HIGHWAY RESEARCH RECORD

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Photogrammetry and Aerial Surveys

7 Reports

Subject Classification

21	Photogrammetry
55	Traffic Measurements
84	Urban Transportation Systems

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Foreword

The application and utilization of photography and photogrammetry in various phases of highway engineering, which have made notable progress in recent years, will be further advanced by the seven papers comprising this RECORD. In addition to information of interest to the photogrammetrist, applications of photogrammetry to traffic flow studies and to highway planning are covered.

Treiterer and Taylor describe the development of a method designed to measure traffic movement in a manner which is appropriate for the testing and validation of most of the present theories of traffic flow. The primary objective was to develop a method for determining vehicle spacings and speeds for a platoon of vehicles at a relatively short time interval.

Jeter outlines the development of annotated aerial photographic mosaics which have gained acceptance for highway planning in congested suburban areas in Oregon.

Three papers deal with systems for obtaining ground surface information by photogrammetric methods and recording and storing it by electronic data processing methods. Colner describes a unified information system and MacLeod an integrated system of quantitative surface information. Wilbur tells of methods and procedures currently being utilized by the Pennsylvania Department of Highways in the collection of map data for engineering computer programs as required by the highway planning staff.

Konecny introduces a numerical method for the orientation of a model in a Kelsh Plotter which is much faster than the trial and error procedures presently used. Since a significant portion of work time is devoted to orientation, this method can result in a material increase in production.

Infrared photography and thermal imagery are relatively new to highway engineering. Becker and Lancaster describe these potentially useful tools, compare them with conventional photography and suggest applications to problems of the highway engineer.

Contents

Traffic Flow Investigations by Photogrammetric Techniques

JOSEPH TREITERER and JAMES I. TAYLOR, Transportation Engineering Center, Ohio State University

This paper pertains to the development of a method designed to measure traffic movement in a manner which is appropriate for the testing and validation of most of the present theories of traffic flow. The primary objective was to develop a method for determining vehicle spacings and speeds for a platoon of vehicles at relatively short intervals of time.

The basic procedure consisted of placing a vehicle in the traffic stream and following it by a helicopter from which photographs were taken at fixed intervals of time.

The equipment and data reduction techniques are described and samples of resultant data are shown.

•THE PHENOMENA of traffic flow have been investigated from different angles and numerous models have been developed to predict the movement of vehicles on roads and streets. Two basically different areas have been covered in these studies. These areas are the microscopic investigations, made to determine the interaction between lead and trailing cars (car-following model), and the macroscopic models, which describe the principles governing the simultaneous movement of a great number of vehicles. Both fields have not been combined yet and, although the reactions of a trailing vehicle to changes in velocity of the lead car can be described fairly well by different theories, knowledge on the propagation of disturbances in a platoon of vehicles, the amplification or attenuation of such disturbances and their influence on velocity and traffic capacity is rather limited. It was felt that this is partly caused by the present methods used to measure the behavior of traffic and by the lack of a theory of traffic flow describing these phenomena explicitly. This paper is concerned with the development of a method designed to measure traffic movement in a way which is appropriate for the testing and validation of most of the present theories of traffic flow.

MEASUREMENTS OF TRAFFIC

The primary objective of developing a new method for data acquisition by aerial photography was to obtain data on the movement of vehicles as they progress along the roadway.

Figure 1 shows the trajectories of a platoon of vehicles progressing along a section of I71. Line A represents the data which can be obtained by gathering information from a fixed location at the roadway. These data comprise types of vehicles, number of vehicles per time interval, time gaps between vehicles and—by making use of suitable equipment—the velocity of vehicles when passing section A. No direct information can be obtained on traffic density. Calculating an average density of traffic from the relationship $k = q/v$, however, was found to give rather unreliable results. Line B represents the data which can be obtained from an aerial photograph which displays informa-

Paper sponsored by Committee on Photogrammetry and Aerial Surveys and presented at the 45th Annual Meeting.

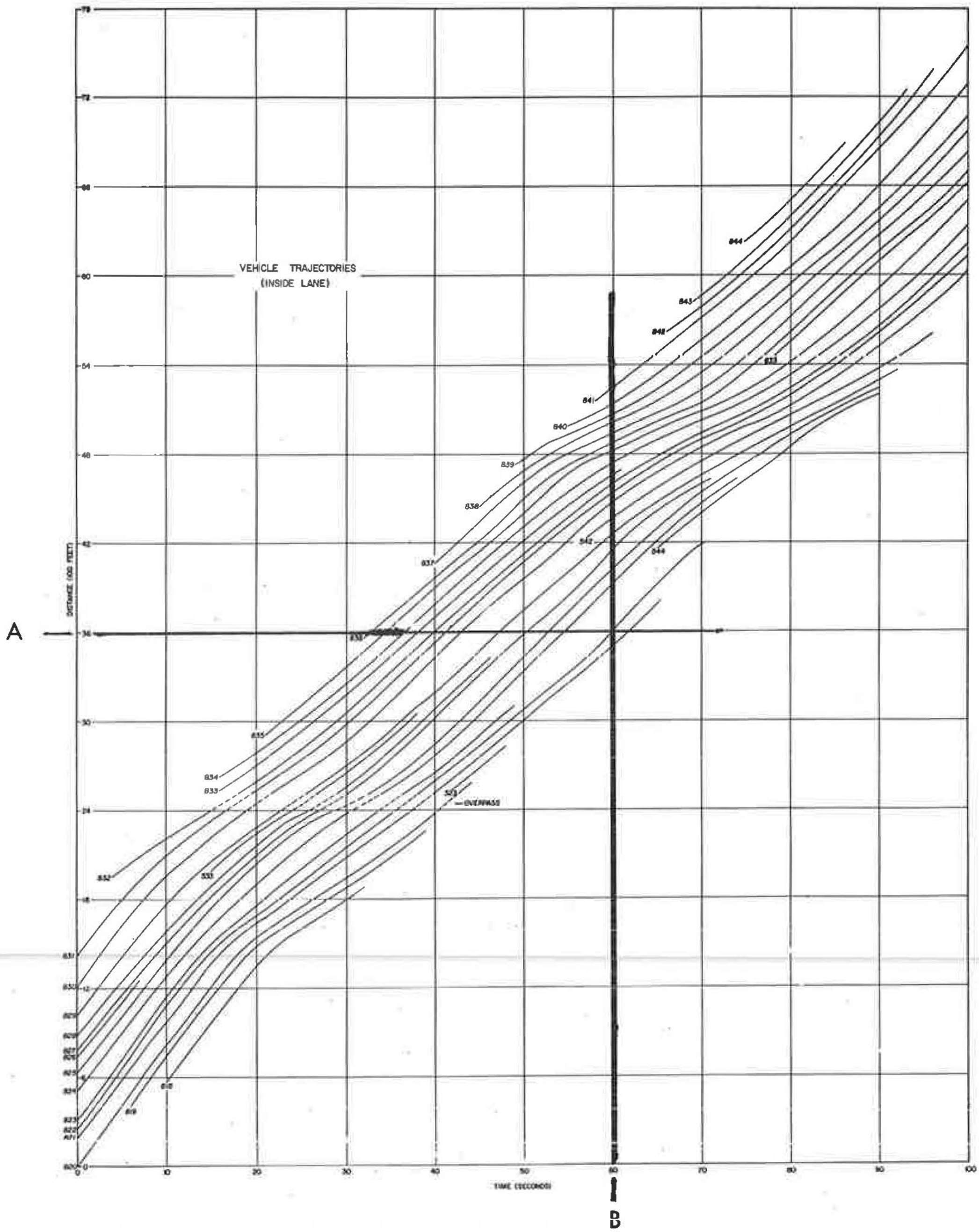

Figure 1. Traffic measurements.

tion on traffic density but no information on traffic volumes or velocity. The method chosen for aerial photography is actually a combination of the two methods described in a previous paper.

The basic procedure involves a test vehicle traveling with the traffic stream and followed by a helicopter from which photographs are taken at fixed intervals of time.

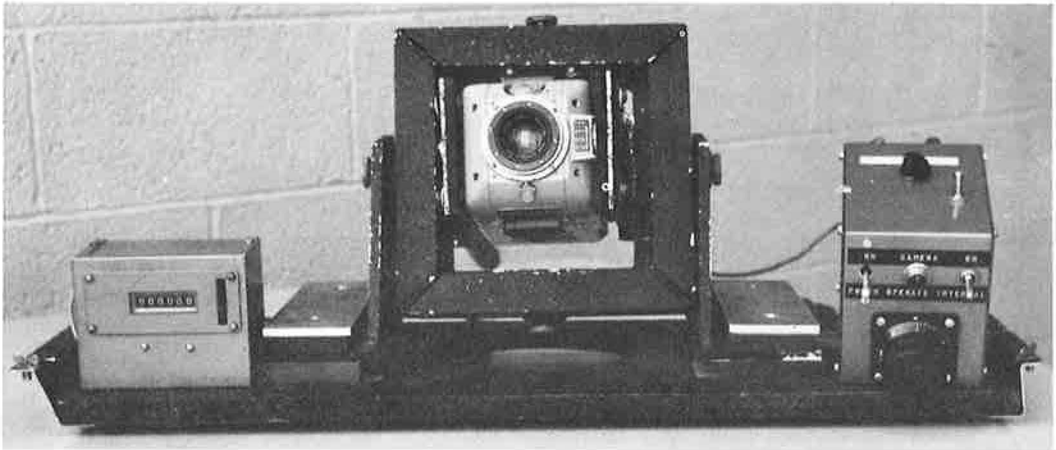

Figure 2. Frame counter, camera, mount, and intervalometer.

Figure 3. Camera and auxiliary equipment installed in helicopter.

The function of the test vehicle is threefold: (a) it serves as a guide for the helicopter pilot by carrying a distinctive mark or a light on its roof; (b) it serves as a generator for disturbances which can be initiated by radio contact from the helicopter to study certain traffic situations; and (c) some of the data obtained by aerial photography can be checked against data on velocity, accelerations and decelerations collected by a recorder in the test vehicle.

EQUIPMENT

Test runs carried out with a vehicle equipped with a multichannel recorder for recording velocity, accelerations and decelerations indicated the aerial photographs must be taken at intervals of one second or less in time if speed changes and the longitudinal propagations of disturbance are to be detected and if meaningful measurements are to be made. This basic condition ruled out the use of full-size format (9 × 9 in.) aerial cameras which would have been most suitable for the photogrammetric measurement of essential data.

To retain the largest possible film format for accurate measurements, a Maurer P-2 70 mm reconnaissance camera with a 76 mm f/2.8 Kodak Ektar lens was finally chosen. It was found that frequently an aperture of f/2.8 or larger is required for photography during the peak traffic periods before 8 a.m. and after 5 p.m. This is another restricting factor in selecting the camera.

A special mount was designed and built, and special care was taken to dampen the transfer of vibrations from the helicopter to the camera by mounting the camera and the support of the frame accepting the camera between rubber pads of different stiffnesses. The frame holding the camera consists of a universal joint so that the operator can maintain the optical axis of the camera near vertical during flights by using a control stick and a level. The camera, mount, intervalometer, and frame counter are shown in Figure 2. The mount with the camera can be placed in the Ohio Department of Highways helicopter by removing one section of the floor. The installed camera and its controls, consisting of the intervalometer with power and aperture control, the frame counter, and the control stick, are shown in Figure 3.

DATA COLLECTION

In order to obtain motor vehicle velocities with the desired accuracy, ground positions within approximately one foot were required. This consideration dictated a maximum flying height of about 3,000 ft. Roadway coverage of approximately 2,250 ft can be obtained with 70 mm camera at this height, with a photography scale of 1:12,000, or 1 ft per 0.001 in.

A total of seven 50-ft rolls of film was used to photograph traffic flow movement in the Columbus, Ohio, area. Six rolls were taken over I71 between Fifth Avenue and Morse Road during the evening when peak flow traffic conditions existed, and one roll was taken over the Olentangy Freeway just prior to an Ohio State University football game. Four rolls of film were Plus-X Panchromatic and the other three were Infrared Ektachrome. The infrared film exhibits decided advantages in sharpness and eliminates the shadow problem which is bothersome in the black-and-white photographs. Also, the color is of some help in vehicle and control point identification. An enlargement of a typical aerial photograph is shown in Figure 4.

Each of the seven rolls of film was examined and part of one roll was selected for detailed analysis. This film was selected primarily because the traffic density was initially low, then increased to the point where the vehicles nearly stopped, and then decreased again. This density-speed fluctuation occurred within a 100-sec interval of time. The photographs in this group were very sharp, but the photography flight height was somewhat lower than designed. Thus the roadway coverage per photograph was 1,750 feet instead of 2,250 feet.

Ground control points in the area adjacent to the freeway were selected from an inspection of the photographs. The majority of the points selected were light poles, although manhole covers, guardrail posts, and ends of curbs were used in a few instances. A total of 41 ground control points was necessary to provide eight to ten

Figure 4. Enlargement of typical aerial photograph.

points on each photograph. The average spacing between ground control points was 186 ft and the maximum was 260 ft. The ground coordinates of these points were determined from measurements made by standard ground surveying techniques.

DATA REDUCTION AND ANALYSIS

The negatives were mounted on glass plates with the emulsion out so they would be in focus when inserted in the Nistri Analytical (Stereoscopic) Plotter at the Ohio Department of Highways (Fig. 5).

The photograph x and y coordinates of each ground control point, the front-center of each vehicle, and the center of the photograph were measured with the AP/C for each of the 101 photographs used. Flight, photograph, lane, and vehicle identification numbers, as well as the photograph coordinates, were printed out by the electric typewriter of the AP/C. A sample printout page is shown in Figure 6.

The first line on the left side gives the photograph coordinates of the center of the grid on the photograph. This line is prefixed by 0000001, followed by the x-coordinate

Figure 5. Nistri Analytical (Stereoscopic) Plotter, Model AP/C.

in microns, the y-coordinate in microns, and finally the number 0030119. The coordinate system is arbitrary. The first three digits of the final number signify the flight number and the last four digits denote the photograph number.

Following this line are the ground control points, prefixed by a number with four zeros and then a three-digit number which identifies the ground control point. The other three numbers in the line represent the same items as for the center point.

The data for the vehicles in the inside lane follow the ground control points. The first number identifies the lane (first digit), vehicle being measured (second, third, and fourth digits), and the vehicle in front of the one being measured (fifth, sixth, and seventh digits). The vehicles were position-measured in order from the rear to the front in the direction of travel. A negative sign in front of the lane number indicates the vehicle was under a grade-separation structure. The last three digits of the first number are 999 when the front vehicle is being measured. The last three numbers in the line are for the same items as for the ground control points.

The numbers on the right side of the paper are the corresponding data for the vehicles in the outside lane (lane 2).

To reduce the photographic data to ground data and then compute headways and velocities of the vehicles, a computer program was written for the IBM 7094 computer.

The photograph coordinates of the vehicles in each photograph were transformed to ground coordinates using the transformation equations

$$X_G = Ax_p + By_p + C$$

$$Y_G = Ay_p - Bx_p + D$$

where X_G and Y_G are the ground coordinates, x_p and y_p are the photograph coordinates, and A, B, C, and D are transformation coefficients to be determined. The data from each photograph contain the photograph coordinates of from eight to ten ground control points. The transformation coefficients were calculated for each interval between successive ground control points by substituting the photograph and ground coordinates of the two ground control points in the transformation equations and solving

0000001	-0080027	-0075730	0030119
0000210	-0107794	-0078342	0030119
0000211	-0102246	-0077310	0030119
0000212	-0096792	-0076496	0030119
0000213	-0091288	-0075864	0030119
0000214	-0086974	-0075570	0030119
0000215	-0079846	-0075288	0030119
0000216	-0074304	-0075232	0030119
0000217	-0068156	-0075474	0030119
0000218	-0062074	-0075850	0030119
0000219	-0056726	-0075748	0030119
1818819	-0105237	-0079151	0030119
1819820	-0102799	-0078665	0030119
1820821	-0100525	-0078245	0030119
1821822	-0096447	-0077629	0030119
1822823	-0094073	-0077313	0030119
1823824	-0091051	-0076941	0030119
1824825	-0086321	-0076565	0030119
1825827	-0084289	-0076447	0030119
-1827828	-0082707	-0076277	0030119
1828533	-0080701	-0076277	0030119
1533829	-0077641	-0076313	0030119
1829830	-0075917	-0076293	0030119
1830831	-0070791	-0076411	0030119
1831832	-0066921	-0076655	0030119
1832833	-0064317	-0076833	0030119
1833834	-0060417	-0077071	0030119
1834835	-0058061	-0077161	0030119
1835999	-0054411	-0077431	0030119

2517518	-0104863	-0078648	0030119
2518519	-0102377	-0078192	0030119
2519520	-0099913	-0077734	0030119
2520539	-0098253	-0077428	0030119
2539521	-0096481	-0077072	0030119
2521522	-0095423	-0077120	0030119
2522523	-0094191	-0076884	0030119
2523524	-0092799	-0076712	0030119
2524536	-0090991	-0076526	0030119
2536525	-0089567	-0076342	0030119
2525826	-0088451	-0076274	0030119
2826534	-0086545	-0076178	0030119
2534526	-0084747	-0075964	0030119
-2526532	-0083471	-0075958	0030119
-2532527	-0081729	-0075898	0030119
2527528	-0080373	-0075896	0030119
2528529	-0078493	-0075818	0030119
2529531	-0075281	-0075832	0030119
2531530	-0069901	-0076000	0030119
2530535	-0068849	-0076114	0030119
2535537	-0067009	-0076164	0030119
2537538	-0063411	-0076460	0030119
2538540	-0060583	-0076624	0030119
2540541	-0056669	-0076828	0030119
2541999	-0053935	-0077020	0030119

Figure 6. Photograph coordinate data.

the resulting simultaneous equations. The first ground control point in the direction of travel of the vehicles was assigned the coordinates (1,000.00 and 1,000.00) for X and Y so negative ground coordinates for the vehicles would not occur. The x-axis was nearly parallel to the highway for each photograph. The ground control point interval in which the x photograph coordinate of each vehicle fell was found and the appropriate coefficients were used in the transformation equations to determine the ground coordinates of the vehicle. If the vehicle preceded the first ground control point or followed the last one shown on a photograph, the coefficients of the first or the last ground point interval were used, respectively.

LANE 2

VEHICLE	FOLLOWING	GROUND X	GROUND Y	DISTANCE(FT)	HEADWAY(FT)	VELOCITY(MPH)
517	518	2763.40	1202.14	1770.25	77.86	32.52
518	519	2841.22	1198.70	1848.11	76.71	29.58
519	520	2917.98	1195.80	1924.83	51.68	23.20
520	539	2969.44	1193.65	1976.51	55.41	17.73
539	521	3024.63	1192.23	2031.92	31.28	15.88
521	522	3055.79	1183.58	2063.20	38.43	16.75
522	523	3094.07	1182.19	2101.62	42.77	16.47
523	524	3136.68	1177.80	2144.39	55.56	16.96
524	536	3191.79	1170.93	2199.95	44.18	18.04
536	525	3235.55	1166.70	2244.13	34.10	18.46
525	826	3269.33	1161.12	2278.23	58.11	17.75
826	534	3326.90	1151.04	2336.34	55.74	19.57
534	526	3381.91	1145.26	2392.08	******	19.13
526	532	*******	*******	*******	******	*****
532	527	*******	*******	*******	******	*****
527	528	3512.67	1117.73	2525.47	57.67	*****
528	529	3569.21	1107.21	2583.14	98.14	23.07
529	531	3664.91	1084.80	2681.28	163.72	24.69
531	530	3823.30	1043.63	2845.00	31.39	27.35
530	535	3853.66	1033.18	2876.39	55.89	25.57
535	537	3907.58	1019.41	2932.28	108.22	24.40
537	538	4011.45	986.45	3040.50	85.74	26.72
538	540	4093.74	963.02	3126.25	118.51	29.77
540	541	4207.49	931.80	3244.76	82.45	29.69
541	999	4286.62	908.54	3327.21	******	31.03

Figure 7. Traffic flow data.

To compute the headways and velocities of the vehicles, an origin was selected on the highway from which the accumulative distance traveled by each vehicle in each photograph could be computed. Using such a distance, the headway between two vehicles could be obtained simply by subtracting the accumulative distance of the following vehicle from that of the lead vehicle. The velocity of a vehicle was calculated by subtracting its accumulative distance obtained from one photograph from its accumulative distance obtained from the next photograph and dividing by the time interval between photographs.

