SOME OPTICAL ASPECTS OF COPYING CAMERAS*

Reynold E. Ask
Photogrammetric Engineer, U. S. Coast and Geodetic Survey

EDITOR'S NOTE: The optical data presented in this article will apply chiefly to precision copying cameras which are used for such work as map reproduction. Many of the principles discussed, however, will apply equally well to several types of photogrammetric instruments such as reflecting map projectors, multiplex equipment, and certain transforming apparatus.

Some remarks are included concerning the following materials used for making mirrors; speculum metal, silvered glass, evaporated reflecting films, stellite and stainless steel. This information may be of value to those interested in mirror stereoscopes, reflecting map projectors, etc.

THE optical data presented in this article will apply chiefly to precision copying cameras which are used for such work as map reproduction, accurate color registration, etc. Regardless of how perfectly a process camera is constructed mechanically, it will produce accurate negatives only if it is equipped with an optical system of high quality. The first subject to be considered will be lens characteristics, this to be followed by a discussion of conjugate focal distances, lens tests, prisms and mirrors, and errors caused by glass plates.

Photographic lenses are designed for specific types of work. Lenses used in copying, commonly called process lenses, differ from those used in other photographic work. The more important characteristics of process lenses include the following:

(1) Lenses are designed for finite object distance.

(2) Large relative apertures are rather unusual, seldom being larger than f/8.

(3) Angular field is usually rather small, ranging from 30 to 50 deg.

(4) Lenses must be free from distortion for the desired finite object distances. The allowable amount of distortion depends on the type of process work being performed and each case must be considered individually. It is also desirable to mention that the distortion has a different value for each scale ratio.

(5) Lenses must give excellent definition. This is secured by limitation to a small relative aperture and a small angular field. To obtain good definition it is necessary that the image field of the lens be flat.

(6) Optical design is usually symmetrical. At a scale ratio of unity, with a perfectly symmetrical lens, there will be no distortion. In case an unsymmetrical lens is used it is desirable that the front (engraved side) of the lens be on the side having the greater conjugate distance.

(7) Lenses must be highly corrected for color if multi-color work is to be done. Lenses with such a correction are termed apochromats.

CONJUGATE FOCAL DISTANCES

The object distance (lens to copy) and the image distance (lens to negative) are known in optics as conjugate distances (see Fig. 1). The values of these distances can be computed from two very simple formulas:

$$\text{Object distance} = F + F/M \tag{1}$$

$$\text{Image distance} = F + FM \tag{2}$$

in which F is the quivalent focal length of the lens and M is the magnification or scale ratio. For a reduction in copy size M is less than one; and for an enlarge-

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ment, greater than one. The object and image distances as computed from the above formulas are not measured from the center of the lens but from the front and rear nodal points respectively, which usually are very close to the center. The separation, S, of these nodal points (N and N^1) does not enter into the computation of the conjugate distances, but must be considered in computing the exact distance from copy to negative, if such a distance is needed for camera design or calibration purposes. It should also be noted that the nodal points occasionally overlap, that is, they are reversed in position as shown by the dotted lines in the upper part of Fig. 1. The nodal points are sometimes referred

