DEVELOPMENT OF THE ER-55 PROJECTOR*

Russell K. Bean, Chief, Section of Photogrammetry, Topographic Division, U. S. Geological Survey

Definition

THE ER-55 projector (Figure 1) is a new kind of photogrammetric projector for stereoplotting by the direct double-projection method. The principal distinctive feature of the instrument is that the light for projecting the image is condensed by an ellipsoidal reflector instead of by a condensing lens system. The designation "ER-55" is derived from two of the physical properties of the projector: "ER" signifies "ellipsoidal reflector," and the principal distance of the projector is 55 millimeters.

Objectives of the Development

The development of the ER-55 projector was planned and carried out in accordance with three guiding principles:

First, it was recognized that there are certain exploitable advantages in double-projection instruments, such as the Multiplex. These advantages are:

1. Low initial cost.
2. Low maintenance costs.
3. Ease of operation, requiring brief training.
4. Minimum of moving parts, including a stationary light source.
5. Direct anaglyphic viewing of projected images.
6. Rapid stereotriangulation.

Russell K. Bean

Second, it was recognized that previous instruments of this type had certain disadvantages, namely

1. Loss of resolution due to the process of greatly reducing the aerial negative to a small diapositive in the diapositive printer.
2. Poor illumination.
3. Limit of permissible magnification imposed by resolution and illumination limits.
4. Aberrations of the condensing lens system.

Third, it was recognized that if a practical instrument could be developed retaining the advantages of the simple double-projection instruments while overcoming previous disadvantages, the product would be one of great usefulness, efficiency and economy for both vertical and low-oblique photography. In the light of these general guiding principles, the specific objectives of the development can be stated as follows:

1. Permit the use of a larger diapositive plate in conjunction with wide-angle photography and thereby provide increased resolution in the stereoscopic model over that presently afforded in the Multiplex.

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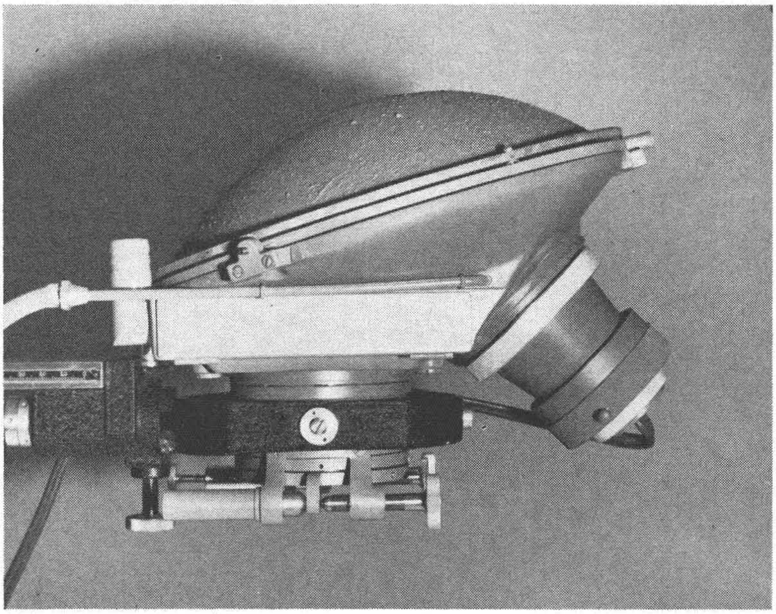

FIG. 1. ER-55 projector.

2. Provide improved lighting over that afforded in the Multiplex; in particular, provide increased illumination in the corners of the stereoscopic model.
3. Provide increased magnification of the projected image as compared to the image on the negative.
4. Eliminate the condenser lens with its attendant chromatic and other aberrations, and its relatively high cost.
5. Attain compactness without the use of moving parts.
6. Permit versatile and effective use of the projector for either vertical or low-oblique photography.
7. Provide a projector that can be reproduced in large quantities more economically than those using either condenser elements of glass or moving-type illuminating systems.

PRINCIPLE OF THE ER-55 PROJECTOR

The principle of the new projector is based on a well-known property of a concave mirror conforming to a prolate ellipsoid of revolution (see Figure 2); light rays emanating from a light source located at one focus of the ellipsoid are directed by reflection toward the second focus. The main components of the projector, namely the light source, the reflecting surface and the projection lens, are so configurated and oriented as to exploit this property. It will be noted that the reflector is unsymmetrically positioned with respect to the axes. A diapositive plate, *F*, is suitably positioned in the system at the appropriate principal distance from the lens. Light rays emanate from the light source at one focus, *B*, of the ellipsoid of revolution, pass through a red or blue filter and strike the ellipsoidal reflecting surface, *S*. The rays are then reflected so that they pass through first the diapositive, *F*, then the projection lens, *A*, at the second focus, and thence to the platen of a plotting table. This system results in the projection of the image of the photography in a color corresponding to the color of the filter.

