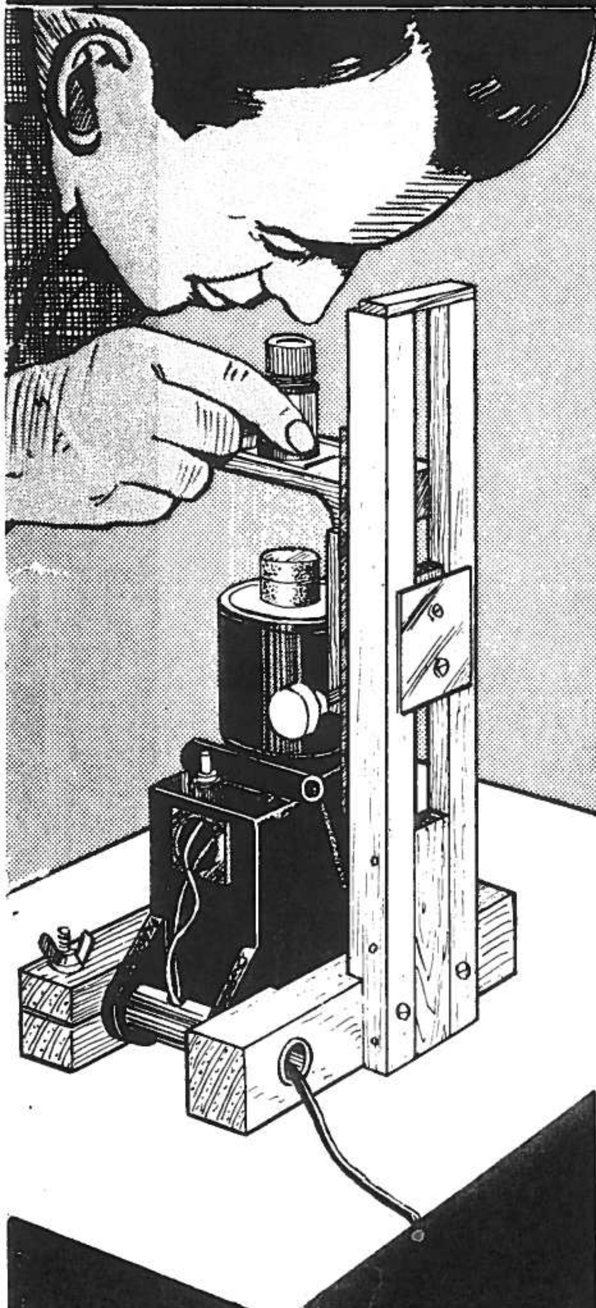
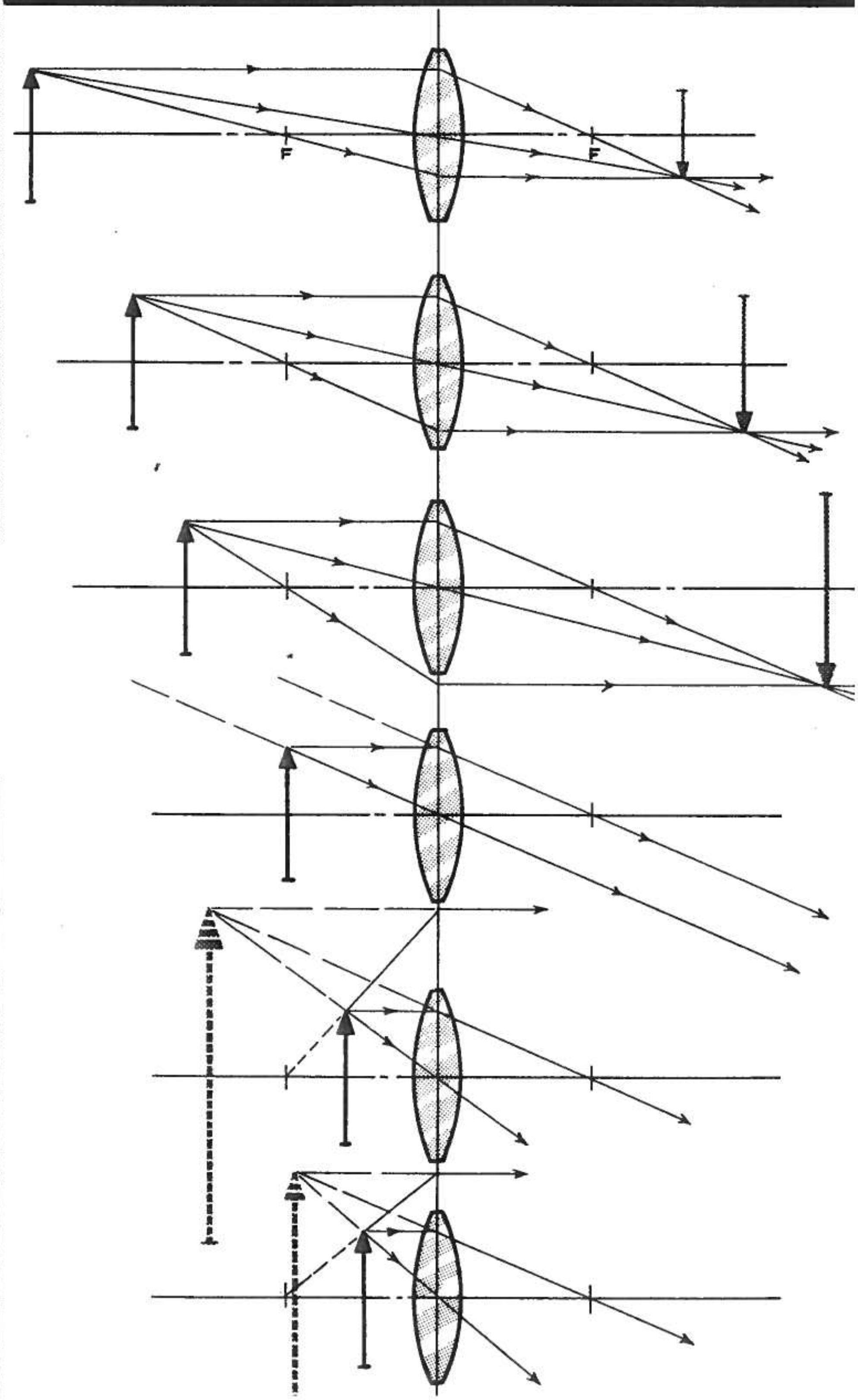
telescope OPTICS





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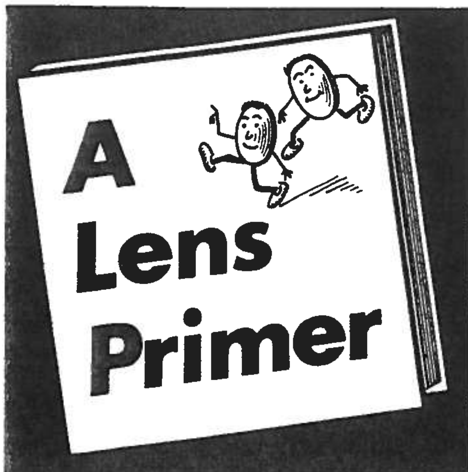
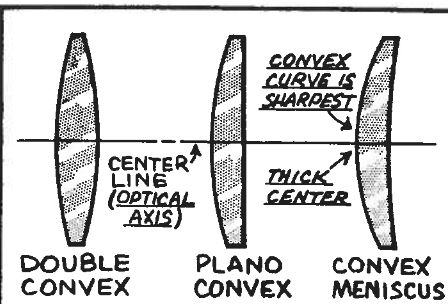
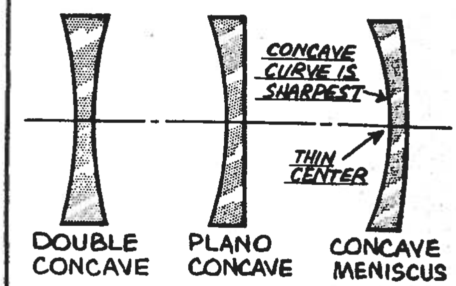




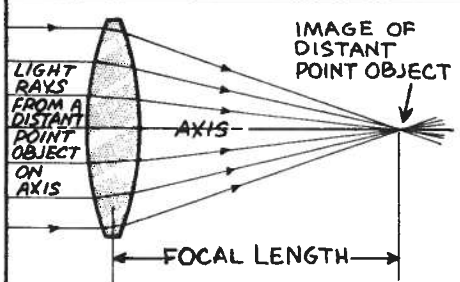
POSITIVE LENSES

A LENS IS POSITIVE IF IT CAN CONVERGE PARALLEL LIGHT TO FORM AN IMAGE. IF THE LENS IS A SINGLE PIECE OF GLASS, IT IS A SIMPLE LENS



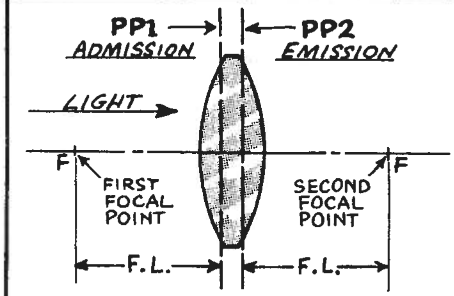
NEGATIVE LENSES

NEGATIVE LENSES CAUSE PARALLEL LIGHT RAYS TO DIVERGE — NO IMAGE IS FORMED. USED ALONE AT EYE, A NEGATIVE LENS REDUCES



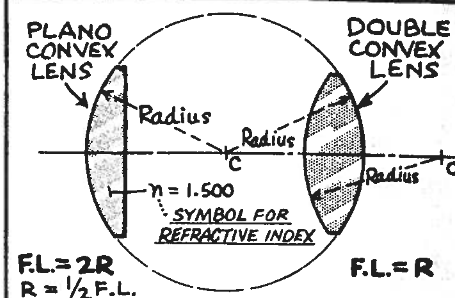
FOCAL LENGTH

DISTANCE FROM A LENS TO POINT WHERE IT FORMS AN IMAGE OF A DISTANT OBJECT. *USUALLY MEASURED FROM CENTER OF LENS ALTHO NOT EXACT*



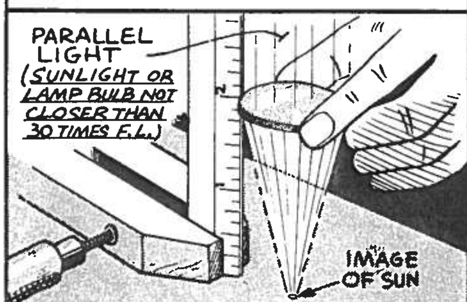
PRINCIPAL PLANES

IMAGINARY PLANES FROM WHICH EXACT FOCAL LENGTH MEASUREMENTS ARE TAKEN. IF THE LENS IS SYMMETRICAL, THE PP'S ARE SYMMETRICAL



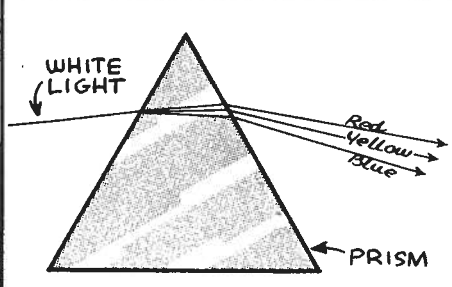
RADIUS of CURVATURE

ALL SIMPLE LENSES HAVE SPHERICAL CURVES. THE RADII DETERMINE THE FOCAL LENGTH. *FORMULAS ARE APPROX. ...EXACT ONLY FOR THIN LENS, INDEX 1.5*



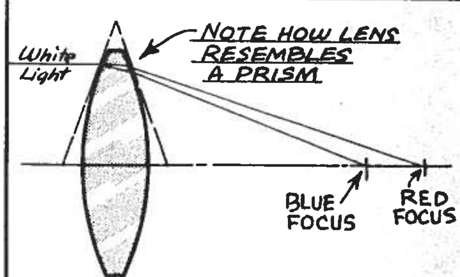
FINDING F.L. of a LENS

HOLD THE LENS IN SUNLIGHT AND ALONGSIDE A RULER. MOVE LENS UP AND DOWN TO FORM SMALLEST IMAGE OF SUN. READ THE F.L. ON RULER



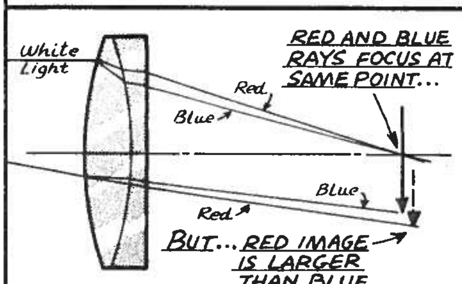
WHITE LIGHT

WHITE LIGHT IS COMPOSED OF ALL THE COLORS. A NARROW BEAM OF SUNLIGHT DIRECTED THRU A PRISM WILL EMERGE AS A COLORED BAND - THE SPECTRUM



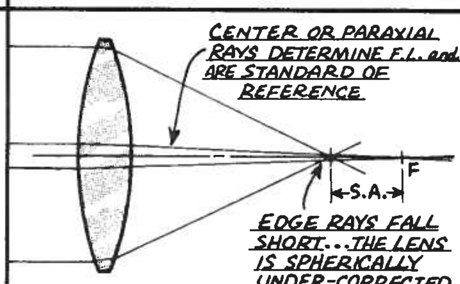
LONGITUDINAL COLOR

SIMPLE LENS BREAKS UP WHITE LIGHT JUST LIKE A PRISM. BLUE RAYS FOCUS CLOSER THAN RED. THE FAULT IS CONSTANT OVER WHOLE FIELD



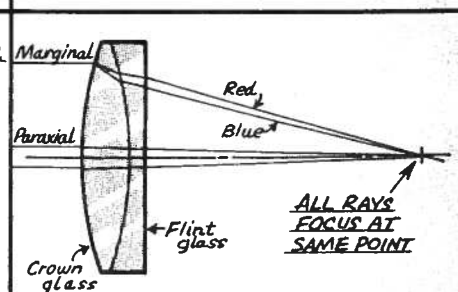
LATERAL COLOR

FAILURE OF THE LENS TO FORM SAME IMAGE SIZE IN ALL COLORS. THIS FAULT INCREASES WITH FIELD ANGLE... IS NOT PRESENT ON AXIS



SPHERICAL ABERRATION

AS SHOWN, A POSITIVE LENS IS SPHERICALLY UNDER-CORRECTED. **S.A.** VARIES WITH f/VALUE OF LENS AND IS LESS FOR A SMALL APERTURE



ACHROMATIC LENS

ACHROMATS ARE TWO-ELEMENT LENSES CORRECTED FOR LONGITUDINAL COLOR AND SPHERICAL ABERRATION FOR AN AXIAL OBJECT

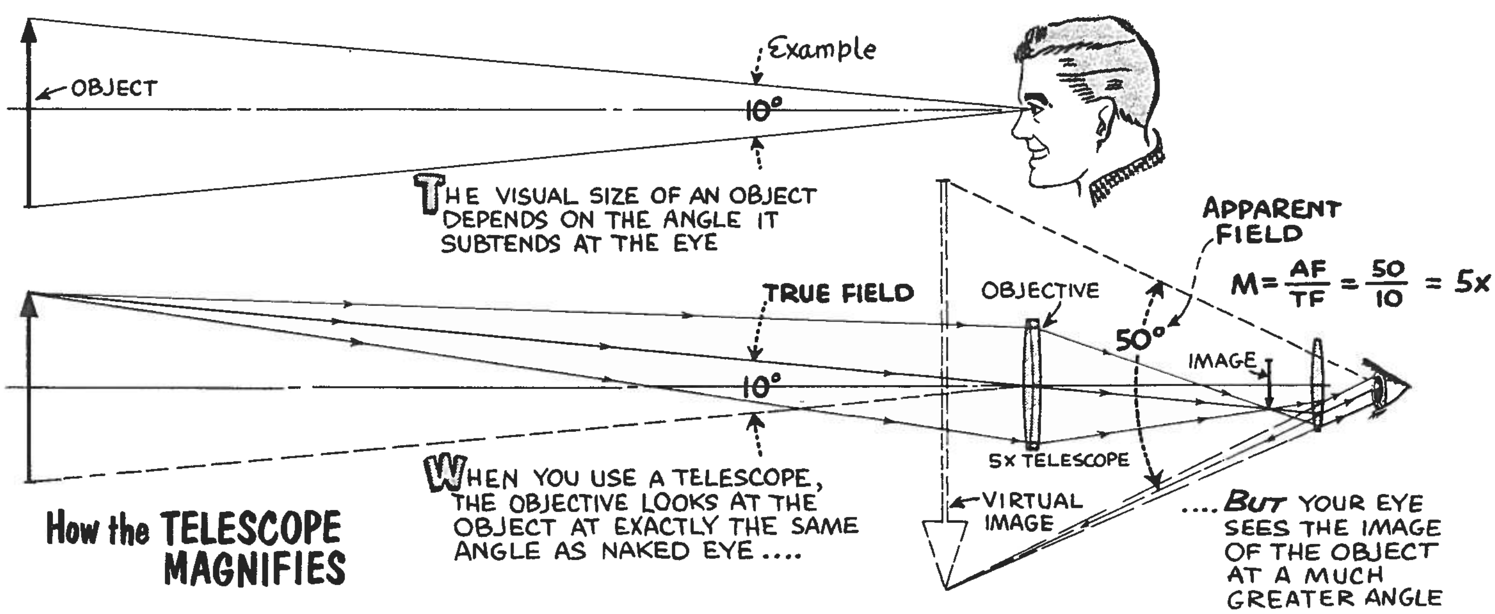
telescope OPTICS

edited by Sam Brown

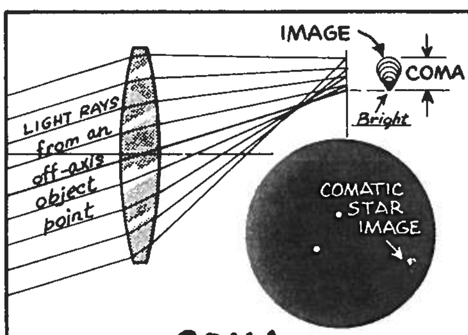
OPTICS is a big subject. Most beginners avoid lens design, knowing very well that such work is a mathematical jungle. The simpler approach is to buy lenses, prisms and mirrors readymade and take it from there. Then the math work reduces to simple lens equations. If you use stock optics of good quality, you can be assured of good imagery. The problem of designing a telescope is just a matter of getting light through the instrument to form an image of a certain size at a certain location.

The astronomical telescope is a narrow-field instrument of 1 degree or less. As a result the objective is nearly immune to the off-axis aberrations--coma, distortion, field curvature and astigmatism. The two axial faults are chromatic and spherical aberration. As you may already know, chromatic aberration is non-existent for reflected light. In brief, if your interest is in reflecting telescopes, your only problem in image quality is that of spherical aberration. Even when you make your own mirror, the job of fashioning and correcting a single surface is well within the capabilities of the average person.

Where is the image? Even in simple observing, you sometimes wonder. All optical drawings of telescopes assume the final image to be a virtual one formed at infinity. As a matter of fact, most persons will focus "in" a little more than necessary, causing the emergent light rays to diverge slightly as required to form a virtual image at 20 to 40 inches, as shown in drawing below. In any case it makes no difference in the magnification, which is strictly a matter of angular subtense which is the same at any distance.

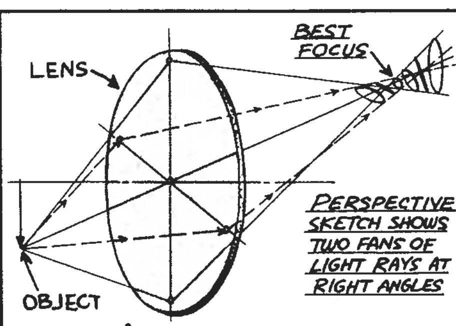


How the TELESCOPE MAGNIFIES



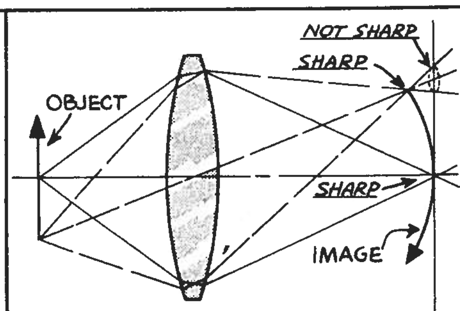
COMA

COMA IS OBLIQUE SPHERICAL ABERRATION. IT OCCURS ONLY OFF-AXIS WHERE THE UNSYMMETRIC DEFORMATION PRODUCES A COMET-SHAPE IMAGE



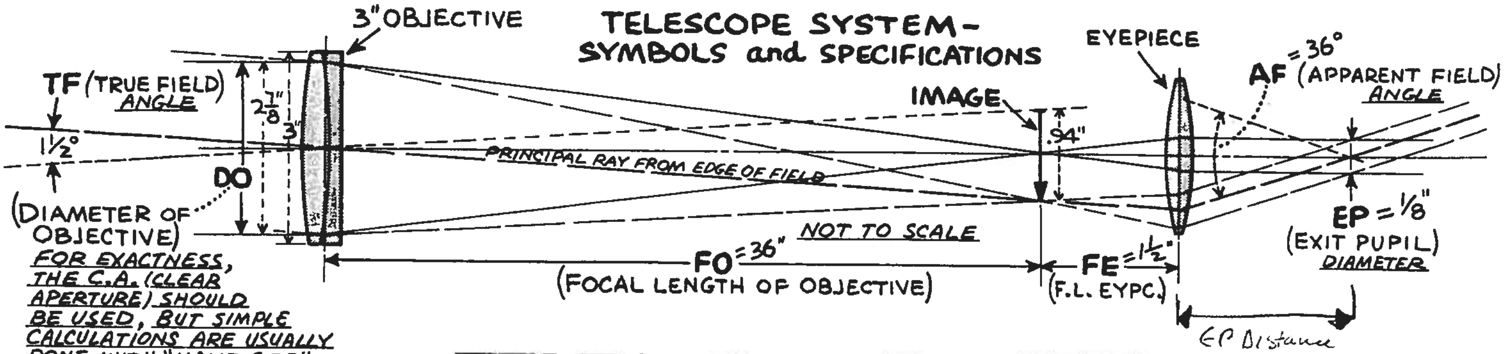
ASTIGMATISM

THIS FAULT SHOWS AN IMAGE POINT AS A SHORT LINE, WHICH CHANGES FROM HORIZONTAL TO VERTICAL POSITION ON EITHER SIDE OF BEST FOCUS



FIELD CURVATURE

THE NATURAL TENDENCY OF A LENS IS TO FORM A SHARP IMAGE ON A CURVED SURFACE BENT TOWARD THE LENS



TELESCOPE ARITHMETIC

EP distance = 1/FE - 1/(FE+FO)

	THREE WAYS TO CALCULATE MAGNIFICATION	EXAMPLE
1	$M = \frac{FO}{FE}$	$\frac{36}{1.5} = 24x$
2	$M = \frac{DO}{EP}$	$\frac{3}{1/8} = 3 \times \frac{8}{1} = 24x$
3	$M = \frac{AF}{TF}$	$\frac{36}{1.5} = 24x$
	M. MUST BE KNOWN FOR OTHER CALCULATIONS	
4	$FO = M \times FE$	$24 \times 1\frac{1}{2} = 36''$
5	$FE = \frac{FO}{M}$	$^{12}/\frac{36}{24} = \frac{3}{2} = 1\frac{1}{2}''$
6	$DO = M \times EP$	$24 \times \frac{1}{8} = 3''$
7	$EP = \frac{DO}{M}$	$^{3}/\frac{3}{24} = \frac{1}{8}''$
8	$TF = \frac{AF}{M}$	$^{12}/\frac{36}{24} = \frac{3}{2} = 1\frac{1}{2}°$
9	$AF = M \times TF$	$24 \times 1\frac{1}{2} = 36°$

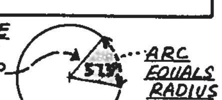
ONE OF the first things you have to know about any telescope is its magnification. This is easily calculated by the No. 1 equation in box at left, a formula well-known to even the beginner.

Equations involving the field angle--Nos. 3, 8 and 9--can be applied to a part of the field as well as all of it. For example, if the separation of a double star is 6 seconds of arc (its true field angle) and you want to see it at 6 minutes of arc apparent field angle, you use equation No. 3, first changing the 6 minutes to seconds. Then by equation No. 3, M equals 360/6, equals 60x. Of course, you then have to find out what f.l. eyepiece will give 60x, or, in other words, you have to find FE when M and FO are known. The solution is equation No. 5.

The image diameter is easy to calculate if you know the apparent field, equation No. 10, and a simple transposition of this, No. 11, reveals the apparent field angle when the image size is known. The linear field diameter for any normal focal length can also be obtained directly from the Image Table in the chapter on eyepieces.

	CALCULATION OF IMAGE DIA. and APPARENT FIELD by RADIANS*	EXAMPLE (AS ABOVE)
10	IMAGE (DIA.) = AF (RADIANS) × FE	AF = 36° 36° = .628 Radians (FROM TABLE) IMAGE = .628 × 1.5 = .94"
11	$AF_{(RADIANS)} = \frac{IMAGE}{FE}$	$AF_{(RADIANS)} = \frac{.94}{1.5} = .63^R$ .63 Radians = 36° (FROM TABLE)

* THE UNIT OF CIRCULAR MEASURE. ONE RADIAN EMBRACES AN ARC OF A CIRCLE EQUAL TO ITS RADIUS. 1 RADIAN = 57.3°

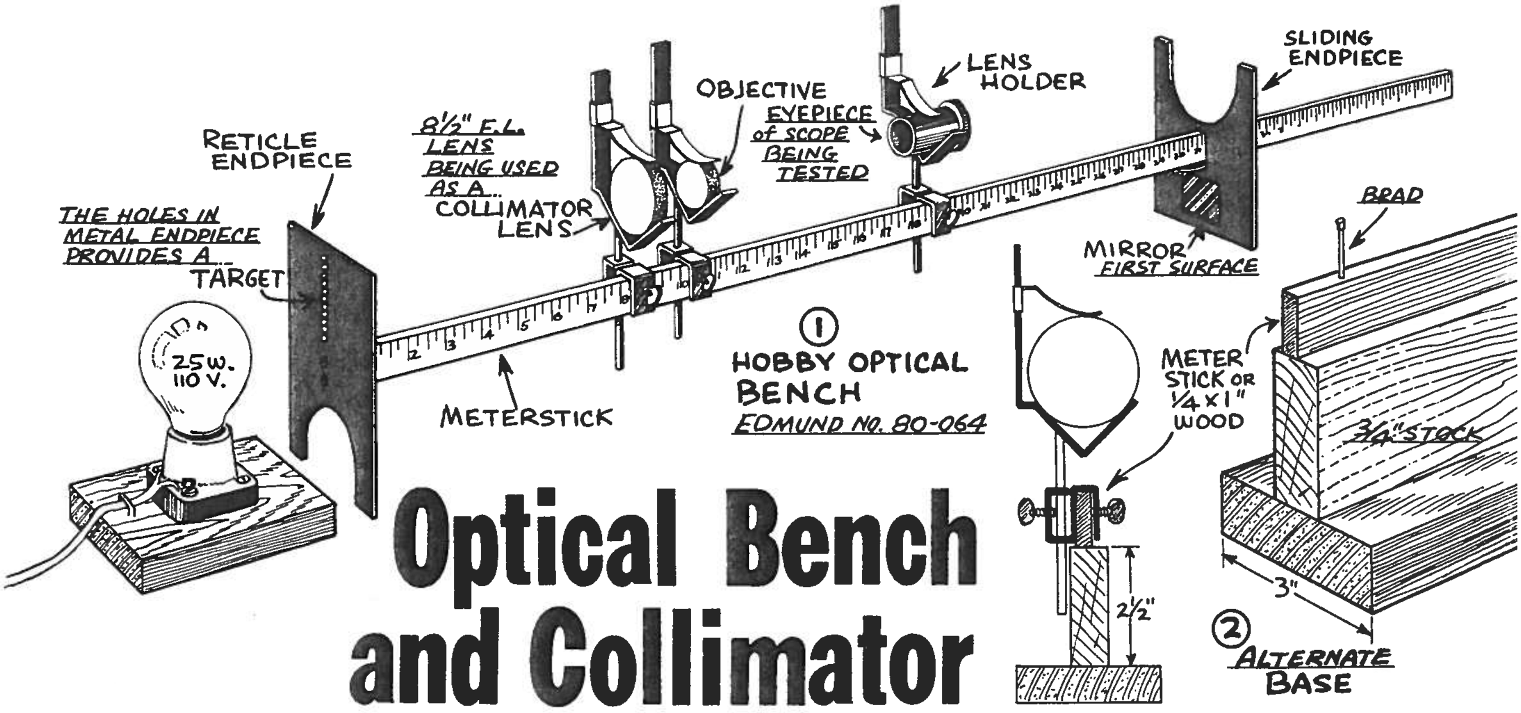


f/VALUE ... IS THE RATIO OF FOCAL LENGTH TO APERTURE

12	13	14
$f/VALUE = \frac{FO}{DO}$	$DO = \frac{FO}{f/VALUE}$	$FO = f/ \times DO$
EXAMPLE AS ABOVE: $f/ = \frac{36}{3} = f/12$	$DO = \frac{36}{12} = 3''$	$FO = 12 \times 3 = 36''$

