STEREOSCOPIC PHOTOTOPOGRAPHIC MAPPING*

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Introduction

THE Geological Survey in the United States Department of the Interior is the official topographic mapping agency of the Federal Government. It is therefore intensely interested in and is constantly investigating all mapping methods and instruments that hold out any promise of increasing speed or accuracy or of reducing costs in the preparation of standard contour maps. From the beginning of experiments in mapping with the aid of the camera, the Survey has participated in the development of methods by which photographs taken either from the ground or from the air can be effectively utilized in map work, as carried on in the United States and its possessions. It has, of course, followed closely European and American development of instruments and methods, has acquired some of the more promising of these instruments, has redesigned certain features of them, and has improved the methods of their application.

History of Use of Photography in Mapping

The greatest advance of the past twenty-five years in map making is undoubtedly the application of aerial photography to the preparation of planimetric and topographic contour maps. The use of photography as an aid in the preparation of topographic maps was forecast a century ago, when the discoveries made by Niepce and Daguerre[1] in 1839 were presented to the French Chamber of Deputies.

The credit for the first practical work in adapting the camera to surveying probably belongs to Col. A. Laussedat, who began his work in 1849 under the Engineer Corps of the French Army and carried it through many years of great activity. The accounts of his progress published from year to year established him at the head of topographic engineers in the use of photography, and he is now known as the father of photogrammetry. Much of his material on photography is now available in convenient form for the use of others.[2]

The development of the various uses of photography in mapping is briefly outlined as follows:

Ground Surveys

By phototheodolite.—The use of landscape perspectives for a geometrically true representation of the terrain in horizontal plan was first realized by combination of the theodolite and camera, either in a composite instrument known as a phototheodolite or by a camera and a theodolite used separately over the same station. The first successful use of a phototheodolite in mapping was by Laussedat, who, at the Paris Exposition of 1867, exhibited the first known phototheodolite, and a plan of Paris based on his photographic surveys, which compared favorably with plans made earlier by ground instrumental methods.

Laussedat and his associates were frequently called on to make photographic

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[1] Flemer, J. A.: *Phototopographic Methods and Instruments*, p. IV, John Wiley & Sons, New York, 1906.

[2] Laussedat, Aime: *Recherches sur les instruments, les methodes et le dessin topographiques*, Paris, Gauthier-Villars, pt. 1, 1901; pt. 2, 1903.

surveys apart from their regular military duties, and scientists and engineers of other countries, particularly Germany, Austria, Switzerland, Italy, and Canada, did much to popularize and improve this method of surveying. Among the best known of these pioneers were Meydenbaur, Jordan, Finsterwalder, and Pulfrich of Germany; Koristka, Pollack, and Scheimpflug of Austria; Simon of Switzerland; Porro and Paganini of Italy; and Deville of Canada.

Early work in ground photogrammetry in western Canada was carried out by means of separate instruments, a theodolite being used for control and a camera mounted on the same tripod for the photographic work. The same type of equipment was employed in the topographic survey of the area adjacent to the Alaska-Canada boundary line. These instruments were first used in Canada in 1888 under the direction of Capt. E. Deville, Surveyor General of Dominion Lands. A single photographic surveying party, composed of J. J. McArthur and three assistants, surveyed in that year about 500 square miles in the Canadian Rockies, with resulting maps on the scale 1:20,000 with a contour interval of 100 feet. Deville's book,[3] entitled *Photographic Surveying*, is perhaps the first treatise in English on this subject.

Instrument makers, such as Carl Zeiss and Hyde of Germany, Wild of Switzerland, and others, now make precise phototheodolites in composite instruments that measure accurately the required horizontal angles both for control and for photographic recording. Use of these instruments is now restricted largely to mountainous terrain, surveys of other areas being accomplished by use of aerial photography. Only one of these instruments is known to be in the United States. This was used first in the survey of the site of Boulder Dam, resulting in maps on a scale of 50 feet to the inch with 5-foot contours, and later in the survey of the dam site at San Gabriel, Calif., resulting in maps on a scale of 30 feet to the inch with 2½- and 5-foot contours. The Geological Survey experimented with instruments of this type in 1921, but found the method applicable only to the relatively small area of high-mountain terrain in the United States.

By panoramic camera.—Soon after Laussedat made his first experimental surveys with ground cameras, French and Italian engineers began experiments with the panoramic principle, photographing the entire horizon by one or more exposures from a ground station. Porro apparently developed in 1858 the first instrument of this type, which was fitted with sighting telescope compass, and level and which recorded the photographs on a strip of sensitized paper on the surface of a cylinder. In the same year Chevallier developed a photographic plane table (Planchette photographique) which recorded the entire horizon on a horizontal plate, the light rays being turned at right angles by means of a prism as the sighting device was rotated. Available records do not indicate that these and other early devices were used in topographic surveys, but in 1884 Moessard developed and used the "cylindrographe" for this purpose. Moessard's instrument was equipped with a sighting device which rotated the lens in a horizontal plane and exposed a strip of film wound on a cylinder. It seems to have been well conceived but did not find much favor among topographic engineers of France, probably because the films then available were much inferior to those procurable at the present time.

The most successful ground photographic surveys accomplished in the United States were made by the use of the panoramic camera (see pp. 112–113).

[3] Deville, E.: *Photographic Surveying*, 232 pp., Ottawa, Government Printing Bureau, 1895.

Aerial Photography

From kites.—The first aerial photographs were probably taken from kites. As early as 1858 Laussedat experimented with a plate camera supported by a string of kites ("cerf-volant" in French, "drachen" in German), but about 1860 he apparently abandoned his experimental work with aerial photography and confined his experiments to ground photography with a phototheodolite. Others, particularly Capt. Theodor Scheimpflug, of the Austrian army, continued the experiments with kites but soon dropped them in favor of photography from captive balloons and later from dirigible balloons.

