THE READING PLOTTER

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THIS discussion may well be regarded as a brief preliminary report upon the instruments associated with the nine-lens camera and their operation as employed in the Division of Photogrammetry of the Coast and Geodetic Survey in the production of topographic maps. Although the system has been demonstrated to work satisfactorily, it is being steadily perfected to give greater production, greater accuracy, and lower mapping costs. A more detailed report is to follow when a few obvious improvements have been applied, when the second plotter is placed in operation, and when more data are available.

The stereoscopic mapping instrument has been in successful operation with nine-lens photographs[1,2,3], since February, 1945. It is a precision instrument for producing an orthogonal projection of contours and planimetry from untilted photographs at their datum scale. It is constructed large enough to accommodate the 35×35-inch photographs resulting from the special nine-lens camera of this Bureau. The instrument is universal in the sense that it may be used correctly with any focal length, angular field, or ratio of photographic enlargement or reduction.

The device is the crowning unit of four separate instruments, which includes the nine-lens camera[1,2,3], the transforming printer[2], and the rectifying camera[4]. Each of these was developed under the direction of Commander O. S. Reading, assisted by Thomas W. McKinley, John F. McGinley, Reynold E. Ask, and others. The parts for the plotter were made by the J. G. Saltzman Co., New York, and it was assembled and adjusted in Washington, D. C., by the Coast and Geodetic Survey.

The plotter was designed primarily to function along with the other three special units to meet a specific need of the Bureau in mapping at large scale in rugged and intricate coastal areas where control is sparse and where single-lens photography is at a disadvantage. The instrument is dependent upon the transforming printer to furnish a composite photograph equivalent to a single lens, wide-angle near-vertical one, from the one vertical and eight oblique views on the negative; it is dependent upon a radial line plot for bridging between horizontal control points, and for furnishing map positions of pass points for the making of a rectification templet; and it is dependent upon the rectifying printer for the removal of camera tilt and for the change of scale. Each of the units is large, the camera alone being portable. Because of their close inter-relationship, a brief description is included of each of the other units before discussing the plotter. Some of these descriptions are given in greater detail in previous articles (Footnotes 1 and 2).

THE NINE-LENS CAMERA

The camera (Fig. 1) consists of nine lenses located essentially in a common horizontal plane in front of a film which is 23 inches wide. Eight of the lenses form a regular octagon with the ninth in the center. The lenses are matched

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[1] O. S. Reading, "The Nine-Lens Camera of the Coast and Geodetic Survey," PHOTOGRAMMETRIC ENGINEERING, Vol. 1, No. 5, pp. 6–13, 1935.

[2] O. S. Reading, "The Nine-Lens Camera of the Coast and Geodetic Survey," PHOTOGRAMMETRIC ENGINEERING, Vol. 4, No. 3, 1938, pp. 184–192.

[3] *Manual of Photogrammetry*, American Society of Photogrammetry, Pittman Publishing Company, New York, 1944, p. 120.

[4] *Manual of Photogrammetry*, p. 56.

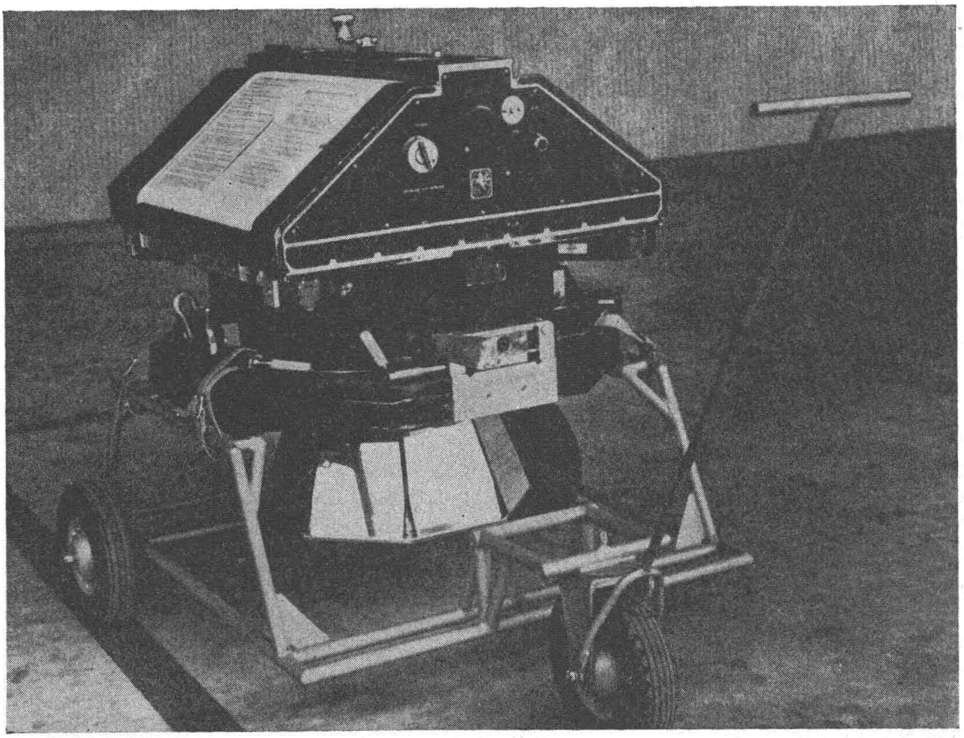

FIG. 1. The Nine Lens Camera.