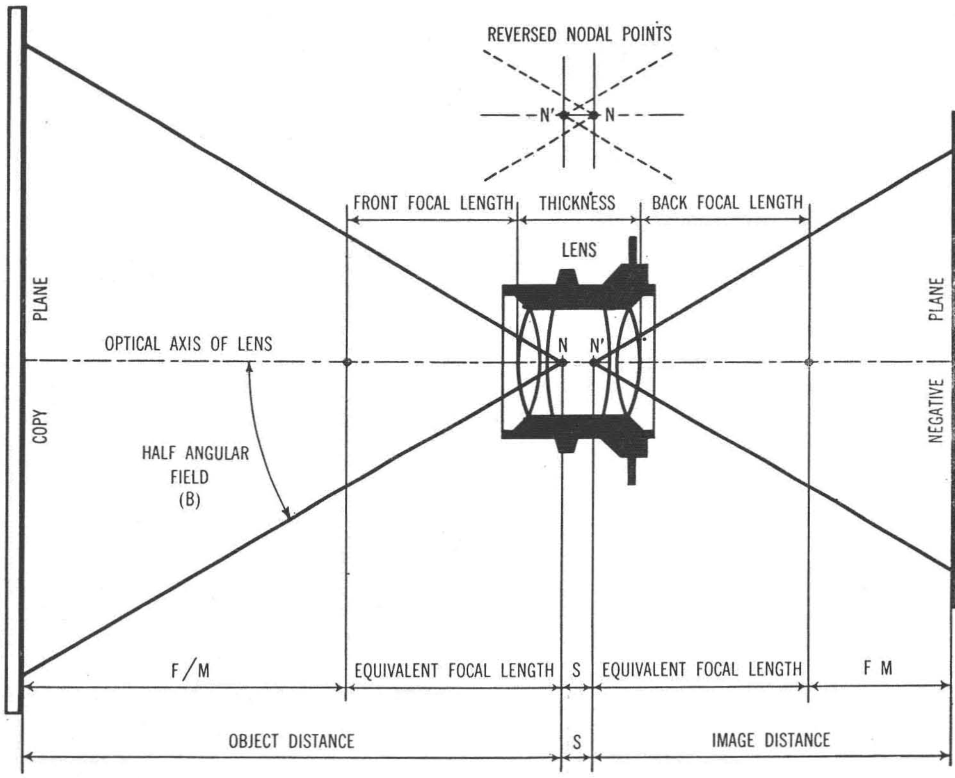

FIG. 1. Diagram of optical system of a typical photographic objective, showing important optical dimensions and relation between subject and image planes.

to as principal points; the two designations can be considered identical in the present discussion. The front and back focal lengths shown in Fig. 1 are used when it is necessary to compute the distance of image or object from the lens vertex. The back and front focal lengths are equal only in case of perfectly symmetrical lens. Also shown are the two distances F/M and FM; these are sometimes termed the "extra-focal distances." It will be noted that their product equals F^2. It is desirable to mention here that the focal length engraved on the lens is only a nominal value. For an accurate determination of focal lengths and nodal point separation the lens must be tested in an optical laboratory.

In regards to lens aperture it can be stated that the effective aperture for any scale ratio, M, can be found by multiplying the relative aperture as engraved on the lens by the quantity $(M+1)$. If an exposure meter is used in copying work it is necessary to multiply the exposure as indicated on the meter by the quantity $(M+1)^2$ to obtain the correct exposure.

Lens Tests

The cost of process lenses depends both on the focal length and upon the degree of optical perfection desired. Since this cost is considerable it is very important that the purchaser know whether a given lens meets his requirements. The proper way to determine this is by suitable tests, which fall into two categories; optical laboratory and camera tests.

In the laboratory an optical bench is used to obtain quantitative measurements of such lens constants as back, front, and equivalent focal lengths, and nodal point separation. Also it is often desirable to measure such lens errors as distortion, chromatic aberration, spherical aberration, and curvature of field. It might be desirable to mention that only a few organizations have available precise optical bench equipment for testing lenses. Among these are large optical manufacturers, the National Bureau of Standards, and a few universities. Lens manufacturers usually conduct tests in their own laboratories and the prospective purchaser can often obtain the results of such tests. In submitting a process lens to a testing laboratory it is necessary to specify at what scale ratios and apertures the tests are to be conducted.

In addition to the above laboratory tests it may be desirable to run additional tests with the lens mounted in the camera in which it is to be used. This is often possible because the final selection of the lens need not be made until the mechanical construction and adjustment of the camera are completed. The chief purposes of these tests are to study lens definition, shift in focal plane with change of aperture (spherical aberration), color correction, and covering power. The term "definition" really represents a summation of the effects of several lens errors.

