

# RECONNAISSANCE MAPPING FROM AERIAL PHOTOGRAPHS IN UNEXPLORED COUNTRY

*With a Description of a Reconnaissance Map Covering the Coast of Wilkes Land  
and Adjacent Coasts in Antarctica*

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## INTRODUCTION

Within the three or four decades since World War I, the mapping of the earth's topography by the use of photographs from airplanes has achieved a magnitude and an importance equal to the mapping by long established methods from the ground. A new science has been built up around aerial photography, known as photogrammetry. Ingenious new machines have been invented and constructed, new cameras used, personnel trained, and efficient procedures developed, whereby the wealth of information on a series of aerial photographs is translated into useful maps, charts, and three-dimensional models. [“Manual of Photogrammetry”, Amer. Soc. of Photogrammetry, Pitman Publ. Corp., New York. A preliminary edition was issued in 1944 and a later edition in 1952.]

Those who wonder at these achievements or who make everyday use of these amazing developments rarely recognize or realize that the present gigantic photogrammetric system and the procedures which it employs are based upon the availability of adequate and accurate ground control. Expressed as a general rule it may be said that somewhere in every photograph subjected to photogrammetric instrumentation there must be at least two recognizable features whose geographic positions and elevations on the earth are known. This requirement is based upon the assumption that the plot resulting from what may be called aerial triangulation shall have the same order of precision, and perhaps nearly the same absolute error, as one made by the older methods, working from the ground.

Progress in the art is such that, when a small set of photographs is analyzed simultaneously by a battery of machines designed to work together, the two control points may be required only for the small set, and not for each individual photograph.

NOTE: *Part 2 of this paper will be published in a forthcoming issue of “The International Hydrographic Review”.*

For the aerial pilot, photographer, and mapper working over unexplored and unknown country, such as much of that in Antarctica, the problem is vastly different and many times more complicated than for the crew working over known and occupied country. In the first place the pilot of an exploratory flight has to remain clear of unexpected clouds, and of unknown mountains suddenly encountered which are higher than the airplane. This means that he cannot always fly on a chosen course or in a predetermined straight line. The navigator has to keep track of the airplane route in an unfamiliar region, where no one may have flown before. Almost of necessity both of them have to investigate important new topographic features as they appear, if they are to bring back the maximum of information about the country. This means changes of plan during a flight, unexpected side trips, and short cuts through regions of steep slopes and violent winds.

The navigator is, in all probability, far beyond the range of Loran and others means of long-range plotting, which help to guide him and position the airplane in country that is already occupied and mapped. The navigator may, indeed, be flying with a pilot who "smells" his way around, and who disdains flying on predetermined routes or keeping any kind of flight records.

The aerial photographer on an exploratory flight must take pictures where and when he can, and be thankful when the airplane can fly level and on a straight course for an appreciable length of time. The mapper, who almost never sees the new country himself, must work from the navigator's log and the photographer's pictures. He must try to find out just where the airplane was, over the earth's surface, when the various exposures were made, if the pilot and navigator have not done this for him. He must then come up with some kind of a map, based on the photographs and using as much supplementary information as he can collect. He may be fortunate to have two control points whose geographical positions are fairly well known in the photographs for a whole flight, instead of two control

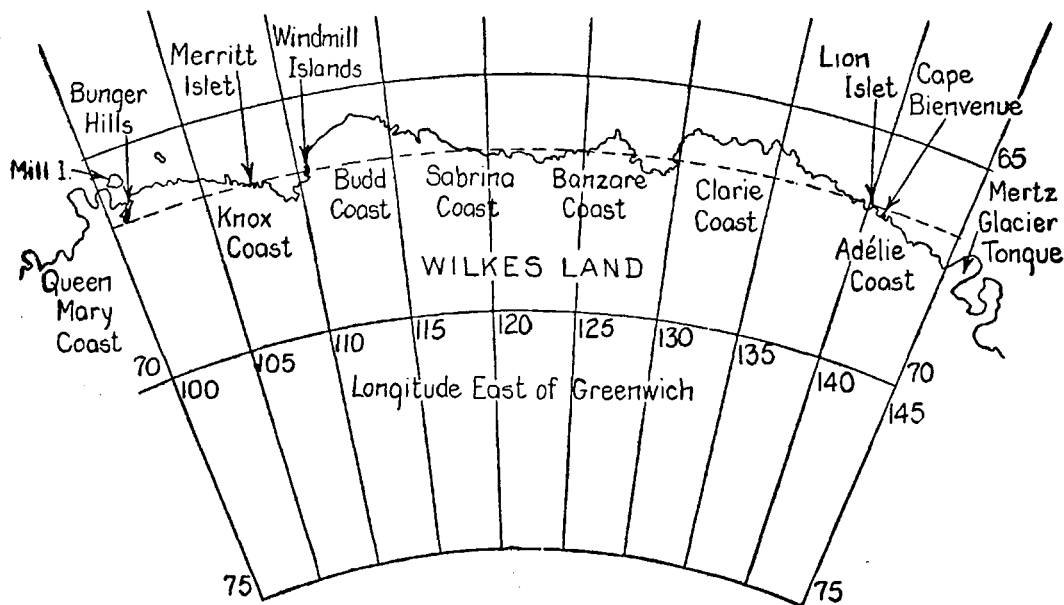


Fig. 1.

Sketch of the Coasts of Wilkes Land, Antarctica, showing control points available in 1953.

points on every photograph. He may know only the position of the starting point, the general direction flown, the approximate airplane speed, and the fact that the crew brought themselves and the airplane back again.

For example, in the construction of the 1955 reconnaissance map of the coasts of Wilkes Land and the adjacent coasts in Antarctica, described in Part 2<sup>(1)</sup> of this paper, there were control points only at the ends of the map. The sketch in Fig. 1 shows three control points at the west end and two points in the cluster at the east end, over 700 (nautical) miles away.

An admirable example of reconnaissance mapping from oblique aerial photographs, with inadequate ground control, is the set of twelve maps constructed by H.E. Hansen in Norway and known as the Hansen Atlas of 1946. These maps cover three segments of the coasts of Antarctica from Lon. 21° 00' E. to 27° 00' E., from 36° 50' E. to 42° 20' E., and from 55° 00' E. to 82° 00' E., respectively. They are drawn to a scale of 1:250,000 and they show a great wealth of detail, with a considerable amount of contouring, despite the long distances from the airplane track to the features delineated. They demonstrate what can be done in the way of useful mapping with a limited number of aerial flights and the exercise of patience, time, and talent.

What the mapper achieves in the way of a delineation of the new country which has been photographed does not deserve, in the opinion of many topographers, to be called a map. Nevertheless, call it what you will, many an acceptable and useful sketch of this kind has been made of previously unexplored country, with little or no ground control. Many more will be made in the years to come. This paper endeavors to describe how the task was accomplished in the past and how it may be repeated, by intelligent but relatively untrained and inexperienced personnel, in the future. The methods described require no elaborate equipment, no large working area, no appreciable working force, and hence relatively little expense. The precision of the result is usually superior to the precision of the *individual* components of the original data.

## DEFINITIONS AND NOMENCLATURE; PHOTOGRAPHING METHODS

The chart or delineation resulting from the procedure to be described is known as a *reconnaissance map*. It represents or pictures, as its name implies, what was seen on an exploration or reconnaissance flight, the general location of the geographic features, and the track or path of the airplane during the flight. It makes little pretence of being drawn to exact scale in all its parts, or of showing the principal features in their exact positions on the earth, but it should and usually does show them in their correct positions *relative to each other* and relative to the coordinates of latitude and longitude. It should enable one flying over the country again, or traveling over the ground, to recognize the delineated features and to identify them properly if they have been named.

As an example, the reconnaissance map prepared by the senior author to depict the country traversed by Rear Admiral R.E. Byrd's Eastern Flight of 5 December 1929 from Little America, published in the April 1933 issue of *The Geographical Review*, had a scale that was too large by some 18 per cent. This was due to the uncertainty in position of Scott Nunataks, one of the two control points available for the whole map. Nevertheless, several field parties of the Second Byrd Antarctic Expedition, traversing this country on the ground, a year or two

(1) To appear in a forthcoming issue of *The International Hydrographic Review*.

later, had no difficulty in finding their way, or in identifying correctly all the new geographical features named on the 1933 reconnaissance map.

The availability of such a map should simplify greatly the work of future mappers in a given area, working to a greater degree of precision, either from the air, from the ground, or from the water. It should indicate the particular ground features which would best serve as control points for a systematic and accurate mapping program in the future. When the astronomical positions of features appearing in reconnaissance photographs are later determined, the marking (by the field to the mapper who undertakes to revise the original reconnaissance. This procedure was recently followed by the Australian National Antarctic Research Expedition in the Mac-Robertson Coast Area, using USN Operation Highjump photographs.

Since the geographic features to be recorded on a reconnaissance flight lie largely on either side of the track of the airplane, rather than directly beneath it, and often at very considerable distances from that track, a system known as *oblique aerial photography* is extensively employed. The aerial camera is held with its axis

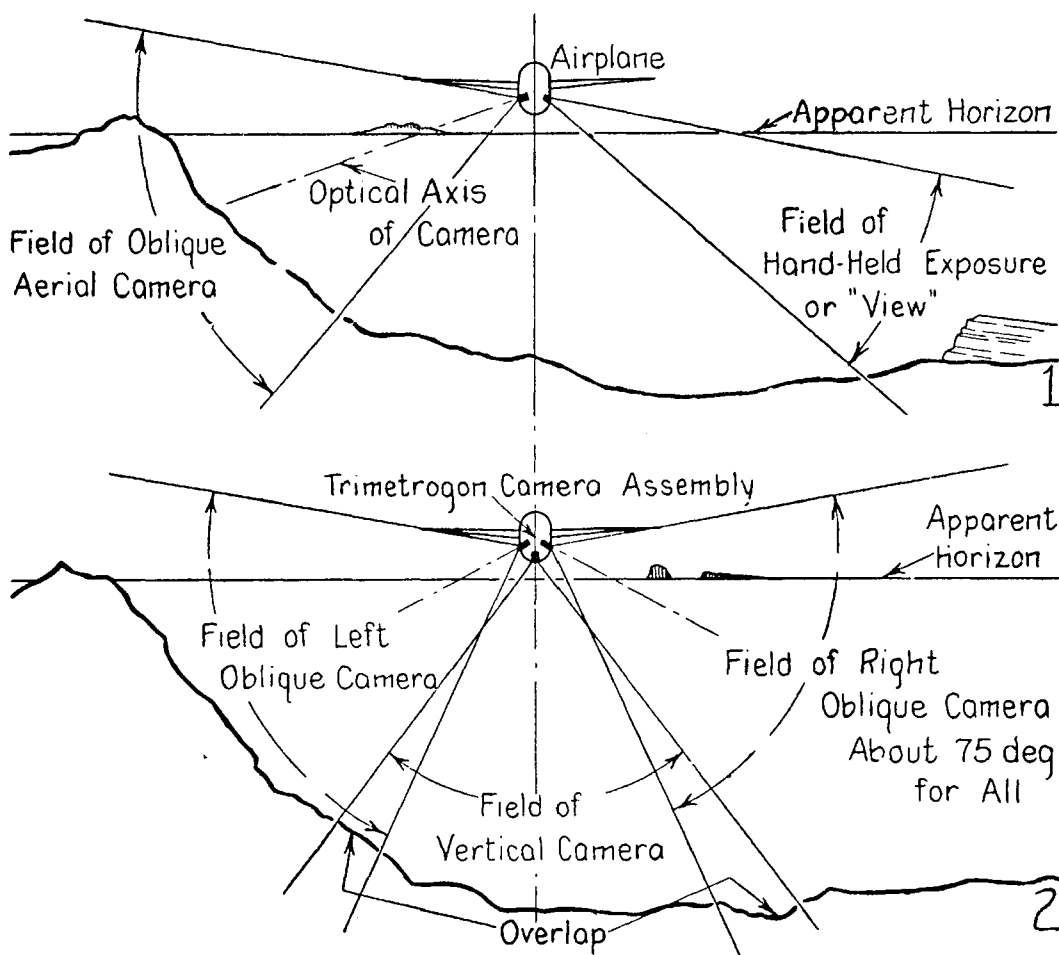


Fig. 2.

Vertical sections through an airplane position, with fields of view of different aerial cameras.

depressed about 20 or 30 degrees below the horizontal, indicated schematically at the left of diagram 1 of Fig. 2, so that the field of view includes everything from a point well above the visible horizon to within a mile or two of the airplane path, depending upon the angle field of the camera lens and the altitude of the airplane. A large overlap parallel to the direction of the flight path is obtained with a reasonable interval between exposures. With the camera in the hands of a trained photographer, and with a reasonable degree of contrast on the print, the detail on objects in all parts of the field is sufficient for all practical purposes.

The early hand-held aerial camera is now largely replaced by the *trimetrogon camera* assembly, in which there are three cameras photographing simultaneously with their optical axes in a transverse plane normal to the airplane axis. Diagram 2 of Fig. 2 shows that two of the cameras photograph obliquely, to the left and to the right, respectively, of the airplane track, at *depression angles* of about 30 degrees to the horizontal. The third camera photographs directly downward, and its field overlaps those of the two side cameras. All three cameras are attached to a single frame, or to the airplane structure, so that their *optical axes* always lie in the same transverse plane, at given angles with each other in that plane. This scheme has the great advantage that one aerial photographer can make simultaneous exposures from both sides and from the bottom of the airplane. The vertical camera covers the smallest area on the ground, so the interval between exposures, with a given percentage of overlap on the "verticals", is governed by the airplane altitude and its speed over the ground.

During a reconnaissance flight, the airplane is held on a steady course whenever practicable, so that a series of oblique or trimetrogon photographs is made at the proper depression angle (s) and at regular intervals, as is customary on mapping-survey flights. During the remaining portions of a reconnaissance flight the course of the airplane may be determined largely by the adjacent geographic features, as when flying through a pass where safe navigation always takes precedence over photography, or when following a curved coast line. Under these conditions, it is not always possible to hold the camera(s) at the proper depression angle or to prevent a certain amount of tilt in the vertical camera axis, occasioned by the banking of the airplane, by bumpy air, or by sudden changes of course.

Other aerial photographs are often taken with a smaller hand-held camera, pointed in all sorts of directions, as diagrammed at the right in sketch 1 of Fig. 2. In the polar regions they are taken to show the details of crevassed ice, the form of bergs, the presence of areas of open water, and any other features of possible interest. The photographs in this category are called hand-held pictures or *views*. Although many of them are entirely unsuitable for mapping, even for reconnaissance delineations, they are often valuable for identification purposes. Those taken at short range show detail not possible in a high-altitude photograph.

With the exploratory flights completed and the camera exposures made, the task of the mapper is to analyze the aerial photographs and to apply the information thus derived to a delineation of the region in the form of a reconnaissance map. For some of this work, known and proved methods can almost always be utilized.

Very complete and readable treatises describing the methods of taking oblique aerial photographs, constructing and using coordinate plotting grids, and making maps from the data obtained by analysis of these photographs have been available for some time past in the following references:

(1) "A Graphical Method of Plotting Oblique Aerial Photographs", issued by the Department of the Interior, Dominion of Canada, 1928.

(2) McKinley, A.C., "Applied Aerial Photography", Wiley, New York, Edition of 1929.

(3) Peters, F.H., "Aerial Photography Applied to Maps", Canadian Engineer, 1930, Vol. 58, pp. 563-569.

(4) McKinley, A.C., "Mapping the Antarctic from the Air", Nat. Geogr. Mag., Oct. 1932.

(5) The Manual of Photogrammetry published by the American Society of Photogrammetry, Preliminary Edition of 1944, contains on pages 578 through 712 four papers on "Mapping from Oblique Photographs". The first of these papers is essentially the same as reference (1) preceding. A later edition of this manual was issued in 1952.

For the remainder of the work, adaptations must be made to old methods and new methods have to be developed. Some of these methods, new two decades ago, were described then by the senior author. [Geogr. Rev., Apr. 1933, Vol. XXIII, No. 2, pp. 195-209]. Others are described in Part 2 of this paper.

As stated in the 1933 reference, page 196, no great degree of accuracy or reliability can be expected by following any single process or method. One type of analysis by itself may give an answer which is possibly correct, or which may be termed a fair estimate. A second and more-or-less independent method may yield an answer very similar to the first, increasing the probability that both are correct. If a third and a fourth method, applied judiciously in turn, are found to produce solutions which satisfy the two previous conditions, the mapping problem may be considered solved, at least so far as a *reconnaissance* map is concerned. Moreover, the solution carries with it a reasonable degree of certainty, despite the admittedly slender basis upon which each of the independent methods may rest.

It is amazing to find that repeated examination of aerial reconnaissance photographs, after all possible sources of information are apparently exhausted and after the map is completed, continues to produce much information of value. This is not surprising in a study of glaciation and drift; it is, however, also true of the more methodical and straightforward mapping problem. The answer is a simple one; the more one knows what to look for and the more one looks, the more one finds. It is not to be considered, therefore, that despite a long background of experience, the present review comprises all the methods of analysis that may be used to advantage or all the information that is to be obtained from a study of the aerial photographs taken on any reconnaissance flight.

## THE THEORY OF RECONNAISSANCE PLOTTING

### *General*

The making of a reconnaissance map from a set of aerial photographs calls first for the assembling of all available back-ground information on the area covered by the flight(s) undertaken in conjunction with the mapping project. For Byrd's Eastern Flight from Little America of 5 December 1929, previously mentioned, only a small portion of the area had ever been visited or seen before. For the U.S. Navy Operation Highjump flights over Wilkes Land, mentioned subsequently in the paper, parts of the areas in question had been seen only from a distance, at elevations close to sea level, and then only under rather unfavorable circumstances.

Actually, the search for and the collection of background information should precede the exploratory flights themselves, but unfortunately this is not always the case. Indeed, those in charge of flights into partly unknown country should take with them photographs of known features along the route, when these pictures

are available. Although Byrd was partly misled by incorrectly titled photographs from one of Amundsen's books, taken along on the South Polar Flight of 29-30 November 1929, this appears to be the exception rather than the rule.