From captive balloons.—Laussedat probably also took the first photographs from captive balloons. As early as 1858 he experimented with a plate camera, supported by a balloon. His principle reason for abandoning his experimental work with both kites and captive balloons seems to have been the difficulty of taking a sufficient number of photographs from one station to cover all of the area that the outlook commanded. Scheimpflug apparently solved this difficulty in about 1900 by his development of the multiple-lens camera, with seven oblique lenses grouped around a central vertical lens, which afforded an extremely wide-angle composite photograph. Scheimpflug also developed the stereoscopic use of two overlapping composite photographs taken from the balloon in two adjacent positions.

The first use in the United States of photographs taken from a captive balloon was by James Fairman, who on August 2, 1887, was granted the first United States patent on aerial photography, No. 367,610, entitled "Apparatus for Aerial Photography," designed to use a camera, attached to a balloon or a kite, with shutter controlled by a clock movement. C. B. Adams was granted, on December 12, 1893, a United States patent No. 510,758, entitled "Method of Photogrammetry," designed to use a camera supported at two positions of a captive balloon so as to provide two aerial photographs of the same terrain and to determine both horizontal and vertical positions of the ground points. So far as is known, neither of these patented devices was ever put to practical use.

Lieut. Dache M. Reeves,[4] Air Corps, U. S. Army, in his book entitled *Aerial Photographs*, states that "as early as 1861, the possibility of using aerial photographs in military operations was considered by the Balloon Corps of the United States Army. However, there is no record that photographs were actually used at that time."

From dirigible balloons.—The difficulty of making satisfactory progress in mapping terrain from photographs taken from different positions of a captive balloon naturally led to experiments with photographs from free balloons. Scheimpflug, in about 1906, was apparently the first to make topographic maps successfully by this method. The chief difficulty with free balloons was the dependence on wind to direct the line of flight, therefore, soon after dirigible balloons were developed much more successful aerial photographs were obtained, and the art developed rapidly in Europe. Probably the most successful of these developments were photographs taken from the Graf Zeppelin in 1931 in its Arctic expedition and in its flight across Alaska.

From airplanes.—Available records show that the first known photograph taken from an airplane was a motion picture taken by Wilbur Wright in a flight over Centocelli, Italy, on April 24, 1909. Wright's motion picture, however, was

[4] Reeves, Dache M.: *Aerial Photographs, Characteristics and Military Applications*, p. 3, The Ronald Press, New York, 1927.

not taken for mapping purposes. The earliest record of photographs actually taken and used for mapping is in a paper by Capt. Cesare Tardivo[5] presented on September 25, 1913, at the meeting of the International Society of Photogrammetry held in Vienna, and showing a mosaic on the scale 1:4,000 of the city of Bengasi, Italy.

History of Use of Photogrammetry in the United States

Early work by the Coast and Geodetic Survey.—The only use of the camera in surveys in the United States prior to the beginning of the Geological Survey's work in Alaska had been in certain surveys carried out by officers of the United States Coast and Geodetic Survey for the International Boundary Commission in connection with the survey and location of the boundary between the United States and Canada, in a survey of the Pribilof Islands, and in a few other surveys of less importance.

Use of panoramic cameras by the U. S. Geological Survey.—Photographs taken from the ground were first employed in topographic mapping by the Geological Survey in 1904, when two members of its staff, C. W. Wright and F. E. Wright, used a panoramic camera in topographic contour surveying in Alaska.

The panoramic cameras used by the Wrights were improvised from commercial instruments by fitting level bubbles on the camera boxes and arranging internal scales that formed shadowgraphs upon the negatives. Although these cameras were not constructed primarily for the purpose of surveying, satisfactory results were obtained with them.

In 1907 C. W. Wright had a new camera made according to specifications which he had drawn up, but it did not become available for use that season, and soon afterward this work was interrupted by his transfer to another field. Little was then done with the panoramic camera until 1910, when James W. Bagley, one of the topographic engineers of the Geological Survey's staff in Alaska, had an opportunity to use it to a limited extent. His experience at that time was convincing as to the merit of the panoramic camera, and its employment in Alaska surveys steadily increased.

The panoramic camera is a box type in which the lens is revolved about a vertical axis by a spring, the rate of revolution and, in part, the exposure being regulated by detachable fans connected by gearing with the lens shaft. Roll film in 5- or 6-inch cartridges with several exposures each is placed on a circular film guide, so adjusted that when the film is in position for exposure all elements of the cylindrical surface of the film will be perpendicular to the level plane and parallel to the lens shaft. The top of the camera, being the reference plane for leveling, is fitted with leveling bubble slots at right angles to each other. Three leveling screws of the common type are used in connection with an adapter plate which will fit a plane-table tripod, thus avoiding the necessity of transporting two tripods. The horizontal field of view is 126° for each exposure, and the vertical range is from 18° to 22° above the horizon and from 26° to 30° below the horizon, depending on the width of film used. The film is usually developed in the field to check the quality of exposure and the coverage of the area to be mapped.

A photoalidade was designed in the Geological Survey for use with photographs taken by the panoramic camera. Briefly stated, its purpose is to transfer to the map the information obtained from the photographs. It is so designed that the operator may sight any image point in the photograph and determine

[5] Tardivo, Cesare: "Topofotografia aerea," *Internat. Archiv fur Photogrammetrie*, 4, Band, 1913–14, pp. 180–192, pl. 6, Wien and Leipzig, 1914.

the horizontal direction from the station point to the image point, in the same manner in which the topographer operates the telescopic alidade on a plane table in the field. A reading glass with a vertical hair, used with a sighting vane, may be said to represent the lens system in a field instrument. A radial arm represents the plotting base on an alidade, and directional lines are plotted along this arm on the map sheet. The reading glass, sighting vane, and radial arm are controlled by a mechanism of the rack-and-pinion type revolving around a point that represents both the optical center of the lens and the camera station.

In order to obtain differences of elevation for contour sketching, vertical distances of points above or below the horizon line, which appear as shadowgraphs on the print, are measured. A simple formula that uses these measured vertical distances with the corresponding map distance and the principal distance of the photograph gives the difference of elevation. A separate office instrument known as a rotary scale has been constructed to expedite the measurement of the vertical distance.

More than 23,000 square miles of rough mountain terrain have been photographed in Alaska with the panoramic camera, and the resulting photographs have been worked up successfully in map form by means of the above-mentioned instruments.