To compensate for the curvature of the highway, straight-line segments were defined by selecting certain vehicles as distance or D-control points. In the curved section of the highway these D-points were selected close enough together so the distance along the chord between two D-points provided a close approximation to actual roadway distance along the curve. To calculate the accumulative distance traveled by a vehicle,

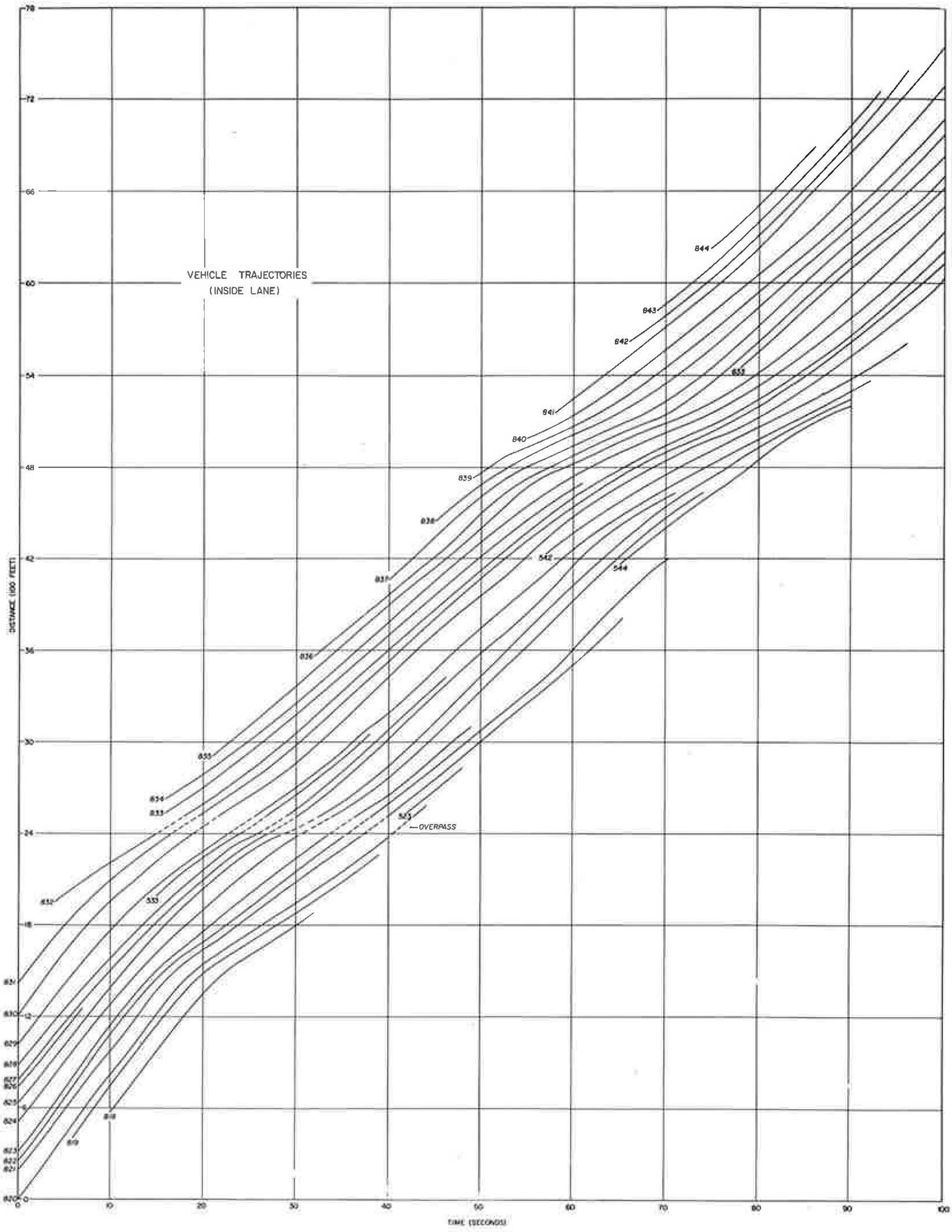

Figure 8. Vehicle trajectories (inside lane).

it was necessary to sum the distances between the D-points the vehicle has passed and add to this the distance to the vehicle from the last D-point passed. The distance between two D-points was calculated using the equation

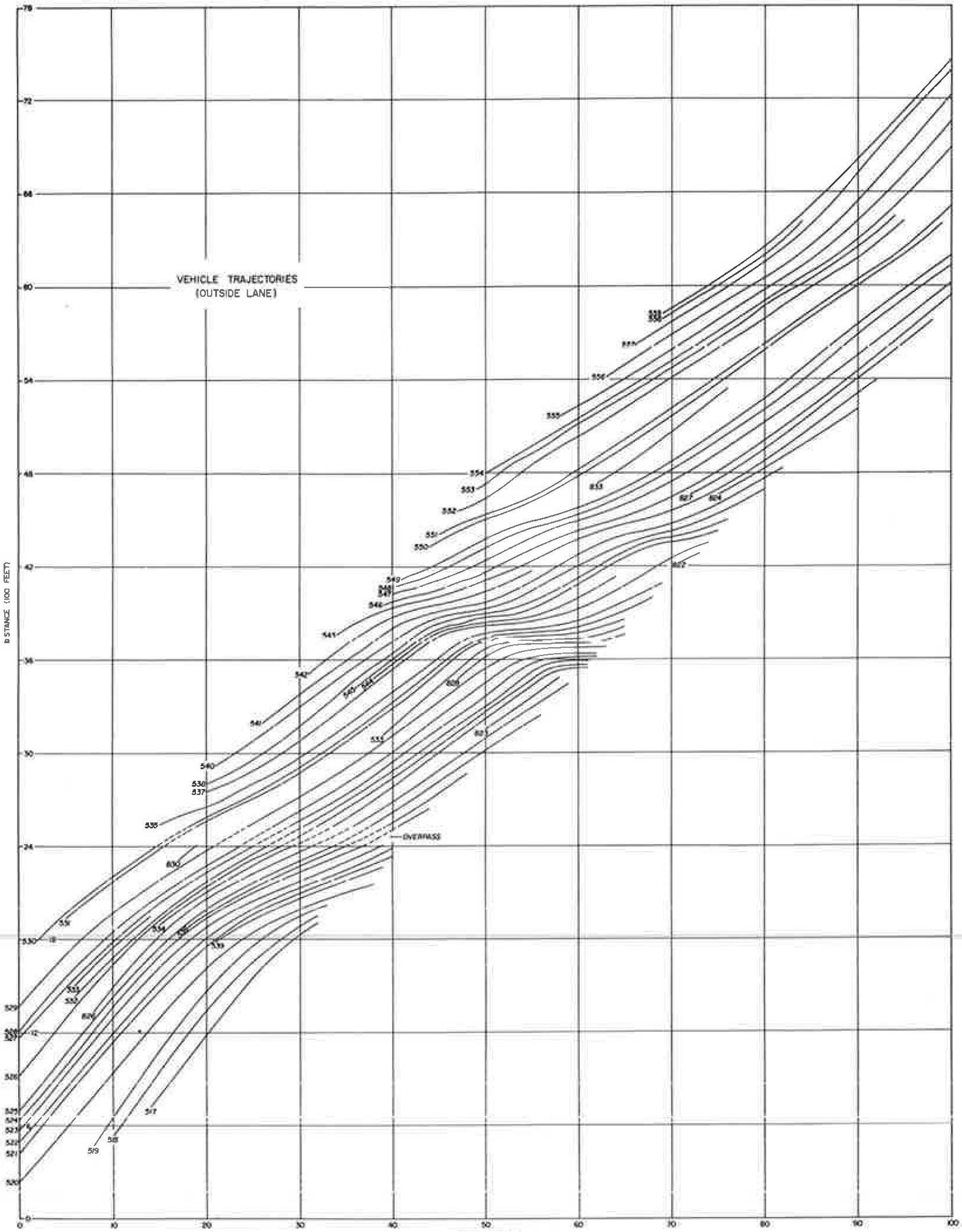

Figure 9. Vehicle trajectories (outside lane).

$$D = \left[(X_{i+1} - X_i)^2 + (Y_{i+1} - Y_i)^2\right]^{1/2}$$

where X and Y are the ground coordinates of the D-points. To determine the distance a vehicle had traveled past a D-point, it was necessary to transform the X coordinate to distance traveled on the roadway using the transformation equation

$$D = AX + B$$

The coefficients A and B were determined by substituting the two appropriate X coordinates and D values and solving the resulting simultaneous equations.

The results thus obtained are shown on the sample output page, Figure 7. For vehicle 541, the asterisks in the headway column indicate it was the lead vehicle on that photograph and no headway calculation was possible. For vehicle 534 there is no headway calculated since it was following vehicle 526. For vehicle 527 there was no velocity calculation since it was under the overpass on the previous photograph.

Time-distance diagrams for each lane were constructed from the computer output data. These diagrams are shown as Figures 8 and 9. For each photograph, the accumulative distance to each vehicle was plotted in a vertical line at the corresponding time. The vehicle trajectories were drawn by connecting the consecutive accumulative distance points for each vehicle. The velocity of the vehicle at any time is equal to the slope of the trajectory at the corresponding time.

RESULTS

Accurate vehicle trajectories were obtained in this investigation by photogrammetric techniques. These trajectories cover a time period of 100 sec and a total distance along the roadway of 7,350 ft—approximately 1 ½ mi. An average of 40 vehicles appeared on each photograph, but only a few appear on all 101 photographs.

The average velocity over the past one second and the distance to the vehicle ahead was obtained for nearly every vehicle on each photograph; i.e., values of these parameters were obtained at time intervals of one second. Data could not be obtained in certain cases, such as spacing for the lead vehicle, velocity for a vehicle which did not appear on consecutive photographs, and data for vehicles under a grade-separation structure.

An error analysis (not included in this paper) indicates that the standard error in the velocity determinations is no more than 1.0 mph, and the standard error of the spacing determination is no more than 1.0 ft.

CONCLUSIONS

The objectives of the investigation were met. Accurate vehicle trajectories, and corresponding spacing and velocity data were obtained. The investigation provides a type of data not heretofore available to the traffic engineer—accurate flow data continuous in time and space. The aerial survey methodology necessary to obtain these data has been formulated and tested.

The major bottleneck was, and still is, data extraction from the photographs. This factor alone will determine the economic feasibility of the technique. Equipment costs and computer programming, which was time-consuming, were the expensive parts of this investigation, but this was due in large part to their developmental nature. The same equipment and programs could be used for further data determination with little additional expense.

ACKNOWLEDGMENTS

This paper is based on a project entitled "Electronic Devices as Traffic Aids," conducted by The Ohio State University Engineering Experiment Station under sponsorship of the U.S. Bureau of Public Roads and the Ohio Department of Highways. Appreciation is expressed to the Ohio Department of Highways for making its helicopter available for the photographic flights, processing the films, and use of the Nistri Analytical (Stereoscopic) Plotter. The authors also thank the U.S. Air Force, Wright

Air Development Center, Dayton, Ohio, for the loan of its camera and intervalometer for use in this investigation.

The Annotated Photomap for Highway Planning In Congested Suburban Areas

FRED JETER, Photogrammetric Engineer, Oregon State Highway Department

•SHORTLY AFTER 1946, the Oregon State Highway Department, in cooperation with the U.S. Bureau of Public Roads, began a comprehensive revision of county maps described as the General Highway Map series. The last map of this series was completed in 1963. Because of the considerable time lapse between completion of the first and last county maps of this series, it was recognized that many county maps were badly in need of revision. An appraisal of the methods used to produce this series was made to determine what procedures could be improved to better the quality and increase production in the revision process.

The appraisal indicated clearly that the counties most urgently needing revision were those including or adjacent to the metropolitan centers of the state. For example, Washington County, formerly an area of mostly rural characteristics, showed a population increase within ten years of more than 80 percent, most of which was in a rapidly expanding suburban area adjacent to Portland, the state's largest city.

Although aerial photography had been used in the mapping process for planimetric mapping of large areas and for inventory of roads and culture for some counties, no direct use of photographs had been made as an integral part of the maps. It was apparent that the solution to the problem of producing large-scale maps of congested areas was the use of aerial photographic mosaics which would photographically portray mapping detail, thereby eliminating time-consuming drafting of the multitudinous cultural items.

It was realized that in order to be an effective substitute for a line map, a mosaic would require an undetermined amount of annotation, such as names and cultural symbols. However, a prime consideration in the choice of the photomap is its superiority in the sheer volume of photographic information shown in land use and occupancy.

It was also recognized that the aerial photomap has certain limitations. Considering this and to determine in some detail what annotation was thought essential by the users of these maps, a letter was circulated to key map users in the Highway Department along with a sample of a line map and a sample photomap of the same area. These key map users were requested to list features shown on the line map which, according to their needs, should be annotated on the photomap.

Compilation of the replies received formed the basis for the annotation of the sample map shown in Figure 1. Principal items requested by the map users were the state highway system by surface type, all minor road names, cemeteries, schools, parks, and major transmission lines. Also requested was a map scale bar in feet and, as on line maps, all political subdivisions and the General Land Office section line grid. It is believed that an objective determination from the map users' viewpoint was obtained from this survey and that the resultant photomaps are at least as useful as the old line maps and are superior in furnishing land use and occupancy information.

It was found that the compilation cost was reflected in a direct ratio to the amount of photomap annotation. Although the original compilation cost estimate was exceeded, the published annotated photomap cost was only half that previously experienced in production of comparable line maps. Furthermore, experience gained from use of the new

Paper sponsored by Committee on Photogrammetry and Aerial Surveys.

Figure 1.

process indicates that the more congested the area being mapped, the greater the percentage of savings in man days compared to the time required for line map drafting.

Briefly, the process used to produce annotated photomaps of Oregon counties is as follows:

The densely populated, highly developed area of a county determines the requirement for large scale mapping. When these areas have been determined, a sheet layout is prepared and new aerial photography at a scale of approximately 1 in. = 2000 ft is procured for the mosaics. The mosaic is compiled from partially rectified photo enlargements at a scale of 1 in. = 600 ft using enlarged $7\frac{1}{2}$-min U.S. Geological Survey quadrangle sheets for control when available. The mosaic is assembled for a large area and is then cut into map-size sheets. Annotation is done on transparent stable base drafting film overlaid on the original mosaic sheets for proper registration of detail. The original mosaics and overlays are reproduced photographically at two scales, one of 1 in. = 600 ft for one-color diazo reproduction (Fig. 1), and one of 1 in. = 1500 ft for four-color lithographic printing (not reproduced here because of printing limitations).

The horizontal place-point accuracy of these photomaps has proven to be greater than the line maps which are being revised, because of the availability of large scale U.S. Geological Survey quadrangle sheets for control that were not compiled at the time the original county maps were made. The mosaics can be compiled with a maximum error of 1 percent, in the areas where maximum differences in elevations exist only.

The use of annotated photomaps to replace the line map enlargements in the County Map Series was begun in December 1963 on an experimental basis. The first published map using the new method was distributed in April 1965. The Photogrammetry Section is presently revising maps of five additional counties which were scheduled for completion by early 1966. These five revisions will provide current highway planning maps of an area containing 75 percent of the state's population.

The annotated photomap furnishes the solution to the problem of providing current maps of rapidly growing and changing suburban areas. It appears feasible to revise the photomaps of these areas every three years or as needed.

The Oregon Photogrammetric Unit is presently experimenting with color aerial photography for use in compilation of the photomaps. While color photography is more expensive, preliminary estimates indicate a further saving in drafting time by reduction in number of overlays. Also, colored aerial mosaics are superior to black and white photography in discernible detail because color is much easier to interpret than various shades of gray.

Studies of cost of previous county mapping using line drafting have shown that the two most expensive items are drafting time and assembly of the information for plotting cultural items, including editing. The aerial photomap reduces these costs to a minimum since nearly all detail is shown on the aerial photographs, except in limited areas of dense ground cover unusual in congested suburban areas.

Aerial Photography in the Unified Information System

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•THIS PAPER reports on a study of the use of aerial photography and data banks in providing a unified information system for highway engineers, who normally require a vast quantity of data to cope with problems in highway planning, design, construction, and maintenance.

Highway engineers need a greater capability to obtain required data quickly and efficiently. Obtaining and handling expanding volumes of data can be facilitated through use of a unified information system which collects, stores, updates, and retrieves data, thus helping speed and improve the task of the highway engineer. The system actually is an integrated photogrammetric data bank which is being developed, using principally aerial photography, semiautomated analog-digital readout equipment, automated line plotters and electronic data processing. The objective of the photogrammetric data bank is to provide data and information to the highway engineer for work in which road and area details are necessary; the advantages are speed, accessibility, and flexibility. The photogrammetric data bank concept is illustrated in Figure 1.

AERIAL PHOTOGRAPHY

Although several types of aerial photography and sensors could be used as the data input source for a data bank, including black and white, color, infrared, and radar, products made from black and white aerial photography have been used thus far in the development of the system. These include (a) contact prints or enlargements; (b) rectified prints, where the effects of tilts are reduced; (c) orthophotographs having not

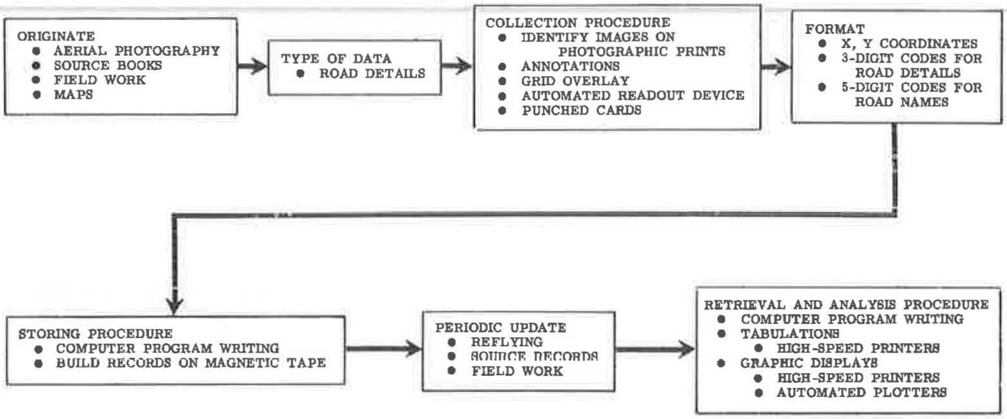

Figure 1. Photogrammetric data bank concept.

Paper sponsored by Committee on Photogrammetry and Aerial Surveys and presented at the 45th Annual Meeting.

MAP SYMBOLS	PROGRAM CODES	
&	001	*FIRST NODE, RESIDENTIAL, 4-LEG INTERSECTION
&	002	SAME EXCEPT COMMERCIAL
&	003	SAME EXCEPT INDUSTRIAL
&	004	SAME AS 001 EXC. 3-LEG INT.
&	005	SAME AS 002 EXC. 3-LEG INT.
&	006	SAME AS 003 EXC. 3-LEG INT.
&	007	SAME AS 001 EXC. 5-LEG INT.
&	008	SAME AS 002 EXC. 5-LEG INT.
&	009	SAME AS 003 EXC. 5-LEG INT.
&	010	SAME AS 001 EXC. OVER 5-LEG INT.
&	011	SAME AS 002 EXC. OVER 5-LEG INT.
&	012	SAME AS 003 EXC. OVER 5-LEG INT.
&	020	SECOND NODE
•	021	NORTH OR WEST SIDE PAVED CURB TO CURB
•	023	NORTH OR WEST SIDE SURFACED
•	025	NORTH OR WEST SIDE UNIMPROVED
•	028	SOUTH OR EAST SIDE
7	029	STREET LIGHT REL. LOW INTENSITY
7	030	STREET LIGHT REL. MEDIUM INTENSITY
7	031	STREET LIGHT REL. HIGH INTENSITY
8	032	TRAFFIC SIGNAL O/H
8	033	TRAFFIC SIGNAL ON CORNER
9	034	FIRE HYDRANT SINGLE
9	035	FIRE HYDRANT DOUBLE
9	036	FIRE HYDRANT TRIPLE
9	037	FIRE HYDRANT FLUSH
‡	038	ISOLATED TREE
•	039	SIDEWALK - FULL CONCRETE
•	040	SIDEWALK - FULL MACADAM OR OTHER
•	041	SIDEWALK - RIBBON - CONCRETE
•	042	SIDEWALK - RIBBON - MACADAM OR OTHER
•	045	CURVED STREET - EDGE
$	046	PARKING METER
*	047	CORNER OR EDGE OF BUILDING - RESIDENTIAL
*	049	CORNER OR EDGE OF BUILDING - COMMERCIAL
*	050	CORNER OR EDGE OF BUILDING - INDUSTRIAL
•	051	CORNER OR EDGE OF DRIVEWAY - CONCRETE
•	052	CORNER OR EDGE OF DRIVEWAY - ASPHALT
•	053	CORNER OR EDGE OF DRIVEWAY - OTHER MATERIAL
•	055	CORNER OR EDGE OF ROAD -PAVEMENT EDGE
□	056	CORNER OR EDGE OF PARKING AREA
M	057	MANHOLE - SEWER
M	058	MANHOLE - WATER
M	059	MANHOLE - POWER
M	060	MANHOLE TELEPHONE
I	061	SEWER INLET
–	063	BUILDING DIVIDER

* SEE FIGURE 3

Figure 2. Sample list of codes for photogrammetric data bank.

only effects of tilt eliminated, but in addition having uniform scales; and (d) mosaics made from these three types. Other types will be considered as system development progresses.

An important consideration governing the selection of the type of aerial photography is cost. The costs of photographic products not only are affected by the type of photography employed but also by factors such as quantity to be produced and quality specified, and by other conditions such as contractor's physical facilities, labor costs, profit, and market conditions.

DATA COLLECTION

The collection operation consists largely of extracting the required data from aerial photographs. During the collection phase, data are selected and recorded digitally as X, Y coordinate positions of image details that are apparent or have been made so by annotations on the aerial photograph. Each set of coordinates locates an image detail, and each image detail is assigned a program code. The codes thus represent image details, such as fire hydrants, street lights, or parking meters and also describe the characteristics of the road. The collection phase is not limited to aerial photography, but includes first-hand observation at the site and searching source records known to be current and accurate.

Sample codes for a hypothetical photogrammetric data bank are listed in Figure 2 together with the image details they represent. Each of the details can be elaborated upon to provide as much code information as necessary for a comprehensive analysis of the road characteristics. The amount of elaboration will depend on the engineering problems the data bank will serve. For example, in Figure 2, codes 039, 040, 041 and 042 give four types of surfacing details for sidewalks. Other types of detail could have been listed for sidewalks and other road details in addition to those given, depending on the need.