Specifically, the reconnaissance mapping involves several principal tasks, described briefly as:

(1) Collecting and correlating all the available supplementary information, such as flight logs, dead-reckoning data on flight tracks, altitude and barograph data, focal lengths and negative dimensions of the aerial cameras, identification of photographic runs and of negative rolls, and method of numbering of the individual negatives.

(2) Analysis of the photographs; that is, taking the necessary information from them. This in itself involves several steps, to be described subsequently.

(3) Making bearing plots, ground topography sketches, and laying out the principal topographic features on work sheets of local areas.

(4) Constructing the reconnaissance map.

It is considered preferable to start this discussion with a description of the plane and solid geometry involved in the aerial camera, and in the plotting methods. This applies actually to task (3) of the foregoing, but it is necessary if the reader is to have a clear understanding of what is involved in the remaining steps.

Several plotting procedures are used for the construction of reconnaissance maps. At least one of these involves only plane geometry, and is as elementary as the methods used by early seafarers and explorers. Others are relatively new, employing photography from the elevated positions made possible by the modern airplane. The preparation of any one reconnaissance map may involve all these procedures, or combinations of them.

The several plotting procedures are listed separately and briefly as:

(a) The bearing system, using a series of horizontal angles between vertical planes passing through the camera lens and selected topographic features such as nunataks or peaks.

(b) The coordinate system, whereby a pattern of topography, lying in one plane and recorded on a photograph, is transferred to a large-scale work sheet or map section ruled in rectangular coordinate lines.

(c) The simplified mosaic method, whereby a series of photographs taken with the camera axis approximately vertical is employed to determine the shape of an airplane flight path and then the relative position of the objects photographed.

There are at least two supplementary procedures necessary to the making of reconnaissance maps. These are described as the explanation of the plotting theory proceeds.

(d) The proper positioning and orientation of the individual layouts or local-area plots with respect to the parallels of latitude and meridians of longitude upon the earth.

(e) The establishment of the proper scale, especially if the available control points are all near one end or one corner of the area being mapped.

In the sections and appendixes which follow, each of the five principal plotting procedures is described in sufficient detail to enable a beginner in this field to understand the plane and solid geometry involved, to make the calculations (either from the appendixes, from information in referenced material, or from



instructions being prepared by the authors), to analyze the photographs, and to draw a reconnaissance map by himself. The five procedures are outlined briefly in this section, to serve as a background for the subsequent descriptions. The lettering is the same, except for the use of capitals, as in the preceding tabulation.

### A. The Bearing System

The plotting procedure involving bearings is a relatively simple one in plane geometry. It is the same as has been used by seafarers for several centuries, when compass bearings of fixed objects are taken by a pelorus and plotted on a chart [Bowditch, N., "Sextant Angles Between Three Known Objects", American Practical Navigator, U.S. Hydrographic Off. Publ. 9, Arts. 152-153]. A similar method, worked up for the analysis of aerial photographs, is described in a somewhat different manner by O.M. Miller ["Planetabling From the Air, An Approximate Method of Plotting from Oblique Aerial Photographs", Geogr. Rev., Apr. 1931, Vol. XXI, No. 2, pp. 201-212; "Additional Notes on 'Planetabling From the Air'", Geogr. Rev., Oct. 1931, Vol. XXI, No. 4, pp. 660-662]. Since the diagrams employed are those plotted vertically on the tangent or ground plane of the earth in the vicinity of the observer, it is immaterial whether the horizontal bearing angles are taken at ground level or at the level of a high-flying airplane.

The general scheme is diagrammed in Fig. 3, representing a plot of objects projected downward to the ground plane of the earth. A group of principal peaks or summits occupying the positions D, B, and E are photographed from an airplane flying along a track such as that from  $A_1$  to  $A_2$  to  $A_3$ . Although shown as straight in the diagram for the sake of simplicity, the path may take the shape of any curve which can be flown by an airplane. Knowing roughly the shape of the flight path and its position over the earth's surface it is desired to plot the positions of D, B, and E with reference to that path. The camera is hand-held and is not fixed to the structure of the airplane. This permits exposures to be made on the bow, beam, and quarter, as indicated in the figure.

At the time  $t_1$  the airplane (and the camera) are assumed to be at the point  $A_1$ . Since the diagram is projected vertically downward, the airplane (and camera) are directly above the point  $A_1$ , so the latter serves for both elevated and ground positions on any orthodox map or chart. Assuming that an oblique aerial photograph is taken at this instant, with its optical axis lying in the vertical plane represented by the trace  $A_1O_1$ , the camera covers the angular width of field shown, in a horizontal plane. Upon exposure it records the principal features D, B, and E on the negative, plus F, C, G, and many other secondary ones. It is possible, by a procedure to be described subsequently, to work from the photographic print and to determine the *horizontal* angles  $DSO_1$ ,  $BSO_1$ ,  $ESO_1$ , and so on, between (1) the bearing lines drawn from  $A_1$  to the several features D, B, E, etc., and (2) the optical axis  $SO_1$ . What is called a *bearing plot*, constructed from this information, embodies the lines SD,  $SO_1$ , SB, and SE (plus SF, SC, and SG), just as they appear in the diagram of Fig. 3, extending for convenient distances from S.

Similarly, separate bearing plots made from the negatives exposed at  $A_2$  and  $A_3$  have bearing lines lettered the same. Their optical axes correspond to the lines  $SO_2$  and  $SO_3$ , respectively. The lines SD, SB, SE, and so on lie in the relative directions shown by Fig. 3 as radiating from the positions  $A_2$  and  $A_3$ .

If it could be known, or determined, that the airplane passed through the geographic positions  $A_2$  and  $A_3$  at the times  $t_2$  and  $t_3$  and that the optical axes  $SO_1$ ,  $SO_2$ , and  $SO_3$  lay in the directions indicated, the mapper could lay down

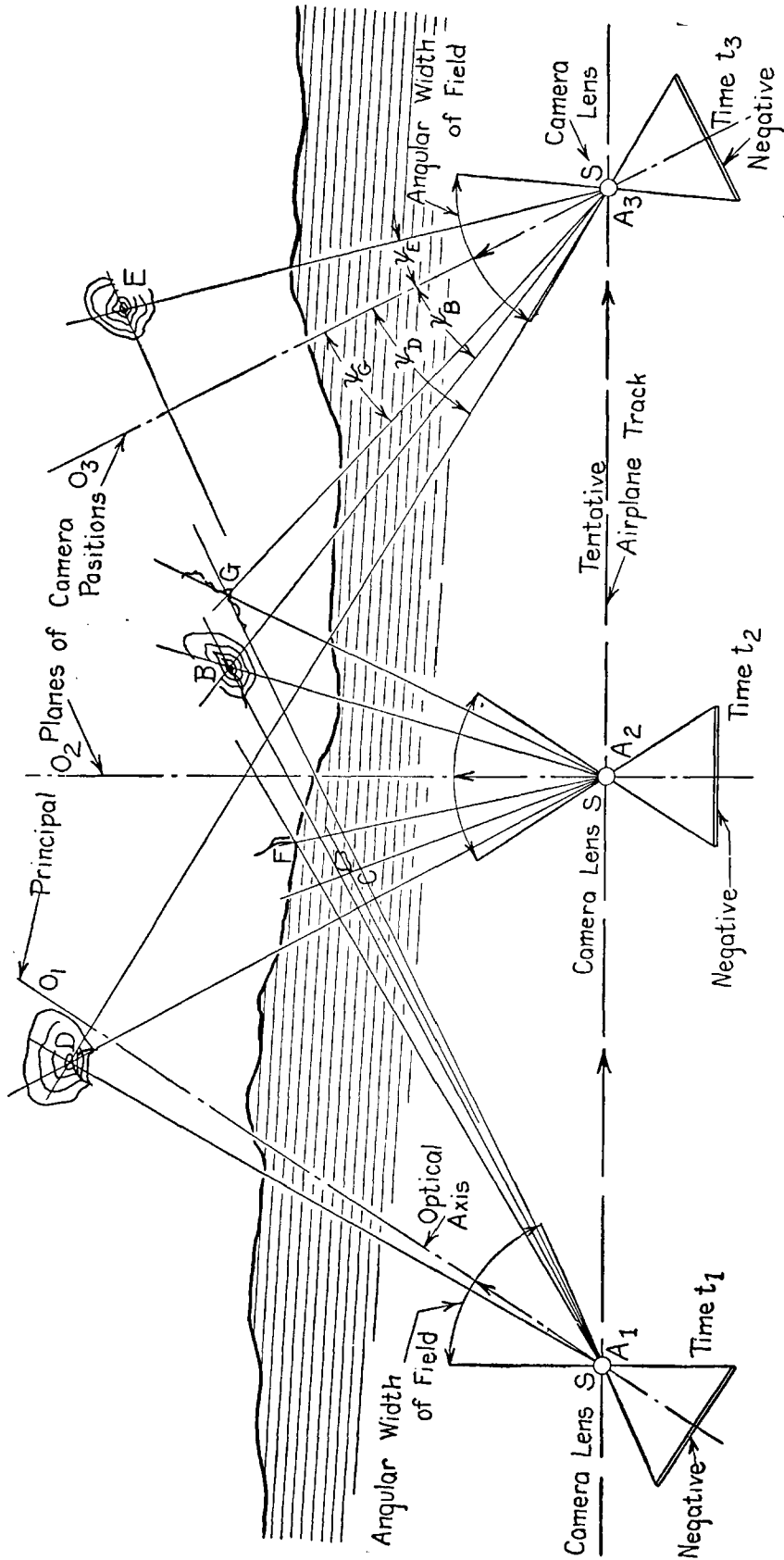


Fig. 3. Bearing and camera angles from three airplane positions, as projected on the ground plane.

the three bearing plots, constructed on transparent material, one over the other. The positions of the features D, F, C, B, G, and E would then be determined by the multiple intersections of the bearing lines at each of these points.

Even though the position and orientation of the flight track on the earth's surface is not known, but the distances from  $A_1$  to  $A_2$ , and from  $A_2$  to  $A_3$  are derived from available data, and the angles  $O_1A_1A_2$ , and  $O_3A_3A_2$  can be determined, it is still possible to fix the positions of D, B, E, F, C, and G with reference to  $A_1$ ,  $A_2$ , and  $A_3$  on a work sheet. The data from this sheet can later be transferred to a map when one or more of the geographic positions D, B, E, and so on are determined. The relation between the lettered positions holds good, even though it is not known just where the group belongs on a map. It also holds good even though the scale of distance is not known.

If the geographic positions of the lettered features in Fig. 3 are known, instead of the airplane positions, it is possible to place each bearing plot, with its several bearing lines, down on a chart showing those features. When three or more geographic features are involved on any one plot, there is one position, and one position only of the camera location S at which the bearing lines will lie exactly over the lettered geographical positions. The fact that this method breaks down if all the points in question happen to lie on the circumference of some circle seems not to interfere with its practical usefulness. Indeed, this is the method which has long been employed by the ship navigator when piloting in the vicinity of carefully charted landmarks and aids to navigation. In the latter case, however, the navigator observes the bearings visually, in quick succession, instead of taking them from a photograph. Whether observed from a surface ship or recorded from the air, the horizontal bearing angles are the same, as is the plotting or positioning method.

The accuracy of the plotting method just described is entirely independent of the height of the peaks D, B, and E above a reference plane such as sea level, or the height of the airplane above the same level. In fact, the airplane altitude need not be the same at the points  $A_1$ ,  $A_2$ , and  $A_3$ . Provided the apparent horizon and all the geographic features are visible, the accuracy is likewise independent of the depression angle and of the tilt of the camera about its axis.

These features make the simple bearing grid and the simpler bearing plot invaluable and well-nigh indispensable aids in plotting data from photographs of unknown and unexplored country. Whatever else may be indeterminate about the position of selected objects in an aerial photograph, it can be found that they lie in certain vertical planes, radiating from the plumb point at definite angles with each other. Their relative bearing can be plotted with reasonable accuracy, and this plot can be moved around on the mapper's work sheet until he finds where it belongs.

## B. *The Coordinate System.*

The second or coordinate plotting procedure is suitable only when there is visible in the camera field a surface that is reasonably flat, and that lies approximately at a constant elevation. This may be a high plateau, an upland, or a tableland. It may be the surfaces of a myriad of inland rivers or lakes, lying at the same elevation, or it may be surface of the sea, with bays, points, islands, and other distinctive features.

Assume first that this horizontal or constant-level portion of the surface of the earth, visibly flat within the field of vision despite the curvature of the earth, is subdivided by a system of imaginary rectangular coordinates, similar to the meridians of longitude and the parallels of latitude. The imaginary grid system in the ground plane need not, however, be oriented in any particular compass direction. It is, in fact, lined up with the *principal plane* of the negative, containing the optical axis of the camera, so that the grid lines may lie in different directions for each photograph. Further, the coordinate system need not necessarily be laid down in squares, although this is convenient and is done for the example described here.

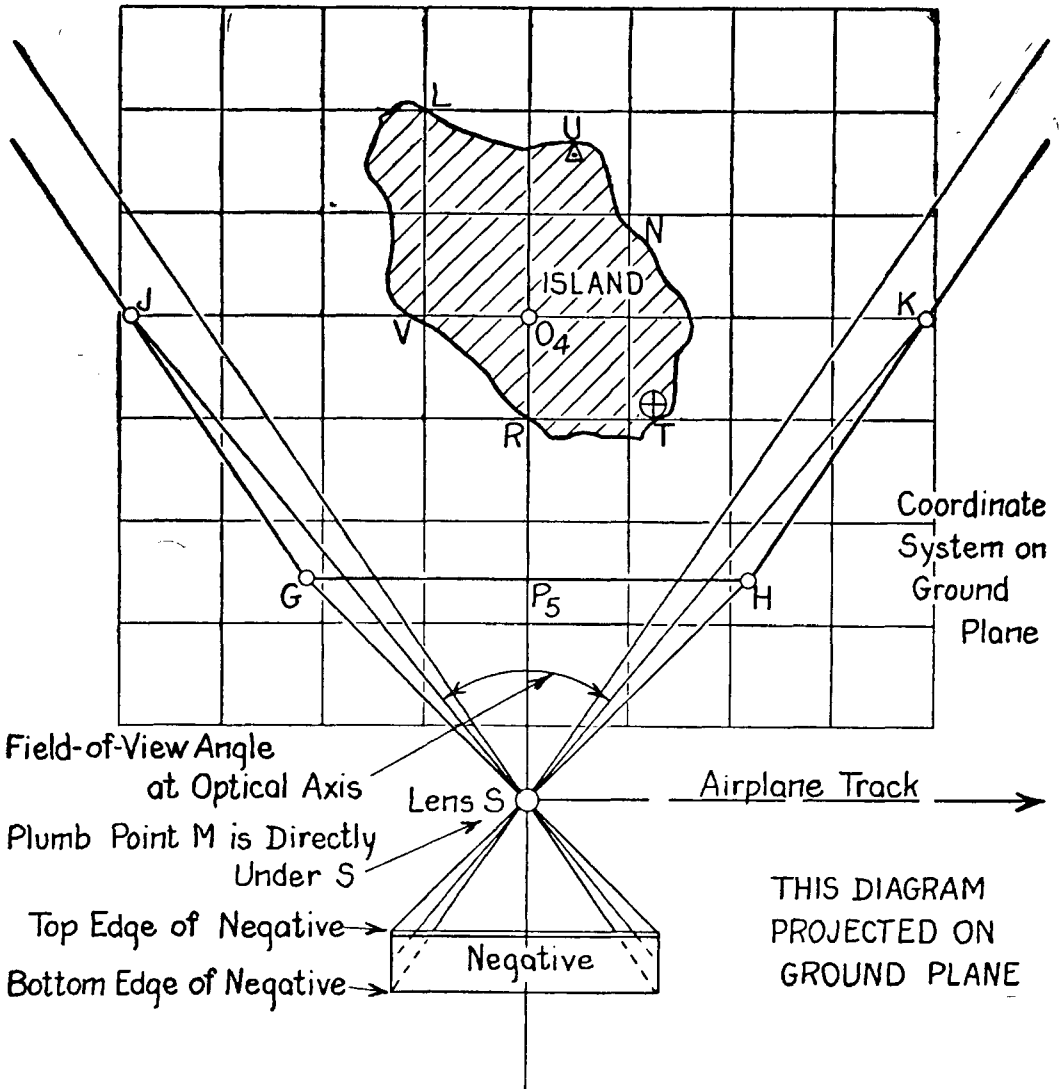


Fig. 4.

Relation between a coordinate plot and an oblique aerial photograph, as projected on the ground plane.

Fig. 4 shows a field of these squares for one oblique aerial photograph, embracing the water area of a lake, with an island near the center. The lens S

of the camera carried by the airplane lies directly above the point M on the ground (or on the water surface), known as the *plumb point*. The inclined negative upon which the picture is being recorded is drawn to an exaggerated scale behind it, as projected on the ground plane. The optical axis  $SO_4$  of the camera lies in the vertical principal plane which intersects the ground-plane grid along one of its divisions. One of the transverse coordinate lines is assumed to pass through  $O_4$ , where the optical axis of the camera intersects the ground plane. If the angular width of the field at this axis is as indicated by the arc with arrowheads in the figure, this width corresponds to the distance  $JO_4K$  along the coordinate line through  $O_4$ . An inclined plane, parallel to the line  $JO_4K$ , and passing through the top edge of the negative, cuts the ground plane in the line  $GP_5H$ . The width of the field along this "front" line is  $GH$ . Thus there is visible on the oblique aerial photograph all the area between the heavy lines  $JG$ ,  $GH$ , and  $HK$ , and extending beyond both  $J$  and  $K$  to the apparent horizon.

