

LAB 8: BINOCULARS

Prism binoculars are, in reality, a pair of refractive telescopes mounted side by side, one for each of the two eyes. The advantages of binoculars over a single monocular telescope are mainly (1) corrected image orientation and (2) depth perception. Three-dimensional information gathered by using both eyes is also enhanced by the binoculars because of the wide separation of objective lenses (approximately 125 mm) compared with the typical InterPupillary Distance (IPD) of human eyes (approximately 68 mm).

Binoculars use either Porro or Roof prisms between the objectives and eyepieces to provide correct image orientation. Porro binoculars are shown in Figure 8.1, with part of the case cut away to show the optical parts. The objectives are cemented achromatic pairs (doublets), or triplets, while the oculars are Kellner or achromatized Ramsden eyepieces. The dotted lines show the path of an axial ray through one pair of Porro prisms. The prisms rotate the image by 180°, so the final image is correct (the image looks the same as the object). The doubling back of the light rays in the Porro prism design has the further advantage of enabling longer focus objectives to be used in short tubes, with consequent high magnification. Figure 8.2 shows Porro prisms and Roof prisms.

Binoculars have many applications that sometimes have different requirements. Characteristics to take into account are (1) magnification, (2) field of view, (3) light-gathering power, and (4) size and weight. Generally, higher magnification results in narrow fields of view and vice versa. For hand-held use, binoculars with five-, six-, seven-, or eightfold magnification (“8x” or “8 power”) are most generally used. Binoculars with magnification above 8 are sometimes desirable, but require a rigid mount to hold them steady. For magnification less than 4, lens aberrations usually offset the magnification, and the average person can usually see better with the unaided eyes.

The field of view is determined by the eyepiece aperture and should be as large as is practicable. For seven-power binoculars a 6° object field is considered large, since in the eyepiece the same field is spread over an angle of 7x6°, or 42° (the very definition of angular magnification!):

$$m \equiv \frac{\bar{u}'}{\bar{u}} \quad \text{so} \quad \bar{u}' = m \cdot \bar{u} \quad (8-1)$$

Binoculars are specified by stating their “magnification x diameter of the objective lens”. For example, binoculars with the specification 6 x 30 (read “6 by 30”) have a magnification of 6 and objective lenses with an effective diameter of 30mm. The specification 7 x 50 means a magnification of 7 and objectives 50mm in diameter. Although binoculars with the latter specifications are excellent for day or night use, they are considerably larger and more cumbersome than the daytime models specified as 6 x 30 or 8 x 30. For general civilian use, the latter two are much more useful.

The diameter of the objective lenses determines the light-gathering ability. As with reflecting telescopes, the light-gathering ability scales with the area of the objective (diameter squared). Large diameters are important only in low-light conditions. Binoculars used for astronomical viewing of faint deep-sky objects often have specs of 15 x 70, 20 x 80, or even 25 x 100. These are HUGE binoculars that require a very sturdy tripod mount to use.

(adapted from Fundamentals of Optics, Jenkins and White, Fourth ed., pp. 207-208).

There is also a controversial, reported phenomenon known as “binocular summation”, which describes an increase in apparent contrast when objects are viewed with two eyes instead of one. Reports of increased contrast supposedly allow a 0.1 to 0.2 astronomical magnitude gain in visual perception (equivalent to an increase of 20% to 40% in light gathering ability) with two eyes/two objectives versus one eye/one objective. Little or no gain in point-source resolution has been reported. “Binocular Summation”, if it truly exists, is probably a physiological sensory enhancement, at the limits of vision, due to the brain processing information from two eyes instead of one. It does not represent an increase of light energy by adding light energy from both eyes.

There is another factor to consider when choosing a pair of binoculars to use for a particular application, namely the size of the exit pupil. Binoculars are telescopes—they are afocal optical systems. As we saw with telescopes, the exit pupil diameter E' and entrance pupil diameter E (the diameter of the objective lens) are related through the magnification:

$$m \equiv \frac{E}{E'} \quad \text{so} \quad E' = \frac{E}{m} \quad (8-2)$$

For a given diameter of objective lens, as the magnification is increased (by designing and using a shorter-focal length eyepiece), the diameter of the exit pupil decreases. The following table shows the exit pupil diameter for each of the binoculars mentioned above:

Specification	Objective Lens Dia. (mm)	Magnification	Exit Pupil Dia. (mm)
6 x 30	30	6	5
8 x 30	30	8	3.8
7 x 50	50	7	7.1
15 x 70	70	15	4.7
20 x 80	80	20	4
25 x 100	100	25	4

Table 8.1. Exit pupil diameter in binoculars.

