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The Universal Automatic Map Compilation Equipment

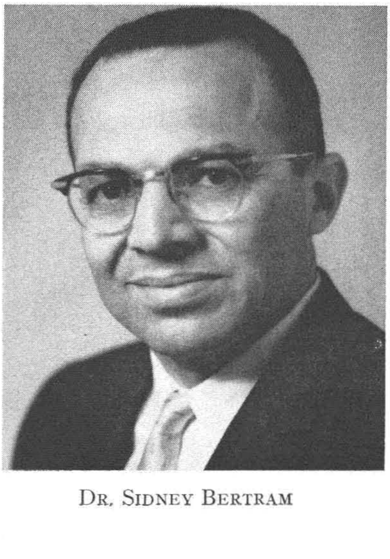
The initial cost, when amortized over a reasonable estimate of the production, should show a lower cost per model than can be achieved with conventional instruments.

(*Abstract is on page 247*)

Introduction

The Universal Automatic Map Compilation Equipment (UAMCE) nearing completion at The Bunker-Ramo Corporation is intended to produce high-quality orthophotos and altitude charts from a variety of photographic inputs, including convergent frame or panoramic pairs of up to 9- by 18-inch format. It will be able to set up its own stereo models from measurements made when operating as a precision stereo comparator.

The design of the UAMCE is based on the principles demonstrated in the very successful Automatic Map Compilation System developed at The Bunker-Ramo Corporation.* It includes a number of new features intended to enhance its utility in a production environment. Like its predecessor, the UAMCE is being developed under the sponsorship of the U. S. Army Engineer Geodesy, Intelligence and Mapping Research and Development Agency.



Dr. Sidney Bertram

This paper reviews the principles of automatic map compilation, describes the implementation for the UAMCE, and outlines the anticipated operating procedures for comparator measurements and for compilation operations.

Principle of Automatic Map Compilation

The principle of automatic map compilation from stereo photographs can be understood by examining the geometry associated with typical aerial photography. An elevation view normal to the line of flight of a camera vehicle, with photographs taken from camera stations C_1 and C_2, is presented in Figure 1. A point $P(X, Y, Z)$ in the common field of view is shown imaged at p_1 and p_2 on the resulting photographs.

Suppose it is desired to determine the altitude of point P from measurements on the photographs. If a low estimate of the altitude is made (as shown in the illustration), the image of P would appear to the left of the image of its estimated position in C_1 and to the right of the image of its estimated position in C_2. If the two photographs are syn-

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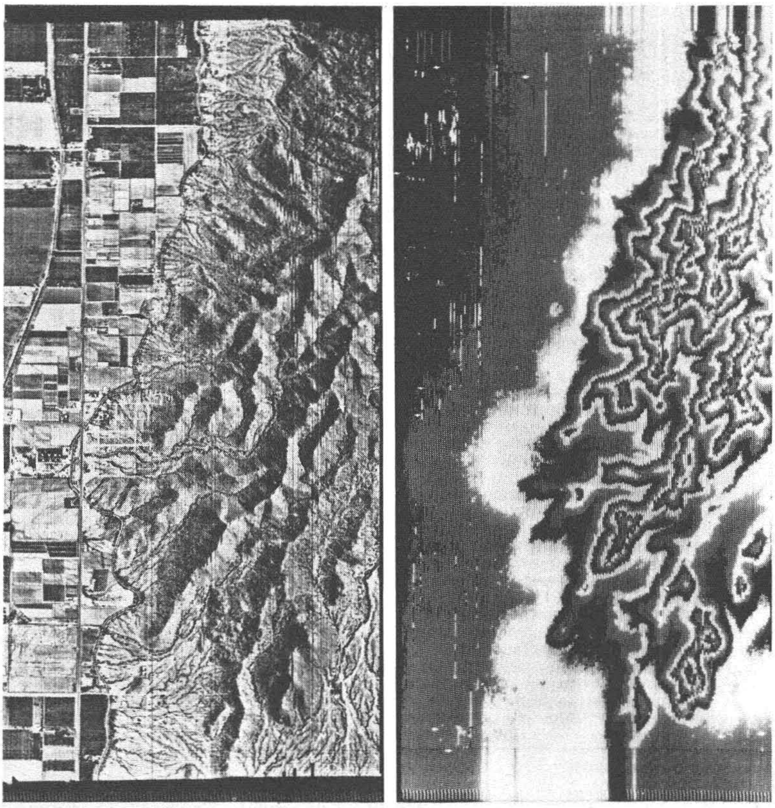
* S. Bertram. "The Automatic Map Compilation System," Photogrammetric Engineering (July, 1963).
S. Bertram. "Application of Hybrid Analog and Digital Techniques in the Automatic Map Compilation System," Proceedings—Spring Joint Computer Conference, 1963.



ORTHOPHOTO ALTITUDE CHART

Map Sheets Prepared by Automatic Map Compilation System

chronously scanned by fine points of light moving from left to right along S_1 and S_2 and centered on the estimated positions of the point, the signal corresponding to p_1 will appear early in its scan while that from p_2 will be late in its scan. While particular imagery is not identified, the differential time between the appearance of related imagery provides a measure of error in the altitude estimate.

CORRELATION OF SIGNALS

The recognition of the similarity between two signals, basic to the measurement of the differential time, is achieved through a correlation process which implements the mathematical expression

$$S(\tau) = \frac{1}{T_0}\int_{t-T_0}^{t} g(t)h(t-\tau)dt \qquad (1)$$

where $g(t)$ and $h(t)$ are the two signals to be compared, τ is a delay, and $S(\tau)$ provides the desired measure of the similarity of the two signals over a range of integration; $S(\tau)$ is a measure of the average correlation level over the integration time, T_0. The delay parameter, τ allows the signals to be compared with different time offsets; the delay that maximizes $S(\tau)$ provides the desired measure of the displacement of similar or "correlatable" elements in the two signals.

