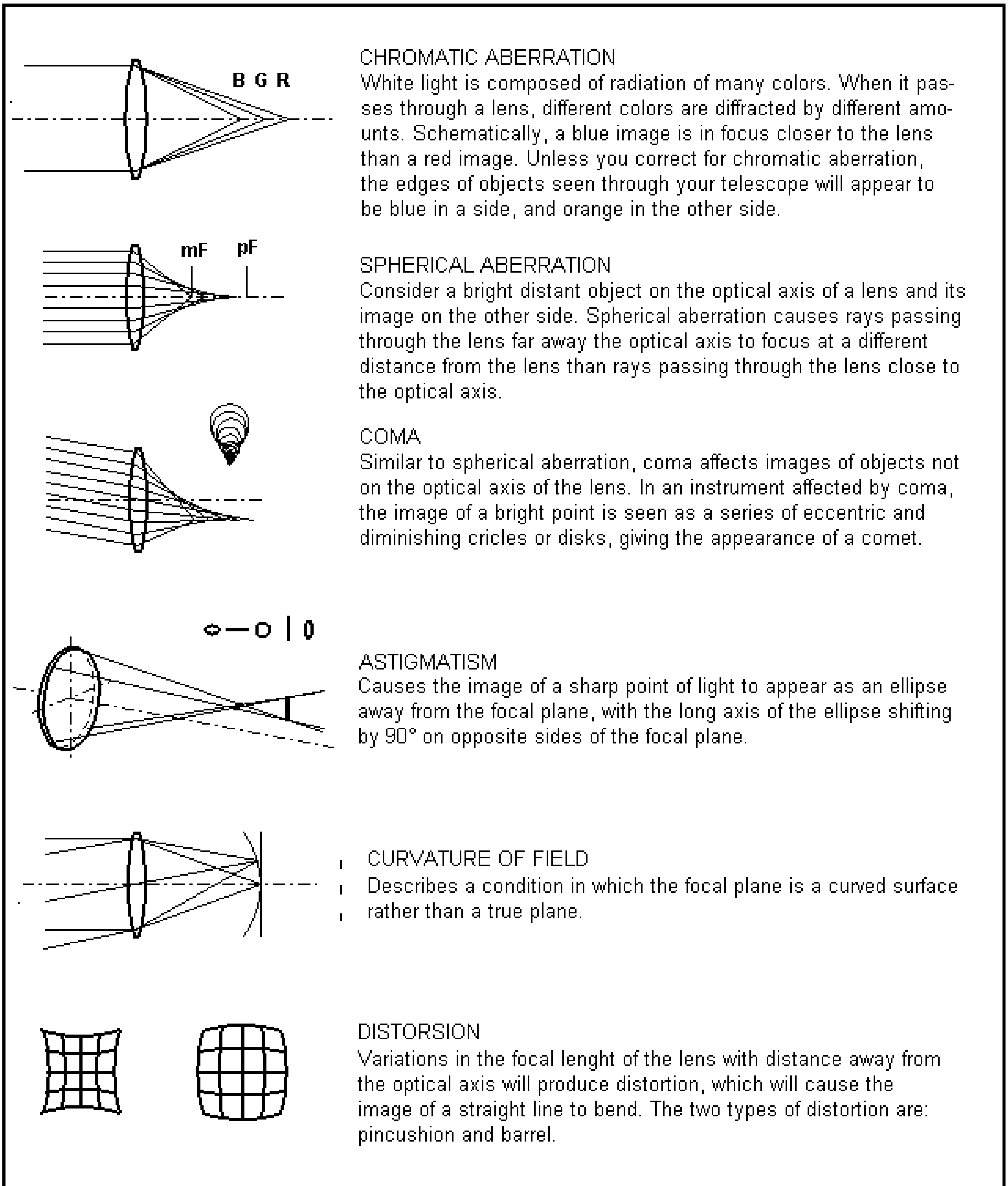

Fig. 3 - main optical aberrations.

