Equipment, Methods and Standards of Accuracy Applicable to Aerial Surveys

ROBERT D. MILES, Research Engineer and Assistant Professor of Highway Engineering
Joint Highway Research Project, Purdue University

This paper is a discussion of the various methods of using aerial surveys and maps compiled by photogrammetric methods in highway engineering investigations. Scales of photographs, mosaics, and maps for different purposes are discussed, along with horizontal and vertical accuracy requirements.

The paper briefly reports on an investigative study that is being made for the State Highway Department of Indiana to develop directly from large-scale aerial photographs bridge site topographic maps at a scale of 30 ft per in. Equipment considerations are presented for a proposed photogrammetric system which will include an aerial camera, processing laboratory, and photogrammetric plotters.

● THE purpose of this paper is to give thought to, with a view to purshasing, accepting or adopting aerial surveys for different purposes. In these considerations it is necessary to discuss equipment, methods, and standards of accuracy as well as the purposes for which the aerial surveys are to be used.

Aerial surveys are used for many purposes, but for the highway engineering profession they may be grouped under three major headings: Reconnaissance of area to determine feasible route alternatives, reconnaissance of alternate routes to ascertain the best, and preliminary survey of the best route for design of the location and preparation of construction plans. Under each of these headings the product of the aerial survey, the aerial photograph, a perspective projection and/or the photogrammetric map, an orthographic projection compiled by photogrammetric methods, has many uses, such as, land use studies, soil studies, drainage studies, right-of-way studies, and geometric design studies, which would include earth-work computations. The techniques of how to make these various studies are beyond the scope of this paper, as innumerable articles are available in technical journals of the American Society of Photogrammetry, the American Congress on Surveying and Mapping, the American Society of Civil Engineers, and the Highway Research Board. Highway engineers should research these articles and determine the techniques that are applicable within their field of interest.

AERIAL SURVEYS

Aerial surveys are considered to be of three types: (1) individual photography, including vertical and oblique; (2) photographic mosaics, including uncontrolled or controlled; and (3) topographic maps with contours at 1-, 2-, and 5-ft intervals, and also planimetric maps and large-scale cross-sections for design and preparation of plans.

There are three methods available for making such aerial surveys. One method is by contracting with photogrammetric companies for the particular type of survey desired. This method requires the compilation of a set of specifications for the end product desired—aerial photography, photographic mosaics, and topographic maps or planimetric maps with profile and cross-sections, or any combination of the three. To assist the highway engineer in specification writing, the Committee on Photogrammetry for Highways sponsored by the American Society of Photogrammetry, and the American Congress on Surveying and Mapping, have prepared a Reference Guide Outline, which may be obtained at nominal cost from the Superintendent of Documents (1). This method has the advantage that it, in effect, increases the productivity of a highway department without increase in personnel.

A second method for obtaining aerial surveys is to contract for the photography and preparation of mosaics, and within the framework of a preliminary engineering section of the highway department to photogrammetrically prepare the maps desired. Production is controlled by the ability of the highway department to plan projects so that advantage can be taken of seasonal conditions to secure all the necessary photography for six to eight months of operation.

The third method is to have an aerial engineering section fully equipped with an airplane, camera, photographic processing facilities and photogrammetric instruments to perform the complete operation. This method has the advantage that the highway department has complete control over the procedures. Production is limited by the number and type of photogrammetric instruments and the availability of trained personnel.

Area Reconnaissance

Most of the state highway departments use aerial photographs in the various steps of area reconnaissance to determine route alternatives. A practical combination is to use Department of Agriculture photographs at an approximate scale of 1: 20,000 in conjunction with the 7½-min National Topographic Quadrange Series of maps enlarged to the scale of the photographs. The only equipment necessary for area reconnaissance using available aerial photographs is a simple lens stereoscope or, if preferred, a mirror stereoscope with binocular attachment. Uncontrolled photographic mosaics of a large area can be assembled by matching vertical photographs in a flight line for use in area reconnaissance, and the seeable portion of each individual photograph in this mosaic, when matched with and oriented to the auxiliary stereoscopic mate photograph, is easily observed by use of the lens or mirror stereoscope.