Figure 2 illustrates the correlation process for the hypothetical case of a sharply defined image element giving rise to a signal in the form of a rectangular pulse of unit amplitude and time duration T. The first signal, $f(t)$, is shown in (*a*). The second signal, shown in (*b*), is assumed to be identical to the first, except for a delay τ. The instantaneous product of the two signals, shown in (*c*), again is a square pulse, but the pulse duration extends only over the overlap of the two contributing pulses. The correlation function for $T < T_0 = 1$ (the area common to the two pulses as a function of the delay) is shown in (*d*). The maximum value of the correlation function, T, occurs when the pulses are co-incident ($\tau = 0$) with a linear rise and fall on either side going to zero where the pulses do not have a common region.

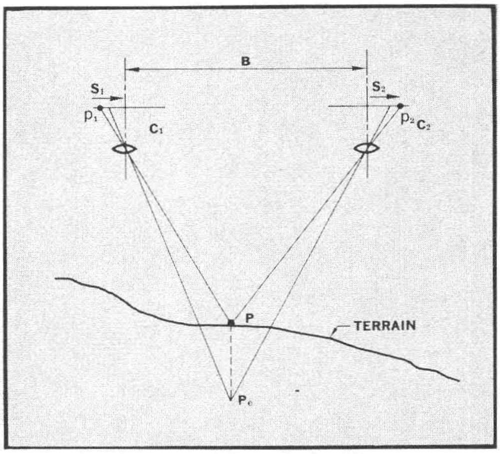


FIG. 1. Development of Height-Error Signal from Stereo Photographs.

It is interesting to examine the correlation function for a set of regularly spaced elements —for example, a row of houses or trees in an orchard. Figure 3 presents this function for a set of three idealized pulse elements. The correlation function has a large peak when τ equals zero; i.e., when the three pulses of $f(t)$ overlap with the corresponding pulses of $f(t-\tau)$. In this case, the principal peak is surrounded by smaller secondary peaks where two pulses overlap and still smaller peaks where only one pulse overlaps. These are of interest because it is possible for a system to have a sufficient error to take it to one of these peaks. In such a case, any tracking device based on correlation would try to pull in to the top of the peak it is on—hence, to an erroneous value.

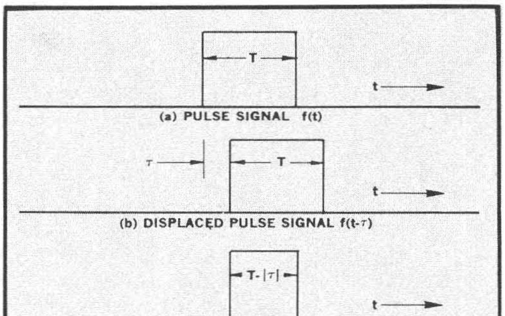


FIG. 2. Development of Correlation Function for Sharply Defined Element.

The possibility of an ambiguous height determination (Figure 3) can be reduced by using a low-resolution scanning system that can resolve the "forest" but not the "trees." This approach would broaden the correlation function so that it has a single peak extending beyond the limits of the original function with only a trace of the original secondary peaks showing (Figure 4). It will be observed that the position of the maximum cannot be determined as easily on this new function, but there is no longer any possible ambiguity.

In an automatic map compilation system it is advisable to use dual correlators, with a high-acuity channel taking advantage of the available resolution in the photographs and a low-acuity channel operating through electrical filters to effectively work only on low resolution imagery in the photography. The high-acuity channel provides tight tracking most of the time, with the low-acuity channel helping over difficult areas (such as abrupt altitude changes).

PRACTICAL CONSIDERATIONS

Imagery is usually characterized by gradual transitions, yielding electrical signals con-

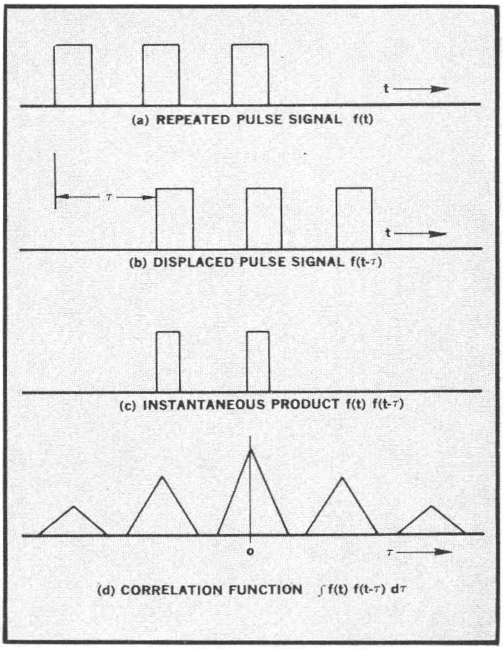


FIG. 3. Development of Correlation Function for Repeated Pulse Signal.

ABSTRACT: *The Universal Automatic Map Compilation Equipment nearing completion at The Bunker-Ramo Corporation is being developed to produce accurate orthophotos and altitude charts automatically in a map-production environment. It will serve as a precision comparator and, using the equipment computer, will perform orientation calculations to obtain the data required for the compilation operation.*

The equipment consists of four identical scanning tables, a control console, a Bunker-Ramo Model 133 Digital Computer with input/output equipment, and associated electronics. Any one of the four tables can be used to carry a diapositive during compilation or comparator operations or to carry a film sheet for exposure of the orthophoto or altitude chart during compilation.

The equipment is designed to perform one hundred altitude measurements per second; detailed 9- by 18-inch, 100% lap, 30-degree convergent stereo pairs can be compiled in less than three hours with an expected accuracy corresponding to a C*-factor of 5000. Smaller models and/or a reduced accuracy requirement would require lower compilation times per model.*

The equipment permits the operator to outline possible trouble areas before a compilation is started and to command appropriate action to be taken when the areas are examined during compilation.