In 1932 R. M. Wilson[6] of the Geological Survey designed a new photoalidade for use with photographs taken by the panoramic camera. It may be used also with low-oblique photographs taken with any single-lens aerial camera whose focal length is more than 4 inches but less than 14 inches. It is used with oblique photographs as large as 10 by 12 inches, which show the plane of the horizon and terrain as much as 10° above to 50° below the horizon. The instrument consists of an adjustable print holder, a telescope for reading horizontal and vertical angles, a centering microscope used to place the station point on the map sheet exactly in the vertical axis of the viewing telescope, and a straight-edge connected with the vertical axis of the telescope so that directions from the station point can be plotted on the map sheet.

Within the field of view presented by the photograph, it is possible to conduct in the office most of the operations that would be possible with an ordinary plane table and telescopic alidade in the field. Topographic features may be located by intersection and their altitude determined, provided oblique photographs of the same terrain have been taken from two or more different points of view. Thus the sketching of contours may be controlled, just as is done by using the intersection method with a plane table. The new photoalidade is particularly adaptable to reconnaissance and exploratory mapping in Alaska because of the extensive areas shown in most oblique photographs. It should be adaptable also to revision of small-scale maps in reasonably flat areas where high ridges do not conceal important features of the terrain.

Development of multiple-lens cameras.—In 1911 there came to the attention of J. W. Bagley and F. H. Moffit, of the Alaskan Branch of the Geological Survey, a memorial on the work of Theodor Scheimpflug, which described his multiple-lens camera. That camera had one vertical center lens and a circle of seven lenses set at angles around the center lens. Bagley and Moffit made a study of this arrangement of lenses and decided to attempt the construction of a multiple-lens camera. Scheimpflug's idea was to have his camera suspended from a balloon. Moffit and Bagley realized that such an arrangement could not be carried out in Alaskan work and that their method of using photographs

[6] Wilson, R. M.: "A New Photoalidade," *Military Engineer*, November-December 1937, pp. 434–436.

taken from the ground was better suited to Alaskan terrain. For that reason, they put aside their experiment temporarily.

When they returned from Alaska in 1916, Bagley found that the Army was much in need of maps along the Atlantic coast, and with the thought that rapid mapping could be done with a multiple-lens camera supported in an airplane, he and Moffit resumed their experiments. Moffit undertook the task of developing the theory and of designing and constructing a universal transformer, while Bagley, with the assistance of J. B. Mertie, devoted all his time to the development of the aerial camera itself. The aerial camera was built from the design of Bagley and Carl H. Au in Au's shop in Washington, D. C. Moffit completed the design of the transformer and supervised the work of making the patterns, machinery, and castings by commercial shops. The principal work on the castings was done in Baltimore, and the instruments were assembled and adjusted in Washington. The National Research Council allotted a small sum for the development of the first experimental cameras, and after the results obtained with them were submitted to General Black, Chief of Engineers, the Corps of Engineers in 1918 made an allotment of $75,000 for the development and construction of aerial cameras and transformers.

In 1917 Bagley was commissioned a major in the Engineer Officers Reserve Corps, and the first photographs were taken with his tri-lens camera at Langley Field in co-operation with the Air Service in the winter of 1917–18. The results of these tests served as a basis for a program to photograph several strips of country between aviation fields, for the purpose of making aeronautical maps. This work was undertaken jointly by the Corps of Engineers and the Air Service, with the Geological Survey contributing aid in a general way. Bagley was then ordered to France and continued his experimental work with the tri-lens camera in the American Expeditionary Force. The activities of the Geological Survey in this field were soon curtailed by the rapidly increasing demands of the World War.

After the War, Bagley at McCook Field (now Wright Field) continued making improvements on the tri-lens camera and finally put on the fourth chamber, making the four-lens camera. As a result of experience with enlisted men as laboratory assistants, he felt the need of a fixed transformer that would require no adjustment and that could be used in connection with a definite aerial camera. On request of Bagley, Moffit made preliminary drawings for building the fixed transformers. These drawings were completed at McCook Field, and the cameras and transformers were constructed.

Later, a five-lens camera was designed and is now manufactured by the Fairchild Aerial Camera Corporation. This is the type of multiple-lens camera now in use by the Corps of Engineers, the Marine Corps, the Hydrographic Office, the Air Corps, and the Geological Survey.

Lieut.-Commander O. S. Reading, in charge of photogrammetric work in the Coast and Geodetic Survey, designed in 1935 a new nine-lens camera[7] which was manufactured in 1936 by the Fairchild Aerial Camera Corporation. This camera carries a single roll of film 23 inches wide and 200 feet long, on which are recorded the images of all nine lenses, the optical axes of all of which are parallel and vertical. The focal length of each of the matched lenses is $8\frac{1}{4}$ inches (215 mm.), and the rays from the fields of view of the eight outside lenses are gathered by means of chromium steel mirrors coated with evaporated aluminum. The field of view of the camera is 130° square, and when each segment is transformed in place on a piece of acetate film by means of a special two-lens

[7] *News Notes*, American Society of Photogrammetry, May–June, 1935.

transformer, a 35- by 35-inch positive is obtained, which can be used in map construction. The first use of photographs taken by this camera was in compilation of planimetric base maps for hydrographic surveys of the Coast and Geodetic Survey.

Application of photogrammetry to planimetric and topographic contour mapping.—The World War focused attention on the value of aerial photography, and many of the 113 topographic engineers of the Geological Survey who served in the military forces, brought back observations that aroused intense interest in application of the method to both planimetric and topographic contour mapping. The war experience of these engineers, in fact, was largely responsible for the Survey's pioneer work in this field.