If the lens is to be tested in the camera it is first necessary to secure a suitable map or test chart containing very intricate detail. This chart should be mounted in the copy holder and should be uniformly illuminated. The ground glass screen is inserted in its holder and the camera focused for the desired scale of reproduction. With lens at full aperture and the center of the field in sharp focus, note whether the corners are also in sharp focus—if not, the lens may be affected by curvature of field. This defect is recognized by the fact that different annular zones of the image are successively brought into sharp focus as the lens-screen distance is changed. The image field of a lens exhibiting curvature is usually concave towards the lens, and in practice it is necessary to adjust for sharp focus at a point somewhere between the center and corner of the screen, thus obtaining an average best focus over the entire screen. The definition of the lens at full aperture may be so poor as to make it impossible to obtain a sharp focus in the screen corner for any lens-screen distance. In this case an improvement in definition may be obtained by reducing the lens aperture. That the lens does not give critical definition at full aperture may not be reason for rejection; it is necessary to consider both the price of the lens and the type of work to be done.

An examination should be made to detect the presence of spherical aberration. In the presence of this error the lens-screen distance must be changed as the lens aperture is reduced, if sharpness of the image is to be maintained. This error is very undesirable as the camera is usually focused with lens at full aperture (to secure sufficient illumination) and then stopped down for the exposure.

During the above tests it is also desirable to note whether the image details are fringed with color. This defect will be greatest in the corners of the field. A noticeable amount of color will impair the lens definition for black and white work and also cause poor registration of color separation negatives.

In addition to a visual examination of the image on the ground glass screen, it is also advantageous to expose a series of test negatives. The lens-plate distance should be changed slightly between exposures so as to include a range on both sides of the plane of best visual focus as shown on the ground glass. Upon examination of these negatives one will be found whose average overall definition is best.

To determine whether the lens has sufficient covering power it is necessary that the size of the above test negatives be the largest that the camera can handle. The scale ratio for the tests should be selected to give maximum angular field at the lens.

In reference to lens distortion it can be stated that modern process lenses have so little of this defect that its magnitude can best be determined by precise optical laboratory tests. However, if one desires to obtain an approximate check on the distortion the following camera test may be useful. Near and parallel to one edge of the copy board mount a narrow strip of material (such as aluminum backed bristol board) on which is ruled a straight line for its full length. After adjusting the camera for focus and scale, expose two identical glass negatives. The negative size need only be a narrow strip of sufficient width to cover the image of the copy. When the negatives have been processed and dried, place them on an illuminated glass-top table with their emulsion surfaces in contact (do not reverse strips end for end). Adjust the negatives by tapping on the edges until the end points of the line image coincide, then examine the middle for any departure from straightness.

A study of the results of both optical laboratory and camera tests should enable the user to decide whether the lens will meet his requirements.

PRISMS AND MIRRORS

In certain types of process work a laterally reversed negative is required. The copy is placed on an auxiliary board located at right angles to the regular copy board. The reversal unit, which may be either a prism or a mirror, is usually attached directly to the lens. Some types are designed for mounting in front of

