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Report of Project MICHIGAN

PHOTOGRAMMETRIC TECHNIQUES FOR DETERMINING THE SPATIAL ORIENTATION OF AERIAL PLATFORMS

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Robert L. Hess
Technical Director
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PHOTOGRAMMETRIC TECHNIQUES FOR DETERMINING THE SPATIAL ORIENTATION OF AERIAL PLATFORMS

ABSTRACT

The general problem of determining the spatial orientation of an aerial platform by photogrammetric means is discussed. Both the stereo and analytical solutions are included. The photogrammetric range, which provides a major portion of the input data, is treated in detail. Five such ranges have been constructed by the Navigation and Guidance Task of Project MICHIGAN. With these ranges and a calibrated metric camera, the X, Y, and Z coordinates of the camera station can be obtained with a probable error of one foot for flying altitudes of 10, 000 feet.

1
INTRODUCTION

For some time the Navigation and Guidance Task of Project MICHIGAN has been utilizing an analytical solution to an exterior orientation problem to determine the position of an aircraft in space. The problem is that of determining the components of tilt of a camera rigidly mounted in the aircraft. If the tilt is known, the nadir of the camera station can be found; and, if the position of the camera with respect to the center of the aircraft is also known, the position of the aircraft can be found.

The entire problem is one of photogrammetric reduction, and it requires input data from an accurately calibrated aerial camera and from a photogrammetric range. The purpose of this memorandum is first to describe the general process involved in determining the spatial orientation of an aerial platform; and second to describe the various photogrammetric ranges, those constructed by the Navigation and Guidance Task as well as those previously in existence.

The photogrammetric reduction problem can be described as one of finding the coordinates and orientation of the focal plane of the camera at the instant of exposure. The coordinates of a camera can be considered to be the X, Y, and Z spatial coordinates. The orientation of the focal plane can be considered in terms of the component of tilt in the three directions: pitch, roll, and yaw. The spatial geometry of the tilt problem is shown in Figure 1, where the nodal point of the lens is at L. P is the principal point or the point where the optical axis of the lens pierces the photograph. A vertical through the nodal point of the lens intersects the photograph at N, the nadir point. This vertical, extended to the ground, becomes the actual nadir of that photograph. The angle between the vertical and the optical axis of the lens is the angle of tilt and is designated by the letter t. Images of the ground control stations A, B, and C are designated on the tilted photograph by the letters a, b, and c. α, β, and γ are the face angles of the pyramid. The principal distance is f. It is obvious that if we know the coordinates of the ground control stations A, B, and C, the problem can be solved. We have two possible solutions—optical or analytical.

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THE STEREO SOLUTION

Working toward the stereo, or optical, solution we obtain a similar geometry problem from a second photograph covering the same area but taken from a slightly different camera station. The two images are then projected through suitable lens systems onto a table on which the X, Y, and Z positions of the ground control stations are physically located. (Throughout this report X and Y refer to ground positions; x and y refer to positions on the photographic plate.) When the rays for each station from each negative intersect at the proper point, it can be seen that the geometry will be satisfied by only one orientation for each negative. A machine that can be used for this stereo method is shown in Figure 2. The spatial coordinates of the camera station must be obtained from suitable scales on the projector head, and considerable precision and care is involved in obtaining accuracies on the order of a few feet. In actual practice the original negative is not used in the projector; a diapositive (corrected for lens distortion) is made from the original. When the stereo method is used, an optimistic value for probable error would be three minutes of arc for the tilt determination, which at a flying altitude of 10,000 feet amounts to an error of nine feet in x and y. This method is somewhat slower than the analytical method, for it generally takes a 24-hour working period to process 12 negatives completely.