If the existing governmental photography of the area of survey is over 6 to 10 years old it would be advisable to obtain for the area reconnaissance survey new photography of the area of interest. This new photography should be obtained at a scale ranging between 1,500 to 2,500 ft per in. Since land use, drainage, urban areas, and general topography are the major controls and since these vertical photographs would not be used for topographic mapping in making the area reconnaissance survey, the photographs could be obtained with a 12-in. focal length camera if desired. Such long focal length photography is especially useful of rugged mountainous regions and large cities where the streets are narrow and buildings are tall.

To assist in area reconnaissance, especially in areas that are deficient in topographic map coverage of the 7½-min series, it would be practical to purchase two sets of stereoscopic photography coverage, one for the development of uncontrolled photographic mosaics using 7½- min quadrangle as the size, and the other for stereoscopic examination. The mosaics could be prepared at an approximate scale of 1: 20,000 by using available governmental photography and existing ground control. Mosaics would be assembled from the strips of photographs by using the effective coverage of each individual photograph fitted on flight-line to the adjacent photographs, and then scale adjusting each strip in line of flight. The mosaic would then be copied photographically and printed to a scale of 1: 24,000. It probably would not be possible to obtain scale-ratioed photographs from the governmental agencies for development of controlled mosaics, but even without the ratioed prints a good uncontrolled photographic mosaic for area reconnaissance survey purposes could be assembled if local relief is not too great.

Such mosaics would be invaluable in all phases of engineering in both area reconnaissance and reconnaissance of alternate routes. Watershed areas and land use could be determined with ease. Urban and rural land use would be shown in detail, and the mosaics would be an invaluable aid in determining feasible highway routes in a minimum of time, while the other set of photographs is thoroughly examined stereoscopically.

These photographic mosaics could be prepared very economically, because fairly recent photographic coverage is available of most areas. Experienced assistants, after proper training, could be used by the highway department to prepare these mosaics, or photogrammetric engineering firms might be interested in preparing the mosaics on a state-wide basis. The cost of this mosaic preparation could be recovered by sales to other interested parties.

The uncontrolled photographic mosaics would not be maps, as all photographic images not on a level plane are displaced perspectively from an orthographic position; this displacement is especially large in areas of high local relief. The mosaics should be annotated to show plane coordinate grid lines, and the grid should be plotted to an accuracy of 1/50 in. or better at the scale of the mosaic. Position of photograph images should be accurate to at least 1/5 in. of true coordinate position. Accuracies of this type enable the highway engineer to select the controlling points of various alternate routes for a highway in moderate relief to within practical working limits on a reconnaissance survey basis.

Preliminary Survey of Best Route

Medium-scale aerial photographs of the highway route, the uncontrolled photographic mosaics, and topographic strip maps are required for the preliminary survey and design of the location. The general practice in rural areas is to have route photographs taken at a scale of about 1,000 ft per in. with a 6-in. focal length camera or 800 ft per in. with an 8¼-in. focal length camera. In commercial practice the 6-in. focal length is generally used. Vertical photographs at these scales are used in the photogrammetric plotter to map at a manuscript scale of 200 ft per in. annotated with contours at a 5-ft interval. In highly developed areas, the accepted practice is to obtain photographs at a scale of 500 ft per in. or 400 ft per in. with 6-in. or 8¼-in. focal length cameras, respectively. The topographic map then may contain a strip of terrain up to ½ mi wide at a scale of 100 ft per in. annotated with contours at a 2-ft interval.

It should be understood that the various photogrammetric plotters in this country are usable for mapping at manuscript scales ranging from three to ten times the scale of the photography—the scale enlargement. The scale enlargement combined with the contour interval desired determine, to a large extent, the taking scale of the preliminary survey route photography. Negative scales smaller than 1,000 ft per in. do not provide the detail that is needed by the engineer in making the preliminary survey, especially in urban areas, even though these smaller scales may be used on some photogrammetric plotters to prepare an accurate topographic map with contours at a 5-ft interval. If only the topographic map is to be used in the preliminary survey and design of the location, then the scale of the photography is controlled by the photogrammetric compilation system. In highway engineering, both the maps and photographs are needed in making the preliminary survey; therefore, the taking scale of the photographic negative is an important item. Often it is desirable to take the photography at scales of 600 or 800 ft per in., compile the maps at a scale smaller than 200 ft per in., and then by scale enlargement techniques reproduce the map for use at the 200 ft to 1 in. scale.