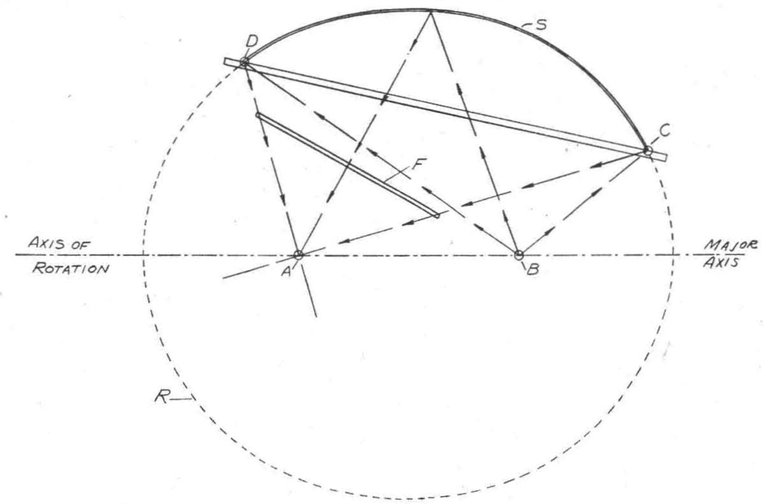

FIG. 2. Paths of light rays within prolate ellipsoid of revolution.

From this point on, the operation is the same as that of multiplex-type instruments.

In the ER-55 system, the available light is used with a high degree of efficiency, and an anaglyphic space model having high qualities of brightness, definition and freedom from aberrations is produced when an overlapping pair of images is viewed through spectacles corresponding to the filters. As in the Multiplex, polarized filters or a synchronized shutter arrangement may be substituted for the colored filters and spectacles. A vital feature of the system is that no light rays pass directly from the light source to the lens through the diapositive; as a result, there is no "hot spot" caused by direct light rays, and the light distribution is relatively even. The reflecting surface consists essentially of only that portion of a complete ellipsoid required for the reflection of the bundle of rays which encompasses the entire area of the diapositive, with the lens as a perspective center for the reflected rays. This surface is represented by *S*, extending from *C* to *D*.

HISTORY OF THE DEVELOPMENT

The principle outlined above was originally conceived early in 1945, and it took some seven years to transform it to a practical working instrument. In 1945, the author discussed the basic ideas of the invention with Mr. T. P. Pendleton, then Chief Topographic Engineer of the Geological Survey, and Mr. C. H. Davey, then Chief of the Section of Photo-Mapping. As a result of these discussions, the Geological Survey authorized a project to be set up for producing a prototype pair of projectors having an ellipsoidal reflector as a part of the light system.

A search was then made to locate a manufacturing process of sufficient refinement for the production of mirrors of the required precision, but the results were discouraging; however, in 1946, the author observed the electroforming process (described below under "Fabrication Problems"), at the Engineer Research and Development Laboratories, Ft. Belvoir, Va., and it was immediately apparent that this process would open the way for the successful fabrication of the special mirror to precise specifications. It was determined that mirrors conforming exactly to the rigid geometric requirements could be produced by electroforming to a glass blank in the form of an extremely precise prolate ellipsoid of revolution.

Preliminary drawings of the device were prepared in 1948 by the Photogrammetry Section of the Topographic Division Staff, U. S. Geological Survey. The actual construction of the pilot model was begun in 1949 and soon encountered a formidable obstacle in the difficulty of fabricating the precise glass blank. This difficulty was eventually overcome and the first pair of ER-55 projectors was completed in time for demonstration to participants in the International Congress of Photogrammetry, at Washington, in September, 1952. The first tests, made immediately upon completion of the pilot pair of projectors, gave extremely encouraging results with respect to resolution and illumination. As was to be expected, there were some minor mechanical "bugs" which have since been ironed out. The actual compilation of maps using these projectors is currently being undertaken, on an experimental basis. Finalization of the design will be based on the experience obtained in the test compilations.

The U. S. Department of Justice has filed an application for a patent on the device, in the author's name. All rights in the patent have been assigned to the Government of the United States.

Problems of Design

The primary problem in designing the ellipsoidal-reflector projector that would fulfill the desired objectives was to determine suitable values for the following interrelated factors: size of diapositive, principal distance and projection distance of the projector, focal length of the projection lens, and size and shape of the ellipsoid. Figure 3 shows the design finally adopted.

To obtain better resolution than is afforded in the Multiplex, it was obviously necessary to increase the size of the diapositive. At the same time, the amount of increase in size was limited by the necessity of maintaining compactness in the instrument so that a sufficient number of projectors could be mounted on the supporting frame for convenient aerotriangulation. After several trial calculations involving the interrelated factors, the principal distance was determined to be 55 millimeters. On the basis of the chosen principal distance and the geometry of wide-angle photography, a diapositive size of 110- by 110-millimeters was chosen. This is approximately twice the size of Multiplex diapositives and half the size of contact diapositives (for a 9- by 9-inch negative format). The desired optimum projection distance was then determined from a consideration of the desired plotting scales, the anticipated *C*-factors, and appropriate spacing of projectors on the supporting frame. The most suitable projection distances were determined to be 518 millimeters for vertical photography and 508 millimeters for low-oblique photography.

With the principal distance and projection distance established, the required focal length of the projection lens was then determined from the lens law to be 49.9 ± 0.3 millimeters. In making the necessary calculations, the optimum projection distance applicable to low-oblique photography was used, as the projector focal length value is more critical for low-oblique than for vertical photography.

