quiring small-scale maps, there are a hundred involving 5′ and 10′ contours, admittedly of smaller areas; but whereas the small-scale job may involve 10,000 square miles at $5 per square mile, the large-scale job, involving 10 square miles at, say, $5,000 per square mile, may be more worthwhile doing. Unfortunately out of the one hundred large-scale jobs potentially available, perhaps only two per cent are yet solved photogrammetrically in Canada. Much education and demonstration yet remains to be done, but as it is done the whole field will widen. As a generalization, it is also true to say the "survey begets survey," meaning that as the small-scale maps become available, plus the reconnaissance resources mapping, the whole country opens up and the demand for large-scale maps is created.

To this picture, we must add the fact that ninety per cent of Canada is unexplored minerally, and represents one of the few fairly accessible, handy and stable areas where exploration companies can seek replacements for their reducing reserves of base metals. For exploration in Canada air survey is an absolute necessity. I conclude, therefore, that the future requirements for air survey in Canada, whether carried out by Government agencies or commercial companies, will certainly not diminish; in fact, a great volume but with increased emphasis on larger scales is a probability.

NEW DEVELOPMENTS IN PHOTOGRAMMETRIC LENSES*

By Irvine C. Gardner, Chief Optical Instruments Section, National Bureau of Standards

FROM one viewpoint, our present process of mapping by a photogrammetric method may be considered to be a process of accurate interpolation. In the multiplex process, for example, the projectors are adjusted until a model is produced which fits the control points. It is advantageous, for accurate orientation, to have the control points include the maximum and minimum elevations present in the model. The position and elevation of any intermediate point is then readily determined by what is essentially an interpolation. If the images formed by the projectors are free of the errors customarily considered, the interpolation will be correct, and it is even safe to extrapolate to some extent when necessary. When satisfactory adjustment of the projectors has been attained, it is said that the principal point of the projected image has been brought into the position corresponding to that of the camera when the photograph was made. If the exact altitude and orientation of the camera at the time of exposure were known, and if the corresponding values could be readily read from scales on the multiplex projector, a comparison of the two sets of values would probably be rudely surprising. It would be found that all of the small errors arising from distortion by the lens, film shrinkage, refraction of the atmosphere, etc., have been automatically absorbed in the process of making the adjustments and that a false positioning of the projector has been determined which smooths out the errors. The greater the errors that are smoothed out in this manner the greater the need for control points and the less satisfactory is any bridging process.

* Paper read at Annual Meeting, American Society of Photogrammetry, Washington, D. C., January 13, 1949.

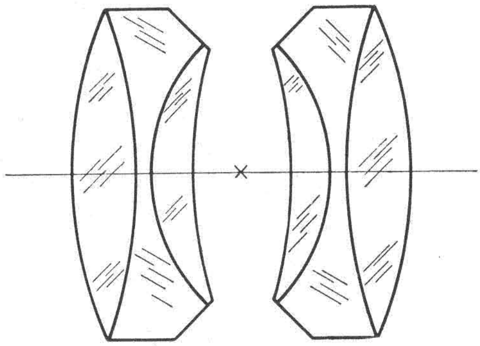
Such a conception of the manner in which errors are absorbed in our present method of mapping is worthy of emphasis for two reasons. In the first place, such a conception makes it clearly evident that control points should be selected if possible, to "bracket" all of the area on a negative which is to be mapped, that is the control points should be near the edges of the negative and should include both the maximum and minimum elevations present if a superior map is to result. By this procedure, the process becomes truly one of interpolation with a minimum of extrapolation. Secondly, if the interpolation conception is not fully appreciated, the accurate maps which result when present methods are wisely applied is likely to give the operator an exalted and inflated opinion of the accuracy of the intermediate steps required to produce the map. Actually, as has been mentioned, large intermediate errors are masked and eliminated from the final map in the present method of operation.

New methods of mapping are now being considered and developed in which the position of the camera at the time of the exposure is determined by the use of shoran (short range aid to navigation) or some other radar method. If one imagines, for the moment, that this method has been developed to such perfection that the position and orientation of the camera is accurately determined, one has a process in which the requirement for ground control can be completely eliminated. The camera thus becomes in fact a recording transit by which accurate angular locations can be simultaneously obtained of all points in the field of view. In such a case, the process of making a map is not one of interpolation subservient to the accuracy existing in the control data but is a method of direct measurement dependent, naturally, upon the accuracy with which the camera's position has been determined. In such an application, all errors must be controlled, that is, either eliminated or evaluated and compensated for, before an accurate map can result. At present, no one contemplates the arrival within the immediate future of such a perfect mapping system for which all control can be abolished, but a lessening of the necessity for ground control is both desired and anticipated. In general, as ground control is dispensed with, measurement to some extent supplants interpolation and errors become correspondingly more important. Consequently as improvement in our mapping methods is attained, greater accuracy will be demanded in all parts of the process and, as a compensation, bridging will become more practicable. Therefore, although surprisingly accurate and satisfactory maps are now being produced, this fact should not blind us to the need for greater accuracy and precision in all or many of the intermediate processes involved in making maps from airplane photographs. The reward of more accurate instruments and methods may to some extent be the production of better maps, but it is quite possible that the greater return may be the ability to make maps with less ground control and less cost.

In view of these considerations, it seems profitable to consider the airplane camera lens in some detail as one of the potential sources of error. Before considering possible methods of improving airplane camera lenses, a brief survey will be given of those typical lens systems which have played an important role in the development of the lenses now in use and also some of the newer lenses which have been used during World War II.

Figure 1 shows, in the usual manner, a section of the Aerotar lens. This lens attained popularity in this country very early in our development of photogrammetry and it is still used when a normal field (70 degrees) is satisfactory. This lens can be used at the relative aperture $f/6.3$ and is exceptionally free from distortion.