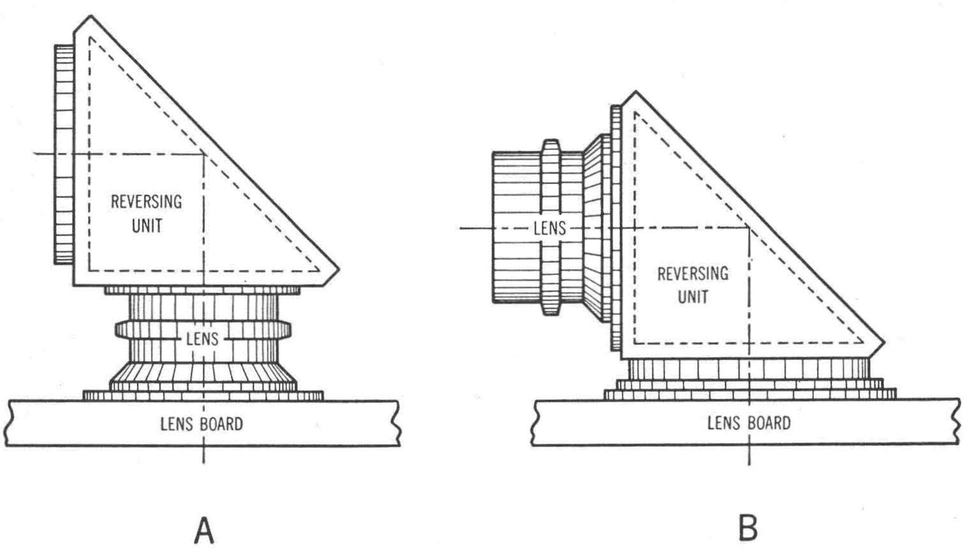

FIG. 2. Reversing prisms. That at *A* is intended to be mounted in front of the lens, while that at *B* is mounted between the lens and the photographic material.

the lens and others behind the lens (see Fig. 2). Front mounting has the following disadvantages; oversize filters must be used, access to iris diaphragm and Waterhouse stops is difficult, and a strain may be developed in the lens, especially in the larger sizes. One particular type of front mounting which does not exhibit the above mentioned disadvantages is illustrated in an article by the writer in the January 1941 issue of *Photo Technique.* In this case the mirror has no direct mechanical connection to the lens but is mounted on a bracket extending from the lens board, thus making it possible to insert or remove the mirror without disturbing the lens.

A prism used in this work is of the right-angle reflecting type, the size of which may vary from two to six inches. The hypotenuse face of the prism is silvered to decrease the light loss on reflection. Formerly, prisms were used almost exclusively for image reversal, but with the development of durable materials for the making of mirrors this type now has preference, especially in the larger sizes. A prism is less desirable because it causes a falling off in lens definition, limits the useful field of view of the lens, and introduces distortion.

A mirror used for image reversal should have its reflecting surface ground and polished optically plane to about a half wavelength of light (0.0003 mm.). The thickness of the mirror should be at least one-tenth of its diameter. A few remarks concerning materials used for making mirrors may be useful.

(1) Speculum metal. This is an alloy of 68% copper and 32% tin. It has a reflectivity of about 60% and has been used extensively for reversing mirrors. Its chief disadvantage is that it tarnishes rather readily in the presence of certain atmospheric gases and cases are known where the reflectivity has been reduced to two thirds of its original value within a few months. The reflectivities for the above and following materials are given for light with a wavelength of 550 millimicrons.

(2) Glass. In addition to the danger of breakage, glass may or may not be satisfactory depending upon what type of metallic coating is deposited on its front reflecting surface. Fresh chemically deposited silver has a high reflectivity (90%), but tarnishes readily and is so easily scratched that it is very difficult to clean. Sometimes a thin protective layer of transparent lacquer is spread over the surface. This reduces the reflectivity to about 70% and so impairs the definition of the reflected image that its use is often unsatisfactory for precise work. Within the past few years an excellent process of making front surface mirrors has been developed commercially. It consists of depositing a thin non-tarnishing film (about one-quarter wavelength thick) of high reflectivity upon a glass surface. The coating is accomplished by thermal evaporation in a high vacuum. Apparently the most successful coating is made by first depositing a thin layer of chromium, which exhibits a strong adhesion to glass, followed by a thin layer of aluminum. The resulting composite film has high reflectivity (90%) tenacity, and durability. The surface can be cleaned with much less danger of scratching than is the case with silver films.

(3) Stellite. Stellite is a trade name for an alloy of chromium, cobalt, and tungsten. This material takes a high polish, does not tarnish, is very hard, and has a reflectivity of 67%. However, it is very difficult to machine and must be shaped by grinding.