Ideally, the diameter of the exit pupil should match the diameter of the pupil of your eye (or be slightly larger). Note that the diameter of the exit pupil is a fixed number (for a given pair of binoculars), but the diameter of the pupil of your eye varies, depending on whether you use the binoculars in bright daylight or in the dark of night. For human eyes, the pupil varies from about 2mm to about 7mm in diameter. The implication of looking through binoculars (or a telescope) with an eye pupil that is smaller than the instrument's exit pupil, is that your eye becomes the aperture stop of the system. This has the effect of “stopping down” the entire optical system, wasting valuable objective lens diameter!!! It also has the effect of trying to look through a window (the exit pupil) that is much larger than your eye—you have to move your head around to see the full field of view. This is annoying and makes the binoculars hard to use.

Daytime:

As an example, suppose you buy a pair of 20 x 80 binoculars to use in bright daylight. As table 10.1 shows, the exit pupil is 4mm in diameter, but the pupil of your eye will be about 2mm in diameter. Your eye, effectively, becomes the aperture stop of the system. In turn, this causes the effective diameter of the objective lens to become smaller:

$$m \equiv \frac{E}{E'} \quad \text{so} \quad E = 20 \times 2\text{mm} = 40\text{mm} \quad (8-3)$$

For this particular example, E is reduced from 80mm to just 40mm!! The net result is that 4 times less light reaches your eye. This may not have great consequences because in general, your eye becomes the limiting stop under bright-light conditions anyway, but it is something to consider when designing optical instruments.

Nighttime:

At night, under low-light conditions, the pupil of your eye can reach about 7mm in diameter. Under these conditions and for this same binocular example, the objective lens remains the aperture stop of the system, and the exit pupil is once again 4mm in diameter. However, this has the effect of trying to look through a window that is “too small,” making it seem as if you can never get your head as close to the exit pupil “window” as it should be. As in the daytime example, the result is similar—it becomes annoying and makes the binoculars hard to use.