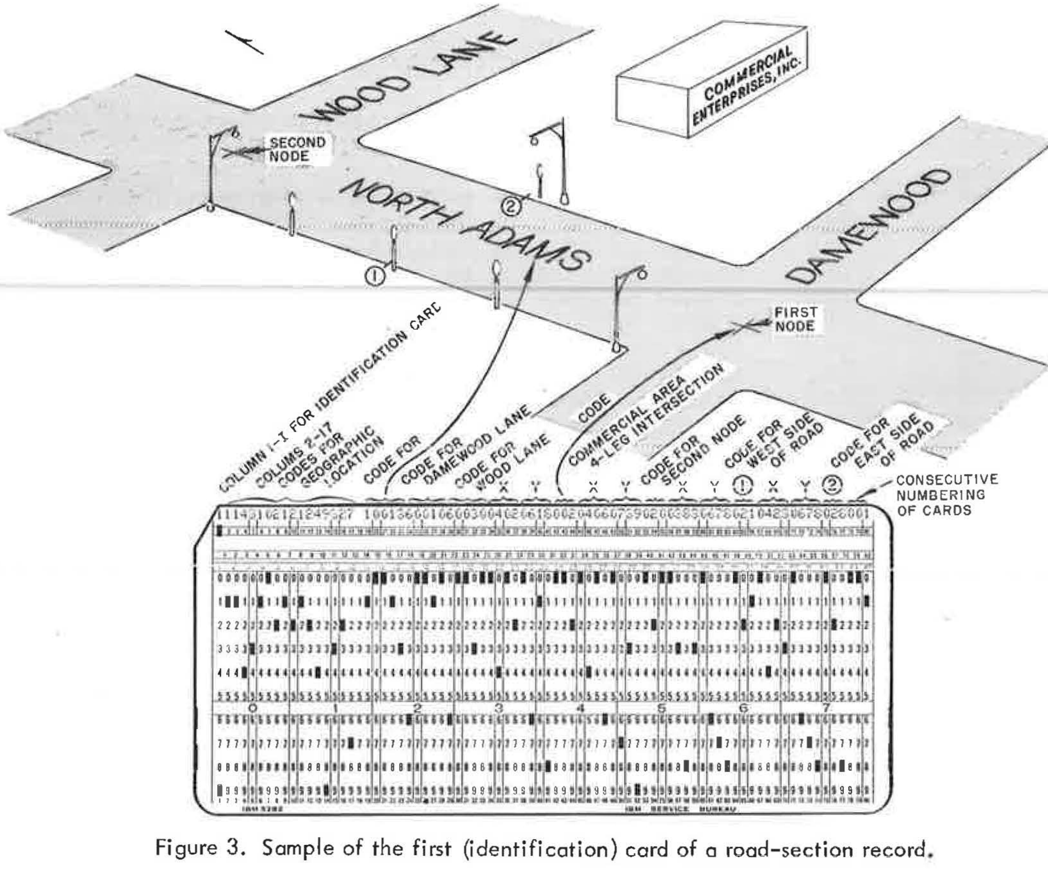

Figure 3. Sample of the first (identification) card of a road-section record.

* 10000	** ARGYLE STREET	
10005	MOUNT VERNON	
10010	SOUTH WASHINGTON STREET	
10011	NORTH WASHINGTON STREET	
10012	SOUTH ADAMS STREET	
10013	NORTH ADAMS STREET	
10015	SOUTH VAN BUREN STREET	
10016	NORTH VAN BUREN STREET	
10018	EVANS STREET	
10020	DALE DRIVE	
10025	WILLIAMS STREET	
10030	CAIRO STREET	
10032	SARAH STREET	
10035	HUNGERFORD DRIVE	
10038	UPTON STREET	
10040	PERRY STREET	
49998	NO SUCH STREET	
49999	DEAD END STREET	N-S
60000	WEST MONTGOMERY AVENUE	
60001	EAST MONTGOMERY AVENUE	
60005	JEFFERSON STREET	
60010	DAMEWOOD LANE	
60015	COMMERCE LANE	
60020	FAYETTE PARK ROAD	
60025	HARRISON STREET	
60030	WOOD LANE	
60032	DAWSON STREET	
60034	NORTH STREET	
60036	MARTINS LANE	
60038	VINSON STREET	
99998	NO SUCH STREET	
99999	DEAD END STREET	E-W

* CODE
** ROAD NAME

Figure 4. Table look up (printout of information stored on computer magnetic tape).

The collected data are recorded on a series of punched cards from which a printout of the type shown in Figure 2 can be obtained. The first card of the series contains identification information that relates the set of punched cards to a given road or area; the second and succeeding cards contain the data on the image details desired.

The first column of the first card, the identification card (Fig. 3), will always be punched as an "I" so that the computer will recognize the initial card in the series as an identification type. The next 16 columns (2-17) of the identification card contain geographical codes, which permit the retrieval of data for any particular geographical entity, such as watershed, enumeration or election district, or census tract. The rest of the columns of the identification card are punched as fields representing codes and coordinates for the road details required.

Five-digit codes are used to identify the road to be observed and inventoried and the two intersecting roads that define the road length. Figure 4 shows a sample printout of 5-digit codes stored on magnetic tape and the roads they identify. Any one of these codes punched on the card enables the computer to select the proper road from the stored information and subsequently to add it to the end of the corresponding road-section record (Fig. 6) for greater accessibility in subsequent printing. The locations of road intersection nodes and edges of the paved portion of the road on the aerial

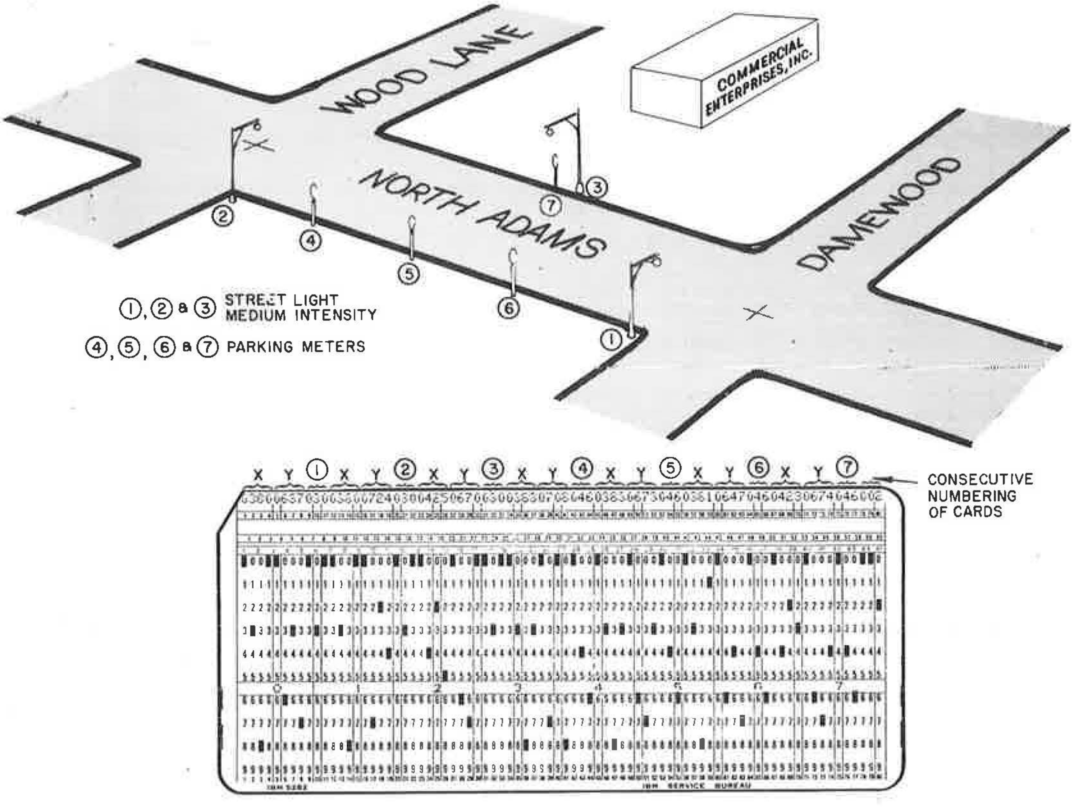

Figure 5. Sample of the second and succeeding cards of a road-section record.

photography are represented by sets of X, Y coordinates. As shown in Figure 3, each X coordinate and Y coordinate contains 4 digits, and the complete set of coordinates (a total of 8 digits) is followed by a 3-digit code representing the characteristics of the image detail being observed. These 3-digit codes, examples of which are listed in Figure 2, were mentioned previously.

The second and succeeding punched cards of a set for a given road section each contain up to seven sets of codes and X, Y coordinates (Fig. 5). The format of a series of codes preceded by X, Y coordinates was adopted to ease the collecting aspect of the unified information system. Since seven sets of eleven digits each require 77 columns, the last three columns (78-80) were reserved for consecutive numbering.

A computer program has been written for storing these data on magnetic tape in a program language called Autocoder. This program as written not only stores but also manipulates the collected data so that the width of the road is computed and recorded, and alters the format of each code appearing on the second and succeeding punched cards and its corresponding sets of X, Y coordinates. The code now precedes a two-digit field representing the number of sets of the X, Y coordinates inserted by the program, which in turn is followed by the series of X, Y coordinates (compare Figs. 5 and 7), whereas originally a code followed each set of coordinates.

A sample road-section tape record from the photogrammetric data bank in which data were stored by the program written for this study is shown in Figures 6 and 7. Figure 7 contains a complete explanation of the data and information shown in printout form in Figure 6. Printed out is practically every column in the first card, the identification card, except for the last three representing the consecutive numbering.

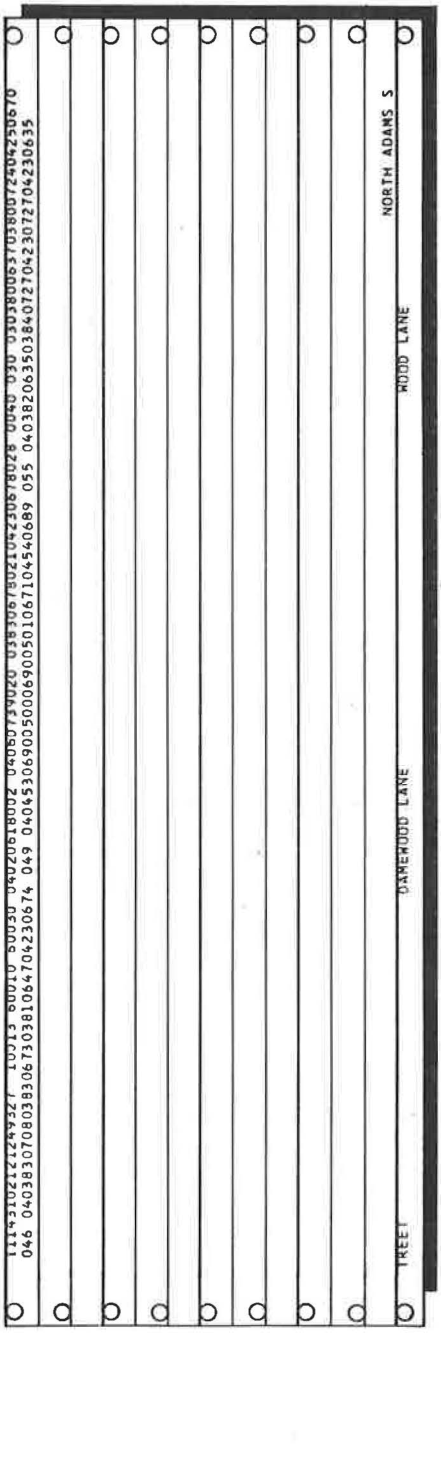

Figure 6. Sample road-section tape record from photogrammetric data bank.

Added were the four digits, 0040, which represent the computer calculation of the width of the road section, namely 40 ft (see fifth line of Fig. 7). Following in the tape record are the reformated codes and their X, Y coordinates with the 2-digit number inserted during the computer operation (example in sixth line of Fig. 7—the 03 following code 030). Deleted are the 3-digit fields representing the consecutive numbering of the second and succeeding punched cards.

LINE-SIMULATED MAP

One useful byproduct of a photogrammetric data bank is a special-purpose map prepared by the computer from the data in storage. With a computer program manipulation, the stored data can be prepared for input to a high-speed printer to produce a line-simulated map of the type shown in Figure 8.

To demonstrate the feasibility of the operation, a map program was written, and a sample deck of approximately 1, 500 punched cards was prepared using an electronic readout system and a fictitious, annotated aerial photograph. As shown in Figure 9, the data included (a) in column 7—a 1-digit command, 0 (zero), to be used for character printing on an electronic line plotter (other commands are 8 for pen down and 9 for pen up); (b) in column 8—an alphanumeric character, $, representing a road item, in this instance a parking meter (see Figs. 2 and 7); and (c) in columns 10-13 and 16-19—the X coordinate (228. 5) and the Y coordinate (185. 0), respectively, which locate the position of the parking meter on the map.

This deck of punched cards could have been produced manually be recording the X, Y coordinates on a form from which keypunching could be done later, but in this sample case, a readout system of the type shown in Figure 10 was used. The digitizing of the X, Y coordinates was done directly by means of the cursor centered on the road-detail image, and by closing a foot switch. The command and character were added later to columns 7 and 8, respectively. Groups of punched cards representing a particular item were bunched so as to facilitate the punching.

The high-speed printer line-simulated map (Fig. 8) was produced by having the X axis represented by the horizontal line

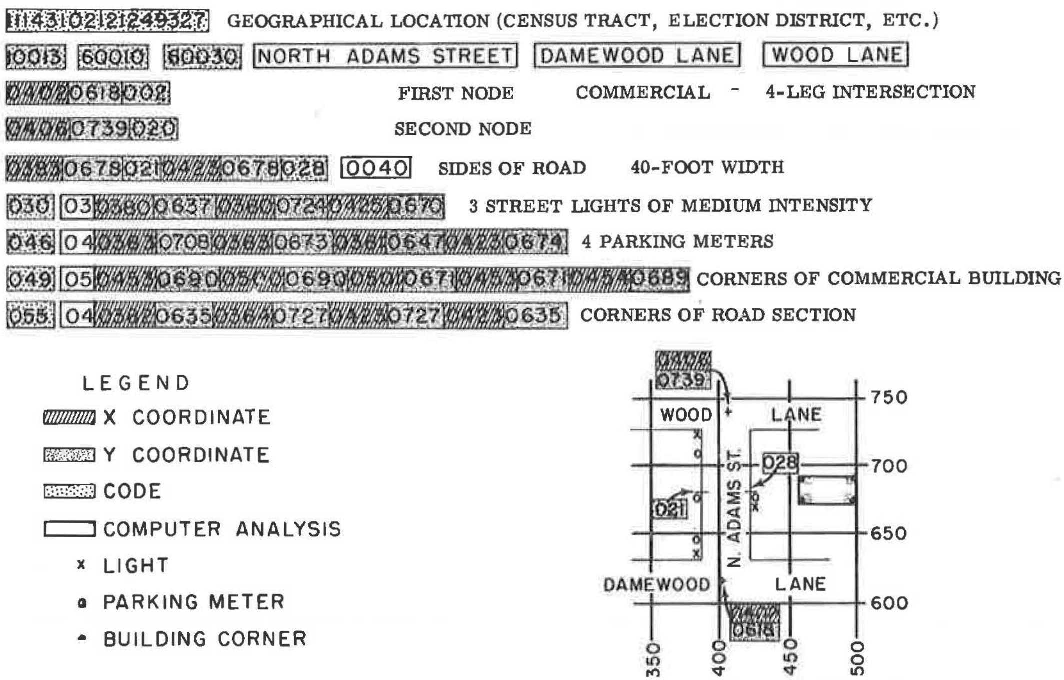

Figure 7. Explanation of sample road-section tape record shown in Figure 6.

output of the printer carriage, and the Y axis represented by the vertical line spacing. The numbers printed on the edges of the map are the last three whole digits of the X, Y coordinates. There were 10 and 8 spaces per inch for the X axis and Y axis, respectively, and at the scale of 20 feet to 1 inch, each X-axis space represented 2 feet in length and each Y-axis space represented 2 ½ feet in length. There was an option in the map program for differing the scale in one direction from the scale in the other direction. The characters specified were printed on one sheet in the X direction until all of the X coordinate print positions (maximum of 132) were exhausted. If more than 132 characters in the X direction had been required, they could have been printed on a second sheet which could be subsequently alined with the first sheet and spliced to it. The program was written so that if 2 or more data points fell in the same location, the last one, and only the last one, would be plotted.

One advantage of the high-speed printer line-simulated map is the capability of automatically suppressing superfluous details from the map and including only details needed in a particular study. One shortcoming is that the output does not truly portray a map in the popular sense; another is that curves are not perfectly represented. These curves, however, may be of assistance in checking the presence of needed points on curves for other possible outputs. Any graphic portrayal could be digitized, stored, manipulated if desired, and then recalled to be displayed by a high-speed printer or electronic line or incremental plotter.

ELECTRONIC INCREMENTAL AND LINE AUTOMATIC PLOTTERS

It is now possible to produce high quality maps, charts, and graphs automatically, which previously had to be hand drafted. Electronic incremental or line automatic plotters, modern concepts of machine drafting, can now provide automated high-speed plotting and annotating. With the use of programmed subroutines and support routines, these plotters with simple commands can be made to draw curves and dotted or dashed

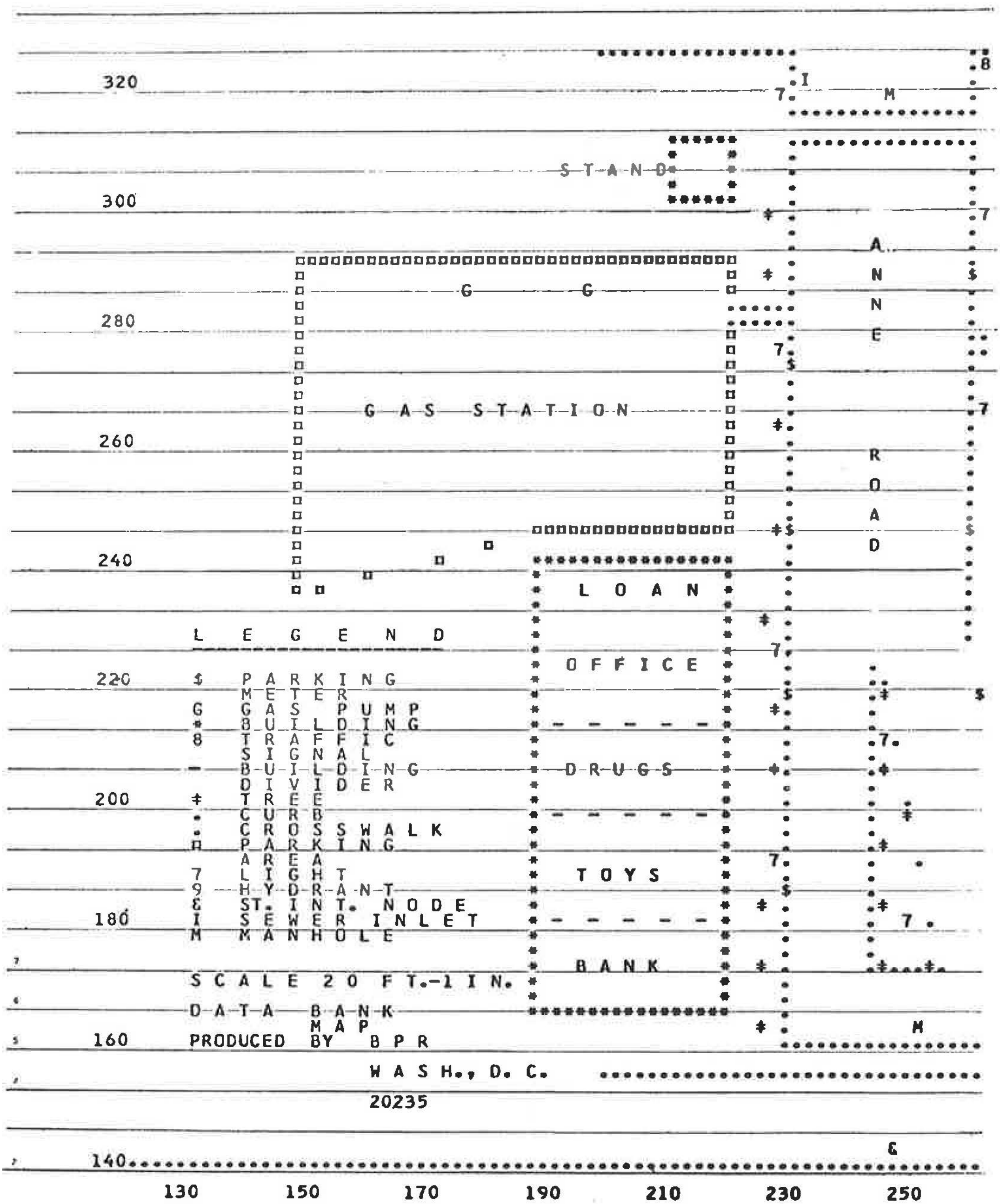

Figure 8. Example of a line-simulated map.

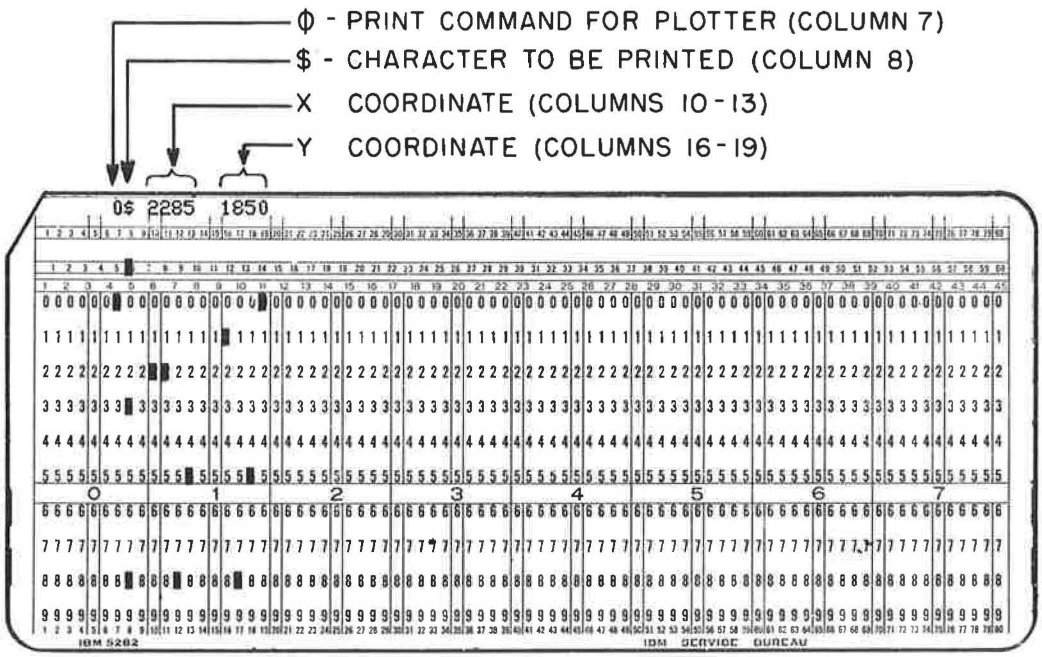

Figure 9. Example of a punched card for a line-simulated map.

