Chapter 2

Binocular Optics and Mechanics

There are three main parts to a binocular's optical system:

- *Objective lens assembly.* This is the lens assembly at the "big end" of the binocular. Its function is to gather light from the object and to form an image at the image plane.
- *Eyepiece lens assembly.* This is the bit you put to your eyes. Its function is to examine the image at the image plane. The focusing mechanism of the binocular lets you move either the eyepiece assemblies or an intermediate "transfer" lens, so that the eyepieces can focus on the image formed by the objective lenses.
- *Image orientation correction.* In modern binoculars this is usually a prism assembly. Without this, the image would be inverted and laterally reversed, like that in an astronomical telescope. The prisms "undo" this inversion and reversal. In large binoculars, the prism assembly may also enable the eyepieces to be at 45° or 90° to the main optical tube. Binoculars are usually classified by the type of prism assembly they use, e.g., "Porro-prism binocular" or "roof-prism binocular" (Fig. 2.1).

Astronomical observation is exceptionally demanding of optical quality; this applies equally to binoculars as to telescopes, despite the much lower magnification usually used in the former. There are a number of reasons for this demand for higher quality:

- Try this experiment: Make a pinhole of 1 mm diameter or smaller in a piece of paper. Hold this page at a distance where it is just out of focus then, with the book at the same distance from your eye, hold the pinhole up to your eye so that you are now looking through it. Do you see how the page has now come into focus? Astronomy is normally undertaken in the dark, so your eye's pupil is at

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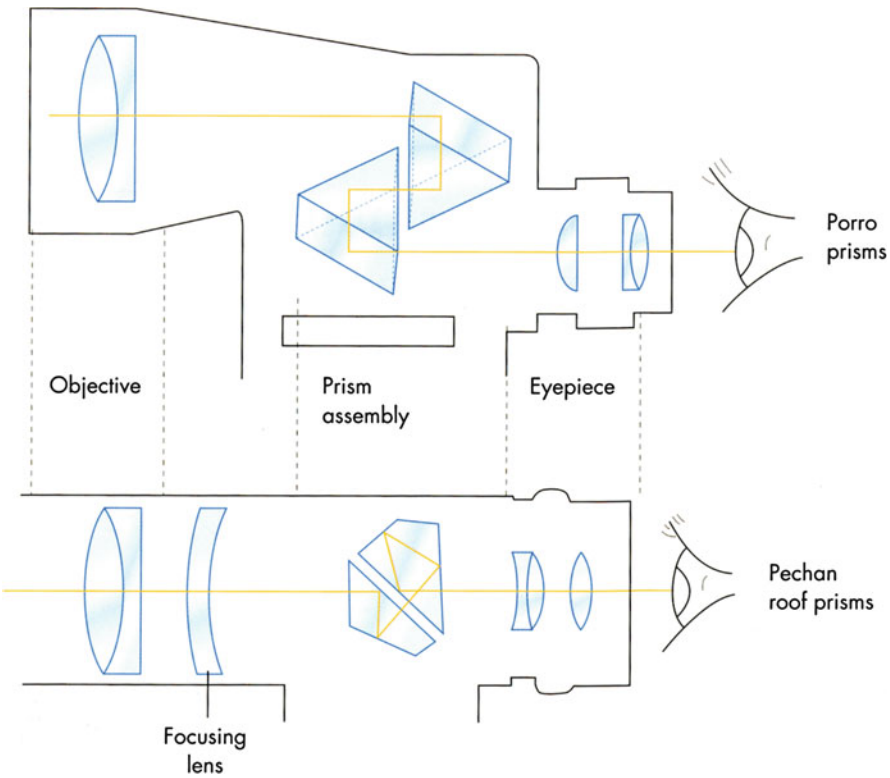

Fig. 2.1 Light-path through prismatic binoculars

its largest. In the daytime, when your eye's pupil is smaller, this smaller aperture can compensate for some optical aberrations in both your eye and the binocular. At night, when the pupil is larger, you do not have this compensation, so any aberrations in the binocular's optics will be much more obtrusive.

- Some visual astronomy involves either objects that are of high contrast with respect to the sky (e.g., double stars). The higher the contrast objects, the higher the demand of optical quality, especially control of chromatic aberration.
- Other visual astronomy involves observing objects of low contrast with respect to the sky (e.g., faint nebulae). Any reduction of contrast in the binocular will make it far more difficult for you to see these objects. All optical aberrations reduce contrast, so these must be kept to a minimum.
- For satisfactory observation of both high- and low-contrast objects, stray light must be minimized. With high-contrast objects, nonimage-forming rays can cause ghost images and reduce contrast if they reach your eye. With low-contrast objects, uncontrolled stray light reduces contrast, rendering the object less visible. Thus, light baffling must be properly designed and implemented, and antireflection coatings of the highest quality should be used on all transmissive surfaces of the optics.

Therefore, unless you are using your binocular only for casual scanning of the sky as a preliminary to using another instrument, it needs to be of the highest optical quality that you can afford. Once you have used a high-quality astronomical binocular, it is very difficult to use one of lesser quality without being dissatisfied, even irritated, by it.

Objective Lens Assemblies

The objective lens consists of two or more lens elements in an achromatic or apochromatic configuration. The achromatic doublet is the commonest lens in "standard" binoculars, but high-quality binoculars, particularly large astronomical binoculars, may have an apochromatic triplet. There may also be additional lenses to correct for other optical aberrations such as spherical aberration (SA), coma, or field curvature. These assemblies containing four or five lenses may be termed "Petzval" lenses, but they are a far cry from the original Petzval lenses, which suffered from a very restricted field of view (about 30°) and a highly curved focal surface. The image "plane" from a simple achromatic or apochromatic lens is actually a curved surface. The purpose of Petzval, and other field-flattening, lenses is to correct the image plane so that it lies on a flat (or, at least, flatter) surface. The binoculars that have these multi-lens designs tend to have coma and field curvature very well controlled. Achromats bring two wavelengths (colors) of light to the same focus. A simple achromatic doublet would have a biconvex element of crown glass in front of a weaker diverging element of flint glass. Modern achromats may use special glasses, such as extra-low dispersion (ED) glass, in order to give better color correction. Apochromats, which bring three wavelengths of light to the same focus, may employ expensive (but brittle) fluorite glass.

Large aperture astronomical binoculars have objectives of relatively small focal ratio, usually as small as f/5, and sometimes less. An achromatic doublet of 100-mm aperture with a focal ratio of f/5 will have significant chromatic aberration, especially off-axis, no matter what glasses are used. This can be particularly obtrusive on bright objects, such as the Moon or the naked-eye planets. Even a fluorite apochromat of this aperture and focal ratio will show off-axis false color on these objects.

Eyepieces

Binocular eyepieces usually consist of three or more lenses in two or more groups. The most common is the venerable Kellner configuration, a design dating from 1849 and which consists of a singlet field lens and a doublet eye lens. Increasingly common are reversed Kellners, a design that was introduced in 1975 by David Rank of the Edmund Scientific Company and used in its RKE eyepieces. The field lens is the doublet and the eye lens is a singlet. The reversed Kellner has the advantages of a slightly wider field (50° as opposed to the 45° of a Kellner), over 50 % more eye relief, and of working better with the short focal ratios that typify binocular objec-

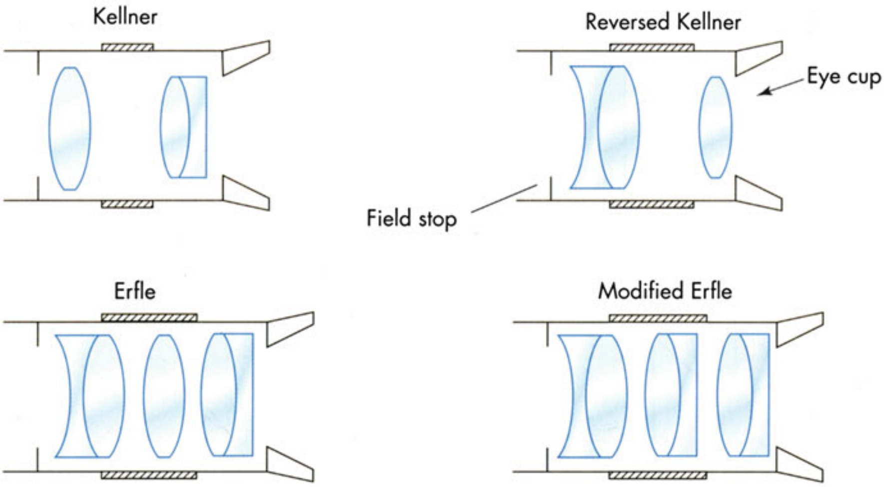

Fig. 2.2 Some common binocular eyepieces

tives. An example of this is the lower-power eyepieces in those 100-mm binoculars, such as the Miyauchi Bj-100B, that have interchangeable eyepieces. Wide-field binoculars usually use modifications of Erfle eyepieces. These consist of five or six elements in three groups. They can have a field of up to about 70°, but eye relief tends to suffer when the field exceeds about 65°. Erfle-type eyepieces have been used extensively in everything from Zeiss Jenoptem and Deltrintem models since 1947 to the current Kunming BA8 models (branded as *Garrett Signature* in the USA and *Helios Apollo* in Europe) (Fig. 2.2).

Prisms

The prisms in binoculars serve primarily to correct the inverted and laterally reversed image that would otherwise result from the objective and eyepiece alone. A secondary effect is that they fold the light path, so that the binocular is shorter than it would otherwise be. For smaller binoculars in particular, this makes them easier to handle. As stated above, binoculars are often classified according to their prism type. For modern binoculars without angled eyepieces, there are two basic types: the Porro prism and the roof prism.