When operated as a comparator, the equipment permits virtually simultaneous stereo measurements on common areas on four diapositives—one on each table. A measurement error of less than 4 μ rms is expected for such operations.

sisting of rounded pulses that merge together. The corresponding correlation functions do not have sharp corners, as shown in Figures 2(d) and 3(d), but curve around the top and taper off towards zero.

To optimize altitude tracking, it is necessary to ensure a high level of useful signal into the correlators with a minimum of noise or extraneous signal. The d-c level, which does not contain any useful information, could obscure small image detail (particularly in high-light areas); letting through the fine detail would result in an unnecessarily high level of photomultiplier (and other) circuit noise entering the correlators. For this reason, the signal processing begins with the removal of both the average, or d-c, level and high frequency components near the resolution limits of the system. In the case of the low-acuity correlators, the high frequency components are further attenuated in order to minimize the possibility of multiple peaks in the correlation function.

The four modified signals (two for the high-acuity and two for the low-acuity height error sensor) are brought to the desired energy level in independent, automatically gain-controlled amplifiers. Thus, only the signal components going to the respective correlators are influential in controlling the input level.

The method of scanning the photographs is critical for optimum correlation. Only signals which can represent height differentials are useful. For example, this implies that the image of a straight line (such as would be produced by a road running parallel to the line of camera separation) should produce a minimum signal because it does not contain any height information. The scan implied in Figure 1 (parallel to the line of flight), satisfies this requirement. For elements in the photography representing tilted ground areas, the appropriate scan is one representing the projection of such a scanning line on the tilted areas as seen in the two photographs.

CORRELATOR CIRCUIT

The correlators used in all Bunker-Ramo automatic mapping equipments resemble a "quarter-square multiplier" or "phase-sensitive detector" as illustrated in Figure 5. To aid in the description, the circuit is divided into an upper (heavy line) and a lower (light line) portion.

In the upper portion, suppose the nonlinear elements $D1$ and $D2$ have current-voltage relationships expressed by

$$i_1 = ke_1^2$$

and

$$i_2 = -ke_2^2$$

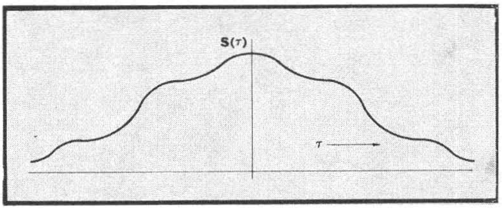


Fig. 4. Correlation Function for Repeated Pulse Signal Using Low Resolution Scanning Signal.

where the sign reversal is obtained by reversing the element. Suppose further that the two transformers have inputs e_a and e_b. Element $D1$ has an effective input voltage, supplied through equal summing resistances, R, of $(e_a+e_b)/2$, while element $D2$ has an input of $(e_a-e_b)/2$. The current into the integrating capacitor, C, is the difference of the currents from the two nonlinear elements:

$$i_c = k\left[\frac{(e_a + e_b)^2}{4} - \frac{(e_a - e_b)^2}{4}\right] = ke_ae_b$$

Because the voltage across a capacitor is the integral of the current into it, the output, taken from across the capacitor, is the desired integral of the product of the two input signals.

The elements used for $D1$ and $D2$ are not square-law devices, but diodes which pass current for one polarity while passing a negligible current for the opposite polarity. The light (lower) portion of the circuit (Figure 5) supplies the currents of opposite polarity. Thus, diode $D1$ supplies current to the capacitor when $e_a+e_b>0$, and diode $D3$ supplies a corresponding current for $e_a+e_b<0$. Similarly, diode $D2$ supplies a negative current for $e_a-e_b<0$ and diode $D4$ supplies a negative current for $e_a-e_b>0$.

In practice, the balance of the correlator is far more important than its linearity as a multiplier. The transformers must cover the frequency range of interest, and the capacitor (with associated resistors) must have a desirable time constant. In the UAMCE the capacitor is replaced by an operational integrator; this integrates linearly until the capacitor is short-circuited by signals from the height counter or computer. One integrator receives the combined output of two correlators connected differentially, as described in the next section.

DEVELOPMENT OF HEIGHT-ERROR SIGNALS

An error in estimating the height gives rise to a corresponding time offset in the appearance of corresponding imagery in the two scanning signals. This, in turn, results in a level of correlation which is as much dependent upon the image content as on the

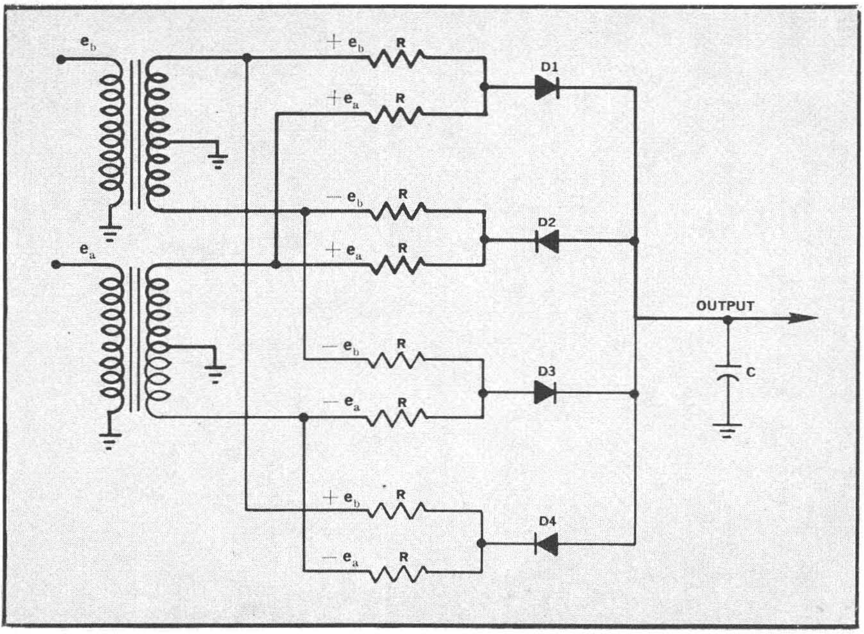


FIG. 5. Correlator Circuit.