In preliminary survey and design it is advisable to secure low oblique photographs in conjunction with vertical photography. Low oblique photographs should be secured at a ratio of 5:1 or 10:1 with respect to each vertical along the line of flight. The low obliques taken from the nose of the aircraft should be secured with a 12-in. focal length aerial camera. They will present a perspective view that will assist greatly in analysis of the preliminary survey location, and in presentation of data, especially in highly developed areas or at proposed interchanges.

Aerial vertical photographs for stereoscopic examination and for compilation of strip topographic maps at a scale of 200 ft per in. or 100 ft per in. in the preliminary survey stage should be secured with a precision cartographic camera of the proper focal length. The distortion characteristics of the camera lens should be known, and, if necessary, compensating distortions should be designed into the photogrammetric plotter to reduce all distortions to an absolute minimum. These items would not be important to the highway department that contracts for all photogrammetric work, but to the highway department that buys photography these items can make or defeat the over-all photogrammetric system. The specifications for photography in this case should include maximum and minimum values of distortion or a description of the distortion correction system, and require a Bureau of Standards or other testing agency report to compare the systems. If the camera used for photography has different distortion characteristics than can be compensated by the photogrammetric plotter, a delay will ensue while corrections are made to the plotter.

The accuracies of aerial photographs, photographic mosaics, and topographic maps compiled by photogrammetric methods with an appropriate contour interval for the preliminary survey are sufficient for the highway design, and the maps are as accurate as maps compiled by any other methods, and are all within practical working limits. The general accuracy requirement for contours is that 90 percent of the elevations determined from the solid line contours shall not vary from true elevation by more than one-half contour interval. The remaining 10 percent should not vary more than a full contour. In heavily wooded areas the contours should be dashed, and their accuracy should be such that 90 percent of the elevations determined from the dashed-line contours would be correct to one contour interval or one-fourth the average height of the ground cover, whichever is the greater (1). In dense wooded areas it would generally be necessary to survey by field methods especially in coniferous regions. The State plane coordinate grid, adjusted to result in true distances at the average elevation of the survey project by scale without need for any correction, should be an essential part of the map and should be accurately plotted to within 0.01 in. of true grid value. Selected horizontal control points measured in the field also should be accurately plotted to within 0.01 in. of true position. Planimetric details should be within 0.02 in. of true position when measured to the nearest grid, and spot elevations on the map should be accurate to one-fourth the contour interval.

Ground control is an essential part of any survey made photogrammetrically. Horizontal and vertical control monuments should be placed at intervals along the route survey so that they may be recovered by field crews. The interval for horizontal control should be about 1,000 ft for preliminary surveys, and points should be referenced to the state plane coordinate system adjusted to apply at the average elevation of the survey project. These points should be advantageously located so that the designed center line (L-line for the highway) can be located on the ground to within a few feet of true position. The lateral tolerance used on the Ohio Turnpike was 10 ft (4). With good ground control a mathematical solution of the location can be developed for preliminary staking in the field, with final adjustment made by the field location engineer.

The Designed Location

The application of photogrammetry and aerial surveys to design of the highway location is the ultimate development for which highway engineers are searching. This requires the accurate measurement of all possible details for preparation of construction plans, including estimation of earthwork quantities, final measurement of earthwork quantities (if necessary), and procurement of right-of-way. In some cases, certain phases of this ultimate utilization of aerial surveys have been reached, as reported in California, Ohio and Pennsylvania (4, 5, 8, and 12).

