Proc. of SPIE Vol. 1168, Current Developments in Optical Engineering and Commercial Optics, ed. R E Fischer, H M Pallicove, W J Smith (Dec 1989)

Binocular performance and design

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1. INTRODUCTION

A binocular extends the range of human vision. Binoculars enable the user to see objects at greater distances or, alternatively, to see greater detail in distant objects. In failing light, binoculars are used to detect objects that the naked eye cannot detect. Binoculars also extend the range of stereo vision of the user; this application is primarily of interest in military fire control.

Binocular design might be expected to emphasize the factors that provide maximum range or maximum resolving power. Instead, current binocular design emphasizes reduced size and weight, low cost, and large fields of view. As will be seen, physiological factors limit the performance of binoculars.

Although binoculars are a common optical-industry product (with estimates of Japanese binocular production in 1977 of 3.7 million[1]), relatively little information on binocular design has been published in the professional literature. Here we survey the basic principles of binocular design, and include more recent information than is available in the traditional texts.[2]

2. THE BINOCULAR RANGE EQUATION

Since a binocular extends the range of human vision, an appropriate figure of merit for binocular performance is the maximum range at which a target can be detected using the binocular Binocular efficiency is defined as

$$E = \frac{R}{r} , \tag{1}$$

where E is the binocular efficiency,
R is the range at which the target is detected with the binocular,
r is the range at which the target is detected with the unaided eye.

Binocular efficiency is determined by the optical performance of the binocular, the scene illuminance, the physiological performance of the human eye, and atmospheric conditions. In addition, binocular performance is affected by the support for the binocular; a hand-held binocular does not perform as well as a solidly mounted binocular, because of tremble or shake induced by the user. Normally, binocular efficiency is not a simple function of magnification (see Figure 1).

Considering only the scene illuminance, the optical performance of the human eye, and the optical configuration of the binocular, Köhler and Leinhos developed an equation for the efficiency of a binocular.[3-5] The validity of this equation is confirmed by independent tests.[6] According to Köhler and Leinhos, binocular efficiency is given by

$$E = M^{1-x} D^{x} T^{z} = MP^{x} T^{z} , \tag{2}$$

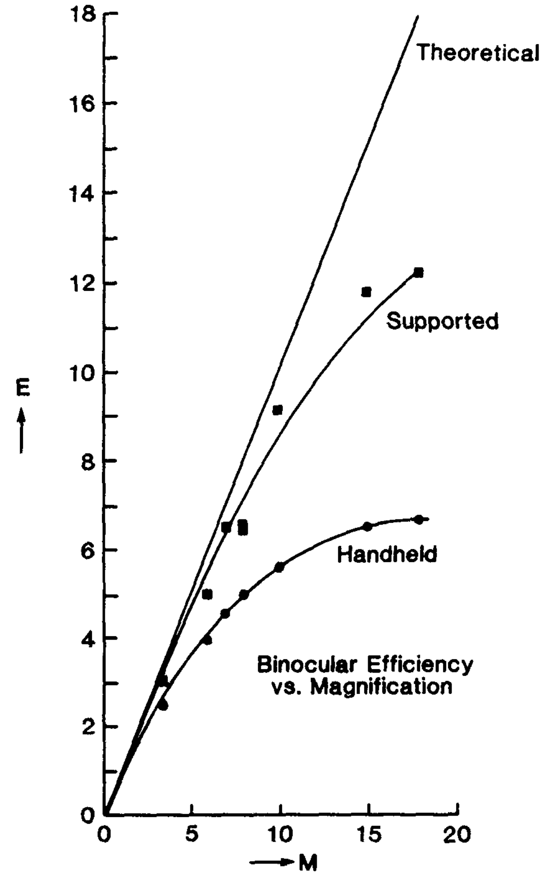

Figure 1. Binocular efficiency versus magnification.

where M is the magnification of the binocular,
D is the objective diameter of the binocular,
T is the binocular light transmission,
P is the exit pupil diameter of the binocular,
x, z are factors depending on illumination.

The illumination factors are a function of the performance of the eye under various conditions, and are given by

$$x \cong \frac{2}{7}(1 - \log I) - \frac{3}{2}(\log I)^2 + \frac{(\log I)^3}{19} + \frac{(\log I)^4}{29} + \frac{(\log I)^5}{245}, \tag{3}$$

$$z = 0.25, \quad I > 10^{-1} \text{ asb}, \tag{4a}$$

$$z = 0.33, \quad 10^{-2.5} \text{ asb} \leq I \leq 10^{-1} \text{ asb}, \tag{4b}$$

$$z = 0.50, \quad I < 10^{-2.5} \text{ asb}, \tag{4c}$$

where I is the illumination in apostilbs (asb).