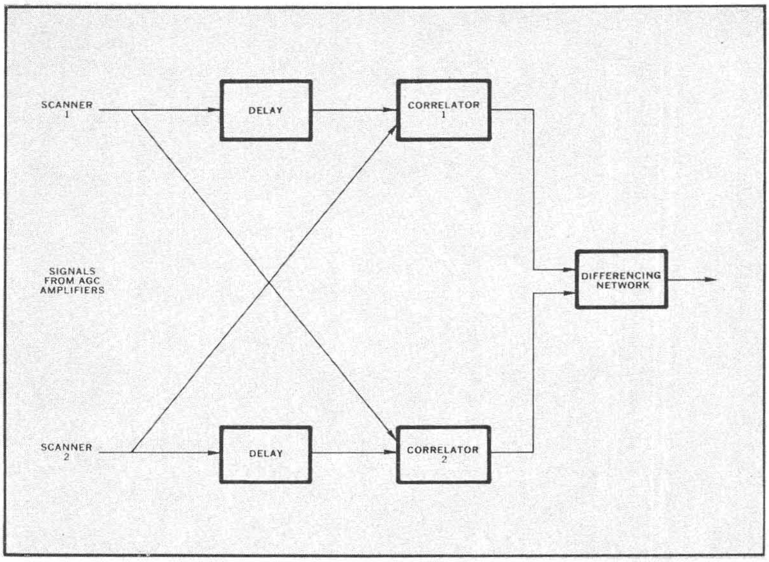


FIG. 6. Height-Error Sensor

error; the output of such a correlator provides no clue to the altitude error.

To obtain a useful height-error signal, two-correlators are used in conjunction with time delay units connected (as shown in Figure 6) so that correlator 1 has a peak output for errors on the low-altitude side while correlator 2 has a peak for errors on the high-altitude side. These, along with the corresponding difference output, are shown in Figure 7. It will be observed that the difference is zero for $\Delta Z=0$ (coincident signals), with a positive output for $\Delta Z>0$ and negative output for $\Delta Z<0$; thus, the difference output is appropriate for use as a height-error signal.

The UAMCE has a high-acuity and a low-acuity height-error sensor. The outputs of these are appropriately summed to provide a net height-error signal.

HEIGHT-ERROR MEASURING UNIT

The height-error signal must be converted to a digital measure of the error. This is accomplished in the height-error measuring unit (Figure 8). The signal from the height-error sensor is passed to an integrator whose output is monitored by a positive and negative threshold detector unit. When the integrated error signal exceeds one of the threshold limits, the detector steps a reversible counter in a corresponding direction and resets the integrator to zero. The counter, in turn, operates an elementary digital-to-analog converter that produces a voltage to deflect the center of one of the diapositive scans in a direction to reduce the observed time differential. If the altitude error has not been completely compensated, the remaining error signal may again cause the threshold to be exceeded, resulting in a second count. Operation

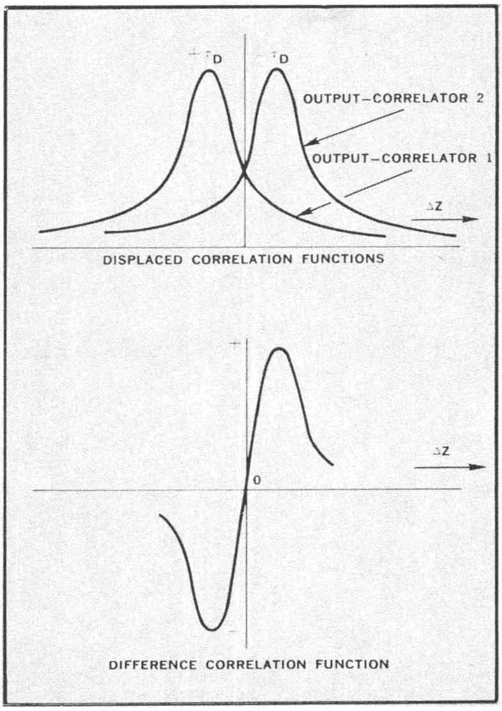


FIG. 7. Output of Differential Correlators.

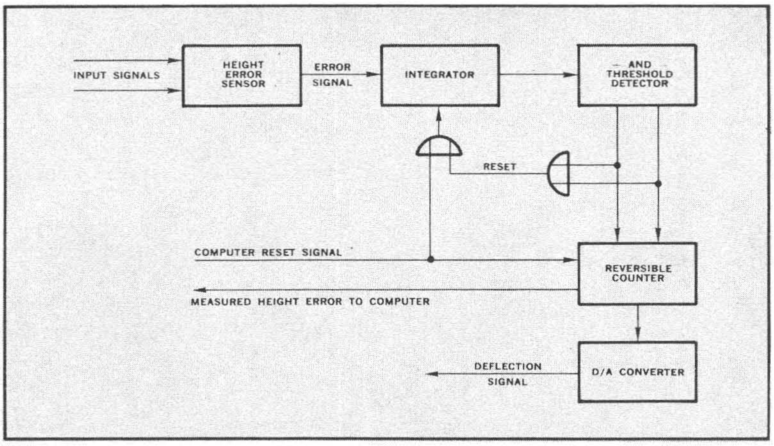


FIG. 8. Displacement-Error Measuring Unit

continues in this manner until the height-error has been compensated and appears as a corresponding count in the reversible counter. In operation, the counter position is then read by the associated computer and the integrator and counter reset to zero so that a new measurement can be initiated. Note that the height-error measuring unit is, in effect, an analog-to-digital converter that provides a digital measure of any height error. Because of the closed-loop operation, the measurement is independent of the quality of the imagery in the field of view. However, the time required to make the measurement does depend on the image content.