For the second telescope, shown in figure 10, we use an **achromatic objective**, made up of two lenses of different shapes, one converging and the other diverging. Sometimes they are glued together by means of Canada Balsam or a synthetic resin (cemented doublet), other times they are kept separated (air-spaced doublet). These two lenses have different indices of refraction, one high (Flint glass), and the other low (Crown glass). Hence, the chromatic aberrations of the two lenses act in opposite senses, and tend to cancel each other out, thus producing a much more distinct image than a single lens could achieve.

Usually, these objectives are constructed to reduce other types of aberration as well. Obviously, achromatic objectives vary in quality. In some of them, it is still possible to perceive a residual chromatic aberration, or the images they produce are well focused in the center only, or they produce a pincushion or barrel distortion. Figure 3 describes the main optical aberrations.

EYEPIECES

In our first telescope, we used a simple magnifying glass as the eyepiece. Also eyepieces made up of a single lens are affected by several aberrations, particularly chromatic, and with a single lens it is not possible to eliminate them. In the early 1700s, Huygens showed that he could eliminate chromatic aberration in an eyepiece using a system of two lenses. Since then, many eyepiece models have been designed to obtain better and better corrections, a wider field corner, etc. However, eyepieces always retain the same basic function of magnifying the real image formed by the objective. The main parameters that characterize an eyepiece are the following:

Parameter	**Defines**
MODEL	Aberration corrections
FOCAL	Focal lengths combine to determine the magnification power of the telescope
FIELD	Determines how wide the image appears to the eye. A wider field makes the telescope more comfortable to use
EYE RELIEF or EYE DISTANCE	Indicates the proper distance from the eye to the eyepiece lens
DIAMETER	Indicates the outside diameter of the eyepiece tube. Most eyepieces have diameters of either ~24 mm or ~32 mm