Ross 68° objectives of $8\frac{1}{4}$-inch focal length. The central lens functions in the normal manner. In front of each of the eight outer lenses is a coated steel mirror inclined at 19° with the vertical, which causes a 38° oblique reverse negative to be formed on the same piece of film in a position separate from the other views. The operation of the nine shutters is synchronized electrically. The film is maintained flat by means of a vacuum back. Forty-five marks are projected onto the film to serve as film measuring or fiducial marks. A clock face and a numbering device are also photographed on each negative. A roll of film is 200 feet long and contains 100 exposures. The camera weighs about 300 pounds without accessories. The camera and transforming printer layouts were submitted to Fairchild Corporation who completed the designs and construction. The adjustment and calibration was done by the Bureau. The original camera was ruined in an airplane crash in Alaska in 1943, in which several lives were lost. The camera had been in use since early in 1937. All the lenses and most of the mirrors were salvaged and used in rebuilding the present or second camera, which was again placed in service in 1945.

THE TRANSFORMING PRINTER

The transforming printer (Figures 2 and 3) was developed in conjunction with the nine-lens camera, along with a device for centering the film in a holder and measuring the shrinkage as indicated by the fiducial marks. Corrections for the amount and direction of shrinkage are applied to the printer in the form of six separate adjustments coupled to dial gauges. The printer is built into a partition to give a photographic dark room on one side.

The instrument is composed of two parts: one for projecting the oblique views and the other for projecting the central portion. For printing the oblique views, the negative holder is placed on a properly inclined wheel whose rotation is synchronized with that of the horizontal paper holder. One view is projected at a time upon the paper, the remainder of the paper being masked to prevent exposure and fogging. The settings of the optical angles and distances obey the usual geometric and optical laws for rectification. For printing the central sec-