The Porro-prism assembly consists of two isosceles right-angled prisms mounted with their hypotenuses facing each other but with their long axes exactly perpendicular. This latter point is crucial; if they are not exactly at right angles, image rotation (usually referred to as "lean" when it applies to binoculars) will occur. The angle of lean is twice the angle of misalignment and opposite in direction, i.e., a clockwise misalignment of 0.5° will result in an anticlockwise lean of 1.0° (see Fig. 2.3). The light path in Porro prisms is shown in Fig. 2.4. There are four

Fig. 2.3 A rotated prism will cause twice as much rotation in the image

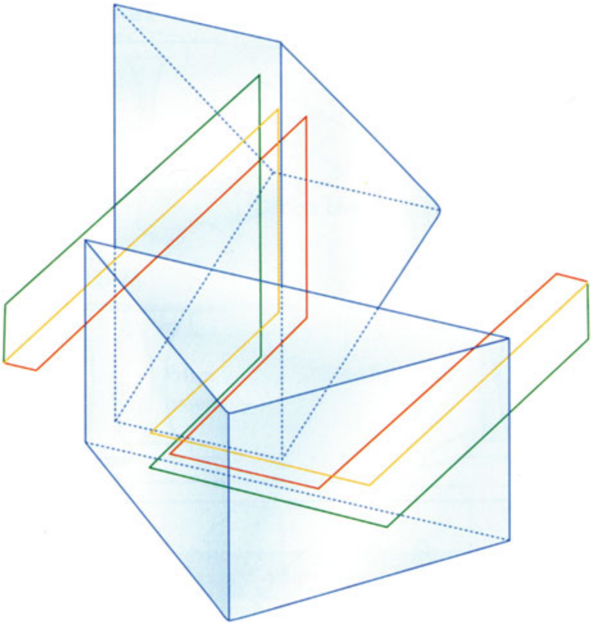

Fig. 2.4 Image inversion and lateral reversal in Porro prism

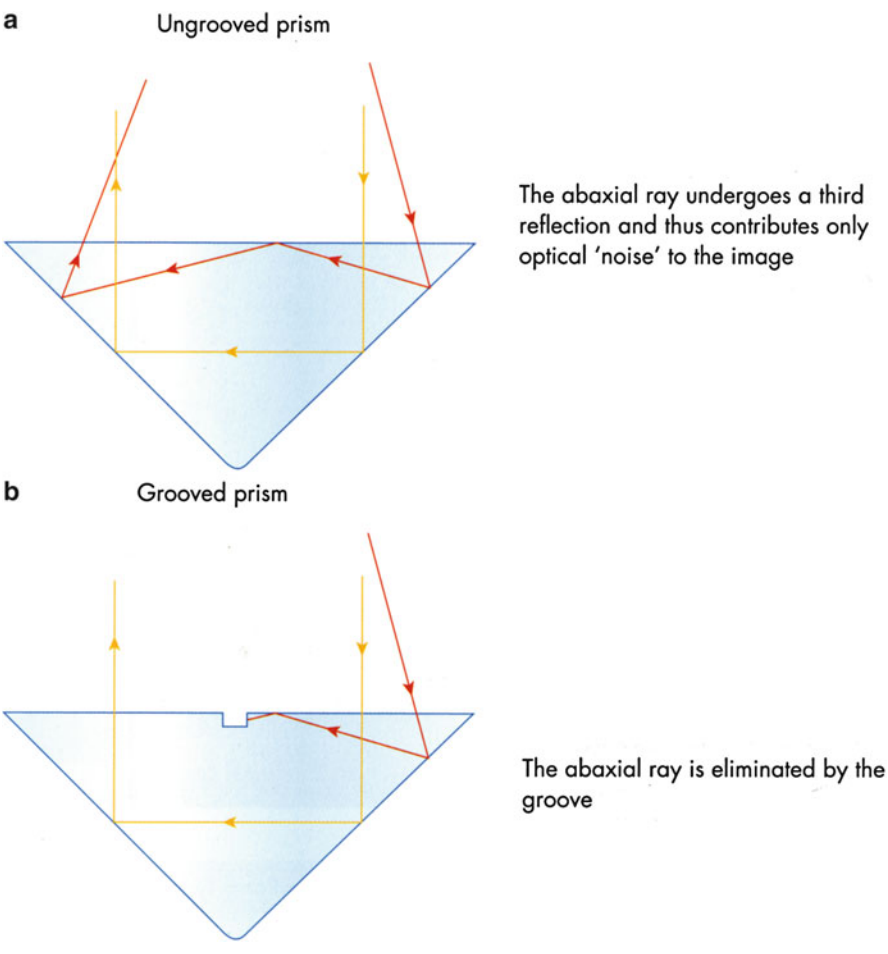

Fig. 2.5 Porro prism groove

reflections, so the result is a right-handed image. The mutually perpendicular orientation of the prism hypotenuses results in one prism erecting the image and the other reverting it.

It is possible, especially when they are used with objectives of low focal ratio, for Porro prisms to reflect rays that are not parallel to the optical axis in such a manner that they are internally reflected off the hypotenuse of the prism (Fig. 2.5a). The ray then emerges from the prism having been reflected a third time and contributes only optical "noise" to the image, thus reducing contrast. This extra reflection can be eliminated by putting a groove across the center of the hypotenuse (Fig. 2.5b). Grooved prisms are a feature of better-quality Porro-prism binoculars.

A development of the Porro prism is the Abbé Erecting System, also known as a Porro type-2 prism, (Figs. 2.6 and 2.7). Its lateral offset is 77 % that of an equivalent

Fig. 2.6 Abbé erecting system, also known as a Porro type-2 prism

Porro-prism assembly,[1] and for this reason, it is most frequently encountered in larger binoculars which would otherwise have to have their objective lenses more widely spaced to allow the eyepieces to have a usable range of interpupillary distance. For medium-aperture binoculars, it is more common in older instruments, particularly military binoculars from the early and mid-twentieth century. Abbé Erecting Systems are usually identifiable by the cylindrical prism housing, although the reverse is not true, i.e., this feature is not diagnostic of the presence of the Abbé system.

Another consideration is the glass used for the prism. Normal borosilicate crown (BK7—the *BK* is from the German *Borkron*) glass has a lower refractive index than the barium crown (BaK4—the *BaK* is from the German *Baritleichtkron*) glass that is used in better binoculars. A higher refractive index results in a smaller critical

[1] Yoder 2002

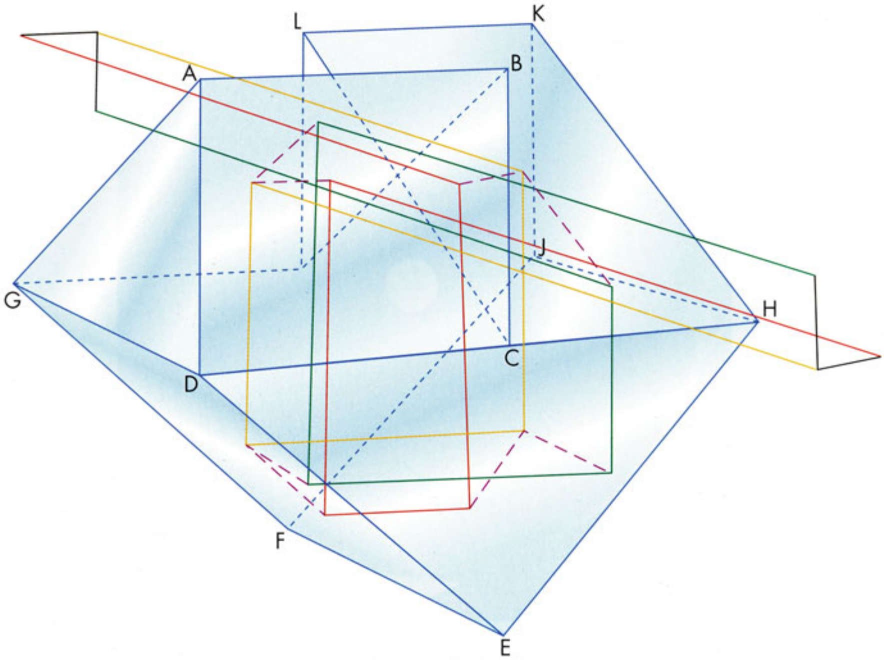

Fig. 2.7 Light path in Abbé erecting system (aka Porro type-2)

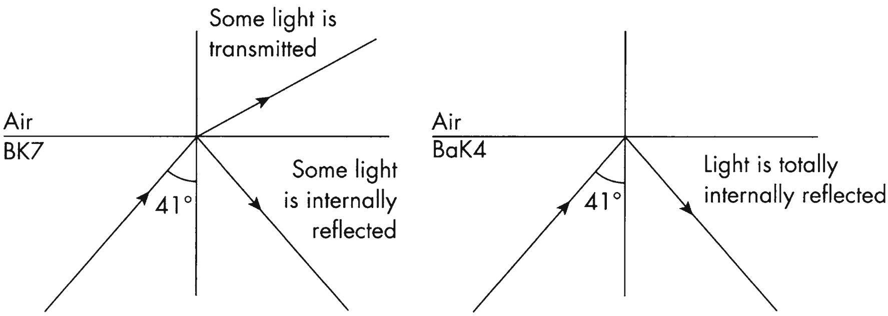

Fig. 2.8 Bk7 and BaK4 glass. At angles close to the critical angle of Bak4 glass, some light will be lost due to transmission in BK7 glass

angle, 39.6° in BaK4 as compared to 41.2° in BK7, so there is less light likely to be lost because of non-total internal reflection in the prisms (Fig. 2.8). The difference is more noticeable in wide-angle binoculars whose objective lenses have a focal ratio of f/5 or less. The non-total internal reflection of the peripheral rays of light cone from the objective results in vignetting of the image. This effect can easily be

