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A Layman's Analytical Plotter: The SDP System

The SDP system, employing point-by-point plotting, is suitable for map revision and for the production of digital terrain models.

ABSTRACT: *The stereoscopic digitizing plotting (SDP) system was developed by the author for revising cadastral and topographic maps. The system uses near vertical aerial photographs and a minicomputer. The computer has the capability of performing numerous digital computations, and it can take in data from a digitizer and drive a plotter. The SDP system is a point-by-point plotting system. It can be used to create a DTM and to draw contours. The SDPsystem can be built at a cost of less than $35,000; $30,000 of this total is for the computer system, which can be put to other uses as well. However, at present day market prices, the cost of a computer system with similar capabilities could be far less. Thus, we have a layman's analytical plotter costing less than $5,000. Using a digitizer of 0.01 in. accuracy and employing 1:3000 scale photography, the noise level of height data is between 2 and 5 feet, and the planimetric map produced by the SDP system agrees well with that produced by the Nistri Stereo Plotter.*

INTRODUCTION

MAPS SHOULD BE REVISED periodically to take into account the economic and political developments that affect the mapped territory. Existing photogrammetric instruments have the capability of plotting maps with speed and accuracy. However, they are unsuitable for revising existing maps because they are too sophisticated, too expensive, and too slow for such revision work.

The Stereoscopic Digitizing Plotting system (SDP system) is being developed by the author for use in revision work. The system uses near-vertical aerial photographs and a versatile desk minicomputer. The computer has the capability of doing numerous digital computations. It can take in data from a digitizer and drive a plotter.

The late Professor E. H. Thompson stated that a photogrammetric plotter should have the following features (Thompson, 1971):

- An optical system of the highest quality.
- A removable vertical parallax to enable the observer to plot large areas of the model without having to make frequent adjustments.
- Heights presented in the form of heights, preferably in some preselected scale and unit, not as parallaxes that require conversion.
- If circumstances compel a departure from a rigorous geometrical solution, errors that increase only with the tilt of the picture, not with the height variation of the ground.
- A plotter convenient and comfortable to use that does not differ in these respects from more expensive instruments.

The SDP system meets all but the second of the desirable features. The SDP system is a point-by-point plotting system; because of its interaction with the computer, the inconvenience of frequent adjustment for stereo observations is more than compensated for by the versatility of the computer that plots, edits, stores, and retrieves data.

THE PRINCIPLES OF THE PLOTTING SYSTEM

The SDP system consists of a digitizer, a computer, and a plotter (see Figure 1). The positive prints of a stereo pair are placed on the digitizer. In order to establish the exact location and orientation of the camera, twelve parameters corresponding to

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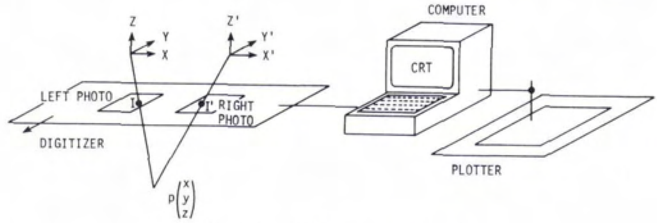

FIG. 1. The SDP system.

the left print (X_0, Y_0, Z_0, κ, ϕ, ω) and to the right print (X_0', Y_0', Z_0', κ', ϕ', ω') have to be determined. These are determined by five or more pass points and three or more ground control points.

The exterior orientation elements are determined by the usual two-step procedure of relative and absolute orientation. The plate coordinates of the left photo (x,y) and of the right photo (x', y') corresponding to the pass points and control points are obtained by digitizing the corresponding points and fiducial points and then determining the transformation parameters using the equation

$$\begin{pmatrix} x \\ \\ y \end{pmatrix} = \begin{pmatrix} A & B \\ \\ -B & A \end{pmatrix} \begin{pmatrix} Px \\ \\ Py \end{pmatrix} + \begin{pmatrix} C \\ \\ D \end{pmatrix}$$

where A, B, C, and D are transformation parameters and Px and Py are the digitized coordinates.

The relative orientation elements, $by = (Y_0' - Y_0)$, $bz = (Z_0' - Z_0)$, $\Delta k \simeq (\kappa' - \kappa)$, $\Delta\phi \simeq (\phi' - \phi)$, and $\Delta\omega \simeq (\omega' - \omega)$, are determined by the least-squares solution of the equation

$$\left(f + \frac{y'y}{f}\right) \Delta\omega - \frac{(x'y)}{f} \Delta\phi - x'\Delta k + (x' - x)by + \frac{(xy' - x'y)}{f}$$

$$bz + y - y' = 0$$

where f is the camera focal length and on the assumption that $bx = 1$.