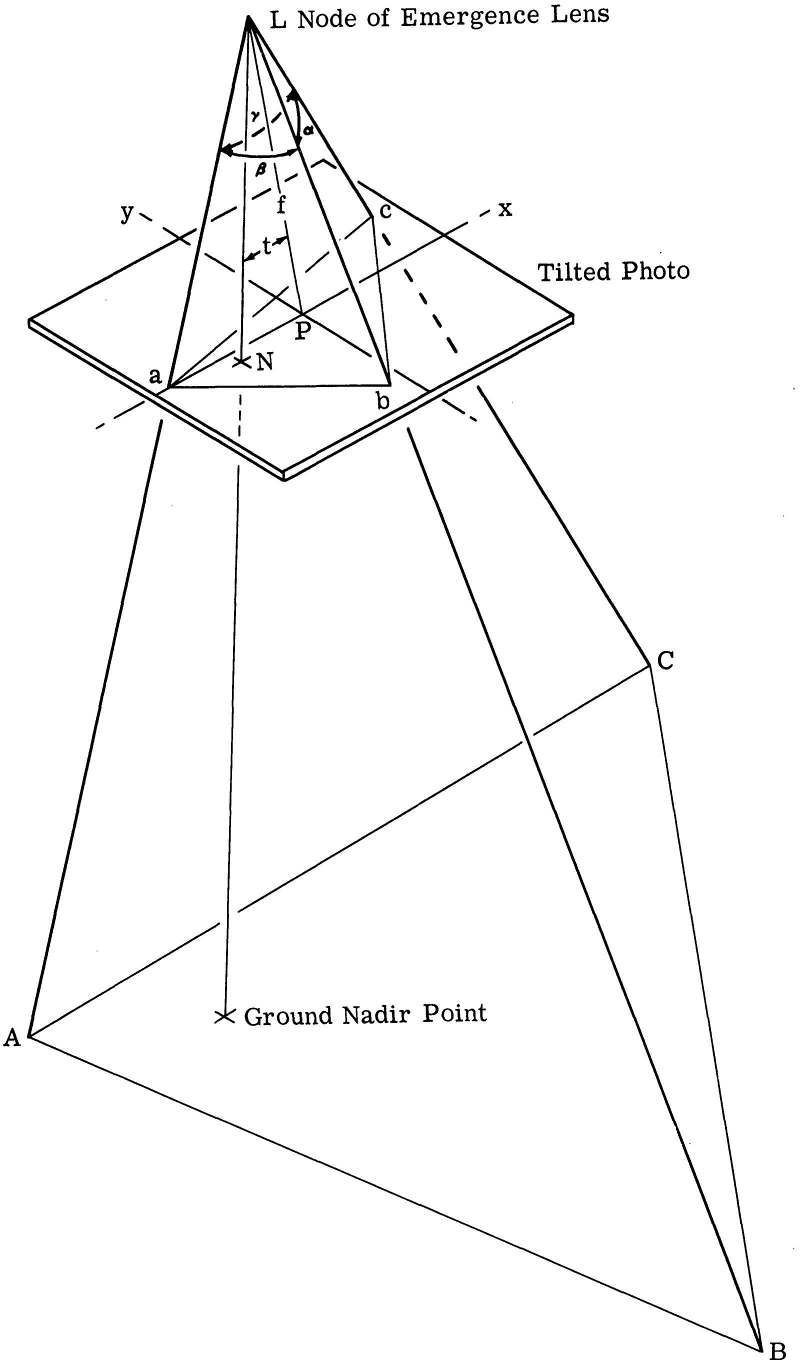

FIGURE 1. GEOMETRY OF TILTED PHOTO

3
THE ANALYTICAL SOLUTION

The second method is an analytical tilt problem. As they appear on the negative the coordinates of the images of the ground control stations are measured with respect to the fiducial axis of the camera. This information together with the camera constants and the ground control allows a complete solution to be derived from a single photograph. We shall discuss the analytical method in some detail and compare it briefly with the stereo method.

The analytical method, of course, requires that measurements be made on the photographic negative. This is done with a precise linear comparator, two of which are used by the Navigation and Guidance Task. One, shown in Figure 3, is a Gaertner comparator with a traveling microscope and a 10 x 10-inch stage. The second is a Mann comparator which has a traveling stage. Both instruments have a least reading of 0.001 millimeter.

The measurements made on these comparators must be done in an air-conditioned room so that dimensional stability is maintained throughout the measuring process. Even though the negatives are stored and maintained in an environment of controlled temperature and humidity, they are not necessarily the same size that they were at the moment of exposure. For this reason a reference dimension is checked in two directions and then compared with the actual camera measurements. The coordinates of the image points as they appear on the negatives are then corrected by the shrinkage or expansion ratio. A typical value of this ratio in the x direction would be 1.0029271 and in the y direction 1.0029572.

Before the negatives can actually be read in the comparator, the various ground control points must be identified and numbered on the negative. A frame ready for measurement is shown in Figure 4. More than three points are shown, because it is desirable to have several solutions for a given problem in case one contains a misread point or an error in transcription.

The plate coordinate information is recorded on the card punch form shown in Figure 5. The form is then sent to the Computing Facility where the necessary cards are punched and the information given to an IBM computer. As the computer program stores the coordinates of the ground station along with other essential information, it is only necessary to feed in the plate information. Actually the Navigation and Guidance Task has two types of programs available, one a three-point solution derived from the basic geometry as mentioned, the second a four-point area distortion solution which is more difficult to explain briefly. It is somewhat less sensitive to residual errors in the plate coordinates and is generally used for higher altitudes, or when greater accuracy is required.