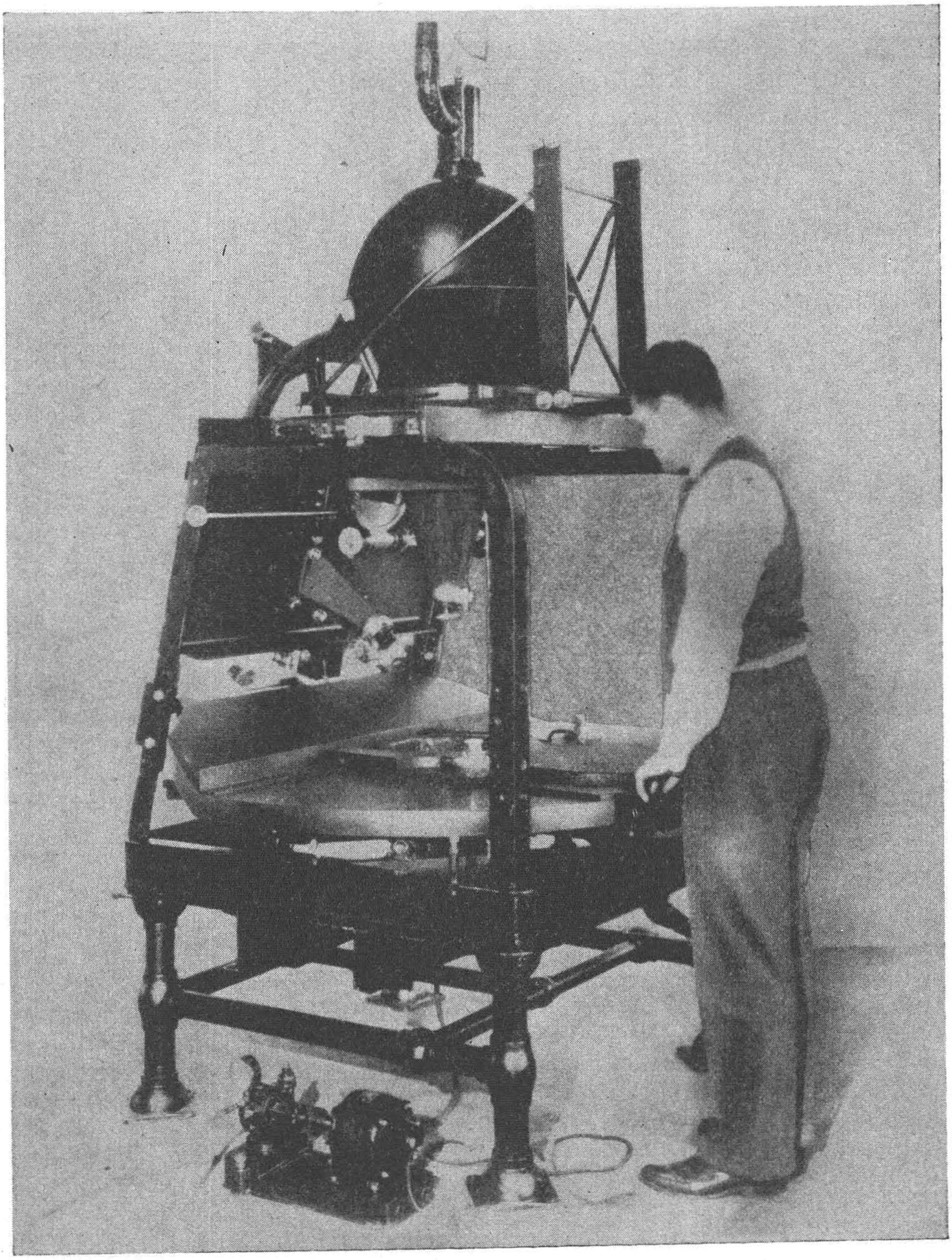

FIG. 2. The Transforming Printer. Darkroom side before installation.

tion, the holder is placed in another position parallel to the paper and the negative is projected at a ratio of about 1:1.

The lenses for the oblique and vertical projectors also match those of the camera. The resulting transformed print is equivalent geometrically to a single lens photograph of 135° angular field, $8\frac{1}{4}$-inch focal length, and taken from the flying height of the original negative. The print is tilted the same as the original camera, which is also that of the central chamber.

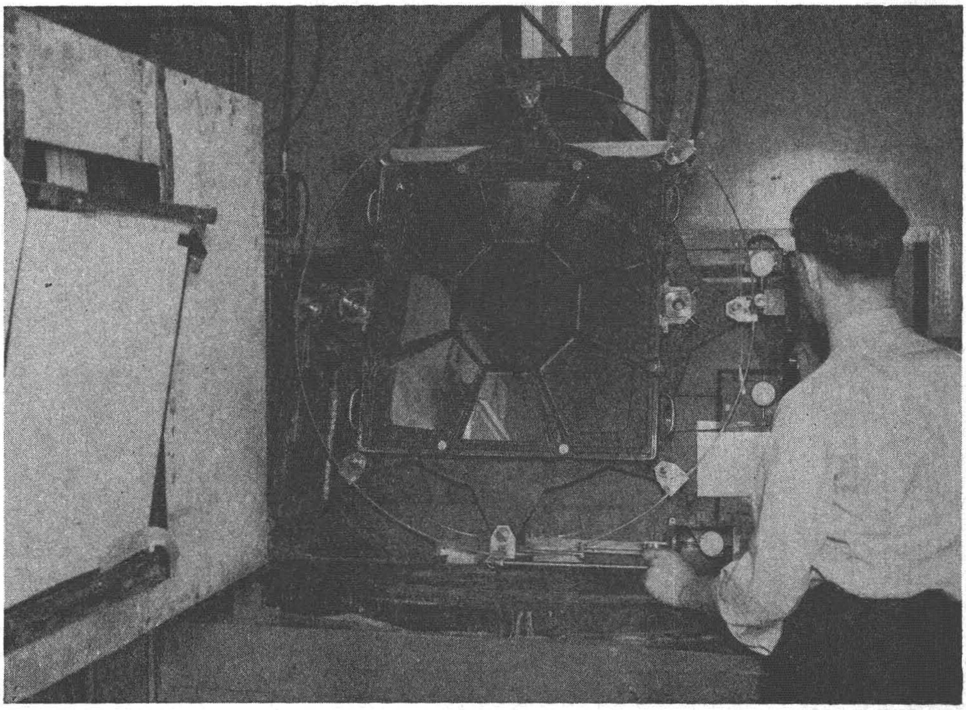

FIG. 3. The Transforming Printer. Daylight side after installation.

THE RECTIFYING CAMERA

The rectifying camera (Figure 4) is constructed on two levels with its axis vertical. It is equipped with a lens of 23-inch focal length to maintain a suitably narrow angular field and good optical characteristics. The device is made large enough to accommodate the nine-lens photographs but is otherwise universal, except that it is limited mechanically to use with near-vertical photographs. It is designed to operate with the system of rectification which refers all settings to the line of centers (principal point line). The planes of the negative, the lens, and the positive (easel) are each normally horizontal, and may be rotated about each of two perpendicular horizontal axes similar to the x-tilt and y-tilt of the multiplex. Graduated circles and verniers are provided for reading the angular settings to the nearest minute. Two vertical linear motions change the positions of the lens and the easel. Scales and optical sights are provided for reading the linear settings to the nearest 0.1 mm, based upon normal settings of zero at 1:1 ratio. The negative or upper plane, which holds the transformed print in position by vacuum, is illuminated with reflected light. The resulting print is ordinarily negative in tone and position, and requires a second photographic

