## Analytical Aerial Triangulation Within the Virginia Department of Highways

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> The Virginia Department of Highways was the first state highway department to use analytical triangulation as a method of control extension as a totally in-house operation. This paper deals mainly with the mechanical operation and the gathering of data rather than the processing of these data in an electronic computer.

> The process described uses a Wild PUG-3 to transfer and mark points and a Mann monocomparator to read photo coordinates. The techniques employed in using the instruments and the results obtained are discussed. It is concluded that analytical aerial triangulation is a satisfactory method of control extension for highway photogrammetric surveys and that the new skills required can be mastered by the average highway photogrammetrist.

•THE Aerial Survey Section in Virginia began operating late in 1957 with three Kelsh stereoscopic plotters, which by now have been increased to a total of seven. Two of these are four-projector K-100 models that are used as two-projector plotters most of the time. The personnel of this section were all drawn from the drafting and survey branches of the Virginia Department of Highways. Four of these men received several weeks of training on the Kelsh plotter, initially at the Bureau of Public Roads photogrammetric center in Washington, and since that time all of our photogrammetric personnel have received in-house training.

In all of our early work, we attempted to control each stereoscopic model and used no control extension. In fact, this policy continued for about eight years, at which time we became interested in some method of control extension. We have never been convinced that the large, optical train, stereoscopic plotting instruments would be satisfactory for large-scale work. Further, these instruments are awkward for measuring cross sections, and we would be using a \$45,000 instrument to do the work that a \$7,000 Kelsh instrument would do quicker. Another reason we never became interested in a heavy plotter was that analytical aerial triangulation seemed to be just around the corner, and the initial investment for instrumentation would be considerably less than the \$100,000 required for a heavy instrument with bridging capability. We had watched the development of analytical aerial triangulation within the U.S. Coast and Geodetic Survey with more than passive interest and when an electronic computer program written for the IBM 1620 computer became available in 1965, we started a program to sell this method of control extension within our own organization.

The method of analytical aerial triangulation we are using was recommended by G. C. Tewinkel of the U.S. Coast and Geodetic Survey, and is based on their two-photo computer program, and use of the Wild PUG-3 point transfer device and the Mann monocomparator with Data Logger. In this system, points are marked and transferred from one plate to the next with the Wild PUG-3. The plane coordinates of these points

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are then measured to an accuracy of  $\pm 1$  micron with the comparator, and the readings punched into IBM cards. This information, along with the ground position of certain select control points, serves as the input to a rather lengthy series of computer programs. This series consists of a coordinate refinement program, a relative orientation program, a cantilever extension program, and a strip adjustment program.

These programs are written for an IBM 1620 computer with 40K storage and, as written, are a nightmare of card-handling, duplicating, sorting, and adding control punches. We have written additional program routines so that all of the programs will run from the beginning to the output of the strip adjustment program with very little attention from the computer operator. Also, several combinations of ground control may be selected for the initial pass through the computer. Normally two adjustments are made during the initial pass through the computer using as varied a combination of control as possible. This allows us to detect and eliminate any point that probably contains an error. A detailed discussion of these computer programs is given elsewhere (1, 2, 3, 6).

The programs for the IBM 1620 with 40K storage allow only a second-degree adjustment in the vertical adjustment program, and this does not always give a good fit to the vertical control. It appears that a better fit would be obtained if the strip could be twisted more.

We like the analytical approach to control extension because of the relatively low investment for equipment and the fact that the operators do not have to be as skilled as those required on a heavy instrument. The cost of the PUG and comparator was \$36,353. The smaller photogrammetric unit, which has an Auto-Trol scaler available that can be spared one day a week, can save at least \$10,000 on this price.

I would recommend the Auto-Trol scaler over the Data Logger that comes with the Mann comparator because the Auto-Trol is a much more flexible unit and can be used to digitize other devices. The Data Logger, although very reliable electronically, is more or less a one-shot deal—good only for digitizing the Mann comparator or a co-ordinatograph.