(4) Stainless steel. This is an alloy of varying composition, one type contains 18% chromium and 8% nickel. This material takes a high polish, does not tarnish, is very hard, and has a reflectivity of about 61%. Some stainless steels may be machined readily.

It is interesting to know that metal mirrors can have their reflectivities increased to about 90% by the deposition upon their surfaces of an evaporated metallic film (such as aluminum) as explained above.

Errors Caused by Glass Plates

Plane parallel glass plates are often used in the optical path of a copying camera. These plates may be in the form of a copy board glass, filter, half-tone screen, or reversing prism. The latter may be considered as the optical equivalent of a thick plane parallel plate plus a plane mirror, the thickness of this equivalent plate being equal to the length of one side of the square face on the prism. To obtain the best possible performance from a process lens, it is necessary

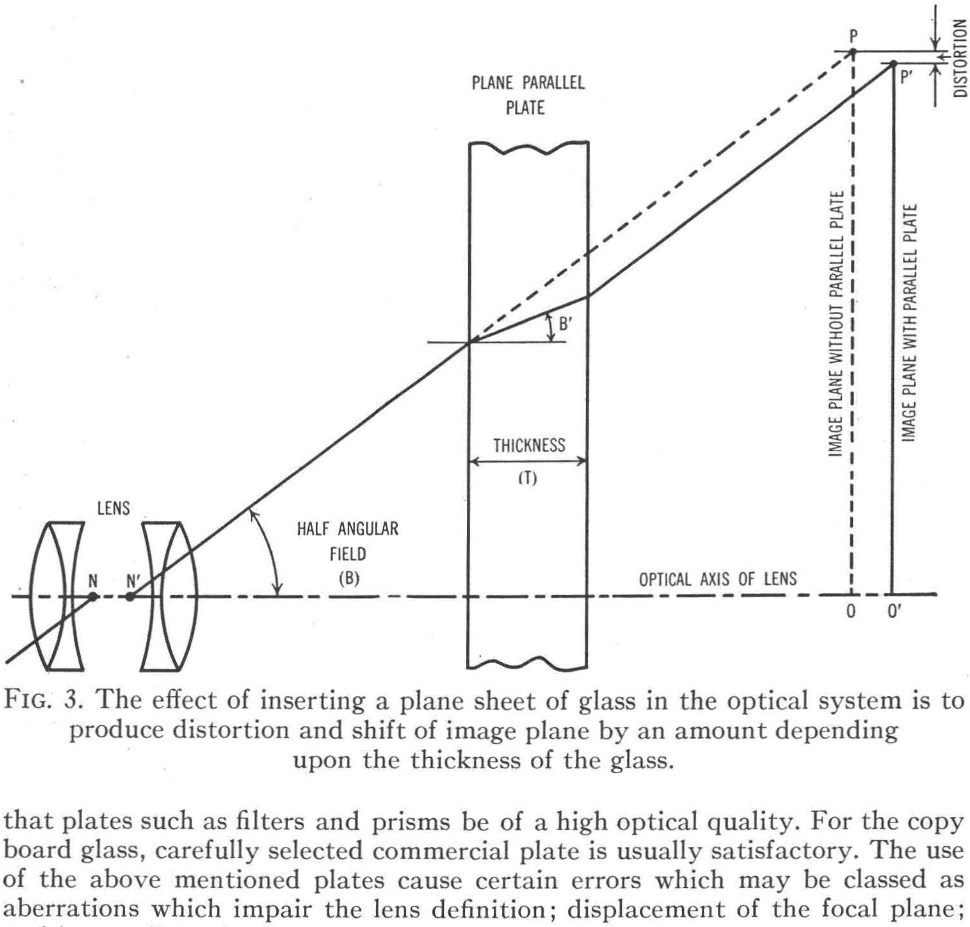

FIG. 3. The effect of inserting a plane sheet of glass in the optical system is to produce distortion and shift of image plane by an amount depending upon the thickness of the glass.

that plates such as filters and prisms be of a high optical quality. For the copy board glass, carefully selected commercial plate is usually satisfactory. The use of the above mentioned plates cause certain errors which may be classed as aberrations which impair the lens definition; displacement of the focal plane; and image distortion.