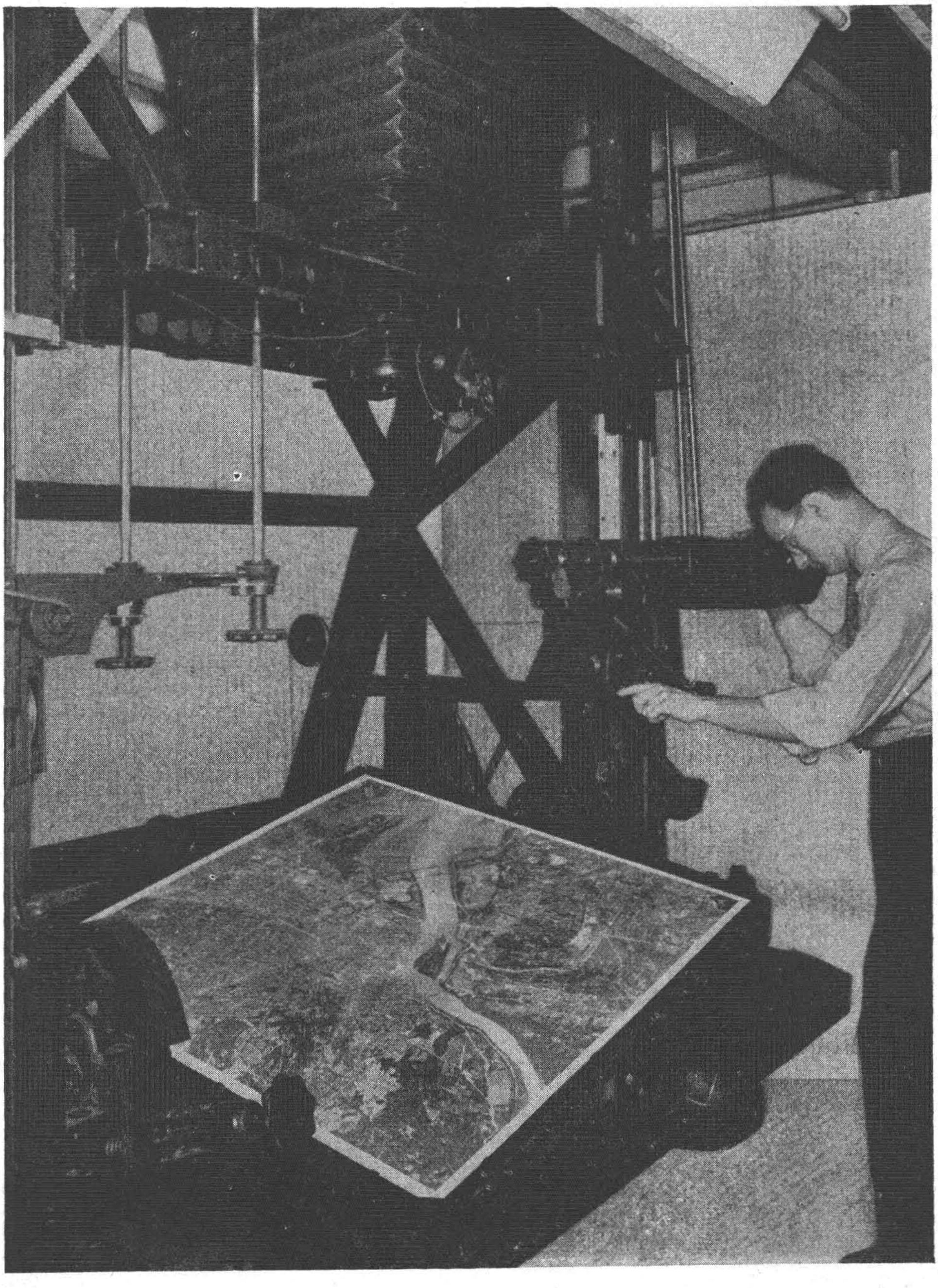

FIG. 4. The Rectifying Camera.

step to produce a positive print. The instrument is also equipped with a focal plane glass plate and transmitted illumination for use with film. It is automatic focus when the planes are not tilted. All settings may be made from the lower level which is obviously a photographic dark room. The rectifier may be used either with computed data, or else with a rectification templet, the settings being coordinated by means of empirical rules and graphs.

The rectifier was designed and constructed largely within the Bureau, with the heavier steel work being done by G. W. Forsberg, Washington, D. C.

THE PLOTTER

The Reading Plotter (Figures 5 and 6) is designed to operate with photographs that have no tilt, which presumes rectification. The map sheet is produced at the datum scale of the photographs, which presumes that all required changes in scale are done prior to the plotting operation and may be combined with the rectification operation, whether the change is due to irregular flying or to the desire for a scale different from that of the negative. Full theoretical correction is accomplished mechanically for the reduction of all planimetry to datum scale regardless of elevation differences, up to the limit of half the flying height. Elevation readings are obtained from an indicator graduated in equally spaced divisions of one-thousandth of the original flying height of the air camera, with tenths of a division estimated. The relation of indicator elevations to flying height remains unaltered by any intermediate common scale change of the photographs.