It is possible, by a procedure to be described, to prepare for the oblique aerial photograph a transparent overlay which carries the criss-cross grid lines of the field illustrated in Fig. 4, as *they would appear to an observer* at the lens position  $S$ . By the well-known principles of perspective, the grid lines parallel to  $SO_4$  would appear to converge at a single point in the true horizon, at the level of the viewer's eye, as do the rails of a straight railway track. The grid lines parallel to  $JO_4K$  would appear as straight horizontal lines, lying parallel to each other but closer and closer together with the distance from the plumb point  $M$  toward the horizon.

Placing a sheet of grid or cross-section paper alongside the aerial photograph and its superposed overlay, it is possible to trace on the paper an outline that appears in the photograph. If this is a low island such as  $LVRN$  in Fig. 4, its shore line is seen to intersect the line  $JO_4K$  at the point  $V$ , about  $1\frac{1}{8}$  grid space to the left to  $O_4$ . It also intersects the trace  $P_5O_4$  of the principal plane in the point  $R$ , one division toward the camera from  $O_4$ . Its near shore line intersects the first grid line to the right of  $P_5O_4$  at a point about  $1\frac{1}{4}$  grid space to the right of  $P_5O_4$ . Its right shore line intersects the line  $JO_4K$  about  $1\frac{1}{8}$  space to the right of  $O_4$ . Following this procedure, the whole outline of the island is sketched in, either by hand or by an ingenious machine which operates in similar fashion.

### C. *The Simplified Mosaic Method.*

The simplified mosaic method of laying down an airplane track and marking a plot of the ground topography is possible with any series of continuous overlapping photographs taken when the camera axis is approximately vertical, provided *each* overlap contains at least two readily identifiable ground features, preferably not too close together. However, the method is somewhat more precise if the camera is held or attached firmly in a fixed position relative to the airplane structure. This is the case with most trimetrogon cameras. The photographs taken with the camera axis vertical are laid down with their overlapping portions coinciding; in other words, so that the ground features shown along the side on one photograph, say the right side, lie directly over (or under) the same features shown along the left side of the adjacent photograph. This is the situation for features  $X$  and  $Y$  in exposures 9 and 10 of the two series depicted in Fig. 5.

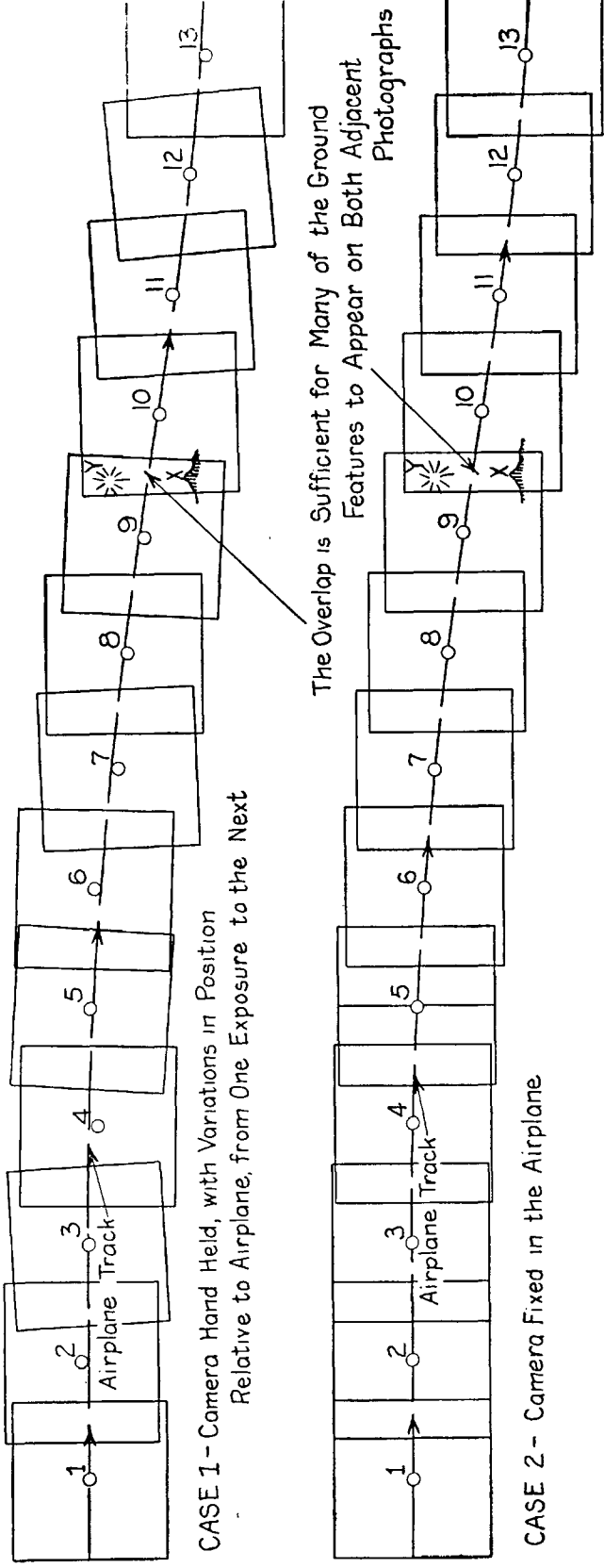


Fig. 5.

Diagrams of two series of vertical prints, assembled as strip mosaics.

Assume first that the camera making the vertical exposures is hand-held, without instrumentation to insure that its optical axis is truly vertical for each exposure. Further, the air is bumpy, so that if the camera is fixed with reference to the airplane structure (resting firmly on some part of it), the tilt and the orientation may change from one photograph to the next. Case 1 of Fig. 5 illustrates, in somewhat exaggerated fashion, the pattern of a group of verticals taken at random orientations under these conditions.

Assume next that the air is smooth (although a strong wind may be blowing), that the airplane is maintained in level flight by an automatic pilot, and that vertical exposures are made by a camera fixed with reference to the airplane, such as by the center (vertical-axis) camera of a trimetrogon assembly. The camera axis remains truly vertical for each exposure, so that at the time of exposure the center of each print is directly over the position of the airplane at that instant, as projected on the ground. A set of vertical mosaics with orientations then has the appearance of the squares in the diagram of Case 2 in Fig. 5.

It is apparent from the Case 2 diagram that, whereas the airplane is headed directly to the right, say to the east, for exposures 1 through 11, it is being blown bodily off course to the south by an unexpected wind from the north when exposures 4 through 11 are being made. On the other hand, there is nothing in the pattern of the Case 1 mosaics to show whether or not the airplane was deliberately steered along the curved track. Case 2 definitely indicates that it was not. Whereas the airplane navigator's log shows that the airplane headed east from exposures 1 through 11 in Case 2, a layout by the simplified mosaic method shows a track that is neither straight nor oriented east and west.

#### *D. Positioning and Orientation Methods.*

On the basis that, when the reconnaissance mapping is begun, there is nothing to start with in the way of a sketch map, and not too much is known about the track of the airplane on the photographic flight, the bearing and the coordinate plotting procedures leave the mapper with not much more than a multiple of individual plots one for each aerial photograph. Although each plot may be accurate within itself, before the data on it can be used to make a reconnaissance map the group requires correlating in correct relative position and placing in proper geographical position, both as to latitude and longitude and as to azimuth or orientation. This need brings into use the supplementary methods mentioned previously.

The positioning of successive individual plots must of necessity start at one or more ground control points whose geographic positions are known. When working both ways from to such points, adjustments are often necessary to permit matching of the plots at the meeting or overlap region between the two control points. When working into an unknown region beyond the farthest control point, the mapper must use all the available data on the course (s) and speed(s) of the airplane, all the common geographic features that he can find on overlaps of successive exposures, and data on the orientation or azimuthal direction of the camera axis at the instant of exposures.

One means of orientation in good flying weather is the use of shadows, of reflections of the sun on ice or water, and of images of the sun itself upon the negative. This method has been described and illustrated in a general way in the technical literature (*Geogr. Rev.*, Apr. 1933, Vol. XXIII, No. 2, pp. 200-202). If a geographic position is known or assumed, and the local or Greenwich time is

known, it is possible to calculate the azimuth of the sun by several methods in use in celestial navigation. By a procedure described subsequently in Appendix I it is possible to determine or to calculate the bearing (relative to the earth) of the optical axis of the camera when taking an oblique photograph embodying one of the sun indications listed at the beginning of this paragraph.

Shadows in a truly vertical mosaic photograph give, by inspection, the sun direction with reference to the various features shown on the photograph.

The most obvious method of obtaining orientation of individual plots, that of using the compass heading of the airplane at the time of exposure, is by no means as simple as it sounds. Assuming that the camera is fixed to the airplane structure, there is no present instrumentation for recording the instantaneous airplane heading on each negative. The magnetic compass heading, even though it could be observed or recorded accurately, may be unreliable because the magnetic variation in the unknown country is usually not known, either before the flight or before the reconnaissance map has to be finished.

#### *E. Methods of Establishing the Map Scale.*

The scale of any map is established by the distance(s) between known control points. These points may be extended by ground triangulation methods from a known baseline or their positions may be determined individually by astronomical observations.

Beyond the last control point the reconnaissance mapper is at the mercy of dead-reckoning data and of plots by bearings from known features. Despite the photographing of the faces of sweep-second watches in the corners of aerial-camera negatives, to record the exact instants of exposure, the dead-reckoning data carry with them large possibilities of error. These stem from the known or uncertain effects of wind drift, variations in airplane speed with consumption of fuel, insufficient observed or recorded data, and many other factors. Airplanes on exploratory flights rarely return by the same route as when outbound, nor do they return when meteorologic conditions are necessarily the same.

The lack of positive methods for checking scale in reconnaissance mapping is offset to a certain extent by the fact that such a map, strange as it may seem, loses only a limited proportion of its value by an error in scale. Perhaps this is because a reconnaissance map prepared from flight data usually shows distances that are too large. The important feature is that the map be properly oriented and that the features shown be in their correct relative positions.

### ELEMENTS OF THE OBLIQUE AERIAL PHOTOGRAPH

It is entirely possible for the mapper to use the reconnaissance-mapping tools in the form of what are known as *grids*, provided by the bearing and coordinate systems for taking the necessary plotting data from aerial photographs, without understanding the geometric principles upon which the grids are constructed. However, it is considered most useful and beneficial, for the photographer as well as the mapper, to know something of the geometry of the system. This is true whether or not he plans to use the methods directly. For the one who has to make the grids, information concerning their solid geometry is almost mandatory. An effort is made to set down in this section the principles and the necessary details of this geometry in relatively simple form.



The diagram of Fig. 6 represents a vertical section through the optical axis of an aerial camera when taking an oblique aerial photograph. It illustrates the relation between the various essential parts of the camera, the position of the airplane (and camera) relative to the earth, the light rays, and the various angles involved. For clarity, the size of the camera is greatly enlarged in comparison to the airplane altitude and other distances over the earth.

The optical center of the camera lens, where all the light rays cross, is at the point  $S$ . The optical axis lies along the straight line  $O_GSO_N$ . The emulsion plane on the negative lies back of the lens, at right angles to the optical axis  $SO_N$ , at a distance equal to the focal length  $F$  of the lens. At the air distances customary in aerial photography for reconnaissance mapping, of the order of miles, the focal length of the lens is practically the same as that required to put in focus all objects at an infinite distance from the camera.

It is appreciated that whereas a print of an oblique aerial photograph, when viewed by the mapper, has the appearance of the country seen by the eyes of the pilot or the aerial photographer, the negative of Fig. 6 is *upside down*. The visible or apparent horizon at the top of the print lies *at the bottom* of the negative when in the camera. It is assumed for this discussion that the sides of the negative are vertical and that the top and bottom are horizontal; in other words, that the camera is not tilted about its optical axis.

The ground plane under the camera lens is some reference plane normal to a radius of the earth passing through  $S$ . The point  $M$  in the reference or ground plane, directly under  $S$ , previously mentioned as the *plumb point*, is called thus because it is where a plumb bob would rest if suspended from  $S$ . The ground or reference plane may be at sea level or it may be at some arbitrary higher or lower level, corresponding to that of a large water or plateau area underneath the camera.

The true horizon passing through  $H_T$  lies on a plane normal to the earth's radius through  $S$  and parallel to the ground plane. It intersects the plane of the camera negative in a straight line through  $H_T$ . The angle in the principal (vertical) plane through the optical axis, between that axis and the true-horizon plane, is the *depression angle* of the camera, represented by the symbol  $\theta$  (theta). The distance on the negative from its center  $O_N$ , at the optical axis of the camera, to the point  $H_T$  is then  $F \tan \theta$ .

A surface passing through  $S$  and through the true horizon all around is a flat plane. However, because of the curvature of the earth, one passing through  $S$  and the apparent horizon, all the way around, is a very shallow cone, with a vertex angle approaching 180 degrees. In the vertical plane passing through the midwidth of the negative and through the optical axis of the camera, namely the plane of the page in Fig. 6, the apparent horizon lies below the true horizon by the amount of the *dip angle*. This is the result primarily of curvature of the earth but it also involves refraction in the atmosphere and other factors. At midwidth of the negative the apparent horizon therefore lies below the true horizon by the distance  $[(F \tan \theta) - F \tan (\theta - \text{Dip Angle})]$ . If the angle of depression below the apparent horizon is taken as  $\theta_1$ , then  $(\theta - \text{Dip Angle}) = \theta_1$ .

In some quarters the distance from the top of the negative to the *apparent* horizon at midwidth of the negative is known as the *horizon distance*, indicated as the distance  $m$  in Figs. 6 and 7. It is known otherwise as the *marginal distance*; the latter is the term used in the present paper.

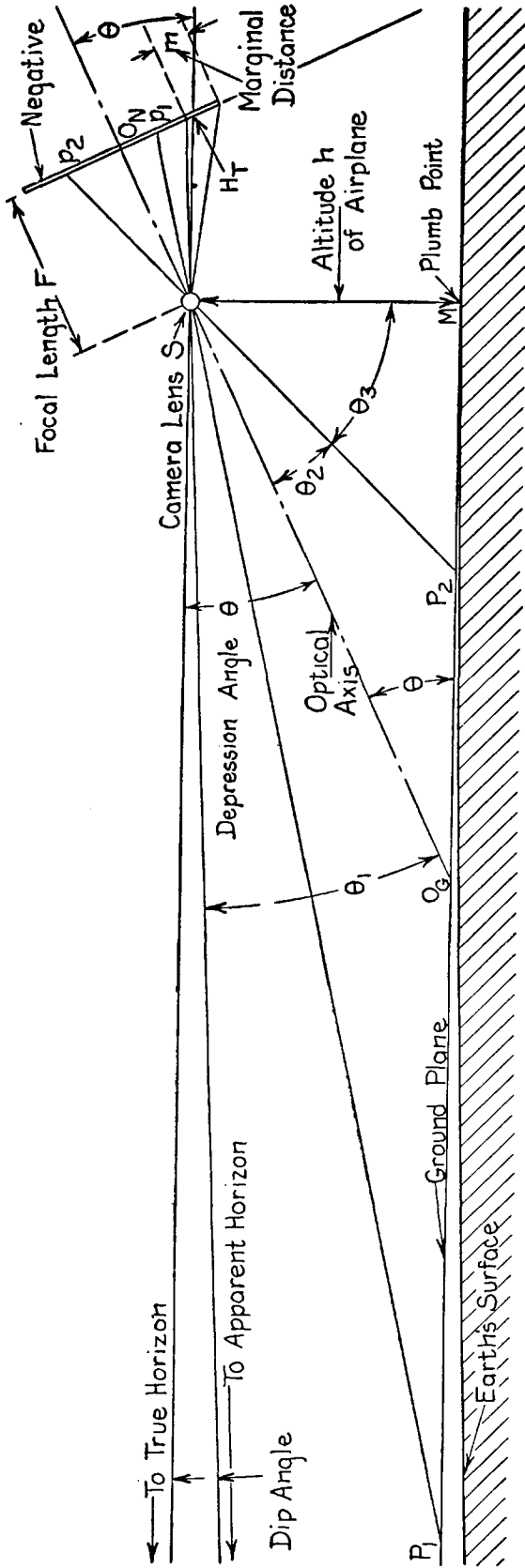


Fig. 6. Definition sketch of elements in the principal plane of an oblique aerial photograph

If  $P_2$  is assumed as any point in the intersection of the ground plane with the vertical plane of the page in Fig. 6, other than the intersection  $O_G$  at the optical axis of the camera, then a straight ray from  $P_2$  strikes the negative at the point  $P_2$ . Similarly, one from  $P_1$  strikes the negative at  $P_1$ .

The altitude  $h$  of the camera (and of the airplane carrying it) is usually reckoned above sea level. If the ground plane is not at sea level, the distance  $SM$  in Fig. 6 does not correspond to the orthodox altitude but it is the distance that would be indicated by an echo-type electronic altimeter.

The sketch of a print of an oblique aerial photograph in Fig. 7 shows a tall mast and a peak behind (beyond) it. The picture is framed by a fixed screen in the camera, placed just in front of the negative. The screen has distinctive marks upon it to indicate the fixed outlines (or corners) of the field. These marks, transferred automatically to the print, permit horizontal and vertical traces to be drawn upon it, intersecting at the exact optical center  $O_N$ . The straight horizontal line near the top is the trace of the plane through the true horizon, intersecting the principal plane of the camera in  $H_T$ . This line can be drawn upon a print but it does not, of course, appear in a photograph. The curved line below it, considerably exaggerated, represents the visible or apparent horizon. It is of interest to note that the sea horizon appears as a measurably curved line in an aerial photograph, when taken from as low as 5,000 feet altitude.

## THE SOLID GEOMETRY OF THE BEARING GRID

The problem of the mapper is how to make a plot of the geographic features visible in an oblique aerial photograph which will aid him in drawing a reconnaissance map. More often than not there is nothing visible in the photograph which coincides with a level ground plane, either at sea level or any other elevation. The mapper may have only approximate estimates, at the best, of the heights of land, ice, peaks, or mountains visible in a set of pictures.