The model coordinates (X,Y,Z) corresponding to the corresponding image points (x_1, y_1, f) and (x_2', y_2', f) are determined using the equations

$$X = \kappa_1 x_1 = \kappa_2 x_2 + B_x$$

$$Y = \kappa_1 y_1 = \kappa_2 y_2 + B_y$$

$$Z = \kappa_1 f = \kappa_2 z_2 + B_z$$

where

$$\begin{pmatrix} x_2 \\ y_2 \\ z_2 \end{pmatrix} = \begin{pmatrix} 1 & -\Delta K & \Delta\phi \\ \Delta K & 1 & -\Delta\omega \\ -\Delta\phi & +\Delta\omega & 1 \end{pmatrix} \begin{pmatrix} x_2' \\ y_2' \\ f \end{pmatrix}$$

and

$$B_x = f$$

$$B_y = f\,by$$

$$B_z = f\,bz$$

κ_1 and κ_2 are determined by the least-squares solution of the equation

$$\kappa_1 x_1 = \kappa_2 x_2 + B_x$$

$$\kappa_1 y_1 = \kappa_2 y_2 + B_y$$

$$\kappa_1 z f = \kappa_2 z_2 + B_z$$

The ground coordinates (Gx, Gy, Gz) corresponding to the model coordinates (X,Y,Z) are determined by the equations

$$\begin{pmatrix} Gx \\ Gy \\ Gz \end{pmatrix} = S\mathbf{R} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} + \begin{pmatrix} TX \\ TY \\ TZ \end{pmatrix}$$

where

S = scale factor

$\mathbf{R}$ = orthogonal matrix

$T = (TX, TY, TZ)$

TX, TY, TZ are the translation elements.

The orthogonal matrix is represented in Cayley's form as $\mathbf{R} = (\mathbf{I} - \mathbf{S})(\mathbf{I} + \mathbf{S})^{-1}$ where

$$\mathbf{S} = 1/2 \begin{pmatrix} 0 & \kappa & -\phi \\ -k & 0 & \omega \\ \phi & -\omega & 0 \end{pmatrix}.$$

The scale factor and rotation elements are determined by least squares using the known ground control coordinates.

The programs developed by the author calculate the required parameters and store their values on tape or disk. Now if the ground coordinates of some unknown points such as (I,I') are required, the corresponding photo coordinates are digitized. The computer program retrieves the required parameters and forms the corresponding ground coordinates. The software, when instructed, will

(a) plot the location of the point in any desired scale,
(b) draw a line from the existing point to the point in any desired scale,
(c) write the elevation at the correct location in any desired scale,
(d) store the X,Y,Z values on a tape or disk.

(a) and (b) are used to plot the planimetric details; (c) is used to interpolate and draw the contours; and (d) is used to draw contours by the digital terrain model (DTM). For further detail see pages 152–170 in Jeyapalan (1972).

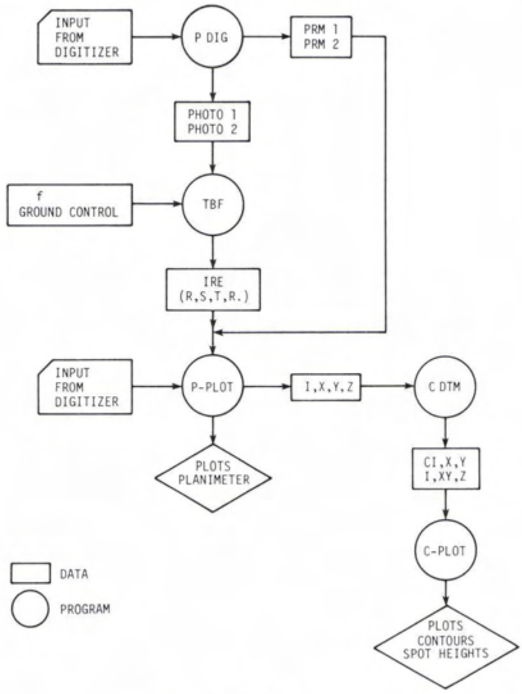

FIG. 2. Flow chart.