Simplified versions of the Köhler and Leinhos equation are popular in discussions of binocular performance. In particular, Köhler and Leinhos are responsible for the concept of "twilight efficiency." Under twilight conditions, where the illumination is $10^{-2.5}$ to 10^{-1} asb, the binocular efficiency is approximately

$$E_{TWILIGHT} \cong (MD)^{1/2}\,T^{1/3} \quad . \tag{5}$$

When the scene illuminance exceeds 10 asb, or under daylight conditions, the binocular efficiency is determined primarily by magnification, and is approximately

$$E_{DAYLIGHT} \cong MT^{1/4} \quad . \tag{6}$$

Finally, when the illumination is below $10^{-2.5}$, or under night conditions, the binocular efficiency is approximately

$$E_{NIGHT} \cong \frac{D}{P}\,T^{1/2} \quad . \tag{7}$$

Because the binocular is a traditional military instrument for target detection under low-light conditions, night glass has been extensively researched. For optimum performance under low-light conditions, the exit pupil of the binocular must match the diameter of the pupil of the human eye. If the exit pupil of the binocular is larger than the pupil of the eye, light is lost, and efficiency is reduced. If the pupil of the eye is larger than the exit pupil of the binocular, target contrast is reduced, and efficiency is again reduced. A night glass does not increase the apparent brightness of an extended object, but acts to increase the apparent size of the object. Since minimum detection target size of the unaided eye increases in low light,[7] the function of a night glass is to increase efficiency by increasing the apparent size of the target. Since pupil matching is so important in the performance of a night glass, some understanding of human pupil size in low-light conditions is important. Traditionally, the pupil diameter of the fully dark adapted human eye is approximately 7 mm,[8] and the classic night glass is designed with a 7-mm exit pupil. Unfortunately, the 7-mm pupil is not a safe assumption for all users Older people, people continually exposed to strong light, or people with inadequate diets may have maximum eye pupil diameters well below 7 mm.[9] Stray light may also prevent maximum pupil diameter from being achieved.

Normally, the binocular is a hand held instrument. Since the user cannot hold the binocular perfectly still, some performance degradation occurs. Hand-held-binocular efficiencies have been determined by Brunnckow et al.[10] and by Ostrovskaya.[1] It is possible to derive the decrease in binocular efficiency that results from the user's muscular tremble by using information on tremble motions of hand-held binoculars and degradation of target detection of the human eye with target velocity.

Bhatia and Verghese[11] have found a relationship between the threshold size of a moving target detected by the unaided eye and the speed of the target

$$0 = a + bV \quad , \tag{8}$$

where 0 Is the threshold size of the target, in radians,
V is the target velocity, in radians per second,
a, b are constants characteristic of the individual .

Schober et al.[12] measured the muscle tremble associated with hand-held binoculars. Their results indicate that only tremble frequencies below 15 Hz are important and that tremble is characterized by two distinct groups of nearly equal size. One group of observers had three characteristic tremble frequencies, between 1 and 2 Hz, between 6 and 9 Hz, and between 10 and 12 Hz, with a sharp maximum between 7 and 9 Hz. The other group of observers had either no distinct tremble frequencies or a flat maximum between 6 and 10 Hz. Schober et al. also determined that the size and weight of the binocular did not affect tremble frequencies. Similar studies were performed by Babayev and Sukhoparov;[13] their work indicates that a good approximation of tremble is simple harmonic motion with a frequency of 10 Hz, and an amplitude of 0.25 degrees. Assuming daylight illumination conditions, and a stationary target, using the results of Bhatia and Verghese,[11] the threshold target size becomes

$$0 = a\ MT^{1/4} \quad . \tag{9}$$

If the binocular moves, the effect is to increase the apparent velocity caused by binocular motion by the magnification of the binocular. The threshold target size is then given by

$$0 = a + bVM \quad . \tag{10}$$

The ratio of support or stationary binocular efficiency to hand-held binocular efficiency is then given by

$$E \cong \frac{a\ MT^{1/4}}{a + bVM} \quad . \tag{11}$$

Finally, to check the accuracy of this approach, data for typical observers from Bhatia and Verghese, and a representative tremble motion, can be substituted. Assume simple harmonic motion, with a frequency of 9 Hz, and an amplitude of 0.25 degrees. Then the average velocity is approximately 79 mrad. From Bhatia and Verghese, the average value of a is 2.85 mrad, and b is 1.83×10^{-3} s; using these values the following equation for the binocular efficiency when hand held is derived

$$E \cong \frac{MT^{1/4}}{1 + 0.05\ M} \quad . \tag{12}$$

Table I gives binocular efficiency computed from the above equation, compared to measurements made by Ostrovskaya[1] and Brunnckow et al.[10] Agreement is better than 10%, which is within the limits of observer-to-observer variation. This equation provides additional support for the statement that there is a useful upper limit for the magnification of a hand-held binocular, and that this upper limit is about 10.

Table 1. Binocular efficiency.