It is possible, nevertheless, to fix a relationship between the bearing of a number of selected objects on an oblique aerial photograph, using a method first developed by B.M. Jones and J.C. Griffiths in Great Britain some three decades ago [*"Aerial Surveying by Rapid Methods"*, Cambridge (England), 1926]. It requires knowledge of the focal length  $F$  of the camera, the airplane altitude  $h$ , and the depression angle of the camera; that is, the angle  $\theta$  in Fig. 6. The latter is determined from a knowledge of the marginal distance  $m$  and the airplane altitude  $h$ . Only the focal length  $F$  need be known with any great degree of accuracy. It is determined once and for all by a special calibration of the camera lens when focused on an object at infinity. The airplane altitude is known from the altimeter record or barograph reading, taking sea level as the reference plane. The depression angle is found with sufficient accuracy whenever the apparent horizon is visible on the print, as is usually the case when making exploratory flights in good weather in unknown country. The determination of the angle  $\theta$  is admittedly less precise when the apparent horizon is partly or completely obscured by clouds or haze. It must be estimated when only high land is visible in the background and there is no apparent horizon.

The bearing relationships determined by this method are the azimuth angles  $\psi$  (psi), measured on the earth's surface at the plumb point, between (1) the vertical planes passing through selected visible objects and (2) the principal plane of the

camera, the latter passing vertically through the points  $C_G$ ,  $S$ , and  $O_N$  of Fig. 6. The angles  $\psi$  are the same bearing or azimuth angles as are observed in ordinary ground surveying with a transit or theodolite or in ship piloting with a pelorus. They are the angles  $\psi_D$ ,  $\psi_B$ ,  $\psi_C$ , and  $\psi_E$  between the bearing lines and the principal plane, as recorded from any one airplane-and-camera position such as  $A_3$  in Fig. 3. One such bearing angle  $\psi$  is that (on the earth) between the principal plane and the centerline of the flag pole or mast in Fig. 7. However, nothing on an oblique print gives this angle directly.

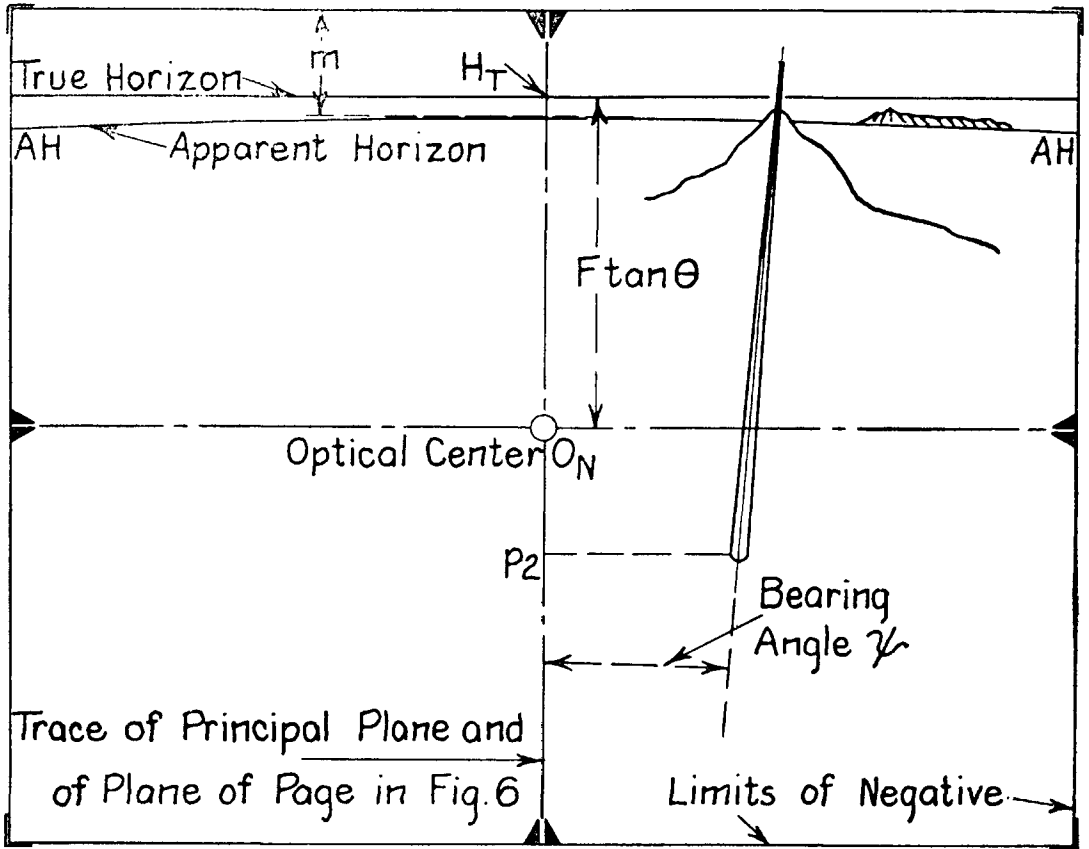


Fig. 7.

Definition sketch of a print of an oblique aerial photograph.

To explain the bearing method of plotting from individual photographs, assume a horizontal ground plane and an inclined negative plane, intersecting in the line  $RN$  of the isometric drawing, Fig. 8. The principal plane through the optical axis of the camera passes through the points  $SO_GM$ , as before. It also passes through the points  $N$  and  $Q$  in the plane of the negative. The vertical line through  $MS$  intersects the negative plane at  $Q$ .

Assume that there appear in the field of view three objects, all about in line, whose relative bearing with reference to the ground trace  $O_GM$  of the principal plane and the plumb point  $M$ , represented by the bearing angle  $\psi$ , is to be determined. These are :

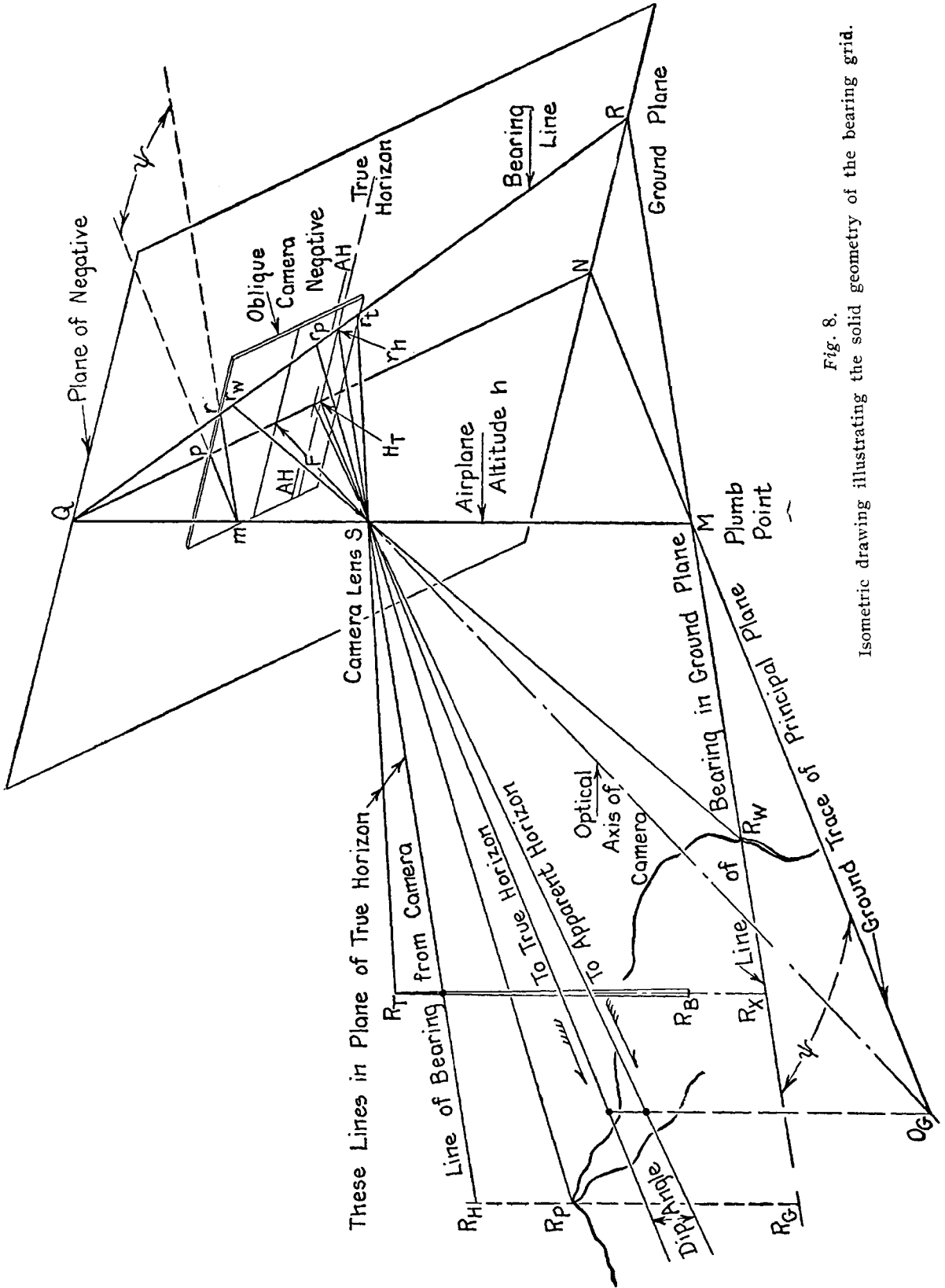


Fig. 8. Isometric drawing illustrating the solid geometry of the bearing grid.

1. The peak  $R_P$ , lying at a considerable altitude above the ground plane
2. The vertical mast whose tip lies at  $R_T$  and base at  $R_B$ .
3. The object lying at  $R_W$  in the ground plane.

Taking first the point  $R_W$ , assume that a radiating vertical plane is passed through the ground line  $R_W M$  and the extended earth's radius through the plumb point, namely the line  $MSQ$ . This vertical plane, lying at the horizontal angle to the principal plane through  $O_C M N Q$ , intersects the ground plane in the line  $MR$ , an extension of  $R_W M$ . It intersects the negative plane in the *straight* line  $RQ$ . This line is straight because it is the intersection of two planes, which is always straight. Hence if a straight ray from  $R_W$  is transmitted through  $S$  to the negative plane, it intersects that plane at  $r_w$ , on the line  $RQ$ .

The radiating vertical plane through  $R_W$ ,  $M$ ,  $R$ ,  $Q$ , and  $S$  intersects the plane of the true horizon through  $S$  in the (imaginary) line  $SR_H$ . The ray from the point  $R_H$  is transmitted to the negative point  $r_h$ . If it is found that the point  $r_h$  lies on the straight line through  $R$ ,  $r_w$ , and  $Q$ , it is known that the points  $R_H$  and  $R_W$  lie at the same bearing angle  $\psi$  from the line  $O_C M$  in the ground plane. If it is found further that the negative end of the ray  $R_P r_p$  lies on the same line as  $r_w$  and  $r_h$ , it is known also that  $R_P$  lies directly below  $R_H$  and directly above  $R_G$ . Also that  $R_G$  lies on the line  $MR_W$  extended.

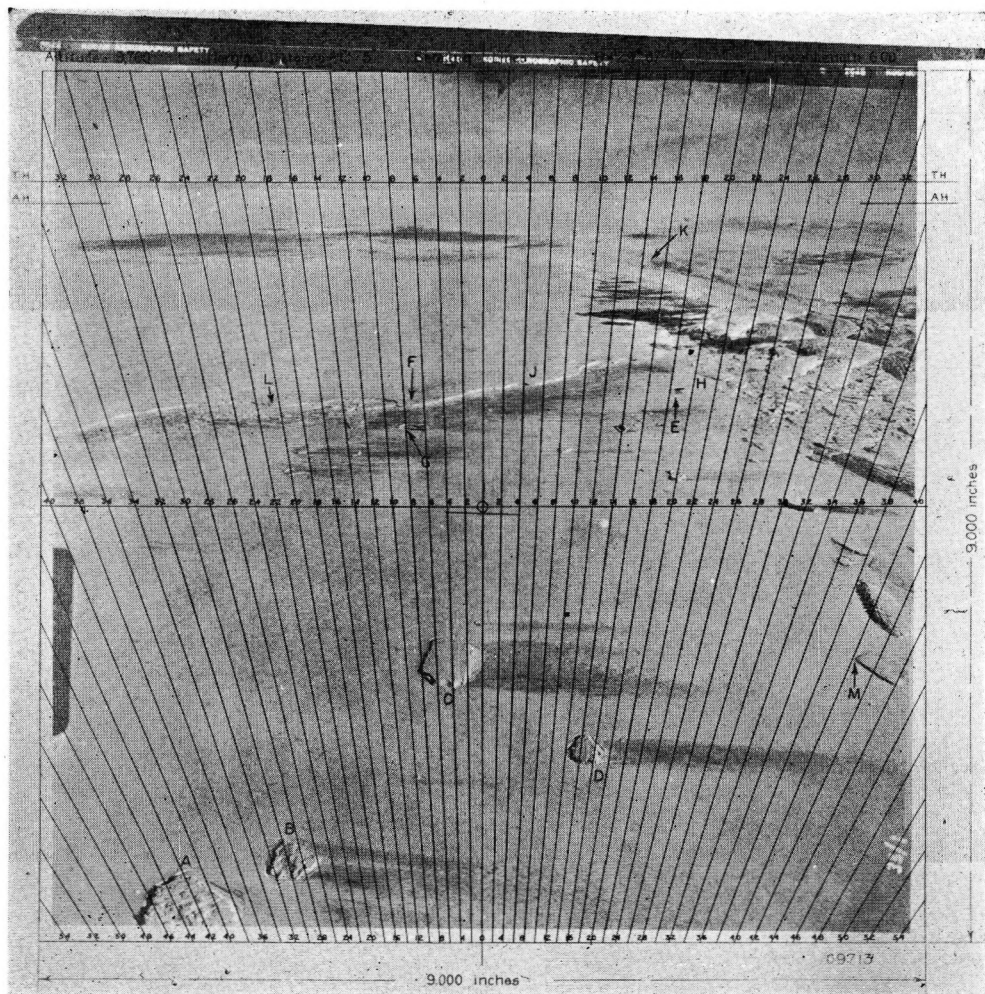
Assume in addition that the ray from the tip  $R_T$  of the mast strikes the negative at the point  $r_t$  along the line  $RP$ . Then if the mast is truly vertical its centerline lies in the plane through  $R_W$ ,  $M$ , and  $S$ . The point  $R_X$  directly under the mast also lies in the line  $MR_W$  extended. In a print made from the negative of Fig. 8, resembling Fig. 7, the mast appears to be leaning outward at the top because its image lies along the sloping line  $r_t r_w$ .

The ground-plane points  $R_W$ ,  $R_X$ , and  $R_G$  lie on a single line bearing making the angle  $\psi$  with the reference line  $MO_C N$ . The trace  $r_t r_w$  on the negative, or on the print, is known as a *bearing line* for the angle  $\psi$ . The images of *all* objects lying in any one of these radiating vertical planes appear along a straight line in the negative, such as  $r_t r_w$ , *regardless of the height of these objects above, or below the level ground plane.*

Using the known focal length  $F$  of the camera, the airplane altitude  $h$ , the dip angle (derived from the altitude  $h$ ), and the depression angle  $\theta$ , a transparent *bearing grid* may be prepared, ruled with lines representing the intersection of a series of radiating vertical planes with the principal plane of the camera negative. When such a grid is placed over an oblique aerial photograph, as in Fig. 9, it is possible to determine by inspection the correct angles  $\psi$  or the bearing between any number of selected points without any information whatever as to the elevation of those points above the ground plane. It is only necessary that there be sufficient information available to prepare or to select the proper grid, and that the apparent horizon be visible in the photograph (or that one be able to estimate its position).

## THE SOLID GEOMETRY OF THE COORDINATE GRID

When the mapper is faced with a considerable number of principal geographic features which lie all at sea level or at a given reference level, the coordinate plotting procedure is employed, making use of a *coordinate plotting grid*. This method has been used extensively for surveys in Canada and elsewhere ("A Graphical Method of Plotting Oblique Aerial Photographs", Dept. of the Interior, Dominion of Canada, 1928, and the references in a preceding section).



*Fig. 9.*

Bearing grid applied to an oblique aerial photograph.

It is almost impossible here to determine the correct position of the apparent horizon but the tilt of the photograph may be estimated from the tilt of the thin cloud strata. The illustrative identification numbers used here correspond to those on the sample bearing plot of Fig. 15. The portion of the coast shown in this photograph lies in about Lon.  $136^{\circ} 42' E$ .

Slips of white paper were inserted under the sides of the grid, before photographing the combination, to make the grid markings stand out prominently.