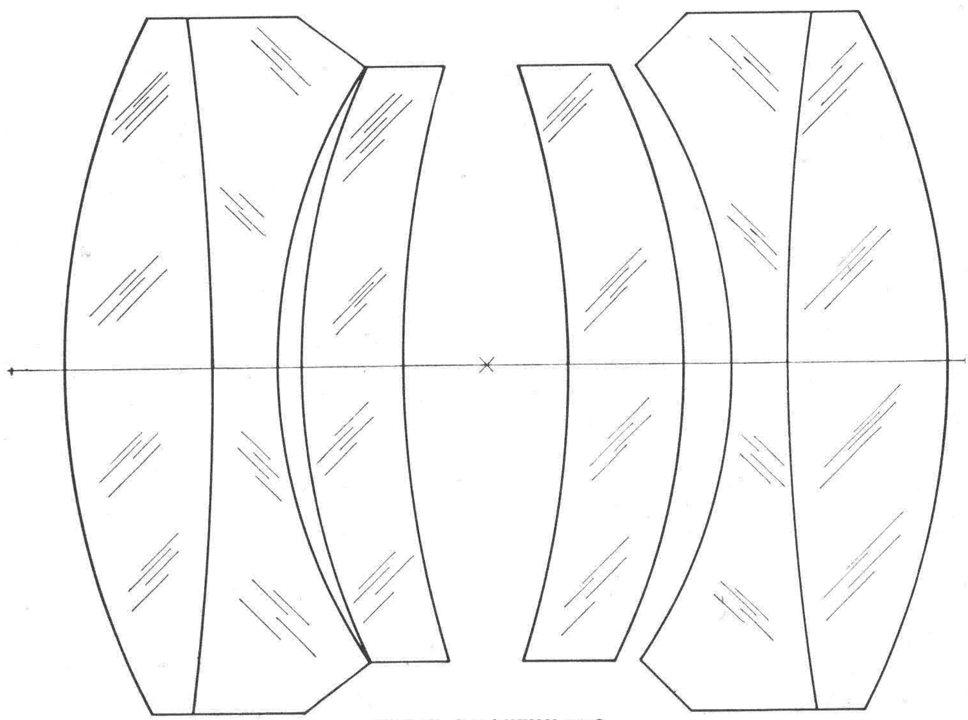
Figure 2 is a sectional drawing of the Zeiss Orthometer lens. This particular lens was never used generally in this country but is shown because a sectionalized drawing of it was available. It is in a general way similar to the lenses of 6- or 8-inch focal length of large aperture (*f*/4 or *f*/4.5) and normal field coverage (60 to 70 degrees) that are used. The chief difference between lenses of this type and the Aerotar is the larger relative aperture. There are six components and three air spaces. This lens is more difficult and expensive to construct than the Aerotar, the additional complications being necessary to attain the increased aperture without loss of definition.



FIELD OF VIEW 70°
MAXIMUM DISTORTION (f=100) 0.03 MM.

FIG. 1. Aerotar lens.

The Hypergon lens, shown in figure 3, was patented in 1902, long before the advent of photogrammetry. It was originally intended for ordinary photographic purposes when an extremely large angular field of view (130°) is required. Even judged by present day standards, the distortion is sur-



FIELD OF VIEW 70°
MAXIMUM DISTORTION (f = 100) 0.04 MM.

FIG. 2. Orthometer lens.

prisingly small for so large a field, and for pictorial purposes it is quite negligible. This lens is used in some of the modern wide-angle transformers and in some multiplex transformers. It is not suitable for use in an airplane camera because it is not corrected for color, and consequently the stop opening is only *f*/22 for focal lengths from 6 to 8 inches. The cosine-fourth-power law plays havoc with the uniformity of illumination over the field. Making no allowance for vignetting, the effective exposure at the edge of the field is approximately one-thirtieth that at the center of the field. The lens was originally marketed with an ingenious rotating central stop to lessen the effective exposure at the center of the field and thus lessen the variation in exposure. With this stop in position, the effective aperture governing the required exposure would be considerably less than *f*/22.

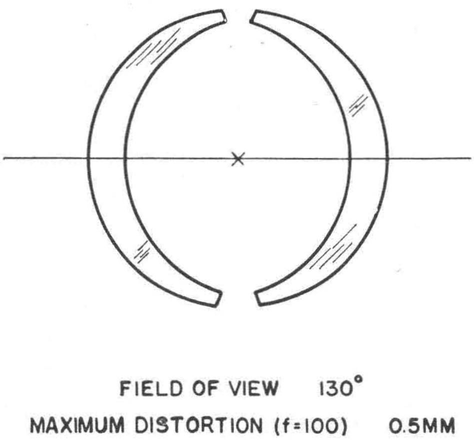


FIG. 3. Hypergon lens.

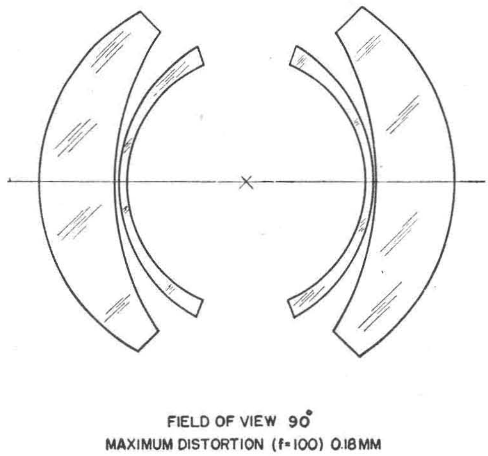
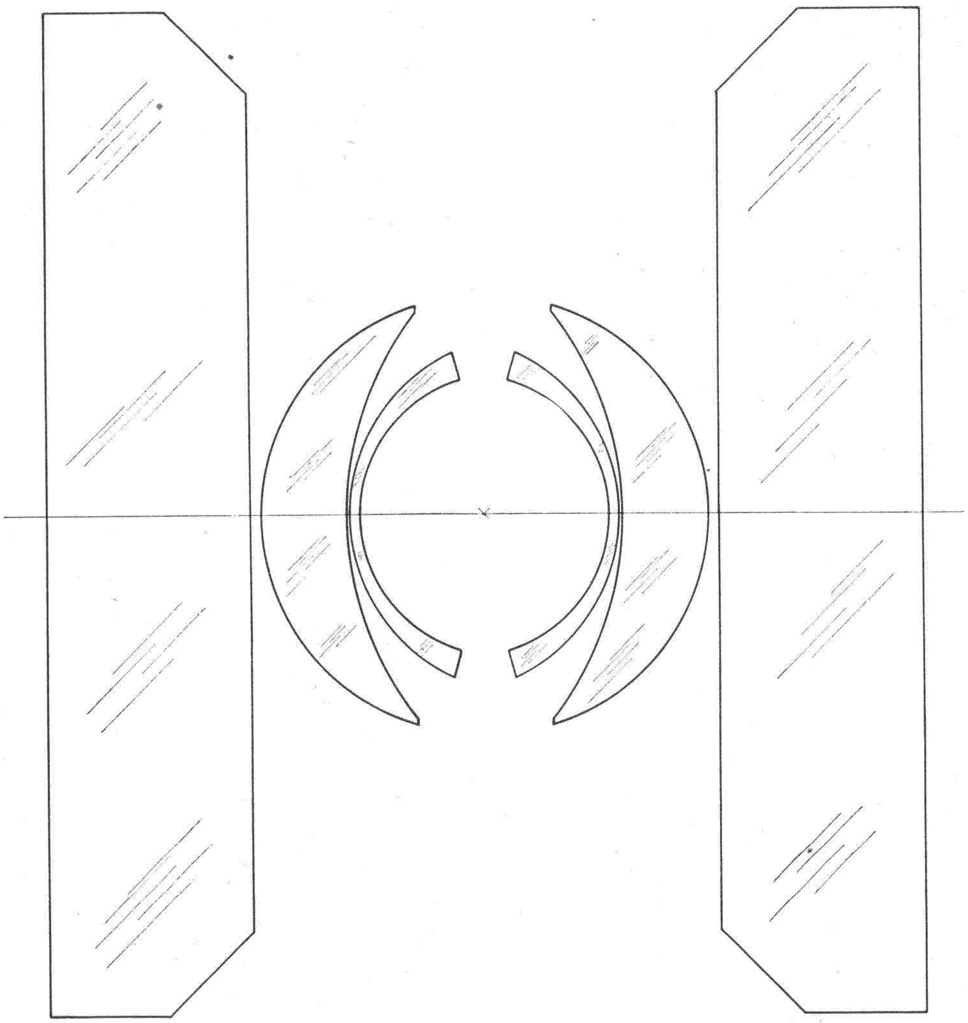


