TELESCOPE EYEPIECES

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The function of an eyepiece is to magnify the image formed by the other optical elements of the telescope, and to present to the eye a bundle of rays covering a fair viewing angle and in a condition to be refocused by the eye easily and clearly on the retina. It is axiomatic that no optical system is perfect; imperfections of one kind or another may vitiate the retinal image, and the aim should be to reduce those from the telescope until they are smaller than the imperfections of the human eye itself. When choosing an eyepiece a compromise is involved, and the factors involved can be itemized thus:

1. Cost.
2. Correction of optical errors which affect performance, *e.g.* spherical and chromatic aberration, coma, astigmatism, distortion, ghosts and flare.
3. Efficiency of light transmission.
4. Angle of field of acceptable definition.
5. Eye clearance.
6. Suitability for projection purposes.
7. Hardness and durability of external surfaces and accessibility for cleaning.

Before considering each item it is desirable to stress that simple and cheap eyepieces may be quite satisfactory for long focal ratio (focal length/aperture) telescopes, *e.g.* f/10 upwards, yet quite unsuitable for those of short focal ratio, *e.g.* f/4 to f/7. The vast majority of reflecting telescopes in use by amateurs have medium focal ratios f/7 to f/10. The ratio referred to is the final focal ratio in the case of compound telescopes or those fitted with Barlow or transfer lenses.

1. Cost. The fewer the elements, the lower the cost, and if the elements are identical and of low-cost glass, so much the better from this one point of view. The most expensive types have five or six elements with several different types of glass of varying degrees of hardness and stability. These complex types are usually designed for wide fields and low focal ratio, usually for use after prisms, and are often bulky and heavy. If used with high focal ratio instruments, *e.g.* the normal astronomical refractor, they may be much inferior to the simple two-element Huyghenian type.

2. Correction of Optical Errors. As already mentioned, simple eyepieces of the one or two-element type can give quite good definition when used with telescopes of focal ratio greater than f/9. For f/4 to f/7 more complex types are essential. They can be of three or four-element type for medium field angles (see under heading *4* for a definition of this), but for wide and extra wide fields, five or six-element types are necessary. At or near the centre of the field, the only errors of significance are spherical and chromatic aberration. To illustrate the effect of these errors and their great dependence on focal ratio, an example will be useful.

If a Hughenian eyepiece is applied to a good f/5 telescope, a halo of aberration will be seen surrounding the image of a bright star or planet. If the aperture of the telescope is then halved by fitting a stop making the focal ratio f/10, the aberration halo will be invisible because it is reduced in diameter by a factor of 8 and by a factor of 64 in area. Thus the visibility of the error can be considered to vary inversely as the fifth power of the f/number, an enormously important variation. Replacing the Huyghenian with an orthoscopic eyepiece of good type, the aberration halo at the full aperture f/5 will be no more than that of the Huyghenian at f/10.

3. Loss of Light in Transmission through the eyepiece is inevitably greatest with complex types, but lens coating (blooming) can offset much of this loss, as shown in figures 1 to 10. Every air/glass surface contributes to this loss. Other small losses occur at cemented surfaces and by absorption in the glass. It is not advisable to coat the lens surface nearest to the eye as this is usually subject to frequent cleaning and the coated surface is more vulnerable to scratches during cleaning.

The reflection loss per air/glass surface is slightly over 4% for crown glass and about 6% for dense flint and dense barium crown. Glasses of the two latter types acquire a natural bloom with age, due to leaching out of the lead and barium in the surface layers in humid atmospheres. This natural state is sometimes beneficial, but eventually the outer surface weathers to a scattering layer of an undesirable kind.

Loss of light by absorption does not usually exceed 1% per element except when cheap green glass is used.

