RECONNAISSANCE AIR MAPPING

OPERATIONAL METHODS OF MAPPING WITH SPARSE GROUND CONTROL*

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INTRODUCTION

USUALLY, in reading a paper on air survey, I am not too bothered. The audience, although technical, can be considered as laymen, that is with regard to the finer points of air survey.

Here, the situation is different since this audience is mainly composed of experts, and includes men whose attainments have made their names household words to us humble folk engaged in the humdrum activities of commercial air survey.

For this reason, I speak with some diffidence.

Some of the techniques described, or suggested, may be at variance with generally accepted practice. I wish therefore to make clear that opinions expressed are my own, as an engineer, and do not necessarily reflect the official opinion, or the policy of the group of air survey companies with which, at present, I am associated.

RECONNAISSANCE MAPPING

In order that the meaning shall be clear, air survey in the sense that the term is used in this paper, includes the following:

Aerial photography, the operation of exposing air film in an air camera from an aircraft—in the right position.
Film processing and printing.
Ground control, or the equivalent.
The compilation of (topographic) maps from these data.

In certain applications, notably forestry and geology, there are specialized interpretative, photogrammetric, and other techniques which are often—and quite properly—considered to be a part of the air survey.

This paper is about reconnaissance air mapping; by this is meant an air survey operation where the mapping is carried out with little or no special triangulation traverse, or levelling, on the ground. It is confined generally, but not entirely, to the field of engineering reconnaissance.

IMPORTANCE OF RECONNAISSANCE MAPPING

Ground control is costly, in inaccessible country very costly, both in time and money. In war time, it becomes virtually impossible to put survey parties out on the ground. It is important, therefore, to investigate substitutes for actual ground work, and to find out what result we may reasonably expect with low density ground information.

In what follows, there is no suggestion that the particular methods described are incapable of improvement, for they certainly are. We haven't all the answers, and there is room for a great deal of research. While the methods de-

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scribed are for the most part those in actual use—we think successful use—there are suggestions which, as yet, are suggestions only, and have not yet been subject to sufficiently complete test.

All the procedures are described for topographic mapping by means of the multiplex, but it is of course possible to apply them to other instruments.

FUNCTION OF CONTROL

CONTROL

Relative orientation having been effected, we have a model which is a replica of the terrain, an exact replica if we neglect photogrammetric error—except for dead ground. In the operation of relative orientation, the relative positions of the air stations to one another, and to the ground, are recovered to scale in the projector exit node positions.

While this model is at an exact scale, its scale is unknown. The air camera measures angles only, the multiplex model is the envelope of the intersections at infinity of triangulations. To determine scale we *must* measure a distance, directly or indirectly. Such a direct or indirect measurement of distance is horizontal control, and enables us to scale the model.

Having determined the scale of the model, there is no reason to suppose that its datum is horizontal, hence the *necessity* for vertical control or the equivalent. Three points determine a plane—thus the model may be levelled by tilting it bodily about two axes, so that our three points of "vertical" control have the required mutual elevation differences.

When the model is scaled, and its datum levelled, we have recovered absolute orientation. This one model is completely controlled.

It is repeated that we *must* have lineal measurements to recover absolute orientation; there is no such thing as mapping without control. Without ground control, yes; without control, no.

SCALE

TEMPLET CONTROL, MEDIUM SCALE MAPPING

So far, we have been considering only one model. In the multiplex, we can of course set up an indefinite number of models in relative orientation. Two precise scale points ($X-Y$ coordinates) will set the scale of a multiplex extension however long.

If the extension is short, the scale will be uniform between scale points.

If the extension is long, and/or there are several lines, there will be local scale errors, the scale will not be constant. It may be held more nearly constant by the expedient of laying a block of templets, cutting these to positions plotted in preliminary multiplex extension. Analysis of the Kelsh tests (1) on contact print templets led to the formula (2)

$$e = k\sqrt{t/c}$$

Where e is the mean position error in millimeters, t the number of templets in the area, and c the number of control points. The value of k for the conditions stated in (1) and (2) is about $\frac{1}{6}$

I know of no existing data to establish the value of k to be used with multiplex templets.

Since we are working at $2\frac{1}{2}\times$ contact scale, the first effect would be to magnify the error $2\frac{1}{2}$ times—other things being equal.