FIG. 4. Metrogon lens.

The Hypergon lens has been shown because it is the direct forerunner of the Metrogon and Topogon lenses so generally used for wide-angle (90°) photography. The simplicity of construction of the Hypergon suggests the presence of large aberrations, and it is this that makes the small relative aperture necessary.

Either the Metrogon or Topogon lens is shown with sufficient accuracy by figure 4. The Hypergon lens consists of only two components, one deeply curved meniscus lens on each side of the diaphragm. The Metrogon or Topogon has two components on each side of the diaphragm, a positive one of crown glass and a negative one of flint glass. This permits the aberrations to be corrected to such an extent that the relative aperture for lenses of 100 mm. focal length may be as large as *f*/6.3, although they are often operated at a much smaller aperture, If vignetting is neglected, the effective exposure at the edge of the field (90°) is one-fourth that at the center. When vignetting is taken into account, this is reduced to one-tenth, approximately. Although the distortion characteristics of this lens are good, the maximum distortion is still larger than desirable for accurate photogrammetry.

Consequently Zeiss brought out a modified Topogon shown in figure 5. Two thick plane parallel plates have been added, one on either side of the lens.



FIELD OF VIEW 90°

MAXIMUM DISTORTION (f=100) 0.07MM.

FIG. 5. Modified Topogon lens.

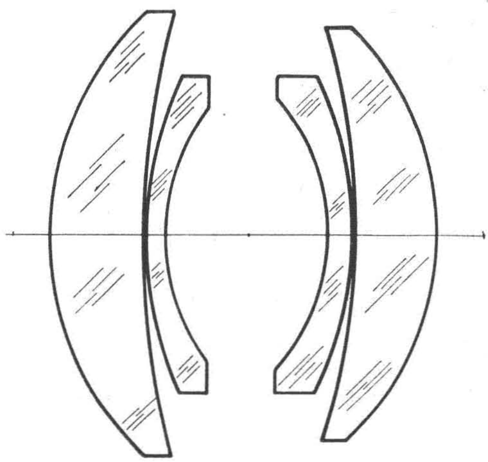
The central system involves only minor changes from the original Topogon. In 1927 A. H. Bennett and I[1] published a paper discussing the use of a plane parallel plate added to a lens to correct distortion. So far as I know, the patent for this lens, granted in 1933 and noted in a wartime German book on optics,[2] is the first commercial application of this principle. Although the German patent

[1] Gardner, I. C., and Bennett, A. H., *J. Opt. Soc. Am. and Rev. Sci. Insts.*, *14*, 245 (1927).

[2] *Handbuch der wissenschaftlichen und angewandten Photographie:* Ergänzungswerk, edited by Kurt Michel. Sprimger Verlag. Vienna, 1943. Page 85, figure 91.

drawing shows two plane parallel plates, when the object is at a great distance, as in airplane camera photography, the plate in front of the lens has no effect. Mr. Russell K. Bean was fortunate in obtaining a lens when in Germany in 1945 which apparently is made in accordance with this design and which has only the one plate which is between the lens and focal plane.

There are two other wide-angle lenses which should be mentioned. The Rectagon, U. S. Patent No. 2383115, Aug. 21, 1945 shown in figure 6 was invented by Dr. Durand. This lens consists of four meniscus components and on superficial examination it looks very much like the Metrogon. Fundamentally, it is quite different as the glasses are so chosen that the crown component on each side of the diaphragm has a higher index than the flint. This gives somewhat flatter curves than the Metrogon, and the overall length of the lens is less. The patent also describes a modified design, like the modified Topogon, with the lens followed by a thick plate, only in this instance the plate is not plane parallel but has one face slightly curved. Only experimental models of this lens have been made. Its relative aperture and field of view are substantially the same as for the Metrogon



RECTAGON

FIG. 6. Rectagon lens

Bertelle, the designer of the Sonnar $f/2$, has designed a lens which is marketed by Wild. Its field of view is 70° but it is said to have better definition over the entire field than the earlier 70 degree lenses. It has 9 components and 8 glass-air surfaces.

The graphs of figure 7 permit comparison of the distortion characteristics of the different lenses that have been described. The curve for the Aerotar lens is based on measurements and is fairly typical of what is regularly obtained. All of the other curves are the published results of computations made by the Zeiss staff.[3] The extremely wide field and relatively small distortion of the Hypergon lens is noteworthy. The improvement in the distortion of the Topogon by the addition of the plane parallel plate and small modifications in the original lens is clearly shown.