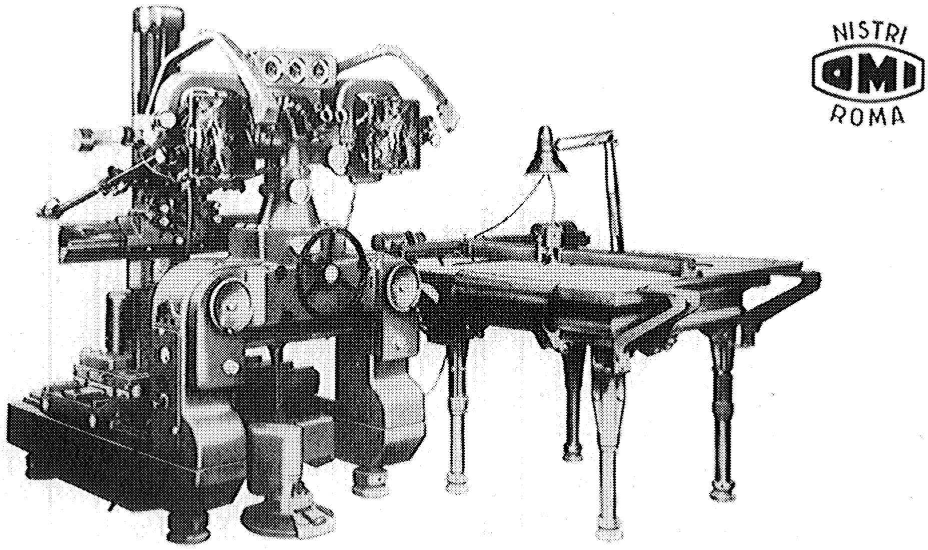

FIGURE 2. BETA II PHOTOSTEREOGRAPH

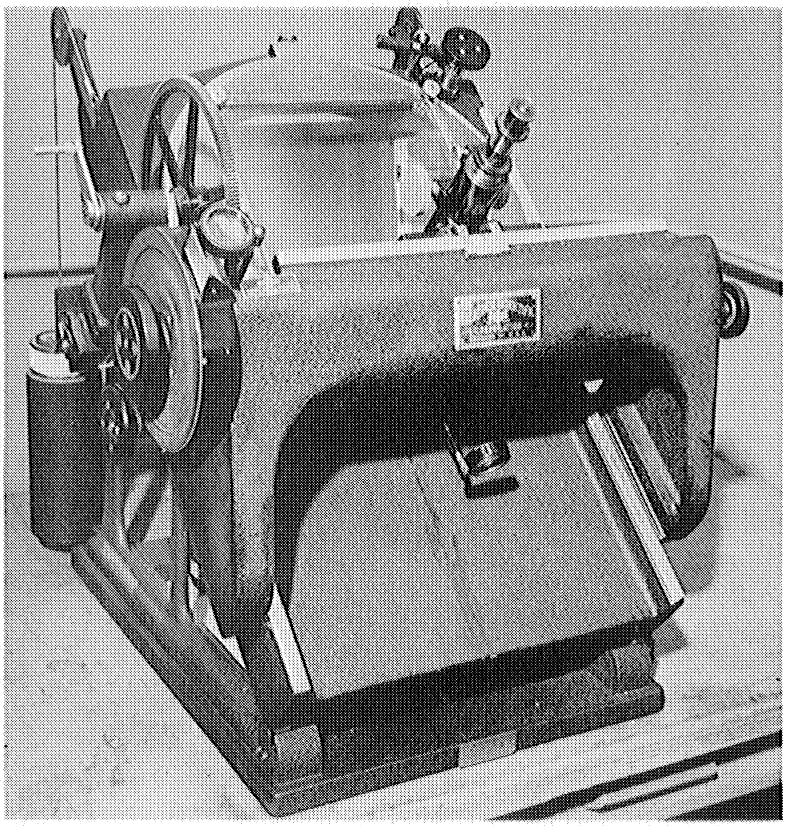

FIGURE 3. GAERTNER COMPARATOR

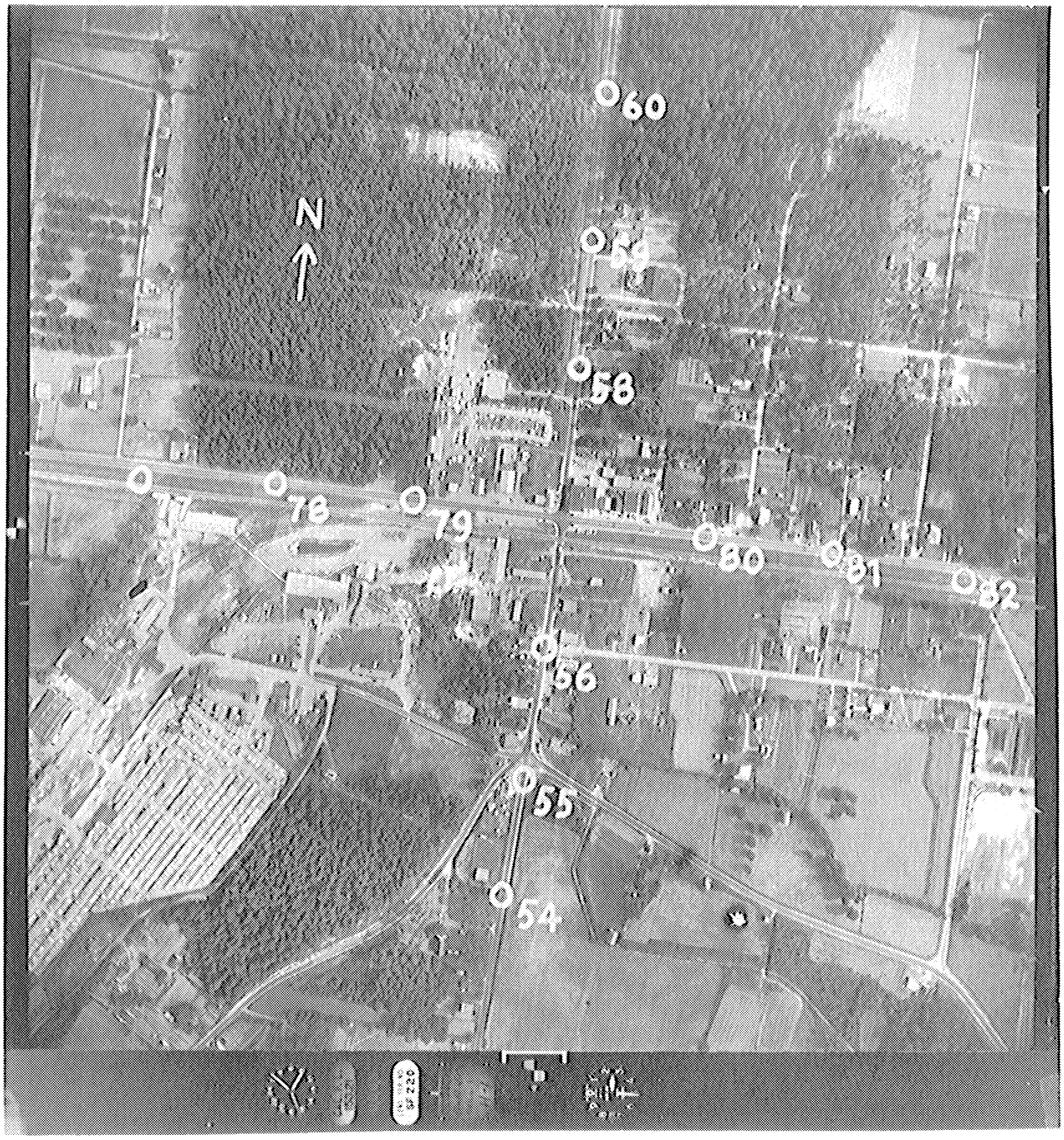

FIGURE 4. FRAME MARKED FOR READING

To consider the three point solution: assuming a perfect system and referring again to Figure 1, we can measure the plate coordinates of a, b, and c with respect to the intersection of the fiducial axis as origin. We must know the value of f, the principal distance, and can obtain it from the camera calibration. The X, Y, and Z coordinates of the ground control stations, which must also be known, are obtained by methods of ground survey, as will be shown in the discussion of the photogrammetric range. From Figure 1 it is apparent that our problem is to make the plate pyramid fit the ground pyramid, and we can do so only after the correct X, Y, and Z coordinates of the camera station are obtained. From the measured plate coordinates and the known principal distance f, the lengths of sides La, Lb, and Lc from the plate pyramid can be computed. The next step is to compute the face angles of the plate pyramid α, β, and γ. It then becomes necessary to find the approximate values of the required space coordinates of the exposure station with respect to the ground control survey. The approximate Z coordinate of the air station can be found from the scale of the photograph and the focal length of the lens, or by the use of a properly set and corrected altimeter. The approximate X and Y coordinates of the principal point (which, for small values of tilt, is near the nadir point) can be found by making a radial plot through the images of the control points and transfering this sheet to a scale drawing of the ground control. The coordinates of the camera station can then be read from the drawing.