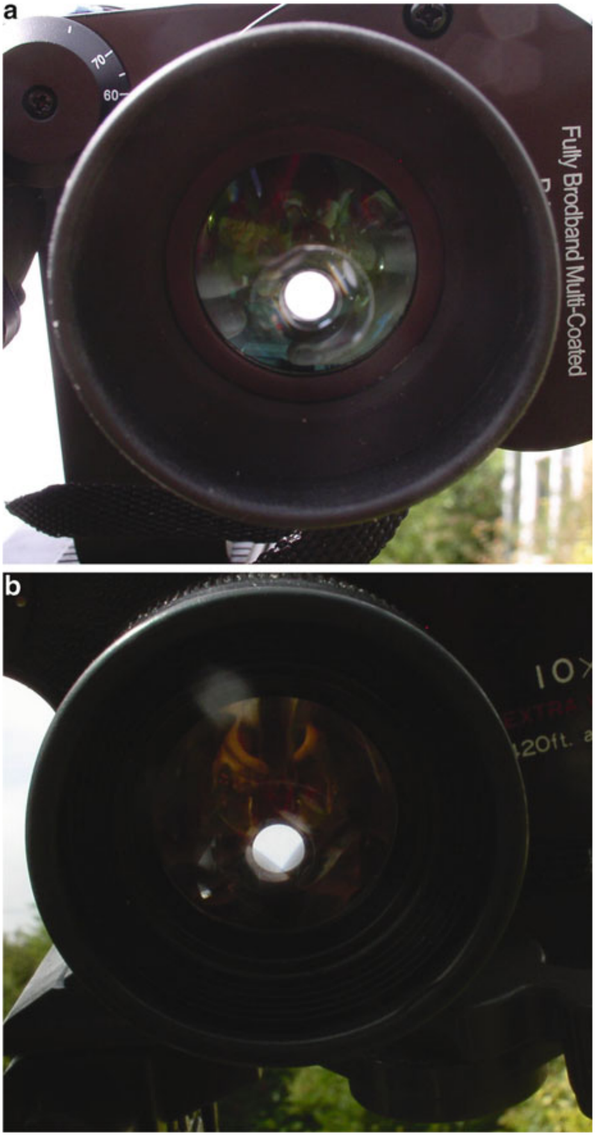

Fig. 2.9 The effect of prism glass on the exit pupil. (**a**) BAK4 prisms. (**b**) BK7 prisms

seen by holding the binocular up to a light sky or other light surface and examining the exit pupil. The exit pupil of a binocular with BaK4 prisms will be perfectly round, while that of a binocular with BK7 prisms will have telltale blue-gray segments around it (Fig. 2.9). (Note: Fig. 2.9b was taken from a slight angle in order to show the nature of the vignette segments. Viewed from directly behind the exit pupil, there is a square central region with vignette segments on four sides.)

Glass Type	Refractive Index	Critical Angle	Dispersion
Schott BaK4	1.5688	39.6°	-0.0523 μm^{-1}
Chinese BaK4	1.5525	40.1°	-0.0452 μm^{-1}
Schott BK7	1.5168	41.2°	-0.0418 μm^{-1}

Fig. 2.10 Specifications of some common prism glass

However, BaK4 glass has a lower Abbé number than Bk7 glass. This means that any rays that are not normal (perpendicular) to the prism when they enter or exit it will be dispersed more by BaK4 glass than by BK7 glass. At the magnification in most binoculars, you are unlikely to be able to detect this in use, but it is one of the reasons that BK7 prisms may be a preferable prism material for specialist high-power binoculars.

It is important to recognize that the prism glass is but one of the many considerations that affect image quality. There are excellent older binoculars that use BK7 glass for the prisms and which give a better image quality than many of the modern budget offerings that have “BaK4” printed on their cover plates. BK7 is also the glass of choice for binoviewer prisms, owing to its lower dispersion and the lack of need to accommodate wide-angle use.

Bak4 is a glass designation used by Schott AG, an old and respected German manufacturer of optical glass. Although there are international standards for optical glass designation, BaK4 isn’t one of them. Anyone can apply it to any glass. The international standard designation for Schott BaK4 is 569561. The first three digits tell you its refractive index (1.569) and the last three tell you its Abbé number (56.1), which indicates how much it will disperse light into its component colors; the higher the Abbé number, the less the dispersion. However, I don’t see customers being willing to learn and compare international standard designation codes: “Bak4” trips off the tongue so much more easily.

This is what you should know: the “BaK4” glass used for the prisms of Chinese binoculars is not the same as Schott BaK4. In fact, it’s not even barium crown, which is what BaK stands for! It is a phosphate crown glass with a lower refractive index and dispersion than Schott BaK4 (but higher than BK7). It also potentially has a higher “bubble count” (Fig. 2.10).

In practice, this may not be all bad. Unless you have very wide-angle binoculars, you are unlikely to notice the effect of the lower refractive index, and the lower dispersion than “real” BaK4 means that there may be less dispersion in the image (not that you are likely to be able to see it). The potentially higher bubble count means there may be more light scatter inside the prism; I’ve not been able to detect it in use.

The roof prism is shown in Fig. 2.11. It is a combination of a semi-pentaprism (45° deviation prism) (Fig. 2.12) and a Schmidt roof prism (Fig. 2.13). The combination is a compact inversion and reversion prism that results in an almost “straight-through” light path. The consequence is a very compact binocular. There is, of

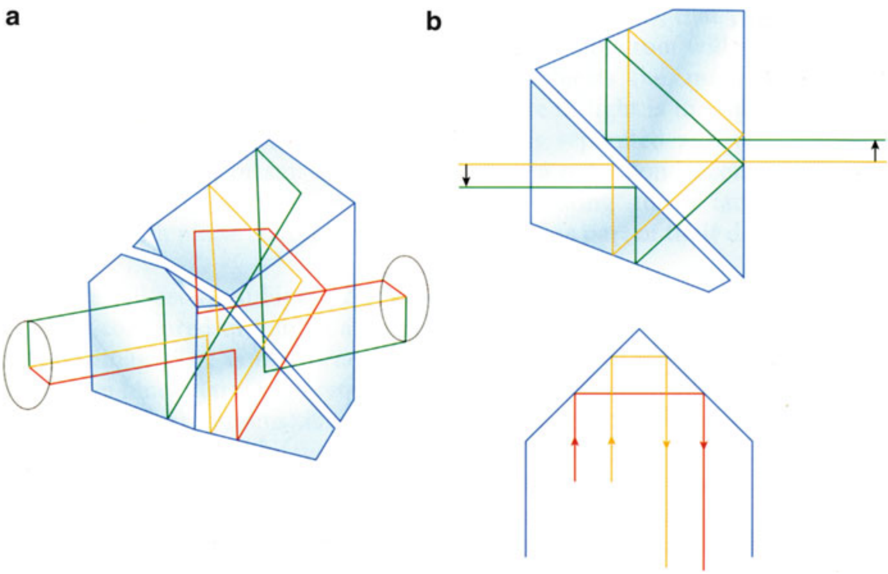

Fig. 2.11 Image reversal in Pechan roof prism

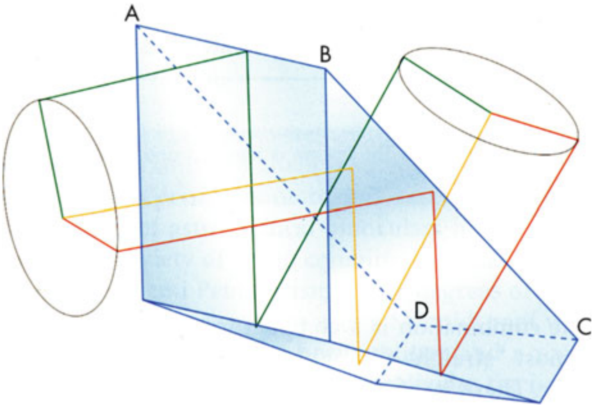

Fig. 2.12 Semi-pentaprism (45° deviation prism)

course, a limit to the aperture of roof-prism binoculars that is imposed by the "straight-through" light path because, the centers of the objectives cannot be separated by more than the observer's interpupillary distance (IPD).