The Wild PUG-3 is used to transfer and mark points on the glass plates on which the aerial photography has been printed. The accurate transferring of points from one glass plate to the next is the most critical job in analytical aerial triangulation when a monocomparator is to be used to measure the plate coordinates. The operation of the PUG-3 requires a skilled photogrammetrist. We find that there are only a few men in our organization who have the stereoscopic vision and the other qualities required to obtain the best results from this instrument.

The selection of pass points is also very critical. These should be in flat areas where the parallax can be easily cleared. We have found that natural image points in areas where there is considerable change in elevation, such as in paved gutters or at corners of buildings, usually have large y-parallax residuals in the output of the orientation program. These conditions usually pertain to horizontal control points. Vertical control points are usually selected where it is not necessary to be on a definite point to obtain the correct elevation, and they do not cause this problem.

In marking a point with the Wild PUG, the parallax is cleared only in the local area. The point is then marked by drilling a hole in the photographic emulsion on the glass plate. These drills come in 40, 60, 100, 180, and 250 micron sizes. We started out using the 100-micron drills, because these are not as fragile as the smaller drills. It was found that the 100-micron drill hole was causing operator bias when transferring the point from one plate to the next for all but our more experienced operators. Also the residual y-parallaxes were much smaller in the first stereoscopic model, where there is no point transfer of previously drilled holes, than in successive models. We then used 60-micron drills in the hope that the smaller hole would improve this condition. There was no apparent improvement in the transfer bias, however, and we will probably make the 100-micron drilled hole standard practice, since this is the smallest hole that can be seen when the photographic images are projected in the Kelsh plotter. A point transfer device that would allow the simultaneous drilling of all three glass plates would be desirable, but we cannot be sure that it would be worth the cost, because the more experienced operators are not obviously biased by one plate having been drilled when transferring points.

As far as we know, there is no practical method to adjust the travel of the drills on the PUG. We are working to micron tolerances, so by necessity there must be a very close fit between the drill and its holder. The drill is so constructed that it telescopes into the holder as the holder is lowered. The drill is spring-loaded to control the pressure on the drill bit. A problem was encountered when the bit would stick in the holder as the drill holder was withdrawn, then release suddenly before the holder was high enough for the bit to clear the plate. This caused the bit to hit the plate a hammer-like blow, which would often destroy the point being drilled as well as occasionally break the bit. This was corrected by placing a shim under the arm that raises and lowers the holder to limit its travel. It is suggested that the movement on this arm be made adjustable during manufacture.

The PUG has caused considerable eyestrain for all of our people who have used it. The optics on the PUG are excellent, and apparently it is just the nature of the instrument to cause eyestrain.

The PUG comes equipped with either of two types of optics. One type is designed to measure glass plates that are made to be used in direct projection plotters with the emulsion side down and the other with the emulsion side up. We did not know this when we bought our instrument. All of our plates are used emulsion side down, and our PUG was made to measure plates that are to be used emulsion side up in what Wild calls the "American design" system. The so-called American design gives a mirror image, makes misidentification of points much more likely, and causes the operator to take greater precaution than would normally be required in identifying a point. We have had the optics changed that caused this reversal of the image.

The Mann comparator can be operated successfully with very little training. The chief problem for the operator of this instrument is keeping the points numbered correctly. The Mann 422F comparator, which we have, is equipped with a Bausch and Lomb zoom binocular microscope and is very confortable to use. Most operators report no eyestrain. The microscope on our instrument gives a mirror image, which is objectionable, but not as much as it would be if we were measuring images instead of drilled points and fiducial marks.

We normally measure a point at least three times with the comparator. The error in pointing is so small that one time would be sufficient were it not for the backlash in the screw-type comparator, which makes it necessary to approach a point with the lead screws turning in the positive, or clockwise, direction. There is always a possibility that the operator will turn the lead screws in the counterclockwise direction when making a pointing, and measuring three times allows an error of this type to be detected. It is our experience that very few of these errors occur—possibly one apparent erroneous measurement for every 20 models—and the error is then usually in measuring fiducial marks, which are difficult to center correctly.

