PHOTOGRAMMETRY FOR SMALL SCALE CARTOGRAPHY*

METHODS AND RESULTS

I. Aerial Surveys

FOR economic reasons and in order to reduce to a minimum the number of ground control points, aerial photographs are taken at the smallest scale compatible with clear definition. This can be done either by flying at greater altitudes or else by using a shorter focus camera. Of these two factors the altitude of the flight is limited by the performance of the airplane and also by meteorological conditions. Experience has shown that best results are obtained when a certain definite numerical ratio exists between the scale of the projected chart and the scale of the photographs. In general, the scale of the photograph should not exceed the ratio of about 1:60,000 to 1:80,000 since otherwise important details necessary for the cartography cannot be clearly recognized.

When a large expanse of territory is to be covered, the trend will be towards photographs taken with the widest possible angle. Already attempts had been made to increase the angle of the objective beyond that which it was possible to obtain with individual objectives by employing cameras with multiple objectives placed at an angle to each other and joined together with a single shutter control.

The individual partial photographs are then generally transformed in an optical apparatus to form a single picture. New constructions of this kind are the Aschenbrenner panoramic camera for very small scale work and the nine-lense camera for the U. S. Coast and Geodetic Survey[1] for medium scale (the latter weighs 340 kg. when loaded for service.) The complications in construction thus brought about have been overcome in Germany by the use of the wide-angle Topogon lense of Zeiss which has a field of 105°. This objective has made possible a considerable advance in aero-triangulation.

An enlargement of the area photographed at a single exposure is also possible by passing from the usual vertical photograph to the oblique photograph. Extensive cartographic projects, such for instance as the Danish and Norwegian surveys of Greenland, the photographs taken on the Forbes-Grenfell Expedition in Labrador, numerous expeditions in Canada, Italian operations during the Abyssinian war, were therefore almost always (and especially before the development of the wide angle camera) taken as oblique photographs. It should be noted, however, that with this method of aero-photography, the scale of the photograph, and therefore the definition of objects in the background, falls off very rapidly. In mountainous country, consideration must also be given to the fact that with increasing obliquity of the photographic rays, an ever greater portion of the terrain will be obscured by the mountains. (This is also true for the marginal rays in the wide angle photographs.) Records published in the press concerning the number of square kilometers taken by the "X" camera at one exposure should be accepted with reserve. Such data give no idea as to what portion of the photograph can be used practically for the purpose intended.

The problem of photography for small scale cartography may then be stated somewhat as follows: The scale of the photograph determined by the altitude

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[1] See *Hyd. Review*, Vol. XIII, No. 2, pages 130–137.

of light and the focal length of the camera should be so chosen as to represent the optimum between the conflicting requirements of good definition and accuracy and economy. The type of relief of the terrain and the character of the proposed map are factors which determine in conjunction with the geodetic and technical considerations whether the vertical or oblique photographs are to be preferred. The fact that the climate can offer serious difficulties for the photography is self-evident. Thus in certain tropical regions between the ground fog, the oblique lighting in the early morning and evening hours and the constant recurrence of thick clouds about noon, a few hours alone remain in the course of the month which are favorable for photography.

II. The Pure Photographic Methods

Everyone knows today that the aero-photographs give the most pictoral and complete representation of the earth's surface. It is often overlooked, however, that it is necessary to distinguish between the utility of the photograph from the view point of definition of detail or reconnaissance and its metric or cartographic value. In particular, in small scale surveys, it must be remembered that the individual photograph counts for nothing while the strip is everything. The aero-photograph comprising several prints or the composite photograph of a hilly or mountainous terrain, may have a high observation value, but its direct utility as a cartographic document diminishes with the magnitude of the altitude differences (and also with the serviceable field of the camera). Although it is possible by simple optical photographic transformation with sufficiently flat terrain to eliminate rapidly and accurately the distortions in perspective produced by the tilting of the camera at the moment of exposure, a mountain which is "upset" by this representation of central perspective can only be "righted" by complicated methods. There is, however, no process by which those portions of the land obscured by mountains can be magically restored. The errors in position on the aero-photograph may be considerable. At the edge of the vertical image taken with the Topogon wide angle objective, there is, for instance, an error of position equal to the difference in altitude of the corresponding points on the ground with respect to the assumed plane of reference. The efforts made by Th. Scheimpflugs at the turn of the centuty (which have often been repeated), to produce the "photo-map" by means of special projection methods in which any desired shape of terrain might be directly represented photographically, have not been practically developed.