TABLE - DEGREES TO RADIANS

DEG.	RAD.	DEG.	RAD.	DEG.	RAD.	DEG.	RAD.
5°	.087R	25°	.436R	41°	.716R	57°	.995R
10	.175	26	.454	42	.733	58	1.012
11	.192	27	.471	43	.751	59	1.030
12	.209	28	.489	44	.768	60	1.047
13	.227	29	.506	45	.785	61	1.065
14	.244	30	.524	46	.803	62	1.082
15	.262	31	.541	47	.820	63	1.100
16	.279	32	.559	48	.838	64	1.117
17	.297	33	.576	49	.855	65	1.135
18	.314	34	.593	50	.873	66	1.152
19	.332	35	.611	51	.890	67	1.169
20	.349	36	.628	52	.908	68	1.187
21	.367	37	.646	53	.925	69	1.204
22	.384	38	.663	54	.942	70	1.222
23	.401	39	.681	55	.960	71	1.239
24	.419	40	.698	56	.977	72	1.257



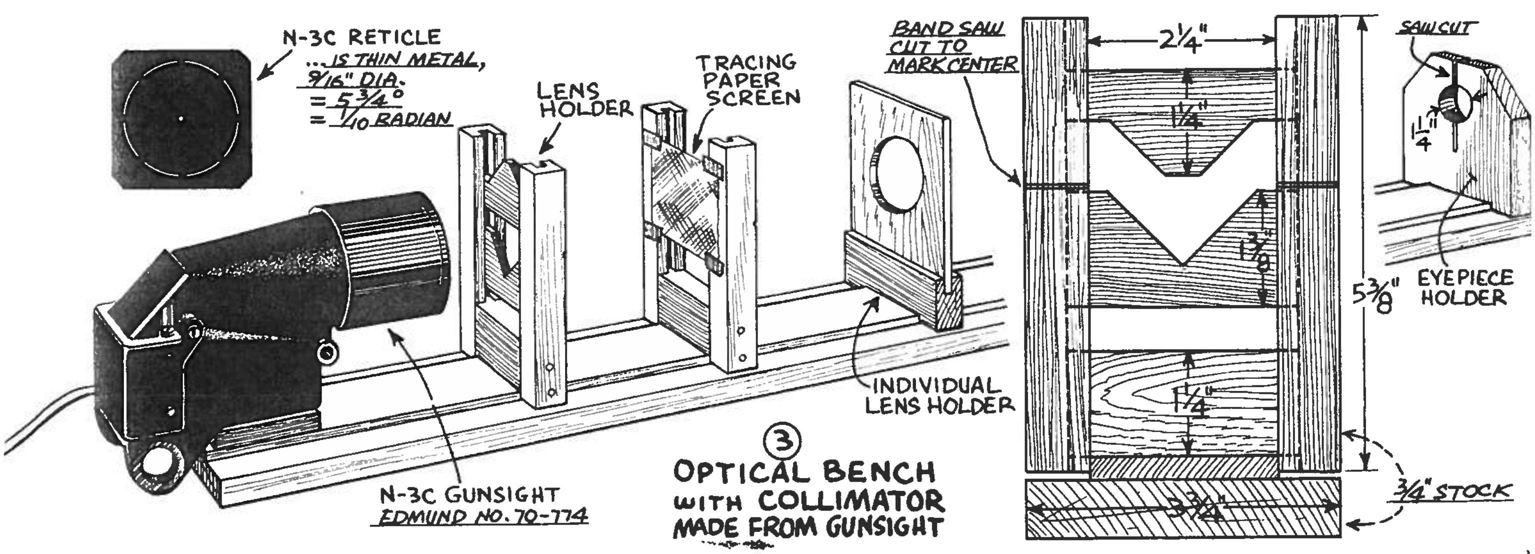
Optical Bench and Collimator

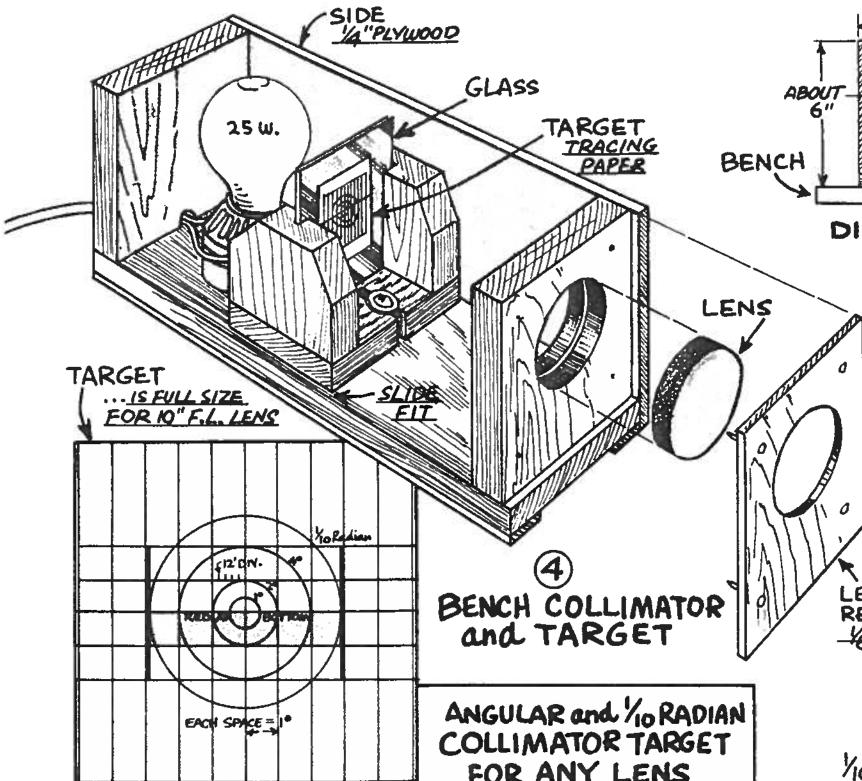
AN OPTICAL bench is the kind of equipment which may cost $5 or $5000. You can buy or build. Fig. 1 shows an inexpensive hobby optical bench you can buy. It is mounted on a wood meterstick. If you need a stronger or longer base, the construction shown in Fig. 2 can be used.

A collimator consists of some kind of illuminated reticle or target in the focal plane of an achromatic lens. Such an arrangement provides the equivalent of a distant target. A collimator can be built right on the optical bench as needed. In the equipment shown, the end plate is perforated with a vertical line of small holes. This is your "target." The collimator lens can be any good-quality achromat of 5 in. or more focal length. It is mounted at exactly one focal length from the reticle plate, a setting which is easily checked by auto-collimation as described on a following page. Fig. 1 setup shows a small finderscope being tested, the bench providing a means of holding the lenses while the collimator supplies the equivalent of a distant target.

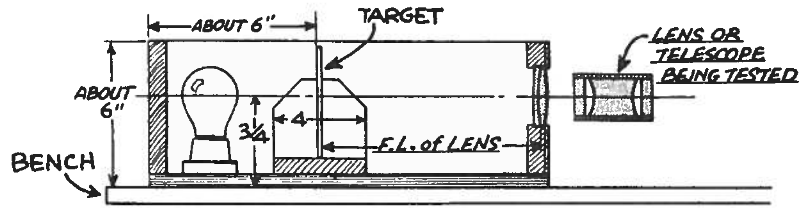
Fig. 3 shows a simple homemade optical bench. The adjustable lens holders can handle lenses to 2-1/8 inch diameter, and sizes over this can be mounted in individual holders. The sliding vee blocks which clamp the lens in the grooved frame should be made of hardwood plywood. The collimator is a military gunsight, which requires only a simple conversion to 110-volt lighting, details of which are supplied with the merchandise.

The obvious weakness of the optical bench and collimator is that the equipment should be somewhere near the physical size of the largest telescope you plan to test. Small equipment works

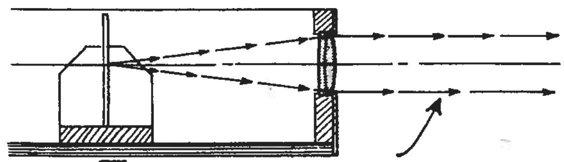




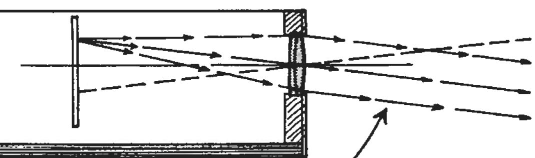
④ BENCH COLLIMATOR and TARGET



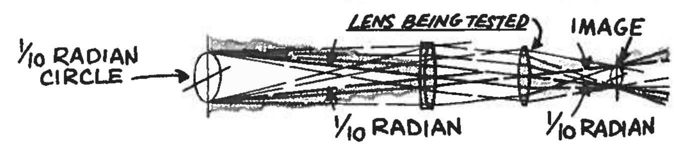
DIMENSIONS DEPEND ON F.L. OF LENS



[A] ALL LIGHT RAYS FROM CENTER OF TARGET EMERGE PARALLEL



[B] ALL LIGHT RAYS FROM A POINT AT EDGE OF TARGET EMERGE PARALLEL



[C] ANY ANGLE OF THE TARGET WILL BE MAINTAINED THRU ANY LENS BEING TESTED

ANGULAR and 1/10 RADIAN COLLIMATOR TARGET FOR ANY LENS

	You want to find	FORMULA	Ex: 20" F.L. COLLI. LENS
MAKING THE TARGET	DIA. of 1/10 RADIAN CIRCLE	.1 Radian CIRCLE (DIA.) = F × .1	20 × .1 = 2.0"
MAKING THE TARGET	DISTANCE EQUAL TO 1°	1° SPACE = F × .0175	20 × .0175 = .35"
READING THE TARGET	TRUE FIELD of a TELESCOPE	COUNT THE DEGREE SPACES. Ex: is about 4°	Example: 2" F.L. YOU DO NOT KNOW F.L. IMAGE WILL READ .200"
READING THE TARGET	F.L. of a LENS BEING TESTED	F = IMAGE DIA. of .1 Radian CIRCLE / .1	$F = \frac{.200}{.1} = 2.0"$
READING THE TARGET	ALTERNATE: FOR LENSES OVER 5" F.L.	F = IMAGE OF 1° SPACE / .017	Ex: 20" F.L. LENS (IT WILL READ .350") $F = \frac{.350}{.017} = 20"$

fine for riflescopes, finderscopes and small terrestrial and astro telescopes. Suitable equipment to test a 6-inch reflector is somewhat of an oversize luxury. However, you can do many tests and operations with a small collimator.

HOMEMADE COLLIMATOR. You can house a collimator in either a box or a tube. Fig. 4 shows a typical box job. The collimator lens should be a good quality achromat of fair size and focal length--3 inches diameter and 24 inches f.l. is a good size, suitable for some tests with telescopes as large as 6-inch aperture. Much smaller equipment is perfectly satisfactory for some operations. The collimator target is drawn with ink on tracing paper. The target is taped or cemented to a piece of glass, as shown. Simple rules for scaling the target to suit any focal length collimator lens are given in the drawing, Fig. 4.

Light from any distant object reaches your eye in parallel bundles. In the same manner, light emerges from the collimator in parallel bundles. That is, a point at the center of the target will send out a beam like A in Fig. 4; a point at the edge of target will send out a beam at some specific angle, as at B. All of the light is in parallel bundles, but the whole light cone is spreading, diverging. In other words, parallel light does not mean quite the same thing as a parallel "beam" of light.

Any angle that the target makes with the collimator lens will be reproduced exactly by any lens or telescope placed in front of the collimator. Fig. 4C shows the situation as it applies to the 1/10 radian circle. This particular unit is used for the determination of focal length. The image of the 1/10 radian circle produced by any lens, eyepiece or telescope will be 1/10 the focal length of said lens, eyepiece or telescope. In other words, if you measure the image diameter formed by any lens, you will know immediately its focal length, which is simply 10 times the image diameter. For short focal lengths under 5 in., a pocket comparator (measuring magnifier) is ideal for measuring the image diameter.

Optical Bench PROCEDURES

FOCAL LENGTH OF A LENS. When you focus a camera or telescope on a distant object, the image forms at one focal length behind the lens. So, if you have a lens of unknown f.l., you simply focus on a distant object and then measure the distance from lens to image, which is the focal length. Indoors, this is done with any bench collimator, as shown in Fig. 1.

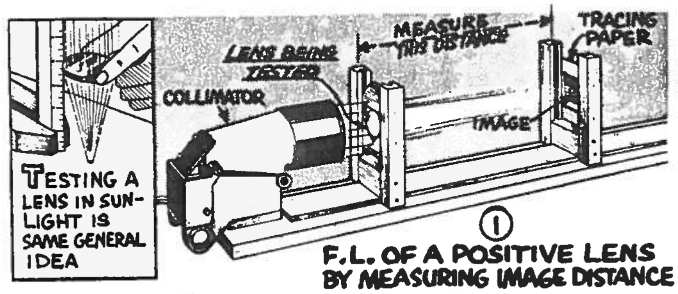
FIELD OF A TELESCOPE. If your collimator target includes degree marks, the field of any telescope or binocular can be seen directly on the target--just count the number of degrees you can see. This is the true angular field. The Apparent Field is TF times M.

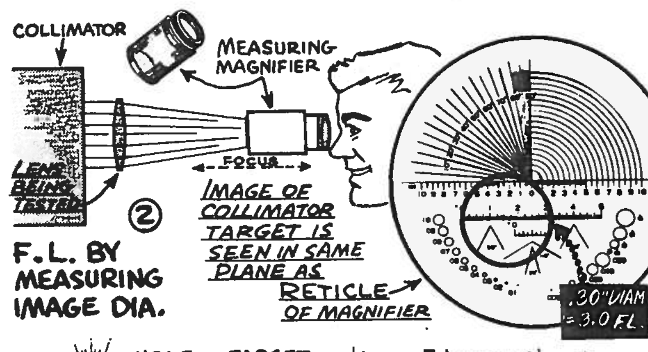
F.L. FROM IMAGE SIZE. This method is especially useful for eyepieces and other combinations of two or more lenses. You need a 1/10 radian reticle target, as described on a previous page. Set up the lens or eyepiece to be tested in the usual manner, and then measure the image it forms with a fine scale or with a direct-reading magnifier, Fig. 2. The focal length is 10 times the image diameter.

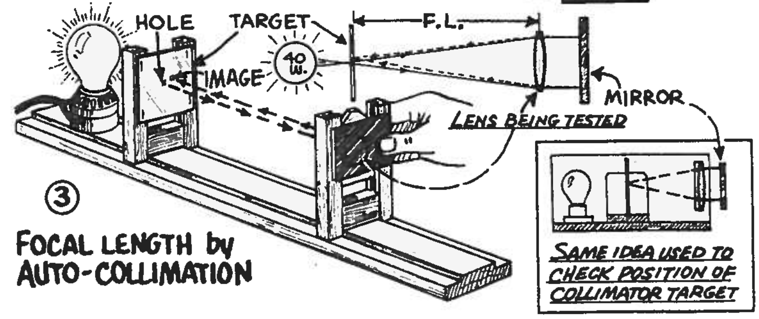
AUTO-COLLIMATION. The target for this is an opaque material in which is cut a small hole. The target is also a screen and should be white on the side facing away from the light. An ordinary flat mirror is held behind the lens being tested. When properly focused the lens will form an image of the target hole on the target itself, as shown in Fig. 3. The distance from target to lens is the focal length.

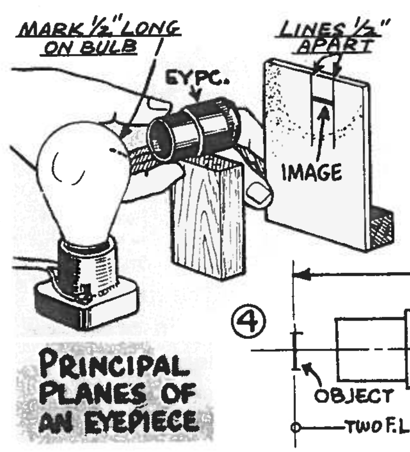
PRINCIPAL PLANES. Make some kind of setup similar to Fig. 4. The general idea is to juggle the eyepiece and screen back and forth until the image on screen is exactly in focus and exactly 1/2 inch long, the same as the target. This is 1x spacing, indicating the PP's are located two focal lengths from the object and image.

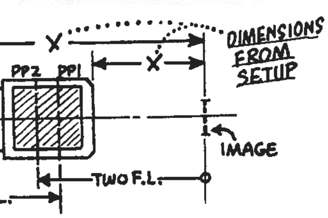
Alternately, PP2 can be located with a collimator, Fig. 5. Reversing the eyepiece would locate PP1, but usually the image will not be accessible. If the eyepiece is symmetrical, PP2 is all you need.

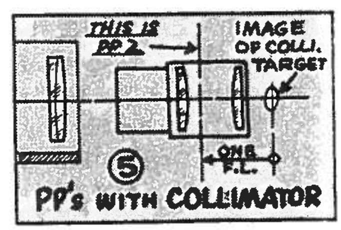






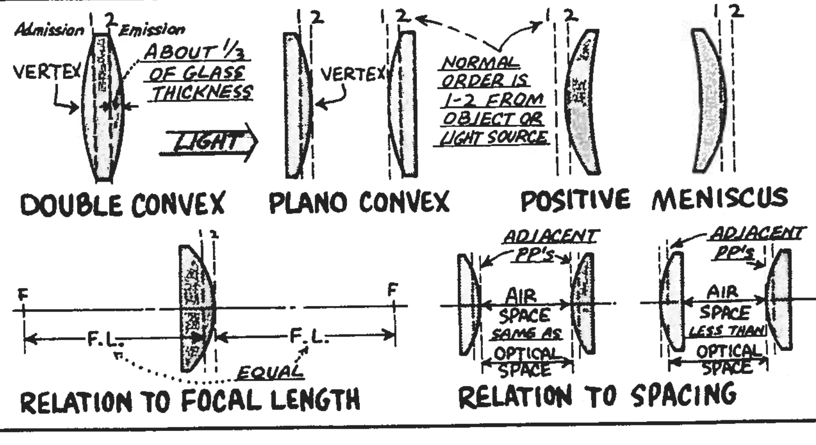






PRINCIPAL PLANES of SIMPLE POSITIVE LENSES

Usually it is close enough to set off the focal length or other measurement from the center of a lens, but if you want to be exact, the proper measuring points are the principal planes, as shown. When you make light ray diagrams, the light goes first to PP1, then parallel with axis to PP2 and then to the image point.



Ray Tracing from bench setups

IN designing a telescope, the first step is to select some suitable lenses for the objective and eyepiece. Next, you do some paperwork to get basic data. The third step is to "test" the design in some fashion, usually with optical bench and collimator target if the telescope is not too large. The end product of optical designing is some kind of plan drawing, showing how light gets through the system. The light path diagram, plus the actual "look and see" test on the optical bench, gives ample assurance that the telescope is AOK.

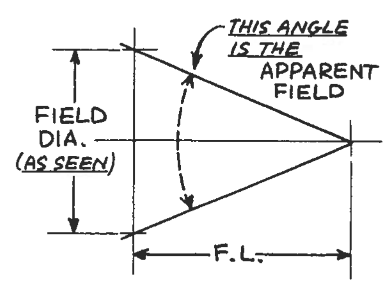
PAPERWORK. An example of a small refractor is shown on the opposite page. Instruments of this size and power are commonly used as finderscopes on larger telescopes. The preliminary data is obtained by applying the formulas given on page 2; information about the field angle and linear image diameter is given in the chapter on eyepieces. The preliminary paperwork reveals on overly large exit pupil of 1/2 inch diameter. Even in the dark, the pupil of your eye is not more than about 5/16 inch diameter. In brief, the design wastes a lot of light. So, if you were actually building this telescope, you would probably substitute a 1-1/4-inch diameter objective of the same focal length. This would assure better optical performance all around while retaining the maximum useful diameter of exit pupil.

BENCH TESTING. The first operation on the optical bench is to set up the objective and locate the image plane, Fig. 2. You can work in ordinary room light. The image is not confined in any manner at this stage and it will spread over a considerable area. Next, the eyepiece is mounted behind the image and moved back and forth until you see the image in sharp focus, Fig. 3. In other words, you focus the telescope--you make the focal plane of the eyepiece coincide with the focal plane of the objective. Under such circumstance, the emergent light is in parallel bundles. The final bench operation is to locate the exit pupil, Fig. 4.

LIGHT RAY DIAGRAM. From the bench setup, it is easy to pick off spacing dimensions and diameters. You can also check the angular field and linear diameter of image. The first stage in the light path diagram is the light cone from a point object at the center of the field. This funnels down to a corresponding point at the center of the image, and then emerges from the eyepiece as a parallel bundle of light rays, Fig. 5. The light cone for an edge-of-field object point is drawn next, Fig. 6. The most important light ray for edge-of-field object point is the ray that passes through the center of the objective. It is not deviated by the objective and goes directly from the point object at edge of field to the point image at edge of image, straight through to the eyepiece. This light ray through the center of the objective is called a principal or chief ray--if you can get it through to the exit pupil you are assured of no less than 50% lighting at the edge of field. You can see that for this particular telescope, the principal ray does get through, but the marginal ray criss-crossing the axis fails to strike the eyepiece. This instrument has a little better than 50% lighting at the edge of field, and such lighting is generally satisfactory, based on the fact the eye is self-compensating for such

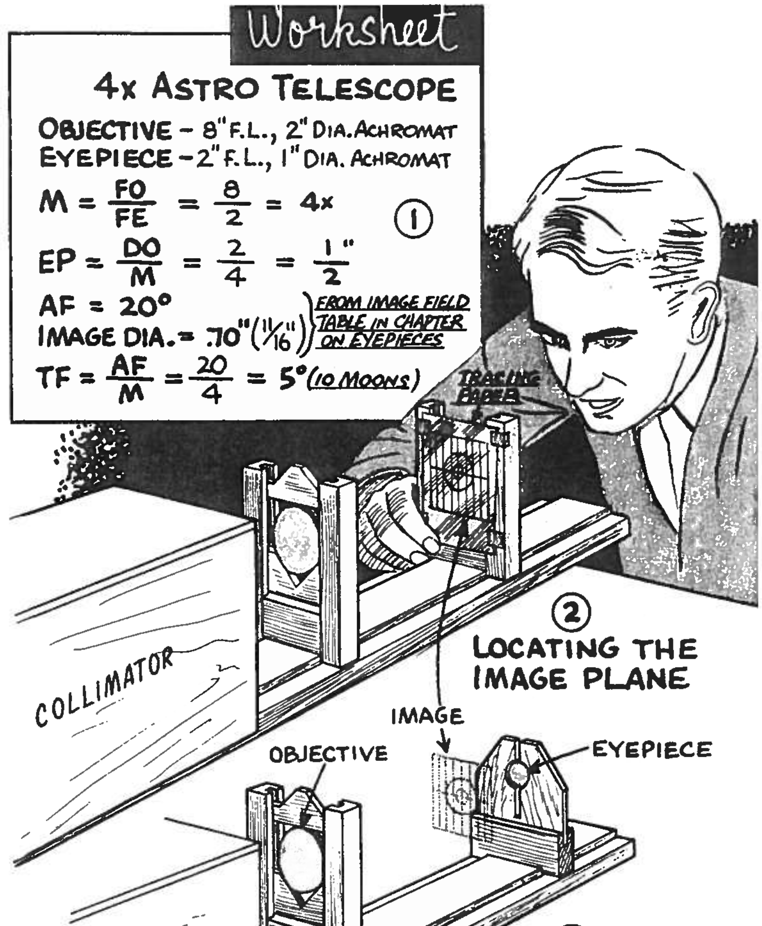
Field of an Eyepiece

You can measure the linear image field of any positive eyepiece by introducing a folded-over strip of tracing paper into the open end. Get the folded-over end sharply in focus. Can you see the whole width of the paper? More? Less? Don't crowd--your eye should be at about the exit pupil position. Once you know the linear field, a simple diagram will reveal the Apparent Field.



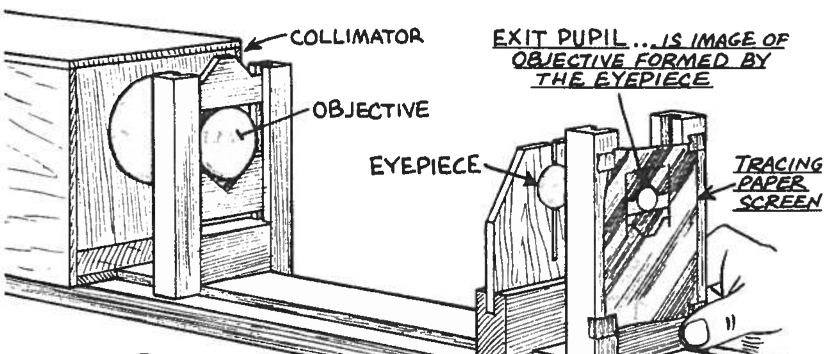
MEASURE THE ANGLE WITH A PROTRACTOR OR ADJUSTABLE TRIANGLE lighting. Your eye sees sharpest at the center of the field, but it detects light and movement more readily at the edge of the field. Hence, if you lose a little light at the edge of field, it will not be noticed. As a matter of fact, you can look as closely as you like and you will not be able to see a 50% light loss at edge of field unless the overall illumination is very dim.

TRACE THROUGH TWO-LENS EYEPIECE. A two-lens eyepiece, Fig. 8, is set up in the same manner as a single lens eyepiece. You can locate the exit pupil. You can check the angular and linear field. From this incomplete data, it is possible to draw light rays on either side of the

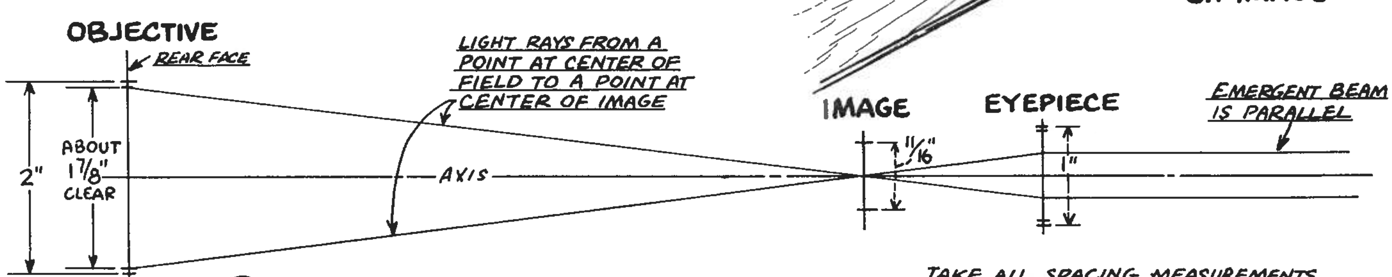


2
LOCATING THE IMAGE PLANE

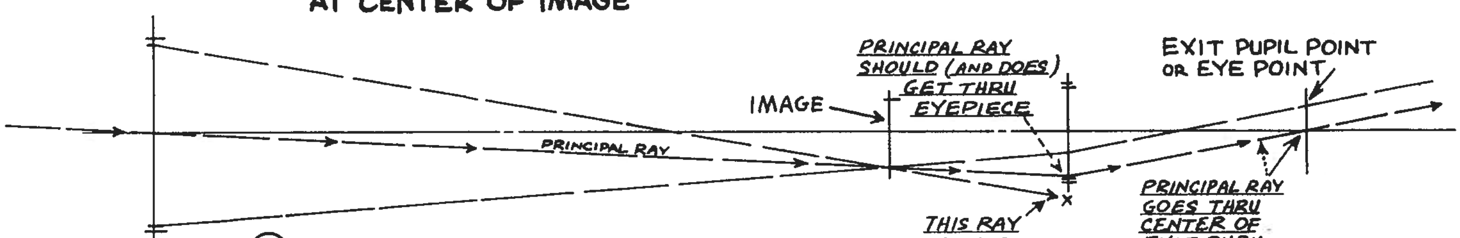
3
EYEPIECE IN PLACE, FOCUSED ON IMAGE



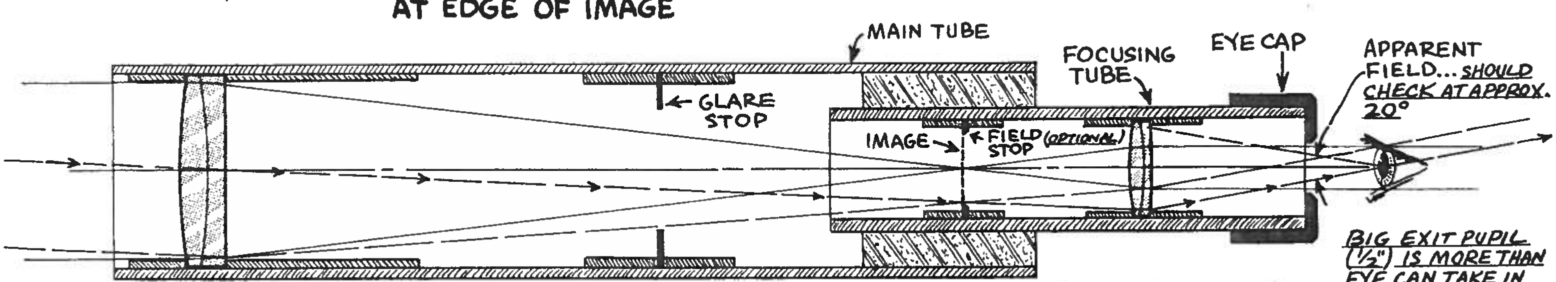
4
LOCATING THE EXIT PUPIL



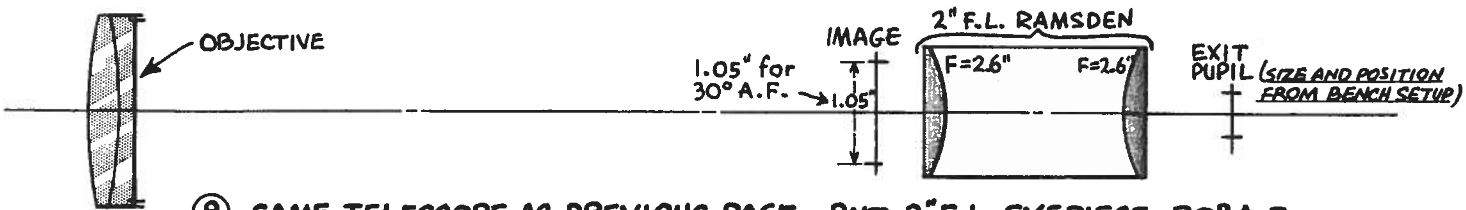
5 LIGHT CONE FOR A POINT AT CENTER OF IMAGE



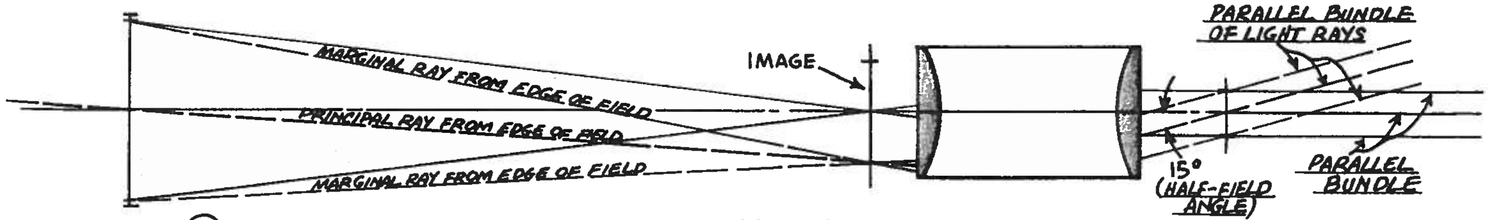
6 LIGHT CONE FOR A POINT AT EDGE OF IMAGE



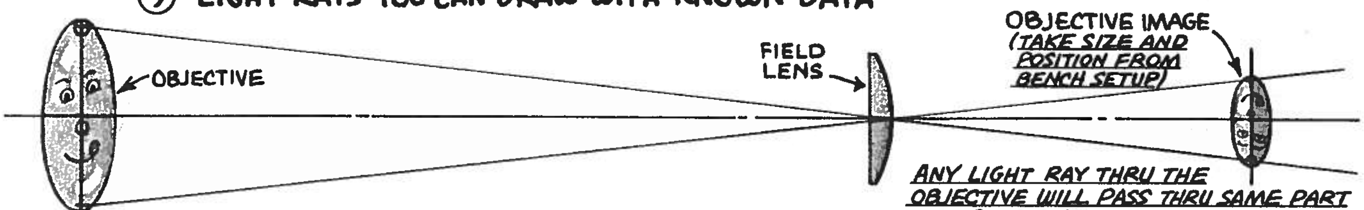
7 COMPLETE TELESCOPE (THIS DESIGN FOR DEMONSTRATION ONLY... NOT RECOMMENDED FOR ACTUAL USE)



⑧ SAME TELESCOPE AS PREVIOUS PAGE, BUT 2" F.L. EYEPIECE, 30° A.F.