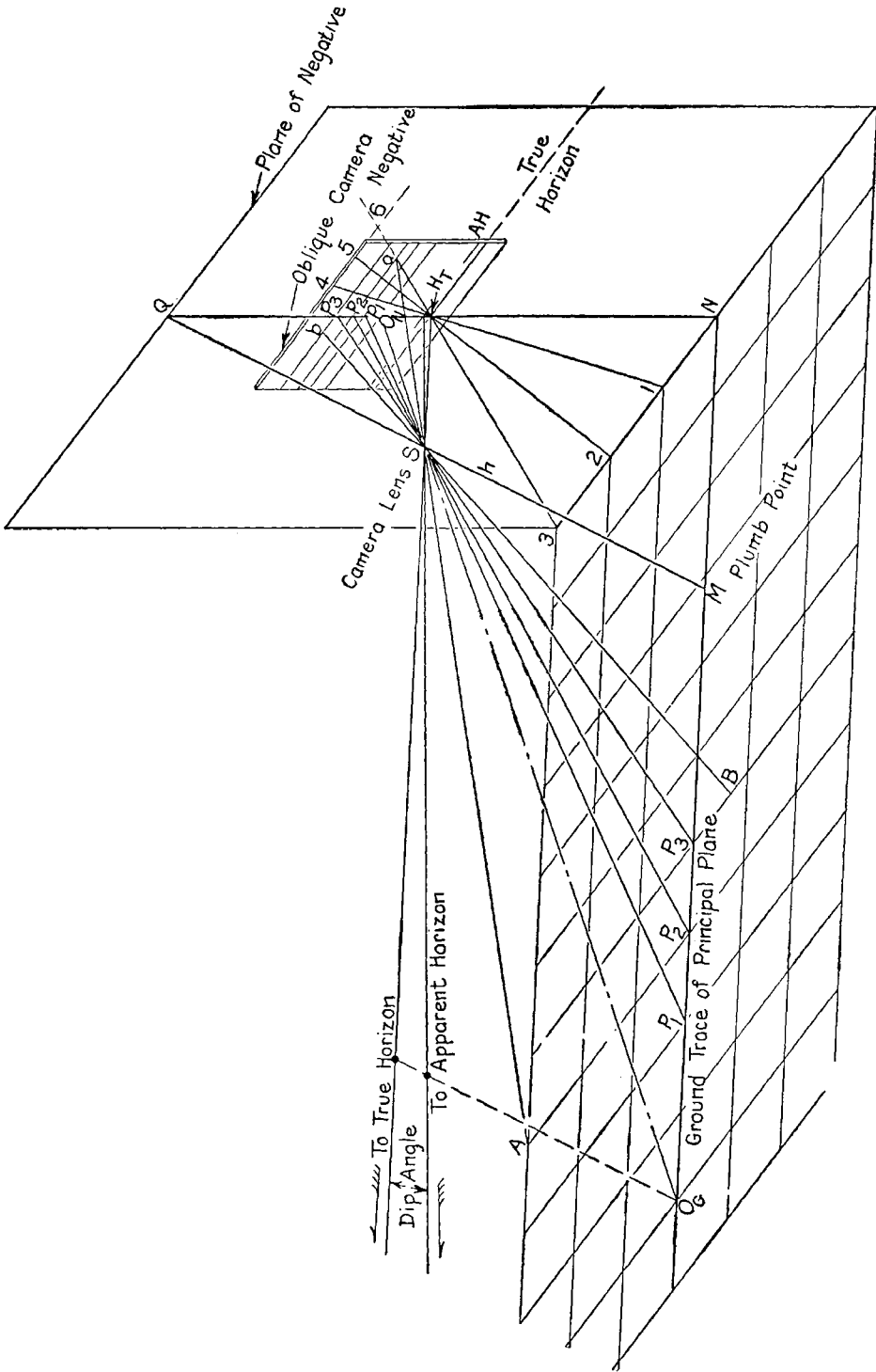


Fig. 10. Isometric drawing illustrating the solid geometry of the coordinate grid.



To explain the plotting method, assume that the flat ground plane tangent to the earth's surface at the ground plumb point  $M$ , passing through the points  $O_G$ ,  $P_1$ ,  $P_2$ , and  $M$  of Fig. 6, contains the geographic features that are to be plotted. Referring to the isometric drawing of Fig. 10, the principal plane containing the optical axis of the camera passes through the points  $O_G$ ,  $P_1$ ,  $P_2$ ,  $P_3$ ,  $M$ , and  $N$ , as well as through  $S$ ,  $O_N$  and  $Q$ . Within the limits of the usual plot from a single negative, the earth's surface is assumed to coincide with the ground plane. As mentioned previously, the plane of the negative, extended to  $Q$  and  $N$ , intersects the ground plane in a straight line through  $N$ , normal to the line  $O_GMN$ . Since the trace on the negative of the horizontal plane through the true horizon is a straight line across the negative through  $H_T$ , so are the traces of other planes parallel to the ground-plane negative-plane intersection at  $N$ , but lying at other depression angles. Three of these intersections, parallel to the line  $N3$ , pass through the ground points  $P_1$ ,  $P_2$ , and  $P_3$ . If the distance in the ground plane from  $O_G$  toward  $M$  and  $N$  is divided into equal intervals such as miles, so that  $P_1$  to  $P_2$  is 1 mile, there results a series of transverse projected lines on the negative passing through  $p_1$ ,  $p_2$ , and  $p_3$ . The vertical interval between each, on the print, represents 1 mile in the ground plane, measured in a direction parallel to  $O_GM$ .

Other coordinate lines may be laid off in the ground plane parallel to  $O_GMN$ , lying at equidifferent transverse distances from that line. One such line is  $A3$  passing through the point  $A$  which lies opposite  $P_2$  at a transverse distance of 3 length units, say 3 miles. A straight ray from  $A$  on the ground is transmitted to point  $a$  on the negative, along the horizontal line through  $p_2$ . If a tilted plane is passed through the intersection point  $H$  in the true horizon plane, the lens  $S$ , and the point  $a$  on the negative, its trace in the ground plane is the line  $A3$ . Its trace in the plane of the negative is the line  $H_T a6$ . Similarly, the ground lines parallel to  $O_GMN$ , through the points 1 and 2 along the line  $N3$ , are represented on the negative by the traces  $H_T 4$  and  $H_T 5$ .

A ground plane ruled in coordinate squares as indicated in Fig. 10, when photographed, appears as a series of parallel horizontal lines crossed by a series of inclined lines, the latter all passing through  $H$  in the true horizon. Both horizontal lines and inclined lines lie closer together with distance from the camera, or from the plumb point, as do the lines representing equidifferent distances in a perspective drawing.

Using the known data as to focal length  $F$  of the lens, the depression angle  $\theta$ , the dip angle, and the altitude  $h$  of the airplane, as well as a convenient grid spacing in the ground plane, it is possible to prepare a transparent grid or overlay for an oblique aerial photograph. This grid, when applied over such a photograph, shown in Fig. 11, indicates the position of the imaginary lines bounding the series of squares in the ground plane. A direct comparison of the ground features on the print and the lines of the superposed grid then gives the positions of those features relative to the assumed system of coordinates, *provided* the edges of the ground features all lie in a level plane, as do islands in a lake or ice floes in an ocean.

## THE SOLID GEOMETRY OF SUN AND OTHER ORIENTATION SYSTEMS

To orient accurately a photograph to which a coordinate plotting grid has been applied and to permit tracing of the features to accurate scale upon a map divided into squares by a system of coordinates embodying meridians of longitude

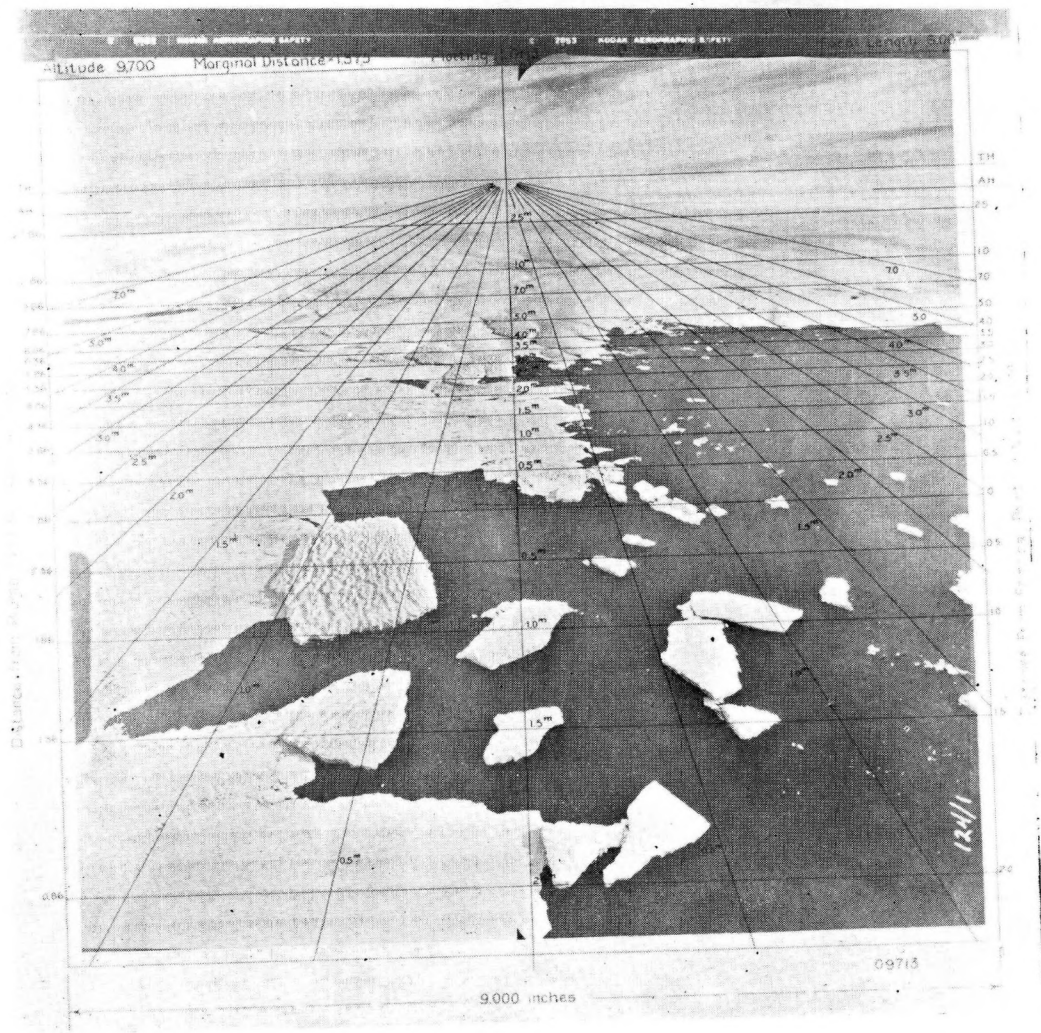


Fig. 11.

Coordinate grid applied to an oblique aerial photograph.

Slips of white paper were inserted under the vertical sides and the bottom of the grid when the combination was photographed in order to show the distance scales and grid markings clearly. These strips cover some of the original area of the print.

A coordinate plot made from this combination is shown in Fig. 15.

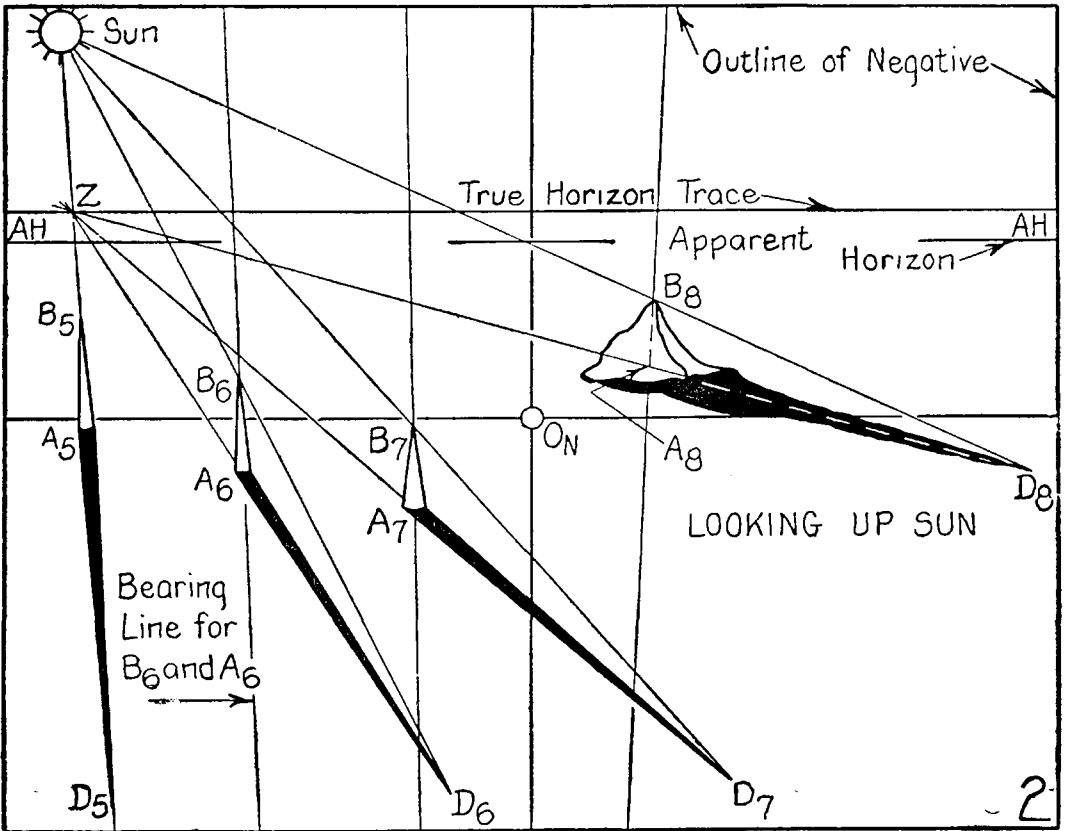
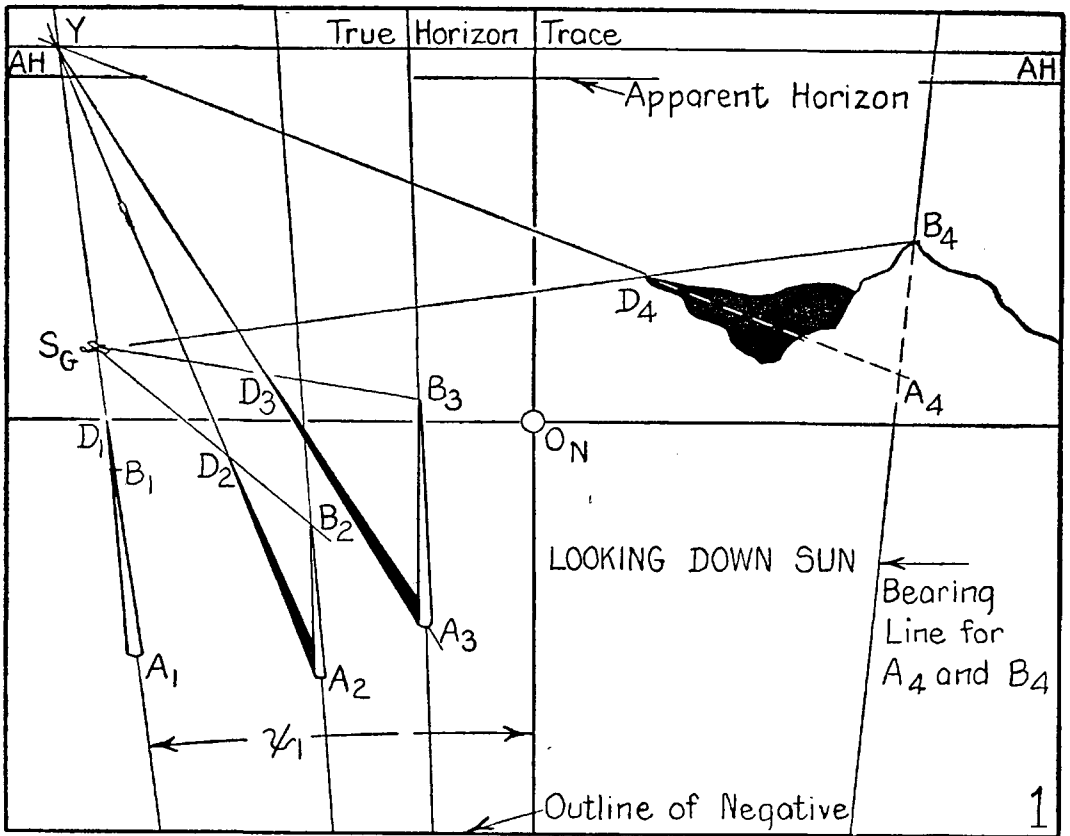


Fig. 12.

Diagrams of two oblique aerial photographs illustrating the convergence of sun lines.

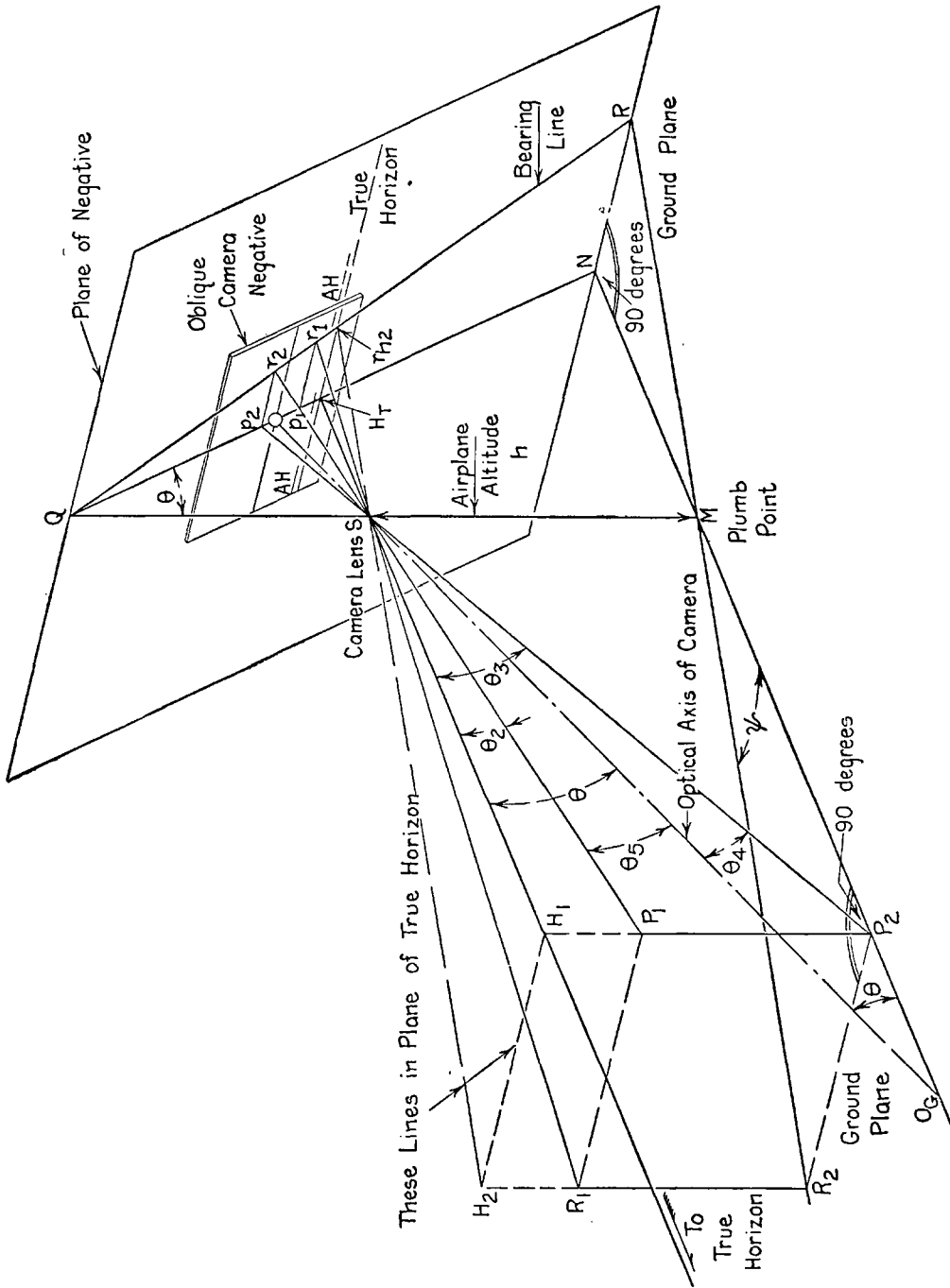


Fig. 13.