The size and shape of the ellipsoid were arrived at by determining the most compact physical arrangement that would accommodate the lens placed at one focus, the light source at the other focus, and the diapositive plate properly placed at the correct principal distance from the lens. The focal separation and the length of the major axis were chosen to give the smallest ellipsoid that

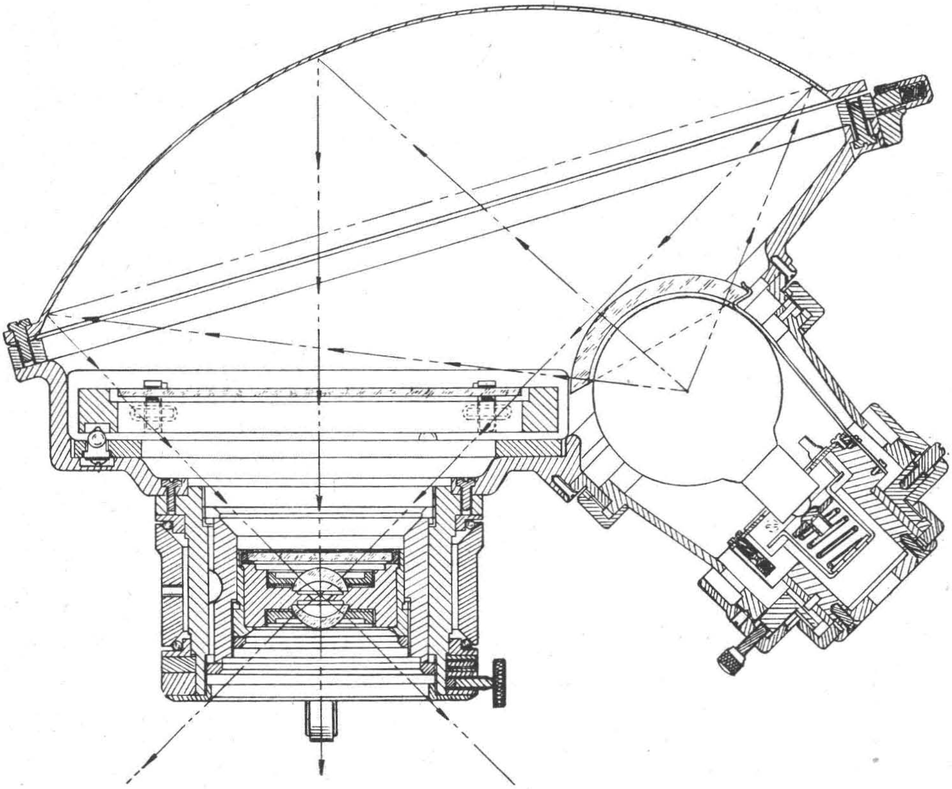

FIG. 3. Cross-section of ER-55 projector.

would physically accommodate the parts and provide necessary clearances. The portion of the ellipsoidal surface used in a projector is limited by the intersection with the ellipsoid of the wide-angle cone of rays whose axis passes through the principal point of the diapositive and whose perspective center is at the rear node of the lens.

The light source selected was a 5-ampere 20-volt globular-type lamp of the kind used in some Multiplex projectors. This light source has not been entirely satisfactory, as it is not sufficiently close to a point source, and also because striations in the glass sometimes show up in the projected image. The filters are made of red and cyan-colored glass, curved to fit over the lamp with the filament as the center of curvature so as to reduce reflection at the surfaces of the filter.

The problem of light distribution in the system was one that had to be worked out carefully in advance. In previous applications of the ellipsoidal-reflector principle, the lens, light source, and center of the reflector lay in an otherwise unobstructed straight line on the major axis of the ellipsoid; as a result, both direct and indirect rays from the light source passed through the lens, giving rise to a "hot spot" and very uneven distribution of light. In the ER-55, the reflector is unsymmetrically positioned so that no light rays pass directly from the light source to the lens through the diapositive; the "hot spot" caused by the direct light rays is eliminated and the light distribution is relatively even.

Another important consideration in the design was that the instrument should be simple, for ease and economy of fabrication. It will be seen that, once the master mold for the reflectors is available, ER-55 projectors can be manufactured in large quantities quite economically.

The arrangement for converting the projector from use with verticals to use with low-obliques, involved two design problems: providing a convenient twenty-degree-step tilt adjustment, and providing a convenient means of canting the lens for best imagery, in accordance with the Scheimpflug condition. The twenty-degree tilt is obtained by inserting a twenty-degree wedge between the yoke and the y-bar. To meet the Scheimpflug condition, the lens is eccentrically mounted in a rotatable sleeve. By rotating the sleeve to predetermined positions, the lens can be correctly oriented for either vertical or low-oblique operation.

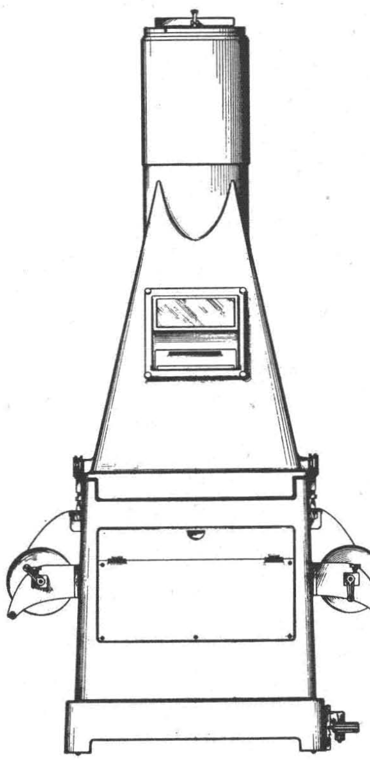

FIG. 4. 153/55 diapositive printer.