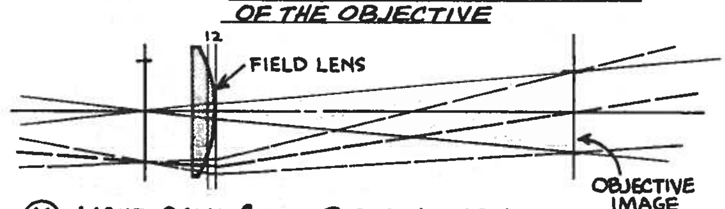


⑨ LIGHT RAYS YOU CAN DRAW WITH KNOWN DATA

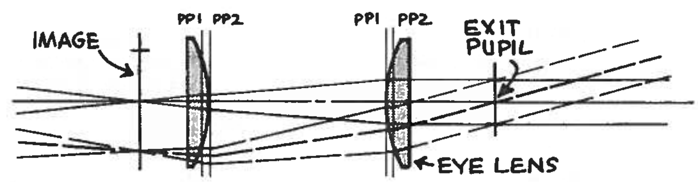


⑩ OBJECTIVE IMAGE FORMED BY FIELD LENS

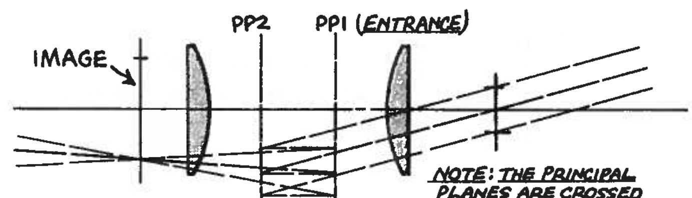
eyepiece, Fig. 9. This is actually all you need know since it can be assumed the light rays get through, but just in case you want to trace the rays in approved fashion, you can do it easy enough if you do one lens at a time. Remove the eye lens but keep the field lens in its normal position. As before, you will pick up an image of the objective some distance behind the lens, Fig. 10. This is a little picture of the objective as formed by the field lens. If you put a mark on the objective, it will appear on the objective image because the objective image is a picture of the objective. If you can imagine light rays making visible tracks through the objective, they would make exactly the same tracks through the objective image. In brief, if a light ray passes through the center of the objective, it will also pass through the center of the objective image. Likewise, rays through the margins of the objective will go through the margins of the objective image. Thus, you have a simple and accurate guide to put the light rays through the field lens, Fig. 11. Then, putting the eye lens in place, you repeat the operation with the whole eyepiece, the final objective image being of course, the exit pupil, Fig. 12. This diagram also shows the manner of drawing light rays if you are using principal planes--you go first to PP1, then parallel with the axis to PP2.



⑪ LIGHT RAYS from FIELD LENS ALONE



⑫ LIGHT PATH THRU EYEPIECE COMPLETED



⑬ ALTERNATE RAY TRACE USING PRINCIPAL PLANES

RAY TRACING TO PRINCIPAL PLANES. When you are using a purchased eyepiece, it is inconvenient to take the eyepiece apart for the lens-by-lens trace just described. Instead, you find the principal planes of the eyepiece as a whole and then draw light rays to the PP's, ignoring the lenses entirely except for the single item of diameter. The method of finding the PP's has already been described; the manner of making the drawing is as shown in Fig. 13. You draw a light ray to the image and keep right on going until you strike PP1. From PP1 to PP2, the ray is parallel to the axis. From PP2, the light ray goes to the corresponding part of the objective image, i.e., the exit pupil.

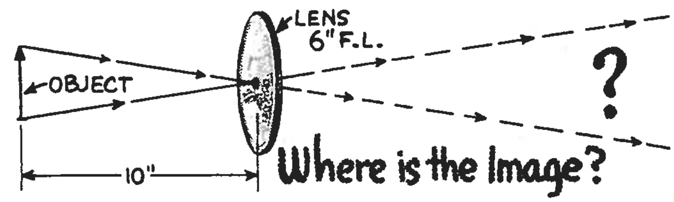
OBJECT-IMAGE MATH

WHERE is the image? This is a basic problem in all optical designing--you can't even get started until you know the answer. The common textbook solution is the classical equation:

$$\frac{1}{F} = \frac{1}{L} + \frac{1}{L'}$$

The F, of course, means focal length. L means "length," the L without a prime mark being the length to the object while the primed L is the distance to the image. Other symbols are often used, notably S (Space) instead of L (Length). Some writers use the letter A for the object distance, and B for the image distance, which is the system used in this book. It is easily memorized from the fact that you must first have an object to look at before you can have an image; hence, A (first letter of alphabet), is the object distance. B is the image distance.

The numeral 1 above each quantity means that the reciprocal of each quantity is used in the calculation. The reciprocal of any number is the number divided into 1. If you have a mirror or lens of 50 inches focal length, its reciprocal is 1/50. Some simple problems can be worked with the reciprocal in this fractional form, but usually you have to convert to the decimal equivalent, which, for this example, can be calculated mentally: 1/50 is 2/100 or .02. In actual work you must refer to a Table of Reciprocals, which can be found in many math and engineering handbooks. For the benefit of beginners who may not have such a table, the basic Gaussian (Karl Friedrich Gauss, 1777-1855, German astronomer and physicist) formula is converted to other

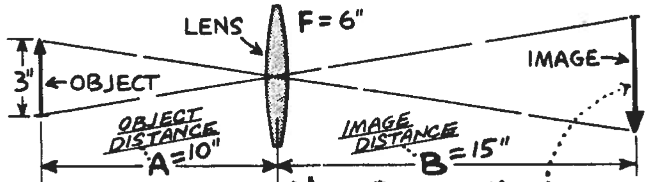


SOLUTION: *THIS IS A CASE 1 PROBLEM* *(See next page)*

YOU KNOW: F = 6"

A = 10"

then CASE 1 [2] $B = \frac{F \times A}{A - F} = \frac{6 \times 10}{10 - 6} = \frac{60}{4} = 15"$



How BIG is the Image?

LINEAR M. ALL CASES $= \frac{B}{A} = \frac{15}{10} = 1.5\times$

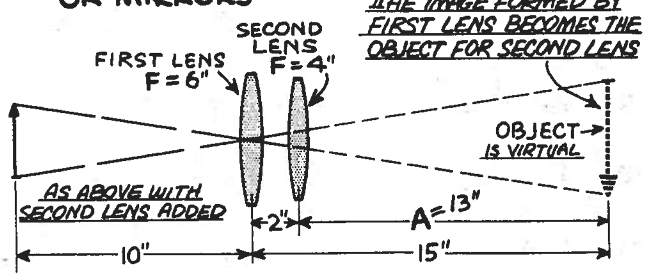
HENCE: IF THE OBJECT IS 3" HIGH AND M. IS 1½×:

① Example OF A CASE 1 PROBLEM

IMAGE SIZE $= 3 \times 1\frac{1}{2} = 4\frac{1}{2}"$

② IMAGE FORMED BY TWO OR MORE LENSES OR MIRRORS

THE IMAGE FORMED BY FIRST LENS BECOMES THE OBJECT FOR SECOND LENS



SOLUTION: *SECOND LENS IS A CASE 4 PROBLEM*

YOU KNOW: F = 4"

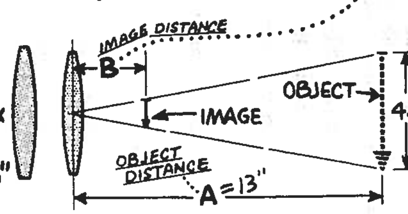
A = 13"

THEN CASE 4 [2] $B = \frac{F \times A}{F + A} = \frac{4 \times 13}{4 + 13} = \frac{52}{17} = 3.06"$

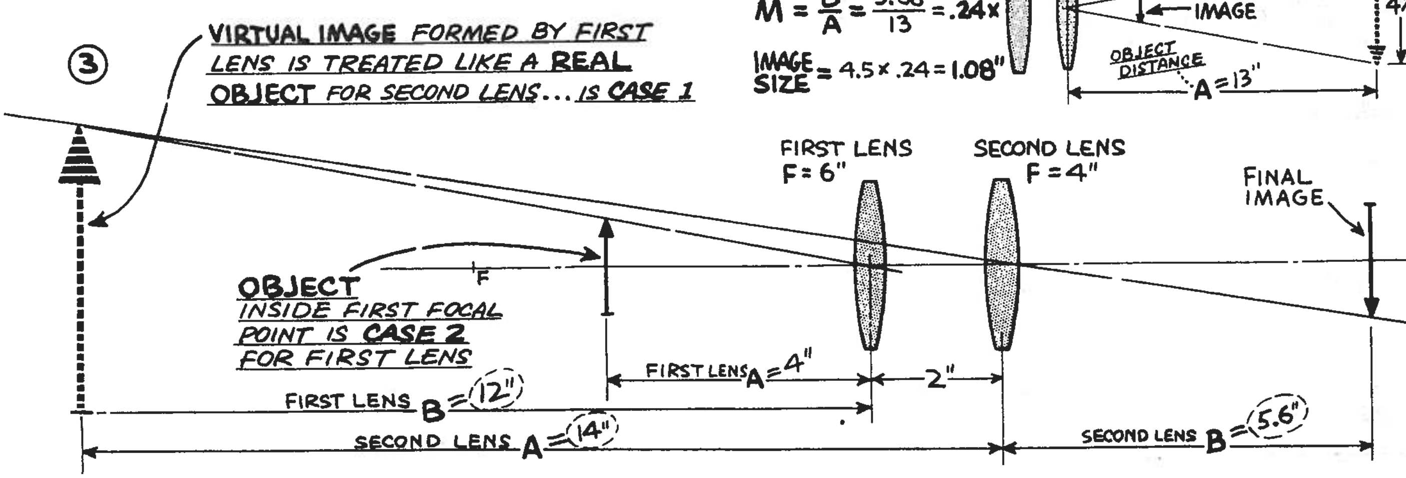
M. FOR SECOND LENS:

$M = \frac{B}{A} = \frac{3.06}{13} = .24\times$

IMAGE SIZE $= 4.5 \times .24 = 1.08"$



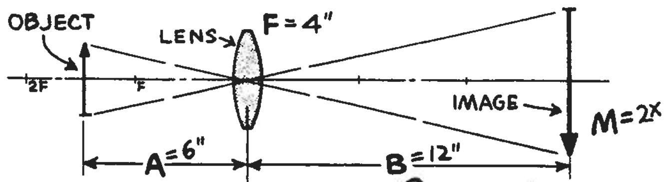
③



$\frac{1}{f} = \frac{1}{a} + \frac{1}{B}$ $M = \frac{b}{a}$

OBJECT-IMAGE MATH for a SINGLE POSITIVE LENS or CONCAVE MIRROR

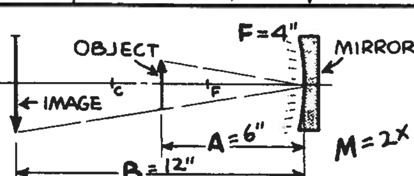
CASE 1 — OBJECT AT MORE THAN ONE FOCAL LENGTH FROM LENS



Example

1	$B = (M+1) \times F$	$B = (2+1) \times 4 = 3 \times 4 = 12''$
2	$B = \frac{F \times A}{A - F}$	$B = \frac{4 \times 6}{6-4} = \frac{24}{2} = 12''$
3	$B = A \times M$	$B = 6 \times 2 = 12''$
4	$A = \frac{B}{M}$	$A = \frac{12}{2} = 6''$
5	$A = \frac{F}{M} + F$	$A = \frac{4}{2} + 4 = 2 + 4 = 6''$
6	$A = \frac{F \times B}{B - F}$	$A = \frac{4 \times 12}{12-4} = \frac{48}{8} = 6''$
7	$M = \frac{B}{A}$	$M = \frac{12}{6} = 2X$
8	$M = \frac{F}{A - F}$	$M = \frac{4}{6-4} = \frac{4}{2} = 2X$
9	$M = \frac{B - F}{F}$	$M = \frac{12-4}{4} = \frac{8}{4} = 2X$
10	$F = \frac{A \times M}{M + 1}$	$F = \frac{6 \times 2}{2+1} = \frac{12}{3} = 4''$
11	$F = \frac{B}{M + 1}$	$F = \frac{12}{2+1} = \frac{12}{3} = 4''$
12	$F = \frac{A \times B}{A + B}$	$F = \frac{6 \times 12}{6+12} = \frac{72}{18} = 4''$
13	$\frac{1}{F} = \frac{1}{A} + \frac{1}{B}$	$\frac{1}{F} = \frac{1}{6} + \frac{1}{12}$; $\frac{1}{F} = \frac{2}{12} + \frac{1}{12} = \frac{3}{12}$, $F = \frac{12}{3} = 4''$
14	$\frac{1}{A} = \frac{1}{F} - \frac{1}{B}$	$\frac{1}{A} = \frac{1}{4} - \frac{1}{12}$; $\frac{1}{A} = \frac{3}{12} - \frac{1}{12} = \frac{2}{12}$, $A = \frac{12}{2} = 6''$
15	$\frac{1}{B} = \frac{1}{F} - \frac{1}{A}$	$\frac{1}{B} = \frac{1}{4} - \frac{1}{6}$; $\frac{1}{B} = \frac{3}{12} - \frac{2}{12} = \frac{1}{12}$, $B = \frac{12}{1} = 12''$

THE SAME EQUATIONS ARE USED FOR A POSITIVE (CONCAVE) MIRROR

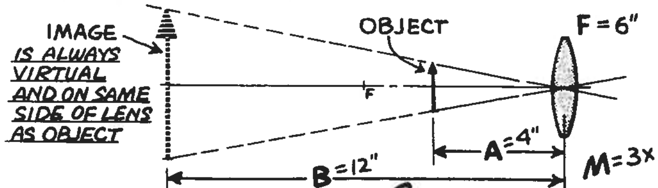


TWO CASES: WHEN THE OBJECT IS MORE THAN **F** BUT LESS THAN **2F** FROM LENS *(SHOWN)*, THE SYSTEM IS PROJECTION-- THE IMAGE IS LARGER THAN OBJECT.

WHEN **A** IS MORE THAN **2F**, **B** WILL BE LESS THAN **2F** AND THE IMAGE WILL BE SMALLER THAN OBJECT

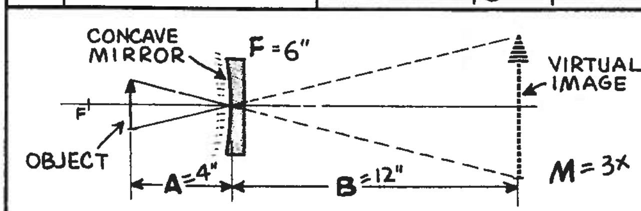
ALTERNATE EQUATIONS USING RECIPROCALS

CASE 2 — OBJECT AT LESS THAN ONE FOCAL LENGTH FROM LENS



Example

1	$B = (M-1) \times F$	$B = (3-1) \times 6 = 2 \times 6 = 12''$
2	$B = \frac{F \times A}{F - A}$	$B = \frac{6 \times 4}{6-4} = \frac{24}{2} = 12''$
3	$B = A \times M$	$B = 4 \times 3 = 12''$
4	$A = \frac{B}{M}$	$A = \frac{12}{3} = 4''$
5	$A = F - \frac{F}{M}$	$A = 6 - \frac{6}{3} = 6 - 2 = 4''$
6	$A = \frac{F \times B}{F + B}$	$A = \frac{6 \times 12}{6+12} = \frac{72}{18} = 4''$
7	$M = \frac{B}{A}$	$M = \frac{12}{4} = 3X$
8	$M = \frac{F}{F - A}$	$M = \frac{6}{6-4} = \frac{6}{2} = 3X$
9	$M = \frac{B + F}{F}$	$M = \frac{12+6}{6} = \frac{18}{6} = 3X$
10	$F = \frac{A \times M}{M - 1}$	$F = \frac{4 \times 3}{3-1} = \frac{12}{2} = 6''$
11	$F = \frac{B}{M - 1}$	$F = \frac{12}{3-1} = \frac{12}{2} = 6''$
12	$F = \frac{A \times B}{B - A}$	$F = \frac{4 \times 12}{12-4} = \frac{48}{8} = 6''$
13	$\frac{1}{F} = \frac{1}{A} - \frac{1}{B}$	$\frac{1}{F} = \frac{1}{4} - \frac{1}{12}$; $\frac{1}{F} = \frac{3}{12} - \frac{1}{12} = \frac{2}{12}$, $F = \frac{12}{2} = 6''$
14	$\frac{1}{A} = \frac{1}{F} + \frac{1}{B}$	$\frac{1}{A} = \frac{1}{6} + \frac{1}{12}$; $\frac{1}{A} = \frac{2}{12} + \frac{1}{12} = \frac{3}{12}$, $A = \frac{12}{3} = 4''$
15	$\frac{1}{B} = \frac{1}{A} - \frac{1}{F}$	$\frac{1}{B} = \frac{1}{4} - \frac{1}{6}$; $\frac{1}{B} = \frac{3}{12} - \frac{2}{12} = \frac{1}{12}$, $B = \frac{12}{1} = 12''$



WHEN THE OBJECT-TO-LENS DISTANCE IS LESS THAN **F**, THE IMAGE IS VIRTUAL, ERECT AND MAGNIFIED. **M** IS NEVER LESS THAN **1X** ... IS GREATEST WHEN OBJECT IS JUST INSIDE **F**.

THE SAME ACTION IS OBTAINED WITH A CONCAVE MIRROR EXCEPT VIRTUAL IMAGE APPEARS BEHIND THE MIRROR form suited to simple arithmetical solution, as shown in the Tables on the following pages.

FIVE OBJECT-IMAGE CASES. A Case 1 problem concerns a single positive lens (or mirror) with the object located at more than one focal length from the lens. Fig. 1 is an example. You know the focal length (F) of the lens and the distance to the object (A). The problem is to find the image distance, B, and this is easily calculated with the second equation in the CASE 1 Table.

If the problem involves two or more lenses, the image formed by the first lens becomes the object for the second lens, as shown in Fig. 2. This example is a continuation of Fig. 1 example, with a second lens added. The problem is to calculate the image position as formed by the second lens, using the image formed by the first lens as the object. In this particular instance, the second lens is a Case 4 problem, i.e., it is concerned with a virtual object to the right of a positive lens. You use Case 4 Table. Again you know F and A, so B is found by using Equation No. 2.

Sometimes the first lens looks at an object at less than one focal length, and this is Case 2, of which Fig. 3 is an example. Fig 3 also shows the situation where the virtual image formed to the left of the first lens becomes the real object for the second lens.

Case 5 covers the situation of a negative lens or mirror inside the focus of a primary lens or mirror, a situation which many readers will immediately identify as the Barlow Case, because this is the way a Barlow amplifying lens works in a telescope. The five cases covered by the tables will handle practically any kind of object-image problem. An important exception is the common telescope situation where the object is at infinity. For such a target, the equations are useless, but

SYMBOLS:

M... IS **LINEAR MAGNIFICATION**... IS ACTUAL RATIO OF IMAGE SIZE TO OBJECT SIZE. *DO NOT CONFUSE WITH ANGULAR MAGNIFICATION USED TO SPECIFY THE POWER OF A TELESCOPE*

F... IS **FOCAL LENGTH**

A... IS DISTANCE FROM LENS TO **OBJECT**

B... IS DISTANCE FROM LENS TO **IMAGE**

FOR TECHNICAL EXACTNESS, SPACING SHOULD BE SET OFF FROM THE ADJACENT PRINCIPAL PLANE OF THE LENS OR VERTEX OF MIRROR

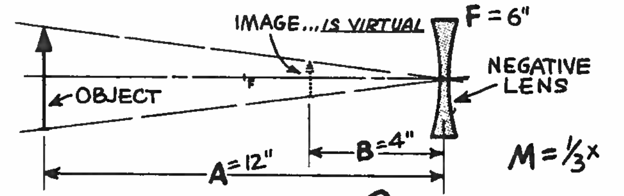
OBJECT-IMAGE MATH INDEX

IF YOU KNOW	FIND, WITH
F and A	M....8, B.....2
F and B	M....9, A....6
F and M	A....5, B....1
M and A	F....10, B....3
M and B	F....11, A....4
A and B	M....7, F....12

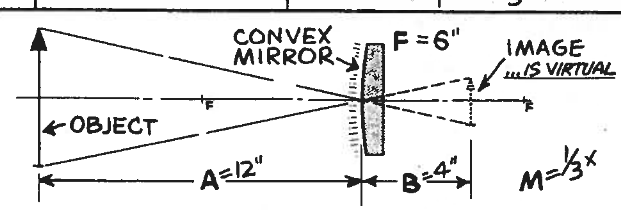
USE THIS INDEX FOR ALL CASES. WORK ALL PROBLEMS WITH SIMPLE ARITHMETIC

CASE 3 — OBJECT-IMAGE MATH

SINGLE NEGATIVE LENS OR CONVEX MIRROR. OBJECT AT ANY DISTANCE FROM LENS



		Example
1	$B=(1-M)\times F$	$B=(1-\frac{1}{3})\times 6=\frac{2}{3}\times 6=4''$
2	$B=\frac{F\times A}{F+A}$	$B=\frac{6\times 12}{6+12}=\frac{72}{18}=4''$
3	$B=A\times M$	$B=12\times\frac{1}{3}=\frac{12}{3}=4''$
4	$A=\frac{B}{M}$	$A=\frac{4}{1/3}=4\times\frac{3}{1}=12''$
5	$A=\frac{F}{M}-F$	$A=\frac{6}{1/3}-6=6\times\frac{3}{1}-6=18-6=12''$
6	$A=\frac{F\times B}{F-B}$	$A=\frac{6\times 4}{6-4}=\frac{24}{2}=12''$
7	$M=\frac{B}{A}$	$M=\sqrt[4]{\frac{4}{12}}=\frac{1}{3}x$ (OR .33x)
8	$M=\frac{F}{A+F}$	$M=\frac{6}{12+6}=\frac{6}{18}=\frac{1}{3}x$
9	$M=\frac{F-B}{F}$	$M=\frac{6-4}{6}=\frac{2}{6}=\frac{1}{3}x$
10	$F=\frac{A\times M}{1-M}$	$F=\frac{12\times 1/3}{1-1/3}=\frac{4}{2/3}=4\times\frac{3}{2}=6''$
11	$F=\frac{B}{1-M}$	$F=\frac{4}{1-1/3}=\frac{4}{2/3}=4\times\frac{3}{2}=6''$
12	$F=\frac{A\times B}{A-B}$	$F=\frac{12\times 4}{12-4}=\frac{48}{8}=6''$
13	$\frac{1}{F}=\frac{1}{B}-\frac{1}{A}$	$\frac{1}{F}=\frac{1}{4}-\frac{1}{12}$; $\frac{1}{F}=\frac{3}{12}-\frac{1}{12}=\frac{2}{12}$, $F=\frac{12}{2}=6''$
14	$\frac{1}{A}=\frac{1}{B}-\frac{1}{F}$	$\frac{1}{A}=\frac{1}{4}-\frac{1}{6}$; $\frac{1}{A}=\frac{3}{12}-\frac{2}{12}=\frac{1}{12}$, $A=\frac{12}{1}=12''$
15	$\frac{1}{B}=\frac{1}{A}+\frac{1}{F}$	$\frac{1}{B}=\frac{1}{12}+\frac{1}{6}$; $\frac{1}{B}=\frac{1}{12}+\frac{2}{12}=\frac{3}{12}$, $B=\frac{12}{3}=4''$



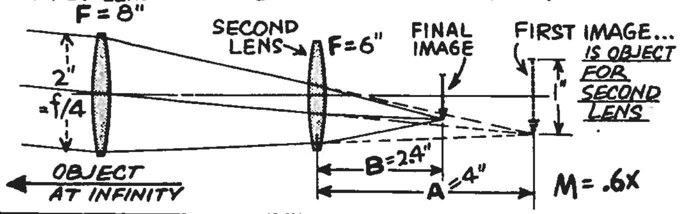
THE IMAGE IS ALWAYS VIRTUAL, ERECT AND REDUCED. **B** IS ALWAYS LESS THAN **A**, AND ALSO LESS THAN **F**. **M** IS ALWAYS UNDER 1X. WHEN THE OBJECT IS AT INFINITY, THE EQUATIONS BECOME USELESS AND UNNECESSARY. IN SUCH CASE:

$A=\infty$ (INFINITY) $B=F$ $M=0$ *(NEARLY)*

OBJECT-IMAGE MATH for Second of Two Lenses with Virtual Object

CASE 4

SECOND OF TWO POSITIVE LENSES OR MIRRORS. VIRTUAL OBJECT AT ANY DISTANCE



1	$B = (1 - M) \times F$	$B = (1 - .6) \times 6 = .4 \times 6 = 2.4"$
2	$B = \frac{F \times A}{F + A}$	$B = \frac{6 \times 4}{6 + 4} = \frac{24}{10} = 2.4"$
3	$B = A \times M$	$B = 4 \times .6 = 2.4"$
4	$A = \frac{B}{M}$	$A = \frac{2.4}{.6} = 4"$
5	$A = \frac{F}{M} - F$	$A = \frac{6}{.6} - 6 = 10 - 6 = 4"$
6	$A = \frac{F \times B}{F - B}$	$A = \frac{6 \times 2.4}{6 - 2.4} = \frac{14.4}{3.6} = 4"$
7	$M = \frac{B}{A}$	$M = \frac{2.4}{4} = .6x$
8	$M = \frac{F}{F + A}$	$M = \frac{6}{6 + 4} = \frac{6}{10} = .6x$
9	$M = \frac{F - B}{F}$	$M = \frac{6 - 2.4}{6} = \frac{3.6}{6} = .6x$
10	$F = \frac{A \times M}{1 - M}$	$F = \frac{4 \times .6}{1 - .6} = \frac{2.4}{.4} = 6"$
11	$F = \frac{B}{1 - M}$	$F = \frac{2.4}{1 - .6} = \frac{2.4}{.4} = 6"$
12	$F = \frac{A \times B}{A - B}$	$F = \frac{4 \times 2.4}{4 - 2.4} = \frac{9.6}{1.6} = 6"$
13	$\frac{1}{F} = \frac{1}{B} - \frac{1}{A}$	$\frac{1}{F} = \frac{1}{2.4} - \frac{1}{4}$; $\frac{1}{F} = .4167 - .25 = .1667$, $F = \frac{1}{.1667} = 6"$
14	$\frac{1}{A} = \frac{1}{B} - \frac{1}{F}$	$\frac{1}{A} = \frac{1}{2.4} - \frac{1}{6}$; $\frac{1}{A} = .4167 - .1667 = .25$, $A = \frac{1}{.25} = 4"$
15	$\frac{1}{B} = \frac{1}{A} + \frac{1}{F}$	$\frac{1}{B} = \frac{1}{4} + \frac{1}{6}$; $\frac{1}{B} = .25 + .1667 = .4167$, $B = \frac{1}{.4167} = 2.4"$