Having found the approximate X, Y, and Z coordinates of the camera station, we can compute the corresponding approximate lengths of the sides of the ground pyramid. With these values and the approximate coordinates of the air station and the exact coordinates of the ground control points, the face angles of the ground pyramid for the position of the assumed air station can be computed. If the assumed position of the air station is correct, the face angles of this ground pyramid will agree with the computed value of the face angles of a plate pyramid. Since this seldom if ever happens, the values obtained fail to satisfy the plate pyramid exactly. The residual errors will be small, however, if we have made a close approximation of the air station, and will show the amount by which the coordinates failed. Corrections ΔX, ΔY, and ΔZ must now be computed and applied to the approximate values of X, Y, and Z. If, for example, we had a ΔX of 1000 feet due to a 5-degree tilt and assumed that the principal point were the nadir point, it would probably require three solutions to bring about convergence by this method. It is known as the Church method and was developed by Professor Earl Church of Syracuse University.

Theoretically, it would seem that the nadir point can be determined from three ground control points regardless of their image location on the photograph with respect to the nadir point. There is one exception, however, which occurs when the nadir point lies on the circle passing through the three control points. In this case, the point sought is indeterminate and both graphical and analytical solutions fail. The strength of the ground pyramid depends on the strength of the ground triangle, and the latter is strongest when the point sought lies at the center of gravity of the triangle. The strength of this figure is carried into the ground pyramid. A careful

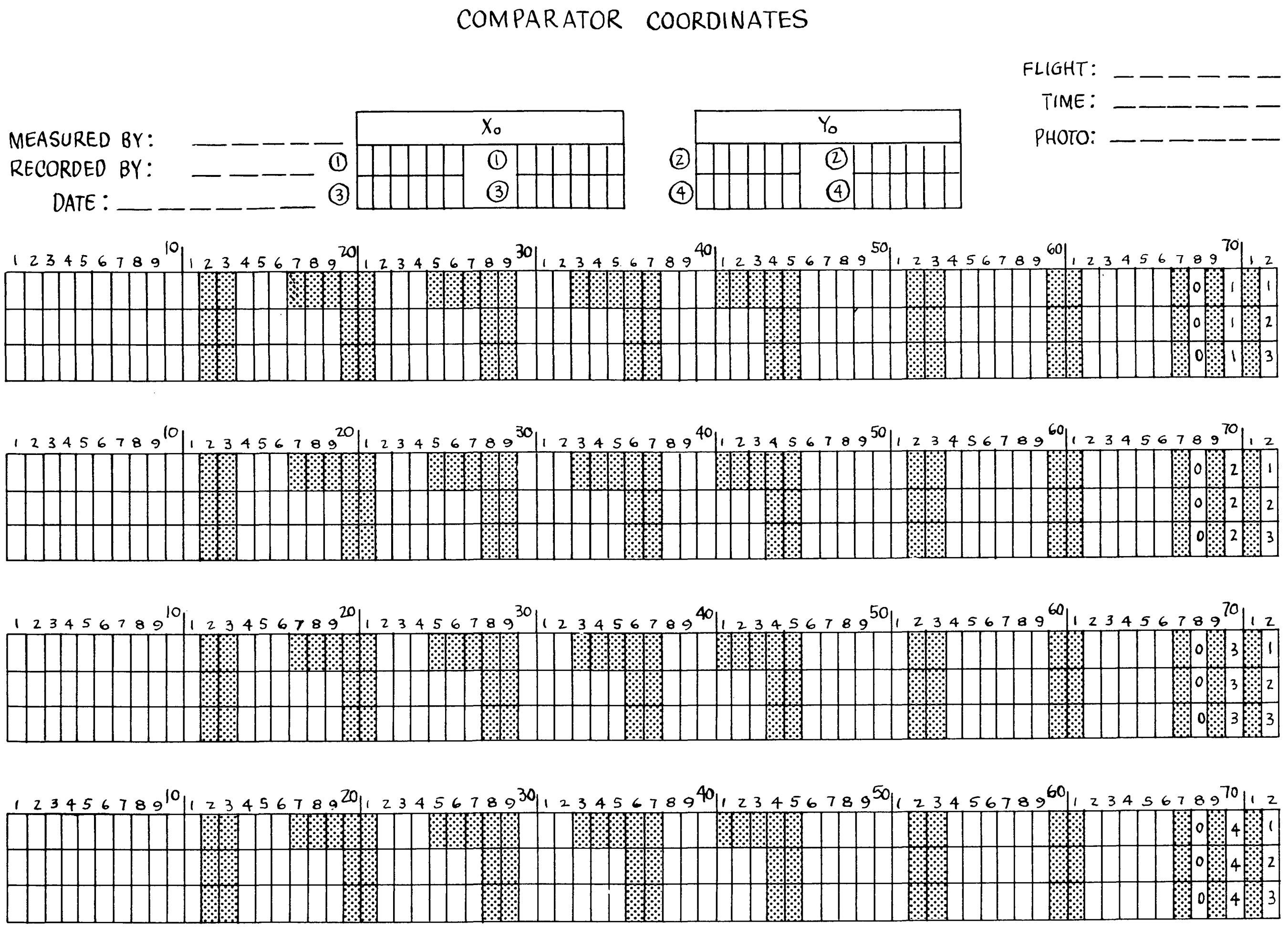

FIGURE 5. DATA FORM (COMPARATOR)