M	$MT^{0.25}$	HAND-HELD EFFICIENCY	CALCULATED EFFICIENCY	ERROR
3.5	3.00	2.50	2.55	0.02
6.0	5.02	3.95	3.86	0.02
7.0	6.48	4.55	4.80	0.05
8.0	6.70	5.00	4.79	0.04
10.0	9.12	5.62	6.08	0.08
15.0	11.75	6.48	6.71	0.04
18.0	12.10	6.60	6.37	0.03

The importance of binocular light transmission varies, depending on the primary purpose of the binocular. According to Eq. 2, binocular efficiency is only weakly dependent on transmission under daylight conditions, and somewhat dependent under night or low-light conditions. A porro prism erecting system binocular, with a cemented doublet objective and Kellner eyepiece has 10 air-to-glass surfaces. If these surfaces are uncoated, with a net transmission across each surface of 96%, total binocular transmission is 66%. Under daylight conditions 66% transmission reduces binocular efficiency to 90%, while under night conditions 66% transmission reduces efficiency to 82%. Increasing the transmission efficiency per surface to 98% reduces the daylight loss to 95%, and the night efficiency loss to 90%. More complex optical configurations are more significantly affected by changes in transmission.

Another critical parameter in binocular efficiency is loss of contrast. Contrast in the image is reduced by stray light reaching the image plane. Since threshold target detection is affected by target contrast, reduction of contrast reduces binocular efficiency. Martin[14] suggests the use of a merit function involving the "glare spread function," to quantify the performance of binoculars with respect to stray light rejection. The glare spread function is the glare expressed as illuminance in the image plane normalized with respect to the flux in the image. Martin proposes the following merit function for determining the relative efficiency of glare control in binoculars.

$$\mathrm{FOM}_{\mathrm{GLARE}} = (\mathrm{GSF})M^2 \ , \tag{13}$$

where $\mathrm{FOM}_{\mathrm{GLARE}}$ is the merit function,
GSF is the glare spread function.

Atmospheric factors reduce contrast along the line of sight between binocular and target. At the low magnification levels of most binoculars, atmospheric turbulence effects or seeing do not appreciably reduce binocular efficiency. However; reduction in atmospheric transmission, or reduced visual range, does affect binocular efficiency. The magnitude of the effect depends on the visibility and range to the threshold target. According to Hardy,[15] the magnification required to detect a threshold target when then target is viewed along an atmospheric path of reduced visibility is

$$M = \frac{R}{r} \exp\left[\frac{1.956\ (R - r)}{R_V}\right] \ , \tag{14}$$

where M is the binocular magnification required to detect the target,
r is the visual range at which the target is just detected by the unaided eye (km),
R is the range at which the target is detected through the use of the binocular (km),
R_V is the visibility (km) .

3. OBJECTIVE DESIGN

Each barrel of a binocular contains three groups of optics: the objective, erecting system, and eyepiece. The optics must be designed as a system.. Aberrations introduced by erecting prisms or the objective can be corrected in the eyepiece.

A simple color-corrected cemented doublet is the most common binocular objective. The traditional military 7×50 binocular utilizes a 28-mm focal-length Kellner eyepiece and a 200-mm focal-length f/4 objective This objective has serious optical aberrations. In practice these aberrations do not affect the user. For daylight use, the eye pupil is about 2.5 mm in diameter. The reduced eye pupil effectively reduces the diameter of the objective to about 17.5 mm, which in turn increases the effective focal ratio to 11.4, with a resulting decrease in aberration. For night use, when the eye pupil opens to 7 mm, the resolving power of the eye is reduced, so that the aberrations of the full aperture of the objective are not noticed. This self-correcting aspect of binocular design is extremely useful, and reduces the need for highly corrected optical systems.

High-performance binocular systems, typically those employing magnifications of 10 or greater, require better performance objectives than the traditional fast doublet. Better aberration correction is obtained through the use of long focal length objectives; although economical, this approach increases the size and weight of the binocular. Alternatively an apochromatic or semi-apochromatic objective is employed. Apochromats usually employ three elements, and sometimes use exotic glasses. Use of an apochromat increases cost, but can reduce size and weight Apochromatic objectives are employed in certain Soviet binoculars.[16]

Telephoto objectives represent another approach to reducing the size and weight of binoculars. Zeiss uses this approach in its "dialyte" objectives, and a three-element telephoto objective is used in the U.S. Army's M19 binocular as produced by Bell and Howell.[17] A two-element "dialyte" telephoto objective is more difficult to correct than a traditional doublet, which suggests the need for the extra element in the M19 design.

Recently Kindred and Moore[18] reported the development of an axial gradient index objective for a binocular. This particular objective utilized a two-element gradient index lens to replace the three-element objective of the U.S. Army M19 binocular. Reduction of elements while maintaining optical performance is possible with this technique. Gradient index objectives may provide further reduction in cost, size and weight in future binocular designs.