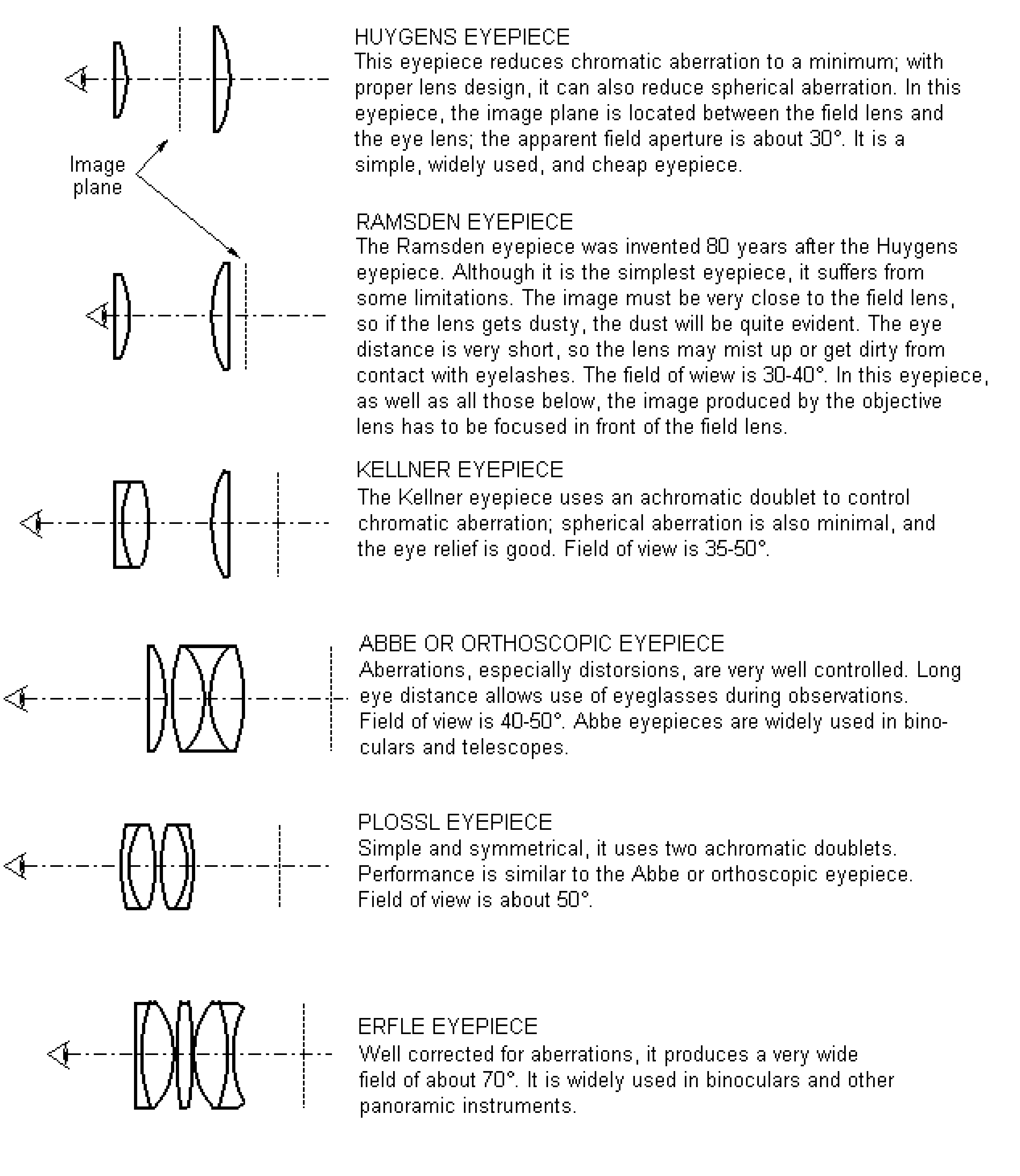

Fig. 4 - The most common eyepieces.

In addition to those shown in figure 4, other types of eyepieces can be made by using more lenses. Such fancy lenses are made for special purposes, and they are usually expensive.

PRODUCING AN UPRIGHT IMAGE

With the first telescope you built, images were inverted, and in the section "From Lenses to Optical Instruments" we explained why. But astronomers don't really care whether they see star images "straight up" or "upside down." In fact, with the exception of the Sun, all stars are so distant that not even with the most powerful telescopeshas anyone ever seen their disks. They appear to us always as points of light, and to see a point of light upright or overturned does not make any difference. However, many people would like to use their telescopes for terrestrial observations, in which case "right side up" *does* make a difference.

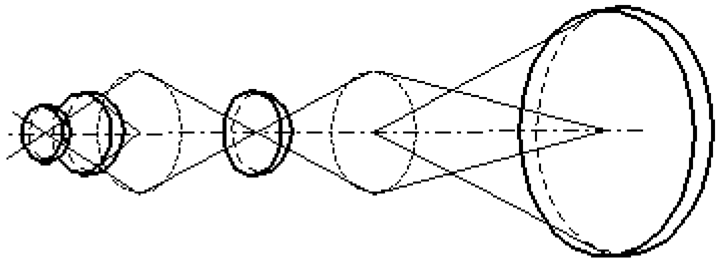

Fig. 5 - The erecting lens is an achromatic lens, inserted between objective and eyepiece, which reproduces and erects the inverted image formed by the objective. This system has the disavantage of increasing the length of the telescope. An advantage is that it makes it possible to vary the magnification of the telescope.