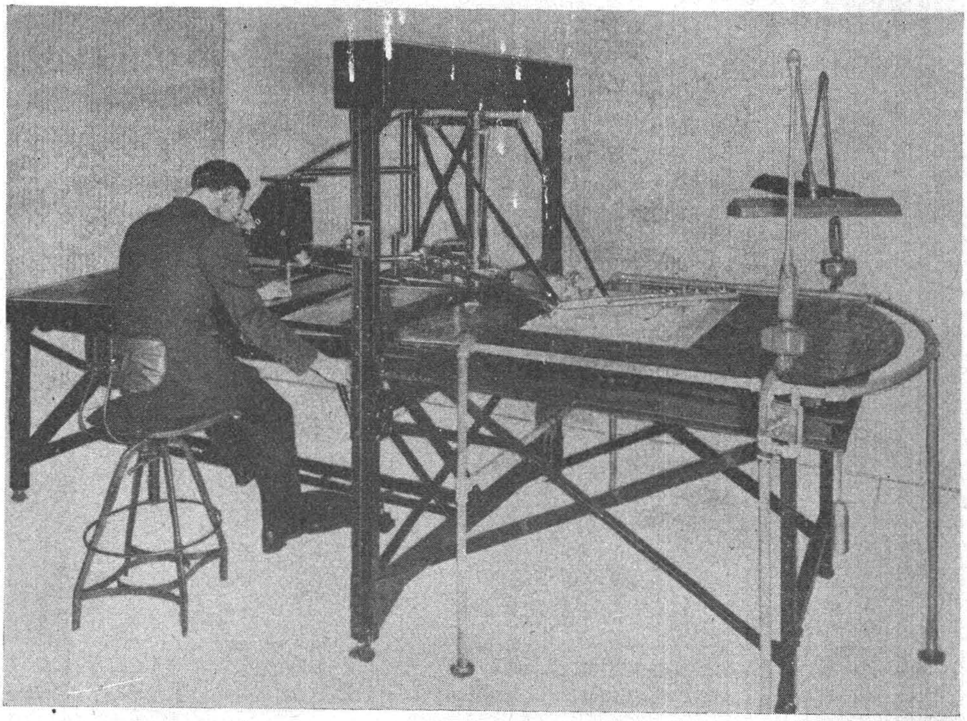

FIG. 5. The Reading Plotter.

The stereoscope is suspended so that it may be moved freely above the surface of the photographs. It is maintained parallel by steel bands in a manner similar to some drafting machines. Movement of the stereoscope is accomplished by means of a convenient handle whose operation is similar to a pencil. The operator views the photographs from a seated position, obtaining a two-time magnification and a field of view of about two inches in diameter. The instrument may be operated from either side by rotating the eyepieces through 180°.

The floating marks are fixed small black round dots on reticles mounted in the optical trains of the stereoscope. The operator moves the stereoscope to make the floating index mark appear to trace the photographic images, which drives the pencil point of the pantograph correspondingly. The floating mark is made to appear in contact vertically with the image by the use of a foot wheel. The objectives of the stereoscope are about forty inches apart, and the stereoscope is mounted off-center.

The photographs are clamped with their nadir points at the centers of their respective tables. They are oriented by rotating the tables individually to obtain stereoscopic fusion. They may be separated by the horizontal motion of the outer table through a special hand wheel. In practice, the elevation of a given control station is set on the indicator by the rotation of the footwheel, and then the photographs separated with the hand wheel until stereoscopic vision is afforded and the floating mark rests on the image. This sets the air base. The floating mark is made to ascend or descend by use of the footwheel which changes the separation of the photographs also by moving the outer photograph. A limited transverse motion of the inner photograph can be used for the removal of any residual y-parallax, which amount is registered on a counter.

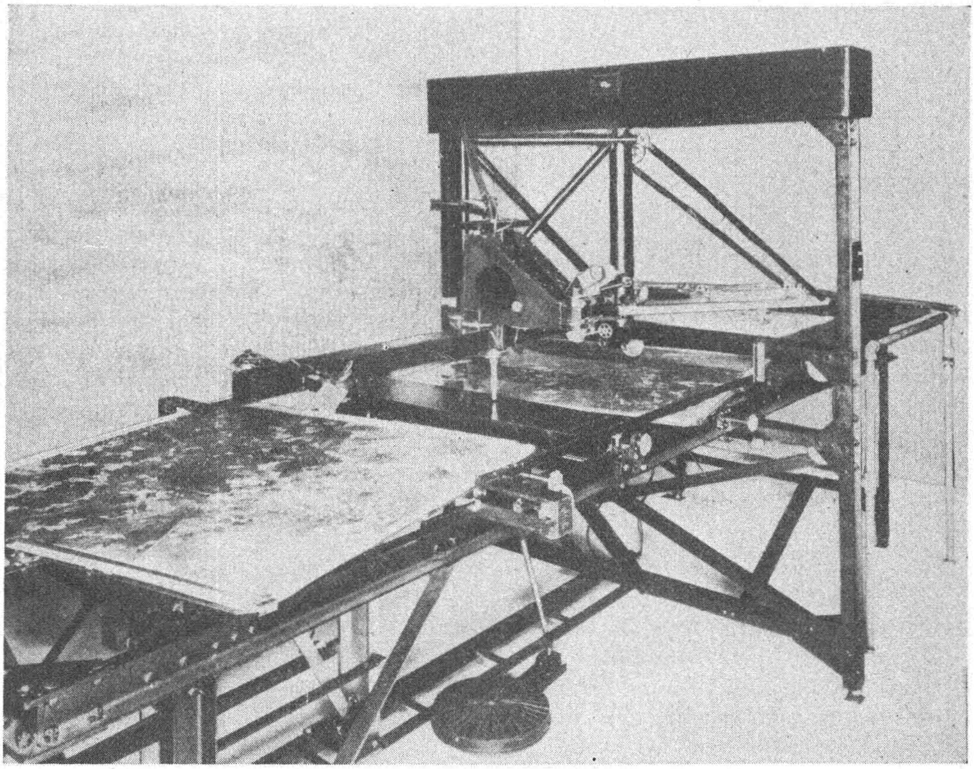

FIG. 6. The Reading Plotter.