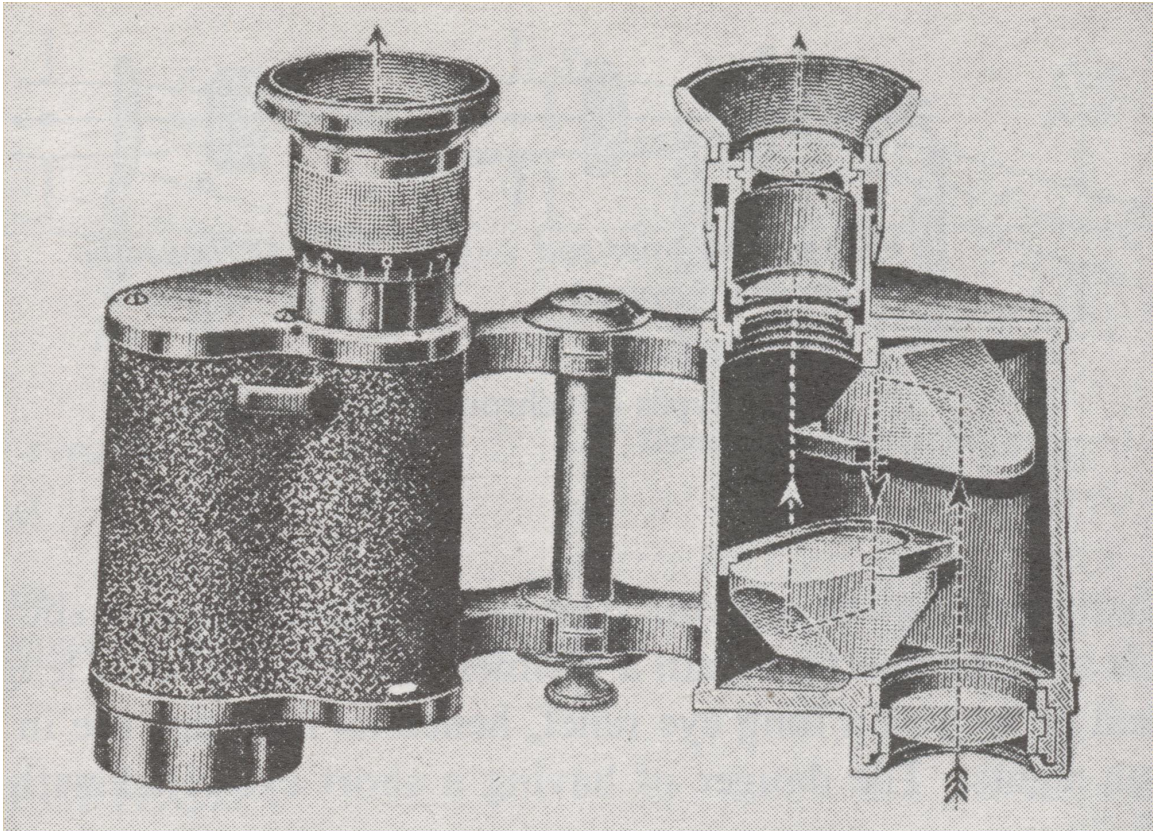


Fig. 8.1 Diagram of prism binoculars, showing the lenses and totally reflecting Porro prisms.

(from Fundamentals of Optics, Jenkins and White, Fourth ed., pp. 207-208).

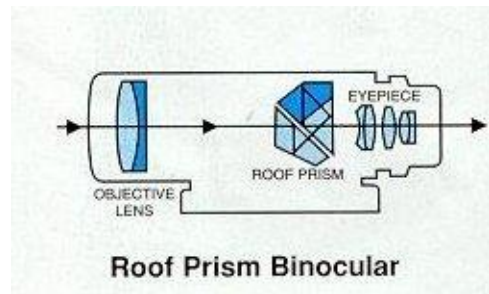
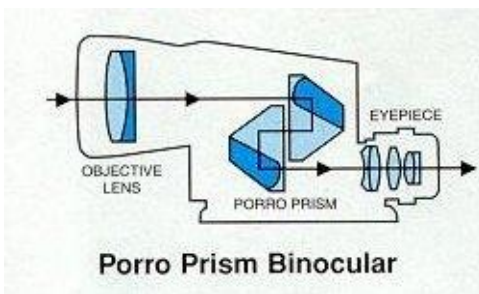


Fig. 8.2 Diagram of prism binoculars, showing the difference between Porro and Roof Prisms.

(http://www.geocities.com/siglx90/Equipment_Page.htm)

"The design of binocular instruments is challenging since comfortable viewing with two eyes presents difficulties that do not occur with monocular instruments. The coordinated motion of the two eyes must not be disturbed. A pupillary adjustment of 50 to at least 76 millimeters should be provided. Magnification differences to the two eyes should not exceed 2%. Some people cannot tolerate more than 0.5% while others may tolerate a little more than 2%. Oculars must be paired so that increased size differences will not occur. Beam splitters should be neutral, otherwise the light to the eyes will cause discomfort from the chromatic aberration of the eye. Should one eye receive a bluish light and the other eye a redish light the accommodation of each would have to be different, which would lead to strain and intolerable discomfort. The amount of light to the two eyes should be balanced, preferably within 10%. Vertical imbalance should not exceed 0.5 prism diopter. Horizontal imbalance need not be quite so small, but in excess of this value it would be fatiguing. Spectacle prescription practice holds to about 0.25 prism diopter. For low power instruments such as a bi-objective, binocular, microscope a 0.33 prism diopter difference may be tolerable. Any twist in the images should be kept to a minimum to avoid strain from complicated and difficult eye movements necessary to align the images on the retinas.

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When the objectives and the oculars of the instrument have different convergent angles, the appearance of depth can be made true (orthoscopic), or it can be increased or decreased (hyper- or hypostereoscopy), providing another variable for use by the instrument designer."

(from MIL-HDBK-141, 4.7.5).

Lab Exercises

Correct Use of Binoculars

If you wear glasses, fold back the rubber eye cups. If you don't use glasses, set the rubber eye cups up. Once the rubber eyecups have been set, the binoculars should provide a field of view without any vignetting, whether or not you wear eyeglasses, if they have sufficient eye relief. Eye relief is the distance from the rear vertex of the eyepiece to the exit pupil. If you want to use your binoculars with eyeglasses or sunglasses, look for binoculars that offer at least 15mm of eye relief.

While looking at a distant object, move the binocular tubes "up and down" (rotate the tubes about the hinge pin, located in-between them). This adjusts the IPD, or Interpupillary Distance. Stop moving the binocular tubes when image overlap from both eyes is as close to a perfect circle as possible. Your eyes will be centered in the ocular lenses at this position, if your eyes' IPD is within the range of the binoculars' IPD adjustment.