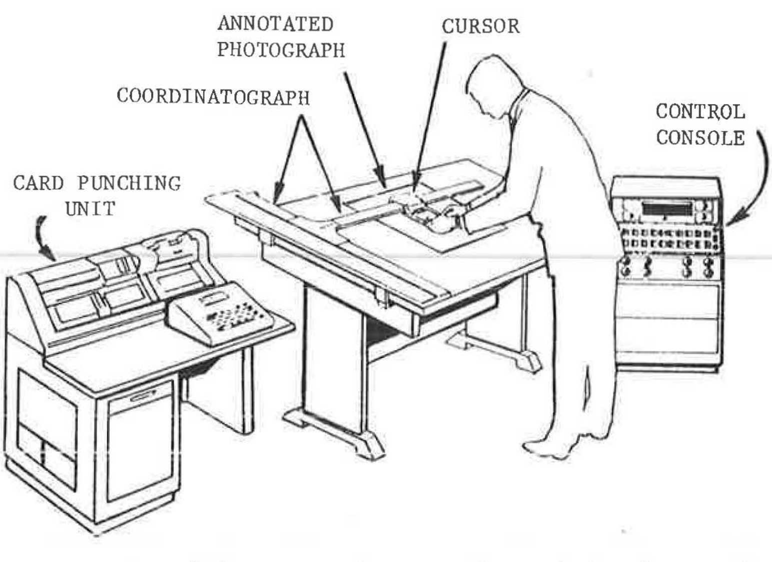

Figure 10. Typical electronic readout system for punched card preparation.

lines, to select pens and advance paper, and to plot alphanumeric characters. Figure 11 shows a typical line plotter with a magnetic tape drive. Figure 12 illustrates an output produced with a plotter that had a punched-card input with a format similar to the one shown in Figure 9.

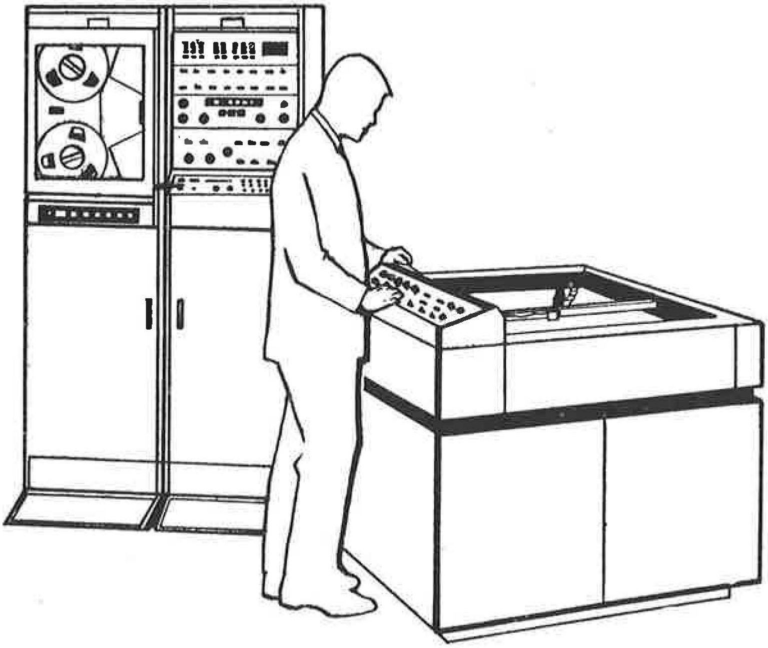

Figure 11. Typical automatic line plotter and tape drive.

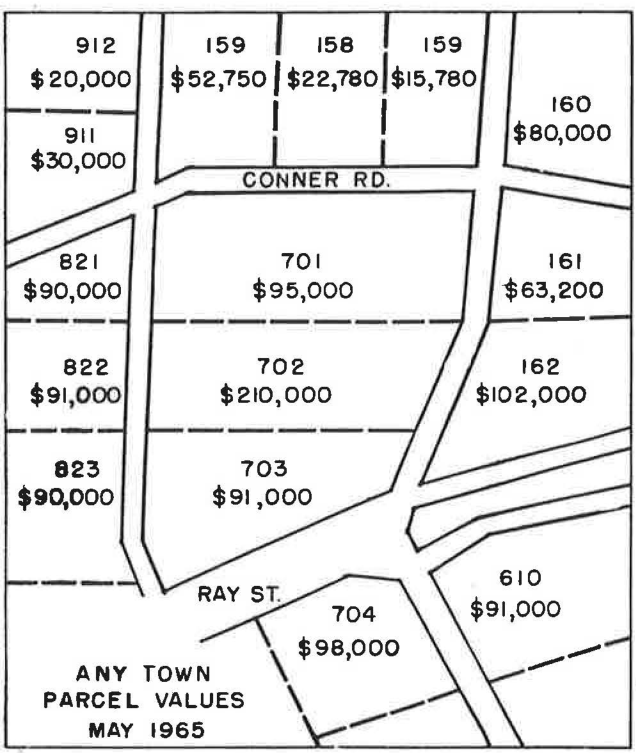

Figure 12. Example of automatic line plotter output.

SUMMARY OF BENEFITS AND DISADVANTAGES

The benefits to be derived from the integration of aerial photography and electronics would be many. It no longer would be necessary to conduct ad hoc surveys because all needed data would be in the information system. The data could be collected intelligently and economically, without duplication and with a minimum of drudgery. With an efficient, established, and proved information system, the strain of handling large quantities of data would be eased. In addition, the information could be more accurate and reliable, in a compact automatic data processing storage setup, and in a single, centralized and highly accessible location.

Some of the disadvantages of a photogrammetric data bank would be the need (a) to compile a code dictionary, (b) to code inquiries, (c) to write computer programs and buy data processing and other expensive equipment, and (d) above all, to do some hard planning. In spite of these disadvantages, it is essential to institute a centralized information system that would permit automated selective presentation of information and improved management through the rapid processing of data. The results of processing could then be made available in time to influence any management process being controlled or monitored.

CONCLUSION

It was not until the appearance of modern data processing, automatic plotting, and digital readout equipment that the concept of a photogrammetric data bank could be considered within the realm of possibility. Now that such equipment not only is available but has been developed to a high degree of sophistication, a photogrammetric data bank, as described in this report, not only is feasible, but should be developed and made available as a service to highway engineers. It is extremely desirable to expedite the coordination of aerial photography techniques with modern electronic equipment through further research and development and thus take full advantage of the progress that has been made to date in the two fields.

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The Photogrammetric Method as a Means of Providing Highway Engineers With an Integrated And Complete System of Surveying

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This paper was written to demonstrate that the photogrammetric method is a science capable of providing highway engineers with an integrated and complete system of surveying for obtaining the qualitative information and quantitative data about the ground surface required for the route location, preliminary survey, design, location survey, and construction stages of urban highway projects. All except the last two stages can be completed prior to a ground survey party occupying the actual centerline of any particular project.

Urban projects are emphasized, because it is on this type of project that maximum utilization of the photogrammetric method can be realized. This is not to say, however, that variations of, or use of portions of, this method cannot be economically applied to all other types of highway projects, as is now being done by a substantial number of highway departments.

IT IS the opinion of this author that in the past too many highway engineers have used photogrammetry only to provide highway information in the traditional form which was previously provided by standard ground surveying methods, rather than realigning conventional highway engineering procedures with the more integrated and complete system of information that can be prepared through the application of the photogrammetric method. The traditional approach has been to establish a centerline (or baseline) on the ground and proceed to tie physically all pertinent information (planimetric and topographic engineering data and cross sections) to this line. This approach places definite restrictions on any project.

A more modern approach is through use of a plane coordinate system whereby a wide band of accurate dimensional data (planimetric and topographic), all surveyed to a common coordinate system, is supplied to the highway engineer, allowing consideration of all aspects of any highway alignment within the band. This approach completely eliminates the necessity of a ground survey of the centerline of any route prior to the actual construction of the highway. The photogrammetric method is presented in this paper as the method capable of providing the information essential to facilitate this coordinated approach. Most highway departments employ portions of this method in their present operaions, but it is the integrated and complete approach which is emphasized in this paper.

It might be reiterated here that photogrammetric engineering applied in the highway engineering field is a highly technical and complicated science which requires a pro-

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fessional approach and strict control throughout each phase of the method. The personnel involved must have a thorough knowledge of both photogrammetric and highway engineering procedures.

STAGE I—RECONNAISSANCE SURVEY

It is not the intention of this paper to dwell on this stage. It is sufficient to state that the application of photo interpretation methods and photogrammetrically made measurements to the reconnaissance survey of area and route locations, supplemented with drainage and hydrology investigations, is indispensable to an efficient highway program and determination of the best route for each highway.

STAGE II—PRELIMINARY SURVEY OF SELECTED ROUTE

For this stage the location and design engineers require a wide corridor of information to appraise all interrelated problems involving one, or perhaps two or more, projected feasible locations for the highway within the selected route corridor.

To satisfy these requirements the photogrammetric engineer can supply topographic maps at a scale of 200 ft per in. with contours on a 5-ft interval. In this early stage of the project survey and design work the photogrammetric engineer is in the advantageous position of being able to carry out these mapping procedures based on control which forms part of the national network of horizontal and vertical control existing within that particular province or state. This should be done. The basic horizontal control would be measured using electronic distance-measuring instruments between properly placed monuments (station markers), and would be presented in plane coordinate form according to the specifications of the national network. It is suggested that this basic control for photogrammetric work be of second order accuracy, with the permanent monuments for station markers spaced every 1 to 2 miles and in specifically important areas along the route corridor being surveyed.

Under direction of the photogrammetric engineer, each station marker in the survey area would be targeted, photographs of the route taken, and standard photogrammetric procedures of aerial triangulation and mapping carried out to compile the topographic maps required. Then, in presenting the maps to the location and design engineers, if time is taken to inform them regarding the full value and accuracy of the maps and the ramifications of a plane coordinate system, they can use the maps for projecting proposed highway location alternatives along the surveyed route, measuring control points and computing a precise description of the horizontal and vertical alignment, and for the basic planimetric presentation of location and design.

Thus the necessity for survey staking of the centerline on the ground to substantiate the findings of the location and design study has been completely eliminated. Results of this study, of course, determine the best location for the highway on the selected route.

It might be noted here that if the digital terrain model (DTM)[1] approach to location and design of highway projects becomes further developed and accepted, it will be a rather simple procedure with present-day digital measuring and recording equipment to use the X, Y, and Z dimensions as measured by photogrammetric equipment at the same time as the stereoscopic plotting of the 200 ft = per in. scale topographic maps.

STAGE III—DESIGN

The design highway engineers require a band of planimetric and topographic data to design the highway and to prepare detailed construction plans. The photogrammetric engineer can supply a topographic map of 40 ft per in. scale (1:480) with contours at

[1]The digital terrain model is a concept developed at Massachusetts Institute of Technology in which the entire route survey corridor is covered by a network of points whose X, Y, and Z coordinates are known and stored in a computer. Further refinements of the concept involve assigning series of weights to these points according to one or more classifications, such as land costs, soil type, and so forth, and the subsequent application of the data to highway location, design, and construction.

an appropriate interval and cross sections measured photogrammetrically. He again finds himself in the advantageous position of being able to request control for this large-scale mapping which, if properly spaced, monumented and targeted on the ground, (a) will form the basic X, Y, and Z coordinate control for the photogrammetric work; (b) will form the basic control for all further highway project surveys, such as land (property) surveys, utility relocation, municipal and soil investigations, and the subsequent location and construction surveys; and (c) will supplement the national network of basic control within that province or state.

To insure that this control remains unaffected as much as possible by future construction of the project, it is necessary that it be approximately positioned jointly by the photogrammetric, design, and construction engineers. The horizontal control, measured with electronic distance measuring instruments, would be based on the second order control as established during Stage II, and would be measured to at least third order accuracy with survey station markers set every 500 to 1200 ft (with increased density of markers at proposed interchange sites) along the route band of topography. The vertical control would, at this time, be monumented and surveyed by precise leveling methods with bench marks every 0.2 to 1.0 mile along the general route.

Under the direction of the photogrammetric engineer, the standard photogrammetric procedures would be carried out. The horizontal and vertical control points would be targeted, flying to take the large-scale photography would be done, and the aerial triangulation and stereoscopic compilation of the maps and measurement of profile and cross sections with precision photogrammetric instrument would be accomplished. The large-scale topographic maps are passed to the design engineers along with prints of the aerial photographs, the survey report, and other pertinent information. Thus, these engineers are provided with an integrated and complete set of information for design of the highway. By using these sources the design engineers are able to determine each possible centerline, to measure the horizontal coordinates of the centerline, to calculate the related highway geometrics and the centerline description, and to plot it on the maps. Then, using the typical design cross sections and measured profile, the centerline design is completed as required. This procedure makes it possible to investigate and compare each feasible location for the centerline and to confirm its suitability and select the best.

Once the centerline has been designed, the design engineer forwards its computed description and plane coordinates to the photogrammetric engineer, who, using his original photogrammetrically compiled manuscripts, accurately plots the centerline, places the same large-scale photography back into the photogrammetric instruments and measures the profile and cross sections. Thus the necessity of substantiating the findings of the design engineer with a ground survey of the centerline, or related lines, has been completely eliminated.

It would be to the advantage of the project if the photogrammetric engineer while doing the large-scale mapping, on completion of such work with each stereoscopic model, could measure cross sections within the area of the model in relation to any baseline as defined in the plane coordinate system. The design engineer would then receive the large-scale detail maps and cross sections of his area of interest before starting the design work. Using the electronic computer and the DTM approach, he could obtain cross sections, profiles, and grading quantities for each possible alignment by defining the plane coordinates of the control points and feeding them to the computer along with the DTM for the particular route band of topography under consideration and the required computer programs. Work in this stage results in a designed location for the highway and detailed construction plans.

STAGE IV—LOCATION SURVEY AND CONSTRUCTION

The construction engineer is interested in physically constructing the highway according to the construction plans, and in determining the quantities of material required to do the work.

Hence, it is only at this stage that a survey party needs to physically establish the centerline and related lines on the ground. To facilitate this location survey, the construction engineer can establish the position of any point or line on the ground by trisecting, using accurate theodolites on previously placed station marker monuments for which the plane coordinates were determined in Stage III. This plane coordinate approach to surveying simplifies the location and construction staking, and is indispensable when it comes to staking complex interchanges and modern highways. Computer programs give the horizontal angles directly to each survey instrument, thus minimizing chances for human error and the accumulation of errors throughout any one project.

The construction engineer utilizes the cross sections measured with the precision stereoscopic instruments during Stage III. It would be desirable if the same DTM as described in Stage III was used for this phase. The construction engineer would simply define the reference baseline in horizontal X and Y coordinates, a line which could be conveniently occupied in the field. Cross sections would then be obtained by using the coordinates of the baseline, the DTM information, and the appropriate programs in the computer.

PHOTOGRAMMETRIC PROCEDURES

The Department of Highways, Ontario, has four KPP-3 Kelsh stereoscopic plotters, two of which are equipped with coordinatographs and electronic digitizing equipment for measuring the X, Y, and Z coordinates within each stereoscopic model. These units are utilized for aerial triangulation and for measuring profile and cross sections.

Aerial Triangulation

All basic horizontal ground control is measured with electronic distance measuring instruments and targeted before photography is taken. All stereoscopic models are bridged for establishing supplemental horizontal control. The photographic diapositives are prepared for aerial triangulation with the Zeiss Snap Markers. The steroscopic model is placed into the Kelsh instrument and inner and relative orientations are made; the model is approximately leveled onto detail within the stereoscopic model or onto available vertical control. The model coordinates of control points and pass points are measured and automatically recorded onto computer cards, with each model in the strip being processed similarly and independently; the model computer cards are processed by electronic computation. (Our computer program performs a linear conformal transformation, with a least squares solution between successive models of the strip, and a linear conformal transformation with a least squares fit of the strip coordinates to the ground coordinates.)

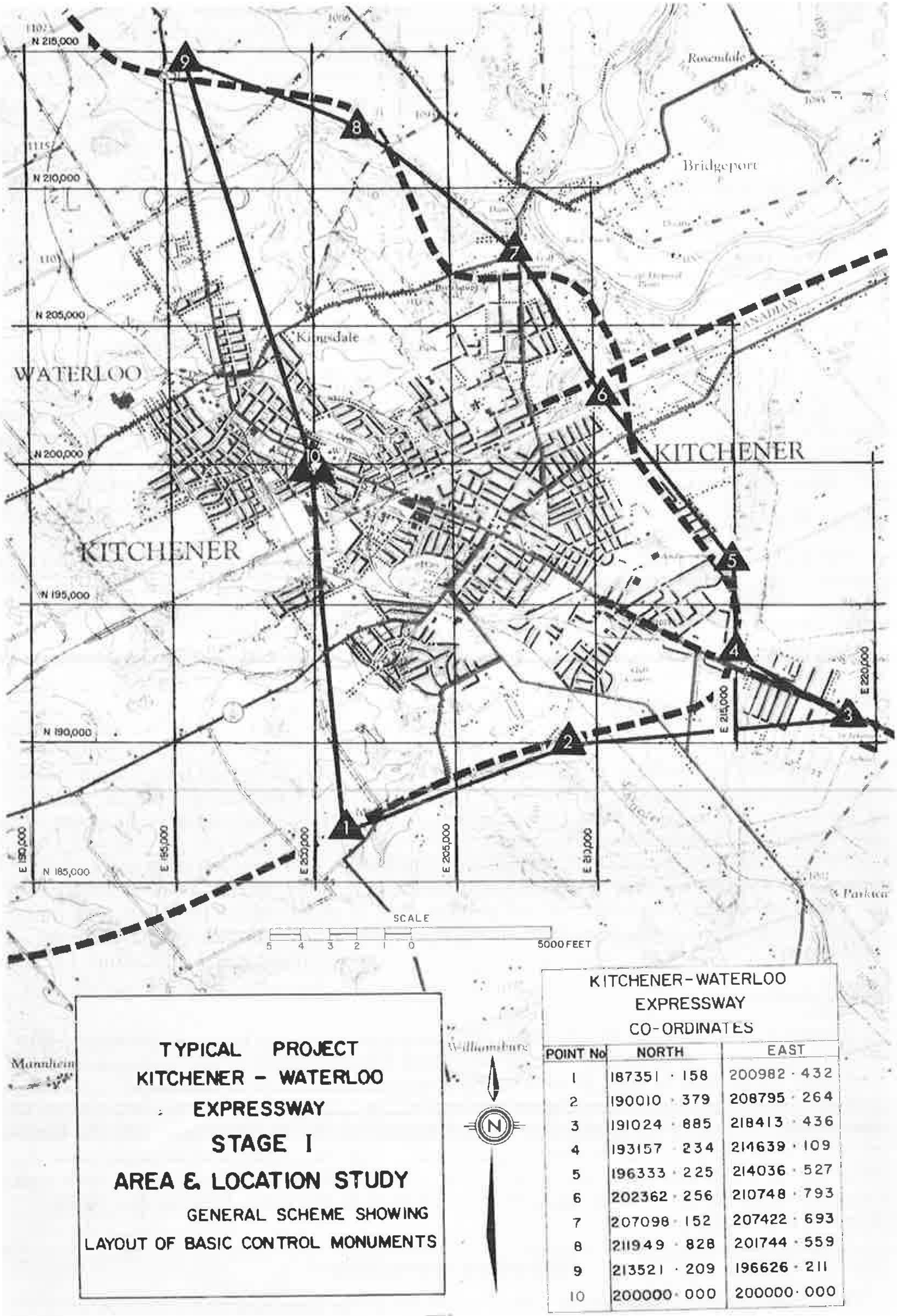
From a highway engineering production standpoint, this procedure is quite ideal. Our experience on all projects shows that the density of horizontal control required for other phases of the project is far greater than is required for the photogrammetric method procedures, indicating that more sophisticated procedures appear to be unwarranted.

Cross Section Measuring

Having established the location for the centerline from the large-scale maps, the design engineers compute and furnish its X and Y coordinates to the photogrammetric engineer. This line is then plotted on the original manuscript of the maps; the original photographic diapositives are placed into the Kelsh instruments and cross sections are measured. Naturally no centerline targets appear on the diapositives, only the targets of basic control points and marked pass points. Our Department is working toward adopting the DTM approach which, it is felt, will greatly facilitate cross section measuring procedures, permitting such work to be done at the same time as the initial large-scale mapping.

A TYPICAL PROJECT

The Department of Highways, Ontario, is using the approach described on several of its major projects. A 14.8-mile controlled-access facility going into construction



KITCHENER-WATERLOO EXPRESSWAY CO-ORDINATES

POINT No	NORTH	EAST
1	187351 · 158	200982 · 432
2	190010 · 379	208795 · 264
3	191024 · 885	218413 · 436
4	193157 · 234	214639 · 109
5	196333 · 225	214036 · 527
6	202362 · 256	210748 · 793
7	207098 · 152	207422 · 693
8	211949 · 828	201744 · 559
9	213521 · 209	196626 · 211
10	200000 · 000	200000 · 000

Figure 1.