In the spring of 1920 the West Indies Surveys Division of the Geological Survey, in co-operation with the Marine Corps, began a systematic aerial photographic survey of parts of Santo Domingo and Haiti, using a tri-lens camera. In the same year the Survey made its first successful attempt to map a standard quadrangle by utilizing single-lens aerial photographs for the preparation of field sheets on which all of the planimetry was shown, but for which contours were delineated by topographers on the ground. The photographs, which covered the Schoolcraft (Michigan) quadrangle, were taken and supplied by the Air Corps. This quadrangle map was issued in 1922 and represented the first quadrangle mapping done in the United States in which aerial photography played a part. In 1923 surveys of the Reelfoot Lake quadrangle, Tennessee-Missouri-Kentucky, were completed, part of the culture and drainage being taken from aerial photographs. In 1921 Bibb County, Ga., was surveyed, and the culture and drainage were taken from aerial photographs supplied by the U. S. Army Air Corps.

The estimated saving effected by the use of aerial photographs on the Schoolcraft project was about \$7 per square mile, or \$1,500 for the 15-minute quad-engineers in the form of nonphotographic blue lithographs on double-mounted drawing paper, to be used as plane table sheets for the delineation of the contouring by ground survey methods. The area was photographed with a single-lens camera in two half-days of flying time. At that time, office methods of compiling the planimetry were crude, and the use of single prints was somewhat expensive, but enough knowledge was gained to indicate that the use of aerial photographs would be of material value in topographic mapping, not only because of reduced field costs but also because of the greater accuracy in the resulting map.

In February 1921 a new subdivision of the Geological Survey was established in the Topographic Branch, designated as the "Section of Photographic Mapping." The function of this section was to investigate the probable usefulness of aerial photographs in making planimetric and topographic maps. It was first successful in the completion of planimetric base maps for use in making standard topographic contour maps and has continued in this work up to the present time.

After the Section of Photographic Mapping had gone into the production of base maps, part of its efforts were turned to the second line of investigation—stereophotography. The use of stereoscopy makes it possible to measure on the photographs themselves distances, directions, and elevations. If two photographs, covering the same area and taken with the same lens, but from a different angle, are brought into a certain position with relation to each other and then viewed stereoscopically, the effect of relief and perspective can be seen. This perception was the foundation for the development in Europe about 1904 of instruments that measure this relief and perspective. Before the World War, photographs were taken from the ground and used in stereo-comparators (stereoscopes equipped to measure rectangular co-ordinates and the "parallax" of objects) to construct maps from pairs of photographs with the aid of known positions and elevations. However, the procedure was very tedious and required a great deal of mathematical or graphical labor.

Instruments employing stereoscopic principles.—During and immediately after the World War several instruments were put on the market with which complete topographic maps could be constructed semiautomatically from pairs of photographs taken from the ground or the air with the help of known ground points. In these instruments the photographs were viewed stereoscopically. With an index mark called a "floating mark" in the field of view, it was possible to follow a contour line in the stereoscopic model and to raise or lower this mark in proceeding from one elevation to another, the result of these movements being a correct delineation of the terrain in both plan and elevation.

In 1924 one of these instruments, the Stereo-autograph, was imported from Germany and installed in the Survey's offices. The results of two tests made with ground photographs taken in the vicinity of Mount Washington, N. H., and in the vicinity of Alexandria, Va., showed that it was entirely possible to construct topographic maps from ground photographs if there were three or more known positions and elevations in each pair of photographs, and it was found that the accuracy of these maps was equal to or in excess of that of maps constructed by ordinary methods. However, because so many known points were necessary for each pair of photographs, and also because aerial photographs with their larger area could not be used, this instrument was not considered economical for American use.

The first commercial use of aerial photographs in making topographic maps in the United States seems to have been by a firm in Philadelphia that later became known as Brock & Weymouth. This firm designed stereoscopic mapping equipment and developed a mapping method that made use of photographs taken with a $6\frac{1}{2}$- by $8\frac{1}{2}$-inch plate camera. This equipment was developed to a high degree of precision and was used successfully in many contracts for private firms and several contracts for Federal agencies, the most successful of which were the topographic mapping of part of the Wabash and White Rivers in Indiana in 1929 for the Corps of Engineers, and the topographic mapping of the area around Boulder Dam in 1930 for the Reclamation Service. In both of these surveys, Brock & Weymouth established high-grade second-order horizontal and vertical control.

The Geological Survey began experimenting with the application of stereophotogrammetry to topographic contour mapping from aerial photographs in 1927, when one unit of a German stereoscopic plotting apparatus known as the Aerocartograph, and using vertical or oblique single-lens aerial photographs, was installed on trial. After a year of experimental work the apparatus was purchased, and became the first stereoscopic plotting instrument owned by the Federal Government. Further tests and experimentation were carried out and, in the spring of 1930, a definite production project was begun—a strip survey along the upper Columbia River in the State of Washington. This was followed in the same year by a survey of about half of Zion National Park and Bryce Canyon National Park in Utah, and in 1931 by a survey of the Lakeport quadrangle, Calif. Use of the Aerocartograph requires three horizontal and vertical control points, established by terrestrial surveying, properly placed at one end of each flight strip, and two similar positions at the other end of the strip;

but experience has demonstrated that one additional elevation established by terrestrial surveying for each optical model aids in the horizontalization of the model and strengthens the plot. In 1935 the Corps of Engineers designed new plate holders for its Aerocartograph to accommodate negatives for the five-lens cameras ,and in 1936 it remodeled the Geological Survey's Aerocartograph in the same manner, so that both instruments can be used to plot contour maps from five-lens photographs. The Los Angeles Division of Fairchild Aerial Surveys also owns an Aerocartograph, but it has not been remodeled to use five-lens photographs.

In 1929, a grant from the Guggenheim fund for the Promotion of Aeronautics was made to the College of Applied Science of Syracuse University. This grant was restricted to the purchase of instrumental equipment, with the understanding that the University would provide the space and teaching staff for carrying a program of instruction in aerial photographic surveying and mapping.

Much of the equipment first purchased consisted of aerial cameras, comparators, stereocomparators, photogoniometers, rectifying cameras, and other laboratory equipment for making measurements on aerial photographic plates. During the first four years, the University concentrated its work largely on the use of solid analytic geometry in computing positions in space from the measurements taken from photographs with these instruments.