In discussing the preceding wide angle lenses, reference has been made to the loss of illumination at the edge of the field resulting from the cosine-fourth-power law. This law as it has been applied is applicable to distortion-free lenses. If there is *considerable* negative distortion, the illumination does not fall off as rapidly for a given field of view as in a distortion-free lens. This is readily understood, because with a large amount of negative distortion a given area near the edge of a picture is much smaller in area on the negative than a corresponding area with a distortion-free lens. Consequently with the lens possessing negative distortion, the light coming from a given area of the object near the edge of the

[3] Merte, Richter, and v. Rohr, *Handbuch der wissenschaftlichen und angewandten Photographie: Das photographische Objektiv*, Vol. 1. Springer Verlag. Vienna, 1932 and of reference 2.

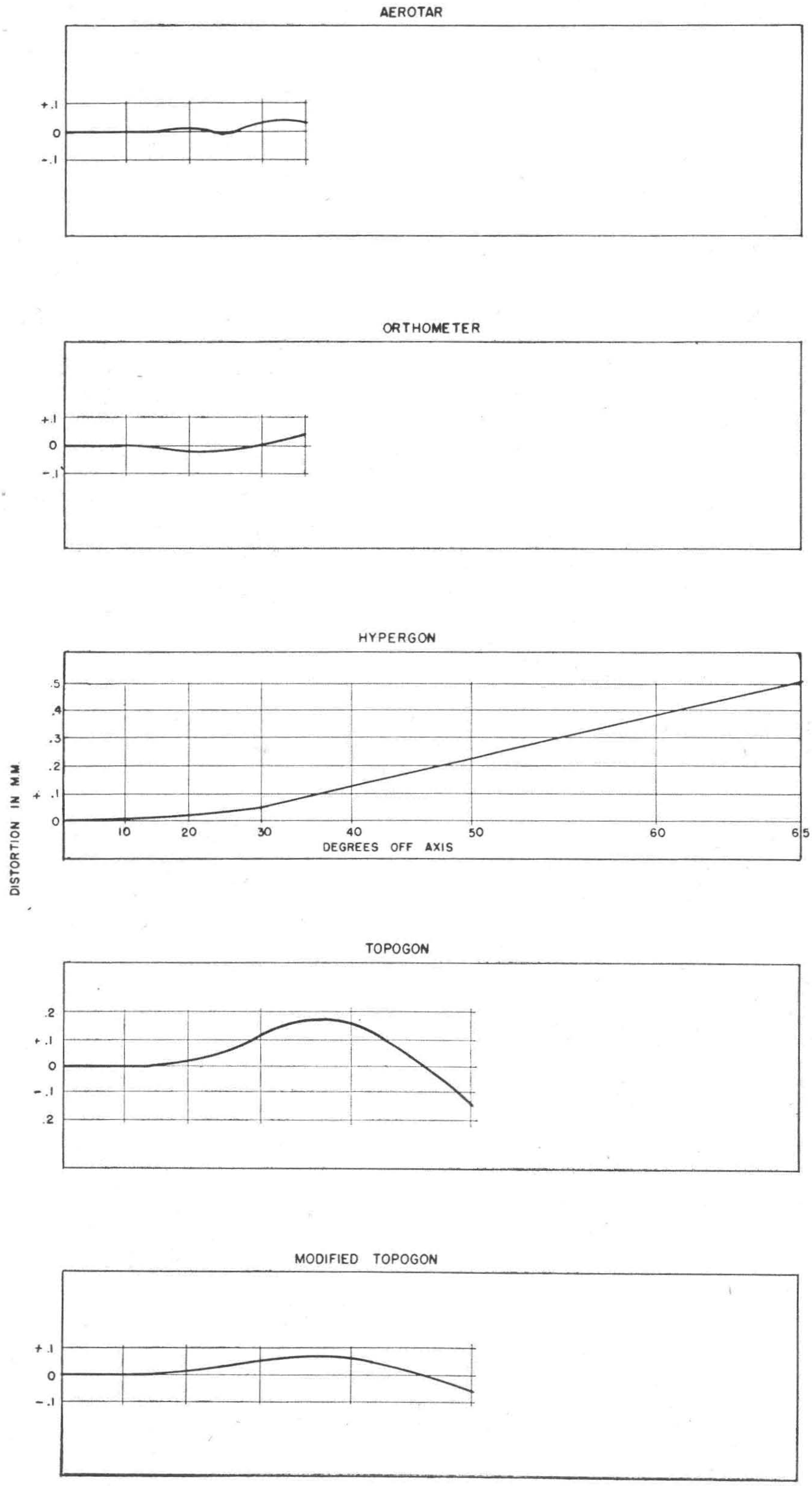


FIG. 7. Distortion of typical lenses.

field is concentrated on a smaller area of the emulsion, and the effective exposure is correspondingly increased. It should be borne in mind that, to apply this means of securing more uniform exposure, the distortion must be of truly heroic proportions. For example, with a picture area 8 inches in diameter, the distortion at the edge may be as much as 2 inches. Consequently, the construction of such a lens for photogrammetric purposes necessarily implies the use of a copying camera equipped with a lens especially designed to make a print free from distortion. Such a method of photography for photogrammetric purposes was disclosed by me in U. S. Patent No. 2037017, April 14, 1936. If θ is the angular distance of an object from the center of the field and r the distance from the center of the negative to the corresponding image, it has been shown that the exposure over the negative will be uniform, regardless of the value of θ, if the distortion is such that $r = f \sin \theta$. The condition for freedom from distortion is $r = f \tan \theta$. To give an idea of the large amount of distortion that this implies, assume that $F = 125$ mm. and that the field of view is 120°. The original negative will be 8 inches in diameter and the rectified print will be 16 inches in diameter. For a point near the edge of the field rectification implies a magnification of 8 diameters in a radial direction.

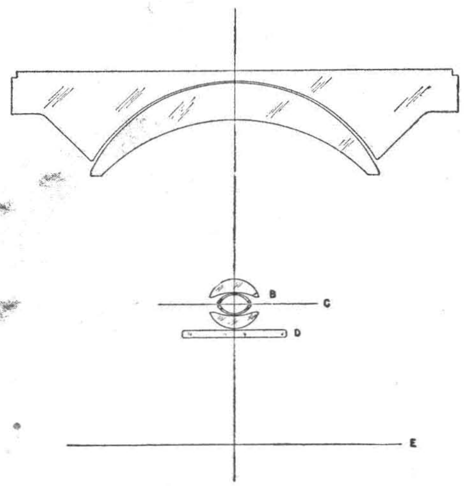


FIG. 8. Pleon "compressed-field" lens.