We have had the fiducial marks on our Wild RC8 camera changed from the opencross type to the interrupted cross with a small dot in the center. At the same time, four more fiducial marks were added, one on each side, so that we now have a total of eight. After this change, there was a 10 to 15 percent reduction in the magnitude of the residual y-parallaxes in the relative orientation program. This was probably because the fiducial marks could be measured more accurately, and better correction for film deformation could be attained. The fiducial marks are still not as easy to measure as a drilled hole.

We are now measuring the glass plates with the emulsion side down, since our plates are printed to be placed in Kelsh plotters this way. The plates are measured in this manner because the drilled points on the plates are much easier to find when they appear in the same relative position on the plate as on a contact print. The images on the plate are difficult to see when the plate is placed on the comparator because the surfaces below the plate are black, unpolished cast iron. We have lined this black area with white paper, which reflects enough light to make the image on the plate visible. This area should be painted white and a light placed below the plate. The original X and Y drive motor switches required both hands for operation. We have replaced the two-hand control with a "joy stick" arrangement, which we consider to be much better. This feature leaves the operator with one hand free to change the Data Logger while moving the measuring system from one point to the next, and he is in a much better position to view his paper print of the photograph. The X and Y axes can be reversed on the comparator by changing the position of the X and Y plugs in the Data Logger, and the apparent direction can be changed by rotating or reversing the photographic plate. This makes it possible to measure the plate emulsion side up or emulsion side down and still have the X and Y axes in the desired position on the plate.

Our Mann comparator is equipped with what is known as a pivot stage. This stage allows as much as 15 degrees of rotation, and the cost is some \$1,200 less than the rotating stage. We have found this amount of rotation to be adequate in all cases. This rotation is used only while aligning fiducial marks of the open-cross type with the reticle in the comparator microscope. We would prefer to have a fixed stage when measuring plates that have our new fiducial marks. We have placed two bosses on the stage to aid in returning a plate to its original position on the comparator in case a point is missed or has to be checked. When the plate is placed on the stage, it is placed against these bosses, which hold the plate in a fixed position on the stage. We have had very good success with points that we have added after the initial measurement of the plate, or with points that were missed in the first measurement. This is more or less an emergency procedure with us, and it is up to the operator to deter-



Figure 1. Aerial triangulation point record (Job No. 052 Photo. No. 180).



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Dimensions given are apparent, as measured by comparison with a point on a plate on the stage of the comparator. Line weights are apparent 5 microns, except for the three circles which shall be apparent 20 microns. Diagonal lines to be centered on center cross. Placement of three circles and dot is not critical.

Figure 2. U.S. Coast and Geodetic Survey reticle.

mine whether to measure the plate over or whether to attempt to remeasure only the missing point. This usually depends on the availability of a card punch and the importance of the point.

Our comparator is connected to a card punch in the Computer Section by about 200 feet of cable. IBM's engineering section advised us that this probably would not work, but to try it anyway. We have an intercom system set up so that the comparator operator can listen to the keypunch operate and communicate with the Computer Section. The operator can tell when the card punch is operating correctly, because the sound on the intercom is the same for every reading. This system has worked so well thus far that, if it were not for running out of cards, the intercom would be unnecessary. There have been very few instances where a point has been missed or where a card was punched incorrectly, once the machine was programmed correctly.

Figure 1 is a form we are using to record the location of the control and pass points and their number. All points are numbered on this form in their approximate position before the comparator operator starts making measurements. The comparator operator draws a line from point to point as he measures it. We do not have a typewriter with our comparator.

We do obtain an IBM listing of the cards and check the listing against our comparator record form to make sure that all points are measured and are numbered correctly. This form is probably not necessary except when measuring more than one pass point in each of the strategic areas of the model or on experimental or research projects, where the ground control is dense and misidentification likely. We also check to make sure that all points meet a certain tolerance.