Although the roof-prism configuration is physically smaller and thus uses less material in its construction, it tends to be significantly more expensive than a Porro-

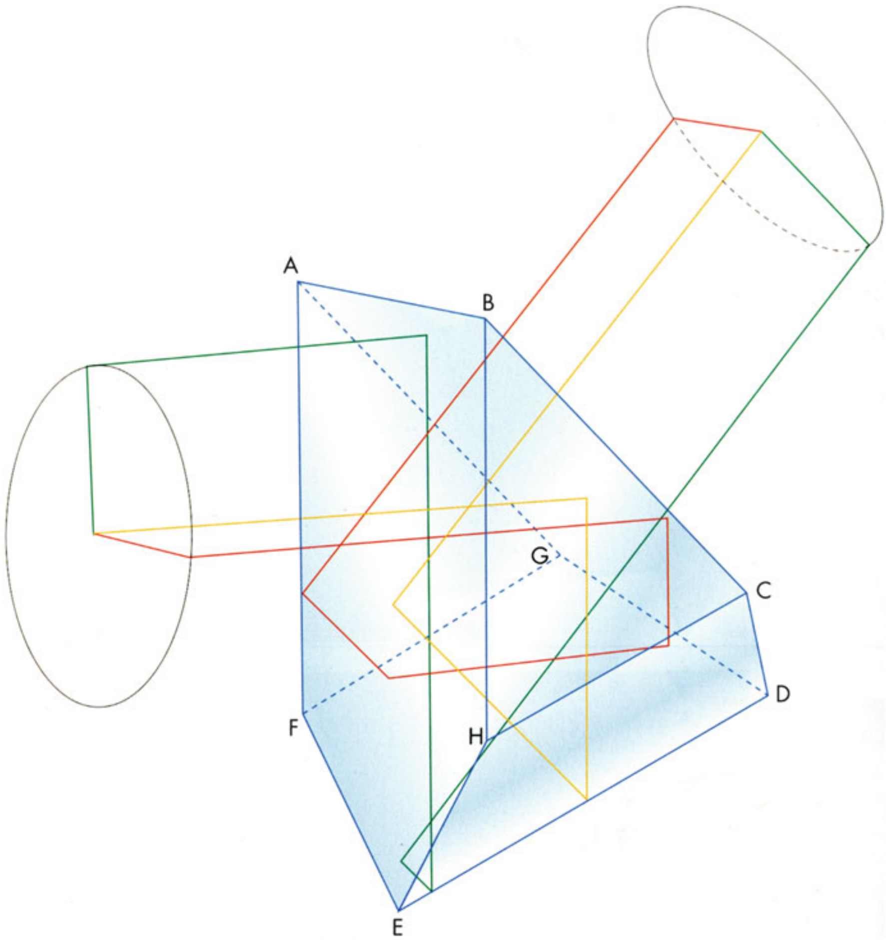

Fig. 2.13 Schmidt roof prism. The image is inverted and reverted. The axis is deviated by 45°

prism binocular of equivalent optical quality. This is because the prism system, particularly the roof itself, must be made to a much higher tolerance (2 arcsec for the roof) than is acceptable for Porro prisms (10 arcmin), i.e., 300 times as precise! Any thickness or irregularity in the ridge of the roof will result in visible flares, particularly from bright high-contrast objects, i.e., many astronomical targets. Additionally, a result of the wave nature of light is that interference can occur when a bundle (aka pencil) of rays is separated and recombined, as happens with a roof prism. The consequence is a reduction in contrast. This can be ameliorated by the application of a "phase coating" to the faces of the roof. Binoculars with phase coatings usually have "PC" as part of their designation (see Appendix 6).

As you will see from Fig. 2.11, the light in a Schmidt-Pechan roof prism undergoes six reflections (as opposed to four in a Porro-prism binocular). This results in a “right-handed” image. A consequence of the extra reflection and the extra focusing lens (as compared to Porro prisms) is more light loss. In order to achieve a similar quality of image, better antireflective coatings need to be used. The Abbe-König prisms used in some better-quality roof-prism binoculars have only four reflections, and the prism thus transmits about 2 % more light than the Schmidt-Pechan.

The demand for better quality of the optical elements and their coatings in roof-prism binoculars means that they will inevitably be more expensive than Porro-prism binoculars of equivalent optical quality. They do, however, offer three distinct advantages:

- They are more compact. This makes them slightly easier to pack and carry; some people (I am one) find the smaller size easier and more comfortable to hold as a consequence of the different ergonomics.
- They are usually slightly lighter. This makes them easier to carry and generally less tiring to hold.
- They are easier to waterproof as a consequence of the internal focusing. Although one does not normally do astronomy in the rain (the possible exception being the nocturnal equivalent of a “monkeys’ wedding”), nitrogen-filled waterproof binoculars are immune to internal condensation in damp/dewy conditions and will not suffer from possible water penetration when used for other purposes such as bird-watching or racing.

It is a matter of personal judgement whether these advantages warrant the extra expense. I find that, on account of their relative lightness and compactness, I observe with my 10×42 roof prisms far more than I do with my 10×50 Porro prisms.

There is a common misconception that roof-prism binoculars are “birding binoculars” and that Porro-prism binoculars are inherently better for astronomy. Whereas roof-prism binoculars are advantageous for birding (lighter, easier to waterproof) and Porro-prism binoculars generally offer equivalent optical quality at a lower price and are not aperture limited because of the design, both can be used for either activity, where the one with the better optical quality will generally perform better. The best handheld binocular I have used for astronomy is a Swarovski EL 10×50 (roof prism): it was light and well balanced, very bright, and had no noticeable aberrations.

An increasing number of astronomical binoculars have 45° or 90° eyepieces. There are a wide variety of prism combinations that will achieve this, such as a Porro type 2 with a semi-pentaprism for 45° or with a pentaprism for 90°. Another 45° system uses a Schmidt roof with a rhomboid.

Binoviewers use a combination of a beam splitter and a pair of rhomboidal prisms (Figs. 2.14 and 2.15). The beam splitter divides the light equally into two mutually perpendicular optical paths. A rhomboidal prism merely displaces the axis of the light path without either inverting or reverting it. In some binoviewers,

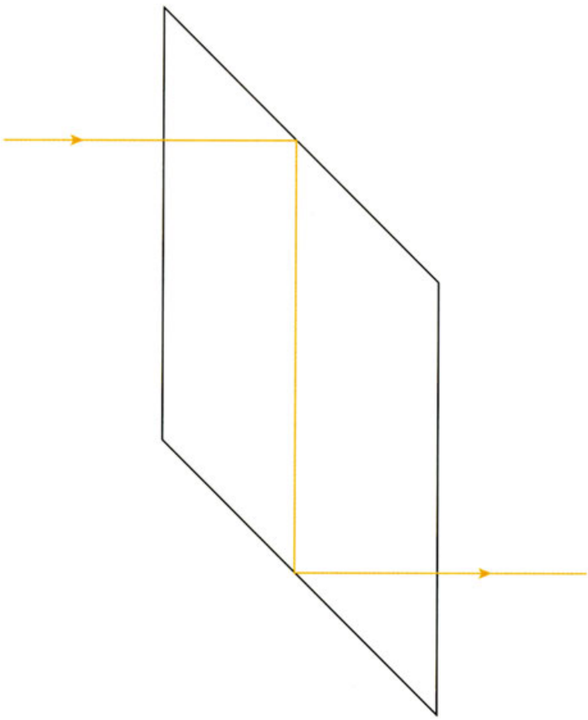

Fig. 2.14 Rhomboid prism. This prism displaces the axis

pairs of mirrors perform the same function. Cylindrical light tubes may be used to ensure that the optical path length is identical on both sides. Interpupillary distance is adjusted by hinging the device along the axis of the light path from the objective lens or primary mirror.

Some observers use image-stabilized binoculars. Image stabilization was first introduced for camera lenses and for military surveillance; the technology was later transferred to astronomical binoculars.

The system of image stabilization that has been most successful for astronomical purposes is that developed by Canon Inc. It employs what Canon calls a Vari-Angle Prism (Fig. 2.16) which consists of two circular glass plates that are joined at their edges by a bellows of a specially developed flexible film. The intervening space is filled with a silicon-based oil of very high refractive index. Microelectronic circuitry senses vibration and actuates the Vari-Angle Prisms so as to compensate for the change in orientation of the binoculars.