One method of developing the preliminary design of the highway location is to survey in the field the center line as determined by the preliminary survey at 200 ft to 1 in. scale, as discussed previously. Center line profiles are obtained after necessary adjustments are made to fix the positions of tangent intersections. If ground detail is insufficient, control points along this line are then signalized by the use of cloth, lime, paint or other contrasting material that will photograph from the air. A flight line to produce route photography at a scale of 250 or 200 ft per in. for 6-in. or $8\frac{1}{4}$-in. photography, respectively, is made. Glass diapositives made from this photography are used to plot planimetric maps along the preliminary center line at a scale of 50 ft per in. These same diapositives are then used to develop spot elevation information for use in plotting cross-sections. Under ideal conditions when vegetation is low or nonexistant, it is reported that photogrammetric spot elevations are accurate to ± 0.2 ft (3). Under average conditions the vertical accuracy is ± 0.5 ft, even though the photogrammetric readings are interpolated and recorded to 0.1 ft of elevation using a foot-reading plotting table. Horizontal accuracies are of the order of 1 to 2 ft measured at a map compilation scale of 50 ft to 1 in.

The L-line location is then resolved by making a paper location using the planimetric map, contact prints of the photographs, and cross-sectional information. This location is made to fit the natural ground and cultural conditions, and other geometric considerations. The large scale of these items enables the engineer to select the controls for this L-line, construction plan location of the highway. Frequently the scale of this paper projected location is then reduced, using a process camera, to a scale of 100 ft to 1 in. and traced to produce road plans.

In some cases the preliminary location is not surveyed in the field, but is used only as a flight plan to secure large-scale photographs for preparation of topographic maps at a scale of 50 ft per in. with contours at 1- or 2-ft intervals. In this case, the engineer uses these large-scale topographic maps to refine further the location before it is actually staked on the ground. This method does not necessarily require the measurement of spot elevations for cross-sections. Various location alternatives are projected on the maps and are studied by measuring cross-sections from the contours or by drawing the proposed grading contours of cuts and fills and measuring volumes of the horizontal slices, pyramids, and wedges produced. Approximately the same accuracies are achieved by this method as before, and both methods should produce earthwork estimates within 2 to 5 percent of the estimates determined by normal field procedures.

Another application of aerial surveys and photogrammetry to highway design is in the field of site plan preparation. Stream crossings, grade separations, interchanges and other items requiring site plans at scales of 20 to 50 ft per in. fall in this category. These site plans are prepared with contour intervals of 1 or 2 ft. The minimum ground control necessary for surveys of this type is four vertical control points and two horizontal control lines for scale for each stereoscopic pair of aerial photographs. A rapid method of determining the horizontal control is by the use of a 2-meter subtense bar and a second-reading theodolite.

Some agencies prepare these site plans at scales of 40 or 50 ft per in. in photogrammetric plotters and then enlarge these photographically to scales of 20 ft per in. In this manner map compilation and drafting inaccuracies are increased by the amount of the enlargement.

The Indiana State Highway Department generally prepares site plans at a scale of 30 ft per in. The Joint Highway Research Project at Purdue University is investigating the possibility of preparing these maps from aerial photographs secured at a scale of approximately 150 ft per in. with a 6-in. Metrogon precision mapping camera. For this project the photography and diapositive plates were secured by contract.

The glass diapositives 0.06 in. thick are printed emulsion to emulsion for projection with the emulsion side up, and are projected in a Kelsh stereoscopic plotter at a 5-diameter enlargement for map compilation at a map manuscript scale of 30 ft per in. Most of the models developed in the Kelsh stereoscopic plotter at these scales appear to be of excellent quality, and the image motion that was expected has not necessarily occurred. Photography of this type requires a very slow flying speed (80 to 100 mph), fast shutter speed, and rapid rewind cycle. Image motion greater than 0.01 in. can normally be detected, and in all probability would prohibit accurate measurements. Some difficulty has been encountered due to the inability of the vacuum system to take hold in the extremely short time between exposures. The negative is therefore not flat during the exposure cycle. This can be corrected by shortening the rewind cycle of the camera. This project is in its infancy, but at a later date it is expected that an analysis will be made of several site plans to determine vertical and horizontal accuracies.