In 1936, the University purchased from this grant a Multiplex Aeroprojector and began to train students in the practical aspects of stereoscopic plotting of contour maps from vertical aerial photographs of moderate scales such as 1:20,000 which are being used by the Geological Survey and the Corps of Engineers. With this additional equipment and an able staff of instructors, Syracuse University should be better fitted than any other school in the United States to turn out well trained graduates in photogrammetry.

Although the Aerocartograph assured the use of aerial photographs by the Geological Survey in topographic contour mapping, the cost of the equipment was very high, hence it was not until the introduction in 1935 of less complex and less costly apparatus, the Multiplex Aeroprojector, that the value and economy of such methods were definitely established. The Geological Survey purchased a nine-fold Zeiss Aeroprojector in 1935 and several other units of this type in 1936 and 1938. The first was equipped with normal projectors, and the latest with wide-angle projectors. These instruments are being used successfully in making contour maps of parts of the Tennessee Valley area. In this work single-lens vertical aerial photographs are used, with one or more terrestrial horizontal control points provided for every third or fourth model in each flight, and one vertical control point on each optical model. Rigid tests of the work in the Tennessee Valley indicate that large-scale contour maps of rough terrain, made by operators skilled in the use of the equipment, are in general more accurate than maps of similar areas made at comparable cost and scale by ground survey methods. However, the development of these stereoscopic instruments and methods to the point of satisfactory precision, has involved time and difficulties. Wide-angle lenses have been adopted in place of the original narrow-angle lenses, and the 1935 instruments have been modified and improved with increase in rigidity and accuracy. In its present stage of development the stereoscopic equipment gives results that are highly satisfactory as to accuracy and cost, when applied to terrain of suitable relief. Even in areas of low relief, where a small contour interval is necessary, mapping by normal plane table methods can be done at less cost if a planimetric base is first constructed from aerial photographs by means of the Aerocartograph or the multiplex projector.

Aerial photographs taken with a single-lens camera with 70° field of view are being used at present in the normal multiplex projectors. This camera has a focal length of 210 millimeters ($8\frac{1}{4}$ inches) and a negative size of 24 by 24 centimeters (9 by 9 inches). The photographs used with the wide-angle multiplex projectors have been taken with a similar camera with a 90° field of view, the focal length of which is 167 millimeters ($6\frac{1}{2}$ inches) and the negative size 24 by 24 centimeters. The Geological Survey has purchased a Zeiss-Aerotopograph model R. M. K.—P 10 wide-angle single-lens camera with a 100° field of view and of a focal length of 100 millimeters (4 inches), which is being utilized for mapping rolling and mountainous areas, resulting in a material reduction in operating costs.

Another German instrument, known as the Zeiss Stereoplanigraph[8] is used in the United States by the Los Angeles Division of Fairchild Aerial Surveys, Inc. This is a larger and more expensive instrument than either the Aerocartograph or the Multiplex, and is considered by most photogrammetrists to be one of the most precise stereoscopic plotting instruments yet made.

Other well known and highly recommended stereoscopic plotting instruments are made in Switzerland and Italy, but none of them are in use in the United States. Among these is the Wild Autograph,[9] made by the Wild Surveying and Instruments Supply Co., at Heerbrugg, Switzerland. The Italian instruments include the Santoni Stereosimplex and the Nistri Fotocartografo, described on pages 34 and 37, respectively, of the Report of Commission 4[10] of the Fifth International Congress of Photogrammetry at Rome in 1938.

Other instruments used in photogrammetry have been developed recently in the United States by officers of the Corps of Engineers and others.

In 1934 Bagley (who, as already stated was formerly one of the topographic engineers of the Geological Survey's staff in Alaska) developed an aerial photograph calculator[11] which is a mechanical instrument designed to measure the axis and degree of tilt of aerial photographs, the height of exposure stations, and the elevation of points on the ground represented by images on the photographs. This instrument is used in the field laboratories of the United States Army Corps of Engineers, at the Engineer School, Fort Belvoir, Virginia, and at the Institute of Geographical Exploration at Harvard University.

Bagley also developed in 1934 a stereoscopic plotting machine[12] designed for use with five-lens photographs. This machine has not been put into general use by the Corps of Engineers but is being used by the Institute of Geographical Exploration.

A reconnaissance stereoscopic plotting instrument known as the stereocomparagraph[13] was developed by Capt. B. B. Talley of the Corps of Engineers. This instrument, designed to train students in stereoscopic plotting of contour maps from aerial photographs, is now being used by several Federal and private

[8] Eliel, Leon T.: "The Stereoplanigraph," *News Notes*, The American Society of Photogrammetry, Nov. 1934, pp. 10–16.

Also Dr.-Ing. Luscher: "Stereoplanigraph, Modell 1938," Generalbericht der Kommission 4, Luftbildauswertung—Fünfte Internationaler Kongress für Photogrammetrie, seite 14.

[9] See PHOTOGRAMMETRIC ENGINEERING, April–May–June, 1939, pp. 64–65.

[10] Generalbericht der Kommission 4, Luftbildauswertung—Fünfte Internationaler Kongress für Photogrammetrie.

[11] For description, see U. S. Patent No. 2,053,019, September 1, 1936, entitled, "Aerial Photograph Calculator."

[12] This machine is covered by U. S. Patent No, 2,044,114, June 16, 1936, entitled "Plotting Machine and Process of Making Maps with Aerial Photographs."

[13] Described in PHOTOGRAMMETRIC ENGINEERING, July–Aug.–Sept. 1936, pp. 64–67.

agencies and by schools teaching photogrammetry, such as the United States Military Academy, the Engineer School at Fort Belvoir, the Department of Geodesy and Engineering at Rensselaer Polytechnic Institute, and the Institute of Geographical Exploration at Harvard University.

As already stated, the Corps of Engineers redesigned its own Aerocartograph and also the one belonging to the Geological Survey. It has used its Aerocartograph with both vertical and multiple-lens photographs in mapping, but is now using this instrument largely for control work and the Multiplex Aeroprojector for contour mapping.

The Soil Conservation Service has developed a reflecting projector[14] which is used to transfer the planimetric details from opaque photographs to the base sheet on which all of the geodetic and photographic control points have been plotted by radial triangulation. The Geological Survey and other Federal agencies have acquired instruments of this type and are using them successfully in planimetric mapping.