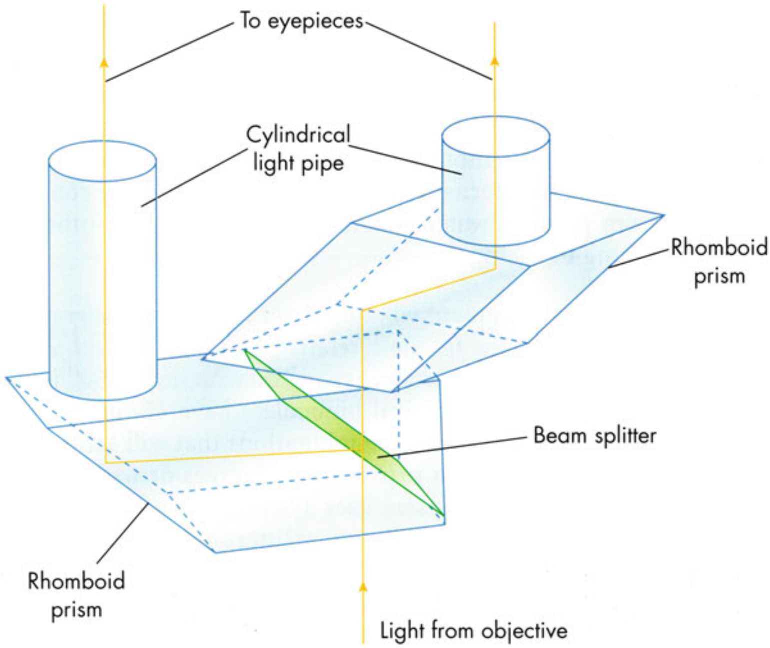

Fig. 2.15 The principle of binoviewer

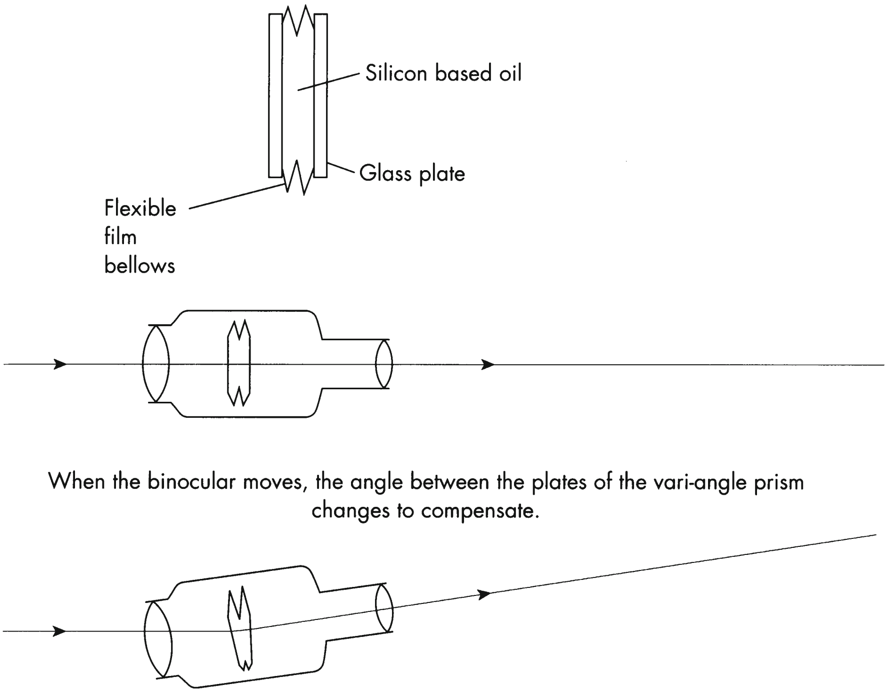

Fig. 2.16 Image stabilization with Canon's vari-angle prism

Coatings

The most important coatings in binoculars are the antireflective coatings on the surfaces of the optical components. An uncoated glass-to-air surface will reflect about 4 % of the light that is perpendicular to it ("normal incidence") and even more of the light that is oblique to it. By using interference coatings, this can be reduced to better than 0.15 % over a very wide range of the optical spectrum. The coatings are usually optimized for a particular wavelength of light, usually in the range 510–550 nm, which is the yellow-green part of the spectrum where the human eye is most sensitive to light. If the coating is optimized, intentionally or otherwise, for another part of the spectrum, the image will have a color cast. An extreme example of this is the "ruby" coatings found on some very low-quality binoculars, where the coating serves to remove light from one end of the visible spectrum in an attempt to conceal the poor color correction that is inherent in a cheap and inadequate optical design. A single coating of a quarter, the wavelength of light will reflect a small proportion of the incident light. The glass behind it will reflect another small proportion. The path length of the wave reflected off the glass is half (2×¼) a wavelength greater; the two reflected waves mutually interfere destructively, eliminating the reflection for that particular wavelength (Figs. 2.17 and 2.18). At wavelengths significantly distant from the wavelength for which the coating is optimized, interference may be constructive, resulting in more reflected energy than would have occurred in uncoated glass. Additional layers of half- and quarter-wave thickness can reduce reflections at other wavelength; this is

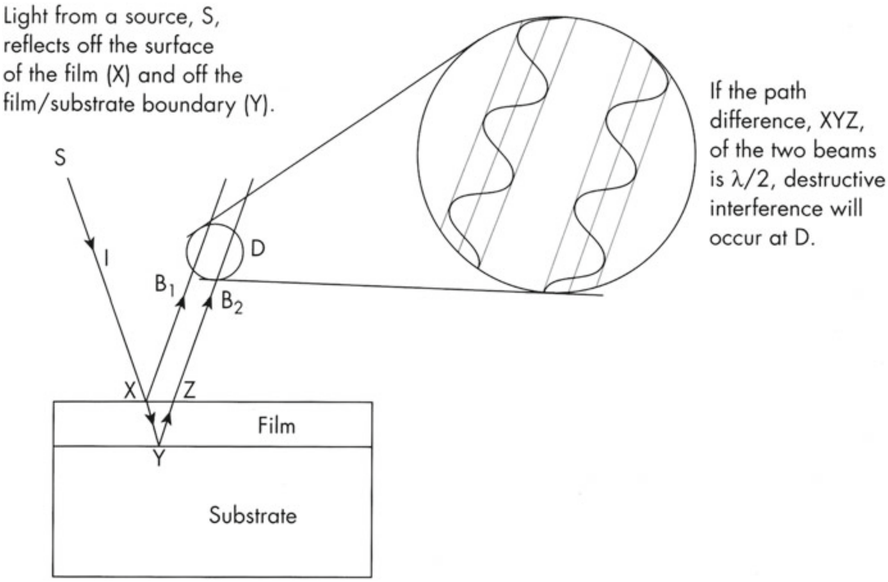

Fig. 2.17 Single layer flim

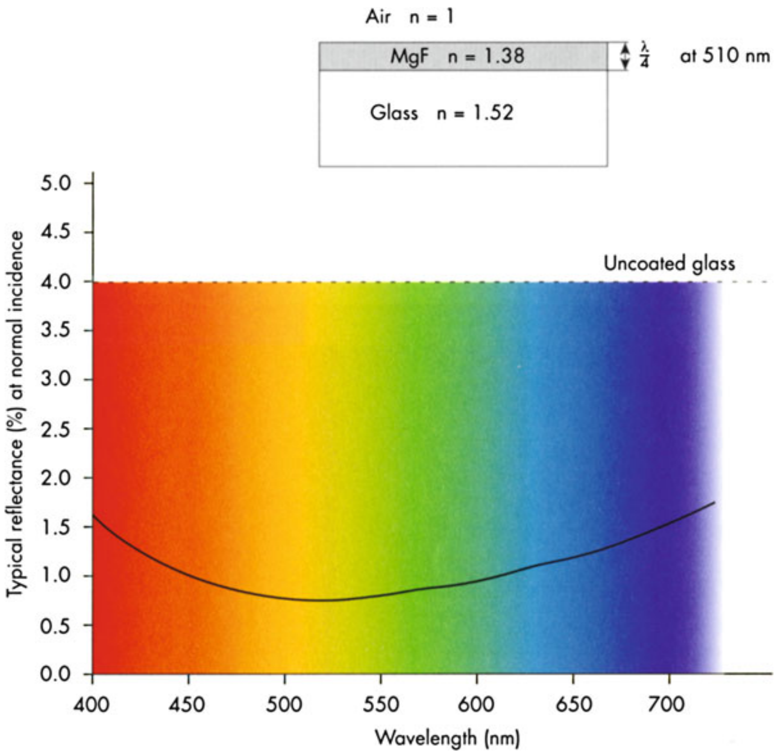

Fig. 2.18 Coated optics: single layer coating

"multicoating" (Fig. 2.19) and "broadband multicoating" (Fig. 2.20). Each additional layer of coating has a progressively lesser effect on improving light transmission. Coating is an expensive process, so there are a number of coatings that become uneconomical. It is rare to find more than seven layers on any surface in commercial binoculars.

Binocular coatings are qualitatively described as "coated," "fully multicoated," etc. There is no universally agreed meaning to these designations, but they are commonly held to have the following meanings:

- **Coated**: At least one glass-to-air surface (usually the outer surface of the objective) has a single layer of antireflective coating, usually MgF_2; other surfaces are uncoated.
- **Fully Coated**: All glass-to-air surfaces of the lenses (but not the prism hypotenuses) have a layer of antireflective coating.
- **Multicoated**: At least one glass-to-air surface (usually the outer surface of the objective) has two or more layers of antireflective coating. The other surfaces may be single-layer coated or not coated at all.
- **Fully Multicoated**: All glass-to-air surfaces of the lenses (but possibly not the prism hypotenuses) have two or more layers of antireflective coating.

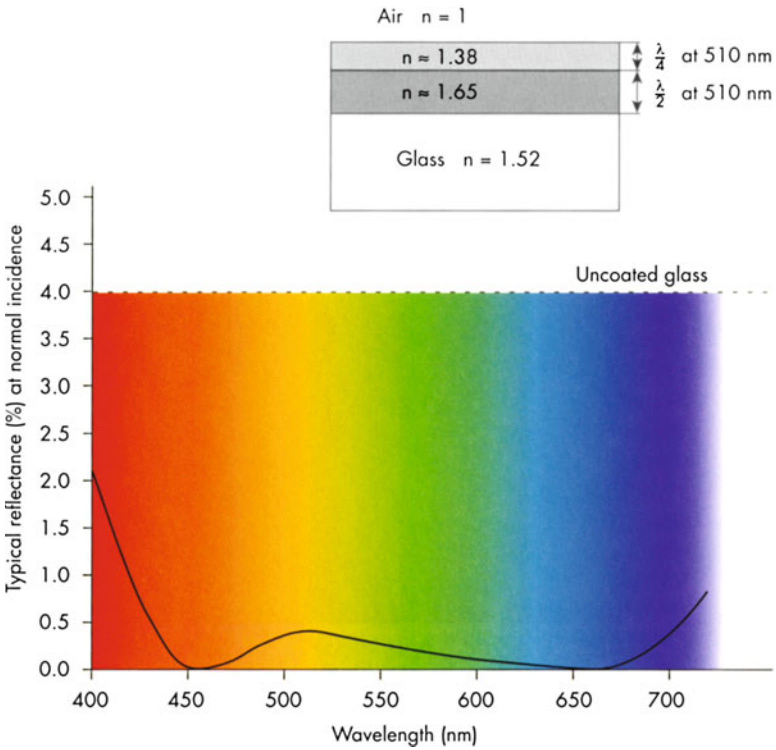

Fig. 2.19 Multi-coated optics: double layer coating

More recently, some binocular coatings have been described as "broadband." Again, there is no industry-wide standard—it can mean anything from three layers upward. Some manufacturers are more forthcoming as to the precise nature of their coatings. For example, Kunming Optical, the manufacturer of the popular *Garrett Optical* and *Oberwerk* binoculars in the USA (branded as *Strathspey* and *Helios Apollo* in the UK, *Teleskop-Service* in Germany), provides the following information about its coatings[2]:

- **Level I**: (Equivalent to *fully coated*) Single layer of MgF_2 coating on 16 glass-to-air surfaces— four for two objectives, 12 (6 per side) for the three optical elements in each eyepiece. The prisms are not coated.
- **Level II**: (Equivalent to a blend of *multicoated* and *fully multicoated*) Broadband multicoatings of 5–7 layers on the four glass-to-air surfaces of the two objectives and the four surfaces of the eye lenses of the two eyepieces. Single-layer MgF_2 coating on all other glass-to-air surfaces, including the hypotenuses of the prisms.