MATHEMATICS OF AUTOMATIC MAP COMPILATION

Operation of automatic map compilation equipment is limited to photography for which the geometry is sufficiently well defined so that the functional relationships

$$x = G(X, Y, Z)$$

and

$$y = H(X, Y, Z), \tag{2}$$

which relate coordinates (X, Y, Z)* on the ground to coordinates (x, y) in the photographs, can be obtained. The functions, G and H, must be in a suitable form for computation by a digital computer.

For ordinary photography the relationships in Equation (2) take the well known form

$$x = f\left[\frac{u_1X_r + u_2Y_r + u_3Z_r}{w_1X_r + w_2Y_r + w_3Z_r}\right]$$

and

$$y = f\left[\frac{v_1X_r + v_2Y_r + v_3Z_r}{w_1X_r + w_2Y_r + w_3Z_r}\right] \tag{3}$$

In this case, f is the focal-length of the camera the coefficients $u_1, u_2 \cdots w_3$ are functions of the orientation of the camera at the time a given photograph was exposed, and X_r, Y_r, and Z_r are measured with respect to the position of the camera station. Equation (3) is augmented by simple equations providing corrections in the film coordinates, x, y, for distortion in the camera lens or film and for corrections in the geographical coordinates for the effects of the curvature of the earth and atmospheric refraction. For panoramic photography the relationships take a more complex form in order to account for the sweep motion of the camera and the motion of the camera vehicle during the exposure.

In the UAMCE a digital computer calculates the photographic coordinates, (x, y), for each of the photographs corresponding to a ground horizontal position (X, Y) and an altitude Z_e obtained by extrapolation from previously measured positions; the (x, y) values are used to position the photographs over the respective scanning units.

The computer also calculates and outputs the partial derivatives of Equation (2) required to develop the appropriate scanning signals. These can be written in terms of the derivatives of the functions in the form

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* For the present purposes a rectangular coordinate system is presumed. Where the curvature of the earth is significant, a suitable correction is used.

$$dx = \frac{\partial G}{\partial X} dX + \frac{\partial G}{\partial Y} dY + \frac{\partial G}{\partial Z}\left(\frac{\partial Z}{\partial X} dX + \frac{\partial Z}{\partial Y} dY\right)$$

and

$$dy = \frac{\partial H}{\partial X} dX + \frac{\partial H}{\partial Y} dY + \frac{\partial H}{\partial Z}\left(\frac{\partial Z}{\partial X} dX + \frac{\partial Z}{\partial Y} dY\right) \qquad (4)$$

Here, dx and dy are displacements in the photograph corresponding to effective scanning displacements dX and dY along the ground;

$$\frac{\partial Z}{\partial X} = Z_X \quad \text{and} \quad \frac{\partial Z}{\partial Y} = Z_Y$$

are the components of the slope at (X, Y, Z). In practice, dX is a fast sweep parallel to the flight line and dY is a slow sweep in the perpendicular direction; these combine to form a TV-like scan along the ground. The sweep components, dx and dy, in the plane of the photographs produce a one-to-one time correspondence between scanning of ground and image points.

The components of slope are measured by analog circuits that implement the scans described by Equation (4), with independent counters representing Z_X and Z_Y. The signals to change the state of the slope counters are derived by comparing the differential height error signals on the positive and negative X halves of the scanned area for Z_X and on the positive and negative Y halves for Z_Y. Because the slope measuring elements form closed-loop analog-to-digital measuring units (as in the height measurement), the measurements are independent of the quality of the imagery in the area. The measured digital slope values are transferred to the computer for use in estimating the altitude for successive elementary compilation areas.

At each iteration the computer calculates the photo coordinates of each new point for the desired X and Y and the best estimate of Z available. The measurement (by the analog system) of the resulting altitude error requires a knowledge of the scale factor relating observed displacements in the photography to altitude errors. In the case of vertical frame photography, the scale factor is essentially constant for a given model; for all other types of photography the scale varies over the compilation field. The scale is calculated by the computer as often as required to have a sufficiently current value for use. The calculations are based on the following:
Let

$$x = G(X, Y, Z), \qquad y = H(X, Y, Z)$$

$$x' = G'(X, Y, Z), \qquad y' = H'(X, Y, Z)$$

be the equations defining the coordinates of a point $P(X, Y, Z)$ on each of the photos of the stereo pair. Assume that the second (primed) diapositive is used to create the orthophoto and that its scan is not disturbed by the altitude correction signals. The problem is illustrated in Figure 9, which shows an elevation view normal to the line between the two camera stations. A high height-estimate is indicated, where the image in the center of the field of view on the second diapositive is shown as P_o (instead of the correct position, P). The image of the estimated point, P_e, on diapositive *1* is displaced $G_Z dZ$ from the image of P, and by $G_H dZ$ from the image of P_o. In practice it is expedient to make the correction using $G_H dZ$ at the first diapositive with the orthophoto signal taken from the second diapositive; the displacement of P_o from P is ordinarily so small as to produce negligible error on the orthophoto. By assuming $\Delta Z = 1$ (i.e., equal to the increment of the height counter), the required height corrections are readily found. Thus,

$$dx = G_X dX + G_Y dY + G_Z$$

and

$$dy = H_X dX + H_Y dY + H_Z \qquad (5)$$

In Equation (5), dX and dY are found from the corresponding equations for the second diapositive by taking $dx' = dy' = 0$; that is,

$$0 = G_X' dX + G_Y' dY + G_Z'$$

and

$$0 = H_X' dX + H_Y' dY + H_Z' \qquad (6)$$

When Equation (6) is solved for dX and dY and the results substituted into Eq. (5), the differential shifts, dx and dy, corresponding to a unit altitude error are determined. These values are outputted to the analog equipment. Because only a very modest accuracy is required, simple approximations are possible and only infrequent updating is required. The calculation represents a trivial part of the total computer problem.