4. THE PRISM PROBLEM

Introduction of the porro prism erecting system is the technical breakthrough that makes the modern binocular possible. Unfortunately, not all erecting prism systems are designed correctly Many good prism designs are handicapped by poor manufacturing. Although a considerable number of prism erecting systems are used in binoculars, the two most important are the porro and roof systems.

In many consumer binoculars, it is common to encounter apparently square exit pupils, as shown in Figure 2. Although often attributed to the use of undersized prisms, square exit pupils in a porro prism binocular are the result of low-index glass in the prisms. In a porro prism erecting system, there are four air-to-glass interfaces. If the angle between ray and interface is less than the critical angle for total internal reflection, that particular ray can escape through the interface and be lost from the system. For a converging bundle of rays, the angle between each ray and interface varies; it is possible for some rays to be totally internally reflected, and for some to be transmitted through the interface, as shown in Figure 3. Smith[19] gives an equation for the maximum ray bundle angle which is passed through a porro prism system with complete total internal reflection of all rays:

$$\theta \cong n\left[45^0 - \sin^{-1}\frac{1}{n}\right] , \tag{15}$$

where θ is the maximum ray bundle angle,
n is the index of refraction for the prism material .

Using this relationship, the minimum focal ratio objective for a given index-of-refraction prism glass that preserves round exit pupils is given by

$$f/no \cong 2\tan\left\{n\left[45^0 - \sin^{-1}\left[\frac{1}{n}\right]\right]\right\}^{-1} , \tag{16}$$

where f/no is the minimum focal ratio. Figure 4 illustrates the relationship between focal ratio and prism index of refraction.

Stray light can be introduced into the optical path by means of the porro prism erecting system. An oblique ray can be reflected from the inactive side of the prism (Figure 5). This source of is eliminated by introducing a cut across the base of the prism, as shown. Stray light can also enter through the hypotenuse of the prism, reflect off the base and then into the beam path. An external opaque housing around the prism suppresses this stray light. The housing must not be in contact with the prism. In most binoculars, a light-tight seal around the entrance aperture of the erecting prism housing, coupled

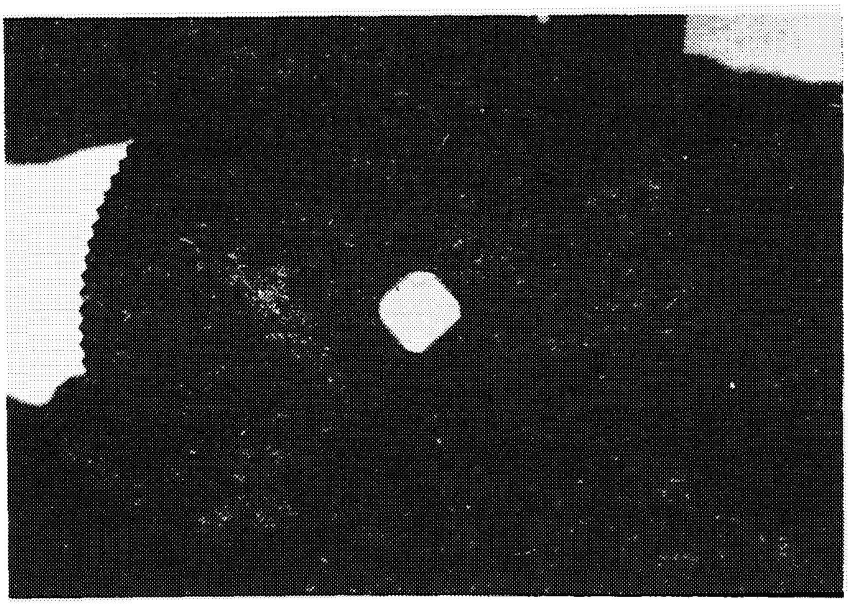

Figure 2. Square exit pupil.

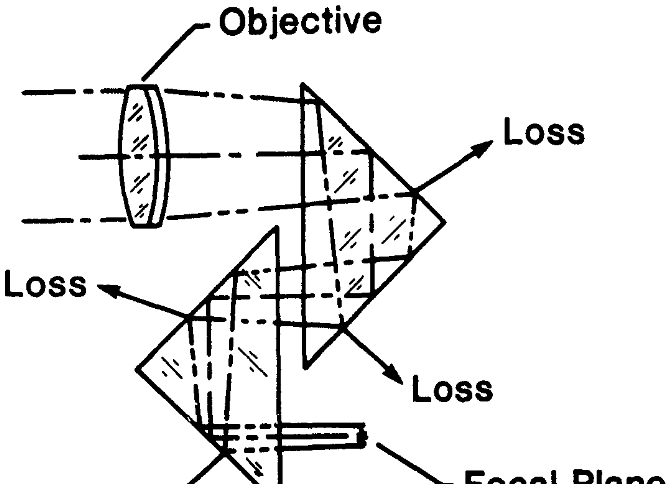

Figure 3. Partial loss of transmitted converging beam in a binocular porro prism erecting system caused by failure to meet critical angle requirement for total internal reflection.

with optical blackening of the prism housing, reduces the stray light transmitted through the hypotenuse of the prism.