EQUIPMENT

In consideration of equipment, it is advantageous to present the experience of the State Highway Department of Indiana as an example. The author has worked extensively with the Department in determining needs and type of equipment for the proposed development of the complete photogrammetric system. The Department has available an airplane of the twin engine type that is suitable for conversion into a photographic plane. Equipment considerations, therefore, revolved around the aerial cartographic camera, the photographic processing laboratory, and the photogrammetric plotters.

Aerial Camera

The first consideration is the focal length of the camera lens desired. The lens should be of a type that has high resolving power under the operating conditions planned and either be distortion-free or have a narrow range of distortion that can be compensated for or removed in the photogrammetric mapping system. Focal lengths may vary from 4 in. to 12 in. or more. In general, large angular field, as obtained in the shorter focal length systems, is desired because of less flying, fewer photographs, less ground control, and a higher mapping accuracy due to the larger angle between intersecting rays which indicate parallax. The 6-in. camera, as mentioned previously, is the one generally used by the photogrammetric mapping companies. Photography taken with the 8¼-in. or longer focal length lens is better for preparation of mosaics and for photographic interpretation; it is also advantageous for mapping heavily timbered areas.

The next consideration is the cycling time. Most of the work of the Department is going to be very large scale photography which requires cycling times of 2 to 3 sec at aircraft speeds of 80 to 150 mph. Most cameras recycle in 3 or 6 sec.

The cameras considered were the government surplus cameras designated K3B, K17B, K17C, and T5, and the new Fairchild T11 (11). The first three are charting cameras that must be converted to precision mapping cameras. The last two are precision topographic cameras. The information available on these cameras indicated that only the K17C 6-in. camera was equipped to re-cycle in less than 2 sec (11). This camera has a re-cycle time of 1¼ sec which would enable higher aircraft speeds for more stable flight. It was decided that the K17C converted to a 6-in. Metrogon precision mapping camera and tested for distortion characteristics by the Bureau of Standards would fulfill the expected needs of the Highway Department. Auxiliary equipment for the camera included the camera mount, extra magazines, intervalometer, dynamotor for converting to 24-v electrical system, electrical cables, and equipment for producing a vacuum for film flatness control.

Processing Laboratory

The processing laboratory is considered as a three phase system with separate darkroom facilities for film processing, print processing, and enlarging. The important pieces of equipment are film developers, film dryers, water jacketed film processing units, large stainless steel sinks and water temperature control devices for the film processing room. The print processing room requires such items as large stainless steel sinks and trays, electronic printers to control density of diapositive plates, 10-in.-by-10-in. contact printers, 4 by 5 enlarger, 40- to 60-in. diameter print washers, and large matte and gloss print dryers. The enlarging room requires large stainless steel tanks and trays, rectifying enlarger for aerial roll film 9½ in. wide, and a 24- or 36-in. process camera for copying mosaics and enlarging or reducing maps compiled by photogrammetric methods. Miscellaneous supplies for the laboratory would include diapositive plate hangers, various sizes of graduates, and 10- to 50-gal. storage tanks and mixing crocks. It is estimated that the equipment would require about 1,000 sq ft of floor area, and cost about $18,000 with some items being rebuilt units or surplus.

Actual selection of the various manufactured models of the items mentioned is naturally an economic study. Compromises are made to fit immediate needs, availability of space, and available electric current supply. This last item can be a considerable cost item in an already overloaded electric system.

Photogrammetric Plotters

There are numerous photogrammetric plotters, and each has particular advantages or applications for surveying purposes. Private photogrammetric mapping organizations or the federal mapping organizations may have a series of plotters with certain types of mapping planimetry, others topography and still others bridging control to name just a few of the applications. A few of the photogrammetric plotting instruments are listed in Table 1 along with some of the reported "C-factors" for contours and for spot elevations.