Typical figures for overall loss of light are:

Single-element type:	Loss	9% uncoated
		6½% coated 1 surface
2-element type:		17% uncoated
		10% coated 3 surfaces
3-element (4-glass/air):		19% uncoated
		11% coated 3 surfaces
4-element (4-glass/air):		21% uncoated
		12% coated 3 surfaces
5-element (6-glass/air):		28% uncoated
		15% coated 5 surfaces
6-element (6-glass/air):		30% uncoated
		16% coated 5 surfaces

The gain from coating in the last item is between a transmission of 70% and 84%: this is a 20% gain in light.

4. Angle of Field. The angle through which the eye moves between an examination of two opposite sides of the field of view is called the 'apparent' angle of view. This must not be confused with the actual field when the eyepiece is used with a particular telescope.

Apparent fields less than 35° are considered narrow, 35° to 50° are medium, 50° to 60° are wide field and 60° to 80° are extra wide fields. In no type of eyepiece is definition at the edge of the field as good as in the centre. The edge deterioration is not particularly serious because an object under close scrutiny should be brought near to the centre.

A wide field is useful for searching purposes or for spectacular views of star clusters or wide spreading objects. Vignetting, or partial obstruction by the mounting of the outer ray bundles is very common in wide and extra wide field eyepieces. This may affect the use in variable star work—but not for general viewing. The majority of telescopes are fitted with medium field eyepieces.

5. *Eye Clearance* is the distance between the outer lens surface and the exit pupil, *i.e.* the image of the primary formed by the eyepiece. It is here that the various parallel bundles of rays from all points of the field converge, and the iris of the eye should be located here if the whole field is to be visible at once. If the clearance is less than 8 mm the iris cannot be placed at the exit pupil, and only part of the field of view can be seen without moving the eye about. A clearance of 16 mm or more is necessary to see the whole field at once by a spectacle wearer. The clearance is rarely more than 80% of the eyepiece focal length, hence a wide field cannot be seen *in toto* without eye movement with eyepieces less than 20-mm focus for spectacle wearers, or 10-mm focus for others. Thus there is no great virtue in wide fields for short-focus eyepieces; even a 30° field is acceptable for really high powers—especially with a clock-driven telescope. For low powers on the other hand it is possible (but not common) to have too great an eye clearance. This results in unpleasant shadowing of the field until the eye is withdrawn to the exit pupil.

6. *Suitability for Photography.* In general the three to six-element achromatized types are most suitable for photography by projection through the eyepiece. The simple Huyghenian, if correctly made, does not show colour fringes when used visually, because the red and blue virtual images are seen of equal size. When used for projection, colour fringes may be troublesome, but not seriously so for large focal ratios.