The effect of rotating the footwheel is four-fold: (1) It causes an apparent change in the vertical position of the floating mark; (2) It operates a mechanical computer to show the result in terms of elevation difference on the indicator; (3) It changes the plotting scale of the pantograph correctly as a function of elevation; and (4). It changes the position of the map sheet table to correspond to the change in the operating dimensions of the pantograph, which is explained more fully later.

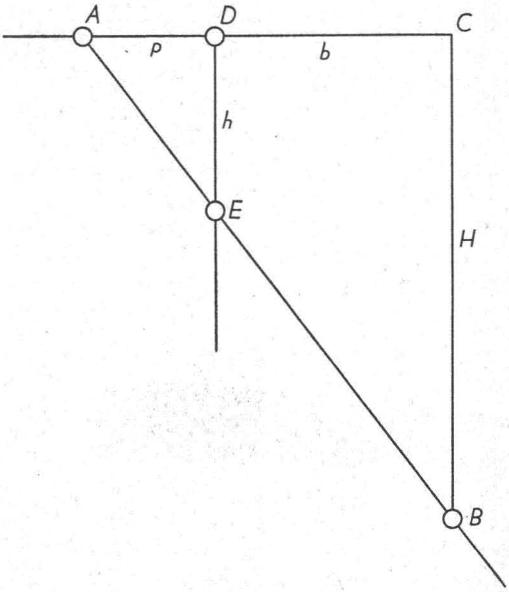

FIG. 7. Schematic Diagram of the Elevation-Computer Mechanism.

The operation of the computing device as driven by the footwheel is quite fundamental. The triangle ABC and the line DE (Figure 7) represent a mechanical linkage which is located beneath the outer photograph. A fixed right angle is at C, and a fixed distance BC represents the flying height H of the photographs. The distance CD is generated by the air-base hand wheel and represents the photograph base b. The line DE is maintained perpendicular to AC. The distance DE is generated by the footwheel which moves point E vertically representing a difference in elevation h. This motion forces a movement A along CD. The point A is attached to the outer photograph and hence represents difference in parallax p. From the geometric relationship of similar right triangles set up by the mechanism,

$$\frac{h}{p} = \frac{H}{b+p}$$

which is the exact mathematical relation true for all values of h.

The change in dimensions of the arms of the pantograph is directly proportional to the elevation h of the object, and also to the element h discussed above and generated by the footwheel. This proportionality is carried out by proper ratios between pulley diameters. The ratio R of the scale change is the photograph scale S' for an object of elevation h, divided by the datum scale S, since $S'=f/(H-h)$ and $S=f/H$, then $R=(H-h)/H$. This agrees with the idea that the photograph scale for elevated objects is always greater than that for zero or datum elevation, and the photograph image position requires a reduction in scale.

Figure 8 is a schematic diagram of the stereoscope—pantograph mechanism in which the stereoscope is mounted at J, the tracing pencil at T_1, a pivot is maintained at P, the arm lengths l_1 of the stereoscope are fixed, the arm lengths of the pantograph are l_1 at 1:1 ratio and l_2 for a reduction. A reduction in the scale of motion at T_2 with respect to J is obviously the ratio $R=l_2/l_1$ where R is the desired scale ratio mentioned above, hence

$$l_2/l_1 = (H - h)/H.$$

The dimension $d=G_1G_2=T_1T_2$ through which G_1 must move to G_2, and T_1 to T_2, to cause a change in scale is $d=l_1-l_2$. By substitution for l_2 from the previous equation, $d=hl_1/H$. Thus d is directly proportional to h. The increment d is

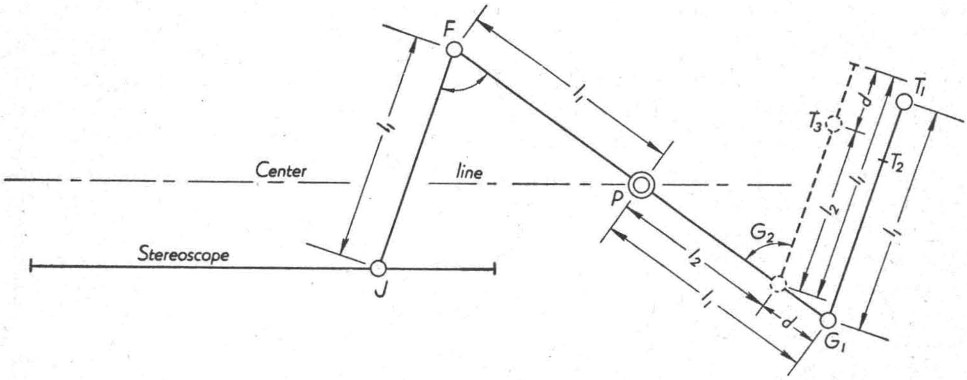

FIG. 8. Schematic Diagram of the Stereoscope-Pantograph Mechanism.

transmitted to G_1 and T_1 by means of piano wire, steel tapes and pulleys, and the scale change is geometrically correct for all elevation differences.