To summarize: All strictly photographic methods, with the aid of which the (central perspective) aero-photograph can be converted into an orthogonally projected map, pre-suppose a sufficiently flat terrain. Where there are great differences in height, in hilly or mountainous country, considerable errors of position result. But under all circumstances, the aero-photographic prints forming a composite representation possess an extremely high reconnaissance value. We again call attention to the articles of C. Troll which are profusely illustrated and accompanied by numerous references.

From a purely cartographic standpoint, the photo-map, at least on small scale, appears overloaded. It contains sufficient material for a dozen special maps (which could easily be deduced from it). When we compare it with the map, therefore, we miss the order and clarity of the cartographic representation. It must eliminate the non-essential, the accidental and the seasonally conditioned features, and must constitute a key to the changing forms of representation in the natural objects in the picture, etc. Therefore, in the cartographic sense, the photo-map is really a comprehensive collection of raw material. Certainly, under these circumstances, it is in need of being perfected along certain lines. Place names and designations are lacking, the condition of the roads, the character of the sturctures, etc., often cannot be determined with any certainty.

The simplest of the purely photographic processes and, therefore, the simplest photogrammetrical method of mapping large areas in a short time, consists in fitting the aero-photographs together into a mosaic. If the flight has been carefully carried out, it will be possible to assemble the mosaic without too many gaps at the edges of the prints. However, with such matching together of many negatives, certain unavoidable discrepancies will result, particularly where large areas are covered. These; however can be conveniently distributed up to a certain point, provided a corresponding number of geodetic control points are available. This process of "controlled mosaic" has been applied to a considerable extent in the United States of America. It is the cheapest process. Its accuracy for small scale is adequate but is limited for large scale.

A considerable improvement is obtained through accurate restitution: i.e., the optical-photographic elimination of the influence which the tilt of the photographic axis, the change in altitude of the airplane, exert on the size and shape of the picture. After restitution, the individual pictures fit together exactly and all have an accurately predetermined scale. The method is longer as a result of the interposition of the restitution process and requires, further, either a large number of control points or a knowledge of the position of the camera in space at the moment the exposure was made. Owing to its high and regular accuracy it is used in many countries for the production of photo-maps on medium and large scale (photo-maps and industrial maps reproduced from them in Sweden to 1:10,000). Large areas are regularly mapped in Finland to the scale of 1:20,000 after restitution. The method there developed makes for rapid work and few control points are required.

From the photo-map it is possible to obtain the conventional planimetric map by drawing in the ground contours with China ink and eliminating the photographic details by means of a reducer. Holland has used this process in a somewhat different form and has brought about considerable refinement in its development. A representation of the heights in the terrain can be added after direct terrestrial survey with the plane table and the alidade or the aneroid. As far as we know, considerable use has been made of this possibility in the U.S.S.R. By viewing stereoscopically two successive or partially overlapping aero-photographs, it is possible to draw in the approximate contours to represent the shape of the heights. This last method was used in part on the Italian maps in Abyssinia as it required very little time.

Although the previously mentioned methods utilized predominantly vertical photographs, in Canada, until a few years ago, use was made of perspective nets with oblique photographs. Into the obliques, which showed the natural horizon, there was copied a distorted grid which was the representation of the calculated distortion of the square resulting from the angle of tilt in question. In this manner one can estimate by eye the location of the details to be mapped in the corresponding meshes of the rectangular cartographic grid. The Canadian lake district with its numerous richly contrasted shore lines, offers a suitable opportunity for the application of this method which forms a sort of transition method to the graphic-calculation method described in the next section ("Möbius" net).

Common characteristics of the methods described in the first section are, viz: practically no measurements and no calculations required; the result is therefore simple and clear. The daily output is considerable. The representation of the terrain contains a great many details; aside from the above mentioned limitations it is complete. On the other hand, in order to attain the clearness of the conventional planimetric chart, it has the disadvantage that it necessitates additional work of draughting, and also that the attainable accuracy depends upon the magnitude of the differences in heights in the terrain.