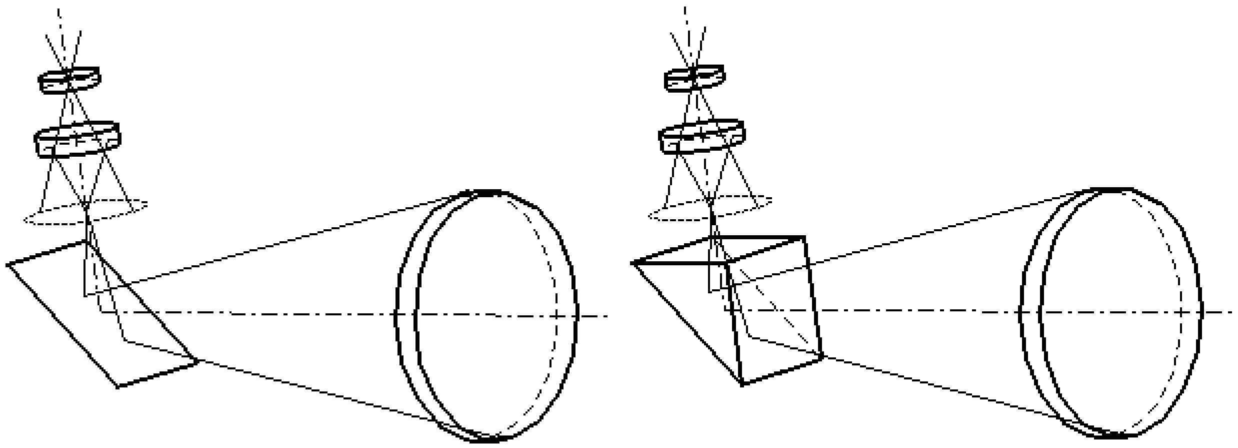

Fig. 6 - A mirror or a prism erects the image in the up-down direction, but the image remains reversed in a right-left sense.

Several different methods allows you to erecting images without significantly degrading their quality. Figures 5, 6, 7, 8, 9 show the main erecting systems. These optical devices are sold with a case and tubes for connecting them with the eyepieces and the focussing systems.

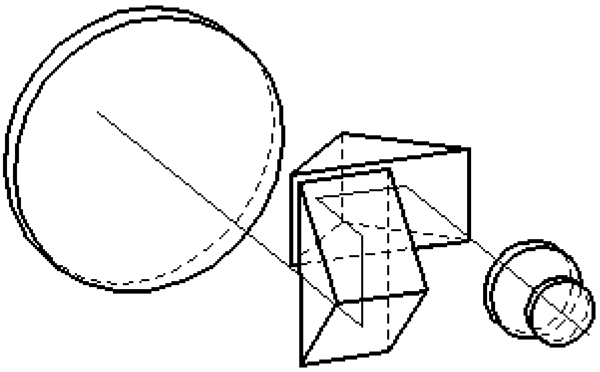

Fig. 7 - Two prisms, coupled as in a set of binoculars, erect the image completely, and also reduce the overall length of the instrument.

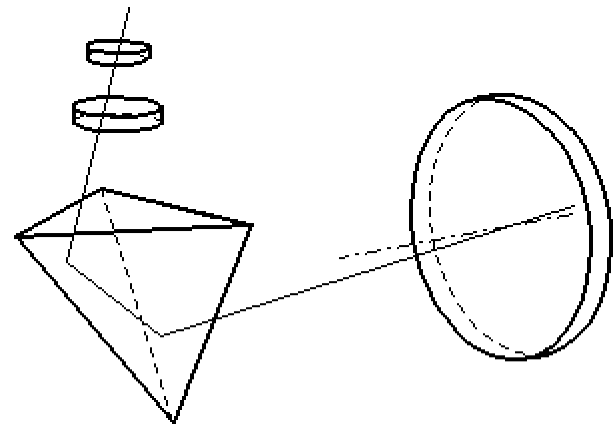

Fig. 8 - In a roof prism or Amici prism erecting system, the image is reflected twice internally by a tetrahedral prism, emerging at right angle to the initial optical path. The image is fully erected, and the 90° bend in the optical path makes it relatively easy to observe stars near the Zenith. Bevels on the prisms have been omitted for clarity