The "C-factor" is the ratio of contour interval on the topographic map to the flight

TABLE 1

PARTIAL LISTING OF PHOTOGRAMMETRIC PLOTTERS

Name	Contour C Factor	Spot C Factor
Multiplex	600-800	3,000
Balplex, ER55		
Kelsh 6 in. or 8¼ in.	850-1,000	4,250
Wild Autograph A5	1,000-1,200	5,000
Wild Autograph A6	900-1,100	4,500
Wild Autograph A7	1,000-1,200	
Wild Autograph A8	1,000-1,200	
Santoni Stereosimplex Model III	1,500-2,000 (7)	
Stereoplanigraph C7	1,200-1,250	6,000

Source of information: Manual of Photogrammetry (11) and various volumes of Photogrammetric Engineering (2, 7, 9).

height. The various plotters are assigned these relative factors based on the experience of the operator, ground control available, and field tests of prepared maps. The above factors are actually based on medium and small scale mapping projects with contour intervals of 10 and 20 ft. There is some question as to their direct application in large scale mapping as required by highway engineers. It is reported that they can be increased about 30 percent for ideal conditions and decreased at least 30 percent under unfavorable conditions where there is little photographic contrast in the ground or where the area is highly forested (9).

In the analysis of photogrammetric plotters, the volume and type of work conducted by a highway department would not justify the expenditure of large sums of money for individual first order universal type plotters. It appears more practical, with limited technicians and small equipment budgets, to have a small group of plotters all performing about the same operations. There are strong arguments against this statement. Of course, the best argument is that ground control for a photogrammetric survey is the expensive item, and to eliminate extensive ground control a first or second order instrument is needed to bridge control and to establish supplemental picture point control for topographic and planimetric mapping.

The ideal conditions are generally realized by the established photogrammetric engineering concerns. Under these conditions the photogrammetric system consists of a first order instrument to bridge and develop the base map with coordinate grid and topography and several second-order or "single model" instruments are used to plot planimetry and sometimes additional topographic details. This system is ideally suited for area mapping of a city, a reservoir or other regional mapping project, and for preliminary survey of a highway route in excess of perhaps 10 mi. It is recommended, for the types of surveys mentioned, that advantage be taken of these elaborate systems (as suggested by Section 121, Mapping, of Public Law 627—Title 1: Federal Aid Highway Act of 1956) to increase the productivity of the highway department.

The highway department can further increase its productivity by having a small but adequately equipped photogrammetric section to make preliminary surveys for design of the location and preparation of construction plans, measurement of profile and cross-sections, and survey of sites for preparation of plans for short highway sections. Using this premise it is appropriate to consider only two photogrammetric plotters of similar capabilities and of comparable price. These two plotters are the Kelsh stereoscopic plotter with either 6-in. Metrogon (wide-angle) lens or 8¼-in. normal-angle lens projectors and the Balplex plotter with ER 55 projectors using 6-in. Planigon or Metrogon photography. Each of these plotters are termed "single model" instruments as they do not lend themselves to extensive bridging applications directly by stereoscopic methods. The Kelsh stereoscopic plotter enlarges original negative scale 4 or 5 diameters, depending on focal length, and the Balplex plotter 3.4 diameters. The

Kelsh is equipped to handle 9½ by 9½-in. diapositives contact printed; the Balplex is equipped to handle 4- by 4-in. diapositives that are prepared in a special reduction printer. One reduction printer may serve several Balplex just as the special electronic printer mentioned previously will serve several Kelsh plotters. Of course, the special electronic printer is not absolutely necessary as a much more economical contact printer will suffice, although prints and diapositives will not be as uniform in quality unless made by a highly skilled darkroom technician.

In analysis of the needs in Indiana for use in conjunction with the K17C 6-in. Metrogon precision mapping camera it was decided that the 6-in. Kelsh stereoscopic plotter with a 5-diameter enlarging factor fulfilled the requirement. Three Kelsh plotters appear to serve the immediate needs. One plotter will serve the Road Location Department, another the Bridge Location Department and the third will be used by the Joint Highway Research Project to handle overflow and to investigate additional applications and limitations.

It is expected that the research applications will be developed by graduate civil engineering students, and the instrument will also be used to assist in training plotter operators for the central office. The plotter located at Purdue will also be used on the undergraduate level in transportation and surveying courses to keep the future highway engineers cognizant of modern mapping methods, applications, and limitations.

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