[2]Kunming Optical Instrument Co. Ltd.

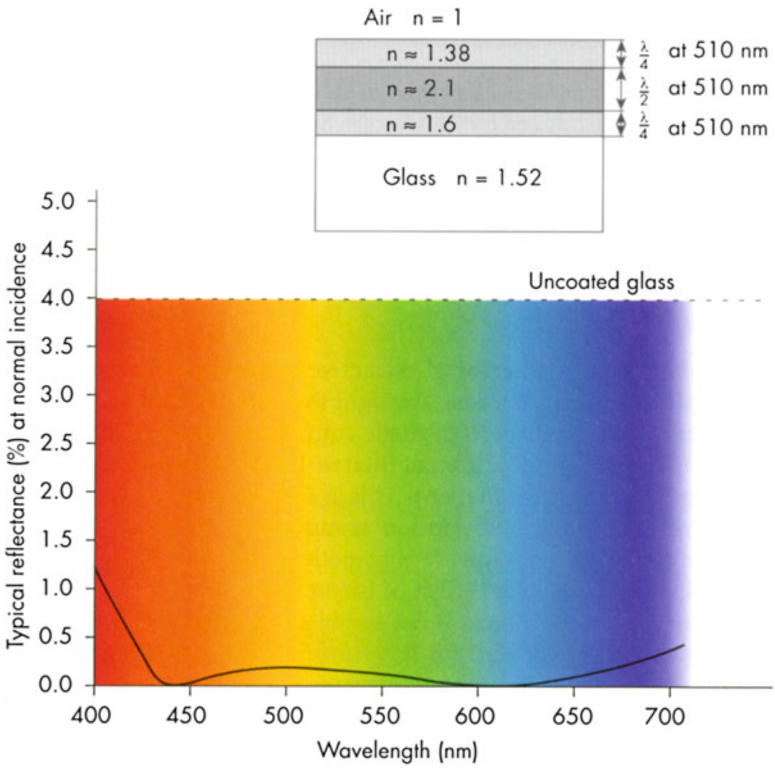

Fig. 2.20 Broadband multi-coated optics: triple layer coating

- **Level III**: Broadband multicoatings on all the surfaces except the prism hypotenuses, on which there are single-layer MgF_2 coatings.
- **Level IV**: Broadband multicoatings on all the surfaces including the prism hypotenuses.

The effect of various coatings can be seen in the reflections of sunlight from objective lenses in Fig. 2.21.

One of the criteria that is often offered, by well-meaning people, as an important consideration in binocular choice is that it should be "fully multicoated." Coatings are only effective if they are properly designed and applied. In budget binoculars, they are often unevenly applied (sometimes giving a "patchy" appearance to the lens surface if the unevenness is extreme), so are less effective. The quality control of these items is also usually extremely cursory in nature, so "fully multicoated" has a reduced value, and there are other criteria, such as control of aberrations and stray light, that are much more important in this class of binocular.

The two 70-mm binoculars in Fig. 2.22 were made in the same factory and ostensibly have the same broadband fully multicoated optics. I photographed

Fig. 2.21 Optical coatings. Clockwise from top left: single-layer coated, broadband multi-coated, multicoated, uncoated

Fig. 2.22 "Fully multicoated" does not always mean the same thing

them under similar conditions. One is three times the cost of the other. Guess which is which.

Aberrations

Aberrations are errors in an optical system. There are six optical aberrations which may affect the image produced by a telescope. Some affect the quality of the image; others affect its position. They are:

- Chromatic aberration: error of quality
- Spherical aberration: error of quality
- Coma: error of quality
- Astigmatism: error of quality
- Field curvature: error of position
- Distortion: error of position

Chromatic aberration is an error of refractive systems and is therefore of consideration for all binoculars. Because any light which does not impinge normally on a refractive surface will be dispersed, single converging lenses will bring different wavelengths (colors) of light to different foci, with the red end of the optical spectrum being most distant from the lens. This is *longitudinal* (or *axial)* chromatic aberration. It usually manifests itself as a colored halo, which changes in color from purplish at best focus to greenish outside focus (known as the "apple and plum" effect), around bright objects. *Lateral* chromatic aberration manifests as different wavelengths of light forming different sized images. It usually manifests itself as *color fringing* on off-axis objects. The term *color fringing* is descriptive of the visual effect of its presence.

Visible chromatic aberration can exist in objective lenses and eyepieces. Chromatic aberration can be reduced, but not eliminated, by using multiple lens elements of different refractive indices and dispersive powers. An achromatic lens has two elements and brings two colors to the same focus (Fig. 2.23).

The choice of glass and lens design will determine not only which colors are brought to the same focus but also the distance over which the secondary spectrum is focused. An apochromatic lens uses three elements and will bring three colors to the same focus. Using nonexotic glass, each additional lens will reduce chromatic aberration by about 80 %. Hence, an achromatic doublet can be expected to have approximately 20 % of the chromatic aberration of a singlet lens. An apochromatic triplet will reduce it to 20 % of the achromat's 20 %, i.e., approximately 4 % of the chromatic aberration of the equivalent singlet. The use of exotic glasses such as fluorite or ED will reduce it even further, to the extent that, say, an ED doublet may have less than 10 % of the chromatic aberration of the equivalent singlet. Such a combination is often termed a "semi-apochromatic."

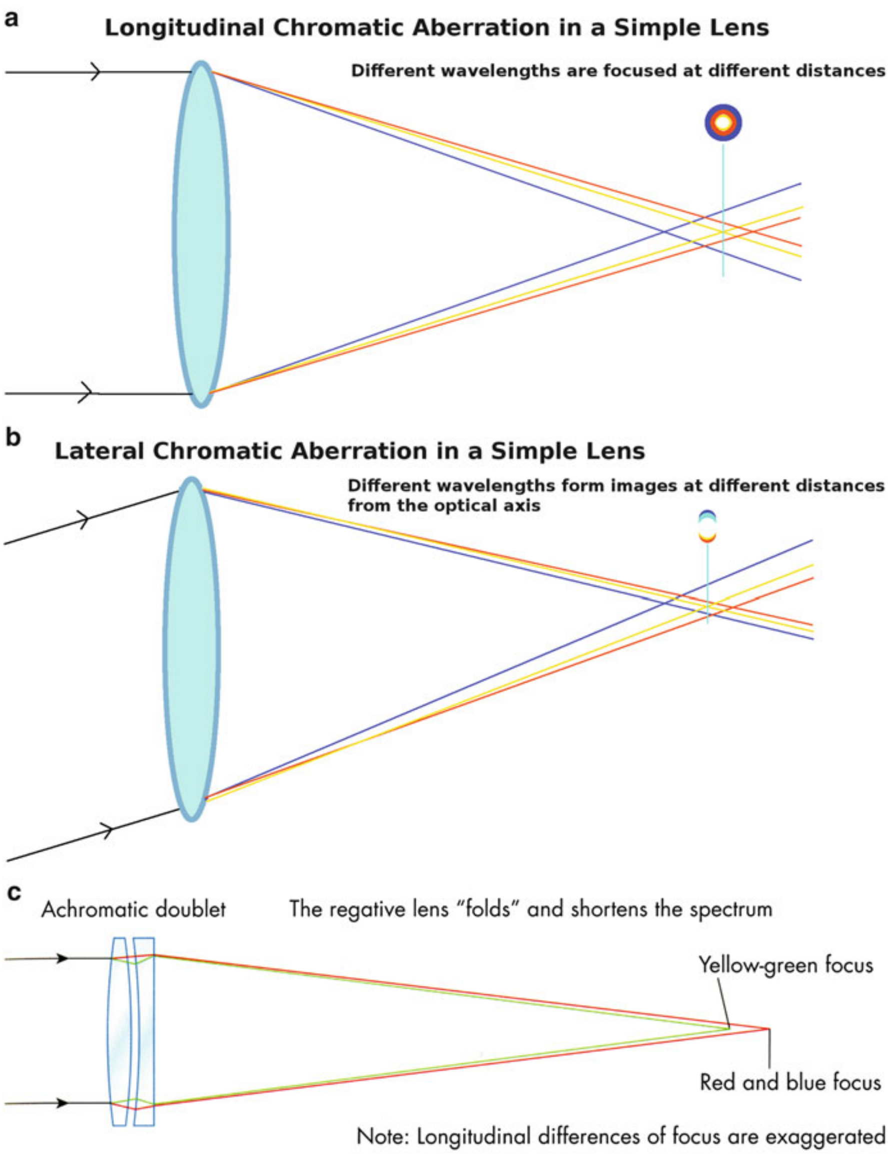

Fig. 2.23 Chromatic aberration

Spherical aberration is an error of spherical refractive and reflective surfaces which results in peripheral rays of light being brought to different foci to those near the axis (Fig. 2.24).