A companion design and development problem, carried on concurrently with the development of the ER-55 projectors, has been the production of a highly efficient diapositive printer designed for the specific purpose of making diapositive plates for these projectors from 6-inch focal length photography. Heretofore, diapositive printing has been a weak link in the chain of photogrammetric operations in systems using small-size diapositives. The new printer, recently completed in prototype form, is capable of capturing and transferring to the diapositive practically all of the detail appearing on the negative. This printer was constructed by the Geological Survey using optical parts furnished by Wild of Switzerland, including a virtually-distortion-free high-resolution lens and an aspheric correction plate. Figure 4 shows the latest design of the new printer, which will not be discussed in detail at this time.

FABRICATION PROBLEMS

The difficulties of developing the ER-55 projector were by no means confined to problems of design. There remained some formidable manufacturing problems before the first pair of projectors could be delivered. The discussion of fabrication problems that follows is limited to the construction of single ER-55 projectors, and will not include the problems of mounting the projectors in the Twinplex plotter.

The most difficult of the manufacturing problems was the production of the precise ellipsoidal glass blank to be used as the pattern about which the reflecting surface is electroformed. The rough blank was made of high-quality glass by the Corning Glass Works. The blank shown in Figure 5 was the first to be produced successfully. It was delivered by Corning to J. W. Fecker, Inc., of Pittsburgh, Pa. who had the contract for finishing and polishing the ellipsoid to its final precise dimensions. The problem confronting the Fecker Company under this contract was unprecedented. The machine shown in Figure 6 was designed

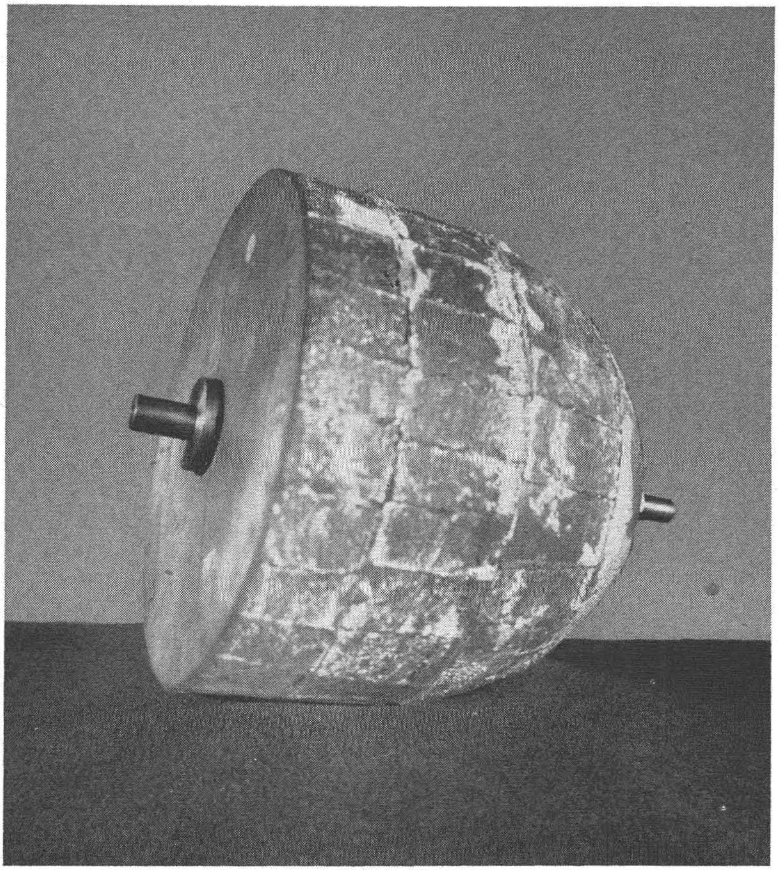

FIG. 5. Rough glass blank produced by Corning Glass Works.

and built by the Fecker organization solely for the grinding and polishing operations required on this job. The hazardous operation of reducing the blank to the precise dimensions required was successfully completed after many weeks of painstaking effort. A testing apparatus, especially designed for the purpose, was then set up for inspecting the finished blank for conformance to specifications. This apparatus is shown in Figure 7. Following the acceptance of the finished blank, it was delivered to the Geological Survey.

The electroforming operation for producing the mirror from the glass blank was done under contract by the General Electroforming Laboratories of the Silver Shop, Washington, D. C. In this process, a thin coating of silver is first plated on the glass blank for permanent protection. A coating of non-bonding material is then applied to the entire surface. The reflecting surface is then formed by electro-depositing silver (or other suitable material) on the non-bonding coating. Copper is next deposited to a thickness of 3/32 inch, to form the body of the reflector. When the reflector is removed, it is thus composed of a copper backing with a silver reflecting surface on the concave side. Although silver was used for the prototype projectors as an expedient, the reflecting surface will eventually be made of a metal less subject to tarnishing.