Our comparator is equipped with motor drive on both the X and Y axes. It takes approximately one minute for the comparator measurement marker to travel from one side of the plate to the other. The fiducial marks are numbered according to the copy of our comparator record form (Fig. 1), and must enter the computer in numerical order. We originally read the plates in this order, which theoretically requires a minimum travel time of  $9\frac{1}{2}$  minutes per plate. By adopting the path as shown on the form, which requires a minimum travel time of 4 minutes, we have actually saved



95-micron outer circle, 55-micron inner circle. Recommended reticle for reading 100-micron drilled holes and fiducial dots. The four open circular areas allow accurate centering of fiducial dots of between 55 and 95 microns diameter.

Figure 3. 95-µ circle.

from 5 to 10 minutes per plate. A plate can be measured in about 45 minutes, and an experienced operator can measure about 9 plates per day. Using this method, it is necessary to run the cards through a card-sorting program, which requires only a few minutes for the entire strip.

We are now measuring only six pass points per model, which speeds up the whole operation. This has naturally reduced the Y residuals in the orientation program from an average of 5 microns when using 12 points in the orientation to an average of about 2 microns. We expected some loss of accuracy, but so far there is no obvious deterioration.

We are using a U.S. Coast and Geodetic Survey reticle design in our com-

parator (Fig. 2). This is a good reticle, but we would probably make some changes in it if we were designing a new reticle based on our experience. At present we are using the center cross and the 95-micron circle. The 95-micron circle gives excellent repeatability when reading 100-micron drilled holes. There is an area of doubt, however, when measuring the fiducial marks that have a center dot varying from 65 to 90 microns in diameter, depending to some extent on the density of the photographic plate. This area of uncertainty could be largely eliminated with a reticle design similar to that shown in Figure 3.

The flash plate, which is made by exposing the fiducial marks of the camera directly on a glass plate, should be mentioned. It is the calibration plate containing the fiducial mark positions and is used in the coordinate refinement program to determine corrections for film deformation by adjusting the X and Y coordinates of all points on the successive photographic transparencies to agree with the camera fiducial marks as imaged on the positioning calibration plate. Determination of the correct coordinates for the fiducial marks is very important. The flash plate should be measured in at least two positions, and possibly four positions, 90 degrees different in orientation on the comparator in order to remove any error due to the fact that the axes are not exactly 90 degrees to each other.

We have been very well pleased with the results obtained from analytical aerial triangulation. We have found that the azimuth tie between models that are bridged is much better than when we controlled every model by use of ground-surveyed supplemental control. This is due to the larger scale base, which results in a better edge check between models. We have done several jobs that could not have been done conventionally. One was a 14-model strip through a wooded, swampy area where we needed to extend cross sections. We had previously measured cross sections through this area photogrammetrically and had to secure 60 percent of the cross sections by conventional ground methods. The new photography had been secured when there was less than  $\frac{1}{4}$  inch of snow on the ground, and it was obvious that we could see the ground, even where the ground cover was the densest. There were not enough natural images on this photography that could be identified on the ground to serve as horizontal control for the photography, and it would have been useless without bridging. We were able to identify enough natural images to control the bridge, and the results were excellent. We did not have to make any cross section extensions by ground survey methods, and the tie in to the cross sections measured previously was unusually good. We have also bridged control on location surveys where we were unable to enter property without a court order.

The determination of errors in production work is difficult. It is not easy to tell what the errors actually are—that is, what part of the error belongs to the ground survey and what part belongs to the photogrammetric work. This is especially true of horizontal control points, and even more so when images of natural objects are used for horizontal control points. With us, the horizontal control point that is a natural image is usually a corner of a barn, or a pole, and is very seldom checked. We can usually sort out the large blunders in this type of control, such as selecting the wrong corner of a building or measuring the azimuth angle to one corner and the distance to another.

There is no way of being sure that other factors causing relatively small errors are detected. We often do not determine the apparent horizontal error in our bridges for this reason and also because there are usually relatively few horizontal control points for sampling. However, we do determine that the errors are small enough so that the horizontal accuracy of the mapping will not be affected adversely.