The computer also outputs a signal to control the intensity of the scanner exposing the altitude chart. For this purpose, the altitude is divided by three times the desired contour

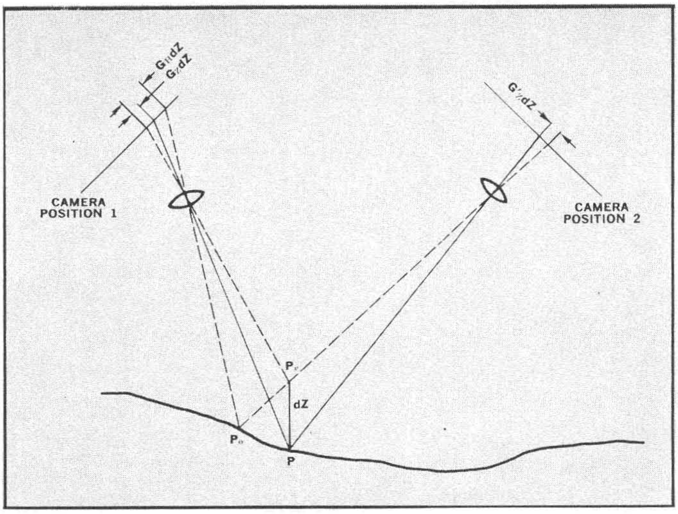

Fig. 9. Development of Height Correction Signal, View Normal to Flight Line.

interval and the remainder, R, examined for assignment of the printout level. The level is assigned as follows:

$0 \leq R < 1/3$	scanner off
$1/3 \leq R \leq 2/3$	scanner medium
$2/3 < R$	scanner bright

This creates a chart (shown on the frontispiece) showing well-defined altitude bands. The rotary sequence of densities permits an unambiguous assignment of altitudes, starting from a point of known altitude.

Reduction of Y Parallax

Creating an adequate stereo model for compilation requires that both X and Y parallax be removed at a number of points in the stereo field so that coordinates of common points in the field can be accurately ascertained. The height-error sensor removes X displacements caused by height errors; therefore, it is directly applicable to the automatic removal of X parallax in the comparator mode. The removal of Y parallax displacements requires additional circuity.

Sensing of Y errors is achieved, in effect, by introducing an artificial Y parallax analogously to the X parallax provided by the delay lines in the height-error sensor (Figure 6). The Y parallax is introduced on a time-sequential basis by shifting the scan in Y on one diapositive, positively for a defined time and then negatively for an equal time. The output of the associated correlator is switched into a positive input of an integrator during the positive shift, and to a negative input during the negative shift. If there is no Y parallax at the point, the inputs during the two time periods are equal, and the integrated output is zero. If there is any Y parallax, the correlator will have a larger output when the artificial parallax partially cancels the image displacement and a lower output for the other half cycle where the two components are additive; therefore, the integrated output provides a measure of the Y parallax.

In the UAMCE, a positive and negative threshold detector (similar to that used with the height-error sensor) provides digital error signals to the computer for reduction of Y parallax during comparator operations. For automatic compilation operations, the integrated output is used to deflect the center of one of the diapositive scans in a direction to reduce Y parallax; this ensures high sensitivity in the height-sensing circuitry, even with a poor model.

Scanning Pattern

It has been noted that the principal scanning for automatic height determination should be along a line parallel to the line joining the two camera stations (i.e., on an X-directed line). This must be augmented by a slow scan perpendicular to the fast scan (on a Y-directed line) to produce an effective area scan providing a TV-like coverage of each small area. This ensures continuity of the image for both the operator and for automatic tracking. The signal from one scanner is used to recreate the scene element for exposure of the orthophoto film sheet.

For automatic operations the time required to sample a given area must be kept as low as possible. For this reason the Y scan is made in an unusual pattern. Every line on the positive side of the center of the scan is followed by a correspondingly positioned line on the negative side. The scanned area is covered very coarsely at first, then gradually filled in. A total of 128 lines is used with substantially uniform sampling of the area in 2, 4, 8, 16, 32, 64 or 128 lines. The total frame scanning of 128 lines takes 20 milliseconds; because a 10-millisecond measurement period is used during compilation, only every other line is used in exposing a given scene element for the orthophoto.

PRODUCTION OF THE ORTHOPHOTO AND ALTITUDE CHART

A television-like reproduction of the small area under observation at a given time is created by displaying the ground scan (dX, dY), appropriately scaled, on a flying-spot scanner with the instantaneous brightness controlled by the video obtained from one of the diapositives. This is centered at the similarly scaled ground position (X, Y) to expose the corresponding area on a sensitized film sheet used to create the orthophoto. The profiling operation ensures a complete coverage of the model area. A second flying-spot scanner, similarly positioned but with its brightness controlled by the three-level contour interval signal from the computer, is used to create the altitude chart.

CHARACTERISTICS OF THE UAMCE

Automatic map compilation devices require scanners to examine the stereo photographs, to produce an orthophoto, and to print an altitude chart. A positioning unit must be associated with each scanner.

In Bunker-Ramo's earlier device, the Automatic Map Compilation System, the two diapositives and single film sheet for the orthophoto and altitude chart were mounted on a common carriage, whose position corresponded to the geographic area being examined. Thus, while fixed scanners and imaging lenses sufficed for the two outputs, the diapositive scan lenses had to be moved by servos under computer command to accommodate for parallax and camera-tilt displacements. This reduced the accuracy requirement of the large carriage, but limited the system's application because of the restricted range of the lens servos used to remove parallax displacements.