The American Geographical Society has developed a single-eyepiece plotter[15] which is sensitive to the nearest minute of arc and employs the principle of a real rather than a virtual index mark. Plans are being made to incorporate this principle in the construction of a general-utility stereoscopic plotting instrument for both vertical and high oblique aerial photographs.

Photogrammetric Methods Now Used by Geological Survey

In modern topographic mapping, aerial photographs are used as pictures of the ground, and from these photographs, directions, distances and elevations of ground features are measured. Thus, the topographer may be said to use wings to secure his basic information, because in swift, photographically equipped airplanes he can cover areas in a few hours where weeks of laborious traversing and plotting would have been required to secure the same information by the old-fashioned ground survey methods. Do not assume from this, however, that it is only necessary to photograph the ground in order to make a map. Quite the contrary, because there is a lot to do besides taking the photographs, as will be seen from the following descriptions.

The Geological Survey does not maintain its own airplanes, but the actual photography for its aerial mapping program is executed by private aerial photographic contractors and by the U. S. Army Air Corps. The Survey does, however, have a few aerial cameras and all of its own stereoscopic plotting instruments.

Aerial Cameras

The most effective aerial camera used by the Geological Survey is a Zeiss Aerotopograph single-lens, wide-angle camera, which has a focal length of 100 mm. (about 4 ins.), an angle of view of nearly 100°, and produces a negative about 7 by 7 inches in size. When loaded with the usual length of film, about 200 feet, there is sufficient footage for several hours flying time—about 300 exposures. Photographs taken by this particular camera are used in the Survey's wide-angle Multiplex Aeroprojectors. The Survey also owns several Hugershoff short focal length cameras, photographs taken by which are used in its Aero-

[14] Kennedy, M. S.: "Overhead Vertical Reflecting Projector," Photogrammetric Engineering, January–February–March 1937, pp. 28–31.

[15] For description see *Journal of the Optical Society of America*, vol. 25, pp. 185–189. This instrument is covered by U. S. Patent No. 1,985,260 issued December 25, 1934, entitled "Stereoscopic Plotting of Contour Maps."

cartograph, the first stereoscopic plotting instrument owned by the United States Government. One of these cameras uses a roll of film affording 300 exposures each 5 by 5 inches in size, and the others have detachable magazines holding either roll film or glass plates taking photographs 5 by 7 inches in size. Much of the photography used by the Survey is, however, taken by new precision single-lens cameras owned by private contractors. These cameras take photographs 9 by 9 inches in size, with lenses having focal lengths of $6\frac{1}{2}$ or $8\frac{1}{4}$ inches.

Planning Flights

When the areas to be mapped photographically are decided upon, the cartographer lays out flight lines on base maps—lines to be followed by the navigator and pilot. Flights are usually planned so that the entire width of two fifteen-minute quadrangles can be spanned in one flight, the distance between adjacent flights being governed by the focal length of the lens and the height of the camera above ground. This means that, with a six-inch lens camera in average latitude, the plane will follow flight lines about thirty miles long, spaced about two miles apart, when flying at 12,000 feet above the ground. Each map thus prepared contains all flight instructions necessary to guide photographer and pilot in securing the desired photographic coverage—sixty per cent overlap in line of flight and thirty per cent sidelap between flights.

For the most successful results, flights are made in the middle of the day, during the winter season when the leaves are off the trees, and at altitudes varying from 5 to 20 thousand feet above the ground, depending on mapping requirements. Map specifications usually require that 85 per cent of the points tested shall have a vertical accuracy of at least one-half the contour interval of the map. To attain this accuracy, it has been found by experience that the flight altitude above average ground level should not be more than 600 times the contour interval of the map. The focal length of the camera has nothing to do with this vertical accuracy, but it does of course affect the scale of the resulting photograph, and the cartographer is required to take these two factors into account in planning the spacing of the flight lines on the flight map. For example, if the contour interval selected is 20 feet, the altitude above ground must not be more than 12,000 feet, and if the focal length of the camera is 6 inches, the scale of the photograph will be 1:24,000.

Photographing the Ground

The cameras are electrically operated and mounted in the airplane on a support that permits the lens to project down through the fuselage, thus clearing the bottom of the ship and giving an unobstructed view of the terrain below. The electric motor winds the negative on the pick-up spool and trips the shutter at the proper time for each exposure. Level bubbles are mounted on the frame of the camera so that the operator can keep the negative plane of the camera horizontal at each exposure, thus compensating for any irregular angle of the plane while in flight. In the ship also is mounted a view finder, known as an intervalometer, which enables the photographer to see the images of the ground and to line them up by the moving splines of the intervalometer, so as to set the camera in the proper direction and to indicate the proper moment to make the exposures, after compensating for speed and drift of the plane in the air.

Developing and Drying Film

As soon as possible after the area is photographed, the negatives are developed. A most important factor is that the film in its roll stage has an even development to insure good reproductions in the later phases of aerial photographic mapping. Perhaps the best way of doing this is by use of developing machines that wind the negative back and forth through the developing solution. Other important factors are the use of proper emulsion bases, and the proper kind of drying technique that avoids any stretching or distortion of the negative. Roll film negatives must always be developed as quickly as possible after exposure, in order to reduce shrinkage to a minimum. After development, the film is dried and left in its roll form. This is usually done on a cylindrical slatted drum, but may be done in an electric drying machine.

Contact Printing

Contact prints of each individual negative are made by the usual method for use by the geodetic engineers in identifying on the ground the images of critical points needed for ground control. Many laymen think that all that is necessary in making a map is to photograph the terrain and a map is immediately forthcoming. It is true that a rough mosaic can be made by joining together photographs by their images alone, but this is not a map, for such a mosaic has no exact scale and both horizontal and vertical ground control are necessary to make any accurate measurements on it. Nevertheless, an accurate map can be made from these photographs if proper control is available and proper technique is used. Triangulation and traverse stations and level bench marks are often available for the terrain being mapped, but these points usually cannot be identified on the photographs and usually are not properly placed for stereoscopic plotting. Therefore, the geodetic engineers must take the photographs into the field and secure the horizontal and vertical co-ordinates of points indicated by the photogrammetrist in the office.