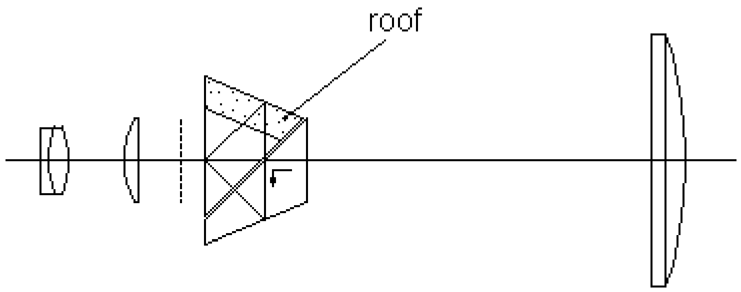

Fig. 9 - This erecting system uses two prisms, one of which is a roof prism. The emerging ray is coaxial with the optical axis. this system is used in mini-binoculars.

AN ACHROMATIC TELESCOPE

During the construction of this second telescope (fig. 10), we will use improved technology and manufacturing methods to achieve better performance than we could get from our simple first telescope. To build this instrument, you will need:

- an achromatic objective with a diameter between 40 and 100 mm, and with a focal length between 600 and 1200 mm
- an eyepiece with a focal length between 20 and 40 mm. Any model show in figure 4 is good, with the exception of the Ramsden eyepiece
- a rack and pinion focussing system. It is made up of two tubes sliding one into the other. The inner one is moved by a rack and pinion couple
- an image erecting system (see figures 5-9)

- the main tube in aluminum #1. Buy it with a length equal to the objective focal length. Its inside diameter must be greater than the diameter of the objective mounting bracket
- adapter ring in black plastic or aluminum
- coupling ring in black plastic or aluminum
- light shade tube.