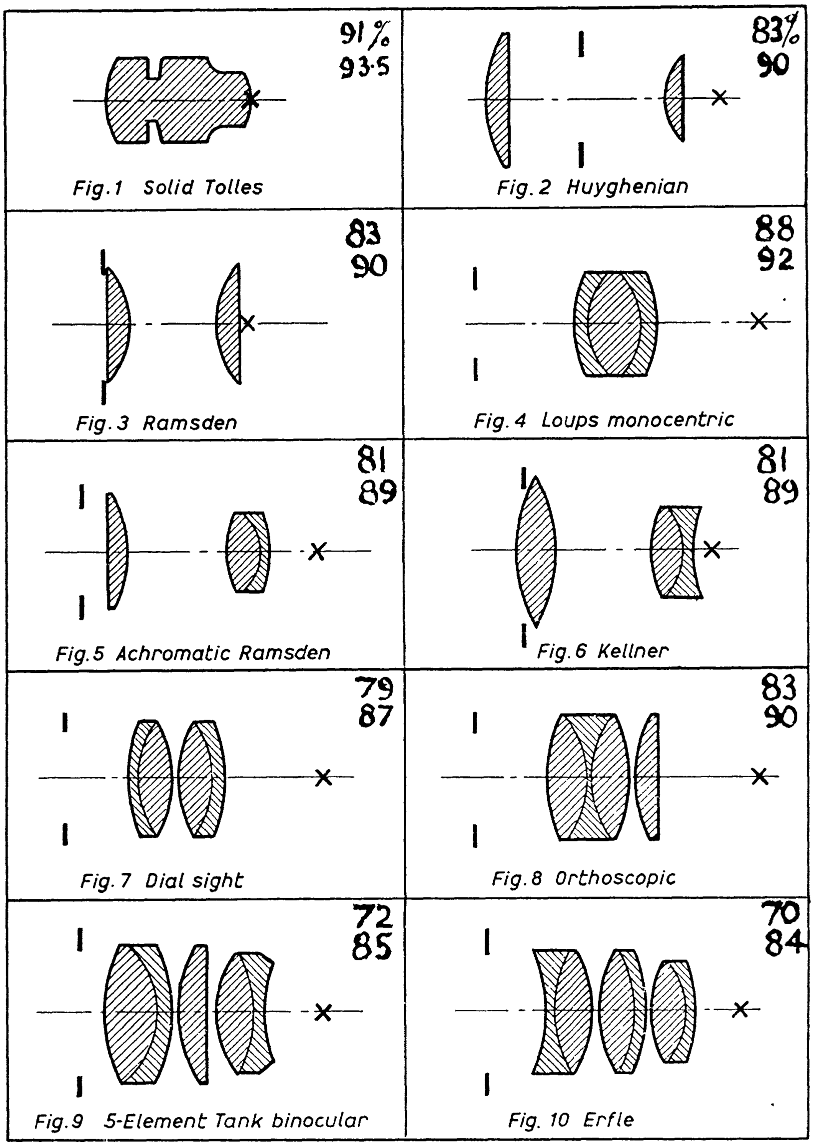
7. *Accessibility* of the elements for cleaning is quite an important point. In particular the surface next to the eye should not be shrouded with an eyecap which would prevent easy cleaning. The outside field surface is also liable to collect dust and should be easily accessible for cleaning yet protected from contact when laid down. The inner surfaces may need attention at, say, yearly intervals and again should be accessible. Permanent burnishing in of elements preventing dismounting should be condemned. Durability of the glass, particularly of the outer surfaces, is worth consideration. This point is dealt with for specific types in the next section.

Descriptions of Eyepiece Types

Figures 1–10 illustrate the form and relationship of all the eyepiece types in common use, given in order of increasing complexity. The small cross shows the position of the exit pupil or eyepoint for each type.

Figure 1 shows the single-element Tolles form—sometimes called solid

Huyghenian. It has high light transmission and no ghosts. Spherical aberration is less than one-fifth that of an equal focus Huyghenian, and it gives crisp and colour-free images even for f/6 telescopes. The disadvantages are fairly severe; considerable field curvature and no eye clearance, also a small field of 28°–30° of which little more than 20° can be seen without eye movement. The focal plane is internal and a groove in this plane forms the field stop. If this is omitted (indeed from any eyepiece) a blurred edge to the field of view results—psychologically less satisfying than a sharp boundary.



FIGURES 1–10. Ten basic forms of eyepiece, with positions of field stop and eyepoint, and giving percentage of light transmission—uncoated and coated. [This illustration appeared in the *Year Book of Astronomy 1963*, published by Eyre & Spottiswoode (Publishers) Ltd. It has been modified by the author.]

Hard crown or barium crown glass is used and the best ratio and separation of the curves vary with the glass type. If the small field is not objected to, it is an excellent eyepiece for planetary and double star observation.

An achromatic version with a cemented eyecap of dense flint glass has been used—this puts it into the class of figure 4 with corresponding advantages but higher cost.

Figure 2 is the common Huyghenian—one of the oldest and cheapest types and well suited to long focal ratios. It is probably more used for refracting telescopes and microscopes than any other kind—both have long focal ratios. Its merits for these duties are considerable. Fields of 40°–45° are usual, flat and colour free, and the lenses are of inexpensive crown glass, durable and not easily scratched. Poor design and manufacture, such as the use of poor non-optical glass, bad centring and wrong separation has often vitiated the performance, but this is not a defect of the type. A real disadvantage is the large amount of spherical aberration, amounting to 3% to 4% of the focal length for f/10 telescopes and four times this for f/5. The effect of this is described in the example under item *2* above.

