FUTURAMIC PHOTOGRAMMETRY*

Frederick J. Doyle, Research Associate, Mapping and Charting Research Laboratory and Lecturer, Institute of Geodesy, Photogrammetry and Cartography, Ohio State University

After attending the Mad Hatter's tea party, Alice wandered down one of the paths in Wonderland. Looking up she saw the Cheshire Cat sitting in a tree and she asked him, "Which way do I go from here?" To which the cat replied with admirable logic, "That depends on where you want to get to."

1. Introduction

MAP makers, geodesists, and photogrammetrists have set up for themselves a pretty simple statement of "where they want to get to." But, "the most information for the least expenditure," is an oversimplification of the objective. The minimum expenditure of time, equipment, brain power, etc., is desired and these may be mutually exclusive. The ultimate criterion is always economic, and the real goal is to find the best ratios of brain power, time, and equipment, and even these ratios change fairly rapidly.

In looking for "the most information" it is necessary to qualify the goal and state what *kind* of information is required. In general there is qualitative and quantitative information, and both are of interest. But they tend to become more and more exclusive, and the paths leading to them diverge widely.

The qualitative road has led to the development of long and ultra long focal length cameras, to photo interpretation keys, and to simplified instruments and procedures. The major part of the information obtained is subjective, and such dimensional information as is obtained comes usually from single picture photogrammetry, or from instruments based on approximate solutions and yielding results of low accuracy.

The other, the quantitative road, has led to the development of the wide-angle cameras and the precise photogrammetric instruments made by Wild, Zeiss, Santoni and others. These instruments are essentially analogue computers with some sort of digital readouts connected to the photo orientation systems and the model coordinate system.

It is perhaps worthy of note that all of the maximum precision instruments, and techniques, have been developed in Europe, while America has taken the lead in the interpretative field as well as in the halfway stations exemplified by the Multiplex and the Kelsh. The reasons for this difference in approach are fairly well known, and need not be elaborated here. This article will briefly define the position on the quantitative road, and then investigate some of the possible future developments in this field.

2. The Problem

It may perhaps be accepted without too much argument that the most efficient use of the Wild A5 or of the Stereoplanigraph is in aerotriangulation. Ground control still represents one of the major costs of aerial mapping and the only way of reducing it is by using the photographs themselves to establish the ground points. Although it is common practice in Europe, most mapping agencies here would consider it uneconomical to use their big plotters for drawing planimetry and contours. Even instruments like the Wild A6 and A8, developed specifically for compilation, find it difficult to hold their own economically against the Multiplex and Kelsh, even though use of the latter instruments may entail some sacrifice in flying height. A detailed analysis of all the factors involved has yet to be made, but this probably represents a fairly correct evaluation of the results of experience.

It is now necessary to review the steps in carrying out an aerotriangulation. The initial stereo pair of photographs is placed in the instrument, a relative orientation is accomplished, then an absolute orientation; the relative orientation may or may not be altered depending upon the amount of ground control and how well the model

* Presented September 24, 1953, at the Semi-Annual meeting of the American Society of Photogrammetry, Rochester, New York.

fits it. Finally a set of digital coordinates for a number of points in the model are read. Then the first photograph is replaced by the third, a few switches are thrown and the whole process is repeated to form a second model. Some of the points in the second model must be common to the first. This procedure is repeated until all the photographs have been used. Depending upon the quality of the photography, the state of adjustment of the instrument, the skill of the operator, and a large factor of luck, the time required may be anywhere between 15 minutes and three hours per photograph. The result is a collection of coordinates of points, most of them read twice, once in model n and a second time in model $n+1$.

At this point the big plotter, the analogue computer, has *completed* all of its work. And yet the resulting collection of numbers is hardly more a map than a random selection of telephone numbers would be.

The next two stages are ordinarily done by digital computation. First, the photogrammetrist must connect the individual models together. True, there is probably some semblance of a correct relationship between the successive sets of model coordinates, depending upon the system employed in the operation of the plotting instrument. But already at this early stage some minor adjustments must take place. This results in putting all of the coordinates in one single system.

The second computational stage is to fit this one homogeneous coordinate system to the given ground control. This is usually done by holding to the control at the beginning of the strip and letting the other points fall where they may. The result is usually distressing indeed. Water frequently flows uphill and the closing errors may amount to several hundreds of feet in horizontal position and what is worse, several hundred feet in elevation.