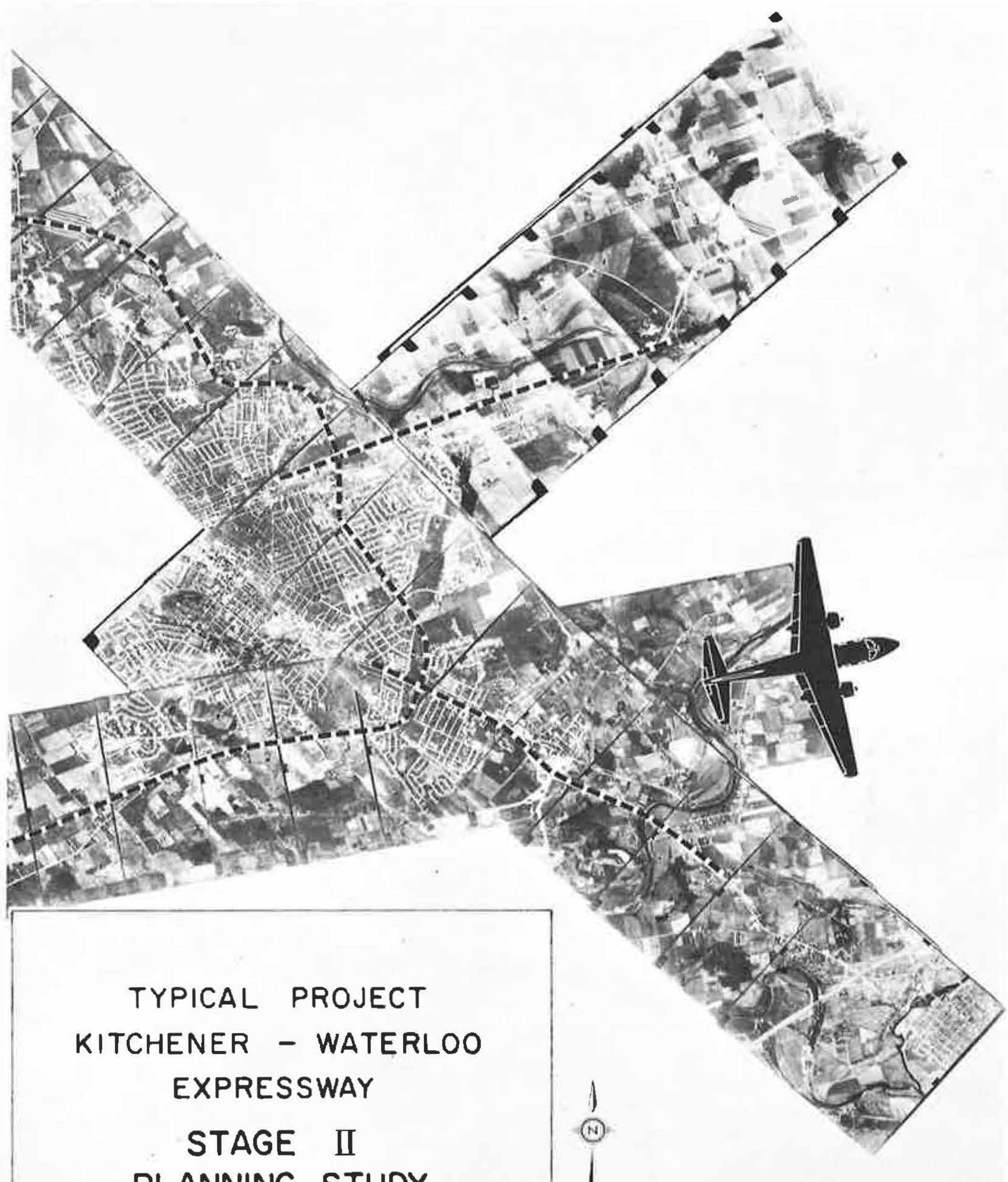

TYPICAL PROJECT
KITCHENER - WATERLOO
EXPRESSWAY
STAGE II
PLANNING STUDY
1" TO 1000' PHOTOGRAPHIC
COVERAGE
N

Figure 2.

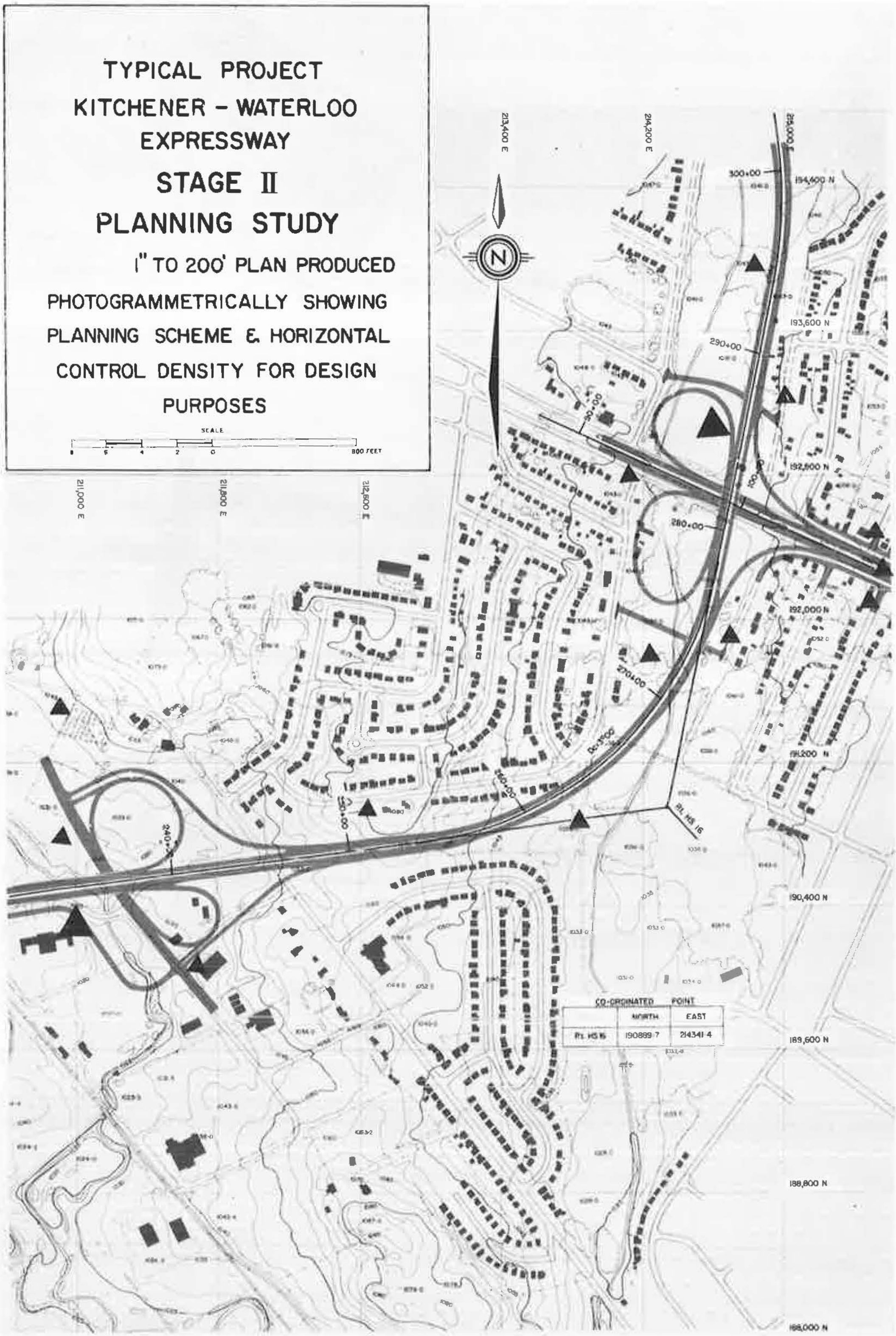

TYPICAL PROJECT
KITCHENER - WATERLOO
EXPRESSWAY
STAGE II
PLANNING STUDY
1" TO 200' PLAN PRODUCED
PHOTOGRAMMETRICALLY SHOWING
PLANNING SCHEME & HORIZONTAL
CONTROL DENSITY FOR DESIGN
PURPOSES
SCALE
800 FEET
N
211,000 E
211,800 E
212,600 E
213,400 E
214,200 E
215,000 E
194,400 N
193,600 N
192,800 N
192,000 N
191,200 N
190,400 N
189,600 N
188,800 N
188,000 N
300+00
290+00
280+00
270+00
260+00
250+00
240+00
PT. HS 16
CO-ORDINATED POINT
NORTH
EAST
PT. HS 16
190889.7
214341.4

Figure 3.

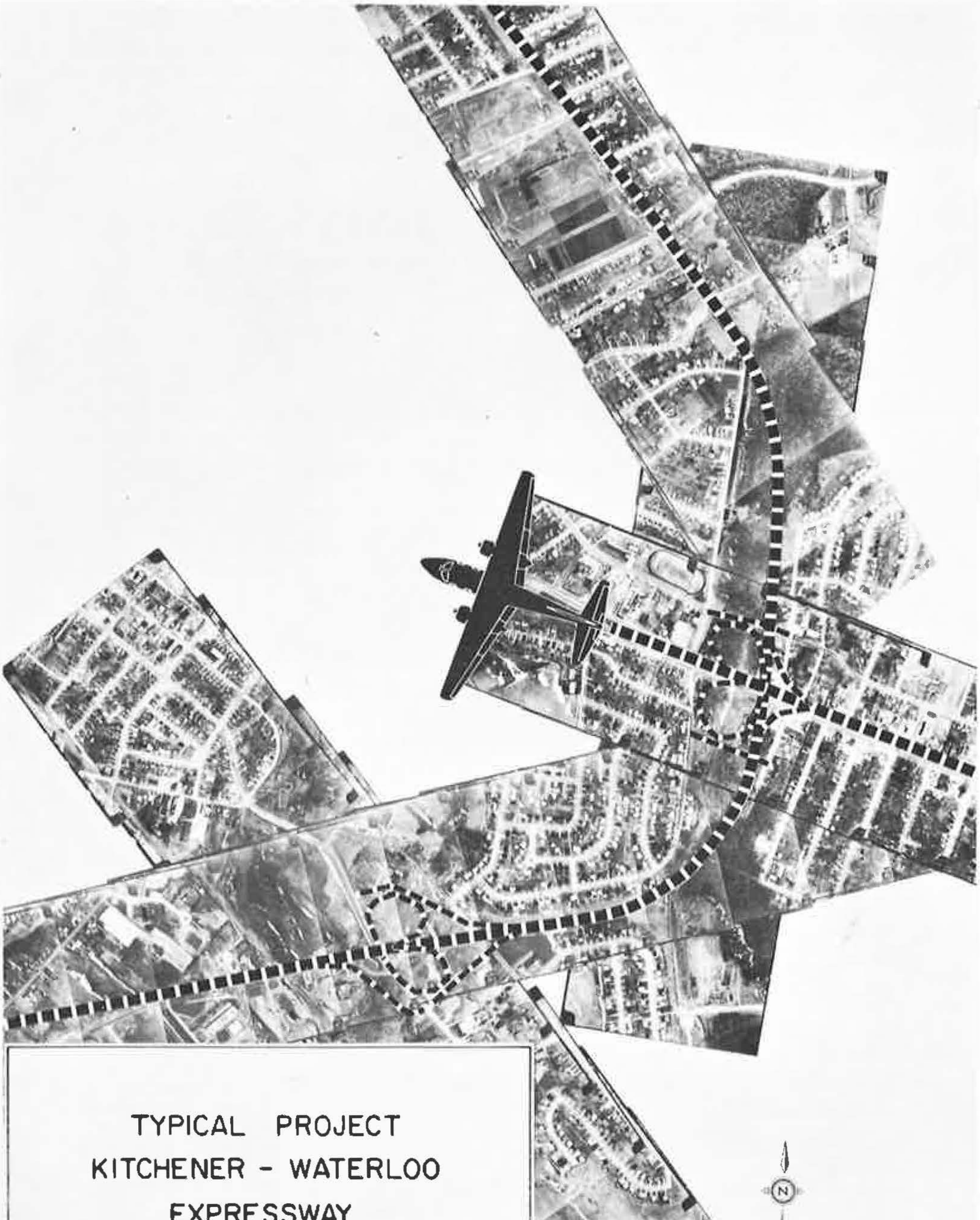

TYPICAL PROJECT
KITCHENER - WATERLOO
EXPRESSWAY
STAGE III
DESIGN
1" TO 200' PHOTOGRAPHIC
COVERAGE
N

Figure 4.

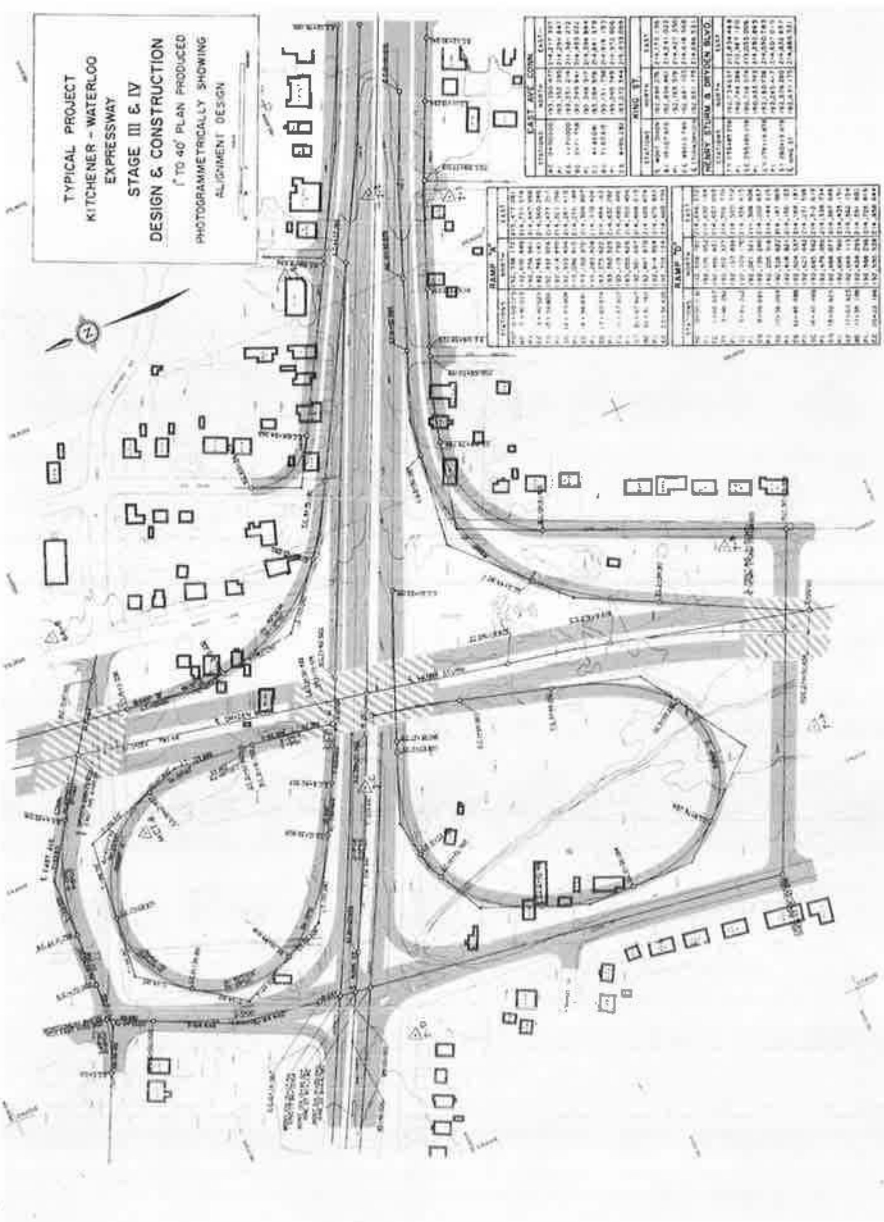

TYPICAL PROJECT
KITCHENER - WATERLOO
EXPRESSWAY
STAGE III & IV
DESIGN & CONSTRUCTION
1" TO 40' PLAN PRODUCED
PHOTOGRAMMETRICALLY SHOWING
ALIGNMENT DESIGN
EAST AVE. CONN.
KING ST.
HENRY STURM & DRYDEN BLVD.
RAMP "A"
RAMP "D"

Figure 5.

this year in the area of the twin cities of Kitchener-Waterloo, Ontario, presents a good workable example (Fig. 1). Because this project had progressed into the preliminary survey stage before the 200 ft per in. topographic maps had been compiled photogrammetrically, such maps were not used exclusively during this phase. A portion of the project was mapped photogrammetrically as well as by ground survey, and a comparison proved the photogrammetric approach to be far more advantageous.

Control points marked by monuments on a plane coordinate system were established every 1 to 1 ½ miles along the proposed route corridor. This control was measured with a Tellurometer and targets were placed on the points before the photography was taken. Figure 2 shows the photographic coverage detained at 1600 ft per in.

Standard photogrammetric procedures of aerial triangulation and stereoscopic plotting were used to compile topographic maps at the usual scale of 200 ft per in. with contours at 5-ft intervals (Fig. 3). After the initial preliminary survey had been made and centerline location designed, the density of basic control was increased with a Geodimeter. Four-foot iron bars or plugs were set every 500 to 1,100 ft along the route corridor outside the probable area of construction and at an increased density in all intersection areas.

Precise leveling was performed to measure the elevation of 70 monuments throughout the length of the project. Basic horizontal and vertical control points to be used for subsequent photogrammetric work were targeted before the photography was taken. The targets used were either painted marks on the edge of the existing pavement or 2-ft-square pieces of tar paper with a distinguishing shape silk-screened onto them in yellow paint. These targets are very suitable because they are small, economical, have built-in contrast and provide a man-made shape as the photographic image.

The aerial photography was taken at the photographic scale of 200 ft per in. (Fig. 4). Aerial triangulation was done to establish supplemental control and 40 ft per in. topographic maps with contours on a 2-ft interval were compiled (Fig. 5). Special sepia paper reproductions of the original map manuscripts were supplied to all interested parties as soon as they were completed and edited by the stereoscopic plotting section. This procedure permitted the various operations of soil investigation, utility relocation, municipal survey, land (property) survey, bridge and railway design, and highway design to proceed without the two-month time lag required to field check and draft for reproduction and use the 1:480 scale maps.

The highway design engineers use these maps to design the centerline by considering any number of location possibilities, measuring the coordinates of the designed centerline on the maps, adjusting these coordinates slightly to facilitate future field staking, and calculating all route geometrics and the centerline description. The plane coordinates of the centerline are furnished to the Photogrammetry Division, the centerline plotted on the original manuscripts, the original diapositives placed into the Kelsh instrument, and the cross sections measured in the usual manner. The cross sections are used initially for accomplishing the design and later for staking the highway for construction. The construction plans are used by the design engineer for contract preparation, and are photographically reproduced and used as removal plans, paving and alignment plans, grading and drainage plans, and detour plans.

The centerline of the designed highway has not been occupied and will not be surveyed until the construction contractor occupies the basic control points and trisects to physically establish centerline stations for construction purposes. The design engineer has done only a normal amount of field surveying to verify to his own satisfaction certain design control measurements on the ground. Only a token number of the cross sections have been field edited and fonnd to be well within requirements of both design and construction.

CONCLUSIONS

The conclusions are self-evident:

1. The photogrammetric method is capable of providing the various highway engineers with integrated and complete information, enabling them to consider all surface qualitative information and quantitative data in one clear pattern.

2. The system allows the highway engineers to function quickly, efficiently, economically, independently (to a large extent), and with a minimum duplication of surveying, at the same time ensuring an integration of all phases of the project.

Automation in Map Data Collection for Engineering Computer Programs

DONALD E. WILBUR, Assistant Chief of Photogrammetry, Pennsylvania Department of Highways

This paper reports the methods and procedures currently used by the Pennsylvania Department of Highways in the collection of map data for engineering computer programs as required by the highway planning staff. The extraction and correlation of the necessary map and textual data and the recording of this information on IBM cards through the use of an Electronic Coordinatograph and Recording System attached to an IBM 526 Summary Punch, the processing of this information on the IBM 7040 computer, and the plotting of the resultant data by the 3500 Dataplotter are detailed.

•THE DEPARTMENT of Highways in Pennsylvania is presently responsible for 43,000 miles of existing state highways as well as planning for the highway needs of the future. In determining future highway needs, many factors must be considered. One of the more important factors is the current and proposed future use of the roads in any given area. This factor, known as traffic count information, is obtained by portable and permanent counting devices and also through visual observation by department personnel. Other factors include type of surface, roadway width, structure capacity, and related data on the existing network.

In years past, the efficiency of the highway planning staff has been hampered because of the lag between the time the traffic count was recorded and the time it finally was correlated with all other associated information and the result portrayed in map and tabular format. The reason for the delay was the volume of the information involved and the manual tabulating, recording and map tracing that was required. As a result, much basic information was becoming obsolete before it was in the hands of the highway planning staff in usable form. To correct this situation, the department purchased an Electronic Coordinatograph and Recording System (ECARS) and a Dataplotter which, with the IBM 7040 computer, would provide the department with a system which would greatly improve its efficiency in map data collection.

TECHNIQUES AND PROCEDURES

Digitizing Legislative Route Information

Selection and Use of Source Materials. —The initial step in the project was to select the type of base map best suited for job requirements. The map series selected was the General Highway maps which are prepared on each of the 67 counties in the state. These maps are 36 by 49 in. in size, at a scale of 5,208 ft to the inch, prepared on the polyconic projection. They are planimetric maps showing the complete road and railroad network, hydrographic features, county, city, township and borough boundary lines, and other minor cultural features. Each road segment, either a state or town-

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ship road, is identified by number on these maps. In Pennsylvania, all highways under the jurisdiction of the Commonwealth are known as Legislative Routes. These legislative route numbers are commonly referred to as LR numbers. They are not the same number and should not be confused with the traffic route numbers, such as U.S. Route 30, Interstate Route 83, or Pennsylvania State Route 137.