selection of triangles will usually eliminate the weak cases. Triangles in which the nadir point lies on or near the great circle must be avoided, as must triangles in which the nadir point falls near one of the control stations. In the latter cases the angle at the air station between the vertical and the control point will be small. For a small angle of 2 degrees the tabular difference of the cosine for 1 minute of arc is 0.000001, which means that one can change the angle without appreciably changing the cosine.

Certain corrections for curvature and refraction must be applied to the raw data. Curvature of the earth causes an inward displacement, while refraction causes an outward displacement of a point as it appears on a photograph. Figure 6 shows the correction curves for both curvature and refraction as well as a correction curve for the combined effect when the altitude of the air station is 20,000 feet and the lens has a 6-inch focal length. If the corrections were omitted and the control points were assumed to be equidistant from the principal point, an error would be introduced affecting the elevation of the air station more than the tilt. That is to say, there would be a uniform radial displacement of the control points on the photograph producing the same effect as would be recorded with a lens of a slightly shorter focal length. A third correction is for distortion of the metrogon lens. The actual distortion curve for the lens that we use has been obtained and is now applied in combination with the curvature and refraction curves so that for each altitude bracket the image position error is extremely small. This combined curve for an altitude of 10,000 feet is shown in Figure 7. A fourth correction considers the expansion or contraction of the negative in the x and y directions, as was discussed in conjunction with the need for air conditioning.

The accuracy that can be obtained with any of these solutions depends, of course, upon the accuracy of the input data. If we were to consider the McClure photogrammetric range (one of the best ranges) and were to use an accurately calibrated metric camera, it would be possible to have a probable error of only 0.48 feet in the horizontal coordinates of the nadir for flights made at an altitude of 10,000 feet. The probable error in the altitude of the aircraft would be less than 1/2 foot. In terms of tilt these errors amount to 10 seconds of arc in pitch and roll, and to 5 seconds of arc in heading. At the other end of the accuracy scale would be flights made over the Hereford control area (a very small area allowing only one and sometimes two solutions). Under the same conditions at 10,000 feet, the probable error in X and Y would be on the order of 10 feet.

The time required to process frames from either of these areas is about 30 or 40 minutes per frame. Marking the targets and picking out the points to be used for each solution would