Now begins the third step, which is to adjust out these closing errors. This may be done graphically or analytically, or by some combination of the two. The closing errors are the result of both systematic and accidental errors, and it is practically impossible to separate the two because in aerotriangulation the accidental errors accumulate in a way that makes them seem systematic. Consequently whatever adjustment procedure is adopted bears only a slight resemblance to the theoretically correct system,[1] which is impossible to apply practically. What usually happens is that all the accurate reconstruction performed by the plotting machine is destroyed by the adjustment process. But eventually, after one instrumental and three computational stages, the photogrammetrist finally arrives at a plausible set of ground coordinates for all the points he has measured on his single strip of photographs. However, if he has an adjacent strip or strips, he is still in a mess and a further adjustment is necessary. The whole business is at best discouraging and at the worst downright frustrating.

3. Current Studies

What steps are being taken to remedy this sad situation? First of all the instrument manufacturers are constantly improving their products. It is impossible to be over-enthusiastic about the skill and precision which these people have built into their newest instruments. The machines are a joy to behold and a pleasure to operate. For the new A-7 autographs, Wild now claims with justification a mean square error of eight microns in measuring parallax at the scale of the photography. Zeiss, Santoni, and Poivillier are in the same range. Although it is a dangerous statement, it seems probable that big analogue plotters have about reached the ultimate in their development. At any rate the capabilities of the instruments are beyond our ability to employ them. This is evidenced by the fact that aerotriangulation results obtained with the A-7 are not sensibly better than those obtained with the A-5.

So a second attack has been directed towards improving the method of operating with the instruments by reducing the changes for error. In the Netherlands and in Scandinavia, Schermerhorn and Hallert have devised systems for measuring the y-parallaxes in a number of points, and then computing the orientation elements by least squares. In France, Poivillier advocates setting up each model completely separate from the others, keeping as many as possible of the instrumental

[1] See R. Roelofs, "Adjustment of Aerial Triangulation by the Method of Least Squares," *Photogrammetria*, Vol. VIII, No. 4, 1951–52.

adjustments constant, and then making the connection between models by computation. Similar systems have been advocated by others. When these methods are applied, the closing errors are not always smaller, but their proponents argue that they have eliminated several, or many, of the sources of error, and that consequently simpler adjustment procedures are justified. But the question is still open.

A third attack on the problem is being made by theoretical photogrammetrists like Roelofs, Bachmann, and Brandenberger. They are attempting, by a rigorous application of the laws of propagation of errors, to determine what actually happens within a strip, and thus to obtain a clearer insight into what corrective measures should be taken. This approach seems eminently sound, and it is regrettable that most practical photogrammetrists will be unable to follow their arduous trail. Consequently several years may elapse before the results of this work appear in everyday practice.

Still a fourth attack has as its objective the development of adjustment techniques which come closer to the theoretical complete adjustment. But the closer they approach this goal, the more complex become the calculations involved.

It is highly significant that, apart from the mechanical and optical changes in the instruments themselves, *every attempt at improving the accuracy of aerial triangulation results in increasing the proportion of computational to instrumental work.*

4. The Apparent Solution

The question immediately arises, "Why not take the bull by the horns, and use a completely analytic system?" The only reasonable answer to this question is that this method should be tried.

Great preliminary investigations in this field were made by Professor Earl Church at Syracuse University. But he has been a prophet crying in the wilderness, and a fair test of his methods has never been undertaken by one of the mapping agencies.

After the original photographic coordinate measurements are obtained (and more will be said about this question later), an analytic solution is freed entirely from the mechanical problems of perpendicularity of axis systems, precision of gimbal intersections, inertia of masses, dynamic deformations, and straightness of ways; from the optical problems of lens distortions, and definition; from the myriad of physiological and psychological problems that affect the operator. Stereoscopic acuity, difference in illumination level. operator fatigue, anaglyphic, polarized, or optical train separation of images all cease to be problems.

Existing analytical systems for aerotriangulation (notably those of Professor Church and the one used by the Ordnance Survey in England) have had three primary drawbacks:

(1) They have been devised to use the minimum number of points required to give determination.

(2) They have not been able to take good advantage of redundant information which may be given in the form of additional elevations, isolated ground control, etc.

(3) The computations have not been designed or arranged in a form suitable for automatic or semi-automatic computation.