Diagram illustrating the solid geometry of the elevation and depression grid.

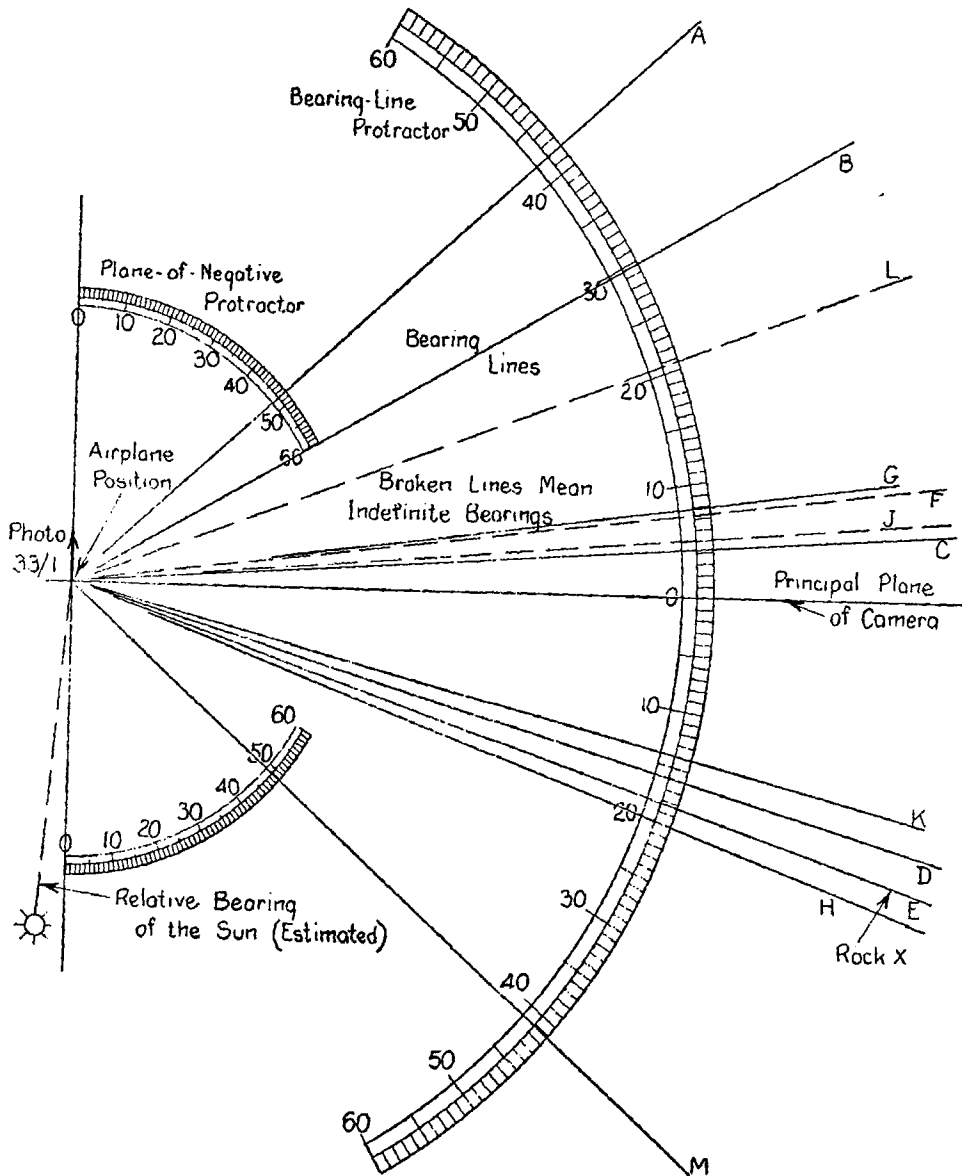


Fig. 14.  
Protractor for constructing bearing plots, with markings on a transparent plot superposed on it.

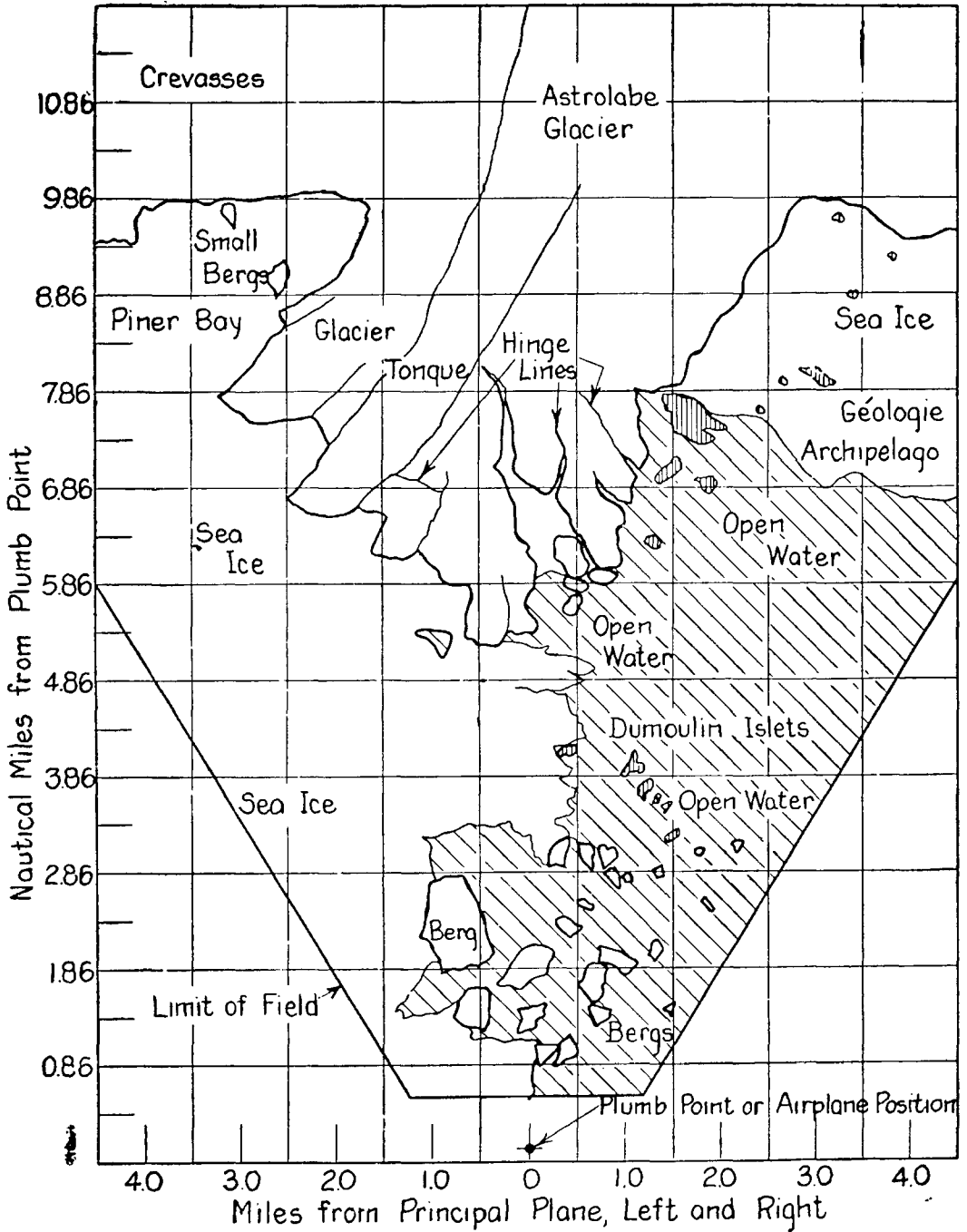


Fig. 15.

Coordinate plot made of a local area visible in the aerial photograph of Fig. 11.

This plot resembles that of Fig. 4, except that it covers much more ground area. The islands of the Géologie Archipelago lie too far away, and the contrast between their bare-rock surfaces and the surrounding open water is too slight to permit plotting them in detail.



*Fig. 16.*

Hand-held view, taken at the head of Vincennes Bay.

The estimated airplane altitude, at the time this exposure was made, is between 3,000 and 4,000 feet.

The confused, broken area of ice and snow in the foreground is the terminus of John Quincy Adams Glacier. At the far side of the inlet beyond the glacier, in the left middleground just above midheight of the photograph, lie the Hatch Islets. Their geographic position is Lat.  $67^{\circ} 00' S.$ , Lon.  $109^{\circ} 42' E.$ , and they mark the geographic division between the Knox and the Budd Coasts. The bare rock surfaces of these islets rise only a few hundred feet above the water. The ice tongue extending all the way across the picture, just above the Hatch Islets, is a projection from the east side of the Bond Glacier.

In the original of this photograph, high land is visible in the midwidth portion, just above the lowest clouds. There are, however, indications that the land would be seen to rise to a still greater height if all the clouds disappeared.

and parallels of latitude, it is necessary that there be, within the field of view of the camera, and in the ground or reference plane, at least two points on the ground, such as T and U in Fig. 4, whose relative and geographic positions are known. These are the control points. When mapping in occupied country, where the points are accessible to humans, they are almost invariably fixed by an independent ground survey, using orthodox methods. For reconnaissance mapping with little or no control, one orientation procedure involves the use of the sun directly, or indirectly of its reflection or shadows, to furnish the orientation of individual plots for which this information is lacking. In the Antarctic, for example, many exposures are made in bright sunlight, with an excellent background of white snow, upon which the shadows of peaks and projections stand out clearly.

In the case of photographs taken toward the sun, or directly into it, there are often definite but not well-defined reflections upon open water or upon glare ice. Unless unusual conditions exist at the ground surface it may be assumed that the midwidth of the reflecting area lies on the same bearing line as the sun. Such a reflection is rarely sharp, owing to waves and slight irregularities in the reflecting surface. It may be possible only to estimate the correct bearing to the nearest one or two degrees, but since the method is a direct one, the error is probably less than in other indirect methods.

Upon occasion there are visible in the photograph circular reflections of the sun from the various air-glass and glass-glass interfaces of the lens assembly. As a rule, these also lie on the same bearing line as the sun.

If the photographs are taken looking up-sun, a relative bearing is taken of the sun or of its reflection with a bearing grid, the same as for any other object in the field. The orientation of the sun is made possible by the fact that for a given local mean time and a given longitude (and geographic position), the azimuth or compass bearing of the sun can be calculated by well-known methods and used as a definite known factor.

Another procedure makes use of the fact that all parallel rays from the sun, when viewed in perspective, meet in a single point, as do other parallel lines in nature. The direction of such a ray is marked by the line between an object and the shadow that it casts on some surface, called here for convenience a "sun line". Such a line extends from the tip of a peak to the tip of the shadow which it casts upon the snow; a considerable number of them are shown in the marked-up photographs reproduced as Figs. 24, 25, and 26 on pages 200-202 of *The Geographical Review*, April 1933, Vol. XXIII, No. 2.

A diagram showing the elementary geometric features involved in this orientation procedure is included as Fig. 12. This diagram illustrates the fact that, when drawn on the print of an oblique aerial photograph, and viewed by the eye, all sun lines are perspective lines meeting at the image of a point S in the ground plane. This point occupies the same position on the negative as the shadow of the camera (or the airplane), if looking away from the sun, or the same position as the sun itself, if looking toward the sun. A determination of the bearing of this perspective point (or of the sun) relative to the principal plane, and a knowledge of the sun's azimuth, gives directly the bearing on the earth of the principal plane of the camera.

Fig. 12 embodies schematic diagrams of the prints of two oblique aerial photographs in which there are :



1. Sun lines from the sun, back of the plane of the negative, converging at a point on the ground surface which coincides with the shadow of the airplane, if that shadow could be seen. This exposure is made "down sun".

2. Sun lines toward the sun, in front of the plane of the negative, converging at a point (within or beyond the confines of the negative) which is the sun's image on the negative. This exposure is made "up sun".

The only sun lines which do not so converge are those parallel to the plane of the negative. For this reason, sun lines in a photograph taken at right angles to the azimuth of the sun are all parallel to each other.

In diagram 1 of Fig. 12 the sun lines  $B_1D_1$ ,  $B_2D_2$ ,  $B_3D_3$ , and  $B_4D_4$  converge at the point  $S_G$ , corresponding to the position of the airplane shadow, if the latter were visible. If it so happened that the pole or mast  $B_1A_1$  lay directly in front of its shadow, the mast and the airplane shadow would both lie at the bearing angle  $\psi_1$  to the left of the principal plane. If the shadows of each of the four masts fell on a level surface, but the surfaces lay at different elevations, the extensions of the ground shadows  $A_1D_1$ ,  $A_2D_2$ ,  $A_3D_3$ , and  $A_4D_4$  would intersect at the point  $Y$  on the true horizon, also lying at an azimuth angle  $\psi_1$  to the left of the principal plane. A series of poles such as illustrated in Fig. 12 is frequently encountered in aerial photographs, supplemented by tall spires, lofty buildings, and monuments. For example, see the photographs on pages 597, 509, 613, and 614 of the article "Flying the 'Hump' of the Andes", by Capt. A. W. Stevens, Air Corps, USA, in the National Geographic Magazine for May, 1931. Other aerial photographs in the present paper, as well as the photographs in Rear Admiral R. E. Byrd's books "Little America" and "Discovery", illustrate how frequently definite sun lines are to be found on aerial photographs, especially in the Antarctic.

If  $B_1$ ,  $B_2$ , and  $B_3$  were, like  $B_4$ , the summits of peaks, all at different elevations in the midst of an irregular ground surface, and if the tips of their shadows  $D_1$ ,  $D_2$ , and  $D_3$  likewise lay on an irregular surface of varied elevation, sun lines drawn from their summits to the tips of their shadows would still, if extended, pass through a point  $S_G$  having a bearing  $\psi_1$  to the left of the principal plane. It is not necessary that the bases of the poles  $A_1$ ,  $A_2$ , and  $A_3$  in the ground plane be visible on the photographs; indeed, if these points represent the summits of peaks, this is never so.

If the vanishing point of the "sun lines" lies within the limits of the negative, the desired bearing or azimuth angle is found at once by superimposing the proper bearing grid and noting the bearing angle of the point of intersection of the "sun lines" with reference to the principal plane. If the vanishing point lies outside the boundaries of the negative it must be fixed by prolonging the "sun lines" beyond the boundaries and determining the corresponding bearing angle by calculation. This is equivalent to the extension of a normal bearing grid beyond the boundaries of the photographic negative.

The method of determining azimuth by the use of shadows or reflections has the great advantage that it can be checked approximately by calculating the altitude of the sun from the results of the azimuth determination and then comparing this altitude with that determined from the shadows on the photograph. An isometric diagram illustrating the solid geometry involved, and the mathematical procedure for accomplishing this are included in Appendix 1. The numerical work is somewhat long; but, where the orientation of a large group of bearing plots depends upon the degree to which three or four azimuths are found, the work is well justified.

Aside from serving as an excellent independent check on the relative bearing of the sun, as determined from an aerial photograph with multiple shadows, the use of the calculated altitude of the sun enables a bearing determination to be made from a photograph with only a single large shadow. When only one shadow can be used, the orientation of the photograph may be determined by using the single "sun line" in conjunction with the computed altitude of the sun. The solid geometry in this case becomes rather complicated; the relationships permitting a solution of the problem, working either backward or forward, are described in Appendix 1.

The orientation of aerial photographs and plots was described by the senior author some years ago in different words and with different photographs (*Geogr. Rev.*, Apr. 1933, Vol. XXIII, pp. 200-203). The prospective user of this method may wish to read both descriptions, especially as the reference describes an auxiliary method of orientation, utilizing the patterns of drifted snow and wind erosion on a substantially level surface.

### THE SOLID GEOMETRY OF ELEVATION AND ALTITUDE SYSTEMS

It was stated previously that the analysis of oblique aerial photographs by the use of a coordinate plotting grid is predicated upon the location of all the objects observed in a level plane tangent to the earth's surface at the plumb point. Nevertheless, adjustments can be made to fix the position of objects above the level plane, but their heights above that plane must be known. This again requires the cooperation of surveying parties on the ground. Conversely, the heights can be determined if the elevated positions are accurately known. Other adjustments must be made if it is desired to fix the position of objects at a considerable distance from the plumb point.

One function of a reconnaissance map is to show the elevations above sea level (or above some other reference plane) of the various geographic features, as nearly as they can be estimated or determined. This requires first, that the distance of each such feature from the plumb point of the airplane be known or be estimated, and second, that there be a ready means of determining vertical angles on an oblique aerial photograph.