If the peripheral rays are brought to a closer focus than the near-axial rays, the system is *undercorrected*. If they are brought to a more distant focus, the system is

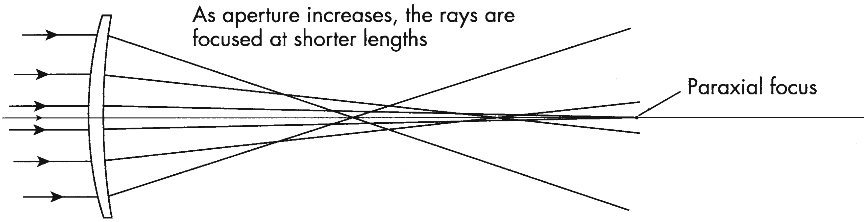

Fig. 2.24 Spherical aberration in a converging lens

overcorrected. Spherical mirrors and converging lenses are undercorrected and diverging lenses are overcorrected.

In compound lenses, spherical aberration can be suppressed in the design of the lens, by using several lenses of minimal curvature as a substitute for one of considerable curvature, by choosing appropriate curvatures for the converging and diverging elements, or as a combination of both. In Newtonian mirrors, such as are used in most reflecting binocular telescopes, the spherical aberration is corrected by progressively deepening the central part of the mirror so that all regions focus paraxial rays to the same point. The shape of the surface is then a *paraboloid*, that is, the surface that results from a parabola being rotated about is axis.

There are other manifestations of spherical aberration, the most common of which is zonal aberration, in which different zones of the objective lens or primary mirror have different focal lengths.

Spherical aberration increases as a direct cubic function of increase in aperture and is independent of field angle.

Coma can be considered to be a sort of a lopsided spherical aberration. If an objective lens is corrected for paraxial rays, then any abaxial ray cannot be an axis of revolution for the lens surface and different parts of the incident beam of which that ray is a part will focus at different distances from the lens. The further off-axis the object, the greater the effect will be. The resulting image of a star tends to flare away from the optical axis of the telescope, having the appearance of a comet, from which the aberration gets its name. In objective lenses, coma can be reduced or eliminated by having the coma of one element counteracted by the coma of another. It is usually particularly noticeable in ultrawide-angle binoculars.

Coma often occurs in combination with astigmatism (see below) (Fig. 2.25).

Coma increases as a direct square (quadratic) function of aperture increase and as a linear function of increase in field angle.

Astigmatism results from a different focal length for rays in one plane as compared to the focal length of rays in a different plane. A cylindrical lens, for example, will exhibit astigmatism because the curvature of the refracting surface differs for the rays in each plane and the image of a point source will be a line (Fig. 2.26).

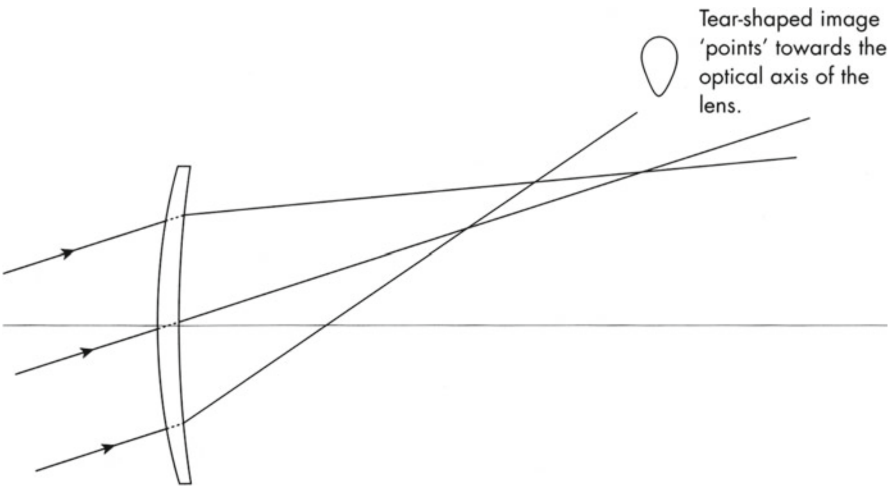

Fig. 2.25 Coma in a converging lens

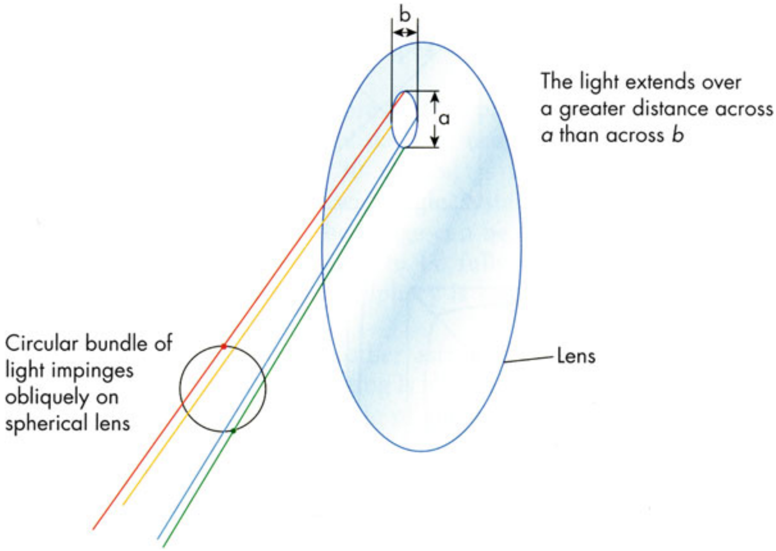

Fig. 2.26 Astigmatism

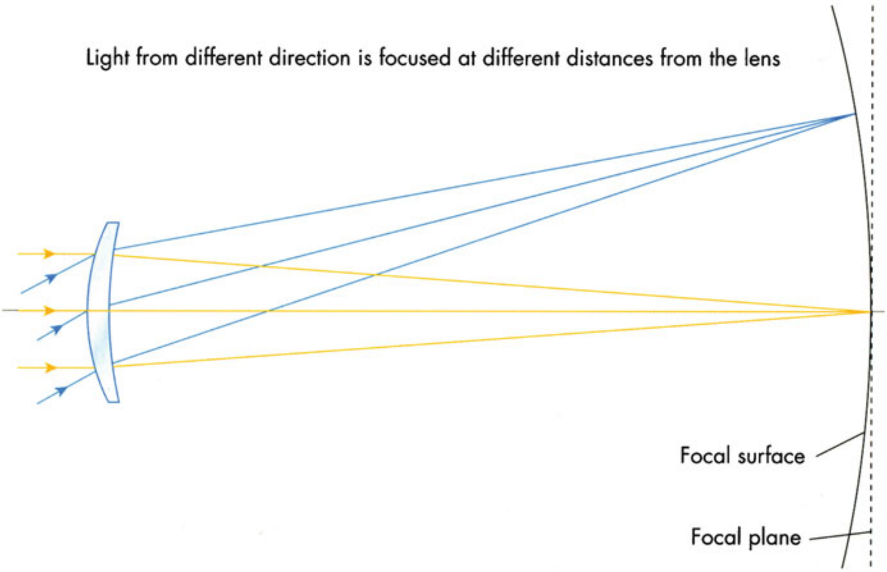

Fig. 2.27 Field curvature. *Amend text at top of image to read: "Light from different directions is focused at different horizontal distances from the lens"*

Astigmatism will therefore result from any optical element with a surface which is not a figure of revolution.

It can also occur in surfaces which *are* figures of revolution. Consider two mutually perpendicular diameters across a beam of light impinging obliquely upon a lens surface. The curvature of the lens under one diameter differs from that under the other, and so astigmatism will occur. Such astigmatism can be corrected by an additional optical element which introduces equal and opposite astigmatism. Astigmatism is not normally a problem in binoculars, which are primarily used for visual work, unless they have very wide fields.

Astigmatism rarely occurs alone and is usually combined with coma; the combined effect is that star images, especially near the periphery of the field of view, appear as "seagulls," i.e., there is a curved "wing" apparent to each side of the center of the star image.

Astigmatism increases linearly with increase in aperture and as a direct square (quadratic) function of increase in field angle.

Field Curvature. No single optical surface will produce a flat image—the image is focused on a surface which is a sphere which is tangential to the focal plane at its intersection with the optical axis (Fig. 2.27).

Field curvature, which manifests as the inability to focus the periphery of the image at the same time as the center is focused, is particularly noticeable when it is present in wide-field binoculars. It can be corrected in the design of the lenses. In particular, if a negative lens can be placed close to the image plane, it will flatten the field.