Roof prisms offer an alternative to the classic porro prism erecting system in binoculars. The Abbe and Hensolt prisms are examples of erecting prism systems using an optical roof. These two prism configurations are shown in Figure 6. Roof prisms offer a nearly in-line configuration, compactness, and possible reduction in weight. Unfortunately, roof prism erecting systems are more expensive to produce than porro prism systems, and have some distinct optical performance drawbacks. Since there is a trend toward the use of roof prisms in binoculars (Ostrovskaya claims that 200,000 roof prism binoculars were made in 1977 in Japan[1]), some elaboration of the optical performance of a roof prism is indicated.

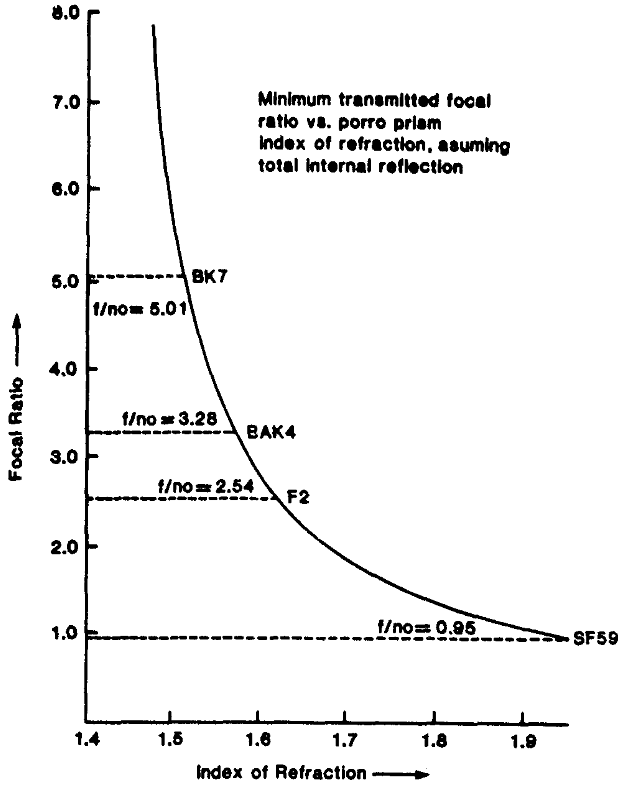

Figure 4. Focal ratio versus index of refraction.

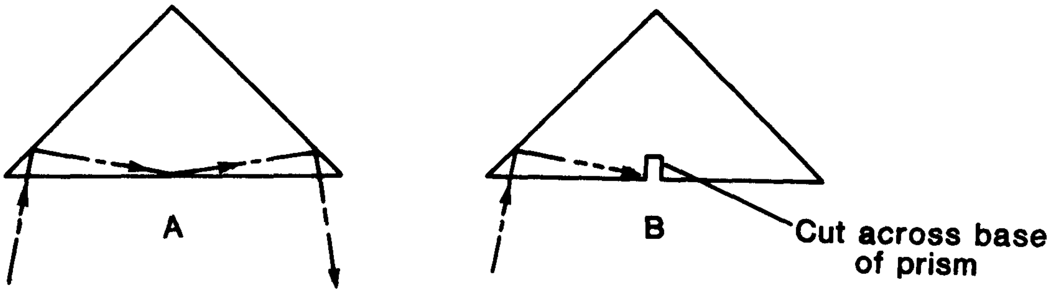

Figure 5. a) Problem: stray light reflects from base of porro prism.
b) Solution: cut across base intercepts stray light.