The increment T_1T_3 is the distance through which the map sheet must be moved so that the pencil point will remain at the same point of map detail. It is directly proportional to the element h generated by the footwheel and is also always parallel to the center line of the plotter. The motion is hence also obtained mechanically with pulley ratios. The proof of the proportionality of T_1T_3 and h is obvious from the consideration of similar triangles of Figure 8. In order to prove that T_1T_3 is parallel to the instrument center line, it is necessary to consider also the motion of the stereoscope J, which changes the positions of T_1, and which is moved in accordance with the mental vertical location of the floating mark, as for example, it is made to "climb" a flagpole represented by a distinct line on each photograph, but by merely a single dot on the map. The motion of the pencil point T_1 along the outer arm of the pantograph, through the freely moving elbow G_1, is such as to constantly maintain an equality between the angle at the elbow G_1 of the pantograph and the angle at the elbow F of the stereoscope. This is done by means of a rather ingenious arrangement of piano wire, pulleys, and a differential gear.

The plotter is designed and used principally as a one-man device. The pencil point is raised and lowered by a solenoid operated through a switch located conveniently at the end of an electric cord.

The rotation of the stereoscope eyepieces for operation from either side is quite automatic. Geared rotating dove prisms are employed which retain the proper stereoscopic orientation. There are three adjustments on the stereoscope eyepieces for the comfort of the operator, namely, interocular distance, focus, and convergence.

The assembly of a second plotter is near completion. It was designed and contracted for at the same time and in the same manner as the first one. The basic principles and most of the working parts are exactly the same as those of the first. It differs only in that the stereoscope is stationary and the photographs are moved as a pair with hand wheels somewhat like many European photogrammetric instruments. The moving photographs may perhaps be considered as conventional design, while the suspended stereoscope of the first plotter may be radical. The second instrument framework is made a great deal larger to minimize the deflections caused by changing the position of the large and heavy photograph table assembly.

MAPPING PROCEDURE

The film is developed, and later printed with the transforming printer on metal mounted paper. The sensitized photographic paper is cemented to sheet aluminum before photography. This metal-mounted photograph is used to make a radial plot employing thin transparent vinylite templets. The horizontal control points are plotted on a state coordinate grid system drawn on a heavy vinylite with the projection ruling machine[5,6,7] of the Bureau. Control points are previously identified and pricked on additional copies of photographic paper prints by field personnel. The templets are assembled and adjusted on the grids, which usually cover several 7½-minute quadrangles. The intersections are then pricked through all the templets onto the grid, and the points on the grid are circled. This completes the radial plot.

The needle holes in the templets represent the map positions of the respective images at the scale of the grids. Ten to twenty of these points, whose elevations are known, are displaced outward for their elevations according to the relation

$$d_e = rh/(H - h);$$

where d_e = image displacement due to the elevation h
r = radial distance from the templet center to the needle hole for the image
h = elevation of the object, usually one of the vertical control stations furnished by the field personnel
H = theoretical flying height corresponding to the scale of the grid and the camera focal length.

The measurement of r, the computation of d_e, and the plotting of d_e, are facilitated by a simple graph which is centered underneath the templet. The displaced image positions are circled plainly and the corresponding images on the metal-mounted photographs are also marked with a circle of slightly different size and of contrasting color. This completes the preparation of the rectification templet. The displaced positions then represent the proper image positions on a photograph which has no tilt and whose datum scale is that of the base grid.

The rectification templet is placed on the lower table (easel) of the rectifying camera, the photograph is placed on the upper table, and all the gauges are set for zero tilt and 1:1 ratio. The easel is tilted in both its directions and the lens position is changed to make the images of the photograph circles coincide with the corresponding circles on the templet. The three settings are then noted and all the settings are adjusted to agree with geometrically correct rectification. The operations of tilting and adjustments are repeated until no further change is required. For most small tilts and small scale changes (2° air camera tilt, and 2% scale change) it is observed that each of the two angular settings for the upper table should be 94% of those for the easel, expressed in minutes of arc. Also, the position setting of the easel should be 2% of the position setting for the lens. For conditions beyond which these empirical rules do not hold, graphs are referred to for making the settings consistent. The graphs are plotted according

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[5] Reynold E. Ask, "The Construction of Map Projections by Modern Methods," PHOTOGRAMMETRIC ENGINEERING, Vol. III, No. 4, p. 37, p. 7.

[6] Stephen Rose, "The Projection Ruling Machine of the U. S. Coast and Geodetic Survey," Bulletin of American Congress on Surveying and Mapping, Vol. 5, No. 3, 1945.

[7] Incidentally, the projection ruling machine was developed also under the direction of Commander O. S. Reading.

to the relations given by Hotine.[8,9] It is observed, incidentally, that the easel tilt is approximately three times as great as the air camera tilt.