The specification for the reflecting surface required that it shall be free

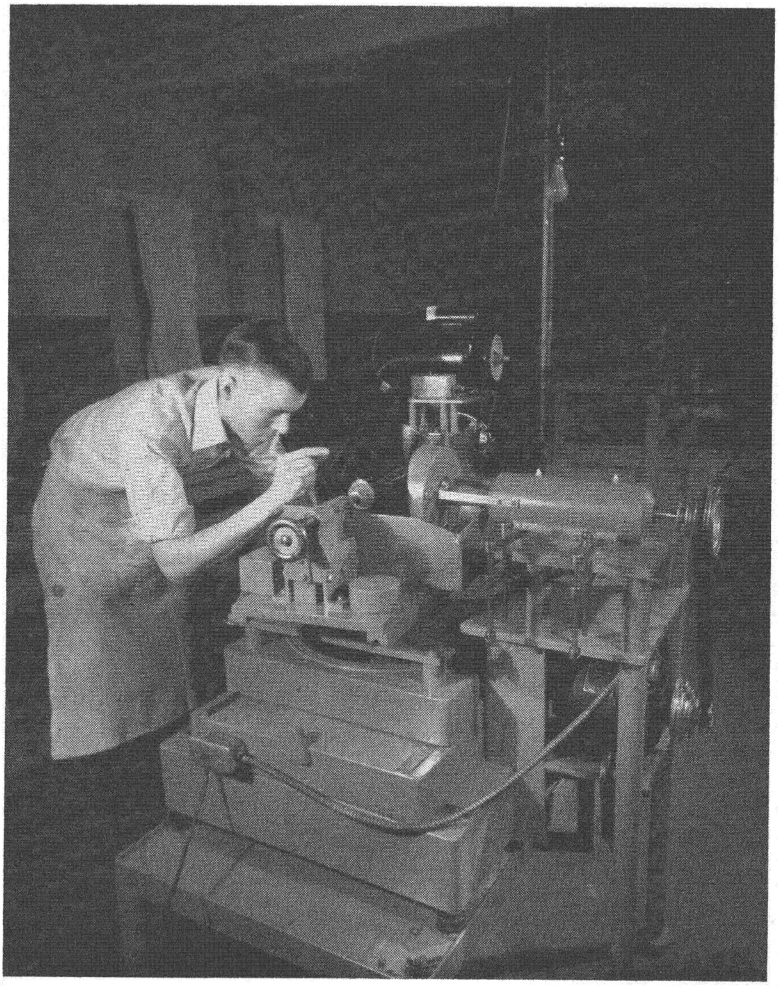

FIG 6. Machine built by J. W. Fecker, Inc. for grinding and polishing prolate ellipsoidal glass blank.

from lumps, dents, peeled areas, blisters, copper spots and stains, orange peel effect, and other blemishes. It was further stipulated that the reflector surface shall have a reflectivity at all points of the surface of not less than 70 per cent of the incident light. As only a portion of the complete ellipsoid is required for each reflector, and a glass blank approaches a complete ellipsoid in extent, three reflectors can be electroformed simultaneously.

Planned Use of the ER-55 by the Geological Survey

The Geological Survey is contemplating the utilization of the ER-55 projector in the following ways: (1) as a vertical projector for compiling or bridging with vertical photography; (2) as a low-oblique projector for compiling single-model convergent or transverse photography; and (3) in the Twinplex plotter for bridging with low-oblique photography.

For using vertical photography, and for compiling single-model low-obliques, the ER-55 projector can be mounted on a standard multiplex supporting frame

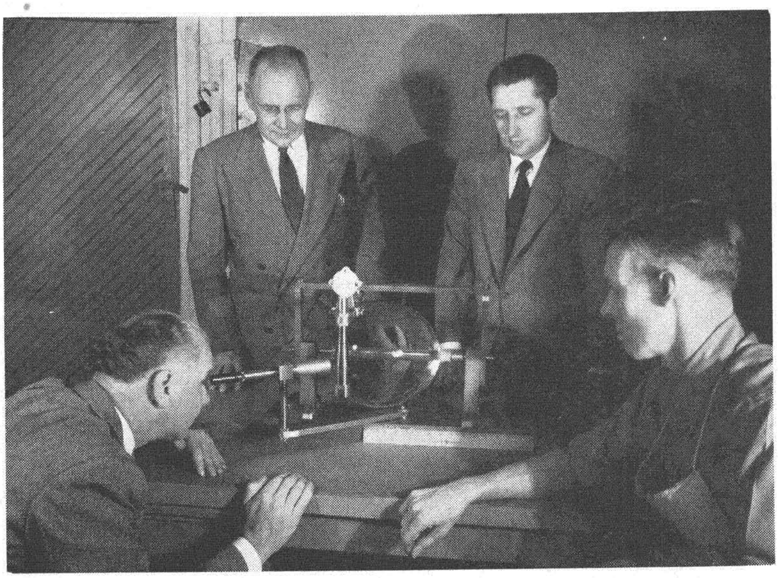

FIG. 7. Checking the finished prolate ellipsoidal glass blank.

for either vertical photography (Figure 8) or convergent photography (Figure 9). In order to obtain the increased projection distance, a simple casting is inserted under the supporting frame at each end of the table.