Preparation of Materials for Measurement. —The Pennsylvania State Plane Coordinate System was selected to be used as the X-Y coordinate system, the primary reason being that coordinates of points measured in this system would have a true geographic location relationship. Thus the possibility was eliminated of any two points in the state having the same coordinates, which might have occurred had an arbitrary grid system been selected. Also, easy-to-use tables were available for converting the geographic coordinates appearing on the maps to their equivalent north and east grid coordinates based on the Pennsylvania State Plane Coordinate System.

A master grid sheet was prepared with grid lines at a 3.84-in. interval. This master grid sheet together with the State Plane Coordinate tables was used to construct and draft the State Plane Coordinate System on these maps with grid lines at a 20,000-ft interval in both the north and east direction.

The textual information which was required to be correlated with the map data was in the Straight Line Diagram Books. A straight line diagram of a highway is a drawing which shows only the lineal character of the road as opposed to horizontal and vertical curvature. It documents important characteristics of the road such as original date of construction; type of surface; width of surface; intersection of road with other roads, railroads, and boundary lines; and locations of bridges, culverts, and so forth.

Each of these features is located in the straight line drawing with a stationing value. Each legislative route has a point of beginning which is assigned a 0+00 station value, with the stationing continuing to the end of that particular route.

All of the state legislative routes within a county are numbered in sequence, and the LR diagrams are bound in books in this numerical order.

A tabular listing was prepared prior to the actual measuring operation as an aid in monitoring the digitizing of each legislative route as it was completed. This listing contained all the legislative routes in the county in the same order as in the straight line diagram book. The mileage of each route and the measurement zone were also recorded. Measurement zones, outlined on the map, were required because of the 30 x 30-in. limitation of the coordinatograph. In most cases, the dimensions of the map area being measured were greater than 30 in. The beginning and ending location of each legislative route determined whether the route was entirely within one zone or extended into more than one zone.

IBM Card Format Used

Card Columns	Data Assigned
1 through 6	Blank
7 through 10	Card number
11 through 12	County code number
13 through 18	Legislative route number
19 through 24	Station value
25 through 26	Type of point
27	Blank
28	Normal or abnormal spur coding on LR
29	Blank
30 through 36	East coordinate value
37 through 42	North coordinate value
43	Blank
44	End of record punch
45 through 80	Blank

Because of the requirement for 44 card columns to record each coordinate point together with its identifying information, more than one point per card was not possible or desirable.

Coding of Points Recorded.—For the requirements of this project, coordinates were desired on numerous points along each legislative route. Following is a listing of the types of points recorded and how they were coded in columns 25 and 26 of the IBM card.

High Order of Type (first column)

Code	Description
1	Intersection with legislative route
2	Intersection with township road
3	Intersection with railroad crossing
4	Intersection with bridge
5	Intersection with municipality line
6	Point on a line (deviation from path)
7	Discontinuance of the LR to be continued separately after traveling jointly with another LR

Note: Code 7 implies presence of Code 1 conditions.

Low Order of Type (second column)

Code	Description
1	Intersection with legislative route
2	Intersection with township road
3	Intersection with railroad crossing
4	Intersection with bridge
5	Intersection with municipality line
6	Point on a line (deviation from path)
7	(Back station of an equation point) or (Back station of a discontinuance)
8	(Ahead station of an equation point) or (Ahead station of a discontinuance)

A zero was used in the second column to indicate a null condition. A null condition for the first column was not allowed. Briefly the rules used in determining the code of each point were as follows:

The priority of importance of the codes was the same as their numerical value; for example, an intersection with a legislative route takes precedence over an intersection with a township road, and so forth.

The code with the highest priority was assigned to the first column of type. If a second condition existed, it was given its respective code and placed in the second column of type. In situations where a third condition existed, it was ignored.

In the case of a normal equation point, the code of the place at which it appeared was put in the first column and the "back" and "ahead" designations were placed in the second column. In the case where this equation point occurred at an otherwise undesignated point, a code for a point on a line was given in the first column and the "back" and "ahead" designations were given in the second column.

A code 7 in the first column has a higher priority than a code 1 by the nature of the meaning of the code 7 (a code 7 is a code 1 with an expanded definition). In the second column, codes 7 and 8 were the most privileged codes and, also, were the only codes allowed with a code 7 in the first column. Thus, the order of priority of the numerical codes for type of points is: First: 7, 1, 2, 3, 4, 5, and 6. Second: 7 or 8, 1, 2, 3, 4, 5, and 6.

The numeric coding used in card column 19 to designate legislative route spurs was as follows:

Code	Description
1	Spur E
2	Ramp or Wye "W"
3	Parallel
4	Spur A
5	Spur B
6	Not used
7	Spur with no letter designation
8	Spur C
9	Spur D
99	Card columns 19 & 20, application route

Operation of the Coordinatograph and Recording System.—The initial operation positioned the map on the tilted surface of the drafting table under the arm and cursor of the coordinatograph. The map was positioned in such a way that the X and Y travel of the cursor was coincident with the east and north grid lines on the map so that an entire zone could be measured without shifting the map.

The next operation was to adjust the X and Y measurement scale factors on the digitizing console. The console was set up for 50 counts per inch on variable measuring scale. The measuring was adjusted slightly from the 50 counts per inch to compensate for the instability in the paper on which the map was printed. After the measuring was completed satisfactorily, the X and Y digital volts meters were indexed to read the east and north State Plane Coordinate grid values as indicated on the gridded map. Upon completion of this phase, the basic setting up of the system was complete.

The actual operation was performed with two operators. One man moved the cursor over the path of the route on the map and changed the data switches to reflect the type of point being recorded. The other man, seated at a table, was required to scan the straight line diagram, extract the necessary information, and set it on the data switches on the digitizing console.

Prior to the start of tracking each route, the man at the console would tell the cursor operator the legislative route to be tracked and where the point of beginning or 0+00 station was located. During the time the cursor operator was locating the starting point, the man at the console would verify that all data switches and the card counter were properly set.

As the cursor operator would move the cursor from one point to another along the route on the map and change the type of point code, the man following his progress along the route in the straight line diagram would set the proper station value on the digitizing console for each point as indicated by the straight line diagram.

To show proper character in the routes, the coordinates of points on curves were recorded at varying intervals. These "points on line," as they were called, did not appear in the straight line diagram book. To determine station values for these points, a circular scale prepared on mylar was superimposed under the reticle in the cursor. This allowed the operator to make rapid measurement approximations of distances on the map. He would use this measurement to determine distances to points on line and call them out to the man at the console. This distance would then be added mentally to the station value of the last known point and the new station value placed on the console.

The two would continue the tracking of each route from beginning to end. A very close coordination and communication between the two operators was necessary to assure that, for each and every point recorded, the location of the measuring cursor was the same point on the map as the station value indicated in the straight line diagram, and that the point was receiving the proper coding.

As previously mentioned, the 30 × 30-in. measuring range of the coordinatograph made it necessary to subdivide the maps into measurement zones. On the maps which contained more than one measuring zone, there were many routes which could not be completed with one setting of the map. As these routes were done, the partially completed deck of cards was removed from the stacker of the 526 and set aside with a note attached as to the zone in which the measuring of the route would continue. After digitizing all the complete and partial routes in a measurement zone, the map was shifted and reset for the next zone. As the digitizing progressed in this zone, the partial card decks would be placed back in the card stacker and the remaining portion of the route digitized. Because each card on each route was automatically numbered sequentially with card no. 1 at the beginning or 0+00 station and the last card number being determined by the length of the route and how many points were recorded, it was always necessary to digitize the beginning portion of the route first in cases where the route traversed more than one measurement zone. The maximum number of measurement zones ever required was four. Even with only four such zones, however, the order of digitizing them most efficiently with a minimum number of resets was not always easy to determine.

To produce a complete map, the perimeter of each county was also digitized. This was accomplished concurrently with the LR digitizing of each county. However, the card decks containing the county perimeters were kept separate from the legislative route decks.

At the end of each day's operation, the cards were edited on an IBM 101 for double punches, blank columns, and coordinate transfer failures. Error cards found were corrected immediately.

Computer Processing

The second phase of the complete operation was the computer processing of the information obtained from the ECARS. A series of four separate computer program operations were performed, followed by a manual edit of the results prior to writing the instruction tape for the Dataplotter.

The complete original card deck as it came from the ECARS was sorted on an IBM 083 or 084. This sort was performed on card columns 30-36 inclusive. In this field, the 7-digit east coordinate of each point is recorded. The purpose of this sort was to put the complete card deck in ascending order by east coordinates with the first card having the lowest east coordinate value and the last card having the highest east coordinate value.

This card deck was read by an IBM 1402 into an IBM 7040 computer. The computer routine performed a selective match of coordinates. Because the resultant map was to show only the legislative route pattern, the computer was instructed at this point to look for coordinate matches only between points with either a digit 1 or a digit 7 code in the high order type card column 25; that is, intersections of one legislative route with any other legislative route. In scanning the deck, if the coordinate points of two cards were within 200 ft of each other, they were considered a match. All information from these two cards was then written on magnetic tape as one record. Each of these records contained the images of the two matched cards. No magnetic tape record contained more than two card images. The cards that had no match were written into single card image magnetic tape records. The output of these matched and unmatched points was in binary-coded decimal and fixed-point mode on the magnetic tape. The record formats for the matched and the unmatched points were similar but not identical.

The records on this tape were then sorted first by LR number, then by spur designation, which is a prefix to the LR number, and last by card number. This placed them in numerical order with all the main legislative routes together, the primary routes first and the secondary routes following. Legislative routes having spur prefixes were in place directly following the legislative route. All application-type legislative routes were at the end.

This tape was then read into the computer again and a coordinate averaging routine performed. In matching the coordinate points originally, a difference of 200 ft in either the north or east coordinate was allowed. Due to unavoidable inherent errors in the coordinate measuring process, this amount of variance was necessary to effect a proper match. Although in some cases the matched coordinates differed by as much as 200 feet, they did in reality represent a single position on the map.

The averaging routine read in the records having the matched coordinate points, and computed a mean north coordinate and a mean east coordinate. This mean coordinate was written into the tape to replace each of the coordinate values used in the averaging process.

This computer routine also checked all coordinate points that were coded as equalities to verify that they were in proper sequence with every "X7" or back-station value point, followed directly by a "X8" or ahead-station value point. If the equalities were in proper order, a two-letter code was written into the tape to indicate this.

The number of equalities for each legislative route were counted by the program and written under a separate name on the magnetic tape for future use.

The concluding computer operation prior to the edit was the production of a printed tabular listing and two identical tapes containing the same information that was being printed on the tabular listing. The generation of two tapes rather than one was for safety reasons in case one was accidentally erased.

The tabular listing contained all the legislative routes of the county and all of the stations where the traced legislative route intersected other legislative routes. At any station along the LR where a matching coordinate should have been found but was not, a "None Found" message was printed together with the station value. Messages which indicated bad equality sequencing were also printed out when the condition was present. The highest and lowest east and north coordinate value were printed at the end of the tabular listing.

This listing was reviewed and wherever an error condition was noted, the original card deck was checked and the necessary corrections made. The deck was then rerun through the preceding computer processes until the final set of coordinate information was error free.

After the edit was performed and the necessary corrections to the cards made, an instruction tape for the Dataplotter was prepared. The input source for this was the complete card deck of all legislative routes plus the card deck containing the county perimeter.

The scale of the finished plot was the same as the original map from which the coordinates were measured. Although the commonly accepted scale of these maps was 5,208 ft to one inch, it was found that a factor of 5,204 ft to the inch was necessary in the computer calculations to have the plot properly fit the map. This discrepancy was due to the instability of the paper it was printed on. The coordinates were recorded to the units position; however, the units and the tens positions of all coordinate values, both north and east, were dummy zeroes wired in from the patch panel on the IBM 526. Therefore, in any 6-digit coordinate value such as 432,600, only the digits 4,3,2, and 6 were significant. Because the last two digits were always zero, they were dropped in all computer calculations.

The coordinates of the points making up the county perimeter were tested to determine whether the difference in the high and low east coordinate or high and low north coordinate was greater. This was necessary, because the usable plotting surface area on the Dataplotter was 38 in. in the Y direction and 58 in. in the X direction. If this test result indicated the coordinate spread in the north coordinates exceeded the spread in the east coordinates, then the north coordinates of all points were multiplied by a minus one. This, in effect, rotated the resultant plot by 90° clockwise so it would be positioned properly on the plotting surface.

The mean north and mean east coordinates were computed, and this point was designated as the center of the usable plotting surface. The mean value was then subtracted from the coordinates of every point making up the complete set of data. The resultant values, now having negative and positive signs, were still in units of feet. These distances in feet were divided by 5,204 to determine the length in inches.

To utilize the maximum plotting accuracy potential of the Dataplotter, the full 20,000 counts were used over the full dimensions of the plotting surface. In the X direction, it was 20,000 divided by 60 inches resulting in a scale factor of 3,333 counts per inch; and in the Y direction, it was 20,000 divided by 45 inches resulting in a scale factor of 4,444 counts per inch. This factor multiplied by the distance in inches determined the board count values necessary for the Dataplotter to travel the required distance.

Each tape record for the Dataplotter contained the signs of both X and Y, the count values of the coordinates, and the command such as lower pen or raise pen. This input tape for the Dataplotter was prepared in binary-coded decimal form.

Legislative Route Network Plot Preparation

The plotter which the Department is using to prepare the final plot of the legislative route network with each county is a Dataplotter, Model 3500, manufactured by Electronic Associates, Incorporated. This plotter has a nominal plotting surface of 45 in. in the Y axis and 60 in. in the X axis. However, the usable area is only 38 x 58 in. because of the requirement of two printing heads—one for symbols and one for line plots. These two heads are mounted adjacent to each other on the X rail.

The plotter can be directed manually from the keyboard, from IBM cards read in by a 514 summary punch or from magnetic tape. The plotter operates from digital information in binary-coded decimal form which is obtained from the magnetic tape prepared by the IBM 7040 computer. The data are converted to direct current analog voltages and stored. The stored data are used by the plotter to make a graphical representation of the digital input information. The plotter has the capability of line plotting or point plotting.

For line drawing, the plotter is equipped with a plotting head containing eight pen wells in a revolving cylinder. Leroy-type reservoir pens containing various colors of ink and different size pens are inserted in these pen wells. These pen wells are numbered so that the computer programmer can write the appropriate instruction to the computer to select the desired pen. The programmer also instructs the computer to write into the tape additional commands to the Dataplotter to raise and lower the pen at the proper time and to activate the automatic paper advance mechanism prior to the start of each plot.

The additional head is for point plotting using selected symbols, numbers and letters, up to a maximum of 48 characters.

Prior to loading the magnetic tape unit, the plotter operator was required to manually set the proper scale factors in counts per inch for both X and Y. The offset value for the origin of the plot was included on the input tape if it was different from the board origin.

The plots were prepared on drafting paper in roll form 42 inches wide. It was of sufficient transparency to allow a visual check when overlaid on the original map.

CONCLUSIONS

As of the writing of this paper, approximately 5,700 man-hours have been spent in measuring the coordinates with the ECARS. Fifty-eight of the 67 counties in the state are now completed, which consists of about 36,000 miles of legislative routes now in digital form on IBM cards.

The most significant problem encountered in digitizing the legislative routes was the one of incompatability of the straight line diagrams and the maps. Some of the straight line drawings were dated back in the 1920's and some of the maps were dated back to 1941. The agreement between them varied considerably from excellent to poor and in a few cases unusable. There were certain legislative routes in some counties which could not be digitized. New maps and updated straight line diagrams, however, are continually being produced and published. After the initial completion of the 67 counties, an updating program will be started to insure that the most recent road network additions, deletions, and changes are reflected in the master deck. It is estimated that the time requirements for maintaining these card decks will be less than 2 percent of the time originally required to digitize the complete legislative route network within each county.

All of the computer programs for the system were developed and written by the programming personnel of the department. The average computer time required per county was 45 min, with an additional 45 min for the Dataplotter to delineate the legislative route network.

A total of 51 counties have had the initial computer run completed. Of these 51 counties, 20 have been edited, corrections made, plotter input tape written, and test plots made with the Dataplotter. Of the 20 plots prepared, 17 will require additional refinement and elimination of errors not previously detected.

A major problem encountered and not solved was the annotating of place names, legislative route numbers, stationing of traffic count figures, and the figures themselves. The placement of these annotations on the plot was not possible at the scale of the original map. Overprinting of the lettering was common even in moderately dense areas. Enlargement of the plotting scale was considered but found not feasible due to the numerous additional problems it created. Another alternative considered was line drawing the annotations rather than printing each character with the symbol printer. Each and every letter would require a series of coordinates to describe it. This also proved unfeasible because of the excessive computer and plotting time required.

At the present time, the final product is a complete network of all legislative routes enclosed in a county perimeter.

In forthcoming operations, data relating to the existing routes to include surface type, widths, and structure capacities will be added to the card decks and thus make a relatively complete inventory.

A Numerical Method of Orientation for the Kelsh Plotter

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•IN LARGE-SCALE photogrammetric plotting, particularly in the field of highways, the Kelsh Plotter is one of the most commonly used instruments in North America. Although recent technical development has gone far in the design of new instruments, ranging from small refinements to automatic plotting devices, and while more and more photogrammetric procedures, from instrumental to analytical aerial triangulation, are being used to obtain photogrammetric model control, the bulk of large-scale photogrammetric plans is still produced on the Kelsh Plotter.

At present a significant amount of work time is still being spent on model orientation. The ratio of time spent for orientation vs plotting may vary from 1:4 to 1:10, depending on the amount of detail in the model, while the ratio of time spent for orientation vs cross-sectioning for highway work may amount to 1:1 or 1:2.

It is therefore appropriate to suggest how the time spent for model orientation may be improved by other methods of orientation. One disadvantage in present trial-and-error procedures is the necessity of repeating the orientation procedures for relative and absolute orientation a number of times before y-parallaxes are removed and before scale and elevation differences are eliminated between model and control points. There is no doubt that a faster convergence for the relative orientation procedure and a direct setting of absolute orientation elements can be made possible by numerical orientation procedures.

Numerical orientation procedures as yet have not been applied to Kelsh Plotters since the instrument itself has no scales for the direct measurement of projector translations or rotations. Suggestions in the past have thus been along the lines of incorporating counters for projector tip, projector tilt and projector swing in the instrument, as well as making provisions for small projector translations perpendicular to the base in y and z directions. This implies the need for modification of the plotter or for a new instrument, entailing additional expense which may not be in proportion to the advantages gained.

This paper makes suggestions how numerical orientation can be applied to Kelsh Plotters without modifications of the instrument. Such numerical orientation can be applied to (a) relative orientation according to measured parallaxes, (b) absolute orientation according to control points, and (c) setting of precomputed orientation elements, determined from instrumental or analytical aerial triangulation. The latter two applications will be the most economically significant, while the first will be of interest in areas where trial-and-error relative orientation has a slow rate of convergence, such as in hilly terrain.

The introduction of any numerical orientation method will require three conditions:

1. The possibility of measuring or obtaining initial data with which calculations are to be performed. These are the y-parallaxes in the case of relative orientation, the scale and height differences for absolute orientation and the camera vector for the setting of orientation elements.

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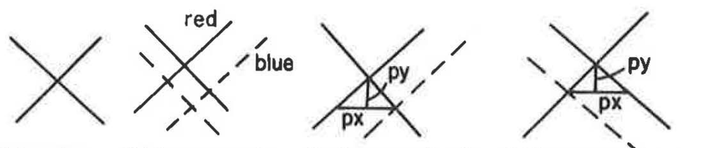

Figure 1. The use of a diagonal cross for parallax measurements.

2. The calculation of tip, tilt, swing and base length in the Kelsh Plotter system out of y-parallaxes, scale and height differences or coordinate transformations of the camera vector.

3. The possibility of introducing calculated model rotations into the instrument.

Since there is no device on the Kelsh Plotter projectors to make measurements, these have to be made on the tracing table. It is obvious that model parallaxes can be measured by dropping left and right images of identical identifiable points onto a base sheet. Linear measurements will be possible by ordinary scales with graphical accuracy (±0. 3 mm).

It is also possible to introduce model rotations as linear displacement of a point in x or y direction. Knowing the height of projection h, a model rotation can be transformed into a linear distance Δdx or Δdy by computation. An identifiable object can be dropped onto the base sheet after the floating mark has been brought to coincide with it. The linear distance can then be scaled off in the appropriate direction on the base sheet. The tracing table can be moved by this distance and the image is then brought to coincide with the floating mark using the rotational element.

By choosing a point close to the principal point, expressions for tilt in flight direction (ϕ) and perpendicular to it (ω) are found as

$$\text{tg } \phi = \frac{\Delta dx}{h} \text{ and tg } \omega \, \frac{\Delta dy}{h}$$

Kupfer (4) originally suggests this procedure for the simpler case of multiplex orientation procedures. Similarly, if b signifies a distance in x direction away from the rotational center, and ϰ is the swing,

$$\text{tg } \varkappa = \frac{\Delta dy}{b}$$

Assuming a graphical accuracy of ±0. 2 mm for the measurement of a point, a distance is determined with $\pm 0.2\sqrt{2}$ mm ≈ 0. 03 mm accuracy. This results, for a Kelsh Plotter height of 720 mm, in a dϕ and dω of $\pm 2.6^c$ (or ±1. 4′) and, since b/h ≈ 2/3, in 3/2 of the amount of dϰ.

NUMERICAL RELATIVE ORIENTATION

Even though a direct linear measurement of y-parallaxes to ±0. 3 mm would be possible by use of the Kelsh Plotter tracing table, it is more convenient and more accurate to use a diagonal cross (2) for the measurement of parallaxes (Fig. 1).