The Pleon[4] lens, shown in figure 8, was constructed in Germany during World War II and represents, to the best of my knowledge, the first commercial application of the use of distortion in a photogrammetric lens to secure uniform exposure over the field of a wide-angle lens. The lens consists of two parts, a negative system which contains lens components approximately 12 inches in diameter, and a second system which resembles a Topogon lens. The negative system is often referred to as a "field compressor" because it receives a field which subtends a large angle, say 130 degrees, and compresses it until the field is small enough to be transmitted by the second part of the system. A lens of this general type may be referred to as a lens with a "compressed field," the negative distortion being, in effect, the compression.

The rectifying unit by which the Pleon negatives are transformed into distortion-free prints is illustrated in figure 9, and a section of the optical system is shown in figure 10.

In the process of rectification, as has been mentioned, different parts of the negative are enlarged by different amounts, and consequently it is necessary to do extensive "dodging" if a print of uniform density is to be secured. For this purpose a filter of varying density was placed over the negative.

The lower curve of figure 11 shows the large negative distortion of the Pleon camera lens. The upper graph shows the compensating positive distortion of the lens of the rectifying unit. The middle curve shows the residual distortion

[4] Gardner, Irvine C., and Washer, Francis E., Lenses of extremely wide angle for airplane mapping. *Jour. of Res. of NBS*, *40*, 93 (1948), RP1858.

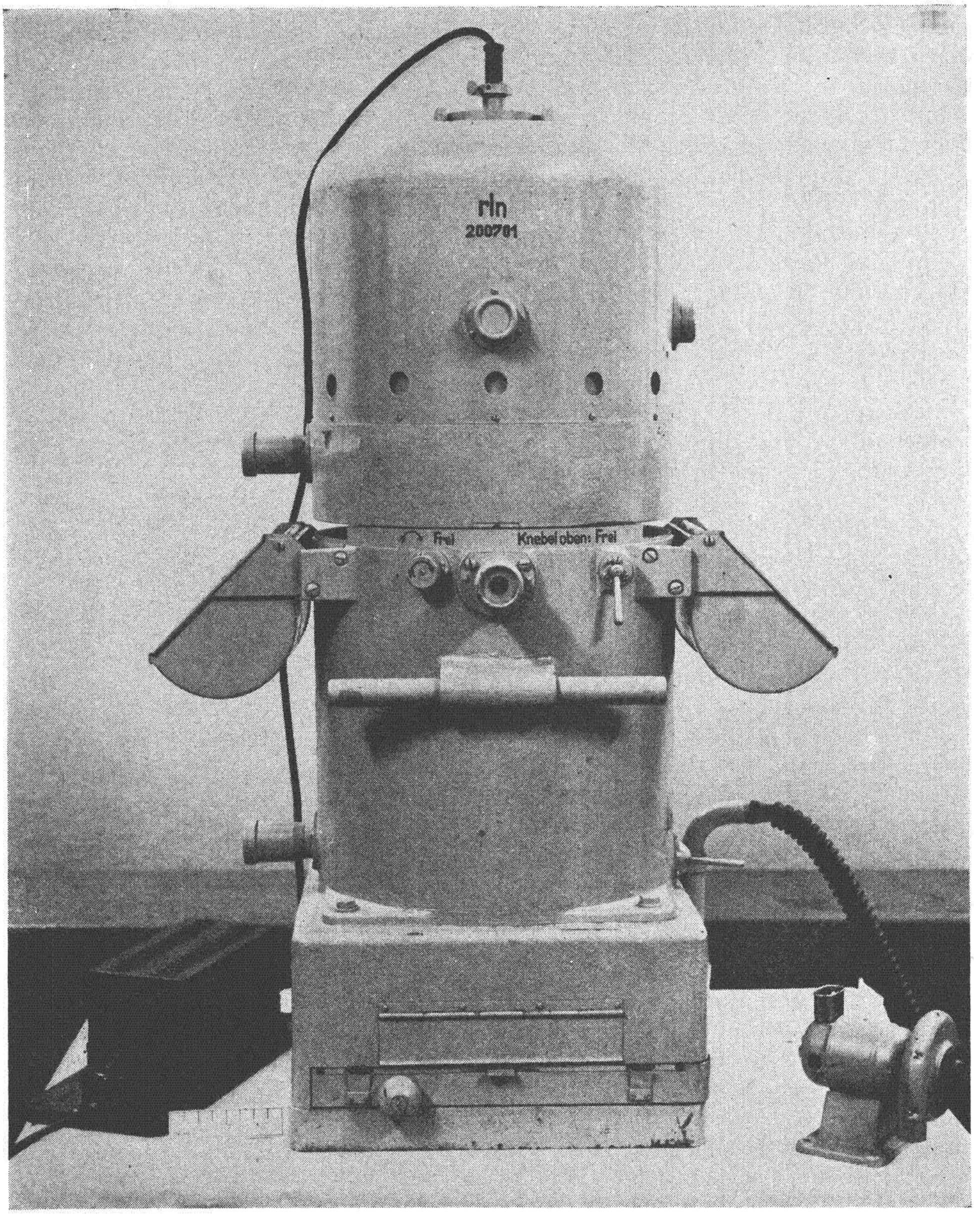


FIG. 9. Rectifier for Pleon lens.

remaining because of the failure of the two systems to give complete compensation. These graphs are based on measurements, made at the National Bureau of Standards, on a camera and rectifier brought back from Germany by the Air Force. Perhaps this failure of exact compensation should not be given too much weight as the rectifying instrument was incomplete and the two instruments may not have been properly adjusted to each other.

A most elegant solution of the wide-angle lens problem has been proposed and experimentally demonstrated by Dr. James G. Baker. It will be noted that the surfaces shown in figure 12 in the section are concentric circles. Consequently, the lens could be made as a series of hemispheres and hemispherical shells, all surfaces being concentric, and it is apparent from the symmetry that the focal plane will also be a hemisphere corresponding to 180° in the object space. Specially ground and polished hemispherical shells are coated with photographic emulsion to provide plates for this camera. By an ingenious focal plane shutter with the slit attached to the lens so that all rotates as a unit to scan the image surface, an image is secured free from distortion except for the fundamental fact that a plane is reproduced as a hemispherical surface, with definition uniform over the entire surface and with uniform exposure.