The advantage of using the ER-55 projectors for mapping with vertical photography is that the project can be planned with a high C-factor, as compared to the Multiplex, because of the improved illumination and resolution, and larger scale.

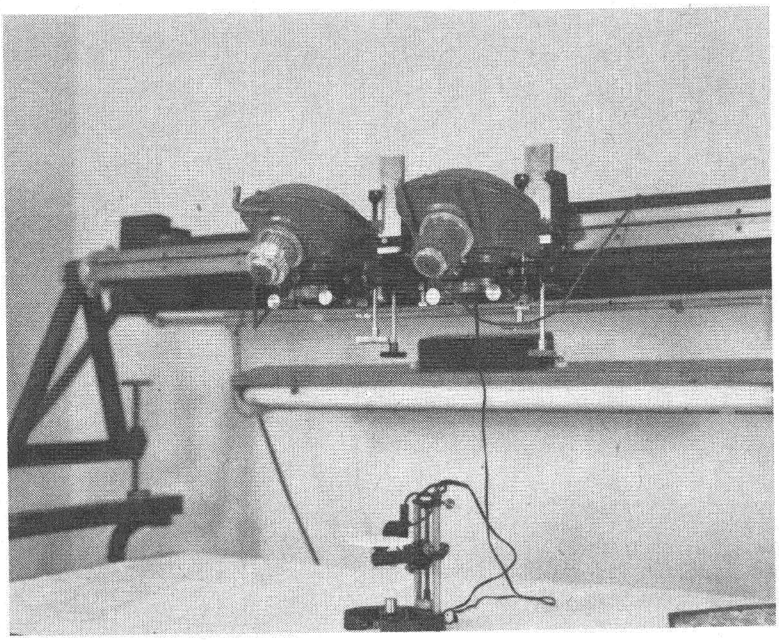

FIG. 8. ER-55 projectors mounted on standard multiplex supporting frame. The projectors are arranged for vertical photography.

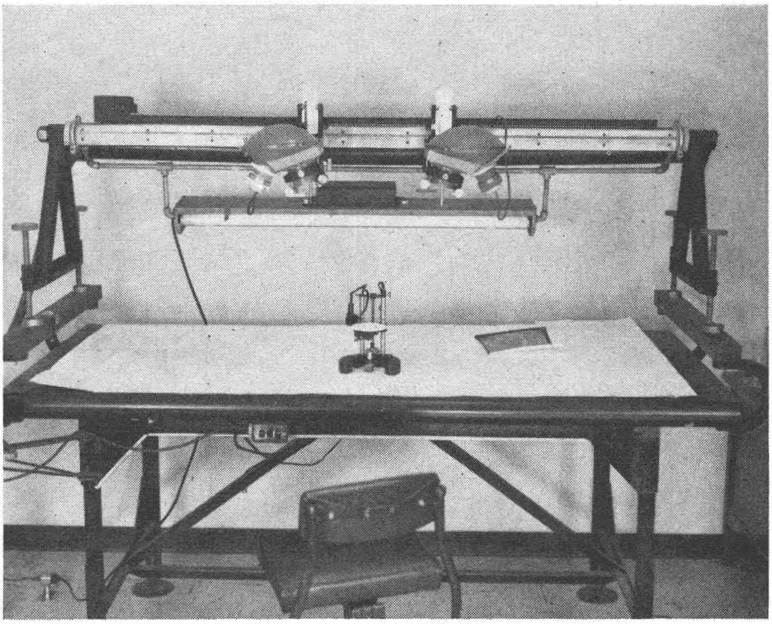

FIG. 9. ER-55 projectors mounted on standard multiplex supporting frame. Projectors arranged for convergent photography.

The use of ER-55 projectors for compiling single-model convergent photography, as shown in Figure 9, will provide, in addition to improved illumination and resolution, and larger scale, all the inherent advantages of convergent photography that have recently been under discussion.[1]

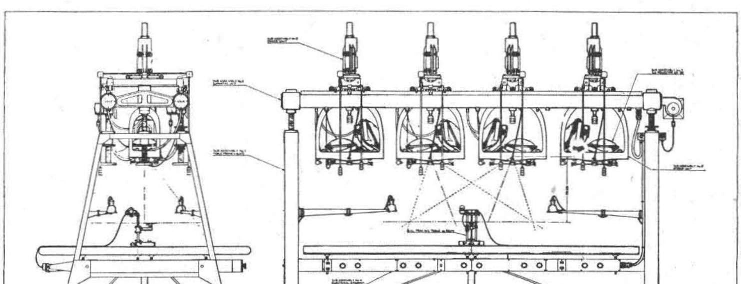

FIG. 10. Twinplex Plotter fitted with twin ER-55 projectors.

Figure 10 shows a Twinplex Plotter fitted with four twin ER-55 projectors. With this instrument, stereotriangulation of low-oblique photographic flights can be accomplished. A simple swing adjustment applied to each projector couple makes this instrument readily applicable to the bridging of either convergent or transverse low-oblique photography. The use of the Twinplex Plotter

[1] Radlinski, W. A., Convergent Low-Oblique Photography and Its Application to the Twinplex, PHOTOGRAMMETRIC ENGINEERING, June 1952.

is fully described in Geological Survey Circular 222, *Twin Low-oblique Photography and the Twinplex Plotter*, which can be obtained free on application to the Director, U. S. Geological Survey.