The cross (Fig. 1a) is superimposed or drawn on the tracing table of the Kelsh Plotter in such a way that its lines are pointed 45° off the x and y axes of the instrument. If both x and y parallaxes are present the eyes will try to merge the images with the result that two apparent images of the cross will be seen stereoscopically (Fig. 1b) in the form of two nonintersecting lines in space. The floating mark can be raised and lowered to the height of both lines (Fig. 1c, 1d) and the height difference, dh = (h/b) (px) can be measured on the tracing table counter, preferably in units in which py is to be expressed, according to

$$py = \frac{px}{2} = \frac{b}{2h} \cdot dh$$

Assuming a c-factor (= $3M_H$) of 1600 for the Kelsh Plotter and a ratio of 3:1 for the accuracy increase for points over contours ($M_H = 3m_H$) one obtains for the standard error of y-parallax measurement

$$m_{py} = \pm \frac{b}{2h} \cdot m_H = \pm \frac{m_H}{3} \approx \pm 0.02 \text{ mm}$$

which means a 15-times accuracy increase.

For computation of orientation elements one can use any existing numerical formulation, such as those by Hallert (1) or Jerie (3), with the appropriate sign changes for a chosen coordinate system.

For the system shown in Figure 2 the parallax formulas for independent pair relative orientation (the Kelsh Plotter has no by and bz) defined as corrections

$$py = dy_L - dy_L$$

become

$$py = x d\kappa_L + (x-b) d\kappa_R - h\left(1 + \frac{y^2}{h^2}\right) d\omega_R + \frac{xy}{h} d\phi_L - \frac{(x-b)y}{h} d\phi_R$$

From these, orientation formulas can be derived. As an example, Hallert's orientation formulas for measured parallaxes at 6 points (assuming a constant h) become

$$d\phi^c_L = \frac{\rho^c h}{2bd}(py_3 - py_5)$$

$$d\phi^c_R = \frac{o^c h}{2bd}(py_4 - py_6)$$

$$d\omega^c_R = \frac{\rho^c h}{4d^2}\left[2(py_1 + py_2) - (py_3 + py_4 + py_5 + py_6)\right]$$

where $\rho^c = \frac{20000^c}{\pi}$.

There is usually no need to calculate $d\kappa^c_L$ and $d\kappa^c_R$, since these are more easily introduced by parallax elimination. Their formulas would be

$$d\kappa^c_L = -\frac{\rho c}{3b}\left[(py_2 + py_4 + py_6) + \left(3h + \frac{2d^2}{h}\right)\frac{d\omega^c_R}{c}\right]$$

$$d\kappa^c_R = -\frac{\rho^c}{3b}\left[(py_1 + py_3 + py_5) + \left(3h + \frac{2d^2}{h}\right)\frac{d\omega_R{}^c}{c}\right]$$

Then $+d\phi_L$, $+d\phi_R$, $+d\omega_R$, $+d\kappa_L$ and $+d\kappa_R$ can be computed and introduced as $+d\Delta x$ at point 1 (with ϕ_L), $+d\Delta x$ at point 2 (with ϕ_R), $+d\Delta y$ at point 2 (with ω_R), $-d\Delta y$ at point 2 (with κ_L), $+d\Delta y$ at point 1 (with κ_R).

Computation will be quite fast if the constant factors are precalculated and if a form is used in conjunction with a desk or hand calculator. The orientation elements will be obtained for $m_{py} = \pm 0.02$ mm with the following accuracy:

$$m^c_{d\phi_R} = m^c_{d\phi_L} = \pm \rho \frac{h}{bd} m_{py} = \pm 0.4^c$$

$$m^c_{d\omega_R} = \pm \rho^c \frac{2h}{d^2} m_{py} = \pm 0.8^c$$

$$m_{d\varkappa^c_L} = m_{d\varkappa^c_R} = \pm\rho^c \frac{m_{py}}{d^2 b} \sqrt{\frac{3}{2} h^4 + 2h^2 + d^4} = \pm 4^c$$

Considering that the most serious model deformation is introduced by $d\omega$ and that $d\omega$ can be set to $\pm 2.6^c$, $m_H \max = (d \cdot d\omega^c)/(\rho c) = \pm 0.19$ mm, or 3 times the standard error of height measurement for a point. This means that one will be able to set the relative orientation elements by the outlined procedure within the c-factor limitation, but not as accurately as by careful trial-and-error procedure. The use of numerical relative orientation may therefore only be of advantage in mountainous models (where elevation differences amount to more than 3 percent of h), for which Jerie's orientation formulas (3), despite the more extensive computations, will lead to a faster and, in practice, equally accurate relative orientation.

NUMERICAL ABSOLUTE ORIENTATION

Absolute orientation, consisting of scaling and leveling of a model, is performed numerically by a comparison of model coordinates x_i, y_i, z_i, x_j, y_j, z_j, . . ., and ground coordinates X_i, Y_i, Z_i, X_j, Y_j, Z_j, . . ., of points $p_i p_j$. To find the proper scale it is necessary to introduce a base correction db to the base b (Fig. 2)

$$\frac{1}{\lambda} = \sqrt{\frac{(x_j - x_i)^2 + (y_j - y_i)^2 + (z_j - z_i)^2}{(X_j - X_i)^2 + (Y_j - Y_i)^2 + (Z_j - Z_i)^2}}$$

Suppose $1/\lambda'$ is the proper scale to be introduced. Then

$$db = b\left(\frac{\lambda}{\lambda'} - 1\right)$$

For the purpose of introducing db on the base bar carrying the projectors it is useful to attach or establish a reference mark, for example, by a needle scratch on the side portion of the base bar, and to measure distances to the projector chosen to be moved by a metal tape or any other suitable scale.

For the determination of common tilt in x direction, Φ, and common tilt in y direction, Ω, usually height differences are measured at the given control points (5).

If Δh_i denotes the difference, actual height of the point minus model height, both expressed in the same units in which measurements are made in the model, then one obtains for a geometrical configuration as shown in Figure 3:

$$\frac{\Delta h_R' - \Delta h_L}{sx} = \tan \Phi$$

$$\frac{\Delta h_U - \Delta h_D'}{sy} = \tan \Omega$$

$\Delta h_R'$ and $\Delta h_L'$ are interpolated proportional to their distance between Δh_U, Δh_D and Δh_L, Δh_D, respectively.

If relative orientation was performed with the base bar in level position (it can be made level using a level bubble), then Ω can be introduced by moving an object located along the line between principal points by an amount $d\Delta y$ in the appropriate direction using ω_L (or ω_R) and eliminating the y-parallax by ω_R (or ω_L, respectively):

$$d\Delta y = h \cdot \tan \Omega = h \cdot \frac{\Delta h_U - \Delta h_D'}{sy}$$

Φ can be introduced, as seen in Figure 4, by

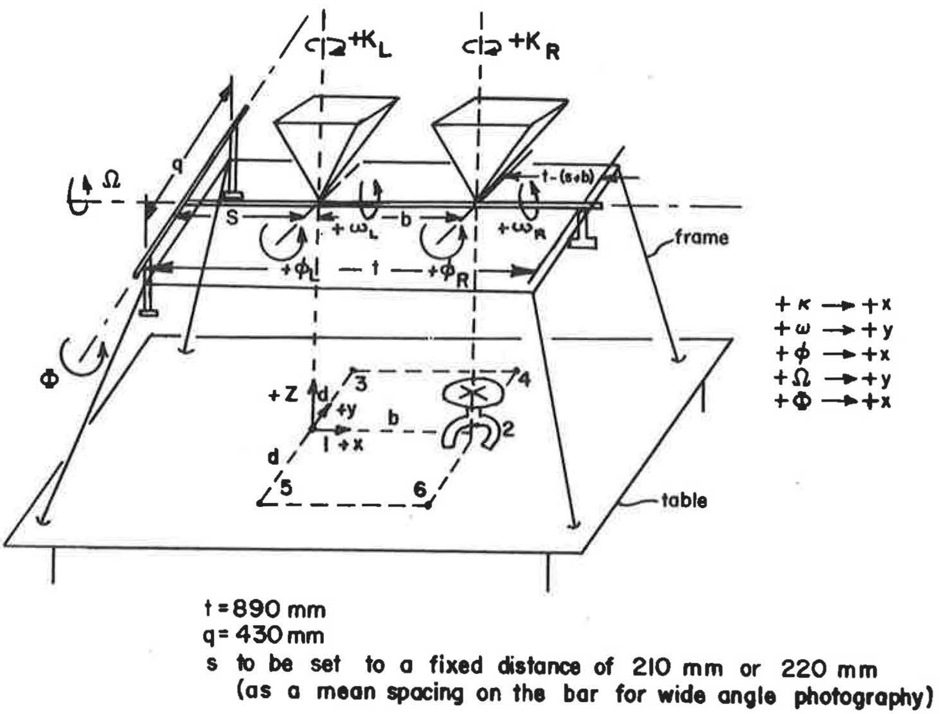

Figure 2. Definition of coordinate axes and axes of rotation for the Kelsh Plotter.

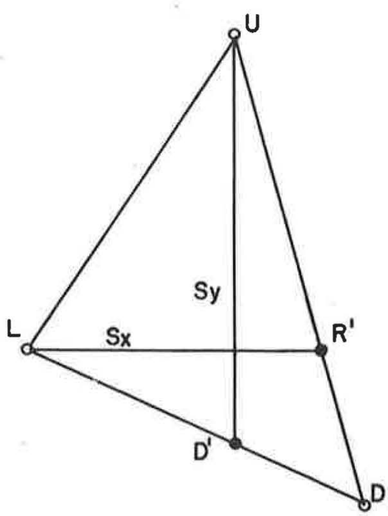

Figure 3. Absolute orientation points L,U,D, and constructed points R′ D′.

$$d\Delta x_L = \left(\frac{s}{\cos \phi}\right) + h \tan \Phi$$

if a point close to or along a line with the same x-coordinate as the left principal point is used, and by

$$d\Delta x_R = \left(\frac{s+b}{\cos \phi} - s - b\right) + h \tan \Phi$$

if a point close to or along a line with the same x-coordinate as the right principal point is used; s can be conveniently set to a fixed distance of, e.g., 210 mm (for reasons of symmetry) for all models.

On the multiplex or the balplex a common Φ rotation can of course be more conveniently replaced by individual ϕ rotations, since corrections $dbz = b \sin \Phi$ and $dbx = b\,(1 - \cos \Phi)$ can be made for these instruments.

SETTING OF PRECOMPTUED ORIENTATION ELEMENTS

Aerial triangulation techniques today and in the future will provide more and more control for absolute orientation of the models. Since, in the aerial triangulation process and its adjustment, photographs are computationally or physically oriented with respect to their relative space position,

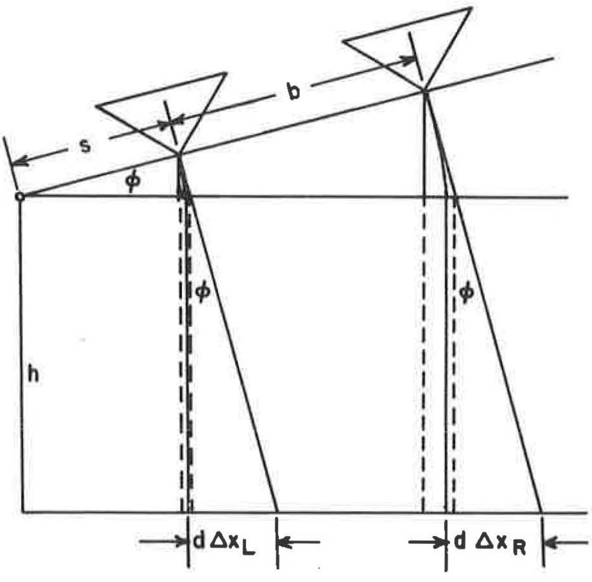

Figure 4. Introduction of Φ by $d\Delta x_L$ or $d\Delta x_R$.

it is of interest whether such orientation data can be computed and directly introduced into the Kelsh Plotter as elements of relative and absolute orientation, as a preliminary approximation by using unadjusted instrument or computation values or as computed final values derived from the adjustment.

To introduce data from instrumental and also analytical aerial triangulation, 3 problems must be solved:

1. The gimbal system of axes (primary, secondary, tertiary) of the triangulation instrument, or of the system used for formulating the analytical triangulation, has to be converted into the Kelsh Plotter system (ϕ-axis primary, ω-axis secondary, κ-axis tertiary).

2. The vectors representing the space position of the camera axis as a function of tilt, tip and swing have to be converted together with the xyz coordinates of points from the unadjusted to the adjusted values.

3. The adjusted values for tilt, tip and swing have to be rotated parallel to the airbase, since no possibility exists of introducing actual bz and by components on the Kelsh Plotter.

The problems can be solved in the following way:

1. Photo coordinates $x'y'f$ can be converted into ground coordinates xyz by aid of an orthogonal rotational matrix:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \begin{pmatrix} x' \\ y' \\ f \end{pmatrix}, \text{ or } X = A\,X'$$

The coefficients a_{11} to a_{33} are functions of the sequential rotations ϕ, ω, κ. The sequence of rotations in A can, for example, be defined as $A = A_{\omega} \cdot A_{\phi} \cdot A_{\kappa}$ or as $\bar{A} = A_{\phi}\, A_{\omega}\, A_{\kappa}$ in which A_i is of the form

$$A_i = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos i & -\sin i \\ 0 & \sin i & \cos i \end{pmatrix}$$

with i ranging from ϕ to $\varkappa$, taking into account the appropriate positive or negative sense of the rotation i.

If the system in which the triangulation was performed is given by A and the Kelsh Plotter system by $\bar{A}$, it is only necessary to set the individual elements $a_{11}/\bar{a}_{11}$, $a_{12}/\bar{a}_{12}$ etc., into proportion in order to determine expressions of $\bar{\phi}$, $\bar{\omega}$ and $\bar{\varkappa}$ in terms of ϕ, ω,' $\varkappa$ (1).

2. To the values $\bar{\phi}$, $\bar{\omega}$, $\bar{\varkappa}$, corrections $\Delta\phi$, $\Delta\omega$, and $\Delta\varkappa$ have to be added because of the triangulation adjustment; $\Delta\phi$, $\Delta\omega$, $\Delta\varkappa$ should be in the same sequential system as used for determination of $\bar{\phi}$, $\bar{\omega}$, $\bar{\varkappa}$. However, differences between a Eulerian system as ordinarily used in the strip adjustment of aerial triangulation will be negligible, taking into account the magnitude of the corrections.

In a least squares adjustment $\Delta\phi$, $\Delta\omega$, $\Delta\varkappa$ are directly computable, and they can also be found in an interpolation adjustment by differentiation of the polynomials used. If

$$\Delta x = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 xy + a_5 y$$

$$\Delta y = b_0 + b_1 x + b_2 x^2 + b_3 x^3 + b_4 xy + b_5 y$$

$$\Delta h = c_0 + c_1 x + c_2 x^2 + c_3 x^3 + c_4 xy + c_5 y$$

then

$$\tan \Delta\phi = \frac{\partial \Delta h}{\partial x} = c_1 + 2c_2 x + 3c_3 x^2 + c_4 y$$

$$\tan \Delta\omega = \frac{\partial \Delta h}{\partial y} = c_4 x + c_5$$

$$\tan \Delta\varkappa = \frac{\partial \Delta y}{\partial x} = b_1 + 2b_1 x + 3b_3 x^2 + b_4 y$$

Finally the corrected coordinates $\bar{\bar{\phi}}$, $\bar{\bar{\omega}}$, $\bar{\bar{\varkappa}}$ become

$$\bar{\bar{\phi}} = \bar{\phi} + \Delta\phi$$

$$\bar{\bar{\omega}} = \bar{\omega} + \Delta\omega$$

$$\bar{\bar{\varkappa}} = \bar{\varkappa} + \Delta\varkappa$$

3. The rotations $\bar{\bar{\phi}}$, $\bar{\bar{\omega}}$, $\bar{\bar{\varkappa}}$ have to be transformed into rotations ϕ^*, ω^*, $\varkappa^*$ which, together with a common rotation Φ, can be introduced into the Kelsh Plotter. If the rotation is to be performed by an azimuthal rotation α and a common tilt Φ, then

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\Phi & 0 & -\sin\Phi \\ 0 & 1 & 0 \\ \sin\Phi & 0 & \cos\Phi \end{pmatrix} . A_\phi . A_\omega . A_\varkappa \begin{pmatrix} x' \\ y' \\ f \end{pmatrix}$$

or

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = A_\alpha \cdot A_\Phi \cdot A_\phi \cdot A_\omega \cdot A_\varkappa \begin{pmatrix} x' \\ y' \\ f \end{pmatrix} = A^* \begin{pmatrix} x' \\ y' \\ f \end{pmatrix}$$

It is now again possible to set $a^*_{11}/\bar{\bar{a}}_{11}$, $a^*_{12}/\bar{\bar{a}}_{12}$, etc., into proportion in order to calculate ϕ^*, ω^*, κ^* out of $\bar{\bar{\phi}}$, $\bar{\bar{\omega}}$, $\bar{\bar{\kappa}}$. It is to be remembered that α and Φ to be used in the expressions are known beforehand and can be calculated from

$$\tan \alpha = \frac{by}{bx}, \quad \tan \Phi = \frac{bz}{\sqrt{bx^2 + by^2}}$$

The calculation of Φ, ϕ^* ω^* and κ^* can be made for each successive exposure station. Thus ϕ^*_L, ω^*_L, κ^*_L, ϕ^*_R, ω^*_R, κ^*_R and Φ can be introduced in the following way: First the base bar is leveled in x direction as well as the projectors in x and y direction. Then Φ is introduced, and subsequently ϕ^*_L to κ^*_R, by calculating and introducing $d\Delta x$ and $d\Delta y$ displacements as outlined previously.

CONCLUSION

Methods have been discribed by which numerical orientation can be applied in the Kelsh Plotter. It is not attempted here to give a generalized practical evaluation of these methods, since local conditions may influence the efficiency with which numerical or trial-and-error procedures can be carried out. The numerical calculation necessary can easily be done on the slide rule for relative and absolute orientation, and the precomputation of final instrument settings from aerial triangulation can be incorporated into the adjustment which in most cases is performed on an electronic computer. In view of this, substantial time savings can be expected from numerical orientation methods.

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Aerial Infrared Surveys: A Highway Research Tool

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•THE CONTRIBUTION of our country's highway system in terms of national prosperity and strength has been tremendous. Recognition of this fact has stimulated much research activity dedicated to fulfilling users' needs within the limits of reasonable costs and safety standards. Basic research skills and innovations on existing technology are being applied to virtually every facet of highway design, construction and operation. Evaluation of systems developed for other purposes as possible tools of highway technology is a vital part of this effort.

One such creation is the topic of this paper. Our purpose is to present a basic treatment of principles which apply to airborne infrared scanning systems and suggest a philosophy for their application as a new highway research tool. For some, this discussion will be an enlightening introduction to the topic. For others, it will serve no doubt as a review of some college physics.

We cannot make any grand claims for the occult powers of these infrared systems in highway engineering, or even whet your appetites with glowing case histories. One can only see what exists to be seen, and then only if he has eyes with which to see. We are, therefore, going to discuss a new kind of eye, which responds in a region of the electromagnetic spectrum many times broader than the visible portion and sees objects in terms of their associated radiation fields instead of reflected visible light.

Figure 1 illustrates a portion of the electromagnetic spectrum. Let us identify the infrared as that portion of the electromagnetic spectrum of particular interest, and place it in proper orientation. With our feet planted firmly in the visible region, which consists of energy radiated at wavelengths from about 0.3 microns to about 0.72 microns, we can project to shorter wavelengths extending successively through the ultraviolet region and thence into soft and hard X-rays, gamma rays, etc. Going in the other direction, we encounter near-infrared radiation from 0.72 to 1.3 microns, middle-infrared between 1.3 and about 5.6 microns, and far-infrared from 5.6 to about 1000 microns, where we begin to encroach on the domain of microwave specialists. These divisions are somewhat arbitrary but nevertheless useful. For example, the realm of optics has been defined as that portion of the spectrum in which we can control the flow of energy by devices involving reflection, refraction, and diffraction—in other words, mirrors, lenses, and gratings. Thus, aside from the specialized ability of our eyes to sense only the "visible" spectrum frequencies, there is no fundamental difference in the character of radiant energy in the region from 0.1 to 1000 microns.

Introduction to the process of conventional aerial photo analysis and interpretation in engineering is not required here. For the sake of discussion, however, let us recall that these analyses involve a systematic study of pattern elements, separately and in relation to each other, and an attempt to diagnose the origin, geomorphic history and composition of separate landscape units. The analyst is concerned mainly with pattern elements which are the photographic expressions of topography, drainage, erosion, soils, land use, and vegetation. The competent photo analyst will rely on judgment acquired from a broad background in geomorphology, ecology, hydrology,

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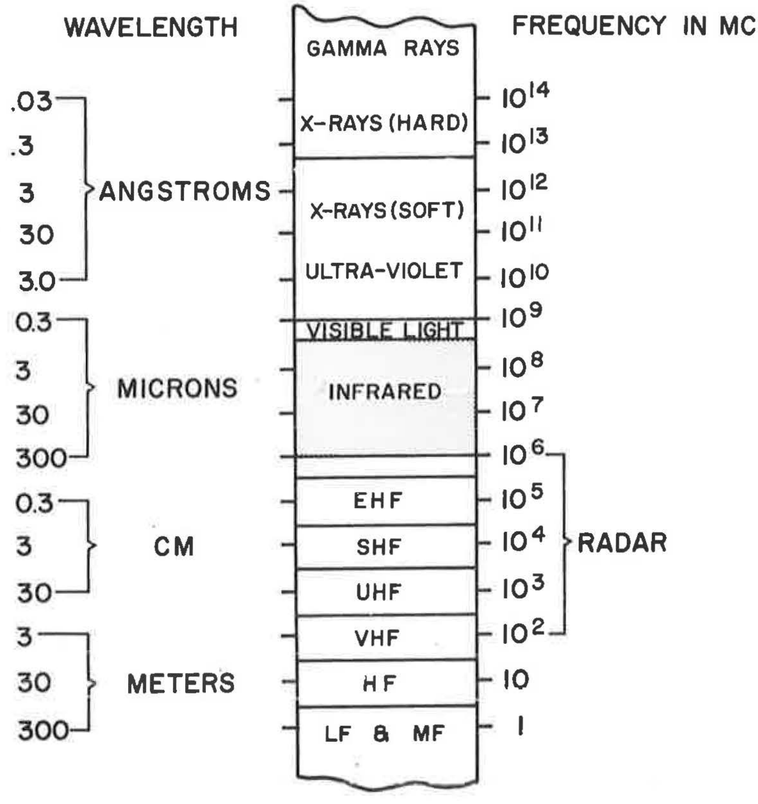


Figure 1. The electromagnetic spectrum.

and other disciplines contributing to his knowledge of the environmental influence on surficial materials.