However, before condemning analytical solutions on these counts, it may be well to point out that exactly the same charges can be levied against the instrumental systems in more common use. The amount of computation involved in rectifying these shortcomings would be prohibitive on desk calculators. But electric and electronic computers are now available and the potentialities they offer ought to be exploited.

Two new proposed mapping systems which give great promise for the future are described in the following paragraphs.

5. A Special Purpose Computer System

The primary element of the first of these systems[2] is a special purpose electronic computing machine of radical design. It, like the existing analogue computers, is designed to operate on one stereoscopic model at a time. The photographic coordinates of a large number of points, perhaps 24 per overlap, are fed into this machine. For the points common to the preceding overlap, the machine computes automatically the y and h discrepancies,

[2] A preliminary analysis of this system is given in the article, "Essai d'Analyse Economique et Instrumentale de Cheminement Photographique Aerien" by R. Zurlinden, in *Photogrammetria*, Vol. VIII, No. 1, 1951.

and for the new points it computes the y discrepancies. These discrepancies for all points are projected simultaneously on a screen where they may be inspected by the operator. Using empirical relationships, or indeed even by following a cut and try procedure, the operator adjusts a series of knobs which control the variable elements of air base components and second photo rotations. The machine then recomputes and projects the new discrepancies. Three repetitions should suffice in the worst case to reduce all discrepancies to zero. A least squares solution is not contemplated, and indeed does not seem necessary, since the operator's visual control of the minimizing of discrepancies is practically equivalent to the same thing.

The computations performed by the electronic calculator are geometrically equivalent to space resection of the second photo station from the established points common to the preceding stereo pair, plus elimination of y-parallaxes at all of the new points in the model under consideration. Thus the maximum use is made of all possible elements of determination. Instrumental readouts supply the elements of photo orientation. The computed results are the XYZ coordinates of each air station and all the photo points—not (as in the case with the big plotters) in an individual model system, but in the same system as the given ground control data.

The construction of such a computing machine seems at first sight to be a formidable undertaking. However, this is not the case. Standardized electronic computing elements are available, and it is largely a question of assembling the proper selection of units. The processes of addition, subtraction, and multiplication are carried out extremely rapidly and cheaply by these units. Division and extraction of roots on the other hand require more expensive and slower units. The formulas, already devised, have taken these restrictions into account, and a preliminary analysis of the operations indicates that about one minute per adjustment cycle is all that will be required. Some problems with regard to the projection system remain to be solved, but no serious difficulty is anticipated.

With such a system the concepts of interior orientation, relative orientation, absolute orientation, scaling, and subsequent transformations of coordinates are all combined and reduced to the single procedure of minimizing discrepancies. The operator works in full daylight, utilizing his eyes in the most natural manner, and the accuracy of his work is not adversely affected by fatigue and eyestrain, which in normal systems may have seriously damaged a triangulation before the operator himself is aware of them. The special purpose computer is not encumbered by attachments and capabilities which are employed in only a small part of its working time. There is no problem of moving heavy masses carrying geometrical and optical components to various parts of the model; no problem of repeated identification each time a point is sighted. (Orientation by standard methods in existing instruments may easily require 100 sightings, hence 100 separate identifications in each stereo model.) The skill and training required of the operator is minimum.

Any system in which stereo models are added one by one will be subject to closing errors. However, inasmuch as all operations subsequent to obtaining the photographic coordinates are practically errorless, the closing errors may be expected to be very small. Consequently an extremely simple adjustment procedure may be justified. It has been proposed to affect this adjustment by re-triangulating the entire strip with systematic changes being applied to the measured coordinates, since these represent the largest remaining source of error. However, this part of the proposal is still under discussion.

6. A General Purpose Computer System

The second system[3] to be described is designed for use on a general purpose computing machine such as the IBM Card Program Calculator. It is the result of an entirely fresh approach to photogrammetry, in which thinking has not been conditioned by the conventional instrumental approach. As in the first system, the required data are the photographic coordinates of all points to be determined and of all known ground control points. In addition an approximate space position and orientation is required for each photo-

[3] The basic work on this system was done by Dr. Paul Herget, Director of the Cincinnait Observatory.

graph. In general this need be nothing more than a map scaled position of the principal point and the camera installation angle in the aircraft.

From this initial information, the first computational phase determines:

a. For given ground control points—the shortest space distance from the given point to the homologous rays defining that point on the photographs.

b. For new points to be determined—the shortest space distance between the two or more homologous rays to that point, taken two at a time.