As a bridging instrument, the Twinplex Plotter with ER-55 projectors is expected to provide unprecedented advantages. When used with convergent photography, it will have a high *C*-factor (estimated as at least 1,000), resulting from both the more favorably base-height ratio and the better resolution and illumination. This will permit higher flying for the same degree of accuracy. The higher flying, together with the increased base-height ratio, will result in

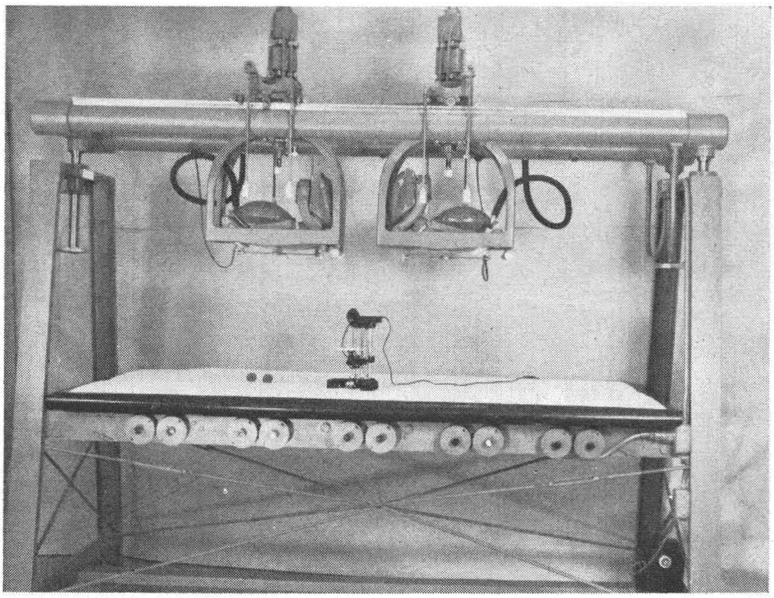

FIG. 11. Geological Survey Twinplex Plotter fitted with two twin ER-55 projectors units. When completed four twin-projector units will be mounted on this instrument.

an area coverage per model equal to several times that of a Multiplex model for the same degree of accuracy, thus leading to obvious savings in the costs of control and compilation. When used with transverse low-oblique photography, the Twinplex Plotter with ER-55 projectors is not expected to have a higher *C*-factor than the Multiplex, but it will have the advantage that flights can be spaced about twice as far apart as flights to be compiled on the Multiplex. Again, there are obvious savings in the costs of control and compilation. Figure 11 shows the Geological Survey Twinplex Plotter fitted with two twin ER-55 projector units. When completed four twin-projector units will be mounted on this instrument.

CONCLUSION

The ER-55 projector meets certain requirements, promises certain economies and constitutes a step forward in the field of simple double-projection instruments. It is expected that it will take its proper place with other photogrammetric instruments, each of which fills a certain need and is best adapted for the performance of certain jobs. The extent to which the ellipsoidal-reflector projector will be used in the future, cannot be determined at this time while it is still in the experimental stage. Until the instrument is given a fair trial, it is the better part of wisdom to be cautious in estimating the scope of its future application.

As a concluding note, it should be made clear that the development of this new projector was not a one-man operation. The author received invaluable assistance in the conception stage from Mr. Heinz Gruner, now of Bausch & Lomb Optical Company. Neither does a finished product result from an idea unless it is given organizational support. In this respect I am grateful to Messrs. Gerald FitzGerald, Chief Topographic Engineer of the Geological Survey, and George D. Whitmore, Chief of the Technical Staff, who whole-heartedly backed the development of the ER-55 projector. Finally, credit is due to the technicians in the author's Section who labored diligently through a mountain of theoretical data and design calculations to make this instrument a reality.

DISCUSSION OF RUSSELL BEAN'S PAPER "DEVELOPMENT OF THE ER-55 PROJECTOR"

DR. K. PESTRECOV, Optical Consultant

Mr. Bean described the ER-55 Projector so well, that there is practically nothing that I can add. Still, I can say something that he did not because of the modesty of an inventor. This is an extraordinary development. I should say even revolutionary, if this term has not been abused by commercial advertising.

DR. K. PESTRECOV

What is so extraordinary? Is it not just another scaled-up model of the Multiplex projector? Yes, it is! But, it has its own foundation and special features which required an insight, imagination and organizational daring.

All of these qualities were needed to make the engineering and managerial decision that it would be a good gamble to design a Multiplex-type projector which would stand somewhere between the original Multiplex and its extremely ingenious modification by Kelsh.

There were two relatively easy ways to the solution of the design problem. If something in between seemed promising, the swinging light source, as used by Kelsh, could be adapted without major difficulties. The other approach could be to use a scaled-up Multiplex condensor. Mr. Bean rejected both available solutions because of good engineering reasons. He chose a third one, an entirely unexplored and unusual approach.