The aberrations which tend to destroy lens definition are small in the case of a copy board glass, filter, etc. whose thickness is under one-half inch and when the half angular field of the system is less than 30 deg. In the case of a reversing prism the aberrations become rather large, although stopping down the lens (which increases the depth of definition) will reduce their effect considerably. It might be added that the distortion error, to be discussed later, is not reduced by stopping the lens down.

The insertion of a glass plate between lens and focal plane displaces the focal plane away from the lens, its amount along the axis being about one-third the thickness of the plate (in Fig. 3 this displacement is the distance 00′). This axial displacement is

$$\text{displacement} = T - T/N \tag{3}$$

in which T is the plate thickness and N its index of refraction. For most commercial plate glass this index is 1.520 ± 0.005. The index of optical glass varies with its composition, usually ranging from 1.48 to 1.65. The type of optical glass used in reversing prisms and filters usually has an index of about 1.52. The above displacement formula is not absolutely correct for "off-axis" rays in that the plate introduces curvature of field which causes image of points near the edge of the field to have a different displacement than the image of an axial point, thus giving a "dished" image field. Fortunately, as mentioned above, the effect of this curvature error is reduced on stopping the lens down, a point which is worth remembering when using a reversing prism.

At this point it is well to mention the use of a reversed ground glass screen, that is, one in which the ground surface is placed away from the lens rather than towards the lens. The advantage of having the ground surface away from the lens is that the camera operator can measure the image size directly on the ground surface, thereby eliminating the possibility of a parallax error due to viewing the image through the glass. When a reversed ground glass is used it must be mounted in a frame so that the ground surface is offset from the image plane (offset is away from lens) by the amount indicated in Eq. (3).

The distortion introduced by the insertion of a glass plate in the optical path of a copying camera results in a radial displacement of an image point toward or away from the center of the negative, depending on whether the plate is inserted between lens and negative or between lens and copy respectively. The magnitude of this distortion is given by the equation

$$\text{distortion} = T \tan B' - (T/N) \tan B \tag{4}$$

where B and B' are connected by the equation

$$N \sin B' = \sin B \tag{5}$$

In the above equations, T is the plate thickness, N its index of refraction, and B the angle that the ray makes with the optical axis (half angular field). The manner in which a parallel plate (placed between lens and image plane) introduces both distortion and shift of the image plane is shown in Fig. 3, the effect of the plate insertion being a shift of the image plane from OP to $O'P'$. Table 1 has been computed from Egs. (4) and (5) giving the distortion error, expressed as a decimal part of the plate thickness, for rays at various angular distances (in deg.) from the center of the field. The index of refraction used in computing the table was 1.52. Since most glass plates and prisms used in copying cameras have an index near this value, the results obtained by using Table 1 will be accurate enough for practical purposes. Computations were made to determine the change in the distortion with change in index. The results indicated that for values of the index between 1.48 and 1.56, the table values are correct to 3 in the 4th place for angles up to 25 deg., and 6 in the 4th place for angles up to 25 and 50 deg. Although the half angular field of present copying equipment is seldom over 30 deg., it seemed desirable to include values up to 50 deg.