In the second computational phase these space parallaxes are assigned to the various photographs:

a. For control points, the entire parallax is assigned to each of the rays.

b. For new points, one half of the parallax is assigned to each of the rays defining the point.

After this arbitrary assignment of parallaxes, the third computational phase is a least squares solution for the best position and orientation of each photograph in order to reduce the assigned parallaxes to a minimum. This computational system has the advantage that the solution for each photograph is entirely independent of the adjacent photographs. Each photograph will have a set of six normal equations and there will be the same number of sets as there are photographs. Consequently the entire flight strip may be solved simultaneously rather than having each photograph depend upon all of those which have preceded it.

The arbitrary assignment of parallaxes which was made may be considerably wide of the true division of responsibility for these parallaxes. Consequently the orientation obtained from the first solution will rarely be absolutely correct. The system is therefore iterative rather than explicit and three or four repetitions of the cycle may be necessary before all parallaxes are reduced to practically zero.

After this has been accomplished the last computational phase determines the final coordinates of all points—again in the same system as the ground control points rather than in individual model systems or a single strip system.

The amount of computation involved in such a solution is immense but the procedure just outlined breaks it down into systematic steps which are ideally suited for automatic computation. The complete solution of a strip might take a full day or more, but there is no fooling around with adjustments at any stage of the procedure. Personnel requirements are at an absolute minimum. A marked advantage of this system is that supplementary information such as spot elevations, Shoran determined air stations, etc. may be included as additional observation equations without upsetting the routine at all.

This method is in a fairly advanced stage of development and it is expected that the results of the first test strip will be available shortly.

7. Obtaining Coordinate Measurements

The raw material required for each of the systems described is the photographic coordinate measurements of all the points involved. This has always been, and still remains, a big problem for any analytical solution. Anyone who has attempted to measure photographs on one of the standard comparators knows that he is lucky to complete three or four photographs in a normal day. With the large number of points envisioned for each photograph in these systems, any time saved in the triangulation would be expended several times over in obtaining the coordinate measurements. It is therefore, not realistic to advocate analytical photogrammetry without giving serious attention to this problem.

While it is not theoretically necessary, it is practically essential that the measurements obtained be corrected for lens distortion, film shrinkage, and possibly even for atmospheric refraction (though this last has not been thoroughly investigated). Despite the many arguments in favor of glass plates, any extensive mapping program will be done with film. Consequently, the problems of lens distortion and film deformations remain to be considered.

The most practical solution of both these problems seems to be the use of a reseau, or calibrated grid, in the focal plane of the cameras. Though this may entail some slight loss of resolution, the gain in the elimination of uncertainties with regard to lens distortion and film deformation is immeasurable. It might be well to point out in passing that only an analytical solution is capable of taking advantage of this determination; for from a mechanical or optical point of view, only symmetrical distortion and over-all film shrinkage may be readily taken into account.

In the calibration of the aerial camera the plane coordinates of each of the reseau intersections are determined. The definitive coordinates of any point appearing within a grid square are then obtained by interpolation between the calibrated values of the adjacent intersections. This system is already in use by the Ordnance Survey of England and is to a large degree responsible for the success which they have had with their analytical work.

So let it be accepted as an accomplished fact that the aerial camera to be used for analytical photogrammetry will be equipped with a calibrated reseau. What then will be the characteristics of the comparator to be used?

First of all since the maximum field that it will have to cover will be only a little more than one interval of the reseau—say about two square centimeters—it can have a stationary optical system. This permits large magnification and high resolving power for precise determination of the point. An important feature of the optical system will be the ability to scan three adjacent photographs simultaneously. The two primary stereoscopic models thus formed will be presented side by side to the operator through one set of eye pieces. Also included within the field of view will be two secondary models formed by images permanently rotated through 90° by means of dove prisms. When the reticule is in contact with the terrain in the primary stereoscopic model the operator is assured that all x-parallax has been removed. No topographic relief can be seen in the secondary models, but y-parallaxes will appear as x-parallaxes. Consequently when the reticule appears to be in contact with the flat terrain in this model, the operator is assured that all y-parallax has also been removed. In this manner the most precise selection possible will be made of exactly the same point in each of the three photographs. When the operator is satisfied with the settings he has made, the points are identified by a permanent mark directly on the film or diapositive. The identification thus made is preserved for future use in compilation of planimetry and contours.