Supplemental Control

This is usually done on a copy of the same flight map used by the pilot and photographer, by outlining the position of each photograph by means of a template representing in size and shape, on the scale of the map, the area included in a single photograph. By laying this template properly on the flight map that guided the photographic ship, the relative position of each photograph is discovered. This is just like laying shingles on a roof and, as shingles must be nailed down to a rigid frame work, so must the relative positions of the areas represented by each photograph and their absolute place on the map be determined. To do this, images of definite points are selected which will show clearly on the negatives and which will provide horizontal and vertical positions of four well-disposed points on optical models formed by about every fifth overlapping pair of photographs in each flight line, and one vertical position on each of the other optical models. These supplemental control points are such easily identifiable points as fence corners, lone trees, corners of buildings, clearly defined highway intersections, etc, and they are located by ground measurements from available primary triangulation stations and level bench marks. Their horizontal and vertical co-ordinates are then computed so that they can be plotted on the projection sheet on which the map is to be drawn.

Diapositive Printing

While photogrammetrists are planning the supplemental control, laboratory photographers are printing each negative on a positive glass plate. This is done in a reducing camera, called a diapositive printer, composed of a base, a projection lens, a diapositive plate support, a light source and a reflector. The roll film negative is supported on a glass platform, with the fiducial marks on each negative registered with extreme precision to corresponding fiducial or control marks on the supporting glass platform. When properly registered, each negative is held in position during the printing operation by a heavy glass pressure plate. The camera, or printer, is of the fixed focus type and reduces the image on the negative about four and one-half times. The printer must be set with extreme care in order to obtain the proper dimension for the reduced image, and to maintain maximum sharpness. The reduced image is projected to a small glass plate known as a diapositive. Making these diapositive glass plates is one of the most critical operations of stereoscopic plotting. They must be made on perfectly flat glass plates coated with an emulsion having high resolving powers and made thin by slight over-exposure. Ordinary photographic methods are not satisfactory. Fine grain developers must be used and the plates handled with great care. After printing, the edges of the plates are carefully ground with an abrasive belt to remove sharp edges and to ensure proper fitting in the plate holders when the diapositives are projected. Each of these plates is stored in its individual envelope containing full information about the plate inside.

Multiplex Aeroprojector

The principal stereoscopic plotting instrument now in use by the Geological Survey is known as the Multiplex Aeroprojector. This instrument was first made by Zeiss Aerotopograph, a division of Carl Zeiss Works, Jena, Germany. However, the American firm of Bausch and Lomb of Rochester, N. Y., now has a license to manufacture this instrument and is making those to be used by the Geological Survey and the Corps of Engineers.

The principle of this instrument is the dichromatic projection of overlapping vertical aerial photographs in alternate complementary colors, usually red and green, and viewing through spectacles of corresponding complementary colors, the spatial model is found by the fusion of the doubly projected images. This principle is commonly utilized in anaglyphs used in three dimensional illustrations in books and sometimes in three dimensional motion pictures.

The multiplex instrument is a series of small projection cameras mounted on an adjustable support. One of the small diapositive plates is adjusted in the focal plane of each projector so that its center coincides with the axis of the projector, and alternate red and green glass filters are placed in the lamp houses of alternate projectors, so that the images from the overlapping diapositive plates in adjacent projectors are projected on the drawing table in the complementary red and green colors.

All the control points are plotted on the projection sheet mounted on the drawing table and, as the successive models are projected, the operator views them with red and green spectacles and sees the three dimensional models in neutral tone. He focuses these models on a white platen on the top of a small movable tracer, in the center of which is a luminous point, technically called a floating mark, which is directly above a pencil point which traces the position of the floating mark on the map sheet. The operator adjusts each projector for tip, tilt and swing, and raises the top of the platen on the tracer (called the tracing table) by a finger ratchet in order to set it for the proper elevation.

Plotting with Multiplex

After all of the adjustments have been made so that the projected images of all four ground control points on the first optical model fall exactly on their plotted position on the projection sheet, the operator then moves the tracing table over the map sheet so that the floating mark follows all of the cultural features on the model—roads, trails, houses, etc.—keeping the elevation of the platen so that the floating mark always seems to touch the ground. The pencil point thus plots all of the cultural features on the map.

The next operation is to plot all the drainage features—streams, lakes and ocean shores—following the same procedure as used in plotting the cultural features, including raising or lowering the platen so that the floating mark always seems to touch the ground. The last operation is to draw the contours, which differs only from the other two operations in that once the proper elevation of a contour is set by the finger ratchet, the elevation of the platen is not disturbed, but the tracing table is forced over the model, around the ridges and up the valleys, so that the floating mark is kept always touching the ground.

Once all of the features on the optical model formed by the diapositives in the first two projectors are plotted, the operator turns off the lights on the first projector and turns on the third, forming the next model in the series, and "bridging" the control used in the first model by not disturbing the adjustment of the second projector in any way. Thus the operator continues with all of the models until the map area is covered. This completes the work of the photogrammetrist with this type of instrument.

Aerocartograph

The Geological Survey has another type of stereoscopic plotting instrument known as the Hugershoff Aerocartograph. As previously stated, this instrument was imported from Germany in 1927 and became the first stereoscopic plotting instrument owned by the Federal Government. This instrument is described in detail in a paper published by the American Society of Civil Engineers,[16] but following is a brief outline of its principles and of the differences of its operation and that of the Multiplex.

The diapositives made for the Aerocartograph are the same size as the aerial negatives and hence much larger than those used in the Multiplex projectors. The method of observing the optical model formed by two overlapping photographs in the Aerocartograph is through an optical system consisting of two telescopes each having a number of lenses and prisms. Each diapositive in the Multiplex is projected directly on the drawing table, but the diapositives in the plateholders of the Aerocartograph are not projected at all. Instead they are viewed stereoscopically by the operator and he guides the movements of the tracing pencils in the three co-ordinates of space by moving two hand wheels and a foot wheel. The operator can move a cylindrical drum under a tracing pencil, as well as moving a pencil over a stationary map. In this way two maps can be made at the same time and at different scales, one on the drum and one on the drawing table. With the Multiplex, the pencil is moved over a fixed drawing and only one map can be drawn at the same time.