The Software

Figure 2 is a flow chart showing the organization of the data and the programs. The photo digitizing program, entitled PDIG, calls for the number of the fiducial points and their calibrated values. It then requests the fiducial points of the photograph to be digitized. The program then computes the transformation parameters and saves them on disk under a user specified name such as "PRM-1" for the left photo and "PRM-2" for the right photo. The program then calls for the digitization of the pass points and control points. Each is digitized and the plate coordinates are determined and saved under a user specified name such as "Photo 1" for the left photo and "Photo 2" for the right photo. In order to terminate the data file, the last point is assigned a point number zero.

The focal length, the number of models, ground control coordinates, initial scaling, and translation points are supplied by modifying the data statements of the program entitled TBF. This program retrieves the plate coordinates of pass points and control points stored in the data file of the PDIG program. The program then computes the relative orientation and the absolute orientation elements and saves these values together with the information on the focal length of the camera used under a user specified name such as "IRE."

The planimetric plotting program entitled P-PLOT calls for the plotting scale, the origin of the plot, and the size of the margin, and retrieves the transformation parameters from the PDIG program and the relative and absolute orientation elements from the TBF program. Function 1 of the program requires the digitization of the corresponding points of the left photo and the right photo, in that order; it then computes the ground coordinates of those points. If the digitization of the right photo initializes flag 0, then the computer drives the plotter from its current position to the computed position with the "pen-up;" if it initializes flag 1, then it drives with the "pen-down." If the digitization of the left photo initializes flag 1, then the program resets itself. Function 2 of the program can be used to write alphanumeric characters of different sizes and directions at any location.

The program CP-PLOT, not shown in Figure 2, is similar to P-PLOT except that it saves X, Y, Z coordinates in a data file under a user specified name.

The program C-DTM calls for the contour interval and increments in X for computing the sets of points of the contours. The program then retrieves the X, Y, Z coordinates from the data file of the CP-PLOT, fits by least squares a linear or second degree function, determines the parameters for each contour interval, and saves the sets of X, Y coordinates for each contour in the data file under a user specified name. The adjusted elevations of the digital terrain model together with their X, Y coordinates are also saved in the same data file.

The program C-PLOT calls for the file created by C-DTM, the scale of plotting, the origin of the plotting, and the margin size. It then reads the data from the file, plots the contours, and writes their elevations. The program also writes the elevation of control points at their locations.

All programs are written in BASIC language. The program statements can be updated in real time. The data files can also be updated or reused.

Hardware

The hardware consists of

- The Wang 2200 system, which is equipped with a central processing unit (CPU), keyboard, cathode ray tube (CRT), line printer, diskette drive, digitizer, and a flat bed plotter;
- A stereo pair cursor unit;
- A mirror stereoscopic unit; and
- A zoom stereoscopic unit.

The CPU is the heart of the Wang system (see Figure 3). The CPU used in the SDP system has a 16k memory whose programs and variables are kept during program execution. The CPU uses the keyboard, the CRT, the line printer, the diskette drive, the digitizer, and the flat bed plotter for input and output operations. Figure 3 shows the keyboard used to enter commands, program lines, and data, and the CRT, which provides a fast and easy means of getting information to the user. While the CRT displays the information on the screen, the line printer generates printed characters and gives a hard copy. Figure 3 also shows the line printer and

FIG. 3. The Wang system.

the diskette drive, which provides non-volatile storage (not affected by the powering system) for both programs and data. The single diskette drive was used in the SDP system. In addition, Figure 3 shows the *x-y* digitizer, which generates pairs of *x-y* coordinates for discrete points on a document and transmits to the CPU, and the digital flat bed plotter, which draws continuous lines or point-plots the data. The dimensions of the flat bed plotter are 121.92 cm by 78.74 cm. The dimensions for the digitizer are 80 cm by 120 cm.

Figure 4 shows the stereo pair cursor unit. It consists of two cursors connected to a junction box, which in turn is connected to the control unit of the digitizer. A switch in the junction box, when moved to the left, transmits a signal from the left cursor to the control unit. When moved to the right, it transmits a signal from the right cursor to the control unit (see Figure 5). A black dot, representing the floating mark, is affixed to the center of each cursor. The cursors are mounted on holders, which in turn are attached to a bar. The holder to which the left cursor is attached can be moved along the bar (*x*-direction) for initial setting; the holder attached to the right cursor can be moved in both the *x* and *y* directions for removing *x*- and *y*- parallaxes. The