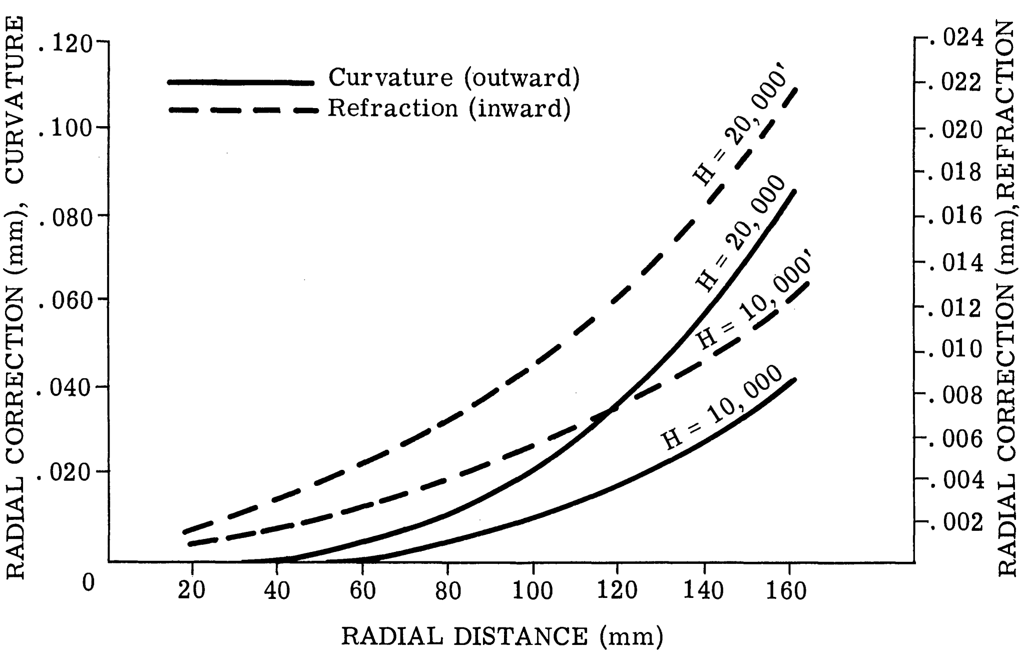

FIGURE 6. CURVE FOR CURVATURE AND REFRACTION CORRECTION

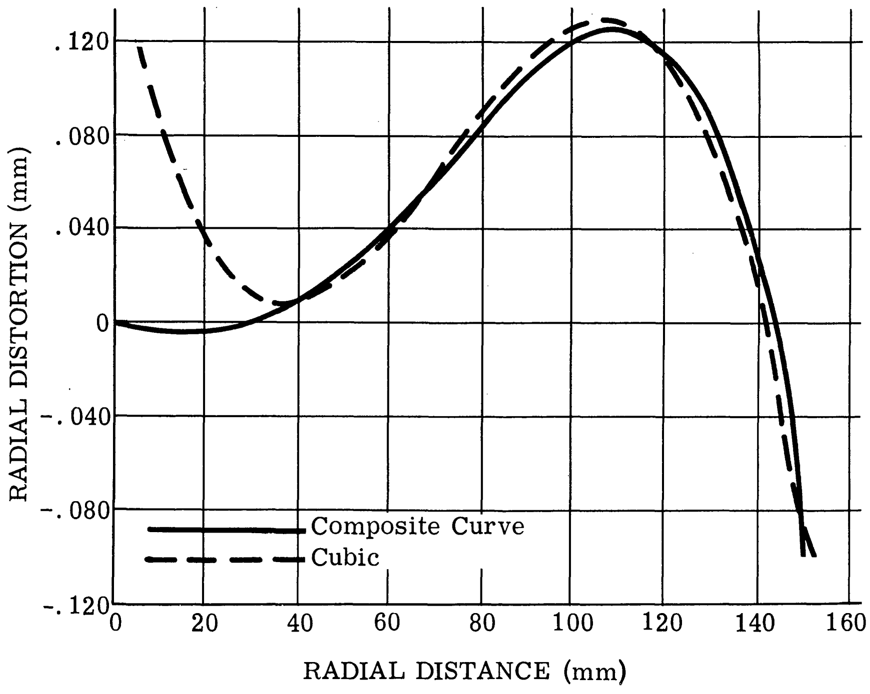

FIGURE 7. COMBINED CURVE CURVATURE, REFRACTION, AND DISTORTION

add an additional 15 minutes per frame. With two comparators in use, it is thus possible to process 24 negatives in an 8-hour working period.

4
THE AERIAL CAMERA

The next item to be considered is the aerial camera. A precise mapping-type camera must be used in this work, and camera calibration information must be available to supply accurate data on image position and camera constants. The basic task is an accurate reconstruction of the geometry of the object space in the image plane. The calibration information should include all the major effects of the lens-film combination which result in a distortion of the object geometry as it appears in the focal plane. This information must, of course, be available in such a form that corrections may be conveniently applied to the coordinates of the image.

The primary factor to be considered in camera calibration is lens distortion, which causes deviation of a light ray as it passes through the lens elements and a resultant displacement of the image. A considerable amount of radial distortion is purposely introduced into the lens in order to remove other lens aberrations (especially spherical and chromatic) over the wide field of the lens. A very small amount of distortion is caused by decentering of the lens; as it tends to be less than one micron, the decentering correction is usually neglected. The radial distortion correction, as a function of distance from the principal point, can easily be applied to the measured coordinates. A second piece of required information is the calibrated focal length of the camera-lens combination. This may be obtained in varying degrees of accuracy from the camera manufacturer. It is also possible to have the Bureau of Standards conduct a calibration on a particular camera. Data can also be obtained by photographing star trails and thereby determining the radial distortion and calibrated focal length of a particular camera-lens combination. The stellar calibration method, which has been employed at Willow Run Airport, is very accurate, because we have an accurate knowledge of the angular position of the stars at a particular instant.

5
THE PHOTOGRAMMETRIC RANGE

In the discussion of the spatial geometry of the tilt problem it was obvious that accurate knowledge of the object space is essential. This object space, generally called the photogrammetric range, is an array of identifiable objects that will be visible on the photographic negative.

These objects can be features of the terrain such as road intersections, corners of fence lines, and tops of buildings, or they can be artificially constructed targets of cloth, wood, or concrete.

Where high precision is required, an artificial target is to be preferred. For the usual mapping camera, with the metrogon lens, these artificial targets should subtend an angle of about 0.0003 radian. This means that for photographs taken at approximately 25,000 feet the target should be 8 feet in diameter; at altitudes of approximately 1000 feet of course it need be only about 4 inches in diameter.

We have implied that the circular target is the usual pattern. It is possible to use a target in the form of a cross, and also possible to use one in the form of a checkerboard. Each has its limitations. The size of the contrasting area of each type of target must be large enough to make the target visible at various altitudes. In the case of a checkerboard target, therefore, each square must be the same size as the circular disk; the same holds true of the cross target, in which each arm of the cross must be the same size as the circular disk. It is quite common to have a checkerboard target 30 feet square, and made of nine 10-foot squares. There is a disadvantage to this type of target in that it is possible for image motion to cause one square to slip over another in such a manner that the entire target panel disappears. There is also a disadvantage to the cross-type target: if the cross is large enough to be visible as a cross, one has difficulty aligning it accurately on the cross-hair of the comparator. Cross-type targets have been used which are 48 feet long and 10 feet wide. They are usable to approximately 30,000 feet. For this type of reduction, the disk type target is generally considered to be the best compromise.

The spacing of targets is determined by the focal length of the lens and the required altitudes. The total number of targets in the photogrammetric range depends upon the type of flight that is to be made in the area. If information is required along a line, the targets must be spread out in the general direction of the line of flight. If, on the other hand, information is only required in one spot and at several altitudes, the range can be of rather limited size.

Most photogrammetric ranges are laid out in a rectangular grid pattern. Examples of these are the ranges at Eglin Air Force Base, Florida; Phoenix, Arizona; Brookville, Ohio; and McClure, Ohio. The Eglin Air Force range has a grid spacing of 10,000 feet, whereas the others have spacings of 5000 feet. In addition to its 5000 foot grid, the McClure range contains many targets interspersed in the grid. These ranges vary in size from 25,000 x 25,000 feet at the McClure range to 150,000 x 170,000 feet at the Phoenix range. They have been surveyed by intersection from first-order triangulation stations. The McClure range, with an error of about 4 inches, is typical of a precise photogrammetric range, while the Phoenix range, with a probable error on the order of several feet, is considered marginal.