The photo carriers will have a full range of movement but only slightly more than the reseau interval needs to be controlled by the micrometer screws. This alone will represent a considerable saving over conventional comparators. Instead of (or in addition to) recording on scales or dials, the micrometer readings will be transmitted to a set of card punches. Prepunched data cards with the calibrated coordinates of the reseau intersections are placed in the comparator. The micrometer readings are increments to these calibrated coordinates and are punched directly on the data cards to be used in the computing machine. The sum of the prepunched calibrated coordinates plus the micrometer reading punches are the definitive coordinates of the point and this sum may be taken as the first step in the computing process.

With such a comparator designed as an integral part of the mapping system, the task of obtaining the required coordinate measurements is reduced to a reasonable fraction of the total job. It is the only part of the work requiring a significant amount of skill and judgement on the part of the operator.

8. Compilation of Planimetry and Contours

One of the objections to analytical photogrammetry has always been its inability to compile planimetry and contours. But before elaborating on this point it may be well to recall that the conclusion has been reached that it is not economical to use the big plotter for this purpose either.

Some progress has been made towards electronic contour finders and microdensitometers which give promise of some day automatizing these parts of the mapping program. But for the immediate future there does not seem to be any real possibility of doing away with human judgement and stereoscopic ability.

The details of a simplified stereoscopic plotter have not yet been worked out. But it should not be difficult to envision an instrument in which the photo orientations and base components supplied by the computing equipment can be set. The large number of points per stereoscopic overlap, located both horizontally and vertically by the computing instrument, serve as a network for controlling the planimetry and contours which are drawn essentially by interpolation between the known points. Such a plotter would probably be similar in complexity to the KEK or the Ryker PL-4. It would thus be in a class to be operated by relatively unskilled personnel requiring little technical knowledge of photogrammetry. A single computing equipment could probably keep a dozen such plotters supplied with data.

Incidentally, it may be of interest to know that this is the type of system adopted by the Russians for the production of their national topographic maps. They have devised a number of ingenious instruments, given the generic name of stereometers, whole sole purpose is to compute stereoscopically the elevations, and in some cases the horizontal positions, of discrete points within each overlap area. These data are fed to simple interpolating plotters for compilation. The accuracy of these instruments is apparently considerably lower than that contemplated here, but it is interesting to know that they have found this system of differentiated processes (abandoned in this country after the Brock and Weymouth equipment) to be the most efficient.

9. Earth Curvature and Map Projections

The modern tendency, particularly in military mapping, is to take photographs from increasingly high altitudes, and to run flight strips up to hundreds of miles in length. One of the results has been that earth curvature, which has always been a m:nor problem, has now become a major one. Neglect of curvature within a single model may often throw contour lines out beyond the limits permitted by national map accuracy standards. For better or for worse, this is a spherical, or more properly, an ellipsoidal earth, and all ground points are located with respect to this ellipsoid. The aerial photograph records ground points in their true relationship to each other. Consequently earth curvature is not truly a photogrammetric, but a map projection, problem Unfortunately, however, conventional photogrammetric computing and plotting instruments are constrained to use rectangular axis systems. Any attempt at altering this condition can be at best a makeshift and is bound to run into difficulty as soon as there is any variation from selected scales.

Analytical photogrammetry, on the other hand is ideally suited for coping with this situation. Any projection system, rectangular, spherical, or ellipsoidal which will fulfill the requirements can be selected as a basis on which to work. If the basic data are given in this system, the computed results will be in the same system. At the moment, a system of Universal Space Coordinates, such as that proposed by Professor Church, with perhaps a rotation and translation of the origin in order to reduce the size of the numbers, seems to be the best choice. In any event, the transfer from one system to another is about as easy a task as can be assigned to analytical procedures. No matter what the scale of the photograph, the number of points selected in each model can always be sufficient to make the terrain between them susceptible of being plotted by interpolation without having to worry about earth curvature.

10. Conclusion

It should not be concluded that analytical photogrammetry is the solution to all problems. There will undoubtedly always be need for the more conventional procedures. And there remain many interesting questions to be resolved before analytical photogrammetry can compete commercially. Not the least of these is arousing sufficient enthusiasm for giving it a fair trial. This is the primary goal of this article. Given an opportunity for development, it does not seem unreasonable to expect that before many years, precise analytical aerotriangulation may be capable of establishing first order control any place in the world. This is a challenge which photogrammetrists should be anxious to meet.