But other things are not equal by any means, first because the multiplex extension avoids nearly all the common sources of error, base lining, point transference, tilt, relief (3, p. 135). But this is not all, because the minor control points (pass points) although at the extremities of longer rays, are probably located at the $2\frac{1}{2}\times$ enlargement, with position error less than that of pricking contact prints.

For the sake of argument, let us assume that $k=\frac{1}{6}$ under these circumstances. One would probably accept the specification of 1 mm planimetric precision, actually attained, for 4 inch mapping of an unexplored area.

Consider an area of 1,000 square miles, to be mapped to this specification. We have, for the number of control points required,

$$\begin{aligned} c &= t/36e^2 \\ &= 125/36 = 3, \text{ say 4 points.} \end{aligned}$$

With Gamble azimuth templets, we probably could control a much larger area to the same precision, from this number of points. Reference is made to the azimuth templet recently developed by Colonel Sam Gamble of the Topographical Survey of Canada. This, in my opinion, is one of the greatest improvements in templet practice since their introduction.

For practical applications on this continent, in mapping an area of this size, it is thus evident that horizontal control need not provide too much of a problem. Almost invariably, that much sound control is available.

CONTROL, LARGE SCALE MAPPING

While control is ordinarily available for the mapping of comparatively large areas at such a scale, this is not the usual circumstance in mapping smaller areas, particularly at large scale.

Where control is by traverse on the ground, as in highway or railway work, ordinarily such traverse would run from one end of the job to the other. The templet system above, although it may be advisable for other reasons, does not materially reduce the ground work.

Conventional radar has no application here, that is radar to fix the aircraft position, the plumb point, in two dimensions. That procedure is applicable economically only to much larger areas.

But why need we measure dimensions in a horizontal plane? Consider the series of triangulations formed by the lines joining successive air stations, and rays from each air station to the ground principal points.

We can solve, or scale, this triangulation by vertical measurement, measurement of height of air station or air base above ground, equally as well as by measurement of any distance, or distances, in a horizontal plane. The narrow beam radar altimeter will do just this for us.

This instrument—the airborne profile recorder (the "A.P.R.")—is a development of the Photographic Survey Corporation of Toronto, following a National Research Council prototype. Its greatest application is perhaps in the field of small scale—as contrasted to engineering—reconnaissance where it provides *vertical* control. This very important development, which changes our whole conception of small scale topographic mapping, is outside the field of this paper.

To return to the *horizontal* control application, let H feet represent height of aircraft above ground, as measured by the radar altimeter, and h millimeters the height of the projector exit node above the model.

In an extension, we can then measure heights, h, and equate their total to the sum of the corresponding radar altimeter heights.

Let s equal model scale in feet to the inch, we then have

$$s = 25.4 \sum H / \sum h$$

thus determining model scale.

It is stressed that the above procedure has not been fully developed.

The question is what scale precision is to be expected, scale being determined by these means.

There are some bugs but not as many as one might think. Radar height will be inaccurate unless the base of the radar cone is on sensibly uniform ground. We can disregard measurements over unsuitable features.

The reflection is from tree tops, so we measure h to the tops of the trees.

Radar axis not coincident with optical axis—this is of little importance (versed sine error only) except over rough ground, and we will have deleted such measurements above.

Instrumental constants—both of radar and of multiplex—are determinate by an obvious calibration procedure.

Particularly must it be noted that if the residual of these errors can be reduced to an accidental error of ±20 feet (the radar people say this is practicable) we have quite good control.

Let us consider 1,320 ft/in model scale mapping, and investigate a 9 projector extension. 20 ft is 0.39 mm, the probable total error is then $0.39\sqrt{9} = 1.2$ mm, since the error is compensating. This is the error of $\sum h$, of $9 \times 360 = 3{,}240$ mm. Hence the error is 1/2,700. Such a specification is acceptable in most large-scale mapping operations.

It should be noted that the control precision across a single model is $200/2{,}700 = 0.08$ mm. That means that a single model within a strip has radar scale error of less than 0.1 mm. This is closer than it can be set up.

Note too, that since residual radar error is not a function of height of aircraft, the precision is higher the smaller the scale of the mapping.

If we double the predicted 20 ft error, we still have 1/1,300 precision (less than 0.2 mm per model), in large-scale mapping.