The final development of the purely photographic methods is represented by that form of radial triangulation developed in the U.S.A. called the "slotted template method." For the basic principle of this method of radial triangulation, see the following section.

The recent form of this method as developed by the Americans consists in cutting in on the negatives the radial directions from the central point of each negative to the different points sighted by stamping. The joining up of the negatives is then accomplished without any calculation, by simply inserting suitably-shaped small metal pegs in the intersections.

III. Graphic Methods Combined with Calculation

These methods utilize the geometrical relations existing between the photographic negative and the portion of the terrain which it represents. As auxiliaries these projection methods require only the use of pencil and ruler where the survey is limited to flat terrain and in other cases covering any kind of terrain, they require in addition the compass, the scale rule and the aid of calculations. Although we might easily be inclined to dismiss some of these methods as high school exercises in descriptive geometry, it should be noted that they are employed to a great extent throughout the British Empire. The processes used with this method are only applicable to small scale work, as opposed to those other groups, and is used in practice exclusively where the exigencies are not over great. In general they are more complicated for the operator than the purely photographic and the instrumental methods.

The simplest from the methodical standpoint is the projective process which is applicable in fairly flat areas such as the "four-point" and the paper strip methods. These are of particular importance for war mapping. They consist essentially in the construction of a base of four objective points whose position on the chart must be assumed as known (as the only determined data) and of obtaining the position of unknown points by simple connecting lines and resection with pencil and ruler. The positions thus determined are transferred to the map. Further, it is possible to develop a reference grid ("Möbius" grid) on both the photograph and the map which permits the lineal transfer of the photographic elements on to the map. In the above mentioned Canadian method the grids are determined by calculation and then photographically transferred to the print.

The graphic form of radial triangulation has attained wide-spread practical importance. The basic idea of this radial triangulation, due to the gifted Austrian Schiempflug, consists in the fact that about two thirds of the overlapping photographs of the strip can be fitted together by angular measurements from the photographs and joined up in length and direction somewhat like a polygon net. Thus this radial triangulation offers the possibility—so largely utilized today—of obtaining several control points for each photograph in a terrain with moderate differences in heights, solely by the use of measurements.

This basic idea has been realized in the graphic form as follows: The azimuth measurements from the center of each of a series of successive photographs, which are essential to the determination of the polygonal angle and the stretches of the polygon chain, are replaced by plots of the radial directions made on tracing paper placed directly over the photographs. By carefully fitting the next following photograph to the various points thus plotted on the tracing paper, the diamond chain continues to grow. Finally by a scale correction and a rotation between the known fixed points, they can be "hung together." Depending upon the accuracy required, free chain lengths up to 20 to 30 km. are permissible.

This process also forms the geometric structure of the Arundel Method: i.e. the photogrammetrical method par excellence of the British Empire. The Arundel Method is extremely well developed and there are quite a few systematic descriptions of it available.[2] Here we can only give the bare outlines: The graphic radial triangulation is carried out with vertical photographs. In each photograph the point on the terrain corresponding to the center of the photograph, together with at least one point on the upper and on the lower edge of the photograph, is carefully plotted in the sparse geodetic net. By means of graphic resections, the network of plotted points is then made denser. With regard to the heights it is assumed that there is available a wide-mesh net of barometric measurements. By means of altitude differences obtained from a simple stereoscopic measuring apparatus, the most suitable heights are interpolated in the photographs (for instance in the topographical contour lines). Finally there follows the stereo-observation of the photographs and the execution of the cartography proper, by means of estimated interpolations between the measured points. Simple as this method may appear from this description, it proves very complicated after a study of the numerous precautions which must be taken on all sides in order to guarantee sufficient accuracy and satisfactory reliability everywhere.

The Indian Method[3] represents a variant of the above described method. The determination of the heights follows with the aid of oblique photographs, in which every individual height must be found by graphical construction or by calculation.