The horizontal bearing grid, mentioned earlier as a special case of the general bearing grid, constructed for photographs where the true horizon passes through the center of the photograph, may be used for this purpose by rotating it 90 degrees. However, a special elevation and depression grid, constructed along the lines illustrated in Fig. 28 on page 204 of the April 1933 issue of *The Geographical Review*, is much more convenient. The depression (or elevation) angles represented by the horizontal lines on the grid are true angles in the principal plane, applicable to objects either in or out of that plane. However, if these angles are used in combination with distances from the objects to the airplane position, the distances must be measured from the airplane position to the positions of the objects as projected perpendicularly to the principal plane.

For a clear understanding of this feature refer to Fig. 13, drawn in isometric projection. Here  $R_1$  represents the summit of a peak and  $R_2$  the point in the ground plane directly under the peak. If the point  $R_2$  were visible on the negative, the two images  $r_1$  and  $r_2$  would lie on a single line of bearing  $QR$  in the plane of the negative. A calculation of angles or heights from these positions only would be complicated.

If, however, the points  $R_1$  and  $R_2$  be projected back to the principal plane of the camera, that is, to  $P_1$  and  $P_2$ , respectively, the height  $P_1P_2$  is equal to  $R_1R_2$  and the depression angles  $\theta_2$  and  $\theta_3$  can be measured directly in the principal plane. By constructing a grid with a series of lines  $p_1r_1$ ,  $p_2r_2$ , etc., representing the perpendiculars to the principal plane  $R_1P_1$ ,  $R_2P_2$ , and so on, the depression (or elevation) angles between any two points on the photograph may be determined by inspection. Since the points  $P_1R_1P_1R_1$  all lie in one plane perpendicular to the principal plane, the lines  $p_1r_1$ ,  $p_2r_2$ , and others like them, are straight and perpendicular to the trace  $QN$ .

Since  $R_2P_2M$  is a right angle, and  $R_2$  lies at an angle of bearing  $\psi$  from the principal plane, the distance from the plumb point to  $P_2$  is equal to  $MR_2 \cos \psi$ . When the distance  $MP_2$  and the altitude of the airplane are known, the problem of determining  $P_1P_2$  from the angles  $\theta_2$  and  $\theta_3$  is a simple one of plane geometry only. If the distance  $MP_2$  is large compared with the airplane altitude  $MS$ , say 3 or 4 times that altitude, a first approximation of the height  $R_1R_2$ , or  $P_1P_2$ , is obtained by multiplying the distance  $MP_2$  into the tangent of the subtended angle  $P_2SP_1$ , or  $\theta_3 - \theta_2$ . For example, assume that a particularly high ice cliff, at the edge of open water, is found by application of a coordinate grid to lie approximately in the principal plane of the camera, at a distance of 5.9 (nautical) miles from the plumb point. Assume also that, by application of an elevation and depression grid, this cliff is found to subtend an angle ( $\theta_4$  in Fig. 13) below the optical axis of 0.4 degree and an angle ( $\theta_5$  in Fig. 13) above the optical axis of 0.5 degree. The total angle subtended is thus 0.9 degree, for which the natural tangent is 0.01571. For a distance of 5.9 miles the *approximate* cliff height is thus  $(5.9)(0.1571) = 0.0927$  miles or  $0.0927(6080) =$  about 565 ft.

## COLLECTION AND CORRELATION OF AVAILABLE SUPPLEMENTARY INFORMATION

### *General Data on Flights:*

The collection of general information and data on one or more exploratory flights, preparatory to the making of a reconnaissance map, appears at first sight to be a routine affair. Theoretically, it is a step that normally can be taken for granted, is well understood by the prospective mapper, and need not be described in specific terms. Nevertheless, it is amazing to discover how many necessary items are overlooked by the aerial photographer who is not also a mapper, and how difficult it is to collect information after the crew of an exploratory flight has been disbanded. It is considered useful, therefore, that a number of the necessary steps be enumerated and described briefly here.

The first of these is to find out where the flight crew went (or where they think they went) and to obtain at least a rough free-hand sketch of what they saw. This sketch should be projected on the ground plane like a map, supplemented by an approximate outline of the flight track (with directional arrows) and by such panoramic sketches as the flight crew are able to make. The formal data include copies of the flight log, dead-reckoning data and plots, lines of position obtained, and indications of the positions along the flight tracks where certain rolls of film were exposed.

A layout of the probable flight track on a plotting chart containing parallels of latitude and meridians of longitude, with marks or numbers along the track to

indicate the film roll identification, exposure numbers, and related information, is known in mapping parlance as an *index map*. The broken-line dead-reckoning flight tracks shown on Fig. 20 of Part 2, covering the Adélie Coast and a portion of the Clarie Coast, together with the data marked on them, constitute elementary portions of an index map.

Barograph records require calibration of the instrument and a certain amount of careful measurement before they can be transposed into simple tables of altitude and time. They possess the great merit, however, of combining records of time with those of altitude. They must include a temperature record to permit adjustment of the atmospheric-pressure readings to standard-temperature conditions.

If near-surface soundings are taken on an exploratory flight, by the method described and illustrated some years ago ("The Flight of Admiral Byrd to the South Pole and the Exploration of Marie Byrd Land", Proc. Am. Phil. Soc., 1940, Vol. 82, No. 5, pp. 815-816), the barograph record gives the altitudes in the "dips" of the airplane path to a reasonable degree of accuracy. With the echo-sounding electronic altimeters now available the distances of the ground (or ice) below can be measured readily while the airplane is flying in a level path.

#### *Direction of Camera Relative to Airplane.*

If photographs were made only from one side of the airplane in certain areas, the particular side should be known. It is surprising how much confusion has been caused in the past by lack of this particular information. There is a powerful argument here for placing or holding the side camera(s) in such positions that a portion of the airplane wing is photographed on each exposure, thus giving an automatic indication of the side on which the photograph is made.

As an aid correlating data of more exact relative directions of the principal planes of oblique photographs and airplane headings, it is necessary to establish the angle, even if only approximately, between the axis of the camera and the axis of the airplane when each photograph was taken.

#### *Time of Exposure of Photographs.*

Recording the exact time of exposure of each photograph, or set of photographs, is a most important item. This is especially true where the airplane dead reckoning must be used to assist in establishing additional control points or prominent landmarks through the medium of successive plotted airplane positions. This feature naturally assumes far more importance when plotting the photographs than when planning the exploration flight, at which time there may be doubt whether the photographer and his camera are even to be carried on the flight.

If the exposure times are not recorded by photographing a watch face in the field of view of the camera, the approximate times must be obtained from the aerial photographer and added to the index map.

#### *Numbering and Identification of Photographs.*

The importance of placing the aerial photographs in their proper order cannot be emphasized too strongly. This is a matter which should result in no grave permanent errors but which may cause much confusion and loss of time in getting underway on the work. For instance, the film roll containing all the photo-

graphs of A.C. McKinley's surveying flight to the Rockefeller Mountains, on 18 February 1929, on the First Byrd Antarctic Expedition, was numbered backward when the consecutive identification numbers were added, following the return of the expedition to the United States. The same fate befell the last of three rolls on the South Polar Flight and the first and third of three rolls on the Eastern Flight of that expedition. This would not have happened, of course, had the numbers been recorded photographically in the camera.

#### *Available Maps, Charts and Ground Control Data.*

All available maps of the area to be charted in detail should be collected and these maps kept convenient for ready reference at all times. Some of them will, of course, be more carefully drawn and apparently more reliable than others. No definite rule, save careful study and the exercise of good judgment, can be laid down for the weight to be assigned to each such map in cases of this kind.

Most important of all, there must be collected all the available information as to the geographic positions of objects and landmarks which may serve as fixed bases or as control points in the plotting. Here again, great care and judgment must be exercised in the appraisal of available data. It may frequently happen that there are many more probable positions for the available control points than there are control points themselves.

As an example, seven different positions were found for Scott Nunataks, a pair of outstanding landmarks on Edward VII Peninsula which served as the second of two control points for the Eastern Flight of the First Byrd Antarctic Expedition, described on pages 177-209 of *The Geographical Review* for April 1933. These peaks had been discovered by R.F. Scott and had previously been visited by Prestrud and his companions, of Amundsen's South Pole Expedition in 1911-1912, and by members of Shirase's Japanese Expedition of the same years. Their geographical positions were determined by Prestrud in 1911 but were never published, so far as could be learned, either by him or by Amundsen. The seven positions for Scott Nunataks, in the ten references consulted, spread over a rectangle comprising 8 minutes of latitude and about 1 degree and 23 minutes of longitude, or roughly 8 miles north and south and 18 miles east and west.

## ANALYSIS OF SURVEY PHOTOGRAPHS

### *Marking of Individual Prints.*

The next step, preliminary to making a reconnaissance map, is to extract, tabulate, or otherwise put into usable form all the available information from each aerial photograph of the country to be mapped. This embodies at least the following:

(a) Name or number of flight, run letter or number, film roll number, and similar information.

(b) Consecutive number of photograph in run or film roll. This is usually marked in india ink on the negatives immediately after processing but may be exposed and printed automatically. It is an unwritten rule that aerial mapping film is ALWAYS to be stored in the archives in complete rolls. It is NEVER to be cut apart into individual negatives. This is because it is often most important, when making a map or in later analyses, to know the exact order in which the exposures were made. Failure to observe this simple rule has rendered whole sets of aerial photographs worthless for map making.

(c) Marking to indicate left (L), right (R), or vertical (V), in the case of film rolls from trimetrogon cameras. Negatives of the same triple-exposure always have the same consecutive numbers. If the camera was hand held, the side (and the quarter, if possible, that is, forward or aft) from which the photograph was made is to be indicated.

(d) Altitude of the airplane, by altimeter observation, barograph record, or guess, when each exposure or group of exposures was made.

(e) Marginal distance from top negative, as established by the negative screen, to the position of the apparent horizon, corresponding to the distance  $m$  in Fig. 7.

(f) Estimated or dead-reckoning geographic position of exposure, to be taken from the index map if no better source of information is available.

(g) The time exposure of each photograph, preferably from a watch or clock face made visible in the field and photographed with the geographic features.

If a good index map is not available, the foregoing data are supplemented by adding to the flight crew's sketch map and airplane track, or its equivalent, symbols or numbers to indicate about where the various sets of exposures were made.

### *Selection and "Pointing" of Landmarks.*

When the photographic prints, usually made as separates, have been placed in their order of exposure, the *known landmarks* on them are picked up and numbered or otherwise indicated. Marking of the identification on the prints is done in such a way that neither the number nor the leader or "pointer" connecting the number to the feature, or pointing toward the feature, is permitted to obscure any essential part of the print. This is especially true for distant features and for areas near the apparent horizon.

The mapper then selects and numbers a long series of geographic features, both in the foreground and the background, that are to serve as locators on the reconnaissance map. He "points" them with arrows, leaders, or other suitable marks so that none of them are marked by having a pencil, ink, or crayon line drawn over them. He is guided by the fact that the mapping or plotting value of a landmark is not always measured by its bold or picturesque features. He notes:

- (a) Its definition on the print
- (b) The number of times it appears on successive photographs
- (c) The ease with which it may be located and identified
- (d) The fact that it lies at sea level or ground level or at any other particular level
- (e) The rate at which its bearing changes from one photograph to another
- (f) The facility with which its bearings can be read from the grids.

He also considers the possibility of its appearing on other photographs, such as those taken on another part of the flight, and the certainty with which the feature or landmark can be identified when viewed from another direction.

When all such landmarks have been selected, it will be found, as the plotting and map making proceeds, that additional features must be picked up to fill in the gaps, to delineate shore lines, ice edges, and so forth.

The foregoing operations may be accomplished conveniently by laying the photographs down in succession, one over the other, with the greatest possible

overlap. The landmarks are brought close together and above each other, so far as practicable. Identification is then facilitated, because each landmark will have a similar appearance in the series of photographs, taking ten or twelve prints at a time.

It will rarely be possible, or necessary, to make a plot from every aerial photograph on a flight. Selections are based upon appreciable changes in bearing angles, new features appearing and old ones disappearing, and rapid changes in azimuth of the principal plane of the camera.

### *Identification of Landmarks.*

Much depends upon the care taken in that most innocent looking but highly important operation, — the *identification* of landmarks. By this is meant, not the marking, "pointing", or numbering of features for reference but making sure, for example, that the feature indicated as 226 on one print is also marked 226 on all other prints on which it appears. Correct identification is especially important in country which has never before been seen or photographed. Survey and exploration flights are frequently made in the form of loops, in which the airplane doubles back on its own course, roughly speaking, and in which photographs are taken on both outward and inward legs of the journey. Between successive photographs of the same objects, going out and coming back, the sun will have changed position so as to produce different shadow effects. The airplane may be just far enough from its original course to cause outstanding landmarks on the first part of the flight to assume the appearance of entirely strange objects when viewed from different heights or other angles. Reliable identification under these circumstances may require hours and even days of intent and patient study. It can frequently only be checked by agreement of the observed positions of these objects with positions calculated or determined from plots of other more definite landmarks. For example, on the Eastern Flight of the First Byrd Antarctic Expedition, Mount Woodward in the Edsel Ford Ranges of Marie Byrd Land loomed up on the outward journey as a large mountain mass, quite separate from the other mountains in the range and easily identified. It was only after much laborious plotting that a small distant peak in the midst of many other mountains, seen low on the horizon from the northern end of the range in another part of the flight, was identified as the top of Mount Woodward.

It cannot be too strongly emphasized that the preparation of the preliminary map must be accompanied by a careful and persevering study of the aerial photographs, individually and collectively. The mapper must go over them not once but many times, then many more times, collecting additional information here and there at each round.

### *Making Bearing Plots.*

The first operation in the construction of a bearing plot for any selected oblique aerial photograph is to apply to it the proper bearing grid, in the manner indicated by Fig. 9. The "proper" grid is the one made up for a camera having the same focal length  $F$ , for the approximate altitude  $h$  of the camera at the time of exposure, say to the nearest 500 or 1000 ft, and for the approximate marginal distance  $m$  on the photograph, say to the nearest 0.1 inch for negatives having vertical dimensions of the order 7 or 9 inches.

Whether the marginal distance on the print is exactly the same as that indicated on the grid or not, the short apparent-horizon lines at the sides of the grid

(marked AH) are placed over the visible apparent horizon on the print. If this moves the optical center of the grid too far from that of the print, another grid is selected and used, with a marginal distance corresponding more closely to that of the print. If the apparent horizon is not parallel to the frame line at the top edge of the print, the grid is rotated on the print until the apparent-horizon lines AH on the grid lie over the apparent horizon on the print, as described in detail in a subsequent section on Tilted Photographs. The optical centers of grid and print should coincide or remain close together.

Clipping the grid to the print temporarily, the bearing angles for the important landmarks are read off and written down, indicating whether they are to the right (R) or left (L) of the principal plane. For example, on the oblique aerial photograph 33/1 reproduced in Fig. 9, the data are as follows :

Landmark Identification	Bearing Angle, deg	Right or Left
A Berg	42.0	Left
B Berg	29.7	Left
C Berg	4.1	Left
D Berg	16.0	Right
E Rock X, left end	18.3	Right
F Ice-shelf point	7.2 (indefinite)	Left
G Undetermined	7.9	Left
H Berg, left end	20	Right
J Ice-shelf point	5.0 (indefinite)	Left
K W. glacier wall	14.0	Right
L Ice-shelf point	20.7 (indefinite)	Left
M Berg	41.2	Right
Sun	95 (estimated)	Right

Here the features lettered F, J, and L are not clearly defined and their correct bearings are somewhat uncertain. The bearing lines for them are drawn as broken lines on the plot; see Fig. 14.

For the work carried out in the past by senior author, involving aerial cameras with relatively long focal length, it was customary to construct bearing grids with lines for integral degrees. For the project discussed in this paper, undertaken by the present authors with photographs taken by cameras of short focal length, bearing lines were included only for even degrees. Even with these divisions there are so many lines on the grid that it has to be lifted frequently to make sure of the identification of landmarks and to check the position of objects lying almost directly underneath the lines. With practice and with sharply defined features, it is possible to estimate bearings by eye to the nearest tenth of a degree. Only rarely do landmarks stand out so definitely as to permit reading accurately to this amount, assuming the grid were graduated in tenths of a degree or less. One-tenth of a degree is roughly 0.1 mile at 60 miles distance and 0.2 mile at 120 miles. The latter is very nearly the limit for visual analysis with good aerial photographs. Weather and light conditions in the polar regions are not good enough to permit consistently clear delineation at these distances.