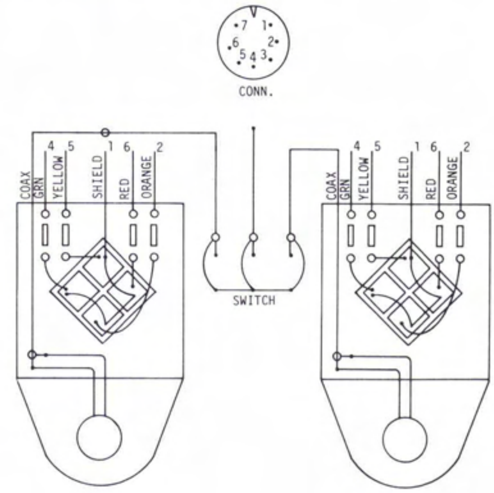

FIG. 5. Circuit diagram of the stereo pair cursor.

bar, together with the holder and the cursor, can be moved along the surface of the digitizer.

Figure 6 shows the mirror stereoscopic unit attached to the base of the stereo pair cursor unit. The mirror stereoscope provides a stereo view of imagery placed under the pair of the cursors. The unit is equipped with an illumination system, which enables the left and right cursors to be illuminated independently. The unit can be moved on the surface of the digitizer to scan the photo or to view the imagery in stereo.

The zoom stereoscopic unit consists of a Bausch and Lomb zoom stereoscoped attached to a bar. The zoom stereoscope is free to move along the bar (*x*-direction); the bar is free to move along the edge of the digitizer (*y*-direction) (see Figure 7). The zoom stereoscope and the bar enable the stereoscopic scanning of a pair of photographs placed on the digitizer. The stereo cursor unit, which can be moved independently underneath the zoom stereoscope unit, enables the left and the right floating marks to be placed on corresponding points and viewed under stereo with large magnification.

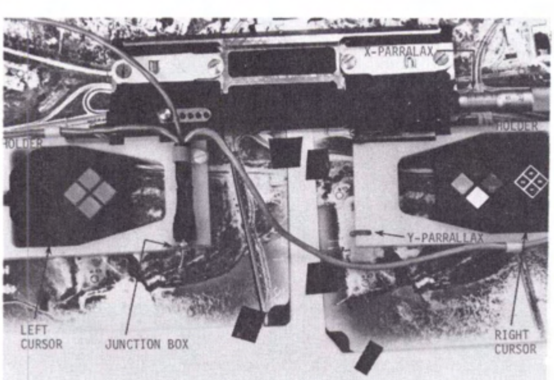

FIG. 4. The stereo pair cursor unit.

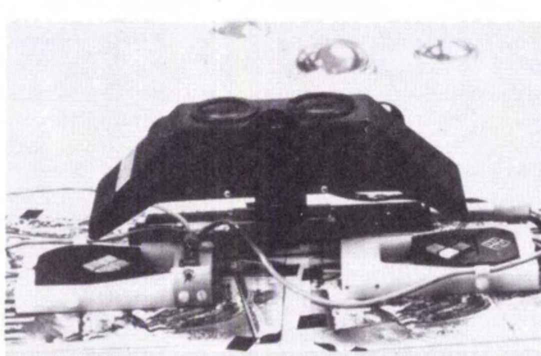

FIG. 6. The mirror stereoscopic unit.

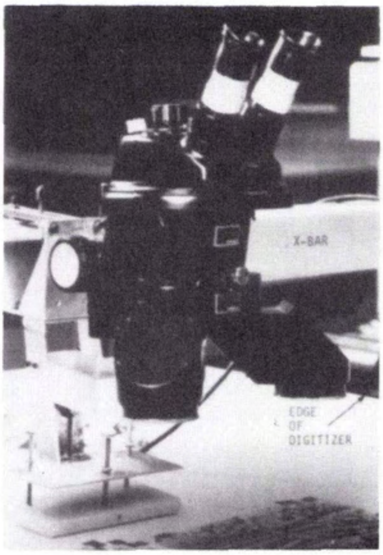

FIG. 7. The zoom stereoscopic unit.

The zoom stereoscopic unit and the stereo pair cursor pair unit can be used for digitizing control points and pass points, and in point-by-point plotting such as in cadastral surveys. The mirror stereoscopic unit and the stereo cursor unit can be used in detail plotting of roads, buildings, and other topographic features. The mirror stereoscopic unit can be used for tracing contours, and the zoom stereoscopic unit can be used for obtaining spot elevations and the digitial terrain model.