A composite example will now be given illustrating the manner in which Table 1 may be used for computing the distortion. The problem will also include computations on the displacement of the focal plane as computed from Eq. (3). The necessary data for the example are given below, and the relative position

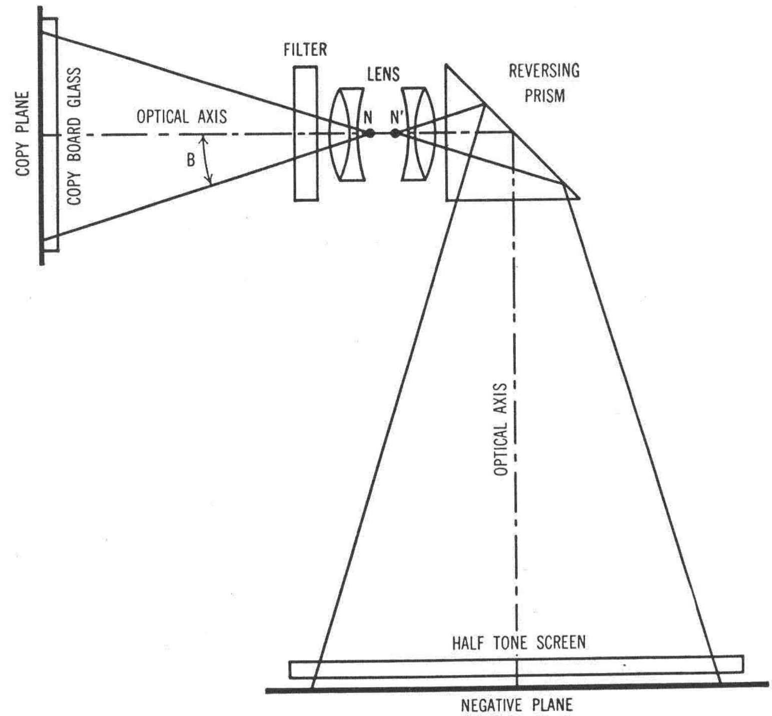

FIG. 4. Diagram of complete optical system of copying camera. The magnitude of the various distortions which may be expected in a typical arrangement of this type are calculated below.

of the various parts is indicated in Fig. 4. The items to be computed will be the object and image distances, and the distortion in the negative.

Equivalent focal length of lens	400 mm
Nodal point separation	5 mm
Diagonal dimension of copy	460 mm
Copy board glass thickness	9 mm
Filter thickness	12 mm
Size of reversing prism (one side of square face)	75 mm
Half tone screen thickness	8 mm
Index of refraction of all plates	1.52
Scale ratio	2.0

If no glass plates were used in the system and a mirror inserted instead of a prism, the object and image distances would be as obtained from Eqs. (1) and (2) respectively. Insertion of a glass plate, however, causes a displacement of the focal plane away from the lens and amount as indicated by Eq. (3). Making use of these equations the following results are obtained:

Object distance without plates	$400+(400/2)$	$=$ 600.00 mm
Displacement due to copy board glass	$9-(9/1.52)=$	3.08 mm
Displacement due to filter	$12-(12/1.52)=$	4.11 mm
Object distance with plates		$=$ 607.19 mm
Image distance without plates	$400+(400\times 2)$	$=$1200.00 mm
Displacement due to prism	$75-(75/1.52)=$	25.66 mm
Displacement due to half tone screen	$8-(8/1.52)=$	2.74 mm
Image distance with plates		$=$1228.40 mm

The total axial distance from copy to negative will therefore be the sum of the object distance, image distance, and nodal point separation; 607.19+1228.40+5.00=1840.59 mm.

In computing the distortion error the following two items should be noted: (1) A plate inserted anywhere between lens and copy causes a radial displacement of the image on the negative away (sign assumed +) from the center of the field, its magnitude being equal to the value in Table 1 multiplied by both the plate thickness and the scale ratio. (2). A plate inserted anywhere between lens and negative causes a radial displacement of the image on the negative toward (sign assumed −) the center of the field, its magnitude being equal to the value in Table 1 multiplied by plate thickness only. The value of tan B (B=half angular field) for the illustrated problem is equal to half the copy diagonal divided by the object distance as computed from equation (1) thus, 230/600 =0.383 and $B=20°58'$. Following the above instructions the distortions in the corner of the negative for the various plates are found to be:

TABLE I.—DISTORTION INTRODUCED BY A PLANE PARALLEL PLATE EXPRESSED AS A DECIMAL PART OF THE PLATE THICKNESS

(B) Half angular field in deg.	Distortion N 1.52	(B) Half angular field in deg.	Distortion N 1.52
1	0.0000	26	0.0197
2	0.0000	27	0.0222
3	0.0000	28	0.0251
4	0.0001	29	0.0281
5	0.0001	30	0.0315
6	0.0002	31	0.0352
7	0.0003	32	0.0391
8	0.0005	33	0.0434
9	0.0007	34	0.0481
10	0.0010	35	0.0532
11	0.0014	36	0.0587
12	0.0018	37	0.0646
13	0.0022	38	0.0710
14	0.0028	39	0.0779
15	0.0035	40	0.0854
16	0.0043	41	0.0934
17	0.0051	42	0.1021
18	0.0061	43	0.1114
19	0.0073	44	0.1215
20	0.0085	45	0.1324
21	0.0099	46	0.1441
22	0.0115	47	0.1566
23	0.0133	48	0.1702
24	0.0152	49	0.1848
25	0.0173	50	0.2006

Copy board glass	0.0099× 9×2.0	=+0.18 mm
Filter	0.0099×12×2.0	=+0.24 mm
Prism	0.0099×75	=−0.74 mm
Half tone screen	0.0099× 8	=−0.08 mm
Resultant distortion of system		=−0.40 mm

It will be noted from the above results that the large distortion introduced by the prism is partly compensated by the distortion of the copy board glass and filter. If the prism had been located on the same side of the lens as the filter, then the resultant distortion in the negative would have been +1.82 mm (the reader might verify this figure for practice).

In certain types of precise copying equipment it is necessary to compensate the distortion introduced by a filter or some other glass plate. This can be done by inserting a compensation plate, of the proper thickness and index, in the system in such a position as to neutralize the distortion that is present. Sufficient information has been given above to enable one to determine the thickness and location of such a plate.

PHOTOGRAMMETRIC AND TOPOGRAPHIC ENGINEERING AIDS NEEDED FOR GOVERNMENT SERVICE

PERSONS trained in engineering are again called upon for Government service. An examination has just been announced by the Civil Service Commission for engineering aids in two fields: Photogrammetry and topography. Salaries range from $1620 to $2600 a year. Persons are particularly needed in the three lower grades (paying $1620 to $2000) in the field of photogrammetry. However, any person qualified for any of these positions is urged to file his application at once with the Commission's Washington office where it will be rated as soon as practicable after receipt. Applications will be accepted until June 30, 1942.

Engineering aids appointed from this examination will perform engineering work in photogrammetric, geodetic, hydrographic, topographic, or cadastral surveying. They will plot survey notes or control points, and project and check scales of photographs. The operation of laboratory apparatus or survey instruments will also be a part of the work.

A written test will not be given but competitors will be rated on their education and experience. Although the completion of 14 units of high-school study is a basic requirement applicants may substitute an additional 6 months of engineering experience for that education. In addition they must have had responsible civil engineering experience including some work in the optional branch selected. Persons who have had the required civil engineering experience but who have not had the specialized work in one of the optional branches may also qualify for some of the positions provided they have successfully completed an approved defense training course in photogrammetry and aerial photographic mapping, or in topographic mapping and closely related subjects. A number of substitutions are provided for the general civil engineering experience. Under certain conditions college study in any branch of engineering, in physics, chemistry, mathematics, or geology may be used to fill a portion of the experience requirement. Persons who have studied in night school or done part-time day study may also be permitted to utilize that study for a portion of the experience.

Persons who are interested in and qualified for this type of Government service are urged to obtain further information and application forms at any first- or second-class post office or from the Civil Service Commission in Washington.