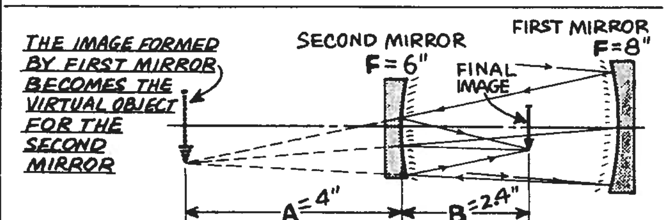
CALCULATIONS USING A TABLE OF RECIPROCALS

WHOLE SYSTEM: *(ORIGINAL OBJECT MUST BE AT INFINITY)*

FINAL IMAGE DIA. = FIRST IMAGE × **M** = 1 × .6 = **.6"**

E.F.L. = F.L. OF FIRST LENS × **M** = 8 × .6 = **4.8"**

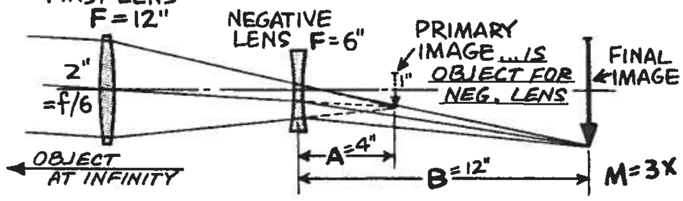
f/VALUE = f/VALUE OF FIRST LENS × **M** = f/4 × .6 = **f/2.4**



SAME SYSTEM WITH MIRRORS M=.6X

CASE 5

THE NEGATIVE LENS OR MIRROR OF A POS-NEG COMBINATION. VIRTUAL OBJECT LESS THAN F



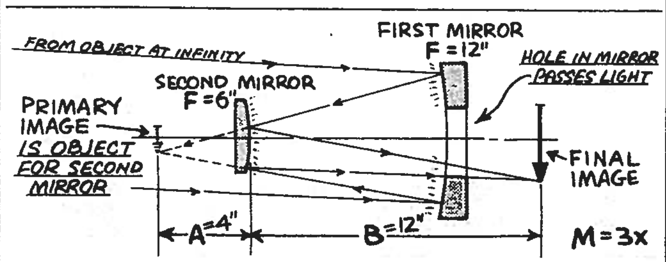
1	$B = (M - 1) \times F$	$B = (3 - 1) \times 6 = 2 \times 6 = 12"$
2	$B = \frac{F \times A}{F - A}$	$B = \frac{6 \times 4}{6 - 4} = \frac{24}{2} = 12"$
3	$B = A \times M$	$B = 4 \times 3 = 12"$
4	$A = \frac{B}{M}$	$A = \frac{12}{3} = 4"$
5	$A = F - \frac{F}{M}$	$A = 6 - \frac{6}{3} = 6 - 2 = 4"$
6	$A = \frac{F \times B}{F + B}$	$A = \frac{6 \times 12}{6 + 12} = \frac{72}{18} = 4"$
7	$M = \frac{B}{A}$	$M = \frac{12}{4} = 3x$
8	$M = \frac{F}{F - A}$	$M = \frac{6}{6 - 4} = \frac{6}{2} = 3x$
9	$M = \frac{F + B}{F}$	$M = \frac{6 + 12}{6} = \frac{18}{6} = 3x$
10	$F = \frac{A \times M}{M - 1}$	$F = \frac{4 \times 3}{3 - 1} = \frac{12}{2} = 6"$
11	$F = \frac{B}{M - 1}$	$F = \frac{12}{3 - 1} = \frac{12}{2} = 6"$
12	$F = \frac{A \times B}{B - A}$	$F = \frac{4 \times 12}{12 - 4} = \frac{48}{8} = 6"$
13	$\frac{1}{F} = \frac{1}{A} - \frac{1}{B}$	$\frac{1}{F} = \frac{1}{4} - \frac{1}{12}$; $\frac{1}{F} = \frac{3}{12} - \frac{1}{12} = \frac{2}{12}$, $F = \frac{12}{2} = 6"$
14	$\frac{1}{A} = \frac{1}{F} + \frac{1}{B}$	$\frac{1}{A} = \frac{1}{6} + \frac{1}{12}$; $\frac{1}{A} = \frac{2}{12} + \frac{1}{12} = \frac{3}{12}$, $A = \frac{12}{3} = 4"$
15	$\frac{1}{B} = \frac{1}{A} - \frac{1}{F}$	$\frac{1}{B} = \frac{1}{4} - \frac{1}{6}$; $\frac{1}{B} = \frac{3}{12} - \frac{2}{12} = \frac{1}{12}$, $B = \frac{12}{1} = 12"$

WHOLE SYSTEM:

FINAL IMAGE DIA. = FIRST IMAGE × **M** = 1 × 3 = **3"**

E.F.L. = F.L. OF FIRST LENS × **M** = 12 × 3 = **36"**

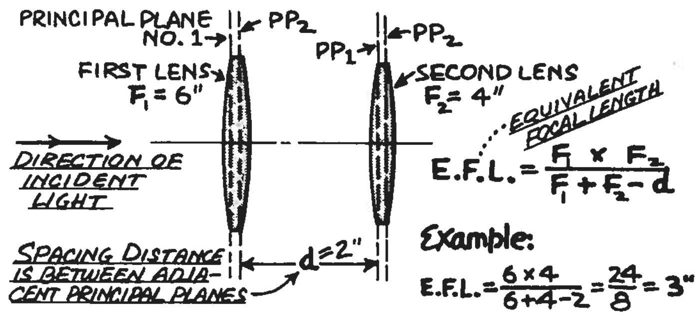
f/VALUE = f/VALUE OF FIRST LENS × **M** = f/6 × 3 = **f/18**



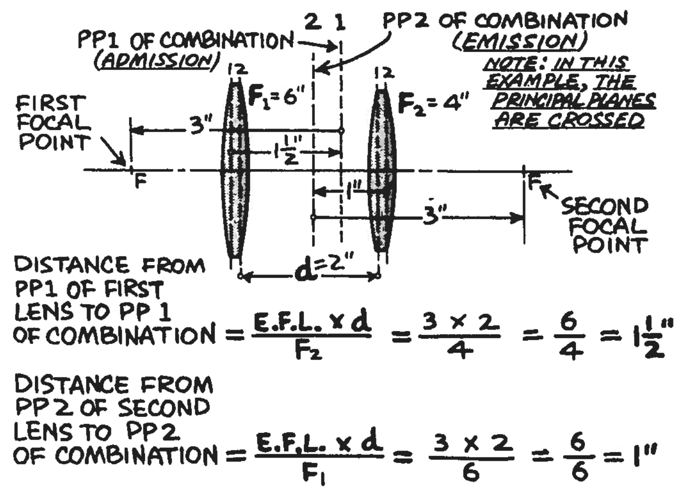
also unnecessary. For example, with an object at infinity, the image distance (B) is always one focal length, and there is no need to make a calculation. Also note that an object at infinity does not permit the calculation of linear magnification. For example, the moon at the focus of a telescope of 50 in. focal length will show an image about 1/2 inch diameter. Comparing this to the actual size of the moon (about 2000 miles) is useless. The kind of magnification used in such cases is angular magnification, which compares the apparent angular size of the object seen through the telescope with the angular size of the object as seen with the unaided eye. Differing from this, linear magnification is the exact ratio of image size to object size--it is B/A for all cases. Usually, magnification is thought of in the sense of being bigger, but linear magnification can indicate same size (1x) or even minification, such as 1/2x, as well as actual enlargement, like 2x.

OTHER CALCULATIONS. Quite often you will have to figure the equivalent or effective focal length of two positive lenses spaced a certain distance apart. Eyepieces are common examples. The E.F.L. calculation is easily made with the equation given in Fig. 4, which also shows an example. The E.F.L. is shortest when the lenses are close together, Fig. 6, increasing as the spacing distance is increased, until "d" is equal to the combined focal lengths, at which spacing the system becomes an astro telescope with virtual image and infinite focal length, Fig. 7.

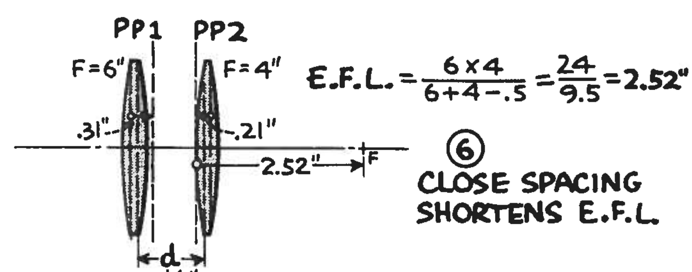
The calculation for the location of principal planes of two combined positive lenses is shown in Fig. 5, and will be found useful if you design your own Ramsden and Huygens eyepieces. After finding the E.F.L. and principal planes, the doublet is treated very much like a single thick lens. Fig. 8 duplicates the example shown in Fig. 3 except the two lenses are now treated as a single unit. The object at same distance as before is now more than one f.l. from PP1, making the calculation a Case 1 problem.



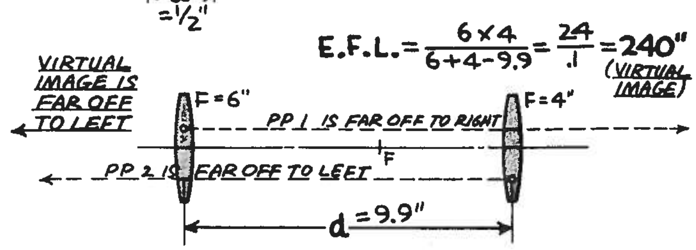
④ E.F.L. OF TWO POSITIVE LENSES



⑤ PRINCIPAL PLANES OF COMBINED LENSES

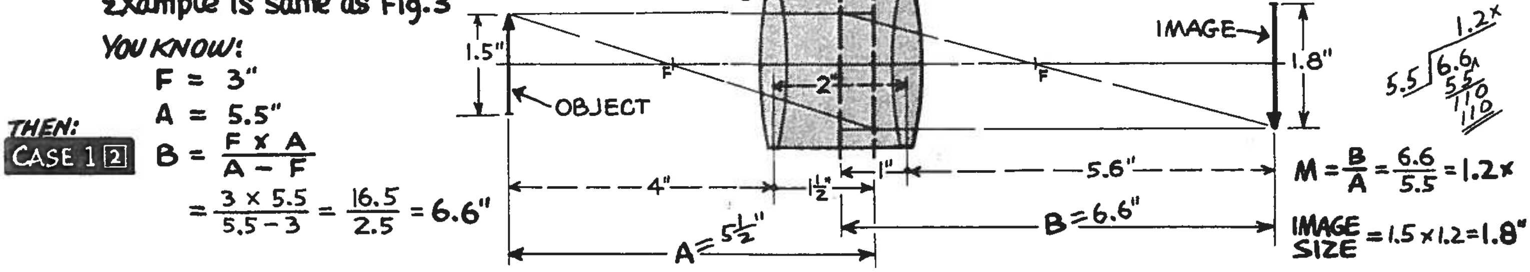


⑥ CLOSE SPACING SHORTENS E.F.L.

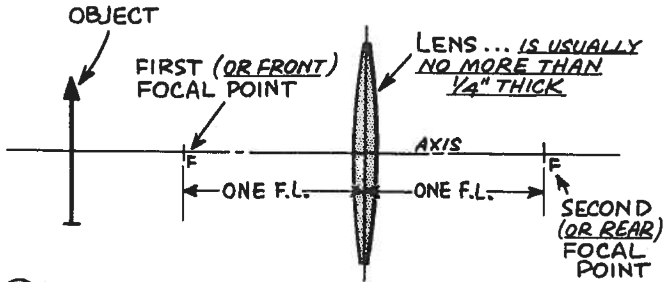


⑦ WIDE SPACING INCREASES E.F.L. (THIS EXTREME EXAMPLE IS PRACTICALLY A TELESCOPE)

⑧ COMBINED LENSES ARE TREATED LIKE A SINGLE THICK LENS
Example is same as Fig.3



graphical RAY TRACING



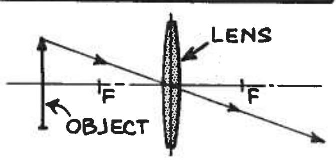
① **LENSES ARE ASSUMED TO BE THIN.**
IF THE LENS IS THIN, A LINE THROUGH THE CENTER PROVIDES A REASONABLY ACCURATE REFERENCE PLANE FOR REFRACTION AND MEASUREMENTS. THE PRINCIPAL PLANES SHOULD BE REFERENCE LINES IF LENS IS THICK

ONE WAY of solving the various object-image problems in optical design is to make an accurate drawing of the system to scale, after which you can run in the needed light rays graphically by following a few simple rules.

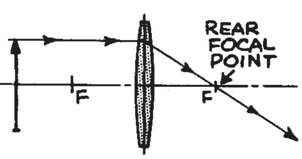
PARALLEL RAY METHOD. You start with the basic drawing shown in Fig. 1. Then, by following the three simple rules shown, Fig. 2, you can trace three light rays through the lens, any two of which will locate the image position. The use

② PARALLEL RAY METHOD - POSITIVE LENS

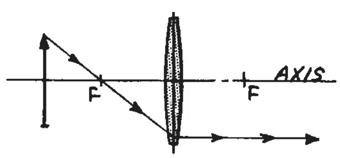
Rule 1: A LIGHT RAY PASSING THROUGH THE CENTER OF LENS IS NOT DEVIATED



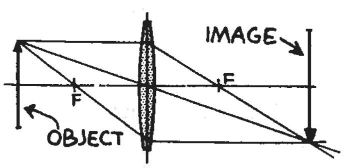
Rule 2: A LIGHT RAY PARALLEL WITH AXIS WILL, AFTER REFRACTION, PASS THRU THE REAR FOCAL POINT

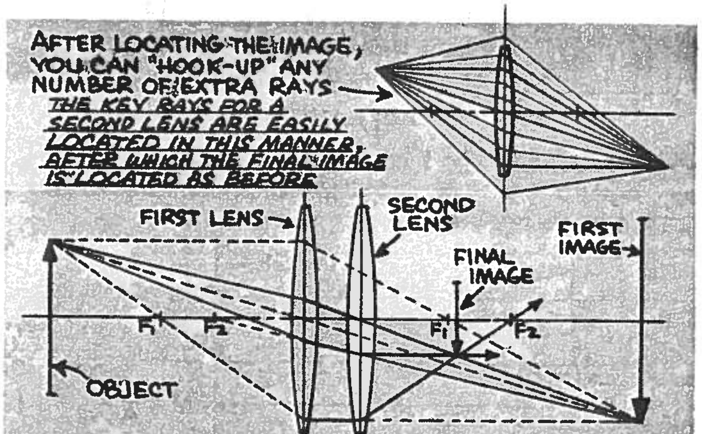


Rule 3: A LIGHT RAY THROUGH THE FIRST FOCAL POINT WILL BE REFRACTED PARALLEL WITH THE AXIS



THE INTERSECTION OF ANY TWO OF THE THREE LIGHT RAYS SHOWN WILL LOCATE THE POSITION OF THE IMAGE

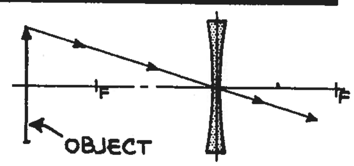




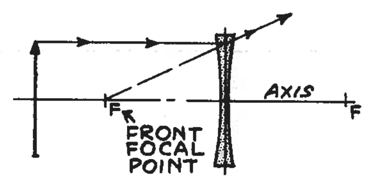
③ **PARALLEL RAY METHOD for TWO LENSES**

④ PARALLEL RAY METHOD-NEGATIVE LENS

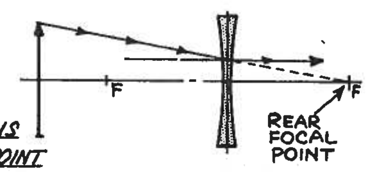
Rule 1: A LIGHT RAY PASSING THRU THE CENTER OF LENS IS NOT DEVIATED



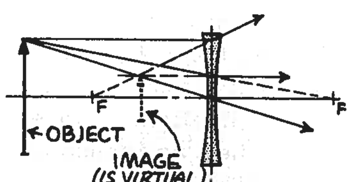
Rule 2: A LIGHT RAY PARALLEL TO THE AXIS WILL, AFTER REFRACTION, APPEAR TO COME FROM THE FRONT FOCAL POINT



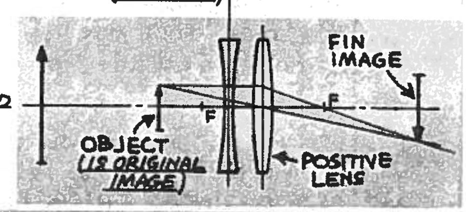
Rule 3: A RAY DIRECTED TOWARD THE REAR FOCAL POINT WILL BE REFRACTED PARALLEL TO THE AXIS.
A BACKWARD EXTENSION OF THIS RAY WILL PASS THRU THE IMAGE POINT

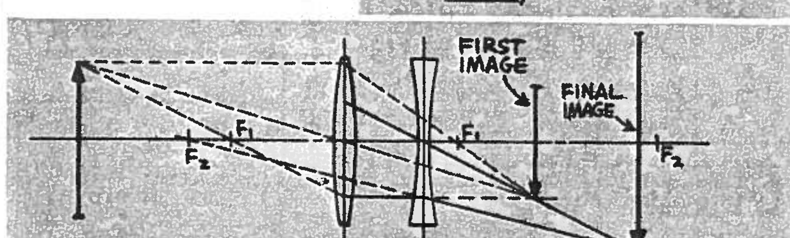


THE INTERSECTION OF ANY TWO OF THE THREE RAYS SHOWN WILL LOCATE THE POSITION OF THE IMAGE

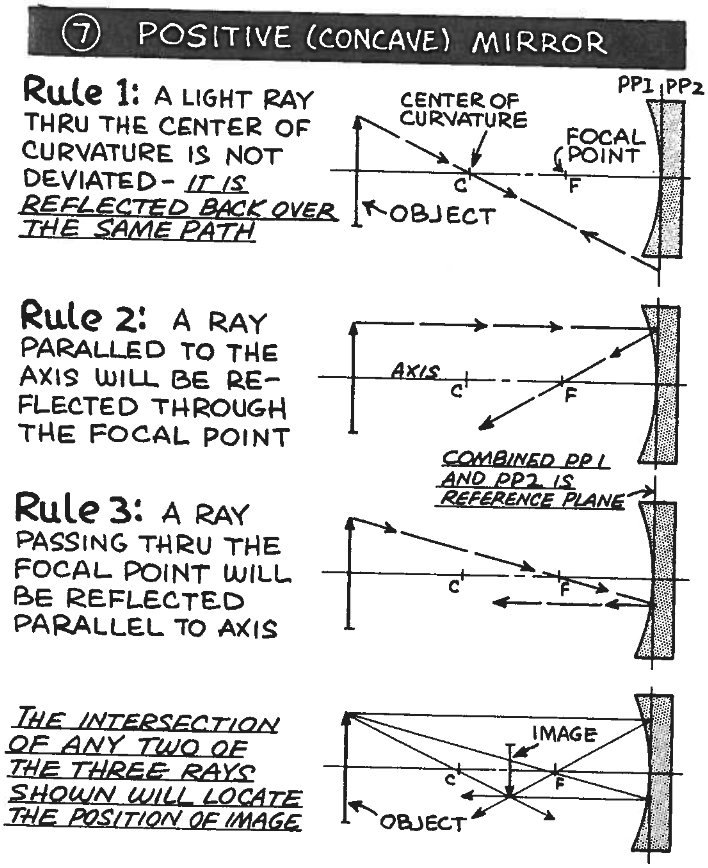


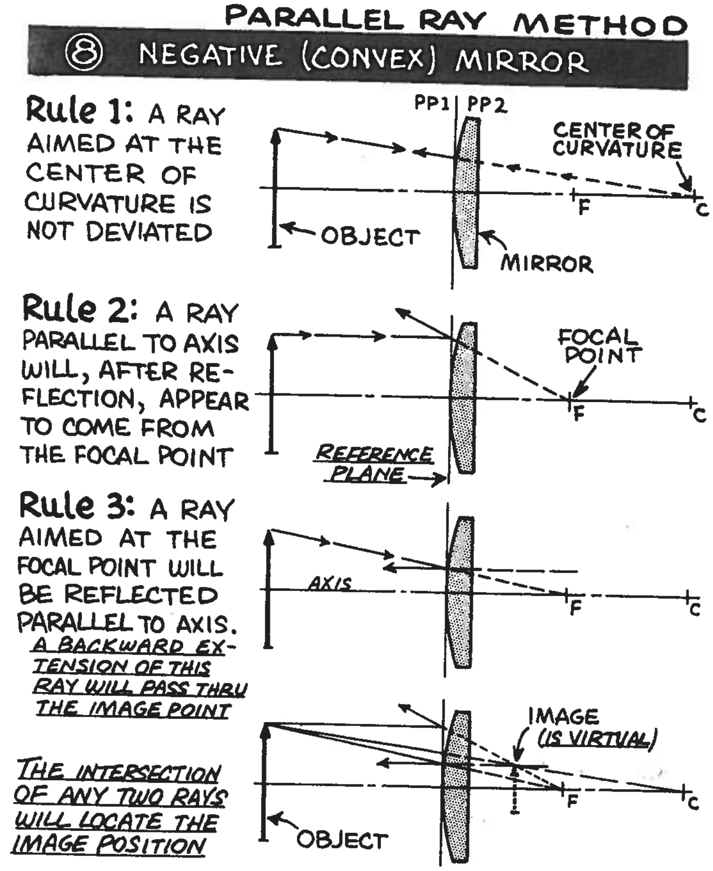
⑤ **NEGATIVE-AND-POSITIVE**
THE VIRTUAL IMAGE FORMED BY THE NEGATIVE LENS BECOMES A REAL OBJECT FOR THE POSITIVE LENS





⑥ **POSITIVE-AND-NEGATIVE**

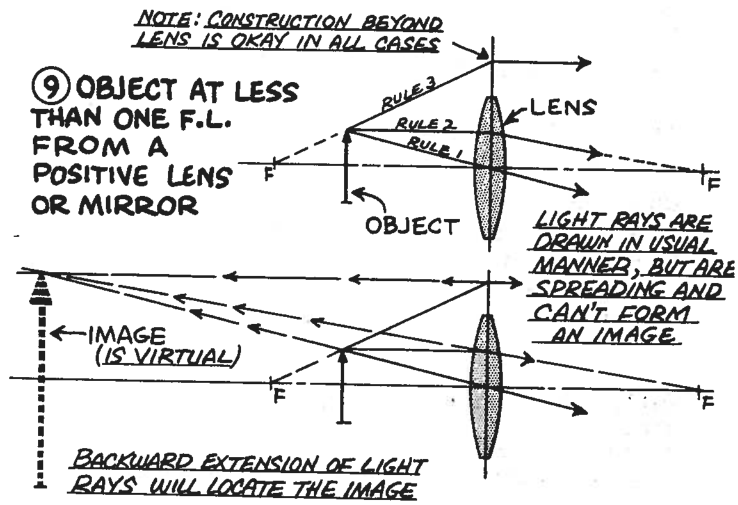


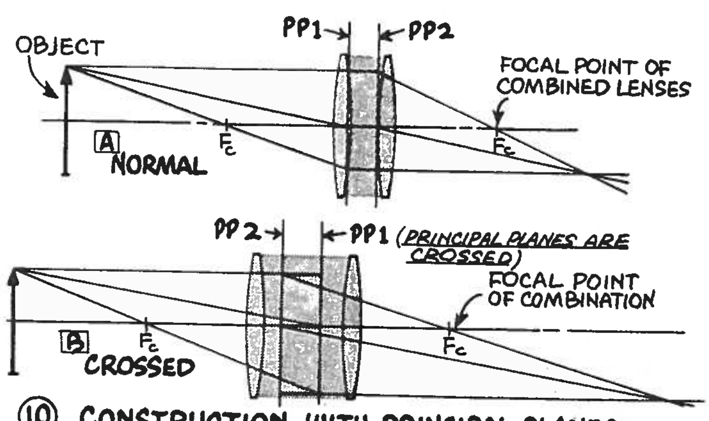


of an entering and emergent parallel ray gives this method its name. Fig. 4 explains the parallel ray method as applied to a negative lens, while Figs. 7 and 8 cover similar situations where a mirror is the optical element.

Once you have located the image, you can run in any number of additional light rays connecting the object point to the image point, Fig. 3. This is the basis for tracing light rays through two or more lenses. The general idea is to locate in the light cone of the first lens, that ray which passes through the center of the second lens. Figs. 3 and 6 are examples. With one parallel light ray already available, you can then plot the image position as formed by the second lens. If the first lens of a pair forms a virtual image to the left, as in Fig. 5 example, the image itself immediately becomes the object for the second lens. Fig. 9 is another example where a virtual image to the left would be immediately available as the object for a second lens.

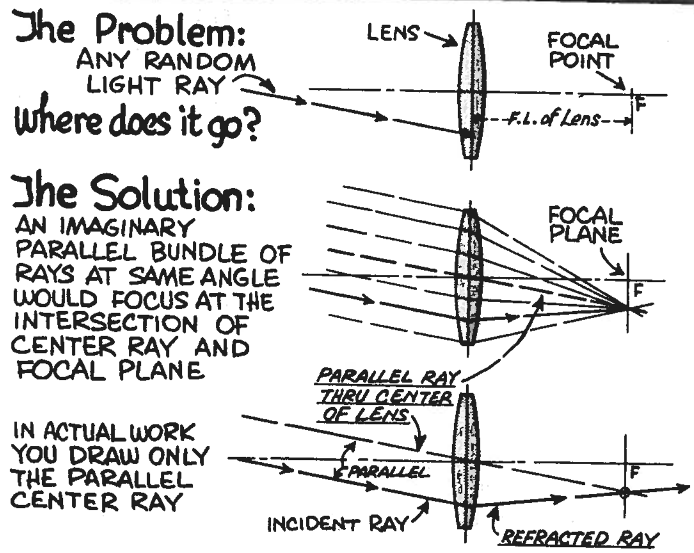
When two lenses are involved, it is often simpler to calculate the e.f.l. and principal planes of the combo, after which it can be treated very much like a single lens. Between principal planes, all light rays are drawn parallel with the axis. You always draw to PP1 first, since this is the plane of admission. If

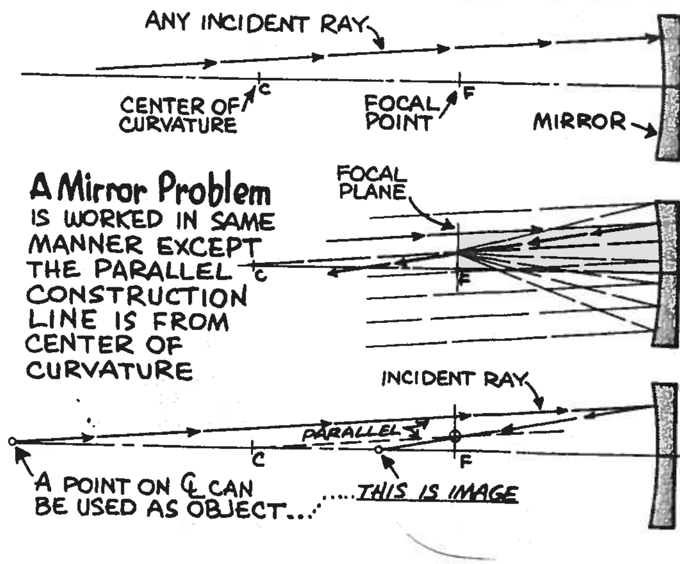


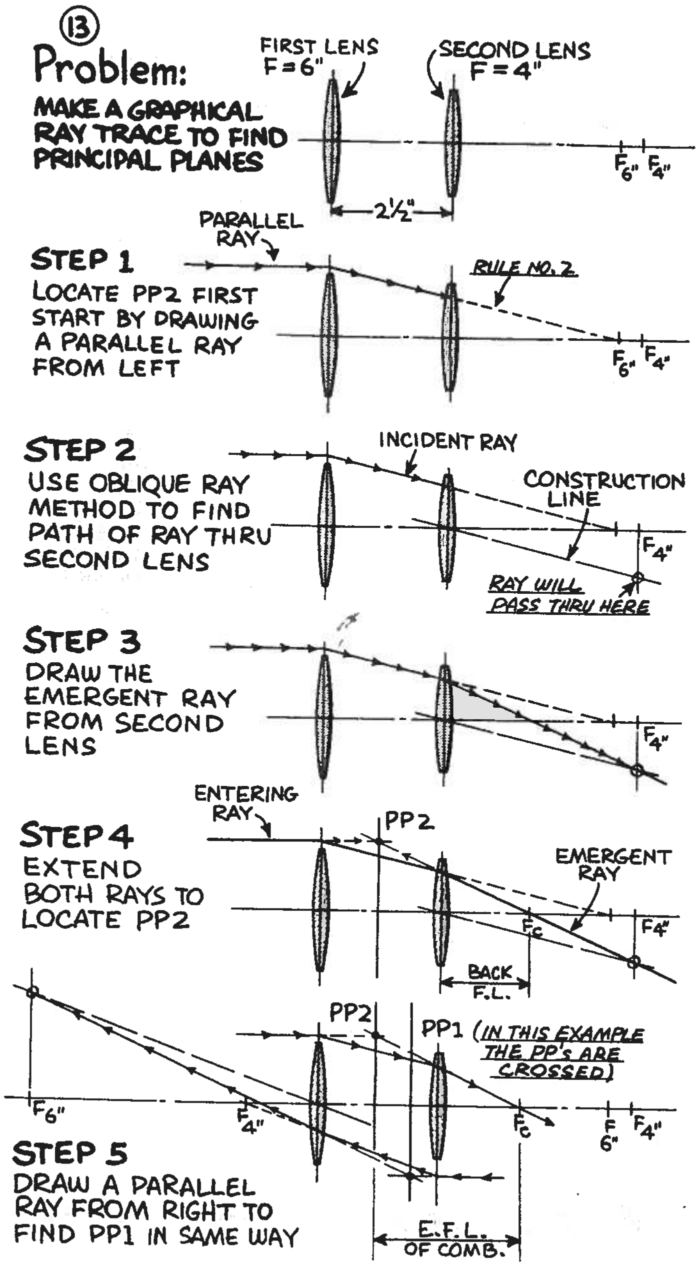


10 CONSTRUCTION WITH PRINCIPAL PLANES

OBLIQUE RAY METHOD (11) with a POSITIVE LENS (12) with a POSITIVE (Concave) MIRROR







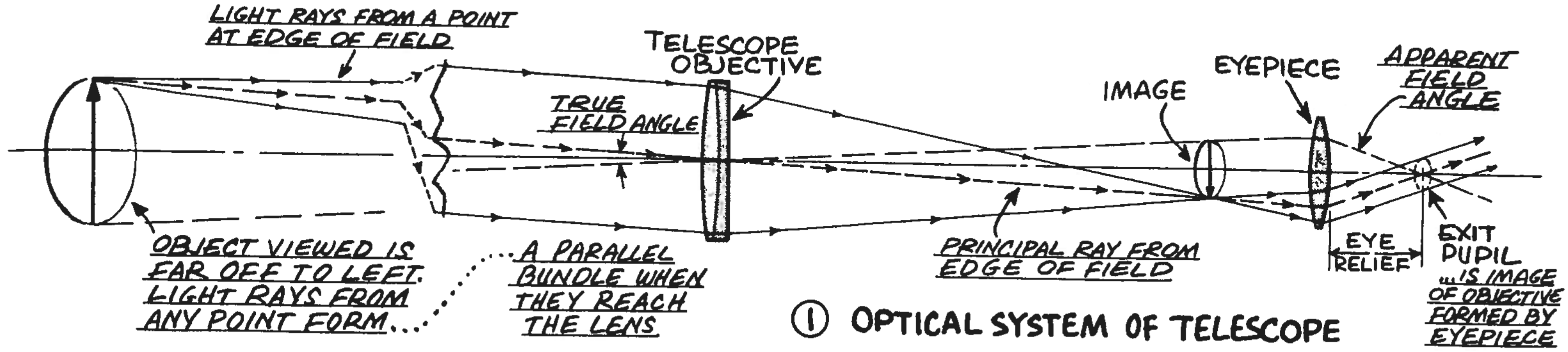
the principal planes are crossed, this means you must then backtrack to PP2, as can be seen in Fig. 10B example.