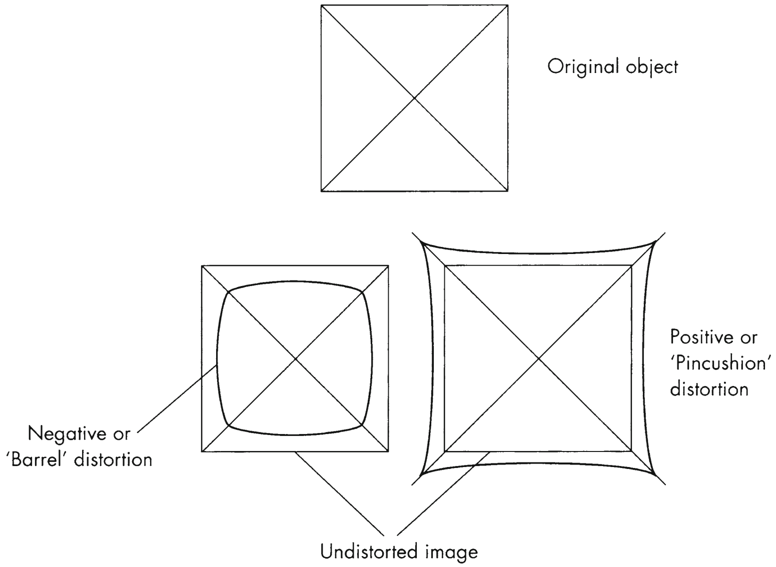

Fig. 2.28 Distortion

Field curvature increases linearly with increase in aperture and as a direct square (quadratic) function of increase in field angle.

Distortion is an aberration by which a square object gives an image with either convex lines (*negative* or *barrel distortion*) or concave lines (*positive* or *pincushion distortion*). It is the only aberration that does not produce blurring of the image (Fig. 2.28).

It results from differential magnification at different distances from the optical axis. It almost always originates in the eyepiece, so any correction should be inherent in eyepiece design. A small amount of pincushion distortion can be desirable because it attenuates the "rolling ball" effect that results in an undistorted field of view (see Chap. 3). This effect, which strictly speaking appears as a "rolling cylinder" as the binocular is panned across the sky, with the axis of the cylinder perpendicular to the direction of panning, can be disorientating and unpleasant, to the extent that it causes nausea in some observers.

Distortion is unaffected by aperture and increases as a direct function of the cube of field angle.

Aperture Stops and Vignetting

Vignetting is the loss of light, usually around the periphery of an image, as a consequence of an incomplete bundle passing through the optical system. A vignetted image appears dimmer around the periphery.

Most binoculars suffer from some degree of vignetting. The exception is some binoculars designed specifically for astronomical use and whose construction is based on astronomical refracting telescopes which themselves give unvignetted images. An example of this is the 22×60 Takahashi Astronomer, which used two Takahashi FS60 optical tubes

In some, it can be so severe that no part of the image is illuminated by the complete aperture. In normal daylight use, we do not notice vignetting unless it is exceptionally severe; 30 % is common and 50 % is sometimes deemed acceptable in wide-angle systems. This is because, at any given time, only a tiny region of the image can be examined by the fovea and it is therefore only this region that needs to be fully illuminated. As long as the fall-off of illumination towards the periphery is smooth, it will not normally be noticed.

Binocular astronomers who, like other astronomers, echo the call for "More light!" sometimes wonder why vignetting is allowed to occur at all. To understand this, we must first understand the role of the aperture stop. An aperture stop crops the light cone and eliminates the most peripheral rays. These peripheral rays have the highest angles of incidence on the optical surfaces and undergo the most refractive bending. For these reasons, they also carry with them the greatest amount of aberration. If they are permitted to pass through to your eye, they will add to the degradation of the image. Part of the process of good optical design is to assess how much of the peripheral light needs to be excluded.

If bundles of rays from all parts of the field of view fill the aperture stop, then there is no vignetting. On the other hand, if some other mechanical or optical component impedes some of this light, vignetting will occur. An unvignetted binocular requires larger optical apertures all the way through the optical system when compared to one in which vignetting does not occur. This in turn requires larger optical components (such as prisms or focusing lenses). Larger components are not only more expensive but also heavier. Heavier components require heavier and more robust mountings. These in turn add to the expense of the binocular. The overall result is a heavier, more expensive, binocular. In short, vignetted systems are usually smaller and lighter and produce better images in comparison to the equivalent unvignetted optical system. Somewhere in the design process, a decision is made as to where an acceptable trade-off lies. The more discerning observer may well be prepared to accept a more expensive instrument, but the general user will almost certainly not want to pay considerably more for a hardly noticeable increase in light throughput at the periphery. Even the discerning observer may balk at an increase in weight if the binoculars are intended to be handheld.

Focusing Mechanisms

There are three different types of focusing mechanism commonly found on binoculars:

Center Focus (Porro Prism)

The eyepieces are connected to a threaded rod in the central hinge. An internally threaded knurled wheel or cylinder causes the rod to move, thus moving the eyepieces. The right-hand eyepiece is usually independently focusable (Fig. 2.29a) in

Fig. 2.29 Right eyepiece diopter adjustment. (**a**) Porro prism. (**b**) Roof prism

order that differences in focus of the observer's eyes can be accommodated; this facility is often called a "diopter adjustment." The advantage is that the eyepieces can be focused simultaneously, which is a consideration for general terrestrial use, but not for astronomy. The disadvantages are that there is almost always some rocking of the bridge, which leads to difficulty in achieving and maintaining focus; the focusing system is difficult to seal, so dirt can enter; and the optical tubes are extremely difficult to waterproof, resulting in increased likelihood of internal condensation (Fig. 2.30).

Center Focus (Roof Prism)

Like the Porro-prism center focus system, there is an external focus wheel and an independent helical focuser (diopter adjustment) for the right eyepiece (Fig. 2.29b); the similarity ends there. The mechanism is internal and focusing is achieved by changing the position of a focusing lens between the objective lens and the prism assembly (Fig. 2.1). It has the dual advantages of permitting simultaneous focusing of both eyepieces and allowing relatively simple dust- and waterproofing. The disadvantage is that there is an extra optical element that must be accurately made, which absorbs a tiny amount of light, and whose movement during focusing alters the field of view slightly (Fig. 2.31).

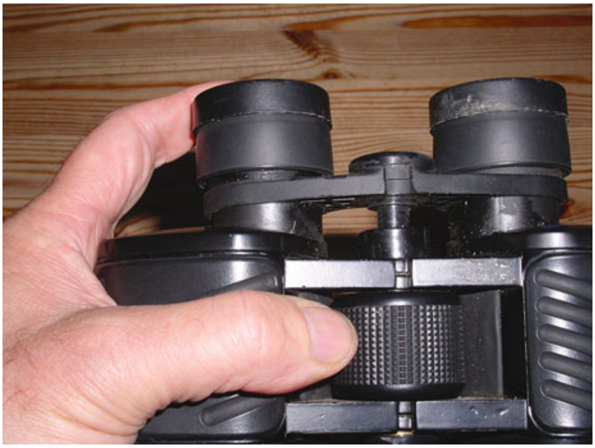

Fig. 2.30 The bridge rocks on this center-focus Porro-prism binocular

Fig. 2.31 Roof-prism center focus

Independent Focus

The eyepieces each have a helical focuser. This is much more robust than a center focus system and is easier to make dirt- and waterproof. The best-quality astronomical (and marine and military) binoculars have independent focusing. The disadvantage is that the eyepieces cannot be focused simultaneously, but this is not an issue for astronomical observation, where refocusing is not necessary once good focus has been attained (Fig. 2.32).

Fig. 2.32 Independent focus—ideal for astronomy

Collimation

Not only must the optical elements of each optical tube be collimated, but the optical axes of both tubes must be aligned. They must not only be aligned to each other but also to the hinge or other axis about which interpupillary distance is adjusted. If this latter criterion is not met, the result is a phenomenon called *conditional alignment* in which the two optical axes are only aligned at the interpupillary distance that was set during collimation and will get progressively out of alignment for other interpupillary distances. This may be acceptable if only one person is to use the binocular, but should never be so bad that the exit pupils take on a "cat's eye," as opposed to circular, appearance.

The permitted divergence of the optical axes from true parallelism is determined by the ability of the eyes to accommodate divergence and by the magnification of the binoculars. If these limits are exceeded, either it will not be possible to merge

Table 2.1 Collimation tolerances

Magnification	Step (arcmin)	Convergence (arcmin)	Divergence (arcmin)
×7	2.0	6.5	3.0
×10	1.5	4.5	2.0
×15	1.0	3.0	1.5
×20	0.75	2.25	1.0
×30	0.5	1.5	0.67
×40	0.38	1.13	0.5

the images from each optical tube or, if they can be merged, eyestrain and its attendant fatigue and/or headache results. Acceptable tolerances in the apparent field of view are as follows:

- Vertical misalignment (step, dipvergence): 15 arcmin
- Horizontal convergence[3]: 45 arcmin
- Horizontal divergence: 20 arcmin

To ascertain the real tolerances, you need to divide these by the magnification, to obtain the collimation tolerances listed in Table 2.1.

There are two ways in which the optical axes of the binoculars can be aligned. In almost all binoculars, the objective lenses are mounted in eccentric rings. These can be adjusted to move the optical axis in relation to the body of the binocular. In many other binoculars, the prisms are adjustable, either by grub screws (set screws) that are accessible from the outside or by being housed in a cluster whose adjustment screws are accessible by removing the cover plate on the prism housing. (See Chap. 5 for advice on how to collimate a binocular.) Collimation by eccentric rings on the objectives is preferable, because tilting the prisms will result in the introduction of more astigmatism.

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[3]There are different conventions for the use of "convergence" (and "divergence"), depending on whether the optical axes of the binocular are converging or the optical axes of the eyes are converging (to accommodate the diverging optical axes of the binocular). The usage here is the latter. It is simple to tell which convention is being used: the greater value is for converging eyes (diverging binoculars).

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