PROCEDURE

The principal points are marked on each stereo pair and transferred stereoscopically to the other. The baseline is drawn on the digitizer and the photographs are laid on this line such that the baseline on the photograph coincides with it. The distance between the photographs is adjusted for comfortable stereo viewing. When the floating marks are on corresponding points, appoximately at the center of the baseline, movements of the stereo cursor unit are initialized at the middle of the unit's range. The photographs are then fixed on the digitizer with drafting tape. Pass points are then selected and the control points are identified. The PDIG program is loaded and executed. The fiducial, control, and pass points are digitized and the PRM and PHOTO data files are created. The TBF program is then loaded and executed using the PHOTO data file and the ground control data information to give the IRE data file.

In order to plot the planimetry, the P-PLOT program is loaded and executed using the PRM and IRE data files and the information on scale of plotting, origin of the plot, and margin size. To set the plotting pen at an initial point, the left photo point and the right photo are digitized with the flag 0 button. To draw a line from the initial point, the left photo is digitized with flag 0, whereas the right photo is digitized with flag 1. Using this procedure, all planimetric details can be plotted. In order to make the plotting as continuous as possible, the mirror stereoscopic unit and the stereo cursor units are used as a single unit. The x- and y-parallaxes are removed at the initial point and the unit is moved to the next point, which is then digitized. Minor x- and y-parallaxes are continuously removed. Because these movements are small and at the tip of the right hand, periodic removals do not constitute too much of an inconvenience. The whole unit may have to be rotated slightly from one position to another for comfortable stereo viewing.

The CP-PLOT generates the DTM data file. This data file can be used directly with the C-PLOT to plot spot heights or by means of the CDTM program to plot contours and adjusted elevations. The contours can

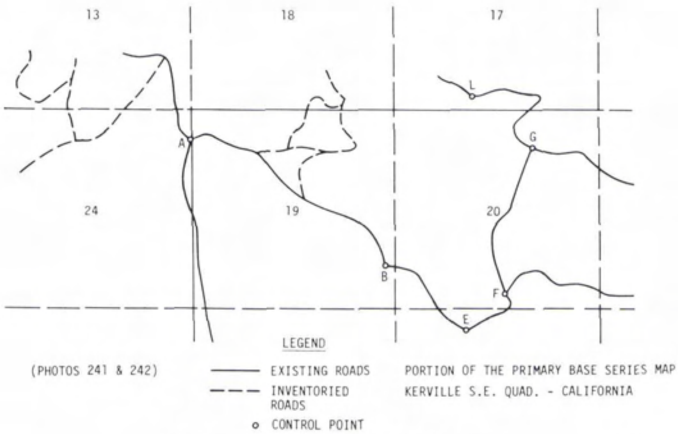

FIG. 8. Revised map by the SDP.

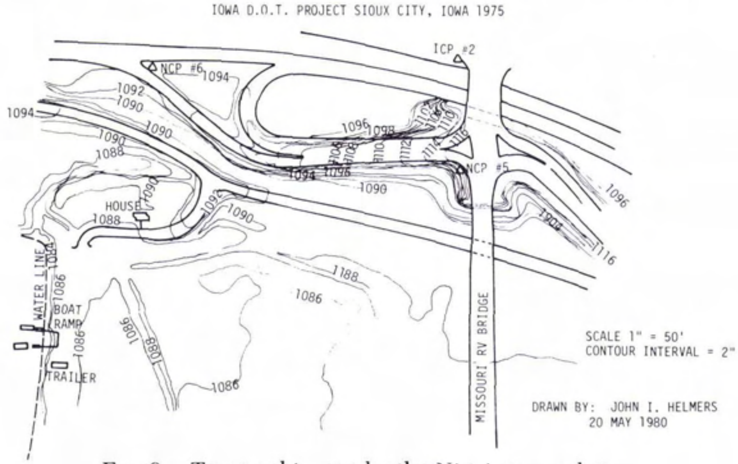

FIG. 9. Topographic map by the Nistri stereo plotter.

be directly interpolated using the spot heights. This is an efficient procedure, considering the fact that any additional elevations can be obtained in real time. The contour interval and the x increment, used for plotting contours, are specified in the CDTM program. Alternatively, the C-PLOT program can be used to plot the contours. The contours are plotted in sections and linked together manually. The section boundaries are decided by topography. High and low points of a section are selected at random to represent the terrain.

The planimetric and contour points can be saved on the disk by using the "image storing" program of the Wang utility program (Wang Laboratories, Inc., 1975b). When digitizing for image storage, the rough corners can be smoothed by setting the digitizing control switch for stream mode. The planimetry and the contours can be plotted at reduced or enlarged scale by using the "image plotting" program of the Wang utility program (Wang Laboratories, Inc., 1975b).