OBLIQUE RAY METHOD. This is probably the fastest way to trace a single ray through successive lenses. The general idea can be seen in Fig. 11--you don't know where the light ray is going, but you do know that an imaginary ray through the center of the lens would come to a focus at the focal plane. By making this ray parallel to the incident ray, you establish a point through which the incident ray must pass.

Fig. 12 shows the oblique ray method applied to a mirror. This is worked very much like a lens, the main difference being that the construction ray parallel to incident ray is drawn through the center of curvature, as shown. It should be noted in both cases that the intersection of the construction lines marks a point through which the light ray must pass--it is not the location of an image.

PRINCIPAL PLANES. By tracing a single ray from the left, you can locate the plane of emergence (PP2) of a simple lens duplet, as shown in successive steps in Fig. 13. It can be seen that this graphical trace also gives the back focal length and e.f.l., both of which can be scaled from the drawing. The graphical trace itself makes use of the parallel ray method to trace the light ray through the first lens, Step 1, followed by the oblique ray method for the second lens, as shown in Steps 2 and 3.

The plane of admission, PP1, is traced in the same manner by running in a parallel ray from the right, as in Step 5. If the two lenses have the same f.l., the PP's are symmetrical.

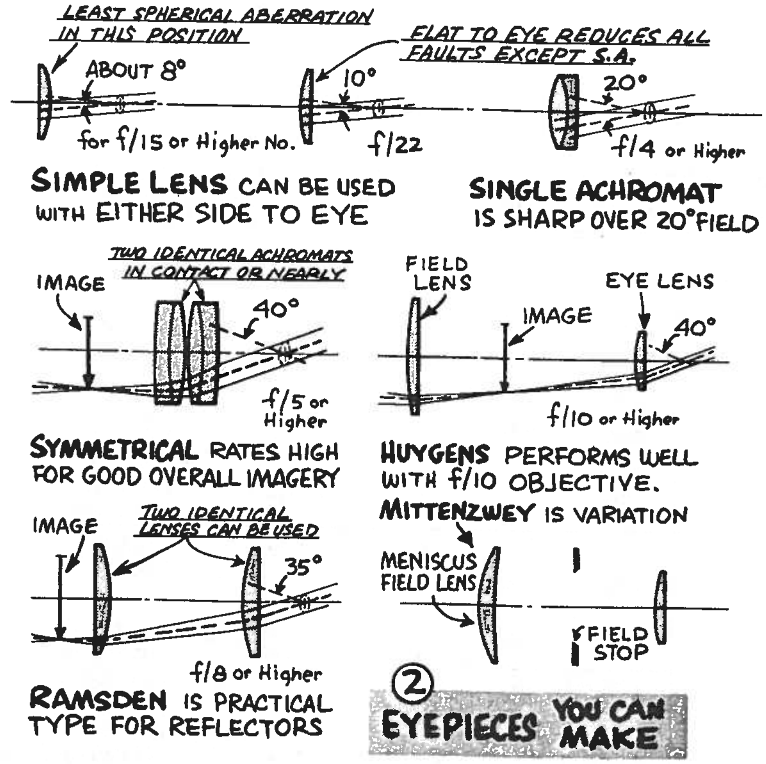


① OPTICAL SYSTEM OF TELESCOPE

EYEPIECES
you can make

WHILE a few hardy amateurs grind and polish their own simple lenses to make eyepieces, the usual "homemade" eyepiece is one assembled from stock lenses. Some common types you can make are shown in Fig. 2. Except for the modest field of less than 40 degrees, homemade eyepieces perform practically as well as complex, expensive oculars.

RAMSDEN. The Ramsden eyepiece is often made of two identical lenses, Fig. 2, since this simplifies construction. However, the eye lens can be made much smaller and still pick up all useful light rays. The original Ramsden is a 1-1-1 design, fully corrected for lateral color, Fig. 4.



② EYEPIECES YOU CAN MAKE

③ LINEAR FIELD OF TELESCOPE IMAGE WITH VARIOUS EYEPIECES

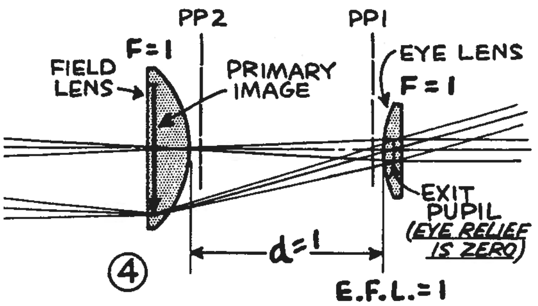
APPARENT FIELD OF EYEPIECE		FOCAL LENGTH OF EYEPIECE 1/6"	1/5"	1/4"	3/8"	1/2"	5/8"	3/4"	7/8"	1"	1 1/16"	1 1/8"	1 1/4"	1 3/8"	1 1/2"	1 3/4"	2"
	65°	.19"	.23"	.28"	.42"	.57"	.71"	.85"	.99"	1.13"	1.20"	1.27"	1.42"	1.55"	1.70"	1.98"	2.27"
AVERAGE ERFLE	60°	.17	.21	.26	.39	.52	.66'	.79	.92	1.05	1.11	1.18	1.32	1.44	1.57	1.84	2.09
	55°	.16	.19	.24	.36	.48	.60	.72	.84	.96	1.02	1.08	1.20	1.32	1.44	1.68	1.92
AVERAGE KELLNER OR ORTHOSCOPIC	50°	.14	.17	.22	.32	.44	.54	.65	.76	.87	.92	.98	1.08	1.20	1.31	1.52	1.74
AV. SYMMETRICAL OR PLOSSL	45°	.13	.16	.20	.29	.39	.49	.59	.68	.78	.83	.88	.98	1.07	1.17	1.36	1.57
LIMIT for HUYGENS	40°	.12	.14	.17	.26	.35	.44	.52	.61	.70	.74	.79	.88	.96	1.05	1.22	1.40
LIMIT for RAMSDEN	35°	.10	.12	.15	.23	.31	.38	.46	.53	.61	.65	.69	.76	.84	.92	1.07	1.22
USUAL FIELD OF CHEAP TERRESTRIAL SCOPES	30°	.09	.10	.13	.20	.26	.33	.39	.46	.52	.55	.59	.65	.72	.78	.91	1.05
	25°	.07	.09	.11	.16	.22	.27	.33	.39	.44	.47	.49	.55	.60	.66	.77	.87
SINGLE ACHROMAT	20°	.06	.07	.09	.13	.17	.22	.26	.31	.35	.37	.39	.44	.48	.52	.61	.70
SINGLE SIMPLE LENS	10°	.03	.03	.04	.07	.09	.11	.13	.15	.17	.18	.19	.21	.23	.26	.30	.35

Example: YOU PLAN TO USE A 50° EYEPIECE OF 1" F.L. WHAT IS IMAGE DIA.? **SOLUTION:** IN LEFT COL., LOCATE 50° A.F. ON SAME LINE UNDER 1" F.L, READ .87" (7/8") DIA. OF FIELD AT IMAGE PLANE

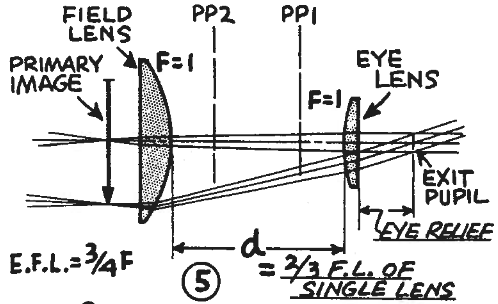
GRAY AREA STANDARD 1 1/4" EYEPIECE HOLDER WILL NOT COVER. YOU MUST MAKE OVERSIZE FOCUSING EYEPIECE HOLDER

HUYGENS EYEPIECE ONLY: READ PRIMARY IMAGE DIA. FROM TABLE... BUT READ FINAL IMAGE (STOP DIA.) 2 LINES DOWN

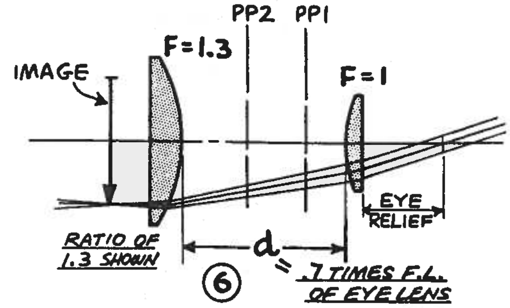
Ex. 1" F.L. HUYGENS, 40° A.F. PRIMARY IMAGE = .70" FINAL IMAGE = .52" (APPROX.)



1-1-1 RAMSDEN IS CORRECTED FOR LATERAL COLOR BUT EYE RELIEF IS ZERO... DUST CAN BE SEEN ON FIELD LENS WHICH COINCIDES WITH IMAGE PLANE



1-1-2/3 RAMSDEN IS STOCK DESIGN WITH LENSES SAME F.L. AND SPACE 2/3 F.L. OF SINGLE LENS. SPACING LESS THAN 1/2(F+F) CAUSES LATERAL COLOR



LONGER F.L. FIELD LENS IS BEST FOR POWERS OVER 10X ... GIVES BETTER COMA CORRECTION ...LONGER EYE RELIEF

POWER	RATIO
10X OR LESS	1 OR 1.1
10X TO 40X	1.1 OR 1.2
30X OR MORE	1.2 OR 1.3

7 RAMSDEN Specifications

E.F.L.	IMAGE 35° FIELD	RATIO OF 1			RATIO OF 1.1			RATIO OF 1.2			RATIO OF 1.3		
		FIELD	EYE	SPACE	FIELD	EYE	SPACE	FIELD	EYE	SPACE	FIELD	EYE	SPACE
1/4"	.15"	.24 x .32" 6 x 8 MM	.14 x .32" 4 x 8MM	.23"	.25 x .35" 6 x 9MM	.14 x .32" 4 x 8MM	.22"	.25 x .37" 6 x 10MM	.15 x .31" 4 x 8MM	.22"	.26 x .40" 7 x 10MM	.15 x .31" 4 x 8MM	.22"
1/2"	.31	.42 x .65" 11 x 17MM	.22 x .65" 6 x 17MM	.45	.43 x .70" 11 x 18MM	.23 x .63" 6 x 16MM	.45	.44 x .75" 11 x 19MM	.24 x .62" 6 x 16MM	.44	.46 x .80" 12 x 21MM	.25 x .62" 7 x 16 MM	.43
3/4"	.46	.60 x .98" 15 x 25MM	.30 x .98" 8 x 25MM	.68	.61 x 1.05" 16 x 27MM	.31 x .95" 8 x 24MM	.67	.64 x 1.12" 16 x 29MM	.32 x .94" 8 x 24MM	.66	.66 x 1.20" 17 x 31MM	.34 x .92" 9 x 24MM	.64
7/8"	.53	.69 x 1.13" 18 x 29MM	.33 x 1.13" 9 x 29MM	.79	.71 x 1.22" 18 x 31MM	.35 x 1.10" 9 x 28MM	.77	.73 x 1.30" 19 x 33MM	.36 x 1.09" 9 x 28MM	.76	.76 x 1.39" 20 x 36MM	.38 x 1.07 10 x 27MM	.75
1"	.61	.78 x 1.30" 20 x 33MM	.32 x 1.30" 10 x 33MM	.91	.81 x 1.40" 21 x 36MM	.39 x 1.27" 10 x 33MM	.89	.83 x 1.50" 21 x 38MM	.41 x 1.25" 11 x 32MM	.87	.86 x 1.60" 22 x 41MM	.43 x 1.23" 11 x 31MM	.86
1 1/8"	.69	.82 x 1.46" 22 x 37MM	.41 x 1.46" 11 x 37MM	1.02	.90 x 1.57" 23 x 40MM	.43 x 1.42" 11 x 36MM	1.00	.92 x 1.68" 24 x 43MM	.45 x 1.40" 11 x 36MM	.98	.96 x 1.79" 25 x 46MM	.47 x 1.38" 12 x 35MM	.96
1 1/4"	.76	.96 x 1.63" 25 x 42MM	.45 x 1.63" 12 x 42MM	1.14	1.00 x 1.75" 26 x 45MM	.47 x 1.59 12 x 41MM	1.11	1.02 x 1.87" 26 x 47MM	.50 x 1.56" 13 x 39MM	1.09	1.06 x 2.00 27 x 51MM	.52 x 1.54" 14 x 39MM	1.08
1 1/2"	.92	1.14 x 1.95" 29 x 50MM	.53 x 1.95" 14 x 50MM	1.37	1.19 x 2.10" 30 x 54MM	.56 x 1.91" 14 x 49MM	1.34	1.22 x 2.25 31 x 57MM	.59 x 1.87" 15 x 47MM	1.31	1.26 x 2.40 32 x 61MM	.62 x 1.85" 16 x 47MM	1.29
1 3/4"	1.07	1.32 x 2.28" 34 x 58MM	.60 x 2.28" 16 x 58MM	1.59	1.37 x 2.45 35 x 62MM	.64 x 2.22 16 x 56MM	1.56	1.41 x 2.62 36 x 67MM	.67 x 2.19" 17 x 56MM	1.52	1.46 x 2.80 37 x 71MM	.71 x 2.15" 18 x 55MM	1.51

LENSES ARE LISTED BY DIA. AND F.L. IN INCHES AND MM. ALL DIAMETERS ARE APPROX. CL. APERTURE PLUS 1/16" FOR MOUNTING

FOR F.L. NOT LISTED: USE VALUES FOR 1" F.L. FROM TABLE AND MULTIPLY BY F.L. YOU WANT

Worksheet 8

YOU WANT 1" (25MM) F.L. RAMSDEN FOR 48X. PREFERABLE FIELD-EYE LENS RATIO IS 1.2 OR 1.3 BUT YOU CAN USE WHOLE RANGE:

DATA FROM TABLE ABOVE	RATIO OF 1	RATIO OF 1.1	RATIO OF 1.2	RATIO OF 1.3
FIELD LENS	20 x 33MM	21 x 36MM	21 x 38MM	22 x 41MM
EYE LENS	10 x 33MM	10 x 33MM	11 x 32MM	11 x 31MM

AVAILABLE LENSES (EDMUND - 1965)

FIELD:
19.5 x 38MM
22 x 40
23 x 41 ← BEST
19 x 42
26 x 42

EYE:
13 x 13 x 31MM
11 x 15 x 32MM
12.5 x 35MM ← BEST

RATIO = 41 ÷ 35 = 1.2 Approx. (OK)

SPACE = 35 x .7 = 24.5MM (SAY 25MM)

E.F.L. = $\frac{41 \times 35}{41+35-25} = \frac{1435}{51} = 28$MM (IS LONG BUT COULD BE USED)

TRY LESS SPACE 35 x .6 = 21MM

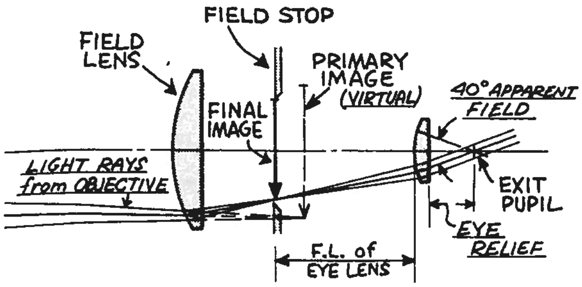
E.F.L. = $\frac{41 \times 35}{41+35-21} = \frac{1435}{55} = 26$ MM (OK)

This construction is excellent for an erecting system or for a projecting eyepiece, but it is poor for ordinary telescope use in that there is no eye relief.

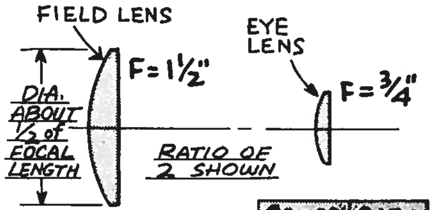
To provide eye relief and also move the image away from the field lens, a spacing of 2/3 the f.l. of the individual lens is often used, and this is the standard Ramsden, Fig. 5. The eyepiece is improved slightly by making the field lens a little longer focal length, Fig. 6. The specifications in Fig. 7 Table can be juggled a little to suit, an example being as shown in Fig. 8. Spacing can be reduced to as little as 50% of the f.l. of the eye lens without introducing an excessive amount of lateral color.

HUYGENS. In Huygens' time, (Christian Huygens, 1629-1695), the refractor was the only telescope of note, and this eyepiece was designed

⑨ GENERAL FEATURES OF THE HUYGENS EYEPIECE

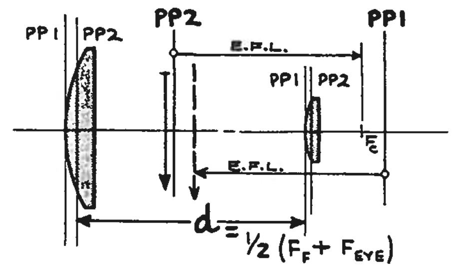


LIGHT PATH: WITHOUT EYEPIECE, THE TELESCOPE OBJECTIVE WOULD FORM PRIMARY IMAGE AS SHOWN. THE FIELD LENS INTERCEPTS THE LIGHT RAYS AND FORMS A REAL FINAL IMAGE WHICH IS VIEWED BY THE EYE LENS



RATIO: FIELD LENS IS ALWAYS LONGER F.L. THAN EYE LENS. BEST RATIO DEPENDS ON POWER OF SCOPE AND SHOULD BE SELECTED FROM TABLE →

POWER	RATIO
3x	1.3
4x	1.35
5x	1.4
10x	1.7
20x	2.0
30x	2.3
50x	2.6
or More	3.0



SPACING: LATERAL COLOR IN ANY SIMPLE EYEPIECE IS CORRECTED BY SPACING OF ½ THE COMBINED FOCAL LENGTHS. *(LONGITUDINAL COLOR IS NOT CORRECTED)*. SPACING IS MEASURED BETWEEN ADJACENT PRINCIPAL PLANES

⑩ HUYGENS Specifications - 40° FIELD

E.F.L.	RATIO OF 2				RATIO OF 2.3				RATIO OF 2.6				RATIO OF 3			
	FIELD	EYE	SPACE	STOP	FIELD	EYE	SPACE	STOP	FIELD	EYE	SPACE	STOP	FIELD	EYE	SPACE	STOP
1/4"	.25 x .38" 7x10 MM	.13 x .19" 4 x 5 MM	.28"	.13" D.	.25 x .42" 6x11 MM	.12 x .18" 4 x 5 MM	.30"	.13" D.	.25 x .45" 7 x 12 MM	.14 x .17" 4 x 5 MM	.31"	.12" D.	.25 x .50" 7 x 13 MM	.14 x .17" 4 x 5 MM	.33"	.12" D.
1/2"	.44 x .75" 11 x 19 MM	.20 x .37" 5 x 10 MM	.56	.26	.44 x .83 11 x 21 MM	.20 x .36" 5 x 9 MM	.59	.25	.44 x .90 11 x 23 MM	.22 x .35" 6 x 9 MM	.62	.25	.45 x 1.00 12 x 26	.22 x .33" 6 x 9 MM	.66	.24
3/4"	.62 x 1.13" 16 x 29 MM	.27 x .56" 7 x 14 MM	.84	.39	.62 x 1.25 16 x 32 MM	.27 x .54" 7 x 14 MM	.89	.38	.62 x 1.35 16 x 34	.29 x .52" 8 x 13	.93	.37	.64 x 1.50 17 x 38	.29 x .50 7 x 13 MM	.99	.36
7/8"	.71 x 1.31" 18 x 34	.30 x .65" 8 x 17 MM	.98	.46	.71 x 1.44 18 x 37	.30 x .63 8 x 16 MM	1.04	.44	.71 x 1.57 18 x 40	.33 x .60" 9 x 15 MM	1.08	.43	.74 x 1.74" 19 x 44	.33 x .58" 9 x 15 MM	1.16	.41
1"	.81 x 1.50 21 x 38 MM	.34 x .75 9 x 19 MM	1.12	.53	.81 x 1.66" 21 x 42	.34 x .72 9 x 18	1.19	.51	.81 x 1.80 21 x 46	.37 x .69" 10 x 18	1.24	.49	.84 x 2.00 22 x 51	.37 x .67 10 x 17 MM	1.33	.47
1 1/8"	.90 x 1.68 23 x 43	.37 x .84" 10 x 22	1.25	.59	.90 x 1.86 23 x 47	.37 x .81" 10 x 21	1.33	.57	.90 x 2.02 23 x 52	.41 x .77" 11 x 20 MM	1.39	.55	.93 x 2.25 24 x 57	.41 x .75 11 x 19 MM	1.49	.53
1 1/4"	1.00 x 1.88 25 x 48	.41 x .94" 11 x 24	1.40	.66	1.00 x 2.08 25 x 53	.41 x .90" 11 x 23	1.49	.64	1.00 x 2.25 25 x 57	.45 x .86 11 x 22	1.55	.61	1.04 x 2.50 27 x 64	.45 x .84 11 x 22	1.66	.59
1 1/2"	1.19 x 2.25 30 x 57 MM	.48 x 1.12" 12 x 29 MM	1.69	.80	1.19 x 2.49 30 x 63	.48 x 1.08 13 x 28	1.78	.76	1.19 x 2.70 30 x 69	.53 x 1.04 14 x 27 MM	1.86	.74	1.23 x 3.00 31 x 76	.53 x 1.00 14 x 26	1.99	.71

FOR FOCAL LENGTHS NOT LISTED, RATIO OF 2 CAN BE CALCULATED BY THE FOLLOWING:

Example: 1" F.L.

F.L. EYE = ¾ E.F.L. = ¾ × 1 = ¾"

F.L. FIELD = 1½ E.F.L. = 1½ × 1 = 1½"
or 2 TIMES EYE = 2 × ¾ = 1½"

SPACE = 1⅛ E.F.L. = 1⅛ × 1 = 1⅛"
or 3/2 TIMES EYE = 3/2 × ¾ = 1⅛"

FOR FOCAL LENGTHS NOT LISTED, USE VALUES FOR 1" F.L. AS MULTIPLYING FACTORS

Example → E.F.L. to be .8" RATIO OF 2.3

FIELD LENS = 1.66 × .8 = 1.33" F.L.
EYE LENS = .72 × .8 = .58" F.L.
SPACE = 1.19 × .8 = .95"
STOP DIA. = .51 × .8 = .41"

You Can CHECK $\text{E.F.L.} = \frac{F \times F}{F + F - d} = \frac{1.33 \times .58}{1.33 + .58 - .95} = \frac{.7714}{.96} = .803"$

GENERAL RULES FOR RATIO OF 3:

Example: 1" F.L.

EYE = ⅔ E.F.L. = ⅔ × 1 = ⅔" F.L.

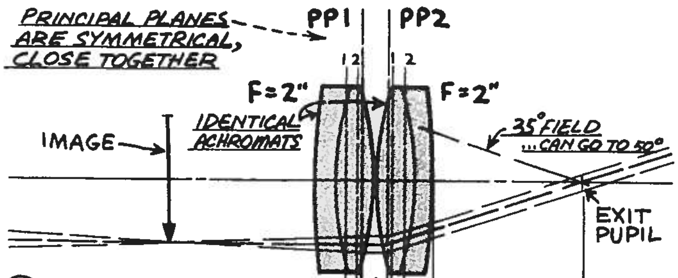
FIELD = 2 E.F.L. = 2 × 1 = 2" F.L.
or 3 TIMES EYE = 3 × ⅔ = 2"

SPACE = 4/3 EFL = 4/3 × 1 = 1⅓"
or 2 TIMES EYE = 2 × ⅔ = 1⅓"

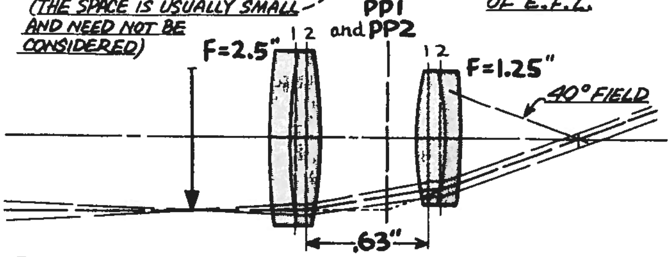
STOP - *FOR RATIO OF 3... IS MIDWAY BETWEEN LENSES*

solely for the refractor with which it functions rather well. Specifically, the Huygens is intended for use with telescopes of narrow aperture--f/10 or higher f/number. The best feature of the Huygens is that it can be fully corrected for lateral color; in other respects it is slightly inferior to the Ramsden. The field lens is always longer focal length than the eye lens. The ratio to use is that which gives the best correction for coma, this being dependent on the power of the telescope, or, more exactly, the number of focal lengths of the eyepiece contained in the distance from eyepiece to objective. If you start out with the proper ratio for a certain power, Fig. 9, the eyepiece will be well-corrected for coma. Fig. 10 Table gives specifications for various focal lengths. These are general calculated values which may be modified slightly to suit such lenses as may be available. For astro use, the field lens-eye lens ratio is preferably 2.3 or more for best coma correction, longest eye relief.

ACHROMATIC DUPLETS. One of the more popular and practical homemade eyepieces is based on the general idea of using two achromats. The



(11) SYMMETRICAL
E.F.L. APPROX. ½ F
(THE SPACE IS USUALLY SMALL AND NEED NOT BE CONSIDERED)



(12) UNSYMMETRICAL DUPLET (SPECIFICATIONS FOR 1" F.L.)

CHANGE (13) Specifications

YOU WILL FIND EYEPIECE DESIGNS IN MANY OPTICAL BOOKS. IF THE F.L. IS NOT SUITABLE, YOU CAN CHANGE TO ANY DESIRED F.L. BY MULTIPLYING ALL "SPECS" BY A FACTOR:

$$\text{FACTOR} = \frac{\text{F.L. YOU WANT}}{\text{ORIGINAL F.L.}}$$

Example: Conrady*, p.498
RAMSDEN EYPC., RATIO 1.25
F.L. = 1.56" (Conrady's specifications:)
FIELD LENS F.L. = 2.42"
EYE LENS F.L. = 1.93"
SPACE = 1.35"

YOU WANT, SAY, 1" F.L., SO MULTIPLYING FACTOR IS:

$$\frac{\text{F.L. YOU WANT} \ldots 1}{\text{ORIGINAL SPEC.} \ldots 1.56} = .64$$

THEN:
FIELD = 2.42 × .64 = 1.55"
EYE = 1.93 × .64 = 1.24"
SPACE = 1.35 × .64 = .86"

Check
$$\text{E.F.L.} = \frac{1.55 \times 1.24}{1.55 + 1.24 - .86} = \frac{1.92}{1.93} = 1'' \text{ APPROX. OK}$$

*APPLIED OPTICS AND OPTICAL DESIGN – A.E. Conrady

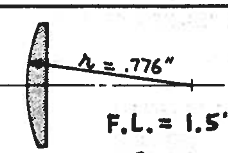
construction is usually symmetrical, Fig. 11, with the two lenses in contact or nearly so. Many excellent eyepieces can be made in this manner. Unsymmetrical construction, Fig. 12, allows you to use a big field lens for light pickup in combination with a smaller and stronger eye lens. The ratio of focal lengths and the spacing can be almost anything; specifications given in Fig. 12 are popular because they are simple and result in a single principal plane for the combination. In any case, the lenses used should be good-quality, conventional achromats, i.e., duplets designed for incident parallel light, corrected for spherical aberration and achromatized for the C (red) and F (blue) lines of the spectrum. Not all war surplus achromats comply with these basic specifications.