We recently had a job eight models in length where the photography was taken at a scale of 1,000 feet to one inch and only four government stations were used to control the bridge. There were several other traverse stations on the survey route some that we had set for a previous mapping job and some government traverse stations of undetermined accuracy. Our previous traverse had passed within 1,500 feet of one of the triangulation stations without tying into it. The party chief probably decided that he could run to the next triangulation station quicker than he could tie into this one. This meant that on this bridge we had three separate systems of horizontal control—that is, controls that had not been tied together and adjusted within the local area. The largest horizontal closure error on this bridge was 1.5 feet. There was some evidence, however, that we had been lucky, because this point was near a triangulation station that had been used in the adjustment and this station missed in the opposite direction.

Vertical control is a somewhat different story. Such control usually contains fewer errors, although in the selection of vertical control points for bridging, there is a tendency to begin and close a line of levels on the same bench mark. Also, if just a little skill is used in the selection of vertical control points, a natural image is about as good as a targeted vertical control point. It is for this reason and the fact that good vertical results are more difficult to obtain than satisfactory horizontal results that we have watched and calculated our vertical results more closely. Our vertical results to date indicate that we can expect a root mean square error of from 0.10 to 0.20 per 1,000 feet of flight height when a 6-inch focal length lens is used. We may possibly be able to reduce this error by 10 to 20 percent with a better vertical adjustment program.

The present vertical adjustment program adjusts to a second-degree curve and applies a certain amount of twist to the strip. It seems that we could secure a better fit of the control if a separate curve could be developed for each side of the strip. These should probably be third-degree curves with certain constraints. These constraints should be flexible and under the control of the photogrammetrist.

The temperature control in the comparator room is not as critical as many have been led to believe. We had a specially controlled air conditioner installed, but we seldon use it because the central air conditioner is stable enough for production work. Our plates stay in the comparator only about 45 minutes and, because both the comparator and the plate are at room temperature to begin with, the small changes in temperature that occur will not affect routine work.

Bridging has the same advantages of all photogrammetric operations over field work. It brings operations in out of the weather to where conditions are much more predictable and where it is easier to keep experienced people working. Of course, it greatly reduces the man-hours required to control each stereoscopic model.

About 3 man-hours per model are required to drill and measure the photographic plates, to prepare the computer input forms, and to check the comparator measurement recordings when six points are used in the orientation. This increases to more than 4 hours when 12 points are used. More time is required if additional adjustments are needed, and of course the additional time depends on how much time is used in studying the results of the initial adjustment.

The organization using analytical aerial triangulation does not need a large staff of experienced photogrammetric programmers, but can adapt programs that have been derived by a larger organization. It should be able to train its existing personnel to handle all of the additional skills required. We feel that our experience proves that analytical aerial triangulation can be used by a relatively small photogrammetric unit whose personnel are primarily highway-oriented to greatly reduce the cost of ground control surveys. In most cases, that quality of the final photogrammetric product will be improved over what is attainable where every model is controlled conventionally by ground surveys.

## REFERENCES

- 1. Harris, W. D., Tewinkel, G. C., and Whitten, C. A. Analytic Aerotriangulation. U.S. Coast and Geodetic Survey Technical Bull. No. 21, July 1962.
- 2. Keller, M., and Tewinkel, G.C. Aerotriangulation Strip Adjustment. U.S. Coast and Geodetic Survey Technical Bull. No. 23, Aug. 1964.
- 3. Keller, M., and Tewinkel, G. C. Aerotriangulation: Image Coordinate Refinement. U.S. Coast and Geodetic Survey Technical Bull. No. 25, March 1965.
- 4. Horsfall, C. T. Electronic Computer Programs for Analytical Aerial Triangulation. U.S. Coast and Geodetic Survey, June 1965.
- 5. Horsfall, C. T. Aerotriangulation Strip Adjustment Using FORTRAN and the IBM
- 1620 Computer. U.S. Coast and Geodetic Survey, March 1965. 6. Umbach, Melvin J. Supplement to: Electronic Computer Programs for Analytical Aerial Triangulation and Aerotriangulation Strip Adjustment Using FORTRAN and the IBM 1620 Computer. U.S. Coast and Geodetic Survey, Feb. 1966.