Transparent bearing plots are next constructed, as shown by the radiating lettered lines of Fig. 14. For the preliminary plot these are made normally for aerial photographs taken at intervals along the airplane course equal to about one-tenth the distance to the nearest landmarks being observed. If the course is



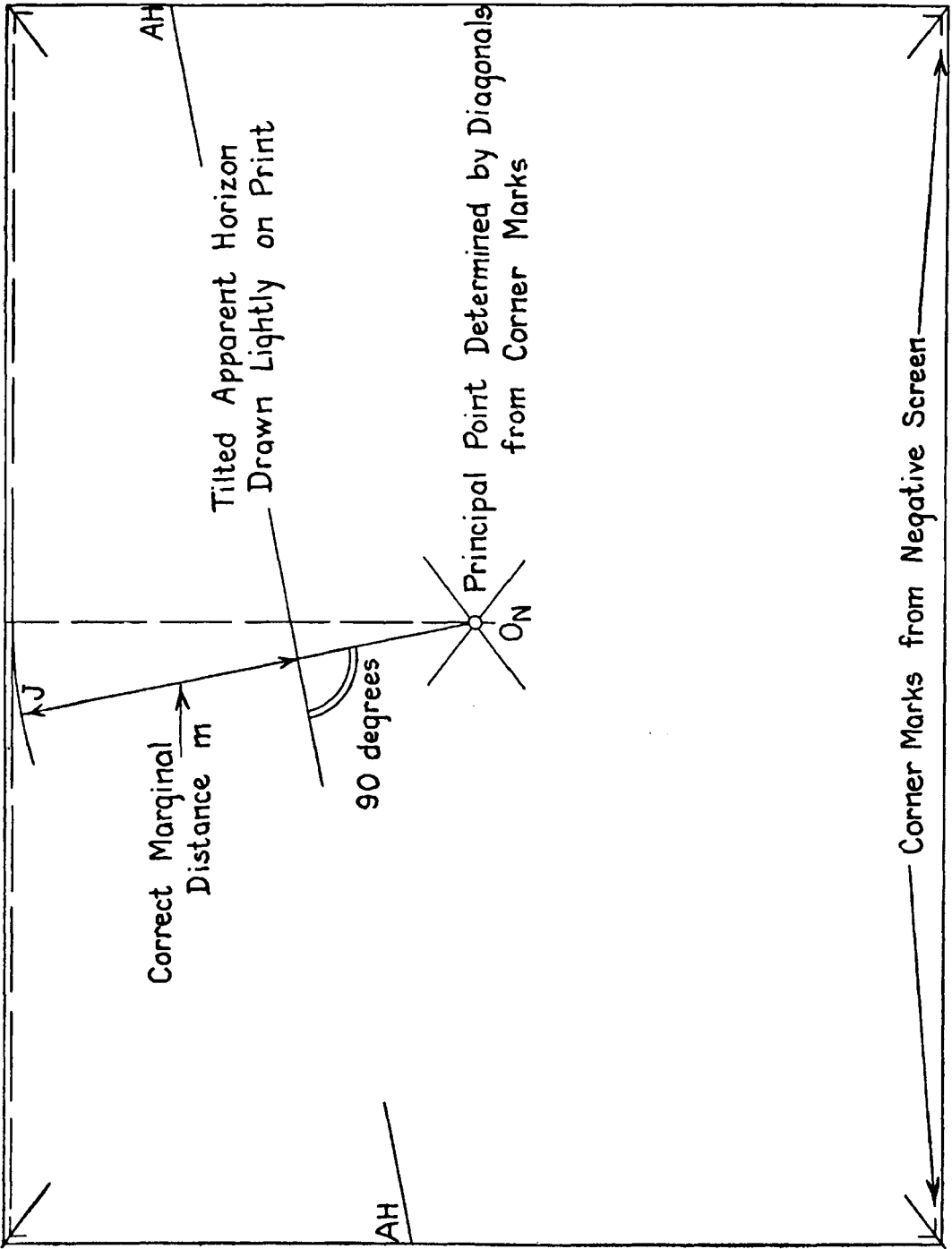


Fig. 17.

Diagram illustrating method of determining marginal distance for a tilted photograph.

changed or new landmarks appear, additional plots are made. A little experience with the individual project will indicate the number of plots and the proper interval, always selecting those photographs which show the greatest number of objects in common with those previously selected. For the Eastern Flight of the First Byrd Antarctic Expedition, made on 5 December 1929, of which some 645 miles were covered by 248 aerial photographs, a total of 124 bearing plots were *eventually* made before the 1933 reconnaissance map was finished (Geogr. Rev., Apr. 1953, Vol. XXIII, No. 2, map opp. p. 208). This rather large percentage was the result of an endeavor to fix certain landmark positions more accurately than would otherwise have been possible. It was also the result of an endeavor to delineate most of the visible features. This is not always possible on a reconnaissance map.

The bearing plot may be made on thin, nearly transparent tracing paper or on pieces of photographic film such as obsolete negatives, from which the emulsion has been removed. Each plot is large enough to cover both airplane position and all visible (or usable) landmarks at the map scale selected. Lines can be drawn on the emulsion side of the used film with India ink and ruling pen as readily as on drawing paper. If the film surface is too smooth for the ink to adhere smoothly, it may be roughened slightly by *gentle* use of a pencil eraser. If mistakes are made or bearings are revised, the ink lines may be removed readily with pencil eraser at the sacrifice of a slight amount of transparency.

For drawing the bearing lines, the transparent film or sheet is placed over a heavy paper protractor which has been prepared for the purpose, as illustrated by the two protractors and the principal-plane trace of Fig. 14. A pin is pushed through the film to the center of the protractor, serving as a mark for the airplane position and as a guide to the straight edge for ruling the bearing lines. These lines are drawn in at the proper angles, one for each landmarks, as given by the tabulated bearing-data sheet.

The plane of the negative and the optical axis of the camera are indicated by the two lines of Fig. 14, at right angles to each other at the airplane position. The direction of the airplane relative to the camera is marked by a short arrow with a heavy shaft. The direction of the sun relative to the negative, or to the principal plane of the camera, is shown by bearing line terminating in a small sun or other appropriate sign. The airplane position is marked by the number of the print or the negative. The landmarks are shown at the ends of their respective bearing lines by numbers or letters or names.

Transparent bearing plots of this kind are easily superposed and moved around individually to obtain satisfactory intersections of the respective sets of bearing lines drawn for each of the selected landmarks. When applied on a chart, the plots may each be held in place by small bits of scotch cellophane tape, pasted down at the edges. If it is found necessary to shift the plots in the course of the work, the tape readily pulls loose from the chart and as readily secures the plot in a new position.

In a subsequent section, under Map Plotting Procedures, there is reproduced as Fig. 18, a plotting diagram which shows how the intersections of the bearing lines from a large group of airplane positions indicate the relative locations of a number of geographic features.

If the bearings have been read correctly from the photographs and the bearing plots accurately made, regardless of whether there are any control points visible

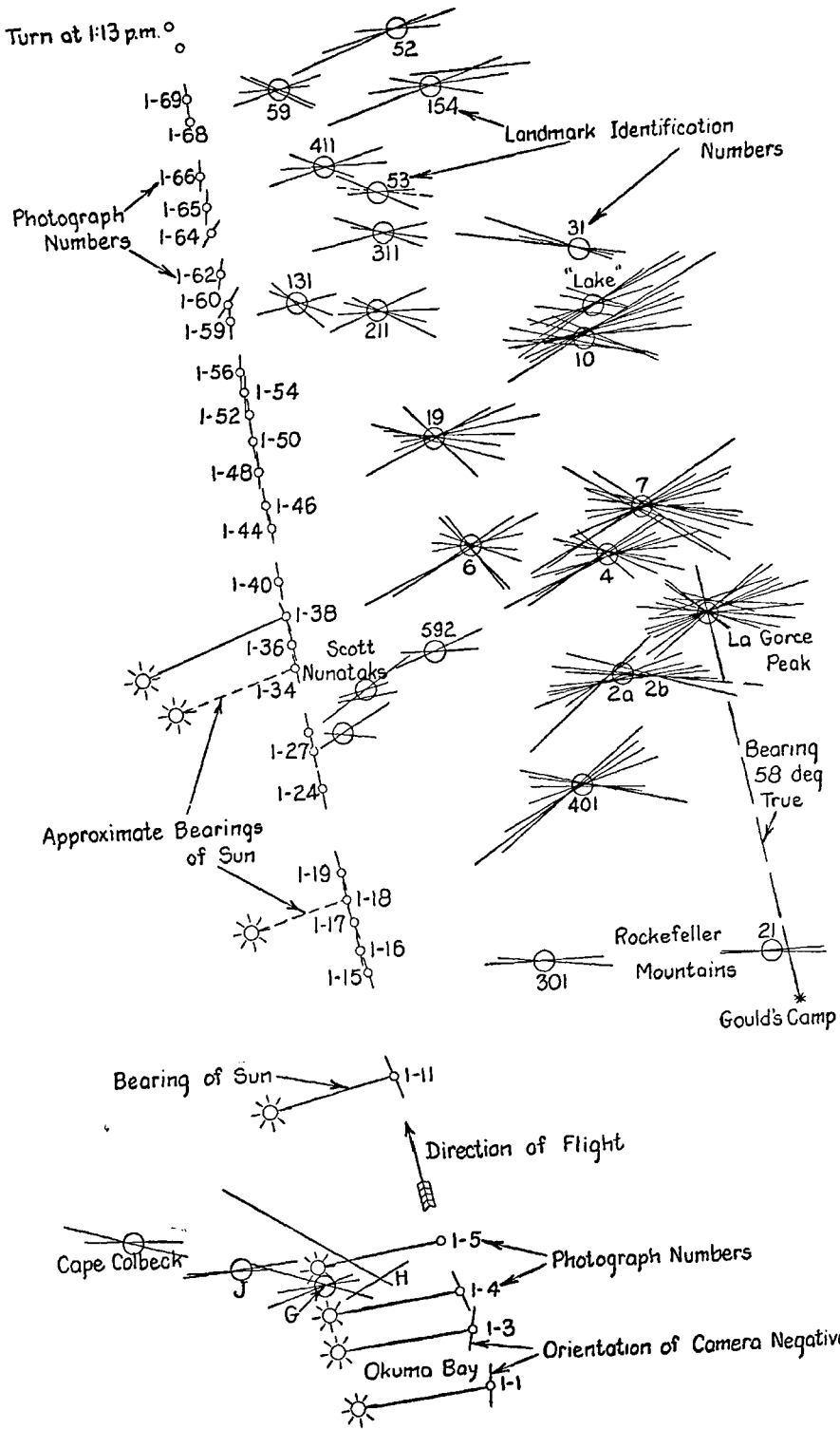


Fig. 18.

Plotting diagram for a portion of Byrd's Eastern Flight of 5 December 1929.

on the prints or not, a definite solution exists to any multiplicity of angle combinations, airplane positions and landmark locations, no matter how complicated. The solution is ultimately found by a process of patience and perseverance, combined with what little may be definitely known (or suspected) as to geographic positions, distance, airplane speeds, and the like.

### *Marking Coordinate Plots.*

For the preparation of the coordinate plot of the local area covered by a single oblique aerial photograph, the "proper" coordinate grid is selected, as described for making a bearing plot. It is applied to the print in the same manner, as in Fig. 11, with its apparent-horizon lines AH placed over the visible apparent horizon on the print. The grid is rotated over the print as before, in case the exposure was made with a tilt so that the apparent horizon is not parallel to the top edge.

Preparatory to sketching the visible features, a sheet of tracing paper is laid over a sheet of heavy paper which has ruled upon it a set of rectangular coordinates spaced at the nominal intervals on the coordinate grid to the scale of the map being constructed. If the intervals on the coordinate grid are nautical miles, and the map is being laid out to a scale of one nautical mile equals one-half inch, then the ruled rectangular coordinate lines on the heavy paper underlay are one-half inch apart.

The manner of sketching features on the transparent paper overlap is described in a previous section describing The Coordinate System. It is probable that a particular feature, say the island of Fig. 4, will have slightly different contours when sketched from different aerial photographs. This may be due to inability to view all the shoreline from any one airplane position, or to unavoidable inaccuracies. At least, the plots made from the several photographs serve as checks on each other.

Fig. 15 is a local coordinate plot made from the superposition of the coordinate grid and oblique aerial photograph illustrated in Fig. 11. While the icebergs and sea ice shown in this freehand sketch are purely temporary, as far as a reconnaissance map is concerned, they are shown here to illustrate how they would appear if they were low islands. As an example of the manner in which these grids were used to measure distances in the Wilkes Land project, the tip of the Astrolabe Glacier Tongue, nearest the airplane, is about 5.22 miles from the plumb point. The head of Piner Bay, to the left of the glacier tongue, is about 9.9 miles from the plumb point and lies about 2.2 miles to the left of the principal plane of the camera.

### *Application of Elevation and Depression-Angle Grids.*

The grid having lines which represent given elevation and depression angles is always applied with its center over the geometric *center* of the photographic print, regardless of the position of the apparent horizon on the print. This is because the plane of reference for both the grid and the print passes through the optical axis of the camera. The horizontal lines on the grid are always placed *parallel* to the apparent horizon.

### *Analysis of Aerial Views.*

The random exposures made by hand-held cameras in an airplane, classified previously under the general category of "views", are not survey photographs in

a strict sense. Fig. 16 is the reproduction of a photograph of this type. Nevertheless, these views are often found to be extremely valuable contributions to a reconnaissance mapping project. This applies also, but in lesser degree, to the individual exposures of a moving-picture film made from the airplane on an exploratory flight. Most of these random views are obliques, and they are useful for bearing or coordinate plotting. If so used, however, special bearing grids or coordinate grids, or both, must be made for them to suit the focal lengths of the cameras involved. The nominal focal lengths given in catalogs or on the cameras themselves are usually only approximate, especially for the infinite-focus positions required to photograph objects at distances of one mile or more. There is described in Appendix 2 of Part 2 a method of determining the focal length of any such camera.

### *Tilted Photographs.*

Since the focal length of the camera does not change with position, all objects are shown in their true relation to each other, whether the camera is in its normal position or whether it is tilted up on its side (in the plane of the negative). The problem resolves itself simply to the same one that is involved for survey photographs, that of finding the angle of depression of the camera axis with the horizontal plane.

To find this angle for a print made from a tilted negative, as diagrammed in Fig. 17, locate the center  $O$  of the print by intersecting diagonals from the marks at the opposite corners or by lines from the marks at midlength of the sides. Then draw a light line across the upper boundary of the print, as marked by the upper etched corners or other frame marks. Draw a second light line  $O_N J$ , through the center of the print perpendicular to the apparent horizon. With a compass, strike an arc from the center  $O_N$  with a radius equal to the distance to the upper boundary, intersecting the line normal to the apparent horizon in the point  $J$ . The distance from the intersection  $J$  thus found to the apparent horizon  $AH$  is the true marginal distance  $m$ . The line  $OJ$  perpendicular to the apparent horizon represents the principal plane on the negative.

Using the apparent horizon and the principal plane as reference, the proper bearing or coordinate grid, corresponding to the altitude of the airplane and the marginal distance  $m$ , is applied to the photograph with the same assurance as to a regular survey photograph.

Whether the tilt is appreciable or not, and whether the marginal distance is exactly that for which the grid is drawn, the apparent horizon lines  $AH$  on the grid are *always* applied to the *apparent horizon* on the photograph.

### *Analysis of Individual Prints by Several Methods.*

The analysis of any oblique aerial photograph is by no means confined to the application of one type of grid or the use of any single method. The reliable exposure data are generally so meager as to render the use of one process quite indefinite or inconclusive. On a given photograph for example, a coordinate grid may be used to determine the distance and relative position of parts of an ice edge in the foreground. A bearing grid may be applied to fix the relative bearings of selected peaks in a mountain range in the background, as well as salient points in the ice edge. The reflection of the sun in open water in the foreground of the same photograph serves to orient the photograph as a whole. The position of the

wing tip in the upper part of the field gives the angle between camera axis and plane axis, and the position of the apparent horizon, of course, the angle of depression of the camera.

As the work of analysis and plotting proceeds and the exposure data which had previously been estimated is confirmed or corrected, it is desirable, and frequently necessary to repeat the analyses of a series of photographs, to improve the accuracy and reliability of the data obtained from each photograph. The mapper should realize at the outset that thorough analysis of this kind means hard and long-continued work, but that it brings its own compensation in the increased reliability of the map upon which he is working and in the facility with which analysis can be carried on with practice and experience.

### MAP PLOTTING PROCEDURES

The exact method to be followed in laying down the general triangulation which forms the groundwork of any reconnaissance map must of course depend largely upon the data available. Few general rules, other than those previously quoted, can be given.

The problem in the piloting or planetabling method, employing bearing plots, is to use a combination of angles between available geographic features and the camera positions along the airplane track to project ahead the path of the airplane and to determine the airplane position when each photograph of the available adjacent landmarks was taken (or each one for which a bearing plot is made). From the airplane position thus determined, a new set of angles, applying to the features previously available and to one or more additional points, is laid off, by the method known as resection. Using the dead-reckoning data as to courses and speeds, new airplane positions are marked down for successive photographs following the first. From the plotted bearing angles of features registered in these photographs, taken from different positions, intersections are found for successive additional geographic features, giving their positions relative to the selected landmarks. The geometry of this method is that outlined in the section on The Bearing System and diagrammed in Fig. 3. It is illustrated in Fig. 18, as a step-by-step procedure, based upon data prepared for plotting the reconnaissance map of Byrd's Eastern Flight of 5 December 1929 (*Geogr. Rev.*, Apr. 1933, Vol. XXIII, No. 2, map opp. p. 208).

Here, at the airplane positions at which photographs 1-1 and 1-3 were made (photographing to the left), the geographical position of Okuma Bay was known reasonably well. Until the photograph series 1-15, 1-16, ... was begun, making exposures to the right, the airplane was carried along a great-circle course by dead reckoning. The bearing lines from 1-15 and 1-16 intersected at features 301 and 21 at extremely small angles, but since the position of feature 21 was known approximately, this gave reasonable assurance that the bearing line projected forward for 401 was correct. An approximate bearing of the sun in 1-18 served as a check on the orientation for this group of five photographs.

[Working forward in this manner, and checking for azimuths with the sun bearings in photographs 1-34 and 1-38, there were obtained bearing-line intersections for features 2a, 2b, 592, 4, 6, 7, and La Gorce Peak. Since the bearing of the latter from the recorded position of Gould's camp was reasonably well known, the bearing-line intersections could be held to this line and the airplane and other positions adjusted accordingly. For carrying the plotting along to the 1:13 p.m.

position, the mapper had the great-circle compass course and not-too-accurate information as to the airplane speed, but he could (and did) make use of the resection data from the fixes of features 19 through 52.

For the reconnaissance plotting involved in the present project, along the coasts of Wilkes Land, there were no such definite and identifiable features, located at such convenient and useful distances from the USN Operation Highjump airplane tracks. Part 2 describes the uncontrolled mosaic, flight-track intersection, and other methods that had to be used.

### SUGGESTIONS FOR FUTURE AERIAL MAPPING DURING RECONNAISSANCE FLIGHTS

As a matter of interest, the authors are engaged in the preparation of a set of instructions and suggestions for planners and airplane crews engaged in reconnaissance flights, based upon instructions prepared by the senior author and used during the Second Byrd Antarctic Expedition of 1933-1935.

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