DESIGN PROCEDURE. For conventional Huygens or Ramsden eyepieces, the specific lenses needed are given in the tabular data. For other types, you can find diameter in a roundabout way from Fig. 3 Table, which gives the image size. For most eyepieces the field lens must be a little larger than the image diameter. Note that for the Huygens, the final image, which is also the field stop, is slightly smaller than the primary image.

Specifications given in other optical books may be followed if desired, and if radius only is given you can readily convert to f.l. by using the formula given in Fig. 14. When the f.l. specified is not what you want, it is easy to change to any desired f.l. by the method shown in Fig. 13. This can also be applied to any single lens, such as a telescope objective, or to any optical system.

(14)
Conversion Formulas

REFRACTIVE INDEX OF GLASS (n IS SYMBOL) ... n = 1.517
C = 1.29



F.L. = 1.5"

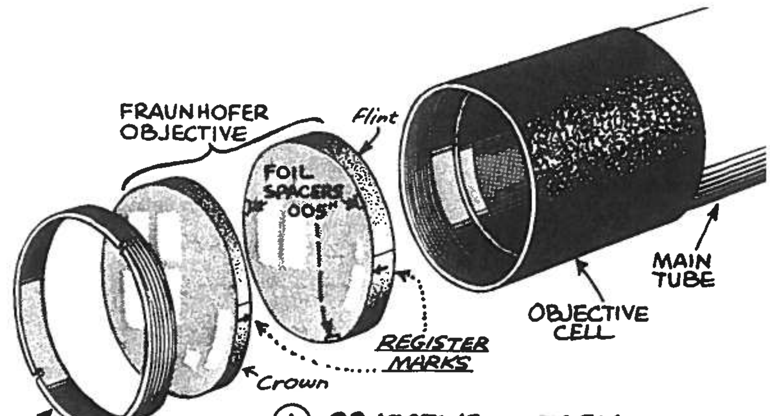
PLANO-CONVEX EYEPIECE LENSES ARE OFTEN SPECIFIED BY RADIUS OR CURVATURE, RATHER THAN F.L.

CONVERT AS NEEDED BY USING THESE FORMULAS

THE APPROX. CONVERSION OF RADIUS TO F.L. IS SIMPLY:
F.L. = 2r
THIS IS EXACT ONLY IF GLASS HAS INDEX OF 1.50. OTHERWISE, USE FORMULA NO. 2

	KNOWN	FIND	Formula	Example
1	radius	curvature	$C = \frac{1}{r}$	$C = \frac{1}{.776} = 1.29$ .... 1.2887 IS EXACT
2	radius	F.L.	$\text{F.L.} = \frac{r}{n-1}$	$\text{F.L.} = \frac{.776}{1.517-1} = \frac{.776}{.517} = 1.5''$
3	curvature	radius	$r = \frac{1}{C}$	$r = \frac{1}{1.29} = .775''$ ... APPROX. OK should use four decimal places
4	curvature	F.L.	$\text{F.L.} = \frac{1}{(n-1) \times C}$	$\text{F.L.} = \frac{1}{.517 \times 1.29} = \frac{1}{.667} = 1.5''$
5	F.L.	curvature	$C = \frac{1}{(n-1) \times F}$	$C = \frac{1}{.517 \times 1.5} = \frac{1}{.776} = 1.29$
6	F.L.	radius	$r = F \times (n-1)$	$r = 1.5 \times .517 = .776''$

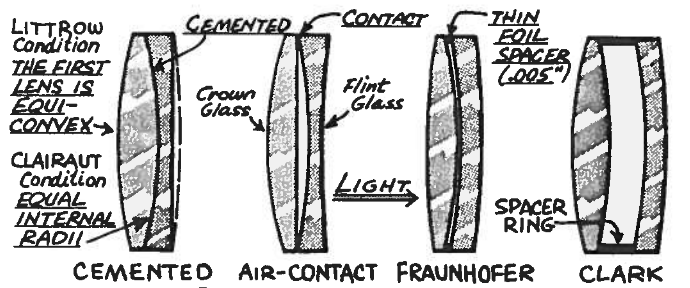
The REFRACTOR



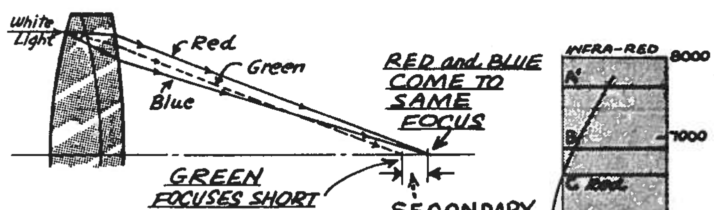
① OBJECTIVE AND CELL

THE TYPICAL refractor objective is a broken-contact or air-spaced style, usually purchased complete with cell, Fig. 1. Sold unmounted, the same lens has register marks to show how the two elements should be put together. Adhesive foil is supplied, from which you cut three pieces about 1/16 x 3/16-inch, attaching these to the concave side of the flint element, as shown. Practically all air-spaced objectives are now coated on all four surfaces, practically eliminating the 18 to 20 percent light loss from four uncoated surfaces.

Small achromats up to 2 in. diameter are usually cemented for convenience in handling and mounting. An equi-convex front lens, identical internal radii and a flat-back flint are conditions often specified for inexpensive achromats, Fig. 2. The same drawing shows the air-contact type used in many inexpensive telescopes. Over 3 in. diameter, air-spacing becomes almost necessary to eliminate the risk of cement failure caused by unequal glass expansion. In top-quality air-spaced objectives, the Fraunhofer-type is a favorite of long standing. The Clark is also excellent. Both of these are corrected for coma, which is usually neglected in a cemented achromat.



② ACHROMATIC TELESCOPE OBJECTIVES



APPLICATION OF LENS	USUAL CORRECTION
VISUAL	C LINE and F LINE (SHOWN)
ORDINARY PHOTOGRAPHY	D LINE and G' LINE
ASTROGRAPHIC BLUE-SENSITIVE ONLY	F LINE and 4050 ANGSTROMS
AERIAL PHOTOGRAPHY	A' LINE and D LINE *

* DG' ACHROMATISM ALSO USED

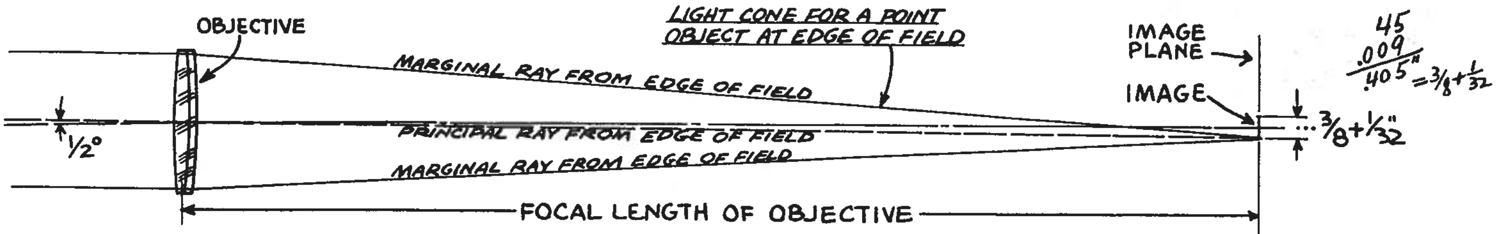
③ COLOR CORRECTION

COLOR CORRECTION. With two glass elements to work with, the lens designer can correct an achromat for any two colors. For a visual instrument like the telescope, the two best colors are the F-line in the blue part of the spectrum and the C-line in the red. These two lines bracket that portion of the spectrum to which the eye is most sensitive. There is, of course, a residual of uncorrected color, Fig. 3, both between and beyond the CF lines. This secondary color will put a hairline of purple light around a bright star, but unless you look you will rarely be aware of the color fringe.

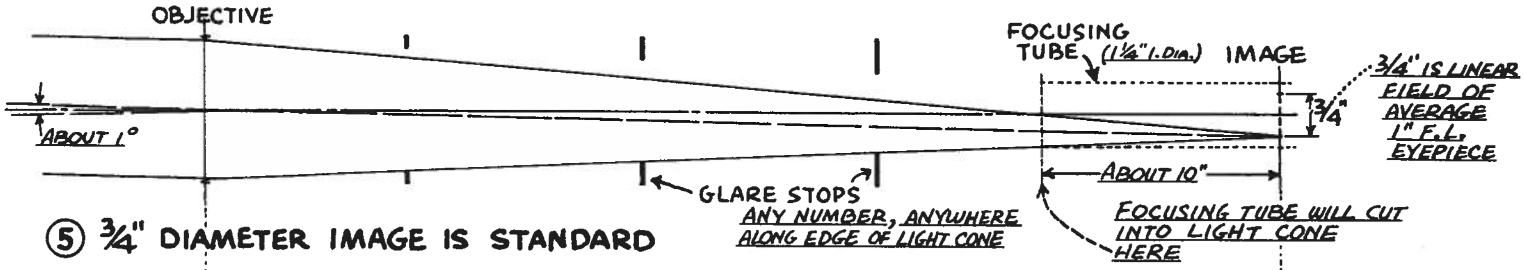
CF achromatism is quite satisfactory for ordinary photography on pan film. A yellow filter is often specified, but this need is universal for long-range daytime photography with any lens. The ordinary photographic objective leans a bit more to the blue end of the spectrum to favor a wider range of film emulsions. An astrographic object glass is often corrected for blue only and can be used only with blue-sensitive, i.e., color-blind film. Some aerial camera lenses are achromatized for the high red end of the spectrum for use with infra-red and other red-sensitive emulsions. Such a glass is poor for visual use because the blue rays are badly out of focus.

THE LIGHT CONE. The moon is 1/2 degree in angular diameter. This is commonly taken as the minimum fully-illuminated field of any telescope. You can find what it amounts to in linear size by multiplying the f.l. of objective by .009. The situation is shown in Fig. 4. The field will be fully-illuminated if you can draw the three light rays shown without obstruction. As a matter of fact, the lowermost of the three rays is the only one that matters--if you get this one through, the others will clear automatically.

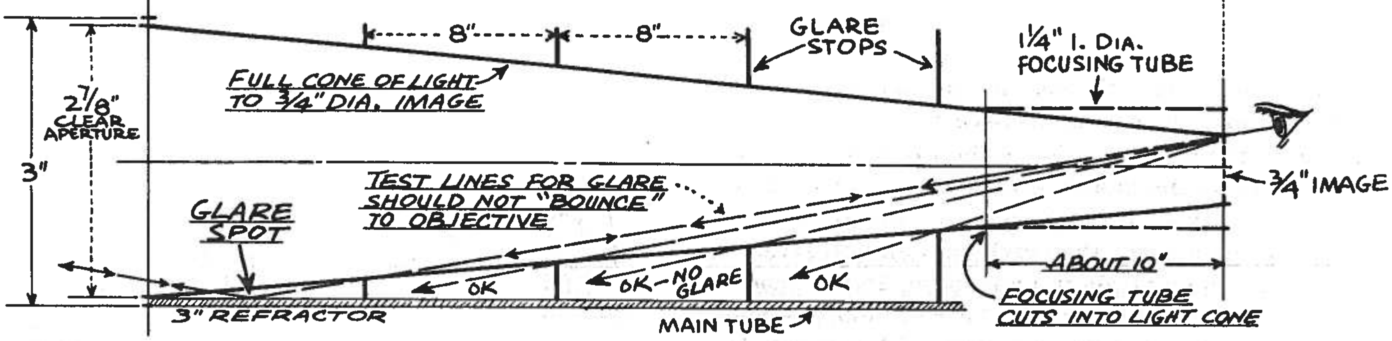
While keeping the minimum field in mind, most builders try for a bit more. A common standard



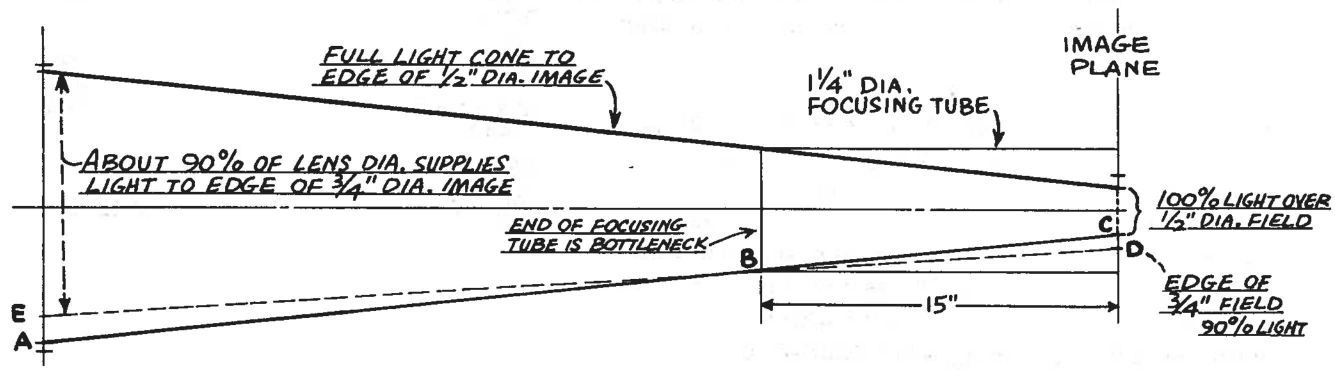
④ MINIMUM FULLY ILLUMINATED FIELD = ½° = F.L. x .009 Example: 3" f/15 REFRACTOR



⑤ 3/4" DIAMETER IMAGE IS STANDARD



⑥ CONDENSED HORIZONTAL SCALE IS CONVENIENT WAY TO DRAW LIGHT CONE

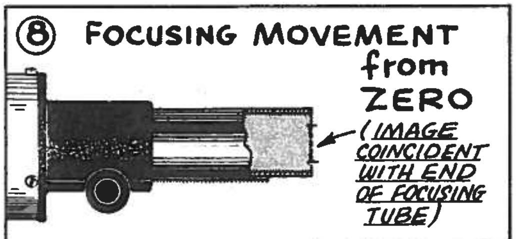


⑦ FOCUSING TUBE TOO FAR FORWARD WILL REDUCE THE SIZE OF FULLY-ILLUMINATED FIELD

is a 3/4 in. linear image field, regardless of objective focal length. This particular diameter is used because it is about the linear size of image seen through a 1-inch eyepiece. In most cases you will have no trouble in lighting a 3/4 inch image. Properly, the bottleneck should be the eyepiece itself, but more often it is the focusing tube that limits the light cone. Fig. 5 shows the situation with 3 in. refractor--the focusing tube can extend 10 in. forward from the image before encroaching on the light cone.

Any light outside the light cone is useless and should be blocked-off to eliminate glare. This is done with a set of 3 or 4 glare stops. You are assured the glare stops are really working if you can draw lines as in Fig. 6 without striking the objective. This diagram shows one glare spot at front of tube, which could be eliminated with a narrow glare stop at that point. Alternately, black flock paper offers fairly good protection and is especially useful when glare stops become too shallow.

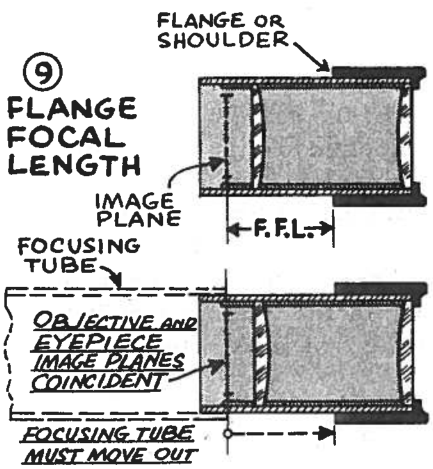
Fig. 7 shows the case where the focusing tube encroaches on the light cone. How much light does this cut off? Make a condensed scale diagram like Fig. 7. Draw a line from the edge of



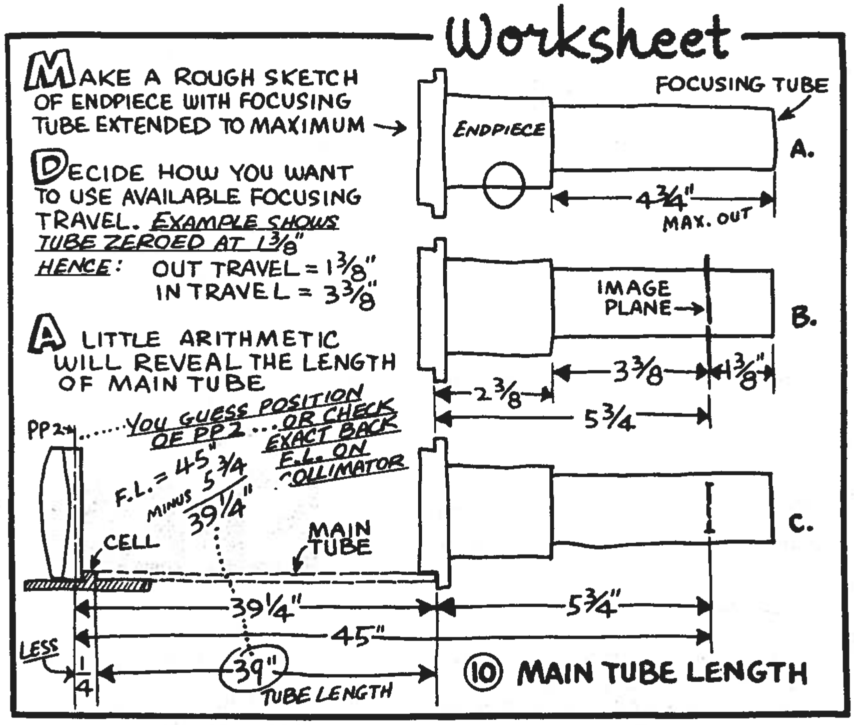
⑧ FOCUSING MOVEMENT from ZERO

	IN	OUT
ORDINARY EYEPIECES	0"	1/2"
BARLOW LENS (1.83" F.L.)	3/8" 2x	1/2" TO 3x
STAR DIAGONAL	3"	0"
SUN DIAGONAL	3"	0"
ROOF PRISM ERECTOR	3"	0"
LENS ERECTOR	0"	1/2"
PORRO PRISM ERECTOR	7"	0"
35MM CAMERA (AT FOCUS)	2"	0"

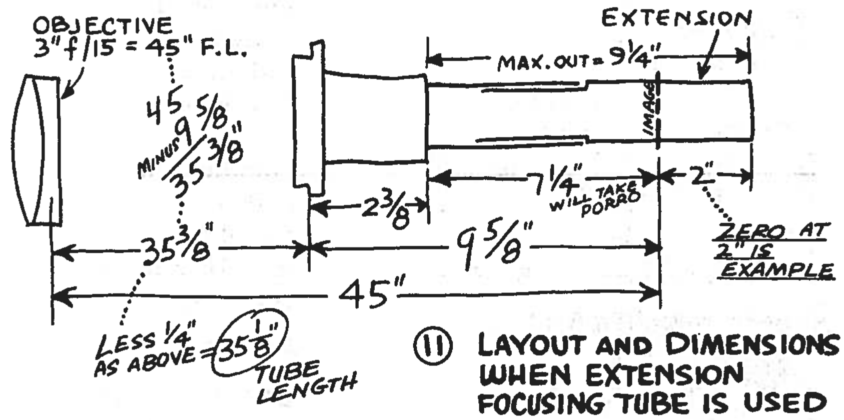
(FOR DISTANT OBJECT ONLY)



⑨ FLANGE FOCAL LENGTH



⑩ MAIN TUBE LENGTH

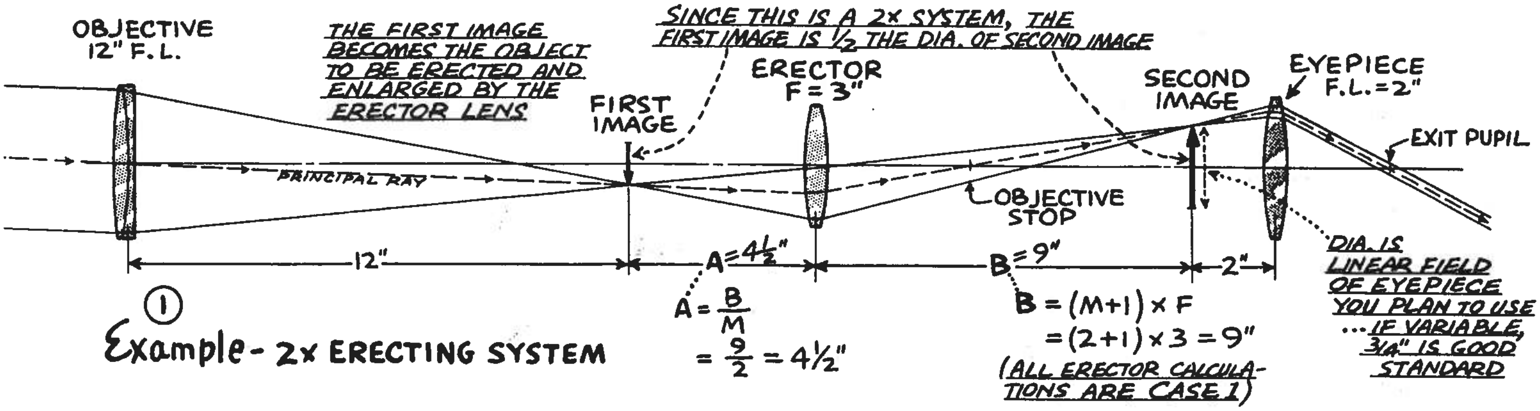


⑪ LAYOUT AND DIMENSIONS WHEN EXTENSION FOCUSING TUBE IS USED

objective at A, to edge of focusing tube at B, finally cutting the image plane at C. This shows the field of full illumination. Now, draw another line from D through B, cutting the objective at E. What you are drawing in each instance is the outermost ray of the light cone. All other rays of the cone will get through, meaning that all of the objective above point E will contribute light to point D at the edge of a 3/4 in. image. As can be seen, this is about 90% lighting and entirely practical--in an actual telescope you can't see this slight light loss even when you try.

LENGTH OF MAIN TUBE. The zero position of the focusing tube, Fig. 8, is a matter of choice, selected according to what accessories you plan to use. Eyepieces alone need only "out" focusing movement from the zero position, as can be seen in Fig. 9, the distance being the same as the flange focal length of the eyepiece.

Fig. 10 Worksheet shows the focusing tube zeroed at a distance of 1-3/8 in. "in" from the maximum "out" position. With a single focusing tube, this position will accommodate all ordinary eyepieces and all accessories except a big Porro erector. The rest of the problem takes a little thinking, but it is just a matter of simple arithmetic to find the proper length of the main tube. It is a good idea to check the exact back focal length of your objective. A 3 in. f/15 objective is supposed to be 45 in. f.l., but may be as much as 1/2 inch more. If you do not check the objective f.l., you can allow for this possible increase by cutting the main tube about 1/2 inch longer than calculated. An actual test of the telescope will then show the exact situation and you can take it from there. A Porro prism erector requires the use of either an extension tube or a draw tube. An extension tube is simplest and cheapest, but has the fault that the combined long length of focusing tube encroaches to some extent on the normal light cone.



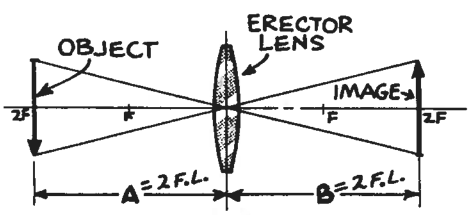
① Example - 2x ERECTING SYSTEM

② TWO WAYS TO APPLY ERECTOR MAGNIFICATION

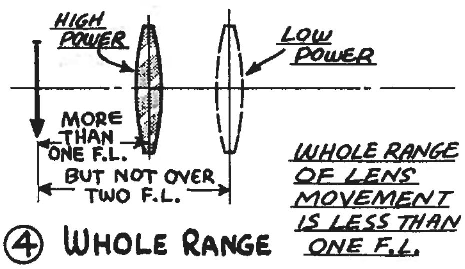
1. MULTIPLY F.L. OF OBJECTIVE BY ERECTOR M. TO GET E.F.L.
   Example (ABOVE): $12 \times 2 = 24''$ E.F.L.

OR

2. DIVIDE F.L. OF EYEPIECE BY ERECTOR M. TO GET E.F.L. OF ERECTING EYEPIECE
   Example: $\frac{2}{2} = 1''$ E.F.L.



③ UNIT MAGNIFICATION (1x)

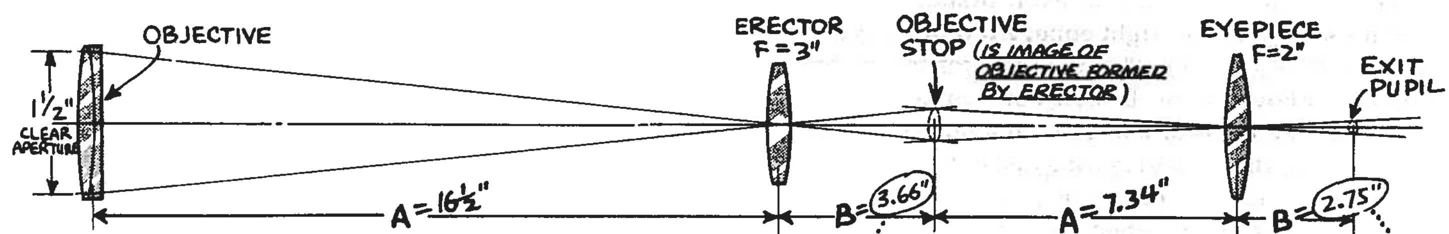


④ WHOLE RANGE

ERECTING Systems

AN ERECTOR lens erects the image. It can also magnify. Obviously it moves the image from one position to another position. From these varied functions, an erector lens is often called an amplifier lens, or a relay lens, or a transfer lens. Call it what you like, it is all one and the same optical system. The magnification factor can be applied to either the objective or eyepiece, Fig. 2, to get an equivalent focal length for the combination. Unit or 1x magnification is obtained when the erector lens is at a distance of two times its focal length from the object, Fig. 3. Of course, the "object" for an erector system is simply the image formed by the telescope objective. High M. is obtained by moving the lens closer to the object, Fig. 4.