Because these errors, even though small, are carried forward, the system will not apply to very large areas. As will be apparent, without ground fixes, we cannot put such mapping on a geographic grid.

It is repeated that this control technique is still in the development stage.

SUMMARY, HORIZONTAL CONTROL

With regard to horizontal control, this conclusion seems logical. With existing geographic control to tie multiplex templets for small and medium scale work with conventional radar control for large areas, and with the possibility of using the narrow beam radar altimeter in large scale work—the day is not far distant when we may stop worrying too greatly about horizontal control for most kinds of mapping.

VERTICAL CONTROL FROM AIRCRAFT ALTIMETER

LEVELLING THE *X*-AXIS

Levelling along the centre line of the flight may be carried out by means of the aircraft altimeter. Altimeter readings, however corrected, are not reliable for absolute elevation. But they do respond to differences in height of successive air stations. Now, the profile of the successive vertical positions of the aircraft is reflected too by the profile of the positions of the perspective centres of an extension of multiplex projectors. Even at flight altitudes of 30,000 feet, the multiplex shows these differences much better than does the aircraft altimeter.

In about 1938 or 1939, E. L. M. Burns and W. K. MacDonald undertook rather extensive experimental work on multiplex bridging at the (then) Geographical Section of the General Staff, Ottawa. I do not think a paper was published, but I was privileged to be associated with Col. MacDonald during the early part of the war, and was thus familiar with his work.

Carrying these experiments further as a part of a War Office research project, there was developed a very simple graphical system of putting the multiplex extension in sympathy with aircraft altimeter *differences*, notwithstanding that these latter do not reflect accurately differences in elevation of successive air stations.

This is done by plotting a profile of differences between altimeter heights and observed projector heights, both in millimeters at model scale. A smooth curve of minimum deviation—this usually is a straight line in short extensions—establishes the most nearly horizontal plane, as indicated by all of the altimeter readings. The procedure is described in detail in (4). Along the base line, spot height precision of H/2,000 was obtained.

The system has error arising from two separate sources. The first is inaccuracy in putting the two profiles in exact sympathy. My personal opinion is that this source of error is very small. The theory of errors—applied to extensions of any great length—seems to bear this out. That is to say, it is suggested that we can make the X-axis practically as level as a millibar line.

The second source and main source of error is that a line of constant pressure is not in fact level. Under certain circumstances this error may be large, and of course lines of equal pressure do not remain at the same altitude throughout the day, or from day to day.

We now have progressed this far with the whole problem. An extension has been set up, and we have scaled it by any of the means suggested under horizontal control. We have levelled it (graphically) to a millibar line in the direction of flight.

The next step is to take out the tilt, to make the Y-axis level.

LEVELLING THE Y-AXIS

If two parallel flights have a side lap of 60%, the principal points of flight 1 become the pass points of flight 2. Thus, in levelling flight 1 along the X-axis, we establish pass point elevations for the second flight. Now, having levelled flight 2 along its X-axis, we can tilt to previously determined pass point elevations (the principal point elevations of flight 1) and so make the Y-axis level. In effect, this is setting up a pair at right angles to the direction of flight.

Theoretically at least, the flights are scaled and levelled.

THE TIME ERROR CORRECTION

In a block of any size, Y-levelling by 60% side lap as above is subject to error much larger than that of levelling along the direction of flight. With 60% side lap, we can physically set up extensions at right angles to the direction of flight. But when we do, altimeter differences are separated, not by the few seconds we had before, but by much longer time intervals. There may even be days between the first and last overlap of the extension. Accordingly, differences are no longer reliable.

We must therefore devise other means for blocks of any considerable size. It is a simple matter to fly one or more tie lines at right angles to the main flight lines. These are levelled in their own X-direction, just as before, and without difficulty we can now put the whole of the altimeter data, and the multiplex differences, in mutual sympathy.

The 60% lateral system may be criticised because, while it does strengthen the datum, it apparently requires twice the line miles of flight to cover a given area.

If the view is taken:

> That wide-angle mapping photography should be exposed from the maximum height consistent with contour interval—if we can get that high;
>
> That detail, or interpretation, photography should be narrow-angle and at a larger scale than that of the mapping photography above;
>
> That we need large-scale detail photography whether interpretation of detail be for military, for geological, for forest, or for just plain mapping, purposes;

Then this objection no longer holds, for the additional cost of the extra wide-angle lines is that of film and processing only. We use two cameras simultaneously.