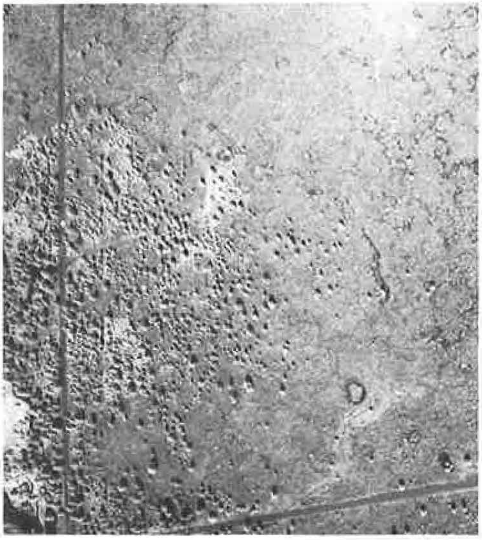
In order to explain the meaning of his deductions in terms of a particular objective [Mollard (1) calls this the interpretation phase], the analyst must be able to draw conclusions from the assembled evidence which reflect a knowledge of the end product—highway construction practice, if you will. When confronted by graphic evidence obtained in the infrared region, the photo interpreter must apply new intellectual skills to those already acquired.

The analyst-interpreter working with near infrared photography will find himself on fairly familiar ground. Landscape scenes will retain much of their conventional appearance, though certain materials, by virtue of selective reflectance which peaks in the near-infrared region, will exhibit highlights not apparent in panchromatic or color photographs. The dyes contained in camouflage detection film (CDF), responding to actinic radiation at approximately 0.9 microns, produce artificially brilliant hues which accentuate differences in reflectivity.

Figure 2 compares aerial panchromatic photography (top) and aerographic infrared film (bottom), the black and white equivalent to camouflage detection film. Note the superior contrast qualities of this latter presentation in which vegetation appears light in tone against a dark background. On CDF, healthy vegetation would appear red against a brown or bluish background. An aerial Ektachrome of the same scene would reproduce vegetation in green tones on a brown background.

State-of-the-art in aerial film emulsions limits the spectral band which can be sensed by infrared photography to around 0.9 microns. Beyond this range in the infrared one must resort to scanned electro-optical image collecting systems and at this point the analysis process becomes quite esoteric.

0.5 - 0.7μ Tri-X



0.7 - 0.9μ INFRARED

Figure 2. Comparison of film types.

Agricultural test plots near Davis, California (Fig. 3), afford a comparison of thermal imagery (right) and panchromatic photography (left). Superficially, the scanned imagery looks like aerial photography. However, instead of seeing objects in their reflected light, the analyst now sees them in terms of earth-radiated energy far beyond the visible spectrum. At first he is somewhat confused by the lateral scale distortion produced by the mapper's panoramic scan and frustrated by lack of stereo overlap; and he is perhaps inhibited by the fact that the pattern elements assume new meanings. Through a modest amount of intellectual effort, he learns to relate the image patterns to the earth's thermal regime. He becomes aware that, given proper control, it is possible to investigate certain dynamic factors in the environment far more rationally than before. Lack of stereoscopic perspective is at least partially compensated by the oblique panoramic scene observed on either side of center. Figure 4 illustrates a thermal image of dissected strata. A lake in the background stands out markedly.

Topographic expression remains in the image but is observed as a map of radiated energy rather than a perspective view of relief. The northern slopes of hillsides receive less isolation during daytime; thus they may appear darker—or cooler—than southern exposures. Percolating seepage and evaporating capillary water cool the surface during the daytime, and thus the image appears dark where moisture reaches the surface. At night, when dry land has cooled rapidly, the moisture-laden materials may appear brighter, or warmer. Partings in sedimentary exposures may serve as seepage channels and clearly manifest their stratified nature. Differences in emmisivity (generally, the ability of an object to absorb and reradiate infrared wavelengths) likewise may contribute to the stratified appearance. Drainage lines in general stand out markedly. Small water-courses are usually clearly defined even when screened by vegetation; the margins of ponds and streams are easily discerned even in imagery flown at night. Indeed, one may prefer to fly infrared scanning systems at night in order to eliminate specularly reflected long-wavelength energy from the sun.

Erosional features will be particularly evident in infrared imagery, though one is limited in his ability to make judgments concerning material plasticity and texture from gully shapes, i.e., the familiar criteria which allow classification of V-shaped, U-shaped and composite gullies. Where gullies cross flat-layered parent material or soils, the horizons of which manifest significant differences in radiant emission or reflectance and thus present a contour-map appearance, one may be able to infer gully shapes from curvatures of these "contours." On the other hand, moisture gradients along gully flanks are readily apparent.

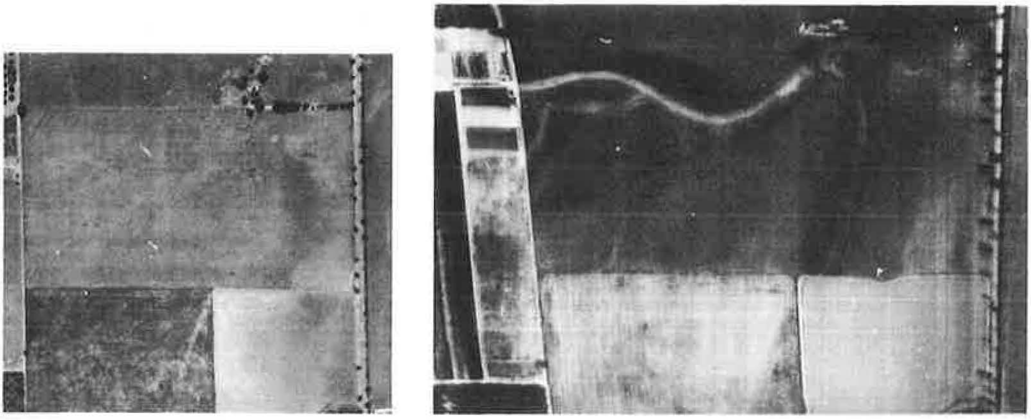


Figure 3. Panchromatic far-infrared image comparison, Davis, California.

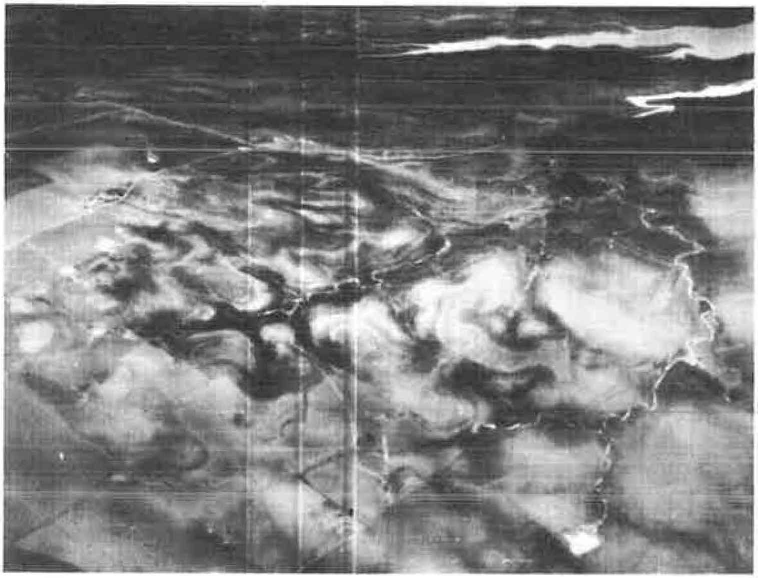


Figure 4. Far-infrared image of terrain near Fort Worth, Texas.

Land use produces various characteristic patterns which are clearly evident in thermal maps. Indeed the application of these systems as powerful tools for military reconnaissance stems partly from their ability to record apparent temperatures of cultural features—vehicles, storage areas, industrial complexes—which may be indicative of their use or purpose. It is a familiar experience that pavements become hotter during daytime than adjacent ground, and maintain thermal differences into the night, hence sharp thermal anomalies are evident in imagery flown at proper times. Buried and concealed objects may be identified by the same phenomenon. In Figure 5, showing an extended lava field of Mt. Pisgah, California, an elongated thermal anomaly has been interpreted as the surface manifestation of a drained lava tube or tunnel.

One of the applications we have demonstrated is the ability to census livestock and wildlife on rangeland, their warm bodies against a cooler night-time background pro-

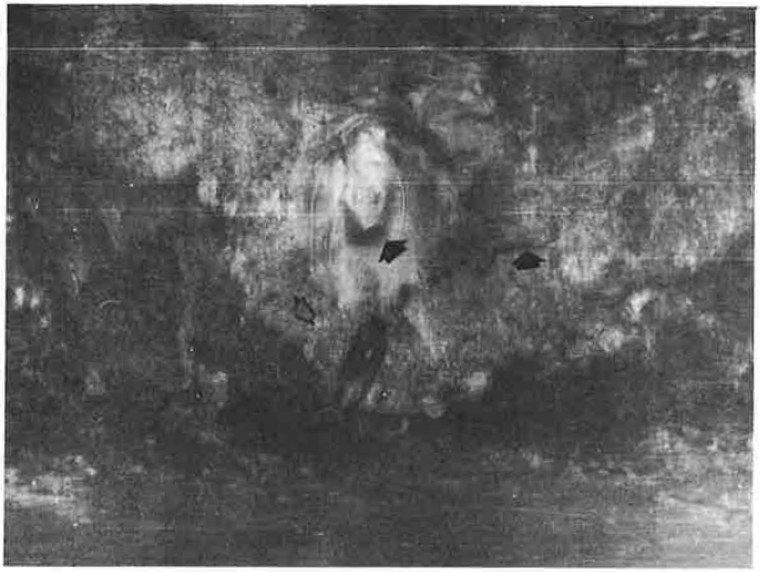


Figure 5. Far-infrared image, Mt. Pisgah, California.

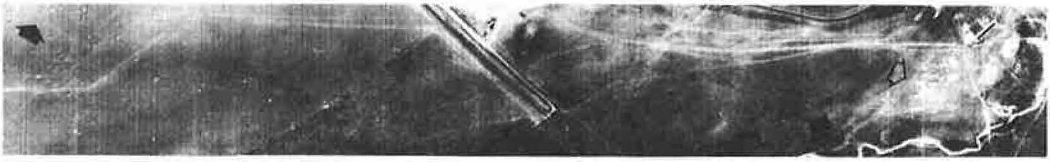


Figure 6. Livestock, near Forth Worth, Texas.

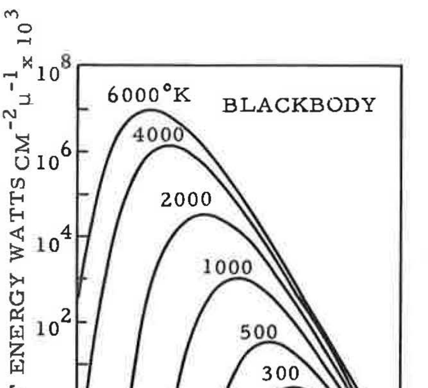


Figure 7. Spectral radiant emission curves for black bodies.

ducing sharp anomalies (Fig. 6). Vegetation is readily recognizable; indeed various species manifest characteristic radiometric signatures in the infrared. Because these spectra are singularly dependent on plant vigor, they have become the subject of considerable research by plant physiologists, agronomists and foresters. It will suffice for the highway engineer to recall the familiar experience that green vegetation is cooled by evapotranspiration, and therefore will appear relatively cool in daytime-scanned infrared imagery.

The physical basis for all thermal imaging systems exists in the fact that all materials whose temperature is above absolute zero radiate electromagnetic energy. Likewise, the atoms and molecules which constitute such matter invariably have fundamental modes of translation, rotation and vibration of various

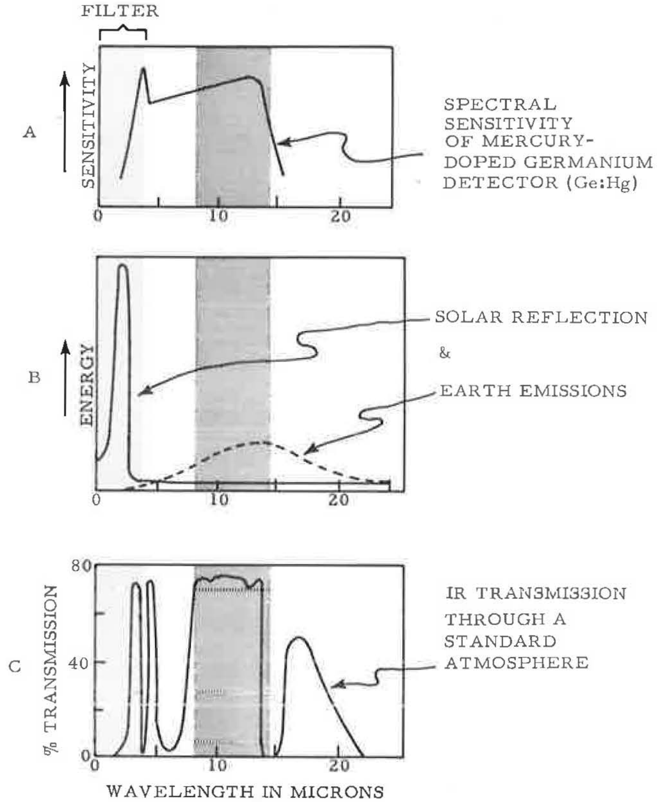


Figure 8. Factors for recording long wavelength infrared imagery.

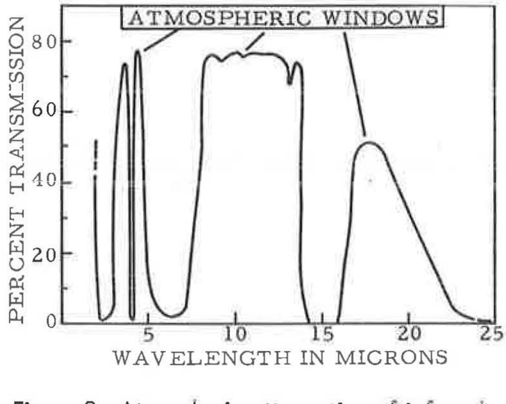


Figure 9. Atmospheric attenuation of infrared wavelength energy.

resonance frequencies at which incident electromagnetic radiation is absorbed. When a body completely absorbs all incident radiation, it is termed a black body; the radiated energy from such a body is the maximum possible. Now, the efficiency with which energy is absorbed and emitted by an object at any given temperature relates to the condition of its surface as expressed by its emissivity. Highly polished, reflective surfaces have emissivities approaching zero, whereas dull, "velvety" surfaces approach the ideal black body emissivity of unity. Those objects which have emissivity less than unity are said to be grey bodies.

It is found that the spectral distribution of a radiating black body at any temperature is a continuum; curves of radiated energy vs wavelength with temperature are approximately as shown in Figure 7. Note that the radiation peak shifts to shorter wavelengths as absolute temperature (degrees Kelvin) is increased, a phenomenon predicted by Wien's law:

$$\lambda(\max)\ T = 2897\ \mu \text{ degrees} = \text{constant} \tag{1}$$

The fundamental relationship for the total radiated energy from a body at absolute temperature T and emissivity ϵ is expressed by the familiar Stefan-Boltzmann law

$$W = \epsilon \sigma T^4 \quad (2)$$

where

W = spectral radiant emittance,
ϵ = emissivity,
σ = Stefan-Boltzmann Constant = 5.673×10^{-12} watt/cm^2, and
T = absolute temperature.

Since emissivity measurements of aerial scenes are almost impossible to make, it is customary to assume surface emissivities of unity and to interpret flux differences in terms of apparent radiation temperatures. Numerous investigations of heat transfer in natural soils, rocks and ceramic materials at elevated temperatures have corroborated this assumption.

If the radiating surface is a plane perfect diffuser, the intensity of radiation emitted will vary as the cosine of the angle between "line of sight" and the surface normal according to Lambert's law of cosines

$$J = \frac{WA \cos \theta}{2\pi d^2} \quad (3)$$

where

W = total radiation from Eq. 2,
A = area of the emitting surface, and
d = distance from source to detector.

(The d term indicates the intensity of electromagnetic radiation is inversely proportional to the square of the distance between the source and the detector. This is known as the inverse square law.)

The sun, which is the ultimate source of energy available to the passive detector system, radiates throughout the electromagnetic spectrum. We shall see, however, that our selection of spectral intervals for practical terrain imaging applications is limited by atmospheric effects and the technology of detector materials. One popular detector material is mercury-doped germanium (Ge:Hg).

As previously noted, all matter absorbs radiant energy to some degree; thus the gas molecules in the atmospheric path through which solar radiation must penetrate to the earth's surface are very effective filters of certain wavelengths. The resonance-absorption spectra of water vapor, carbon dioxide, and ozone are particularly effective attenuators of infrared energy. The zones of high atmospheric transparency or "windows" are evident.

Wien's displacement law says that "black body" terrain objects which have temperatures ranging from -40 F to +150 F (the range of natural landscape temperatures) have peak emissions from 12.4 to 8.6 microns. The spectral sensitivity of Ge:Hg detectors, the spectral emission of normal-temperature earth materials and the spectral location of atmospheric windows are matched in Figure 8. Note the preferred alignment in the region 8-14 microns.

There are many scanning infrared systems in existence today; however, most of these are controlled by the military. The scanning optics of these systems are quite variable although consistent in their function—to scan the terrain and focus received photon energy onto the detector material. (The scanning function is graphically displayed in Fig. 9.) The semiconducting detector element then converts the infrared wavelength energy into an electrical signal which is amplified and then converted to a visible-light signal through a glow modulator or cathode-ray tube display. Standard photographic film is then pulled across an exposure slit at a rate proportional to the velocity and height of the aircraft, thus generating a photo-like strip image of the terrain.

Optics systems and detectors must be matched for maximum sensitivity in this region in order to achieve significant terrain component differentiation (detection). However, to identify surface features of practical interest they must exhibit characteristic thermal patterns or anomalies against their backgrounds. We have collected a variety of examples which illustrate the appearance of various anomalies, but a more useful approach to prediction, an essential part of interpretation, may be through application of, for example, the heat transfer theory. Fortunately, substantial literature relative to such problems and much experimental data have accumulated through the efforts of civil engineers and others interested in effects of freezing on highway pavements, arctic construction practice, and various other thermal problems.

Someone may ask, "Why do we need this?" A straightforward answer would miss the point, of course. However, our hypothesis is this: the various physical elements of terrain surface and subsurface materials possess differences in their molecular structure which, in the aggregate, create characteristic patterns through absorption and reradiation of energy. These patterns can be sensed in the infrared spectral region beyond the visible band and related, on a comparative basis, to the materials which produced them. We know, to at least a first-order approximation, the Fourier conduction theory as applied to earth and rock materials. We have measured and tabulated the principal thermal parameters for a variety of soils—Kersten's work is especially significant in this respect. We can predict—again, to a low order of accuracy—the heat exchange at the ground surface, as Scott (2) has summarized in a nomogram published by CRREL.

With these tools, and a fair amount of diligent mathematical exercise, one should be able to compute theoretical magnitudes of thermal anomalies which a variety of geological features would manifest at the ground surface. Studies of this sort could eventually provide needed insight into the analysis of thermal images of surface and subsurface structure manifestations which far exceed any present capability for analysis on conventional photography. Thermal imaging, in conjunction with conventional photo interpretation, could thus give a new dimension to the evidence which one can collect about the terrain.

Our concluding remarks concerning engineering applications must in part summarize predicted results rather than accomplishments. We believe these systems will be useful in location of engineering materials and their delineation below the ground surface which might otherwise be obscured by vegetation, organic soils, lacustrine deposits, and the like. They will be especially valuable for assessment of water table conditions, vadose zones, springs, and seeps, and for mapping the margins of flooded areas. Recalling a legal proceeding which occurred in California several years ago, a landowner claimed that a low dike constructed by his neighbor to impound a duck marsh had raised the water table sufficiently to damage his vineyard. Infrared thermal imagery might indeed provide evidence to substantiate or refute his claim, by means of the thermal pattern which one would anticipate as a consequence of shallow subsurface irrigation seeping from the reservoir. One is inclined to be particularly enthusiastic about the ability to locate leaks in hydraulic structures, sand boils adjacent to levees, and seepage through dam abutments. Under certain conditions we have detected underground pipes, similar to farm tile drains, through heavy overburden of soil and concrete.

Fractured zones, faults, and slumps may be evident under conditions which preclude detection on panchromatic photography. Sink holes and underground cavities should yield patterns which are more characteristic of their subsurface dimensions than the patterns which one can observe in the visible portion of the spectrum.

In permafrost regions, we predict a bright future for use of these systems in investigation of permafrost and organic terrains. There, especially, the significance of thermal factors in environment is well appreciated. Permafrost and frozen ground should alter the diurnal temperature fluctuations below the surface and produce shifts in the long period surface temperatures so that delineation between dry-frozen, wet-frozen, and other classes of cold region soil phenomena may be possible.

Finally, we affirm that operating motor vehicles have warm engines, and thus are clearly evident in imagery flown during most periods of the day. It has been suggested that one would like to conduct origin-destination surveys and traffic counts during hours and under conditions when visibility is poor; the congested traffic conditions which occur on any typical rainy winter evening in and around Washington, D.C., are classic.

One could fly an infrared scanner during these hours when poor illumination would render a panchromatic camera system worthless.

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