In conclusion we shall cite one older method[4] to which O. M. Miller of the American Geographical Society recently reverted. It was used for the evaluation of the results of the Forbes-Grenfell[5] Expedition in North Labrador in 1931, 1932 and 1935, and recently applied to the data of the Wood-Yukon Expedition. In those oblique photographs taken at altitudes of 2500 and 1500 meters and with a 10° inclination to the horizon, angular measurements were carried out with a simple photograph theodolite which served by resection to fix the position of the camera with respect to several photographed trigonometrical points. From these positions new control points were determined by forward resection, which could then be used for the determination of still further points etc. In order to eliminate errors of calculation, use was made of the analytical differential process. After a sufficient number of individual points had been calculated, the plotting of the hypsometry was accomplished with a simple transformer adapted to oblique photographs. The contour lines were then interpolated by estimation, for which no stereoscopic photographs were available, solely the obliques.

IV. The Instrumental Methods

The integral and exact interpretation of the mathematical relations between the photographs and between the photograph and the terrain by means of

[2] M. Hotine: *Prof. papers of the Air Surv. Comm.* Nr. 3, London, 1927; J. S. A. Salt: *Prof. papers*, Nr. 8, London, 1933; D. R. Crone (Survey of India), Air Survey, Dehra Dun, 1933.

[3] R. C. N. Jenney: The Indian Method of compiling high oblique air photographs, etc. (*Photogrammetria* II, 1939, S. 117–27).

[4] Compare B. R. Hugershoff and H. Cranz: Grundlagen der Photogrammetrie aus Lutfahrzeugen. Stuttgart 1919.

[5] A. Forbes: Northernmost Labrador mapped from the air (*Amer. Geogr. Soc.*, Spec. Public. No. 22, New York 1938).

mechanics and optics, takes its place logically as the last in the series of methods. Here one seeks in various ways and with successive approximations to obtain an exact and complete re-construction of the conditions under which the photograph was taken and of the photographed object in the restitution apparatus. For this the essential factor is the simultaneous evaluation of two photographs of the same terrain and the utilization of the stereoscopic effect. The principal interest, in this methodical investigation, centers about the great universal two-photograph mapping instrument and we shall, therefore, neglect those instruments which are capable of giving only a partial solution.

The basic idea of the solution is simple: Two photographs of an area taken from two different viewpoints are brought into opposition in the instrument in such a manner that they occupy, relative to each other, the same positions occupied by their respective cameras on exposure. The resultant image of the terrain which is formed by the intersection of the homologous rays from the two photographs can be reduced to the desired scale and to the proper inclination to tne horizon. After this operation is carried out we then have a true scale (opti!ac) model of the terrain in all detail which can then conveniently be measured with great accuracy and plotted with respect to planimetry and hyposometry.

In detail the operation is as follows: By actuating a movable measuring marker in three dimensions which passes over the stereoscopically viewed area. this measuring marker can be brought in apparent contact with any position of the terrain. A pencil which is moved together with the measuring marker then gives the planimetry of the point and a counting mechanism indicates its height above sea-level. Methodically, it is also of the greatest importance that an exact and continuous measurement of any given contour, such as for instance the ground contour and above all the height contours, should be possible by a simple optical touching of the apparent model of the terrain. In this manner it is possible to realize an improvement to an extent previously thought impossible in the representation of even the most difficult terrain, and this by means of a very simple process. These precision instruments also permit, by adaptation of each successive photograph to those which have just been measured, the execution of a special aerial triangulation, i.e. the measurement of a chain of triangles in position and altitude, over large stretches. In this possibility, as stated above, lies the great importance of photogrammetry for small-scale cartography. The mastery of the instrument necessitates a two to three months' training period for the personnel, but no special preliminary education need be required. But, as in the case of all other processes, it should be remarked that only those really trained in topographical work are capable of producing satisfactory topographical maps.

The development of photogrammetrical cartographic instruments began soon after the turn of the century in Germany and soon led to the production of the Zeiss-Stereo-planigraphs. Moreover, a small double-projection apparatus, the aero-projector multiplex, acquired the greatest importance. Other countries followed: In France the Stereotopograph was constructed by Poivilliers; in Italy the Stereocartograph by Santoni, in Switzerland the Wild Autograph—to mention only a few of the leading "instruments of first importance."