A brief description has been presented of the different types of camera lenses available in this country that have been designed for photogrammetric work. During the past war, several marvelous lenses of long focal length and relatively narrow-angle with truly excellent definition have been developed. These lenses are well adapted for the construction of mosaics and for military intelligence, but it is believed they have not been seriously considered for the construction of cadastral maps because their relatively narrow field of view greatly suppresses stereoscopic parallax.

Of the distortion-free lenses, the Metrogon type has the advantage of a wide angular field and is relatively free from distortion. Photogrammetrists would probably like to see the Metrogon superseded by a lens,

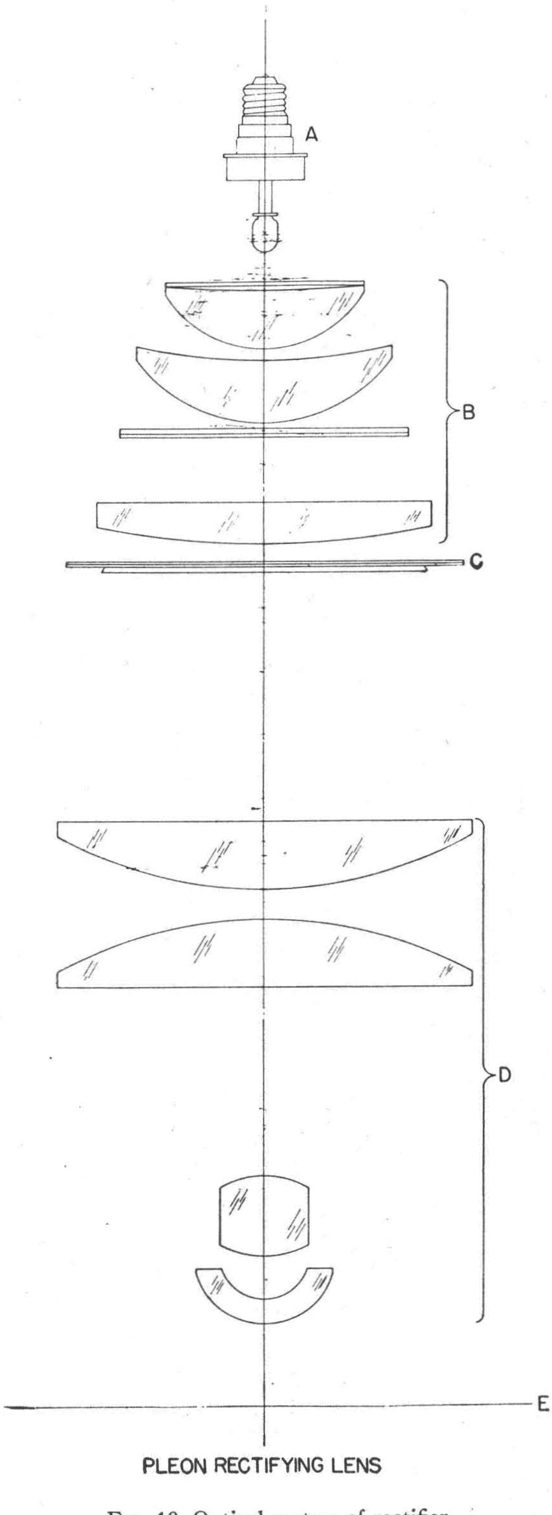


FIG. 10. Optical system of rectifier.

with better definition, even more free from distortion, of larger relative aperture, with more uniform illumination, and with the field no less than 90 degrees but preferably larger. These requirements will be discussed in turn.

For a lens designed for pictorial use, the center of interest usually lies near the center of the picture and consequently some softening of imagery at the corners and near the edge is not detrimental. In some instances it may even be considered desirable. For a camera lens designed for photogrammetric purposes, the desirable although generally not available characteristic is needle sharp imagery over the entire negative. It has been mentioned that the control points

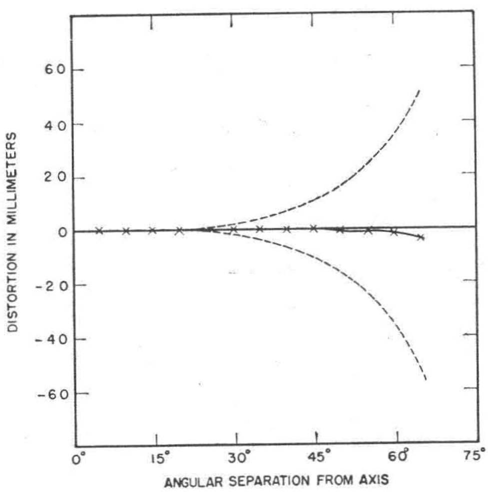


FIG. 11. Distortions of Pleon lens, rectifier, and combination.

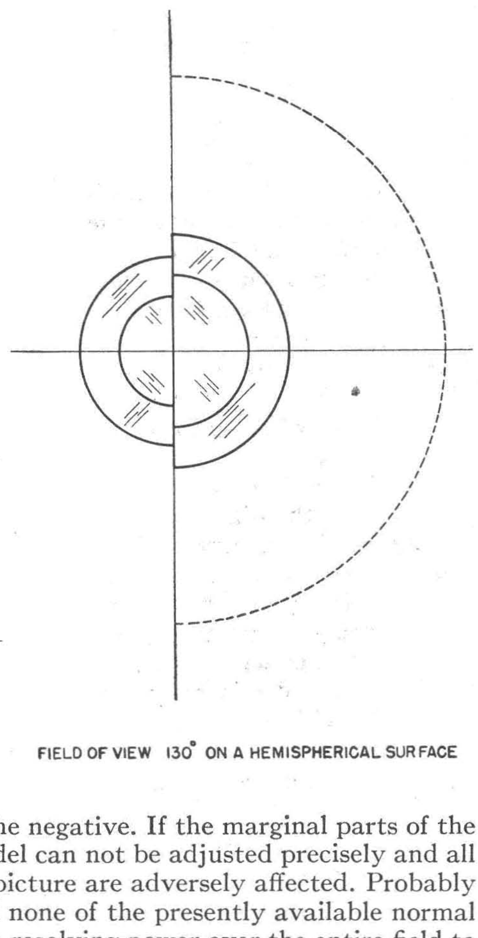


FIG. 12. Concentric lens.