Properly aligned binoculars should have their optical axes parallel to each other. If they are not parallel, the field of view will be different for each eye (each eye will see a slightly different scene in object space). In addition, the two fields of view may not overlap, and your eyes will need to rotate to merge the two images. The images should

NOT look like the view with partially overlapped circles as seen through the “captain’s binoculars” in movies.

Next, set the diopter settings. Binoculars have two different designs for focusing. One is individual ocular focus. In this case, adjust each eye so it is in focus. Another binocular focus design style is center focus. To adjust focus using the center focus design, first look through the left eyepiece with your left eye and turn the central focusing ring to focus on a distant object. Then look through the right eyepiece with your right eye, rotating the diopter adjustment ring to focus on the same object. Now you can focus on any distant object by just turning the central focusing ring, which will adjust both the right and left eyepieces simultaneously. If the binoculars manufacturer set the diopter scales correctly, when viewing with glasses, or without glasses if your vision is 20/20, the scales should read zero when focused at infinity.

To look at a distant object, first look with your unaided eyes, then without changing your gaze, move the binoculars to your eyes and locate the object. If you use the binoculars without using your unaided eyes first, it may be more difficult to find the object.

- (1) ● Use both methods described above to view a distant object. Describe how well each method worked.
- (2) ● Measure the distance between the ocular lenses and report the value in mm. This is your interpupillary distance.

General Observations

Compare what you see by looking through the binoculars first from the ocular end, then from the objective end.

- (3) ● Describe the differences.
- (4) ● What instrument are you reminded of when looking through the objective? What type of instrument might the binoculars be?

Hold the binoculars away from your eyes, so that you can focus on the bright "spot" that appears to float as you move the binoculars around (one at the back of each eyepiece).

- (5) ● What are these spots?
- (6) ● Describe and make a drawing of what you see, both inside of the bright spot and around it. Are the spots round? If they aren't round, describe what the spots look like. There are several possible shapes. What would a non-circular spot indicate about the optical alignment, and how might this affect the quality of the image?

Performance in Bright Light

Take the binoculars outside and look at objects both up-close and then at a distance, both on-axis and at the edge of the FOV. Compare the cheaper Vanguard brand with the more expensive Bausch & Lomb binoculars when doing this.

- (7) ● Describe what you see. Is there any evidence of aberrations (this might be hard to actually see--look carefully, especially for "point" objects and "straight-edge" objects)?

Using the Bausch & Lomb binoculars:

- (8) ● How "close-in" can you focus?
(9) ● How far away can you focus?

Either outdoors, or perhaps inside the lab, look at a bright-dark "edge" positioned to be at the edge of the FOV. Do you see evidence of chromatic aberration?

- (10) ● Describe what you see.

Performance in Dim Light

Take the binoculars into the darkened lab. Look at a bright pinhole point source off-axis, just outside of the field of view.

- (11) ● Describe what you see. Can you see stray or scattered light? Compare the cheaper Vanguard brand with the more expensive Bausch & Lomb binoculars when doing this.

Now, look at the point source on-axis, and then at different points in the full FOV. First, look for multiple faint (ghost) images.

- (12) ● Describe what you see. Where might these be coming from?

Next, look for color "fringing" or chromatic aberration, especially at the edge of the field.

- (13) ● Describe what you see. What type of chromatic aberration is this?

Optical Properties (do the following for both the Vanguard and the Bausch & Lomb)

- (14) ● Measure the "clear" diameter of the objective lens.
(15) ● What are the measured values, and how do they compare to the stated values?

Set up an optical test to measure the magnifying power, MP, of the binoculars. (Objective diameter/exit pupil diameter = magnification).

- (16) • Describe the measurement.
- (17) • What are your measured values, and how do they compare to the labeled values on the binoculars?

Set up an optical test to measure the field of view, FOV, of the binoculars.

- (18) • Describe the measurement.
- (19) • What are your measured values, and how do they compare to the stated values?

Binocular Resolution

Binoculars have low magnification compared to many other telescopes. The size of the objective in any telescope determines the ultimate theoretical resolution (as described by physical optics, diffraction, and the Raleigh Limit). In order to resolve two point source objects, the objective must first separate them into two point images (in the rear focal plane of the objective). However, to be able to see them visually in the image space of the binoculars, requires that their angular separation be greater than 1 arc min (the resolution of a normal “20/20” human eye).