The Navigation and Guidance Task has had two special requirements in regard to photogrammetric ranges. The first is that the range must be located at a geographic position dictated by the location of the other components associated with the experiment. The other requirement for necessary position information is that it be obtained in only one spot horizontally and at as many altitudes as possible—ideally as though from different heights along a flag pole. In view of these special requirements there are only a few places where the ranges can be built, but each range need have only enough targets to get photographic coverage at the various altitudes when the aircraft is located essentially over the same horizontal coordinates. As a result, target configuration for the special photogrammetric ranges constructed by the Navigation and Guidance Task has been in the shape of a cross. One such, shown in Figure 8, is the Gage, New Mexico, photogrammetric range.

A summary of the various aspects of the five photogrammetric ranges constructed by the Navigation and Guidance Task is shown in Table I. The ranges at Hereford, Arizona, and Gage, New Mexico, were located with respect to the Decca chain serving the Ft. Huachuca area. As can be seen by the table, the Hereford range is approximately 2 miles square and contains 9 targets. The lowest usable altitude is 1000 feet and the highest is 8000 feet. If a larger target were used at the extremeties and a slight degradation in accuracy were allowed, it would be possible to have a higher upper limit in altitude. The probable error in aircraft position for flights at approximately 10, 000 feet above terrain is on the order of 10 feet in the X and Y direction and 5 feet in the Z direction. This error could be decreased if additional targets were added to the range in such a manner that several more tilt problems could be solved for each photograph. The heading information, quite insensitive to errors, is probably accurate within less than 30 seconds of arc. Early morning flights in this area are desirable. The proximity of the Huachuca mountains tends to promote extreme turbulence at the lower altitudes in the afternoons, especially in the summer time. The air traffic in this region is rather light.

The Gage photogrammetric range is somewhat larger than the Hereford range, being approximately 5 miles square and containing 17 targets. The lowest usable altitude is similar to that of the Hereford range; but, covering a larger area, this one is usable to a higher altitude. Here again accuracy could be improved if additional problems from each negative were solved. The weather is excellent and turbulence is not severe even in the afternoon; air traffic is also light.

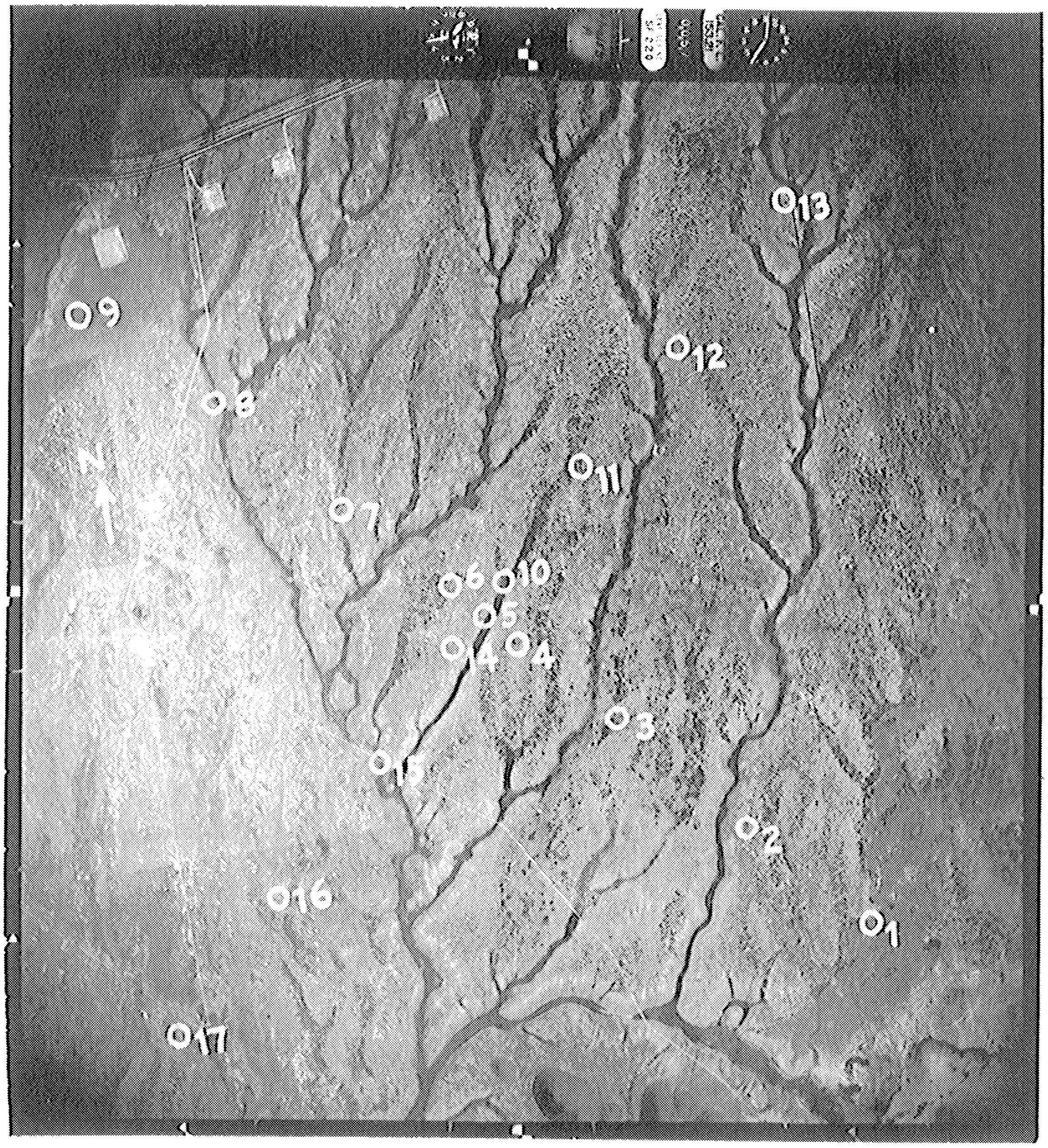

FIGURE 8. GAGE, NEW MEXICO, PHOTOGRAMMETRIC RANGE

Both of these ranges were surveyed by triangulation from first-order triangulation stations. The vertical control for the Gage area was obtained from existing bench marks at Separ and extended by a second-order level loop through the target area. In the Hereford area, an assumed elevation at the center of the area was used as the datum, and second-order levels run from that point.