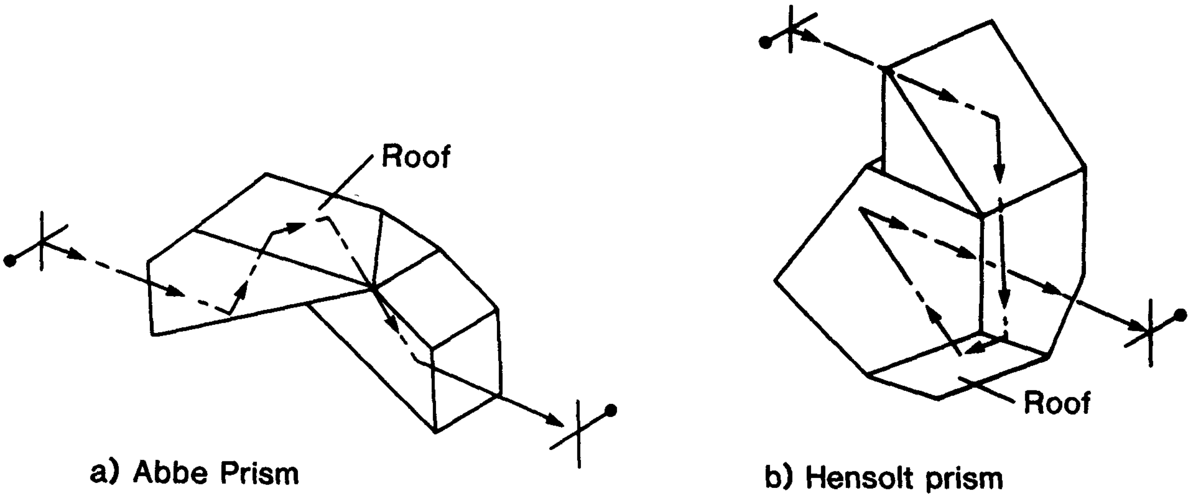

Figure 6. Roof prism erecting system.

In a roof prism, the image is literally split into two parts and then recombined, by two separate total internal reflecting prism surfaces. The two separated images must be recombined accurately, so that there are no gaps or overlaps in the final image. This recombination requires high accuracy of the actual roof angle. The tolerance for the roof angle is[20]

$$\phi_{ROOF} = \frac{F_{EYEPIECE}\ \omega}{4nL_I\ \cos\beta}\ , \tag{17}$$

where ϕ_{ROOF} is the tolerance for the roof angle,
$F_{EYEPIECE}$ Is the focal length of the eyepiece,
ω is the angular resolving power of the eye,' usually assumed to be 1 arc-min.,
L_1 is distance of the roof from the final image plane,
β is the angle of incidence of the optical axis upon the roof,
n is the prism index of refraction .

There are two separate surfaces in the roof, and hence some finite width of gap between the two surfaces. This gap causes a similar gap or line in the final image. There is a maximum size above which the gap is visible in the image plane. The maximum gap size[20] is given by

$$h = \frac{\pi}{4}\ C\ d_p \left[\frac{L_1}{L_R}\right]\ , \tag{18}$$

where h is the size of the gap,
C is the tolerable contrast reduction in the gap area in the final image, often assumed to be about 3%
d_p is the exit pupil diameter in front of the roof,
L_R is the distance of the above exit pupil from the final image .

It is not unusual to encounter roof angle tolerances as tight as 15 μrad (about 3 arc-sec) and maximum roof gaps of less than 0.3 mm. These tolerances present a formidable challenge for the optical fabricator, and are expensive to produce.

Unfortunately, a well-made roof prism may still produce unacceptable results. Levi and Reichert[21] show that small roof-angle errors may produce serious degradation of the modulation transfer function of the roof prism, with resulting loss of contrast and resolving power in the final image. Mahan[22,23] discusses focal-plane anomalies in roof prisms. These anomalies consist of image doubling in the direction perpendicular to the roof edge, while in the direction parallel to the roof edge the image remains sharp. This effect is sensitive to the polarization of the light beam passing through the prism, and is observed in perfect prisms The solution advocated by Mahan is to abandon total internal reflection, and to silver the roof of the prism.

Silvering reduces the magnitude of the problem identified by Mahan. Unfortunately, most silver-on-glass films scatter significantly more light than a total internal reflecting surface. Silver-on-glass films are also subject to degradation with time. The main virtue of Mahan's suggestion appears to be the relaxation of manufacturing tolerances in the roof angle.

It is possible to construct erecting systems for binoculars that use mirrors rather than prisms. There is an equivalent mirror erecting configuration for each of the commonly used erecting prism systems Four mirror erecting systems are sometimes used in place of the conventional porro prism erecting system. At least one zoom binocular built in the Soviet Union uses a mirror system.[24] Mirror erecting systems offer significant weight reductions, but are exceptionally difficult to keep in alignment, and have increased scatter in comparison with total internal reflecting prism surfaces.

5. THE EYEPIECE PROBLEM

The final optical component of a binocular is the eyepiece. Binocular magnification is given by

$$M = \frac{F_{OBJECTIVE}}{F_{EYEPIECE}} , \tag{19}$$

where $F_{OBJECTIVE}$ is the objective focal length,
$F_{EYEPIECE}$ Is the eyepiece focal length .

To obtain higher magnification with a given focal length objective, the focal length of the eyepiece must be reduced. This suggests that compact binoculars should have short focus eyepieces. Eyepiece focal length cannot be reduced indefinitely. Eye relief is the distance between the last lens or eye lens of the eyepiece, and the exit pupil. This distance must be sufficient to allow mechanical clearance so that the user can reach the exit pupil. Typically, an eye relief of at least 10 mm is required; if the user wears glasses, an eye relief of 22 mm or more is desirable. Long eye relief allows the user to wear corrective vision eyeglasses while looking through the binocular. This is particularly important for people afflicted with astigmatic vision. Adequate eye relief is important even for military employment of binoculars; a 1969 U.S. Army survey indicated that at least 37% of all personnel required some kind of correction to their vision.[25] In addition, many military combat units now employ visors intended to protect the eye against ballistic damage (shell fragments) and laser radiation. Future military binoculars must be designed to permit the use of such protective visors between the eyepiece and eye.