After the rectifier adjustments are completed, the templet is removed, a piece of metal-mounted paper placed on the easel, and the exposure made. This produces a negative toned and reversed print which has been used on the plotter successfully but is objectionable. Hence, the negative print is placed on the upper table, the settings returned to zero tilt and 1:1 ratio, a check made with the templet, and the final rectified print exposed again on metal-mounted paper. This print is used on the plotter.

The final rectifier settings are recorded for future use and for determining the nadir point positions of the photographs. Another special graph is used for simplifying the solution of the nadir point. The values of the x- and y-tilts of the upper table are used for entering the graph. This yields a distance and a direction for plotting the nadir point on the photograph. This graph was compiled from the same computed data which were used for the rectification graphs. Still another graph is used to correct the principal-to-nadir point distance for any significant scale change induced during rectification. The correction is a simple function of the linear lens setting.

The plotter delineates all the planimetric features and contours in pencil on a vinylite sheet—a separate sheet for each stereoscopic pair. Radial plot pass points are plotted along with the planimetry.

The map detail is transferred to the manuscript map in acetate ink to fit the radial plot. All line and word information is added to make the map complete. Additional map data are obtained from the photographs which were used in the field. The limits of wooded areas are traced from the photographs to fit the map detail. Roads are shown by center lines and a surface classification number. An attempt is made to show buildings in correct size, shape, and orientation. This completes the manuscript map which shows all detail in correct position but it is not in publishable form. It is then edited both in the field and in the office, and receives an accuracy test before being smooth drafted for publication.

CONTROL DENSITY

The existing second and third order triangulation stations present in domestic areas usually furnish all the needed horizontal control. In the past, the spacing has been approximately seven miles, except near coastal regions where more frequent stations had been established previously. It is pointed out that the 1:20,000 scale nine-lens photograph covers an area about eleven miles square.

The vertical control to date was planned intentionally to give sufficient extra information for the initial test of the plotter, and was more dense than is planned for future work. Also the work was done on 1942 photographs which have undergone drastic differential shrinkage and which were made when the camera had but five fiducial marks compared to the present number of 45. Elevations were requested at half-mile intervals on all well-travelled roads, and few places existed in which the roads were farther apart than 1.5 miles. Thus, very few points have been requested at definite sites where leveling was difficult. Usually, the work has amounted to about 100 miles of level lines per 7½-minute quadrangle.

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[8] Hotine, Surveying from Air Photographs, Chapter 5, London, 1930.

[9] *Manual of Photogrammetry*, p. 58.

CONCLUSION

The plotter has been producing 20-foot contours successfuly using 1:20,000 scale photographs taken from 13,750 feet. The rate of production has been about 1.25 square miles per man-day. The resulting maps were thoroughly checked by means of vertical accuracy field tests and were well within standard accuracy specifications. The tests indicated that contouring was somewhat better than multiplex work done with six-inch wide angle photographs at 12,000 feet in an adjoining area of similar terrain.[10] The multiplex production rate was about 0.7 square mile per man-day. The multiplex operators were more experienced than the operators of the Reading Plotter. A new operator who had some previous planetable experience, was trained in three weeks to use the plotter satisfactorily on shift work in conjunction with the more experienced operator.

The saving in the amount and distribution of necessary horizontal control has already been appreciated. It seems justifiable to presume that after certain obvious improvements, the amount of vertical control can be reduced to about one-third that usually required for comparable multiplex mapping, all of which may be confined to only the better roads.

The system is at its greatest advantage in irregular coastal areas accompanied by bays, inlets, river mouths, and off-lying islands, and where existing horizontal and vertical control is sparse. The photographs possess the further advantage of being of large scale, exhibiting the intricate shoreline pattern with its rocks, etc., whose positions may be used later by the hydrographic party for determining locations of its soundings. The system is broken into several separate steps, thus freeing the plotter operators for the sole task of drawing contours and planimetry. The convenience of working in a lighted room is considered as being a desirable morale factor.

The contour interval permissible under any photogrammetric system is considered as being a function of flying height and of base-height ratio. The latter is equivalent to the ratio of the distance between the photograph centers at contact print scale to the camera focal length. The nine-lens system may utilize as great a ratio as the terrain characteristics will permit up to about 1.7. On most rectangular single-lens photographs, the limit is 0.6. This is increased somewhat in circular photographs of 90° angular field by decreasing the forward lap and increasing the number of flight strips to maintain proper coverage.

The nine-lens system begins to lose some of its advantages in domestic large scale programs where control is plentiful and where the terrain is uninterrupted by large water areas. However, it is certainly at no disadvantage. It still remains to be demonstrated under ordinary domestic conditions what advantages do exist in accuracy, costs, and production rate. The method is still young. Although nine-lens photographs have been used advantageously for making planimetric maps for ten years, they have been used for contouring only two years.

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[10] Subsequent multiplex work in this type terrain was accordingly confined to 10,000 feet flying height, which increased the accuracy and yet maintained the former production rate.

"EVERY MEMBER GET A MEMBER IN 1947"