ERECTOR ARITHMETIC. First, decide what magnification you want. It is then a simple matter to determine object and image positions, using Case 1 equations, which are repeated in Fig. 1 example. This is actually all you have to know. However, if you want to trace light rays through the system, you



Calculation - OBJECTIVE STOP POSITION and DIAMETER

A = 16.5"

F = 3"

$$B = \frac{F \times A}{A - F} = \frac{3 \times 16.5}{16.5 - 3} = \frac{49.5}{13.5} = 3.66''$$

$$M = \frac{B}{A} = \frac{3.66}{16.5} = .22\times$$

DIAMETER OF OBJECTIVE STOP $= 1.5 \times .22 = .33''$

⑤ SAME EXAMPLE AS FIG. 1

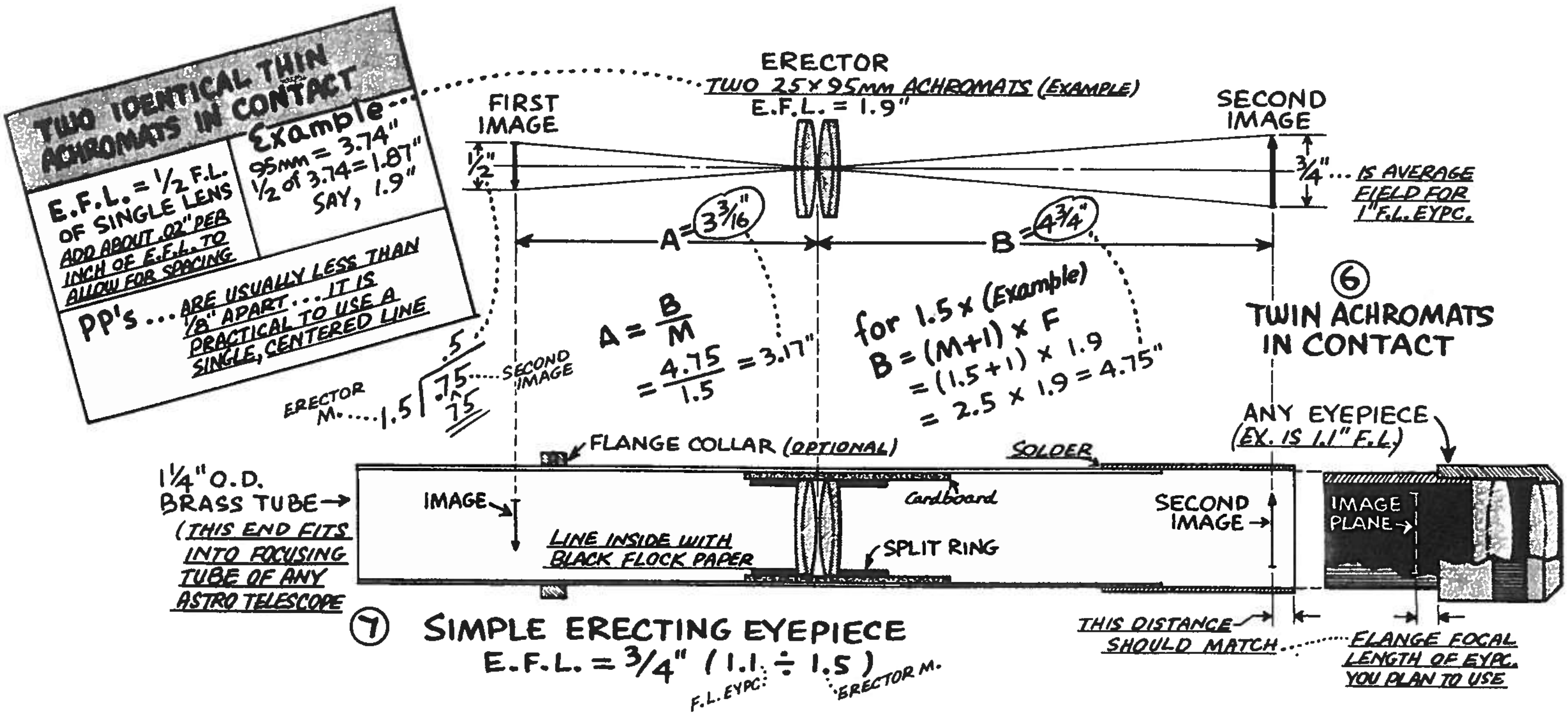
SAME Calculation FOR EXIT PUPIL

A = 7.34" F = 2"

$$B = \frac{F \times A}{A - F} = \frac{2 \times 7.34}{7.34 - 2} = \frac{14.68}{5.34} = 2.75''$$

$$M = \frac{B}{A} = \frac{2.75}{7.34} = .37\times$$

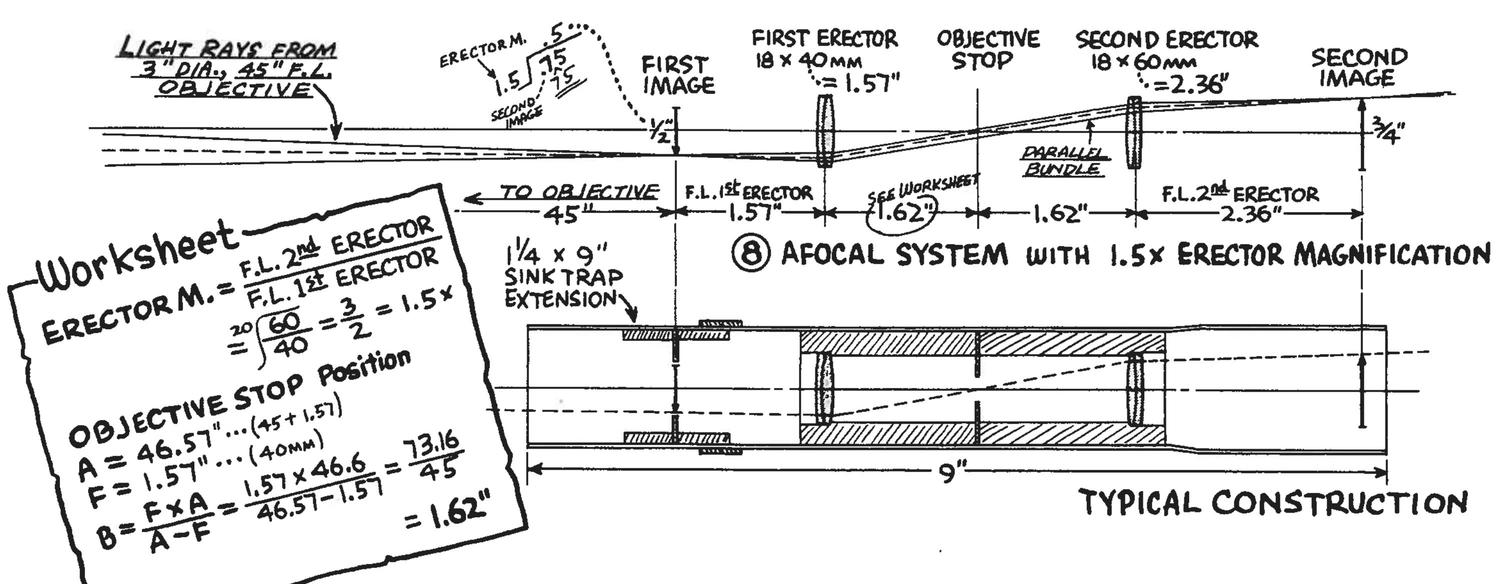
EXIT PUPIL DIAMETER $= .33 \times .37 = .122'' = \frac{1}{8}''$

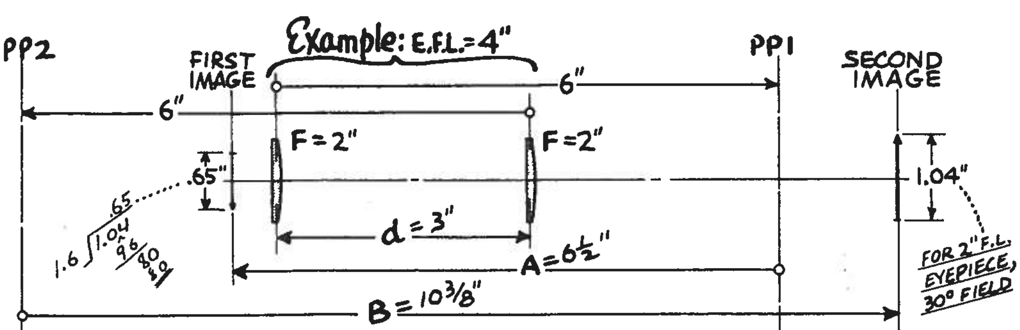


will have to locate the exit pupil. Looking at Fig. 5, you can see that objective and erector alone make up just like any ordinary astro telescope. What would be normally the exit pupil of such a combination now becomes the objective stop. This is a picture of the objective lens as seen by the erector lens. An actual physical stop is usually fitted at this point. The exit pupil of the whole instrument is the image of the objective stop as seen by the eyepiece. The simple arithmetical work is shown in Fig. 5. Note also in this diagram how a simple graphical trace can be used to determine diameters of both objective stop and exit pupil. If you are making a bench setup, no arithmetic is needed because all spacing and stop dimensions are picked off directly from the bench setup. However, it is always a good idea to run through the math work in order to become familiar with the procedure.

TWIN ACHROMATS. For good performance while retaining simple design and construction, a set of twin achromats in contact or nearly so is the most popular, practical erecting system, Fig. 6. The achromats range in diameter from 15 to 30 mm and in f.l. from 30 to 100mm. The odds are that a long focal length system will perform better than a short one, but at the same time it is desirable to keep the system as short as possible. 18x38mm is a nice size for erector lenses where maximum compactness is desired.

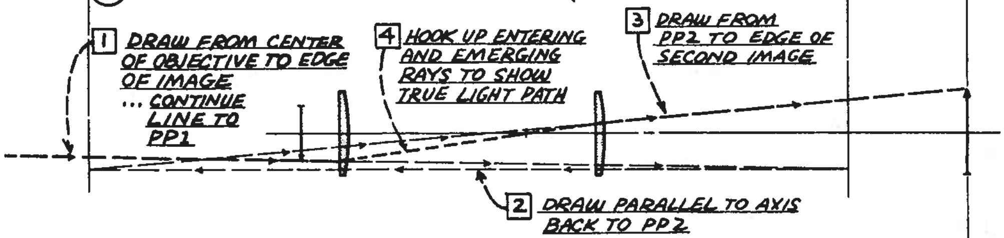
An erector tube for use with any astro telescope can be a very simple device, as shown in Fig. 7. You can improve on this by adding an objective stop, the location and size of which is determined as already described. A stop at the first image plane is often used. This is seen in sharp focus when you look through the whole erecting eyepiece.





General RULES	Example: 4" E.F.L.
F = ½ E.F.L. INDIVIDUAL LENS	F = ½ × 4 = 2"
E.F.L. = 2F	E.F.L. = 2×2 = 4"
d = 1½F	d = 1.5 × 2 = 3"
PP's = 3F ...ARE CROSSED	PP's = 3 × 2 = 6"

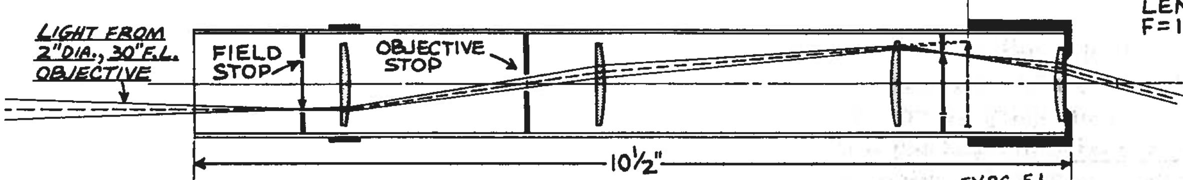
(9) SIMPLE LENS ERECTOR (*EX. IS 1.6×*)



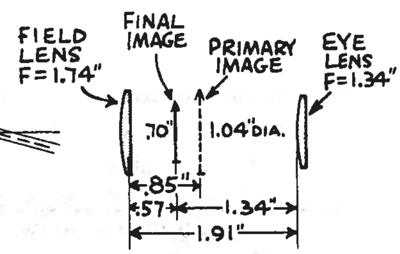
ERECTOR M. SHOULD BE BETWEEN 1X AND 1.8X
HIGHER M. WILL PUT FIRST IMAGE TOO CLOSE TO LENS

Calculate M. AS USUAL
Example IS 1.6X
B = (1.6+1) × 4 = 10.4"
A = 10.4 ÷ 1.6 = 6.5"
SET OFF THESE DISTANCES FROM PRINCIPAL PLANES, AS SHOWN

(10) *DRAWING THE LIGHT RAYS* (*PRINCIPAL RAY ONLY IS SHOWN TO AVOID A CONFUSION OF LINES*)



(11) WHOLE ERECTING EYEPIECE WITH 2" F.L. HUYGENS (E.F.L. = $\frac{2}{1.6}$ = 1.25") — 2 = EYPC. F.L., 1.6 = ERECTOR M.



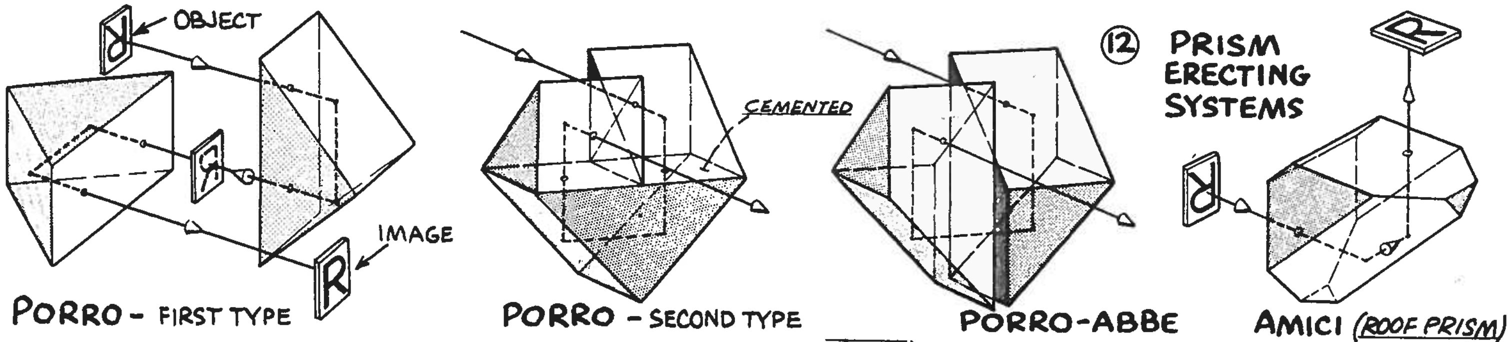
2" F.L. HUYGENS (*1.3 RATIO*) *1.3 TO 1*

THE AFOCAL SYSTEM. This uses two achromats, but of different focal lengths. Each is used in the afocal position, that is, at its own focal length from the respective image. Magnification is obtained by the difference in focal lengths, Fig. 8. A system like this is usually wide-spaced. Since the light emerging from the first erector is parallel, the space between first and second erector is free optical space which can be varied as desired without changing the power of the system. A practical minimum spacing is obtained when the objective stop is located on the surface of the second erector. The practical maximum spacing locates the objective stop midway between the two erectors, as shown.

SIMPLE LENS ERECTOR. Fig. 9 shows an example and gives simple rules for making an inexpensive erector from two identical plano-convex lenses. Light rays can be traced through the system lens by lens, but the more practical way is to treat the two lenses as a single unit with symmetrical, crossed principal planes, as shown in Fig. 10.

Traditionally, the eyepiece for a simple lens erector is a Huygens. This is lower ratio and wider spacing than normal, both departures arising from the fact that the "object" for the eyepiece now becomes the objective stop instead of the objective itself. Huygens eyepieces made for microscope use are suitable since the working conditions are quite similar. Specifications for a suitable 2 inch f.l. Huygens for use with an erecting system are given in Fig. 11. You can scale this up or down as desired by dividing the desired new e.f.l. or lens f.l. by the similar specification given. This gives a factor which is then applied to all of the specifications given. This process is illustrated in the chapter dealing with eyepieces.

PRISM ERECTORS. The most practical way to handle prisms in telescope design is by the "equivalent air block" method. Fig. 13 explains. If you compare the position of the image plane of an objective with and without prisms, you will find the prism setup forms an image closer to the objective than when the objective is used alone. The difference can be taken as the air equivalent of the prisms--it is approximately two-thirds of the glass path through the prisms. More exactly, the equivalent air path is the glass path divided by the index of refraction of the prisms. If you don't know the refractive index you can approxi-

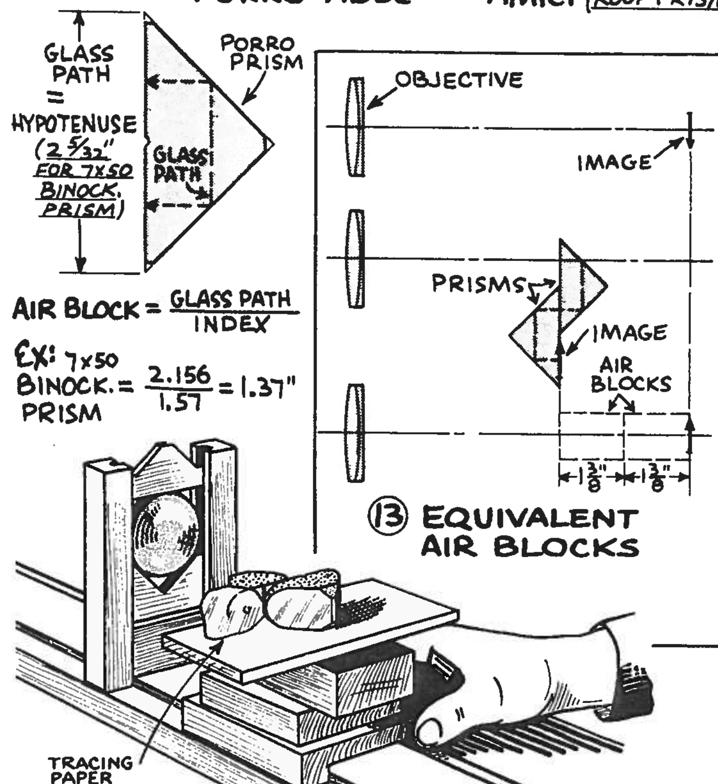


(12) PRISM ERECTING SYSTEMS

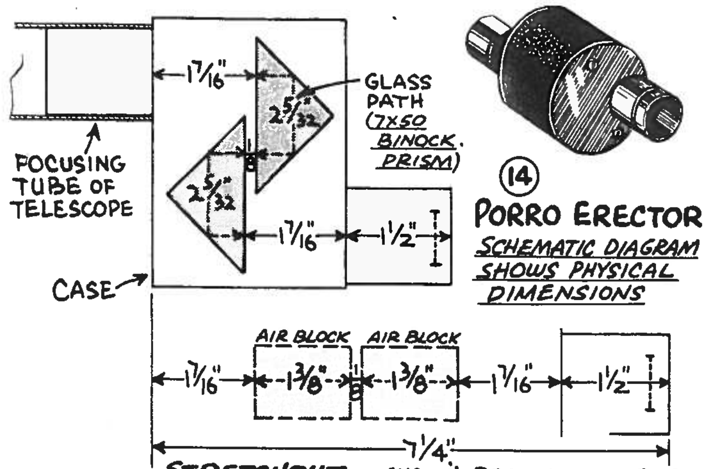
mate by the two-thirds rule, or you can determine air blocks exactly by making the simple bench test shown. The glass path itself of any prism is easily determined from a full-size drawing of the prism. Often the corners of a prism are cut off. When you are making a drawing, the corners should be restored to obtain the full side or hypotenuse from which the glass path is determined.

To design a prism erector attachment for an astro telescope, you start by making a full-size schematic diagram of the system, Fig. 14. This is then redrawn in stretchout form, substituting air blocks for the glass path. Measuring this final diagram will show the amount of "in" focusing movement needed. It is excessive for a Porro system of the first type, being a whopping 7-1/4 inches for the example shown, which is an actual commercial product. You can shorten the eyepiece tube on this to about 1 inch and otherwise "squeeze" the assembly to cut the focusing movement to about 6 inches. If you use a special eyepiece mounted in 7/8 in. diameter tube, it can be worked alongside the prism, eliminating the projecting eye tube completely. The second type of Porro prism is more compact--4-3/4 inches using the same-size prisms and mechanical dimensions. The Porro-Abbe is about the same. A roof prism is treated as a simple right angle prism of the same overall size; this takes less than 3 in. "in" movement, although some of the gain comes from the fact that a roof prism with overall size equal to a right angle prism will be about 25% less in face width.

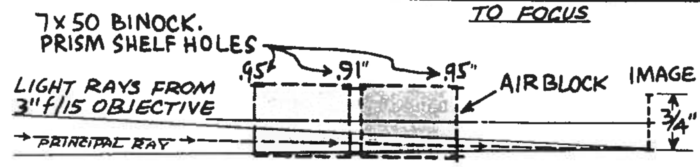
To see how the prisms field the light cone, you simply draw them into the system as air blocks, Fig. 15. The width of the air block is the actual face width of the prism; the length is calculated as already described. For most applications, 50% edge-of-field lighting is satisfactory, meaning that if you can get the principal ray through the prisms, the lighting will be okay. Optically, the effect of prisms is the same as a thick piece of glass with parallel surfaces. Such a glass block has optical characteristics similar to a weak negative lens.



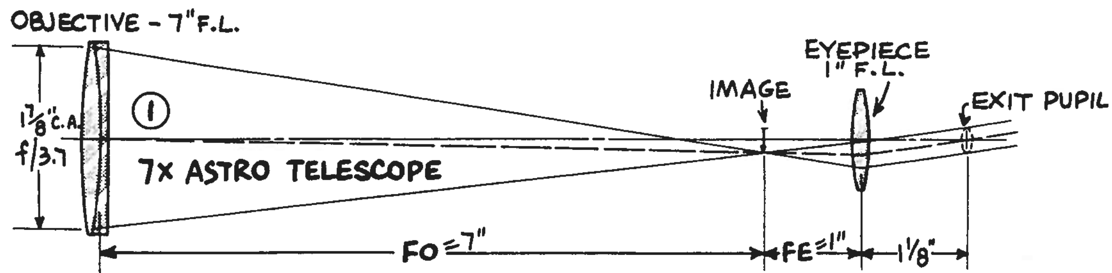
(13) EQUIVALENT AIR BLOCKS

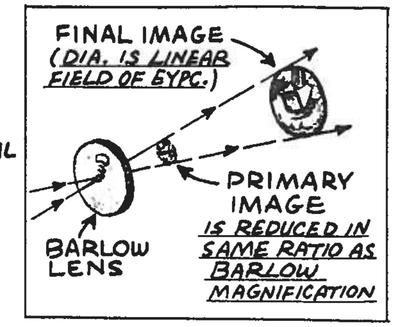


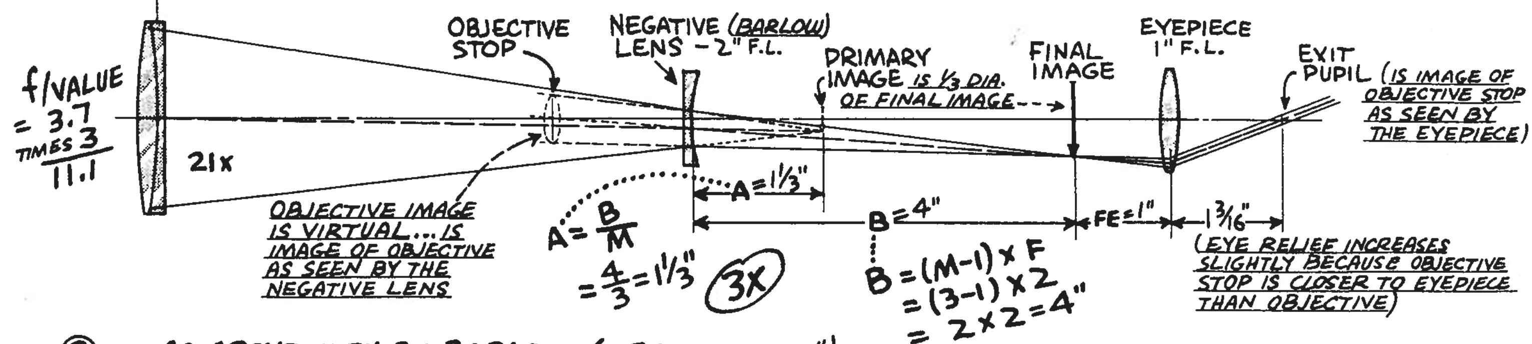
(14) PORRO ERECTOR
SCHEMATIC DIAGRAM SHOWS PHYSICAL DIMENSIONS



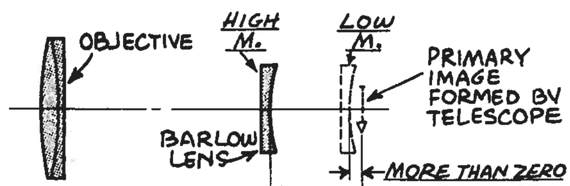
(15) LIGHT PATH - PRISMS SHOULD PASS AT LEAST THE PRINCIPAL RAY. Example SHOWS WHOLE CONE GETS THRU



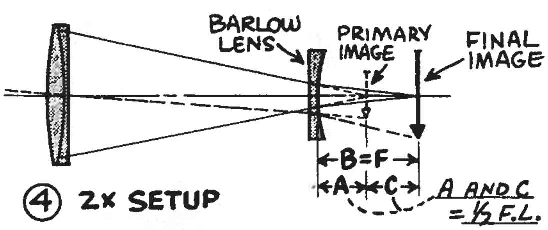




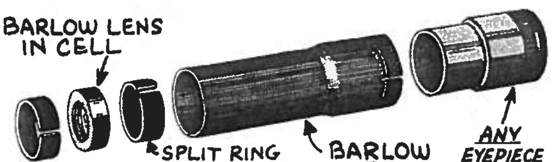
② ... AS ABOVE WITH 3X BARLOW (E.F.L. = 7 x 3 = 21")



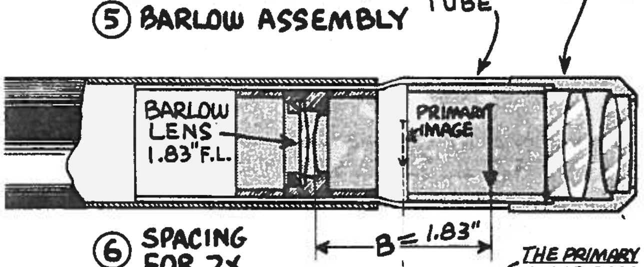
③ POSITION OF BARLOW LENS



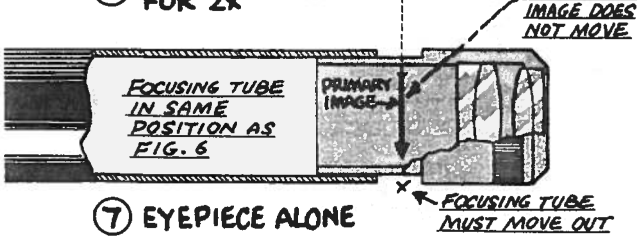
④ 2X SETUP



⑤ BARLOW ASSEMBLY



⑥ SPACING FOR 2X



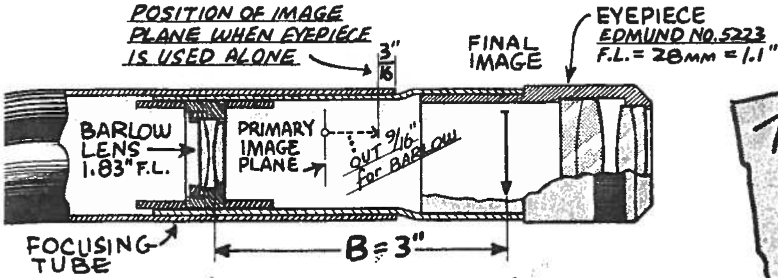
⑦ EYEPIECE ALONE

the BARLOW Lens

A BARLOW lens is a negative lens used inside the focal plane of a telescope objective. Its normal diverging action reduces the convergence of the light cone, forming a larger image at a slightly greater distance. All Barlow lenses are designed for a certain magnification factor--usually 2x--but work well over a moderate range of powers.

TYPICAL BARLOW SYSTEM. A drawing of a Barlow system begins with the usual light rays from objective to image, except, knowing the Barlow will enlarge the primary image, you make it just that much smaller, Fig. 1. A and B spacing distances are then calculated for the desired magnification, using Case 5 equations. The linear field of eyepiece is set off at the final image plane, and the light ray intercepts are extended from the Barlow lens to edge of final image, Fig. 2. If you want to locate the objective stop, it can be done graphically by extending the light rays backwards, as shown in Fig. 2. As can be seen, the objective stop is a virtual image; if calculated, you use Case 3 equations. The position of objective stop must be known if you want to calculate (Case 1) the exit pupil position. In most cases, only the A and B spacing distances are needed. Glare stops can be fitted anywhere along the light cone.

FOCUSING MOVEMENT. Normally a Barlow setup requires "out" movement of the focusing tube. A goodly amount of "out" movement is supplied by the Barlow tube itself, Fig. 5. The net result is that "in" movement of the focusing tube is needed for the popular 2x setup, Fig. 6. Fig. 7 illustrates in reverse fashion--with eyepiece alone



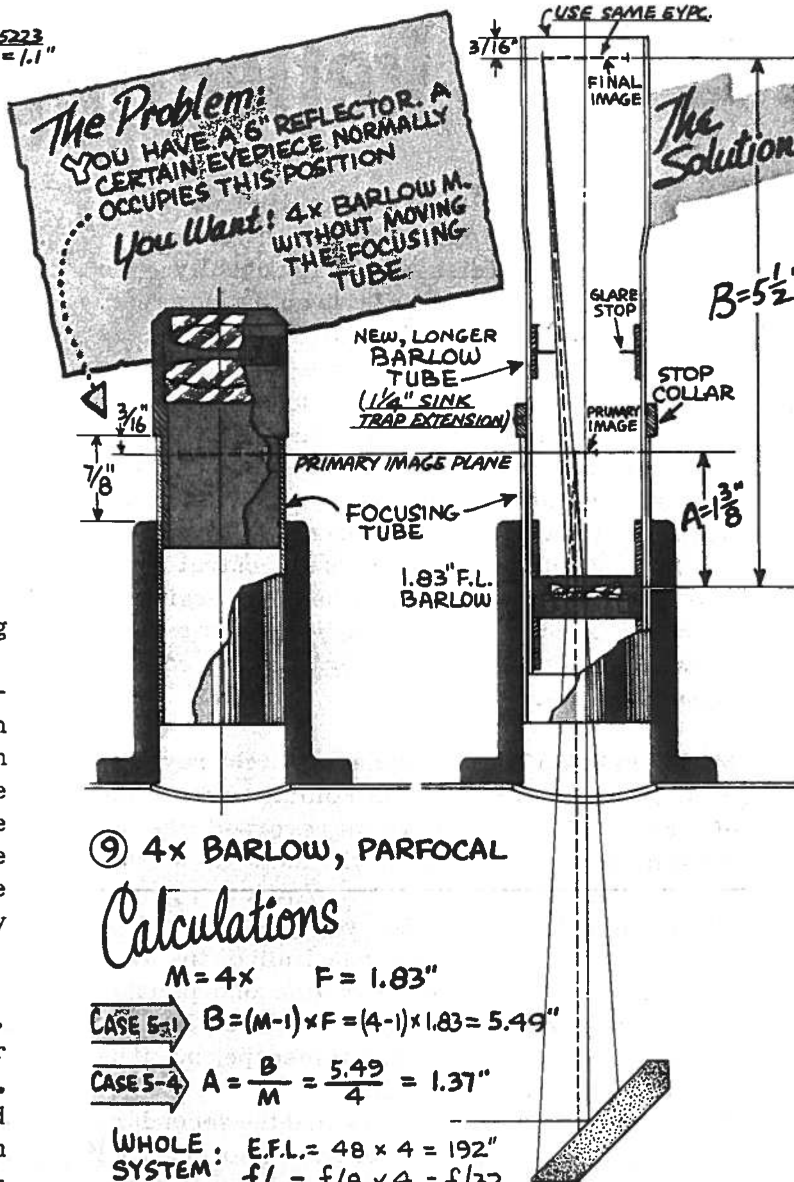
CASE 5 - NO. 9 $M = \frac{3 + 1.83}{1.83} = \frac{4.83}{1.83} = 2.64\times$

CASE 5 - NO. 4 $A = \frac{B}{M} = \frac{3}{2.64} = 1.14" = 1\frac{1}{8}"+$

(8) MAXIMUM M. - EXAMPLE IS EDMUND NO. 40-477 BARLOW and NO. 5223 EYEPIECE

IF M. IS APPLIED TO EYEPIECE:

$$\frac{FE}{M} = \frac{1.1}{2.6} = .4" \text{E.F.L.}$$



(9) 4x BARLOW, PARFOCAL

Calculations

$M = 4\times \quad F = 1.83"$

CASE 5-1 $B = (M-1) \times F = (4-1) \times 1.83 = 5.49"$

CASE 5-4 $A = \frac{B}{M} = \frac{5.49}{4} = 1.37"$

WHOLE SYSTEM: E.F.L. = 48 × 4 = 192"; f/ = f/8 × 4 = f/32

you have to focus "out" about 1/2 inch, indicating that the Barlow setup itself must focus "in."