In the UAMCE, four identical tables with associated flying-spot scanners, under command of the Bunker-Ramo Model 133 computer, are used; they provide virtually an unlimited amount of flexibility. The severe parallax displacements of strongly convergent photography, the distortions of panoramic photography, and a considerable range of output scales for a given input scale can be accommodated. Reducing the output scale makes it possible to automatically prepare mosaic orthophoto and altitude charts from contiguous stereo pairs.

An artist's concept of the UAMCE is shown in Figure 10. The four tables in the foreground can be used interchangeably to carry diapositives or film sheets. The control console includes a stereo-viewer for monitoring the automatic compilation operation; it is arranged to permit stereo observation of images from any two of the four tables, thus providing a capability for making virtually simultaneous stereo comparator measurements on up to four diapositives. To assist in the comparator operation, the images can be rotated 90 degrees to facilitate observation of Y parallax, and the left and right images interchanged to obtain a pseudostereo view. A reference viewer on the console is intended to carry a print corresponding to a diapositive used in one of the tables. The viewer has a carriage which may be slaved to any one of the four tables in accordance with the position of a selector switch. A light moved by the carriage illuminates a small area on the photo print to indicate the area under observation at the corresponding table. A position control, located under the reference viewer, permits the operator to change (through the computer) the x- and/or y-position of any of the tables or the height during compilation. A set of pushbuttons on the console permits the operator to select the desired operational mode.

A Bunker-Ramo Model 133 Digital Computer, shown to the left of the console in Figure 10, calculates the table coordinates and scan coefficients and controls the operations. A typewriter at the left of the console is used for computer checkout and off-line program and data preparation. A two-bay electronic rack carries the timing signal generators, scan generators, correlators, and computer interface equipment. Table servo- and scan-drive amplifiers are located in small racks adjacent to the associated tables.

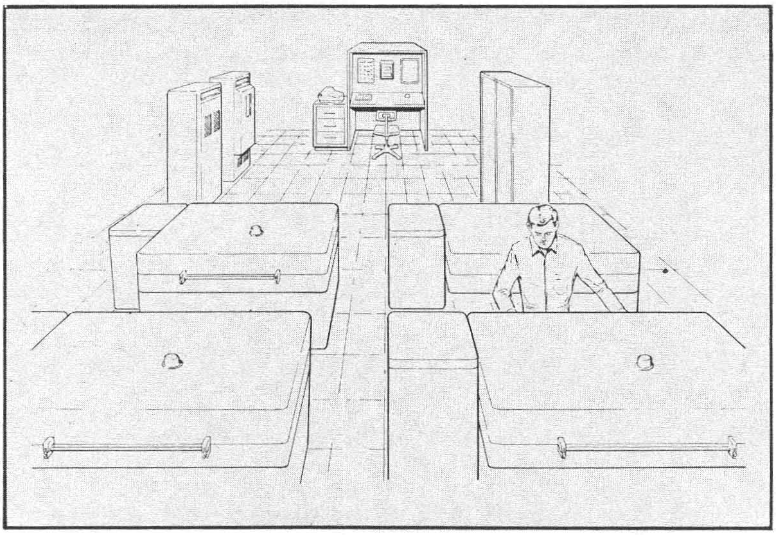

FIG. 10. Universal Automatic Map Compilation Equipment.

SCANNING TABLES

The configuration of a scanning table is shown in Figure 11. The UAMCE requires four of these tables.

The requirements for the table are quite unusual. It must be capable of moving a 9- by 18-inch glass plate at peak speeds of over two inches-per-second on orthogonal axes (with an average speed of one inch-per-second during compilation) and of positioning the scanning to within a 4-micron rms error on the plate. The required two-coordinate motion is provided by dual carriages, with one carriage riding on top of the other.

The base of the table is a composite structure of a highly rigid, stabilized bed casting which is nested in a fabricated steel cradle. The assembly rests on three leveling-type vibration isolators. The flying-spot scanner assembly is precision-mounted from the bed casting, with provisions for access for repair or removal of the unit through the cradle.

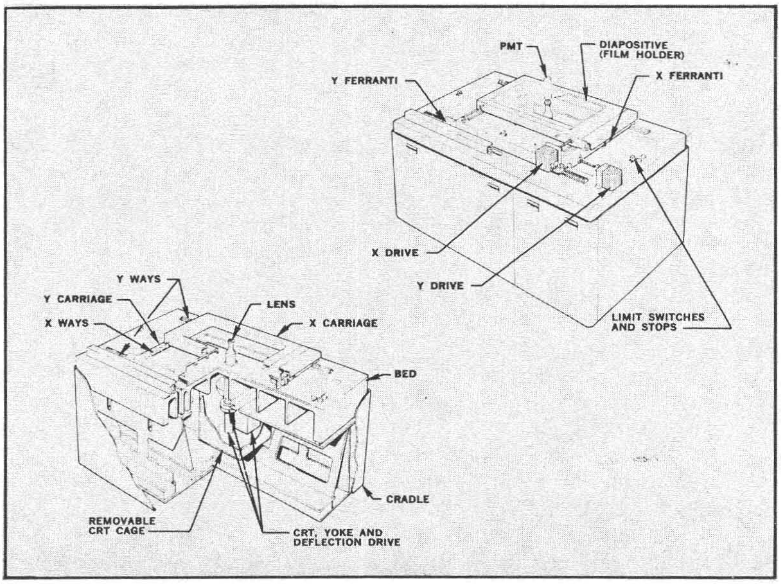

FIG. 11. Scanning Table—Artist's Sketch.