Eye relief is determined by the eyepiece design.[26] The traditional Kellner eyepiece employed in binoculars has an eye relief of about 7 mm for a focal length of 25 mm. More complex eyepieces such as the Erfle and Symmetrical, have eye reliefs of about 21 mm for a focal length of 25 mm. Unfortunately, lengthening eye relief by increasing eyepiece focal length requires a longer focal length objective if magnification remains constant. This in turn increases the size and weight of the binocular.

Use of a telephoto type of objective offers a long focal length without the usual penalty of size and weight, although optical correction may suffer, and cost may increase.

An alternative to increasing the focal length of the objective to improve eye relief is to use a Smythe type eyepiece,[4] which combines a negative element followed by a positive element to provide long eye relief with a short focal length.

Another factor influencing eyepiece design is the binocular field of view. Binocular field of view is given by

$$FOV_{BINO} = \frac{FOV_{EYEPIECE}}{M} , \tag{20}$$

where FOV_{BINO} is the binocular field of view,
$FOV_{EYEPIECE}$ is the apparent field of view of the eyepiece.

The Kellner eyepiece, traditionally used in binoculars, has an apparent field of view of about 40 degrees. More complex designs such as the Orthoscopic and Symmetrical, have fields of view of 50 degrees. Wide-angle designs, such as the Erfle, have fields of view of 65 degrees or more. Since binocular magnification is normally about 7 to 10, fields of view of 9 degrees or more are readily obtained.

One drawback associated with wide field of view eyepieces is the physical size of the eyepiece. The diameter of the eye lens of an eyepiece is given by

$$D_E \cong P + 2L_E \tan\left[\frac{FOV_{EYEPIECE}}{2}\right] , \tag{21}$$

where D_E is the eye lens diameter,
L_E is the eye relief,
P is the exit pupil diameter,
$FOV_{EYEPIECE}$ is the apparent field of view of the eyepiece.

For example, a 25-mm focal length Kellner eyepiece, 40 degree apparent field of view, with an eye relief of 7 mm, used with a 7-mm pupil, requires an eye lens of 12 mm in diameter. An Erfle of 25-mm focal length, with an apparent field of view of 65 degrees and an eye relief of 21 mm, requires an eye lens of 34 mm in diameter for the same 7-mm pupil diameter. Increasing field of view and eye relief dramatically increases the size and cost of the eyepiece.

Often overlooked in eyepiece design is spherical aberration of the exit pupil. This aberration does not affect the sharpness of the final image, but does affect the illumination in the image plane. If the eyepiece has spherical aberration of the exit pupil, it is not possible for the eye to accept the full bundle of rays in the exit pupil unless the eye pupil is larger than the exit pupil. Since binoculars are normally designed for a close match of exit pupil to eye pupil size, spherical aberration of the exit pupil is a serious problem. This aberration is normally visible in the form of shadows moving in the image as the eye scans the exit pupil. It is possible to correct this aberration in the design of an eyepiece. This type of defect is often encountered in extreme wide angle eyepieces, and is sometimes called the "kidney bean" effect after the shape of the shadows in the image.

Most eyepieces are not well-corrected off axis or for tilted image planes. If the user does not set the interpupillary distance of the binocular correctly, an off-axis condition of several millimeters can occur. This is sufficient to degrade the performance of most binocular eyepieces.[27] This indicates the need for care in adjusting the interpupillary setting of a binocular. In addition, a substantial variation in the correction of the user's eyes can lead to the two eyepieces of the binocular being focused at different positions. This variation in focus position causes the face of the user to tilt with respect to the exit pupil plane of the binocular, which in turn degrades the performance of the eyepieces.

Both of the above difficulties are avoided through the use of internal focusing eyepieces. In an internal focus eyepiece, part of the optical assembly of the eyepiece, usually the field lens, moves back and forth to focus the binocular. Use of internal focus avoids the problem of tilting the binocular during adjustment of focus for the user's individual eyes. Internal focus also allows better sealing of the binocular against the entry of water or dust. Finally, internal focus adjustments may permit extending the range of focus, so that the binocular can be used at relatively close distances.

Stray light is often neglected in eyepiece design. Since the eyepiece is very close to the final image, stray light in the eyepiece can be particularly strong and annoying. One overlooked source of stray light is light entering through the eye lens, or reflected in the eye lens. A flat external surface of the eye lens can reflect stray light (or the user's eye!) into the exit pupil. Another error is the use of radii of the eye lens that match the radii of the eye, leading to reflection of the interior of the eye into the exit pupil.