If a telescope is found to be overcorrected (not uncommon in falling temperature gradients), use of this type of eyepiece may well be found to neutralize the error for medium to high powers even for f/6 to f/8 telescopes.

The textbook 3:1 ratio of foci of the elements results in a small eye clearance. A better and much used compromise is a ratio of 2:1 with a separation half the sum of the foci (element foci 0·75 and 1·5 times the eyepiece focus); plano-convex is the standard form of the lenses but variants giving slightly improved results have been used. Another variant with a cemented achromatic eye lens has been used for projection purposes.

Figure 3 is the common Ramsden eyepiece. The textbook form, consisting of two identical plano-convex lenses of crown glass separated by a distance equal to their focus, suffers from zero eye clearance and in having the field lens in focus together with any dust on its surface. In addition there is a great deal of outfield false colour. The first two defects are reduced by making the separation about 70% of the focal length, which is fairly common practice. This gives an eye clearance of about 20%, not sufficient to enable the field of 40°–50° to be seen without some eye movement. The spherical aberration of the Ramsden is much less than that of the Huyghenian, and it can be used down to about f/6 in short foci.

The field stop is just outside the lens, and the type has been much used for micrometers and surveying instruments which have cross wires coincident with the primary image. For non-spectacle wearers the close eyepoint is less inconvenient, and the outfield colour can be made use of to counteract atmospheric dispersion to some extent for low-altitude astronomical objects. Observers with short sight (myopia) find they still focus dust on the field lens too easily, and get more satisfaction from the Huyghenian, with which this does not occur. The Ramsden is the cheapest two-element type to produce, and is used in America to a much greater extent than in England.

Figure 4. A cemented triplet, which has been considerably favoured for its crisp images and economy of light, is the monocentric or its equally satisfactory variant, the 'Loups' triplet. In the former all the six curves are struck from the same point, the centre lens being of crown glass which is nearly spherical; the two outer lenses are of dense flint—relatively soft. With the concentric design, centring of the components becomes of minor importance, but little if any other advantages accrue, and it is noteworthy that many pre-war Zeiss Monocentrics did not follow this design, but were of the 'Loups' type as shown in the figure. With only two air-glass surfaces and a good eye clearance of 80% or more, they make an efficient type of eyepiece very free from errors, and there is less curvature of field than the solid Tolles of figure 1. However, the field of view is small—only 30°. They can be used down to f/5 or even f/4, but are relatively expensive, although the cost of production should obviously be less than the four-element orthoscopic of figure 8.

Figure 5. The achromatic Ramsden is a great improvement on the simple two-element type of figure 3. A common design has a plano-convex field lens of crown glass and a cemented doublet eye lens, with a plane or slightly convex surface to the dense flint element facing the eye. However, many variations are made with the plane surfaces replaced by convex surfaces. The crown component of the eye doublet is usually of barium crown. This achromatic Ramsden is probably the most common three-element type extant, and is fitted to many military instruments and to probably 80% of all prismatic binoculars. It has a field from 40° to 50° and an eye clearance of 30% to 45%: the performance is good and the field flat, and it is usable even down to f/4. The outfield colour of the two-element Ramsden is eliminated by the corrected eye lens, but the dense flint eye surface is vulnerable to scratches. Although made in such large numbers in the focal range 15 mm to 27 mm they are not invariably well made or well designed, although those by well-known makers can usually be relied on. The proper description of this type is achromatic Ramsden, but it is often referred to as Kellner type. The eyepiece properly described as of Kellner type is that shown in figure 6, which has a double convex field lens with a cemented doublet eye lens having a concave surface facing the eye. The type is not common, but had a vogue in microscopy at one time. It has a very wide and flat field (*e.g.* 60°), but such a small eye clearance that much eye movement is required to see the whole field. A further defect is that dust on the field lens is in focus.