Some people may say that there is nothing unusual in utilizing an elliptical reflector as a condensing element. Correct! Elliptical reflectors have been used for a very long time, and one may add that off-axis aspherical reflectors, such as paraboloids, also have been used. But I at least do not know of any previous

* Paper read at Nineteenth Annual Meeting of the Society, Hotel Shoreham, Washington, D. C., January 14 to 16, 1953.

application of an off-axis ellipsoid as a condensor in a precision wide-angle system. Its incorporation in the illuminating system was a daring decision by the research and development section of the U. S. Geological Survey. This decision so far as I know, was made despite some warnings by qualified optical men that the system may not produce satisfactory results. Even I, despite my curiosity for exploring the unknown, and my usual optimism, could not go in my discussions with Mr. Bean, any further than to say that, of course, the reflector will throw a large quantity of light on the diapositive, but this light would probably be distributed in zones which may not be tolerable. As we can detect now, there are some illumination zones in the projection plane. However, they are hardly perceptible in the image of the terrain. To me, a curious optical man, the most unfortunate fact is that these zones apparently originate from the optical imperfections of the glass of the bulb. I should like to break that bulb, just to see what the reflector does by itself.

With the excellent general background of this development, two minor critical remarks should not sound too discordant.

Mr. Bean said that it was obviously necessary to increase the size of the diapositive in order to obtain better resolution, and he referred to some computations substantiating this statement. I have not seen them, but I know that computations of this nature cannot be entirely reliable. The final proof should be in actual measurements. Quantitative data were not given in Mr. Bean's paper. That is a fault. However, I make this remark purely for its rhetorical value. Even without such data, we may expect that, provided a good optical system is used, the image produced by ER-55 Projector should be better than we observe under the Multiplex. The major factor is the larger ultimate image scale of the former. Many recent investigations, particularly those conducted at the Boston University Optical Research Laboratory under the direction of Dr. Duncan E. Macdonald, indicate that many factors besides resolution of minute detail, are of importance for satisfactory recognition of images; among these factors, magnification occupies a place of prominence. It should not be forgotten that in using a photogrammetric system we are primarily concerned with the ability of the operator to detect and recognize significant detail rather than with some abstract evaluations of optical resolution.

My second criticism is directed toward the implication by Mr. Bean that an elliptical reflector has an inherent advantage over a refractive condensing system because the latter is afflicted with aberrations. Please be assured that the original Multiplex condensor is a system with an excellent correction of monochromatic aberrations, and that its chromatic aberrations have been reduced to an acceptable minimum. An elliptical reflector is inherently achromatic, but its monochromatic aberrations are not negligible when a source of substantial size is used.

Then why do we have more light with the ER-55 Projector? The answer is not simple. Forgetting some usual fallacies about condensing systems, the basic factors which determine the usable light in a projection system are: the magnification, the *f*-number, the transmittance losses, and the brightness of the source. The same source is used in both the standard Multiplex projector and in the ER-55. The magnification of the U.S.G.S. Multiplex projector is 12, and its basic *f*-number is about 12. The "*effective*" *f*-number of this system is $13 \times 12 = 156$. The magnification of the ER-55 is about 9, and its basic *f*-number is 16. Its "*effective*" *f*-number is $10 \times 16 = 160$. Thus the "effective" *f*-numbers of both systems are nearly the same, with the Multiplex having a slight advantage. The only factor that apparently can account for a higher illumination with the ER-55 is a major difference in the transmittance losses of the two systems. Another hidden factor may be in the possibility that the ER-55 utilizes a more favorable aspect of the source filament, with the resultant increase of the actual collected light. It would be an interesting project to investigate the theoretical and empirical causes of the increased amount of the projected light by the ER-Projector. And, of course, it would be highly desirable to have quantitative data.

Mr. Bean properly gave the credit to all those who participated in the development of this new unusual device. For historical interest, I may add that several years ago the possibility of utilizing an elliptical reflector was discussed with me by the members of the Engineer Research and Development Laboratories at Fort Belvoir, and that I was rather pessimistic about this idea. As I understand, the project was never given sufficiently high priority and eventually was abandoned.

I may emphasize also the very excellent work done by the Corning Glass Company in overcoming the difficulties involved in producing a very satisfactory glass blank; by the Fecker Company in finishing the blank to an accuracy usually unobtainable for such products in ordinary manufacturing practice; and by The Silver Shop in producing replicas of excellent optical quality.

Summarizing, I may say that we witnessed today the presentation of a new development which may become another milestone in the history of optics and of photogrammetric instruments.

MR. JOSEPH KALLA (President, J. W. Fecker, Inc., Pittsburgh, Pennsylvania):

We had a choice of crown glass, which we preferred and found unavailable, and pyrex which Corning was willing to work with.

The initial stages of grinding the glass were handled on a simple lathe. The blank was a solid glass blank with a hole bored through it longitudinally. It was mounted between centers and brought down to a rough dimension approaching the finished size.

For the intermediate stages of grinding, we built a special machine; this was designed by our Engineering Department. It is essentially an elliptograph. Diamond wheels were used in the final grinding stages. The happy coincidence at the very end of a suitable finished surface which was also to the proper dimensions is due in no small measure to the skilled individual technician involved. This was Mr. McGuire, the head of our Precision Optical Shop.

A very special test set up was shown in another slide. It was Mr. Bean's suggestion which we modified in some small measure, for the application.

Originally we had a great many doubts about the possibility of producing a spheric surface by this method. In the light of our experience with this particular project, we have concluded that the very same method could be used for the production of other similar forms.