An example will help clarify this. Suppose that you have average (“20/20”) human vision, which means that you should be able to resolve two objects separated by 1 arc min. Now suppose that you want to see two stars, separated by 10 arc sec. With naked-eye viewing this is impossible, as the star separation is a factor of 6 less than what your eyes can resolve. Suppose, however, that you view the stars through a pair of 6 x 30 binoculars, which magnify the view of the stars by a factor of six. This is an angular magnification, so quite literally, the stars that you see looking through the eyepiece are now separated by $6 \times 10 \text{ arc sec} = 1 \text{ arc min}$. With just this amount of magnification, you should be able to just resolve these two stars!

Compare the resolution of three different binoculars, each having the same objective lens diameter, but different magnification: Vanguard 12 x 50, Zephyr 7 X 50 and the Belmont 20 x 50 binoculars. Look at the USAF 1951 Resolution Test Pattern at a distance of 100 feet. The table on the chart shows the lines per mm for all of the patterns. The reciprocal of this number is the distance between centers of two printed black lines. Identify the pattern having the smallest distance between black lines that you can just resolve. This is the limit of resolution for your eyes and this particular pair of binoculars.

- (20) ● Determine the lines per mm from the table on the chart (for the pattern that you could just resolve). Take the inverse to calculate the actual distance between centers of two black lines. Using this number, calculate the viewed angle subtended at 100 feet.
- (21) ● Now, test the (angular) resolution of your unaided eye, using no binoculars. Set this test up in the hallway, so you can conveniently use the floor tile (12" apart) to mark off distances. Walk away from the target until the largest group of lines is at the limit of resolution (until you can just barely resolve these individual lines). Record the distance to the target. Using this distance and the line pair separation of 4mm (for the coarsest pattern, Group -2, Element 1), calculate the viewed angle subtended. How close is it to 1 arc min (the average for humans that defines "20/20" vision)?
- (22) ● Typical unaided visual resolution is reported as being 2 arc min per resolved line pair ("The Eye and Visual Resolution" by Bruce H. Walker <http://www.spie.org/web/oer/october/oct97/eye.html>), or 1 arc min from high contrast targets. The resolution of the binoculars should be about 1 arc min/binocular magnification. How does this compare with your eye and binocular resolution tests?

Things to look for in premium binoculars:

- 1) Round exit pupils
- 2) Broadband Fully-Multicoated optics (fully AR-coated, or AR coated do not have the best coatings). If you shine a flashlight into the objectives you should not see any white reflections in premium binoculars, only faint colors. Ruby red coatings indicate inferior binoculars.
- 3) Field of view of each eyepiece is similar, with mismatch in overlap of images less than 5%. Looking through the binoculars should show a single image using two eyes. The images from both eyes should be overlapped in a circular pattern, not like the two partially overlapped areas indicating a view through binoculars in movies.
- 4) Good convergence of images.
- 5) Wide IPD range, preferably from 50 to 76 mm.
- 6) Good eye relief, 16 mm minimum.
- 7) Sharpness of image across the field. It is normal for image sharpness to decrease noticeably at around 70% of the field of view, but the better the binoculars, the less sharpness decrease toward the edge.
- 8) Minimum chromatic aberration. Some is to be expected, but the more expensive binoculars have better correction.
- 9) Waterproof and fogproof. These typically have rubber armor and are dry nitrogen purged. Don't test this!
- 10) Good fit in the hands if they are hand-held binoculars.

"Reverse-Engineering of a Pair of Binoculars"

Work with the disassembled parts:

- (23) ● Measure the focal length of the objective lens. Report its value.
- (24) ● Study the disassembled eyepiece. What type of eyepiece is it?
(see Fundamentals of Optics, Jenkins & White for information).
- (25) ● Measure the optical properties of the separate lenses, and then the eyepiece (hold the lenses together using a V-groove lens holder and the black tube from the binocular). What is the effective focal length of the eyepiece?
- (26) ● Consider how the lenses are oriented in the eyepiece. Does this give large or small amounts of spherical aberration? Look through the eyepiece. Do you see spherical aberration?
- (27) ● Assemble the eyepiece and objective into a telescope. What kind of telescope did you just build?
- (28) ● Compare the physical length of this telescope to the original binoculars. By what distance does the Porro-prism pair "fold-up" the system?