BRIDGING

The above levelling procedures are scarcely bridging, in the ordinary sense. Major J. I. Thompson, R.E.C. discussed bridging and the $z=ax^n$ equation at the annual meeting two years ago (5), The basic system, and certain refinements not previously published, are described in (3), p. 134 et. seq. Thompson gives average intermediate error as H/1,000 (5) but, considering only base line heights, precision of H/2,000 and better is obtainable. Why this is the case has been explained under X-Levelling.

It is seen that the solution of a particular reconnaissance air survey problem may require flight design to use all these levelling means: bridging between vertical control, or from sea level to sea level, taking full advantage of lakes large and small, applying everything that can be inferred from the drainage pattern (because water flows down hill, it must flow down hill on the levelled model) and levelling to altimeter differences with or without cross flights.

SUMMARY, ALTIMETER DIFFERENCE LEVELLING

By means of aircraft altimeter differences, a flight may be levelled along its base line.

The multiplex extension reflects true differences in height of air station, as an aircraft flies along a nearly level line. These differences are subject to photogrammetric error only.

Notwithstanding lag, and other phenomena, the aircraft altimeter responds to these differences, but the response is not complete.

A simple graphical construction effects a "best mean fit" between these two sets of data.

If the two are put exactly in sympathy, the error in levelling along the axis is only the slope of the millibar line.

If we have 60% side lap, and some tie strips, tilt can be taken out with the same, or nearly the same, precision.

This kind of levelling is better on long strips at fairly high altitudes. It is not applicable to large-scale low altitude work.

In all cases we have standard photogrammetric error and, *in addition*, error due to millibar gradients.

A few spot heights on the ground will always strengthen the compilation.

APPLICATION OF RECONNAISSANCE MAPPING

GENERAL CONSIDERATIONS—RECONNAISSANCE MAPPING, OR CLOSE GROUND CONTROL

It has been implied that, at least before long, we need not worry too much about horizontal control. Let us then consider the requirements for datum accuracy in various mapping applications,—how nearly level the datum really must be, since this is the most important factor. The only difference between topographic air mapping to dense vertical ground control, and reconnaissance mapping, is that the datum of the latter is not a level, plane surface throughout the whole of the mapping area.

IRRIGATION

Water won't flow up hill. The datum must therefore be level. Dumpy level control on the ground.

FLOOD LINE

For design purposes, to estimate total flooded area, or for clearing, water level will often, but not always, give enough control. If the size of the lake is such that the required mapping photography will include both sides of the lake in one frame, the difficulty is in setting up the water models. Sometimes an additional line, say at twice the height, will give photogrammetric levels outside the flooded area, but strong enough, and in such a position, that they can be used to level the low altitude flight along the shore line.

For cadastral purposes, to determine the alineated area of small flooded parcels, air survey is of little value where, for land registration purposes, the flood contour must be set out on the ground.

It is interesting here to note that, in British Columbia, "natural" boundaries on a plan for land registration may now be shown by the air survey. So, if final settlement of compensation can be delayed until actual flooding, it is only necessary to photograph the flood line.

RAILWAY LOCATION

In railway work, maximum permissible grade is very critical, and small datum slopes might cause large differences in location on the ground. The requirement will vary with the nature of the terrain, and the interval of the mapping.

For initial preliminary work, reconnaissance mapping might be at 4 inches with 25 foot contours. Bear in mind that it is only a practicable preliminary location, or locations, that is the end product of such mapping. Though there will, or at any rate should be, a later stage of large scale close interval air mapping, the line must be examined, and eventually staked out on the ground. Topography is one factor in location; nature of the overburden, depth to bedrock, or firm foundation, possibility of rock or snow slides, and a host of other factors enter into any location.

A seven projector extension can readily be held level to a millimeter or two along the base line by the means described. At this scale, that is 50 to 100 feet in 12 miles—5 to 10 feet per mile.

Hence any location struck on a 25 foot VI map made in this manner will not have to be modified because of datum gradient.

HIGHWAY LOCATION, LOGGING ROAD LOCATION

These applications are less critical. The only difficulty, applicable chiefly to highway work, is that the requirement is a narrow strip of mapping. Here we must fly two strips, 60% lateral, to take out tilt.