Figure 7. Dial Sight Orthoscopic, Plossyl, etc. This type was used in large numbers in military instruments, and gives a large eye clearance of 80% combined with a good flat field of 40°. The design is also used for rifle sights where a large eye clearance is a vital requirement, and for erecting purposes in gun sighting and other telescopes. It consists of two fully corrected achromats placed crown sides together and nearly touching. Usually the two cemented achromats are of crossed convex form and are identical, but a number of variations in design exist in which the eye doublet is of shorter focus than the other. By this means, fields of up to 50° are achieved. Other variants have

plane outer surfaces. They are excellent for astronomical use for foci down to 15·24 mm and the only disadvantage is the vulnerability of the relatively soft eye lens to scratches. The old Browning achromats can be considered as variants of this form, but the separation of the doublets is much greater than for the dial sight type.

Figure 8. True Orthoscopic. This type, to which the name was originally given, is distinguished by the plano-convex eye lens with the plane side next to the eye, and a triplet field lens. This cemented triplet is overcorrected to balance the errors of the simple eye lens, and consists of a double concave dense flint lens between two hard crowns—symmetrical in some designs, but not in the best ones, in which a field of 50° is achieved; the field is usually 35°–40°. The eye clearance is as large as the dial sight type, *viz.* 80% of the focus. It has all the other merits of the dial sight type and it is unique in four-element eyepieces in having all the exposed surfaces of hard and durable glass. There are numerous variations in the pattern, but maintaining the characteristic of a plano-convex eye lens. One variation by Goerz, with a plane outer surface to the triplet and a dense barium crown eye lens, achieves a field of 60° at the expense of soft and relatively unstable glass at both ends. A further variant used in some German military instruments has a cemented quadruplet field lens, and a field of 75°–80° is attained with long eye relief. Large fields have also been obtained by using an aspheric eye lens with a triplet field lens.

Figure 9 is a five-element eyepiece used in tank binoculars and giving an extra wide field of 75°. This is selected as one example of the numerous designs of five-element eyepieces that have been used in military instruments. Most of these designs have six air-glass surfaces, and all suffer to some extent in giving ghosts, which detract from astronomical use. The eye clearance of most designs is 40% to 50%, and their chief merits from an astronomical point of view arise from their wide fields and their availability at reasonable prices in the form of war surplus lenses.

Figure 10 is typical of the 'Erfle' six-element eyepieces available today and made for military use. They consist of three separated cemented pairs. The eye lens is undercorrected and the field lens overcorrected. Normally fields of 65°–70° are given, but some rather uncommon ones achieve 80°. The most common of this type in England was made for predictor sights, and has a focal length of 19 mm. For astronomical use it is advisable to beware of scratched eye lenses (made of soft glass), also of deteriorated cement in the three doublets, while they are also prone to giving one or more ghosts of bright objects. If in good order they are excellent for wide-field spectacular views and their suitability for projection. The eye clearance is about 50%, and for planetary observation they are not very suitable.

Zoom eyepieces have become available recently from Japanese sources. They have a large number of separated elements and although coated there is a strong danger in humid climates of light scattering developing from condensation and filming between the elements, which are not readily accessible for cleaning. For this reason and for the relatively high losses it is doubtful if they are advisable for astronomical use, especially as the power range covered is only 2·5:1 and refocusing is desirable after a power change. The alternative of combining a short-focus achromatic Barlow lens with a normal eyepiece of moderately low power can, with equal overall length, give a power ratio of about 4:1, and the fewer elements are all accessible for cleaning. An equally rapid power change to the Zoom, is given by a turret of three or more parfocal eyepieces.

Binocular Eyepieces for Astronomical Duties

The beam-splitter principle as used with high-power binocular microscopes is quite applicable for astronomy, but some loss of light compared with the monocular view is inevitable; this is minimized by using dielectric beam splitters instead of metal films. Matched pairs of eyepieces are, of course, necessary, and add to the cost. However, the view of astronomical objects, particularly the Moon and planets, is enhanced and made comfortable by the use of the two eyes.