The Aerocartograph is very accurate, its most successful use being in completing the mapping of Zion National Park, Utah, where the contours plotted in the office joined without adjustment those mapped by an exceedingly skilled topographer in the field.

Completion Survey

After all of the basic information has been traced from the diapositives, by either of these (or by any other) stereoscopic plotting method, it is necessary to finish the map by what is called a completion survey. This must be done in the field by ground survey methods, so as to make an accurate check of essential topographic features as well as to add such information as is not visible on the

[16] Birdseye, C. H.: "Stereo-Topographic Mapping," Paper 1843, *Transactions*, American Society of Civil Engineers, Vol. 98 (1933), pp. 771–825.

photographs. These field examiners determine city, county and state boundaries, classify roads, locate farm buildings, obtain names of streams, hills, towns and similar data, and plot all other features not obtainable from the photographs.

Thus the work of the photographer, the cartographer, the surveyor and the photogrammetrist has all been co-ordinated and fitted together. The final hand-drawn map is thus completed, ready for shipment to the Washington office for editing and reproduction in colors—black for cultural (man made) features, blue for water features, brown for contours, green for woodland areas, and red for road classification.

Map Reproduction

Most of the maps drawn by stereoscopic plotting instruments are reproduced by multi-color photolithography. There are of course several ways in which pencil drawings can be reproduced in colors, and the Geological Survey selects the one that seems best adapted to a particular project and promises the quickest and cheapest results. The maps may be reproduced by engraving on copper plates, by engraving on glass, or by inking a separate drawing for each color and making a photolithographic plate for each color. A complete discussion of this subject of map reproduction would require a book, and the writer does not know of one that is complete and up-to-date, except a new British book entitled *Practical Photolithography*, by C. Mason Willy, published by Sir Isaac Pitman and Sons, Ltd., London, in 1938. The writer, however, presented a short illustrated paper entitled "Map Reproduction" at a meeting of the American Association for the Advancement of Science at Rochester, N. Y., June 17, 1936. This paper covers briefly the three subdivisions of the subject, but was not published.

The third method mentioned is perhaps used most commonly in reproducing maps plotted by the Multiplex Aeroprojector, and is described briefly as follows: The scale of pencil drawings made on the Multiplex depends partly on the height of the aerial camera above the ground, and partly on the focal length of the aerial camera. However, if the aerial photographs are on the scale previously cited, *viz.*, 1:24,000 (2,000 feet to the inch), and the map is going to be published on the scale of 1:31,680 (2 inches to the mile), the multiplex plot will usually be drawn in pencil on the scale of 1:15,840 (4 inches to the mile), and this pencil plot will usually be inked on the scale of 1:24,000. Therefore, in this example, the pencil drawing is photographed to the scale of 1:24,000 and several nonphotographic blue line prints on metal mounted drawing paper are processed from the same glass negative.

These drawings are copied photographically by one of the largest map copying cameras made, taking wet plates as large as 50 by 50 inches in size. When these wet plate negatives are developed, they can be processed direct to a sensitized metal printing plate, or to a sensitized sheet of drawing paper mounted on a metal plate to prevent shrinkage or distortion.

On an extra blue line print that is not mounted on metal, the map editor carefully checks every line, elevation and symbol as a guide to the topographic draftsman, so that the final published map will come up to Geological Survey standards of accuracy, clarity and presentability. The editor also checks the names of features given on the lettering diagram accompanying the drawing, confirming their spelling from various authentic sources, such as atlases, postal guides, decisions of the United States Board of Geographic Names, etc.

While the editors are checking the lettering, topographic draftsmen ink on one metal mounted blue line print all of the cultural features, on another all of the drainage and on a third, all of the contours. Each of these prints is inked in black ink, because of better photographic quality, although the second is printed in blue and the third in brown in the actual printing processes. The metal mounted sheets prevent distortion of the different drawings and result in perfect register of the different colors in the final printed map.

All names and legends selected by the editors for the final map are printed on transparent tissue paper in specially prepared sheets and accurately pasted in position on one of the metal mounted blue line prints. This lettering sheet is photographed separately from the sheet carrying the cultural features, but can be processed to the same printing plate because both features are to be printed in black.

A separate drawing is not made for the highway classification until a combined proof copy of the culture, drainage, contours and lettering data are available, and nonphotographic blue line prints on metal mounted drawing paper are made, so that the highway classification, when printed in red, will not interfere with any of the other printed data.

Boundaries of the woodland areas are sometimes indicated on the pencil drawing, so that they will show faintly when photographed and these are cut by a glass engraver on a specially prepared stained negative during the reproduction process. If these woodland boundaries are not indicated on the drawing, they are shown on a tracing of the pencil drawing, are photographed to the publication scale of the map, and a separate printing plate is made by a lithographic artist by transferring a chalk offset impression of the woodland areas from the photographic negative.

A large modern plant with eight presses is maintained and operated the year round by the Geological Survey, and here the topographic maps are printed on high speed lithographic presses, either direct or offset.

After careful inspection, the finished maps are sent to the stock room, which has storage space for more than eight million maps. From here the Survey distributes more than one million maps each year.

Uses of Topographic Maps

The uses to which these million maps are put are as unique and interesting as the story of their creation. Topographic maps are essential to national defense programs, for only from knowledge of the terrain can troop movements be carried out quickly and accurately, assuring perfect maneuvering for defensive or aggressive action. Such maps are the first tools for development and construction of flood control and power projects, for existing physical conditions are the basis on which these projects are built. The maps show the best routes through which modern highways can be built: in fact in undeveloped country, savings in highway funds are much greater than all mapping costs. Land reclamation, soil conservation, study of water resources, study of drainage problems, inventory of mineral and all other natural resources—all these attempts to make the earth more permanently productive—are based on the information shown on topographic maps. In fact, they are essential to any activity that has to do with the use of the land.

Washington, D. C.,
December, 1939.