Range	Latitude and Longitude of Target Center	Area Covered (miles)	Number of Targets	Lowest Usable Altitude* (feet above terrain)	Highest Usable Altitude* (feet above terrain)	Elevation of Center MSL	Probable Error In Aircraft Position at 10, 000 Feet Above Terrain			Probable Error in Tilt (Pitch and Roll)	General		
							X Y	Z	Heading		Weather	Air Traffic	Terrain
Hereford, Arizona	31°-27'-27''. 493 110°-09'-07''. 337	1. 8 x 1. 8	9	1000	8, 000	4340. 0	10 ft	5 ft	30 sec	2 min of arc	Excellent AM Good PM	Light	Desert and ranch land
Gage, New Mexico	32°-08'-58''. 437 108°-21'-30''. 408	4. 6 x 4. 6	17	1000	21, 000	4453. 5	10 ft	5 ft	30 sec	2 min of arc	Excellent AM and PM	Light	Desert and ranch land
Willow Run, Michigan	42°-20'-05''. 0 83°-32'-48''. 5	4 x 4	13	1400	18, 000	814	** 2 ft	** 1 ft	10 sec **	20 sec of arc**	Good — summer Poor — winter	Heavy	Farm land
Beulaville, North Carolina	34°-55'-23''. 7 77°-46'-26''. 4	6 x 6	45	570	26, 000	85	3 ft	1 ft	30 sec	30 sec of arc	Poor to fair	Medium	Town, farm, and swamp
Hallsboro, North Carolina	34°-19'-24''. 0 78°-35'-54''. 0	6 x 6	45	570	26, 000	65	3 ft	1 ft	30 sec	30 sec of arc	Poor to fair	Medium	Town, farm, and swamp

*Assuming the use of a 6-inch lens with 9 x 9-inch frame.

**Anticipated.

TABLE I. PHOTOGRAMMETRIC RANGES CONSTRUCTED BY THE NAVIGATION AND GUIDANCE TASK

Both the Beulaville and Hallsboro, North Carolina, ranges are 6 miles square and contain 45 targets. The lowest usable altitude is on the order of 600 feet and the highest is on the order of 26, 000 feet. The probable error for these ranges is on the order of 3 feet in the X and Y directions and on the order of 1 foot in the Z direction. Heading information can be obtained to at least 30 seconds of arc. The biggest disadvantage of these North Carolina ranges is that few days offer suitable weather for flights covering the entire vertical requirement. Air traffic in this area would be classed as moderate.

The photogrammetric range labeled Willow Run, Michigan, is actually located at the intersection of Napier and Warren Roads, a few miles north of Willow Run Airport. A marked photograph of this range is shown in Figure 9. The closest target spacing is 1/2 mile, and the extremeties of the range are 4 miles. Therefore, the lowest usable altitude is 1400 feet and the highest usable altitude is 18, 000 feet. The probable error in aircraft position will be on the order of 2 feet horizontally and less than 1 foot vertically for flights made at 10, 000 feet. The summer weather is classed as good; the winter weather, fair to poor. The only disadvantage of this range is the extremely heavy air traffic at certain times of the day, for the range is located very near the Salem VOR intersection, which is used by approximately one-third of all flights arriving and departing Willow Run and Detroit Metropolitan Airports. In spite of the periodic heavy traffic, the Willow Run photogrammetric range is a valuable asset for determining aircraft position and altitude.

The horizontal control for these last three ranges—which are located at Beulaville, Hallsboro, and Willow Run—was obtained by a transit and tape traverse. The vertical control was obtained from second-order leveling extended from existing bench marks except for that of Beulaville, which was based on an assumed elevation of 85 feet for the center of the target structure. The orientation of the Hallsboro and Beulaville grid systems was obtained by determining the angle to the meridian by an observation on Polaris. The Willow Run photogrammetric range is tied directly to the state coordinate system and all points are located on the state grid. The Beulaville and Hallsboro ranges are constructed on a floating, rectangular grid with coordinates of 25, 000 feet taken as the center of the range.

The cost of surveying and reducing the field notes for these ranges depend largely on the type of terrain involved. In the North Carolina area, where most of the survey can be conducted along relatively level highways, it is possible to put in target points for approximately \$50 each. In the western portion of the United States, where the distances are comparatively great, combined triangulation and level surveys will cost about \$100 a point. While these photogrammetric ranges are not costly, it obviously pays to use an existing range if possible.

FIGURE 9. WILLOW RUN PHOTOGRAMMETRIC RANGE

In conclusion, it should be stressed that these ranges are properly used only when exact answers are required. In spite of the fact that the analytical solution is considerably faster than the stereo solution, a great deal of very exacting work is required for each position report. Additional information on any of the ranges constructed by the Navigation and Guidance Task is available at the Institute of Science and Technology.

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PHOTOGRAMMETRIC TECHNIQUES FOR DETERMINING THE SPATIAL ORIENTATION OF AERIAL PLATFORMS by Wendell E. Young. Dec 60. 18 p. incl. table, illus., 4 refs.
(Rept. no. 2900-230-R)
(Contract DA-36-039 SC-78801) Unclassified report

The general problem of determining the spatial orientation of an aerial platform by photogrammetric means is discussed. Both the stereo and analytical solutions are included. The photogrammetric range, which provides a major portion of the input data, is treated in detail. Five such ranges have been constructed by the Navigation and Guidance Task of Project MICHIGAN. With these ranges and a calibrated metric camera, the X, Y, and Z coordinates of the camera station can be obtained with a probable error of 1 foot for flying altitudes of 10,000 feet.

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