6. MECHANICAL DESIGN

Collimation is the most critical issue in the mechanical design of binoculars. Comfortable use of a binocular for a prolonged period of time requires that the two optical axis of the binocular be parallel. If the two optical axis are not parallel in the vertical plane, the error is termed dipvergence. If the two optical axis converge in the horizontal plane, the error in alignment is termed convergent error, and if the two axis diverge in the horizontal plane the error is termed divergence.

The actual error tolerable in binocular alignment is controversial. Normal tolerances in a binocular are about 8 arc minutes in dipvergence, 90 arc minutes in divergence, and 0 arc minutes in convergence.[28] The U.S. Army M19 binocular alignment tolerance is ±15 arc minutes of dipvergence, and 20±20 arc minutes of divergence.[17] Based on experimental trials, Ostrovskaya et al.[29] suggests that alignment tolerances of 30 arc minutes dipvergence, 40 arc minutes convergence, and 100 arc minutes divergence are acceptable. Observation periods of up to 60 minutes are employed in these trials.

Home[30] suggested that instead of attempting to maintain the optical axis of the binocular parallel, that the axes should be set to converge. Home suggests that the two axis be set to converge at a distance equivalent to the accommodation of the user's eye. For most users, this represents a distance of about 1 m from the hinge pin of the binocular. Tests of this principle by Home showed a 20% improvement in contrast sensitivity in binoculars set to converge at the accommodation distance.

Alignment tolerances have substantial impact in binocular fabrication. In the fabrication of the U.S. Army M19 binocular, an alignment error of one arc minute could be introduced by a manufacturing error of 0.0001.[17] In the M19, alignment is maintained by precision manufacturing; while most binoculars the alignment requires a tedious manual adjustment during fabrication. Further alignment adjustments may be necessary during the lifetime of the binocular. In keeping with the desire to reduce size and weight, binoculars are normally made of lightweight materials. Aluminum is the most common material, although magnesium has been employed. Recently, several prominent binocular manufactures have begun to use glass-filled polycarbonate plastics in the barrels of binoculars. The U.S. Army World War Two vintage M17 7x50 binocular weighs 1.5 kg; while the current M22 design, using glass-filled polycarbonate materials in the structure, weighs about 1 kg. A mounted 15x80 binocular using traditional materials such as aluminum weighs 8 kg, by using lightweight polycarbonate materials the weight is reduced to 1.6 kg. These new materials permit this size binocular to be hand held with roughly the same fatigue level as a smaller World War Two vintage binocular. Use of plastic materials reduces fabrication cost as well. A serious concern with any plastic is long-term dimensional stability, which may affect binocular alignment.

Any binocular in severe service requires sealing against foreign matter. The critical seal is between the eyepiece and barrel, because relative motion is required in this area to focus the binocular In older designs, a dynamic O-ring is used to seal this area. This O-ring is a high-friction component, wears out rapidly, and is easily damaged by foreign matter. More recent designs use bellows or rolling diaphragm seals.[31] Another approach is to use internal focus. Two types of binocular configurations are used with porro prism erecting systems: American and German (or Zeiss). In the American configuration, the erecting prisms are mounted to a plate which is then mounted to the binocular barrel; only a single aperture in the barrel is required. In the German, or Zeiss, configuration, the prisms are mounted directly to a shelf in the barrel, requiring openings in both ends of the barrel for assembly. The American configuration is somewhat easier to seal while the German configuration is lower in production cost.

Sometimes neglected in the mechanical design of binoculars are stray light baffles Simple opaque aperture stops inserted along the optical axis of the binocular can significantly improve the stray light rejection of a binocular. Although the design principles of these baffles are well understood,[32] they are often omitted from even quite expensive binoculars, usually on the basis of cost and weight. When baffles are fitted, it is not uncommon to find errors such as reflective baffle edges that actually increase rather than decrease stray light. Use of a fore baffle or sunshade around the objective can also dramatically reduce glare in the image.

7. SUMMARY

Several trends are seen in contemporary binocular design. First, the more expensive roof prism erecting system is becoming more common. This may the result of a desire for reduced size and weight. Second, eye relief of binoculars is increasing, and is likely to continue increasing even in military applications. Third, more complex optical configurations (apochromats, telephoto objectives, and internal focus) are being used. Fourth, new materials, such as the glass-filled polycarbonates, are being employed to reduce weight and cost. Fifth, although the harmful effects of stray light on binocular performance are well understood, control of stray light is often neglected even in more expensive designs. Sixth, the zoom binocular has yet to make an impact on the professional binocular market. A number of new technologies have yet to mature. Stabilization of binoculars allows use of high-powered hand-held instruments. Unfortunately a low-cost binocular stabilizer has yet to be developed, restricting current expensive stabilized binoculars designs to the government market. Gradient index materials may permit substantial reductions in cost and size, but are not yet ready for mass production at an affordable price.

Although a common consumer item, the modern binocular is a complex instrument requiring considerable effort on the part of the optical designer, opto-mechanical engineer, and production engineer. The challenge is to produce a binocular with good optical performance, reduced size and weight, and to a specified cost.

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