FIELD OF VIEW 130° ON A HEMISPHERICAL SURFACE

should preferably be near the edges of the negative. If the marginal parts of the picture are not sharply defined, the model can not be adjusted precisely and all subsequent map readings taken on the picture are adversely affected. Probably without exception, it can be stated that none of the presently available normal or wide-angle lenses has sufficiently high resolving power over the entire field to tax the capabilities of the extremely fast film of moderate resolving power that is generally used for airplane photography.

Map makers, for obvious reasons, will probably always want camera lenses more free from distortion. At present, there is a limiting freedom from distortion beyond which further improvement gives diminishing returns because of the differential shrinkage of the film base upon which the emulsion is carried. Perhaps this value is approached when the distortion, referred to the calibrated focal length, is reduced to 0.02 or 0.03 mm. over the entire negative. However, if the time arrives when a considerable part of the orientation of the camera is determined by shoran or other means independent of the resulting negative, it will probably be necessary to develop a more stable film base or return to the use of glass plates after which the tolerance for lens distortion will probably be set by the accuracy and precision with which distortion can be measured in the laboratory.

The average amateur photographer uses a lens of large relative aperture in order that he can make photographs of fast-moving objects or when the lighting conditions are adverse. The large aperture of an airplane camera lens contributes in an entirely different manner to improve the photographic results. Present camera mounts are not sufficiently well stabilized to entirely eliminate the effects of airplane movement at the time of exposure. There are several methods by which the forward translation of the plane can be compensated, such as swinging the camera, translating the lens, or translating the film. But the effects of vibration and of the rolling and pitching of the plane may still cause detectable blur. These effects can be lessened by improving the camera mount or shortening the exposure. Shortening the exposure demands better shutters but it also demands a lens of larger relative aperture. If the definition of the airplane camera lens is sufficiently improved, it will be necessary to develop a finer grained fast film or to use one of the present fine grain slower films, and in this event an additional need for the larger relative aperture will arise.

Reference has been made to the desirability of a more uniform effective exposure over the entire field of view. The present lack of uniformity arises from vignetting and the cosine-fourth-power law. The cosine-fourth-power law, as usually given, states that the illumination or effective exposure varies from the center of the plate outward as the fourth power of the cosine of the angular distance of an object point from the axis. It applies rigorously to distortion-free lenses with the diaphragm between lens and object. With a ninety-degree field, if there were no vignetting, the exposure at the edge, on the basis of this law, would be one-fourth that at the center. In present lenses, because of vignetting the effective exposure decreases even more than is predicted by the cosine-fourth-power law. Consequently, if possible, lenses should be designed with less vignetting than is now present. Slussareff,[5] a Russian physicist, has called attention to limitations of the application of the cosine-fourth-power law not hitherto recognized and indicates that lenses have been designed in Russia which give greater effective exposure at the edge of the field for a wide-angle distortion-free lens than has previously been thought possible.

The lenses with compressed fields readily give the large field of view that is desirable with effective exposure uniform over the entire negative. Freedom from distortion in the final print depends upon the perfection with which the rectifier operates, but since its use is entirely a controlled laboratory process any reasonable freedom from distortion can be attained provided that lens and rectifier are paired. To increase the relative aperture of the lens with distortion probably offers the same difficulties that are presented in connection with the distortion-free lens. There is one difficulty, however, with the compressed field type of lens, for which no solution appears. With the excessive negative distortion present, the scale of the picture decreases greatly from the center of the picture to the edge. If, for example, the central part of such a distorted picture is reproduced by the rectifier without reduction, the peripheral parts may be magnified from five to seven diameters. In the Pleon lens, the central portion is reduced somewhat in order that the magnification at the edge may be less, the two magnifications being 0.82 and 4.86, respectively. This large peripheral magnification makes the grain apparent in the outer parts of the picture and becomes even more detrimental if the rectified negative is placed in a plotting machine and

[5] Slussareff, G., L'Eclairment de l'image formée par les objectifs photographiques grand-angulaires. *J. Phys. U.S.S.R. 4*, 537 (1941).

further magnified. With the concentric lens and the hemispherical shell for receiving the image, this same trouble also appears if an optical means is used for transferring the image to a plane. In fact for a point 90° from the axis, the required magnification for rectification is infinite. Aside from this, however, it is not anticipated that the full 180° will ever be satisfactorily recorded because of haze, distant clouds, and other atmospheric conditions which generally limit the range of seeing. A more realistic appraisal of the useful field of view would probably be 120 or 130 degrees. For a field of 130°, the radial magnification at the edge of the field required by rectification is 2.7, a value more favorable than the corresponding compressed field lens with flat field. The optical solution presented by this lens is complete and perfect, and it can be readily designed to operate at a relative aperture sufficiently large to permit the use of fine grain emulsions. A prototype lens of this type of 6-inch focal length for use with spherical shells embracing a field of 120° was designed and constructed. With a working speed of $f/3.5$ a resolution of 60 lines per millimeter on Super-XX was obtained. A rectifier giving a plane 3-diameter enlargement was also built. Obvious disadvantages of this type of lens are the cost of the hemispherical shells upon which the emulsion is coated, the disadvantages of the shells for automatic serial photography, and the large amount of careful engineering and development that is required before so radical a new idea can be put into every day use. If a large rectified print is made from one of these compressed field cameras, it seems probable that the outer parts of the picture will be only useful for orientation purposes and that the field containing details to be transferred to the final image will be smaller than the total included field.

For these reasons, it is my opinion that the lens designer's time, at present, can be most usefully expended upon the improvement of the distortion-free type of airplane camera lenses. Without for a moment wishing to assume the role of a prophet, it is interesting to survey the situation and try to determine what facilities are available.

When designing a photographic lens, there are algebraic methods which permit a direct solution by which an approximate design for the lens is obtained. Many trials may be made before a satisfactory approximate design is obtained. From this point forward the computations proceed indirectly. Changes in the approximate design are assumed, and the result tested by tracing selected rays through the lens. This portion of the task is very laborious because the computations for each ray are long and must be done precisely with many significant figures. For a long-focus narrow-field lens, the final solution closely resembles the algebraic solution and the final solution is obtained without excessive labor. It is perhaps partly for this reason that the long-focus telephoto airplane camera lens has attained greater perfection than the wide-angle photogrammetric lens. With the wide-angle lens, the final design differs greatly from the preliminary approximate design, and an enormous amount of computational labor is required to pass from the one to the other. This limits the number of types of lenses that can be experimented with, and the number of trials that can be made, when designing an airplane camera lens. With the many new computing machines that are now being constructed and the very great speeds of computation that are being attained, it will become feasible to try out a greater variety of designs, and it may be anticipated that, from this cause alone, better designs will be obtained.