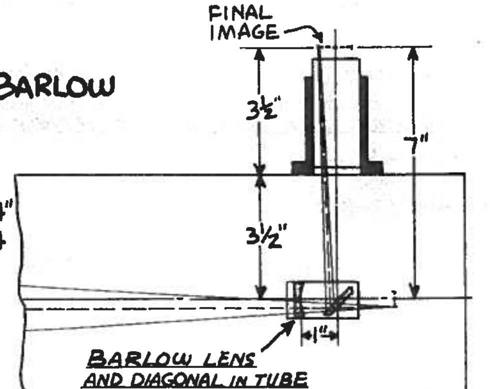
Increased M. pushes the image back and requires more "out" movement. The maximum case for the equipment specified is shown in Fig. 8. This takes actual "out" movement of the focusing tube. To determine the focusing tube movement on a drawing like this, you measure from primary image plane to the position the focal plane of the eyepiece would normally occupy if used alone.

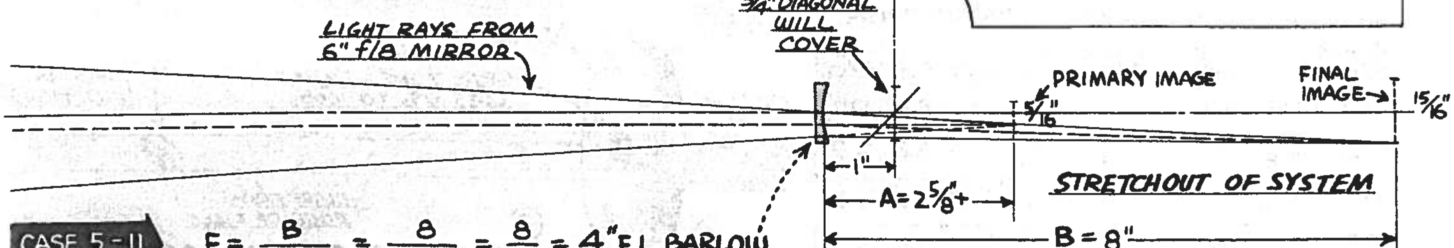
SPECIAL SETUPS. The parfocal Barlow, Fig. 9, has the same focus for either eyepiece alone or with Barlow--the focusing tube does not move. For this kind of setup, you simply space A and B distances from the primary image plane, which is made coincident with the focal plane of the eyepiece used alone.

A Barlow system is sometimes built-in as a permanent part of a telescope. Fig. 10 is an example. Because the diagonal is close to the primary image, which itself is reduced in size, it is possible to field the full light cone of an f/8 mirror with a 3/4 inch diagonal. For the arrangement shown, spacing distance B is fixed at about 8 in. You select some suitable magnification and then calculate F as shown. A good-quality simple plano-concave lens of the specified focal length will usually perform quite well.

(10) BUILT-IN BARLOW
$M = 3\times$

WHOLE SYSTEM:
E.F.L. = 48 × 3 = 144"
f/ = f/8 × 3 = f/24





CASE 5 - 11 $F = \frac{B}{M-1} = \frac{8}{3-1} = \frac{8}{2} = 4"$ F.L. BARLOW

Reflecting TELESCOPES

A REFLECTING telescope uses mirror optics instead of lenses. A big advantage is that a mirror reflects all wavelengths of light equally--you have no problem at all with false color. However, the other axial fault--spherical aberration --is still there, and, with the single surface of the mirror, can only be corrected by making the mirror surface aspheric (not spherical). The aspheric curves used are the ellipse, parabola and hyperbola. The familiar sphere is also used. In all cases, the focal length of a mirror of any shape is 1/2 the radius of curvature of its central zone. Like lenses, mirrors are either converging or diverging. A converging (positive) mirror has a concave shape; a diverging (negative) mirror has a convex shape.

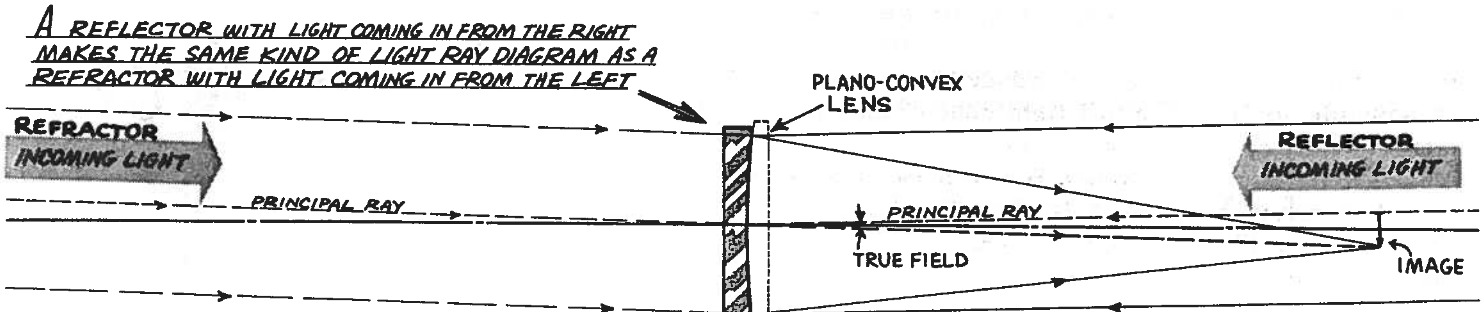
IMAGE FORMATION. Normally a light ray diagram is made with the light coming in from the left, but if this procedure is reversed, the net performance of a mirror is the same as a lens, Fig. 1. The light cone from a point object at edge of field is the only one you need draw. The outer ray of this cone defines the limit of the useful light. The principal ray (the one passing through the center of the objective) never actually gets through in a reflecting telescope, but it is no less useful as a guide line.

A common rule of thumb is that the secondary flat for a Newtonian reflector should not obstruct more than 6% of the incoming light. Some additional light is lost in a gray zone about twice the diameter of the diagonal silhouette, Fig. 2. In compound telescopes with secondary mirror, the obstruction may be as large as one-half the primary diameter, resulting in a light loss of 25%.

NEWTONIAN REFLECTOR. The manner of making a layout for a Newtonian reflector is shown in Fig. 3. Steps 1 to 5 are obvious. Step 6 requires the selection of some practical image size, which can be 3/4 in. for any telescope, although the example shown is somewhat larger. The edge-of-field light cone misses the diagonal slightly, Step 10. This is fairly standard practice, but the lighting should not fall below 50%. Step 11 shows that about 70% of the objective diameter contributes light to the edge of field. You will want to know what size image gets 100% lighting, and this is revealed by Step 12.

A final check is to see that the incoming light clears the main tube. Steps 15, 16 and 17 show that it does, even as far out as 6-3/4 in. from the eyepiece centerline. However, to assure adequate clearance, the front tube projection is usually trimmed to 3-1/2 or 4 in. as shown.

COMPOUND TELESCOPES. All astro telescopes are compound optical instruments in the sense that an enlarged image is formed by the objective and this image is further enlarged by the eyepiece. However, the accepted meaning of a compound telescope indicates an instrument with a built-in secondary optical system which en-

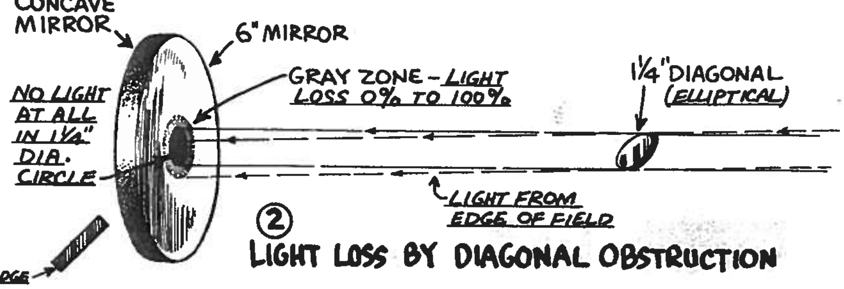


① IMAGE FORMATION BY REFLECTION

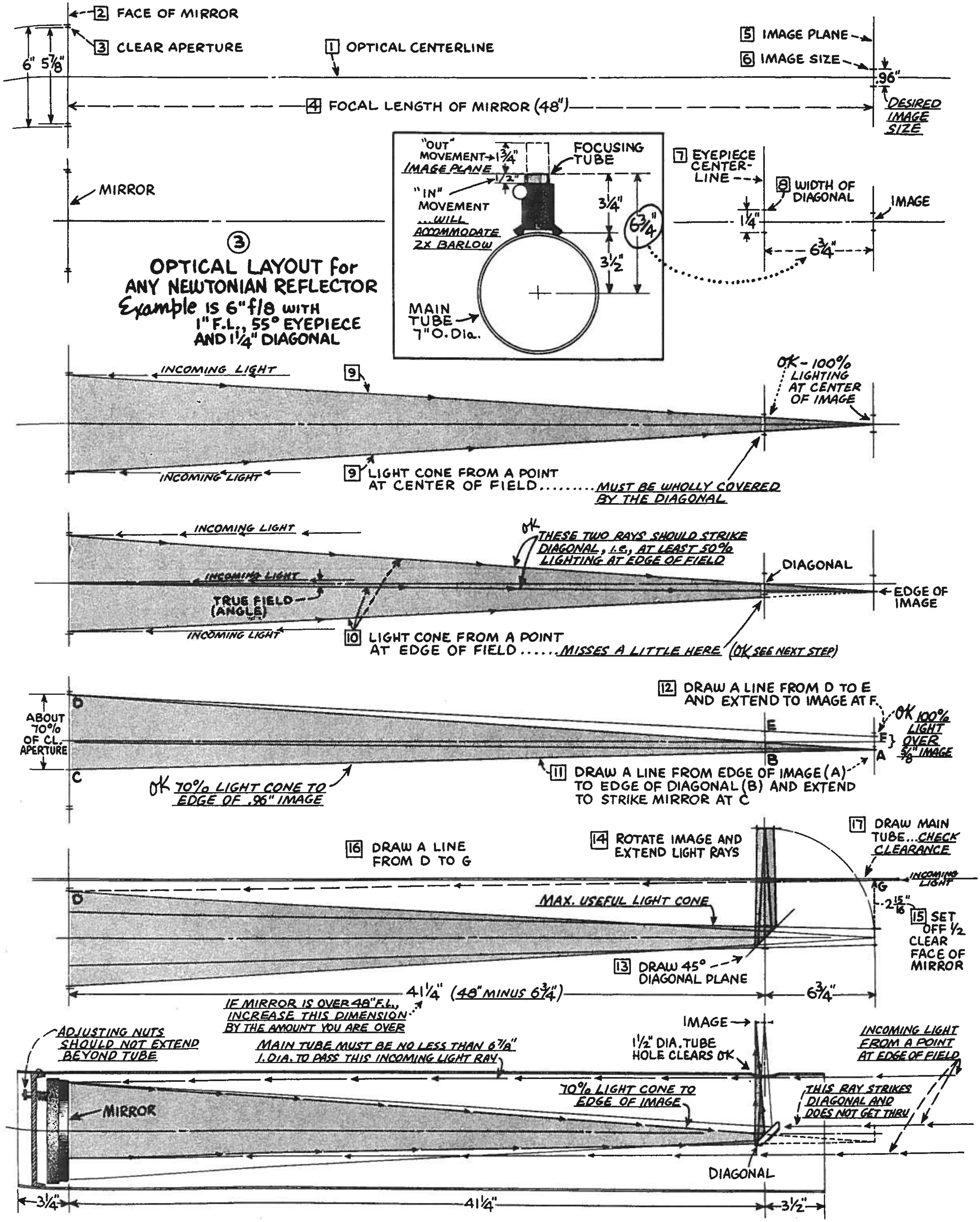
LIGHT LOSS BY DIAGONAL OBSTRUCTION

MIRROR NAME DIA.	MIRROR C.A.	MIRROR AREA	USUAL DIAG.	LOSS-Sq. In. ELL.	LOSS-Sq. In. RECT.	LOSS-% ELL.	LOSS-% RECT.
3"	2 7/8"	6.49 SQ. IN	7/8" WIDE	.60 SQ. IN	.87 SQ. IN	8.8%	12%
4 1/4"	4 1/8	13.36	1 1/16	.87	1.30	6.6	9.9
6"	5 7/8	27.11	1 1/4	1.23	1.89	4.5	7.0
8"	7 7/8	48.71	1 1/2	1.77	2.64	3.6	5.4

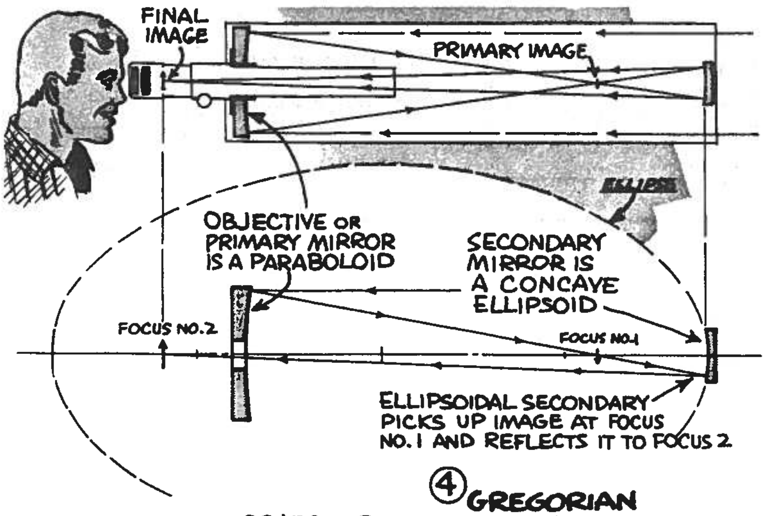
ELL.-ELLIPTICAL SHAPE RECT.-RECTANGULAR, LOSS INCLUDES EDGE



② LIGHT LOSS BY DIAGONAL OBSTRUCTION



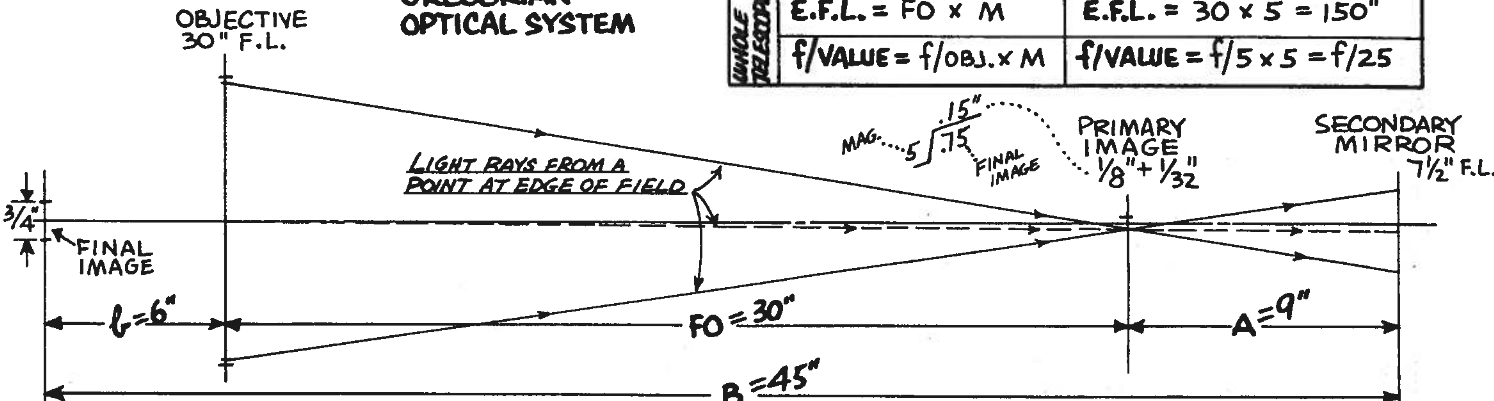
2 FACE OF MIRROR
3 CLEAR APERTURE
1 OPTICAL CENTERLINE
5 IMAGE PLANE
6 IMAGE SIZE
6" 5⅞"
.96"
DESIRED IMAGE SIZE
4 FOCAL LENGTH OF MIRROR (48")
MIRROR
"OUT" MOVEMENT 1¾"
IMAGE PLANE
½"
"IN" MOVEMENT ...WILL ACCOMMODATE 2X BARLOW
FOCUSING TUBE
3¼"
3½"
6¾"
MAIN TUBE 7" O. Dia.
7 EYEPIECE CENTER-LINE
8 WIDTH OF DIAGONAL
1¼"
IMAGE
6¾"
3
OPTICAL LAYOUT for ANY NEWTONIAN REFLECTOR
Example is 6" f/8 with 1" F.L., 55° EYEPIECE AND 1¼" DIAGONAL
INCOMING LIGHT
9
OK - 100% LIGHTING AT CENTER OF IMAGE
9 LIGHT CONE FROM A POINT AT CENTER OF FIELD.........MUST BE WHOLLY COVERED BY THE DIAGONAL
INCOMING LIGHT
OK THESE TWO RAYS SHOULD STRIKE DIAGONAL, i.e., AT LEAST 50% LIGHTING AT EDGE OF FIELD
DIAGONAL
TRUE FIELD (ANGLE)
EDGE OF IMAGE
10 LIGHT CONE FROM A POINT AT EDGE OF FIELD......MISSES A LITTLE HERE (OK SEE NEXT STEP)
12 DRAW A LINE FROM D TO E AND EXTEND TO IMAGE AT F.
OK 100% LIGHT OVER ⅜" IMAGE
ABOUT 70% OF CL. APERTURE
D
C
E
B
F
A
OK 70% LIGHT CONE TO EDGE OF .96" IMAGE
11 DRAW A LINE FROM EDGE OF IMAGE (A) TO EDGE OF DIAGONAL (B) AND EXTEND TO STRIKE MIRROR AT C
16 DRAW A LINE FROM D TO G
14 ROTATE IMAGE AND EXTEND LIGHT RAYS
17 DRAW MAIN TUBE...CHECK CLEARANCE
INCOMING LIGHT
G
2 15/16"
15 SET OFF ½ CLEAR FACE OF MIRROR
MAX. USEFUL LIGHT CONE
13 DRAW 45° DIAGONAL PLANE
41¼" (48" MINUS 6¾")
6¾"
IF MIRROR IS OVER 48" F.L., INCREASE THIS DIMENSION BY THE AMOUNT YOU ARE OVER
ADJUSTING NUTS SHOULD NOT EXTEND BEYOND TUBE
MAIN TUBE MUST BE NO LESS THAN 6⅞" I.DIA. TO PASS THIS INCOMING LIGHT RAY
IMAGE
1½" DIA. TUBE HOLE CLEARS OK
INCOMING LIGHT FROM A POINT AT EDGE OF FIELD
MIRROR
70% LIGHT CONE TO EDGE OF IMAGE
THIS RAY STRIKES DIAGONAL AND DOES NOT GET THRU
DIAGONAL
3¼"
41¼"
3½"



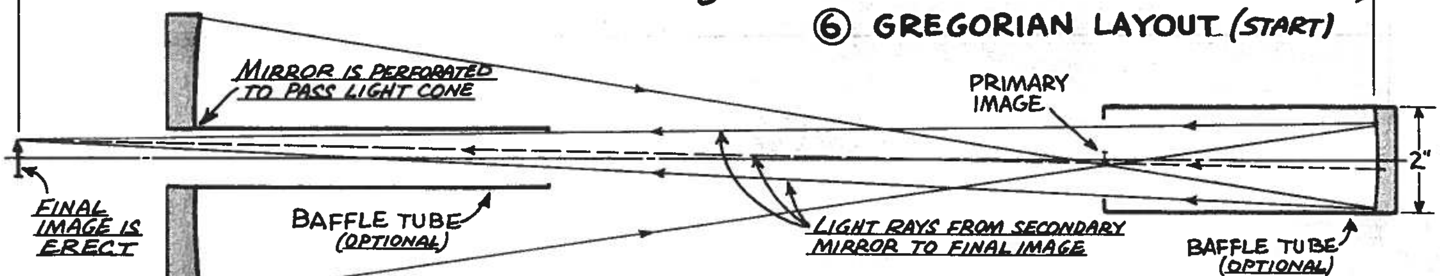
④ GREGORIAN OPTICAL SYSTEM

⑤ HOW TO *Calculate* A GREGORIAN

You Specify	**OBJECTIVE MIRROR** ANY DIA., 3" AND UP USUALLY LOW f/- f/5 TO f/8	**Example** (DRAWING BELOW) 6" DIA., 30" F.L. = f/5
	M. M. OF SECONDARY USUALLY 4X TO 6X	5×
	ℓ IMAGE DISTANCE BEHIND OBJECTIVE	6" THIS ALLOWS "IN" TRAVEL FOR A STAR DIAGONAL
You Calculate	GREGORIAN $A = \frac{F+\ell}{M-1}$	$\frac{30+6}{5-1} = \frac{36}{4} = 9"$
	CASE 1, NO. 3 $B = A \times M$	$9 \times 5 = 45"$ B WILL BE SELF-EVIDENT FROM DRAWING
	CASE 1, NO. 11 SECONDARY $F = \frac{B}{M+1}$	$\frac{45}{5+1} = \frac{45}{6} = 7\frac{1}{2}"$ (=15" radius)
WHOLE TELESCOPE	E.F.L. = FO × M	E.F.L. = 30 × 5 = 150"
	f/VALUE = f/OBJ. × M	f/VALUE = f/5 × 5 = f/25



⑥ GREGORIAN LAYOUT (START)



⑦ COMPLETE GREGORIAN LAYOUT

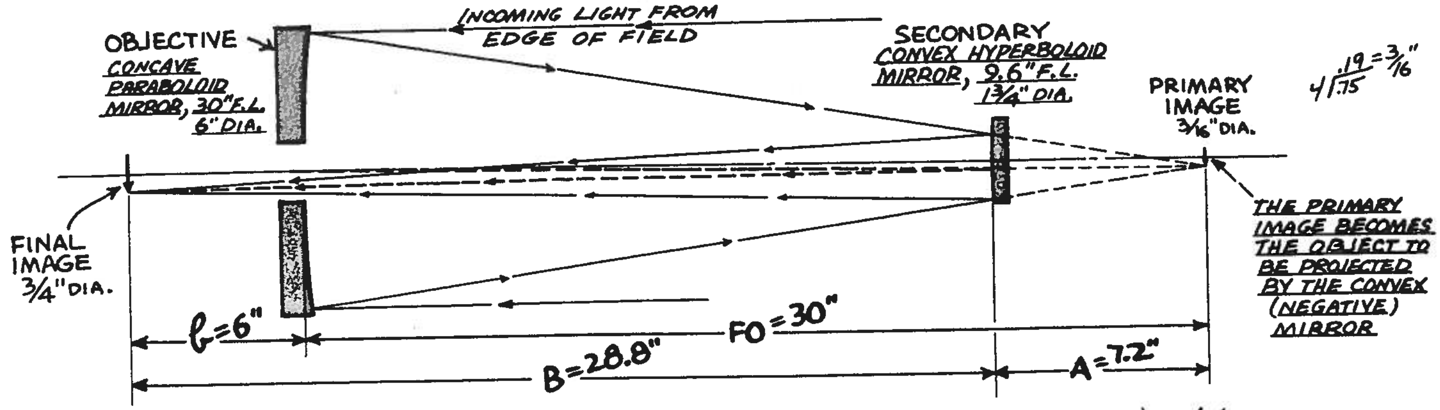
larges the primary image. So defined, a Newtonian is a simple reflector rather than a compound one. The Gregorian and the Cassegrain are the two basic compound reflectors.

The GREGORIAN reflector makes use of positive projection to erect and enlarge the primary image. The primary image itself is formed by a paraboloidal mirror. This image is then magnified and erected by a concave ellipsoidal mirror, Fig. 4. The optical nature of an ellipsoidal mirror is such that a light ray passing through one of the conjugate foci is reflected without aberration to the other. As shown in the drawing, one foci is made to coincide with the focal plane of the objective; the other coincides with the final image.

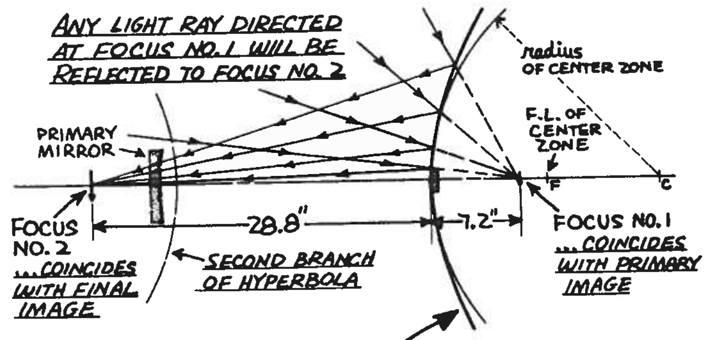
You can calculate a variety of Gregorian telescopes by the simple rules given in Fig. 5. However, if you try to make a low-power design, such as 2x, you will find that the long throw and large secondary mirror will make the design impractical. A performance fault is that stray light can barrel right down the main tube and into the eyepiece. If you want to use a Gregorian for daytime observing, you must use baffle tubes to limit the light rays to exactly that cone of light which contributes to the image.

As usual, you start the layout by drawing the edge-of-field light cone from objective to primary image, Fig. 6, extending the rays to strike the secondary mirror. The intercepts at the surface of the secondary mirror are then hooked up with the final image, Fig. 7, to complete the layout of the optical system. As usual, only one side of the light cone need be drawn; the outer ray of this is your guide for glare stops or baffle tubes.

A CASSEGRAIN telescope shows the usual inverted astro image. This system is more compact than the Gregorian. If you understand the Barlow lens, it is easy to visualize the Cassegrain



⑧ CASSEGRAIN OPTICAL SYSTEM – 4X EXAMPLE



⑨ CONVEX HYPERBOLOID

as being a similar system done with mirrors. All calculations are the same as for a Barlow (Case 5) except you need one preliminary equation to include distance b, which is image distance behind the primary mirror. This is given in Fig. 10, together with the two Case 5 equations needed to complete the math work.

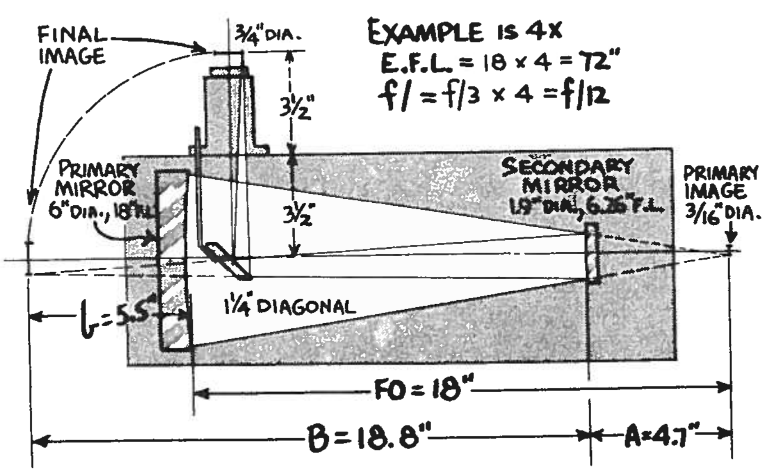
The drawing of a Cassegrain system is quite simple after you have determined the spacing. As usual, a cone of light is drawn to the edge of the primary image. At the points where these rays cut the surface of the secondary mirror, the rays are reversed and drawn to the edge of the final image, Fig. 8. The outer ray of the light cone is your guide for all diameters along the light cone; it tells you how big to make the secondary mirror, hole in primary, glare stops, etc. Like the Gregorian, the Cass needs glare stops or a baffle tube to stop stray light.

Like any mirror, the hyperbolic secondary may be used at various object-image positions, but it has one specific set of conjugate foci that give perfect imagery without spherical aberration. This pair of stigmatic foci are made to coincide with the positions of the primary and final images, as can be seen in Figs. 8 and 9. The foci should not be confused with the focal length of the mirror, which is, as usual, one-half the radius of the center zone.

Both the Gregorian and Cass can be built with unperforated primary mirrors. Amateurs often favor this construction to get around the sometimes difficult job of cutting a hole in the primary. Fig. 11 shows a typical unperforated Cassegrain. The right-angle bend in the light cone can be handled with the diagonal and mechanical parts used for a Newtonian reflector. The bend in the light cone serves also as a light baffle. It also erects the image but leaves it reversed left to right. The Cass requires good optics and the beginner should not tackle this work until he has completed the simpler Newtonian reflector.

⑩ HOW TO Calculate A CASSEGRAIN

			Example: (DRAWING ABOVE)
You Specify	OBJECTIVE MIRROR	ANY DIA., 3" and UP, USUALLY LOW f/–f/2 to f/6	6" DIA., 30" F.L. = f/5
	M.	M. OF SECONDARY 2X TO 6X	4X
	b	IMAGE DISTANCE BEHIND OBJECTIVE	6"
You Calculate	CASS	$A = \frac{F+b}{M+1}$	$\frac{30+6}{4+1} = \frac{36}{5} = 7.2"$
		$B = A \times M$	$7.2 \times 4 = 28.8"$
	SECONDARY	$F = \frac{B}{M-1}$	$\frac{28.8}{4-1} = \frac{28.8}{3} = 9.6"$ F.L.
WHOLE TELESCOPE	E.F.L.	= FO × M	E.F.L. = 30 × 4 = 120"
	f/VALUE	= f/OBJ. × M	f/VALUE = f/5 × 4 = f/20



⑪ CASSEGRAIN with UNPERFORATED PRIMARY

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