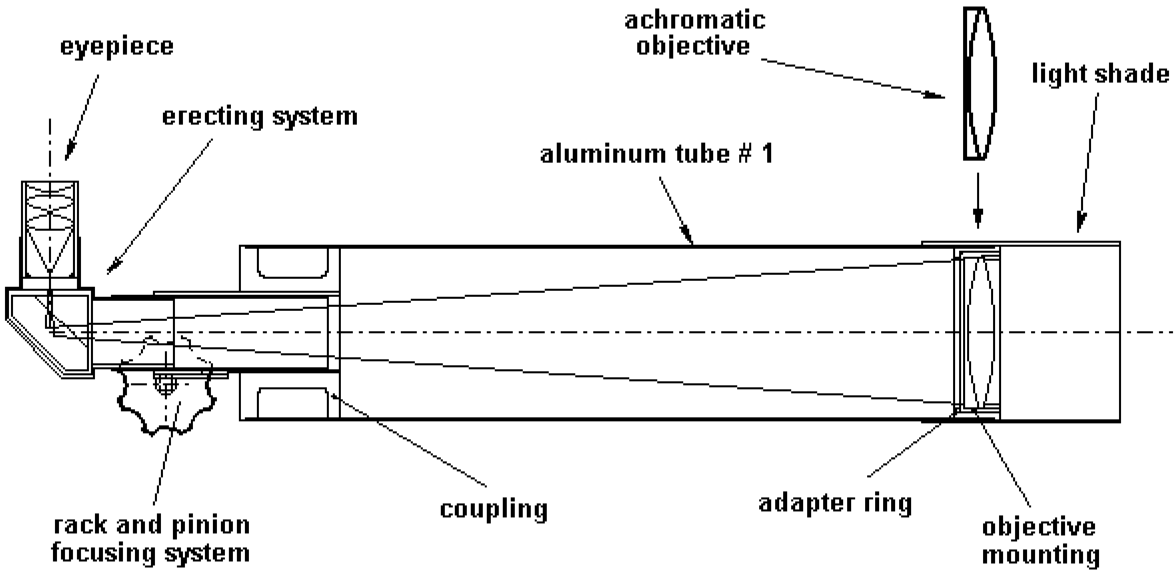

Fig. 10 - The achromatic telescope

You can buy objective, eyepiece, erecting and focussing systems from suppliers who advertise in astronomy magazines, or you can ask an amateur astronomy club for advice. In any case, make sure to choose diameters for your components such that they will fit each other; otherwise, you will need to fabricate fitting rings. You will have to make the principal mechanical parts with a lathe. If you do not have one, you can go to a machine shop. Since the parts are all quite simple, you shouldn't need to spend a lot. In any case, ask for a cost estimate. Students of high schools, technical colleges and universities can often get access to their school laboratories. If you want to get your own machine tools, you can find commercial Chinese-made lathes that are available for less than a thousand dollars. For the same price, you can buy also a small used lathe.

RESOLVING POWER AND MAGNIFICATION POWER

The magnification of the telescope (M) is given by the ratio between the objective and eyepiece focal lengths: $\mathbf{M = F_{ob}/F_{ep}}$. You cannot simply magnify at will, seeing more and more details. The maximum magnification you can reach with a telescope is limited by the diameter of the objective. The larger the diameter of the objective, the closer are the points it is able to distinguish as separated.

The **resolving power (RP)** of a corrected objective, expressed in seconds of arc, is given by **RP" = 120/D** where **D** is the diameter of the objective in millimeters. The human eye has an RP of about 60". Hence, the maximum magnification you can obtain from an objective (MM) is given by the ratio between the RP of the eye and that of the objective: $\mathbf{MM = RP_{eye} / RP_{ob}}$.
For instance, an achromatic objective with a diameter of 80 mm has an RP of 120 / 80 = 1.5". Hence, the right magnification using this objective should be 60 / 1.5 = 40X. In practice, you can double this value, but it is better avoiding to go further, because the amount of visible detail will not increase. In the end, follow this simple rule: the magnification power of a telescope has not to exceed the diameter of its objective, expressed in mm. Check the real RP of your instrument by means of double stars whose angular distances are tabulated in astronomical books.

OBSERVATIONS AT THE TELESCOPE

The most spectacular heavenly body to observe with a telescope is without a doubt the Moon. The best time to observe the Moon with your telescope is at the first quarter, when it appears only half illuminated. Under these conditions, lunar mountains and craters project long shadows, making them better visible from the Earth.

Make your first observations with the simple telescope, the one with the eyeglass lens as objective. At the beginning, keep the objective at the maximum aperture. At the edge of the objects, you can see the blue color at one side, and the orange color at the other side. These colors are produced by chromatic aberration. The image will appear quite confusing. Now place the diaphragm on the objective. It will greatly reduce the aberrations, you see the difference! But on the other hand, the brightness of the image will be dramatically decreased as will the resolving power. Using an achromatic telescope, instead, these defects are by comparison nearly imperceptible even without a diaphragm. In fact, with this type of instrument, the diaphragm is not needed.

Other objects to observe are the nearest planets. Jupiter shows four satellites aligned along the equatorial plane, appearing as a model of the solar system. For observing the Rings of Saturn, you will need of an instrument of good quality and high magnification power. The comparison between the apparent sizes of Jupiter and Saturn give you an idea of great distances in astronomy. You can also see Venus, which shows phases as the Moon, and you can even see star clusters and double stars.

WARNING:
DO NOT USE THE TELESCOPE TO OBSERVE THE SUN!
You will burn the retina of your eye!

What you can do, instead, is to project the image of the Sun on a screen or on a wall of your room. You can do this during a solar eclipse. You will enjoy an amazing spectacle, which you can share with many friends.

Terrestrial observations are also amusing. With the telescope, you can appreciate that the birds flying in your garden are not all sparrows, but also titmice, robins, finches, blackcaps, etc. With your telescope, you will be able to recognize the various species by their colored plumage. You can also observe the insects flying on the flowers, without getting your nose stung!

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