RESULTS

Figure 8 shows a map of the Sequoia National Forest in California, revised using the SDP system. The original map was drawn by the United States Geological Survey at a scale of 124,000. Points that are easily identifiable both on the map and photographs are selected as control points. These points are indicated on the map. Their X and Y coordinates are obtained by digitizing the original map and the Z values are obtained by interpolation. The revised map was checked by U.S. Forest Service personnel in Porterville, California, and found to be satisfactory. The control points fitted the digitized plate coordinates satisfactorily.

Figure 9 shows a map of Sioux City, Iowa, drawn using 1:3000 scale photographs and a Nistri stereo

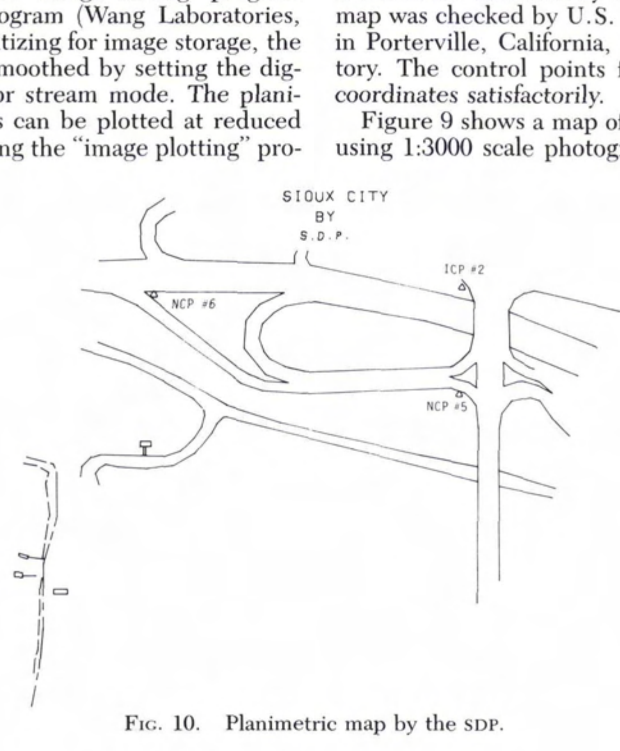

FIG. 10. Planimetric map by the SDP.

FIG. 11. Digital terrain model by the SDP.

plotter at a scale of 1:600. Figure 10 shows the planimetric map plotted by the SDP system, Figure 11 shows the digital terrain model obtained by the SDP system, and Table 1 gives the residuals at the control and check points. The residuals are good for revision work. The planimetric map plotted by the SDP system agrees with that by the Nistri plotter. The spot elevations indicate a noise level between 2 and 5 feet in height data. For greater accuracy, it would be necessary to use a digitizer with an accuracy of 0.001 inches. The SDP system used a digitizer with an accuracy of 0.01 inches.

CONCLUSION

The SDP system is very satisfactory for revising maps. Using the point positioning mode (digitizing corresponding image points on the left and right photos without auxiliary devices for stereo viewing) a layman could update the map; thus, the name Layman's analytical plotter. The accuracy in X, Y, and Z could be improved by using a digitizer with an accuracy of 0.001 inches. Using a digitizer with an accuracy of only 0.01 inches (the least count of the system is 0.01 inches and the manufacturer claims an accuracy less than 0.01 inches (Wang Laboratories, Inc., 1975a) and neglecting the systematic errors less than 0.01 inches (at photo scale) and employing 1:3000 scale photography, the present SDP system has a noise level between 2 and 5 feet in height data. The resolution can also be improved by using rear illumination instead of the reflected illumination of the present SDP system. Digitizers with an accuracy of 0.001 inches and rear illumination are available. The SDP system can be built for approximately \$35,000; \$30,000 of this total is for a computer system that can be used for other work as well. In the present day market, a computer system with similar capabilities could be purchased at lower prices. Thus, we have developed an analytical plotter costing approximately \$5,000.

TABLE 1. RESIDUALS IN CONTROL AND CHECK POINTS

Point Number	Residuals in x (ft)	Residuals in y (ft)	Residuals in z (ft)	Remarks
1	8.2	1.8	−5.1	
2	−4.5	5.8	−1.1	
3	0.0	0.0	0.0	
4	−4.9	8.1	3.6	
5	—	—	1.8	Height Control
6	—	—	−4.9	Height Control

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