TRANSMISSION LINE MAPPING

Particularly in bad, inaccessible country, the cost of a control survey may exceed the total cost of the remainder of the air survey. The time factor is another important consideration.

Again, the purpose of this map is one choice of a practicable preliminary location. As in most other work, the nature of the ground, the probability of rock or snow slides, flood and washout, accessibility, and a host of other factors must be taken into consideration on the ground itself. Air survey conserves the ground time of the location engineer, ensuring that he does not waste it in unnecessary exploration.

The transmission engineer will specify how closely, for his preliminary purposes, he would like to know *differences* in adjoining tower base elevations sited on the map, and how accurately intervening topographic features should be shown. He wants this information to work out span, tower heights, and clearance, for a part of the preliminary estimate of total construction cost.

The air survey engineer can now specify the flight altitude—on the assumption of tight ground control. He will then say, without putting out a control party "I can hold the datum flat to one or two feet per thousand along the flight line." Will this datum gradient upset any of the transmission engineer's calculations above? The answer is no.

This application requires of course, two parallel flights with 60% side lap. In the direction across these flights, datum slope will be much greater than in the direction of flight. However this tilt should not exceed about 20 feet over the distance between flights. This will seldom cause trouble, and in any case the location will run generally along, not across, the flight lines.

RECONNAISSANCE MAPPING PROJECTS

TRANSMISSION LINE MAPPING

Recently in Vancouver, we completed an interesting transmission job employing nearly all of these systems, both of horizontal and of vertical control.

Scale, 4 inches to 1 mile, VI 25 feet. Total length 62 miles, average width about 1 mile.

The first section was a water-level to water-level bridge 12 miles long. The first model was set to high water mark, and extended to the full 12 miles, 6 overlaps. Extension was held level to the altimeter. Closing error, 50 feet. Horizontal control was to geographic positions at either end, and presented no difficulty.

The second section was a dog's leg, 50 miles long. We used templets to fairly good geographic positions at either end. There seems to be no way of telling how well scale is actually held, at least not for some time. There is however no reason to suppose that scale control will not be satisfactory.

In the approximate centre of the 50 mile section, we had a single helicopter barometer height, with estimated reliability of ±100 feet—landing could not be made. From each end, an extension was pushed through, held to altimeter heights. We were 70 feet low at the spot height, and so left it at that.

The project was in unexplored, and previously unphotographed, country. It comprised some very rough sections, from sea level to 10,000 feet, although peaks of this height were not encountered in the area actually mapped. It is quite far north, 53°, and the season is short.

The cost of obtaining this information by means other than air survey would have been fantastic.

RAILWAY RECONNAISSANCE

There is a feature of some interest in a project upon which we are now working—railway reconnaissance mapping in Ontario.

The vertical control density is rather greater than in the kind of work we are discussing, and the extensions were without interest.

For horizontal control there are two geographic positions, one of which appears on one photograph only. There are two pairs of scale points, of known distance apart, but of unknown position.

On the preliminary extension, both geographicals were plotted. The "one ray" point was plotted by assuming an elevation for it. This assumption was fairly close.

Multiplex templets were cut, and laid, holding scale by the two pairs of scale points. The two geographic points were then set to be the required distance apart, some twenty-two miles, as computed for a polyconic grid.

It is again difficult to estimate how closely scale is held; the block assembly was quite solid and went down well. There has been no difficulty, at any rate as yet, in setting up the final models to control either horizontal or vertical.

CONCLUSION

In a Christmas message to the staff of The Photographic Survey Corporation, Kenneth MacKenzie, K. C., the President of the company had this to say of photography as it was at the beginning of this century.

"A photographer was a man who put iron ground control on his unfortunate victims, and shuffled plates beneath a black shroud."

Many engineers and surveyors still seem to be reluctant to take full advantage of the results of modern air survey techniques. Perhaps because of lack of familiarity, they may distrust our magnificent precision instruments, both airborne and earthbound. Until they themselves have used our work on the ground, run transit and level over it, they perhaps will be disinclined to believe that, from swiftly moving aircraft, we can measure with sufficient precision to draw contours, correct to one, or two, or ten, feet.

And it is amazing, all in all.

But it is our job to see that they do not, like the victim of Mr. MacKenzie's photographer of 1899, remain helplessly bound to the iron pins of ground control.

This is 1950.

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