Although our better hand camera lenses contain from 6 to 8 pieces of glass, the Metrogon lens contains only four. The results obtained with so few components indicate skillful designing and full utilization of all possibilities. Although the Metrogon lens is a satisfactory lens, there is opportunity for improvement as regards definition, distortion and vignetting. It seems quite certain that improvement in these directions may be attained by increasing the number of components. In fact, efforts are already being applied in this direction. In the past, the loss of light by reflection at the different glass-air surfaces has tended to discourage the use of a large number of surfaces. As is well known, each pair of glass-air surfaces that is added to a lens has, in the past, meant a further reduction of the transmitted light by from 8 to 10 per cent. Now, however, we have the reflection-reducing coatings and this loss is reduced to from 1 to 2 per cent. For airplane camera lenses, the use of reflection-reducing coatings is particularly advantageous because the useful spectral range is limited by a yellow filter and a reflection-reducing coating may be made to act over the shorter spectral range with approximately uniform effectiveness. With reflection-reducing coatings, it should be quite feasible to construct a lens with 8 or 10 components instead of the 4 now used. The additional components will enable the distortion to be adjusted with greater nicety, the definition in the peripheral parts of the field to be improved, and the relative aperture to be increased.

There is an important group of lens aberrations that arise because optical glass and other optical materials refract light of different wave lengths (or color) differently. These are referred to as the chromatic aberrations. Chromatic aberrations particularly affect the definition of the marginal parts of the field of a wide-angle lens. Although the chromatic aberrations arise because of the presence of color, their correction is essential for black-and-white photographs as well as for color photography. Unfortunately, the chromatic aberrations cannot be eliminated by simply increasing the number of lens elements in an objective, but in addition glasses of suitable optical properties are required. Available glasses do not always meet the requirements of the lens designer, and there is a need for a greater variety of optical materials with a greater variety of optical properties. Important new optical glasses have been developed during the past decade, and it is not unreasonable to anticipate that new glasses will continually become available of which some will be advantageous for the correction of chromatic aberrations. Furthermore, the production of synthetic crystals in homogeneous pieces sufficiently large for the construction of lenses make available new optical materials some of which differ from the optical glasses in a spectacular manner. It is not unlikely that some of these new crystalline materials may find use in photogrammetric lenses. The use of new optical materials and of more components are the conventional means by which lenses of better definition can be produced.

Photogrammetric lenses may also be improved by the application of more precise testing methods and more individual care and attention in centering and mounting. In connection with this reference to centering and mounting, it is pertinent to note that tangential distortion, in which all photogrammetrists are now so much interested, is not caused by faulty lens design but must be due to faulty glass or to imperfect centering of the lens components. This fault may arise when the lens is originally assembled or subsequently when the parts are mounted in a shutter. Now that the importance of freedom from tangential distortion is fully recognized,[6] it may be anticipated that tests to be applied

[6] Pennington, John T., Tangential Distortion and its effect on photogrammetric extension of control. PHOTOGRAMMETRIC ENGINEERING *13*, 135, 1947; Sharp, J. V, and Hayes, H. H., Effects on map production of distortion in photogrammetric systems. Privately distributed, 1949.

during production will be developed and that the lens of the near future will be satisfactorily free from this defect.

A large number of airplane camera lenses are manufactured and sold but only a very small number are actually used for the production of accurate maps. The cost of a camera lens, in comparison with the cost of the plane which carries it and of the maintenance of the plane and crew, is quite negligible. Consequently, for the few lenses actually employed for mapping, the cost could be multiplied several times without an appreciable increase in the cost of the overall project, and such increased cost is quite justifiable provided that it does actually result in better performance. It is justifiable, therefore, to use the additional surfaces suggested in the preceding paragraph, and to elaborate the testing and perfection of mounting to any reasonable extent, always provided that the end result is equipment which will produce a better map. The photogrammetric lens is, in effect, a precision instrument and should be so considered. It is, if you please, a very precise surveyors' transit which, in a small fraction of a second, makes a record from which bearings on all points in the field of view can be obtained. In connection with this suggestion for more care in the construction of photogrammetric lenses, attention should be called to the new testing instrument which is now being shown in the exhibit of the National Bureau of Standards. This will enable the distortion in two meridians to be rapidly and accurately determined. It will permit the measurement of small irregularities in the distortion that have at times been neglected in the older methods of lens testing.

There is another possibility for the improvement of photogrammetric lenses, spectacular in character but requiring considerable technological development before it can be successfully applied. At present all photographic lenses are designed with spherical surfaces. This is not primarily because it is easier to design a lens with spherical surfaces but rather because the spherical surface is the simplest surface to construct to precision tolerances. Two surfaces ground together, with relatively simple precautions until a good fit is secured, will be spherical to an amazing degree of precision. The ordinary machine for polishing lenses depends upon this property that a spherical surface has of generating itself, and it is not necessary to build the accuracy in the machine. It is possible, in optical systems, to employ non-spherical surfaces or aspheric surfaces, as they are commonly called. The aspheric surface offers an additional degree of freedom. In general, for a given number of components, the use of aspheric surfaces will produce a better lens, or for a lens of given quality a fewer number of surfaces will be required. Aspherical surfaces have not been used in photographic lenses because of technological difficulties in making them. In this country, such surfaces, produced by pressing, are commonly used in television projection systems where surfaces of the greatest precision are not required and in Schmidt cameras for astronomical photography. For this latter purpose the greatest possible precision is required and each surface is custom made. In Germany, the production of aspheric surfaces has progressed to such an extent that commercially made aspheric surfaces are used in the eyepieces of some of their most popular binoculars. According to the information that I have obtained, the successful routine production of aspheric surfaces sufficiently precise for use in high grade photographic objectives has not been achieved but it is an anticipated step. The application of aspheric surfaces may constitute the next spectacular step in the improvement of photogrammetric objectives.