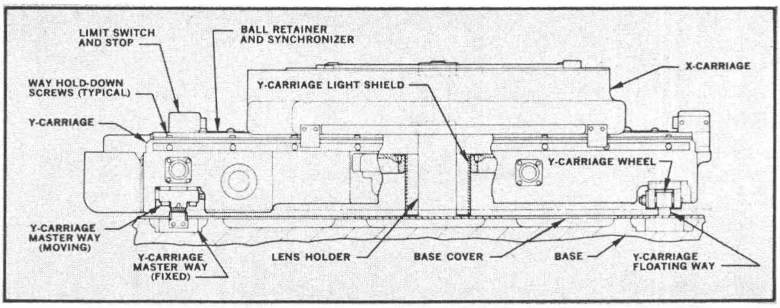

FIG. 12. y-Carriage Ways.

The main supporting sections of the cradle fall directly under the sections of the bed which carry the longer (y-direction) ways. The bed, a stabilized Mehanite casting, is ribbed to provide substantial rigidity and is mounted in place along supporting sections; special screws capable of fine adjustment are used to remove any small errors in the y-direction way geometry.

The scanning table has two carriages (as indicated in Figure 11). Each moves independently of the other; their motions combine to position the transparency or film to the proper location over the scanner. They are made of cast magnesium alloy which is selected and treated for maximum dimensional stability. It is interesting to note that the magnesium alloy chosen, when properly stabilized and stress-relieved, has a high internal damping factor that operates to prevent "ringing" of the carriages when they are rapidly accelerated by the servo; such vibrations, though of small excursion, could adversely affect the operation of the Ferranti Moiré fringe counting element used for the position measurement.

The carriages have extensive ribbing, which gives maximum structural rigidity. The lower carriage rides on the y-ways and supports the upper carriage on the x-ways; the relationship of these two ways determines the orthogonality of the table. Fortunately, the center opening in the lower carriage has to be only large enough to clear the lens tube for one directional motion; therefore, it is constructed as an almost completely closed box, making it very rigid structurally.

The x-motion carriage has a smaller effect on the performance accuracy of the table because its motion is completely determined by the ways on the y-carriage. Because it carries the transparency or film adapter, it must have a center opening equal to the largest diapositive area to be examined.

The ways have a very important effect on the performance of a precision machine. Ball-bearing, anti-friction ways are used in the UAMCE because of their low friction and because the small number of parts involved in the guiding action makes it easier to achieve the desired accuracy. The guiding way makes use of "V" grooves on each member. The floating way makes use of a linear ball-bearing wheel that is free to move and rotate on its axis to minimize side loads and to relax the setup tolerances. The ways, made of hardened steel, are floated in the related member to prevent strains caused by temperature variations. The y-carriage with its ways, with the x-carriage superposed is shown in Figure 12. The construction of the x-carriage ways is similar to that of the y-carriage ways.

The illustration also shows the lens holder and y-carriage light shield. The lens holder is rigidly attached to the table base and appears in a slot in the y-carriage. Extensive light shielding is used throughout to ensure against fogging of the photosensitive film sheet during the long time required for a compilation.

Each of the carriages is driven by a servo motor through a gear train, which, in turn, drives a recirculating ball-bearing screw. Two-micron Ferranti Moiré fringe measuring elements, independent of the drive, operate with reversible counters to provide a running count of the table position on each axis.

The tables are provided with adapters for holding either glass plate transparencies or film sheets. A vacuum hold-down and an arrangement similar to that used in a cut-film camera to facilitate handling is used for the film sheets.

During operation of the UAMCE the computer calculates the desired x and y positions for the carriages on each of the four tables. The digital outputs of the computer are converted to eight analog voltages, corresponding to the desired x and y positions of the four tables. The pulse outputs from each optical measuring unit are accumulated in a reversible counter; the state of the counter represents the instantaneous position of the corresponding table axis. To obtain the servo drive error signal, the counter state is converted to an analog voltage, which is then subtracted from the analog voltage representing the corresponding computed table position. The servos, acting in response to the error signal, drive the appropriate table axis in a direction to make the actual table position equal to the computed table position.

Because analog servos are limited in speed, the accurately scaled servo error signal is also used to move the position of the scanning raster (or printout raster) in a direction to nullify the effects of any servo error. The response of the deflection system is about 1000 times faster than the analog servos; the area under investigation on the diapositive, or the printout area in the film plane, is therefore essentially free from delays and identical to the desired value. The measuring elements provide counting pulses at two-micron intervals, so that approximately 2^{18} pulses are required for the 20 inches (500,000 microns) of table travel; hence, 18 bits are required to represent the position in the computer. Because 18-bit digital/analog converters are prohibitive to implement, only the 11 least-significant bits of the table positions are transferred to the analog units; once the table comes under control of the computer, the position error will be a very small part of the total range of control, and the larger bits would be redundant. The total range of the digital/analog converters is (2048) (2 microns) = 4096 microns (or 0.16384 inch) of carriage motion. The servo system must keep the position error less than half this value to prevent ambiguity (as described later).

The difference between the computed and actual table position is found by taking the difference between the d-c voltages appearing at the outputs of the two digital/analog converters. This is accomplished by a differential amplifier, whose output is the servo error signal. This output is later summed with the desired scan signal for the particular table to obtain the composite signal used to position the scanning spot.

The servo error signal is also used in compensating for a problem caused by dropping the largest bits from the positioning unit. The division of the table position into 11-bit units, in effect, sets up a periodic measuring system in which the digital/analog converters change over their full range in each period. This is illustrated by scale S1 in Figure 13, where the numbers represent digital/analog outputs for the given table position. Suppose that at time A the command position is at 6 and the table position at 4; then there is a two-unit error signal forcing the table to the right. At a later time B, the command position, e_c, will have exceeded the full count of the digital to analog converters. Then the output is, say, 0.3 instead of 10.3, while the actual position, e_t, is 8.3; the difference signal would be minus 8 instead of 2.

This situation is corrected by setting up a second scale, S2, displaced from the first by half the periodic interval (i.e., an amount equivalent to the largest bit used). Conversion between the two scales is then obtained by complementing the largest bits in both digital/analog units (e_c and e_t). When the excessive error is observed at B, the complementing would take place to shift the scale

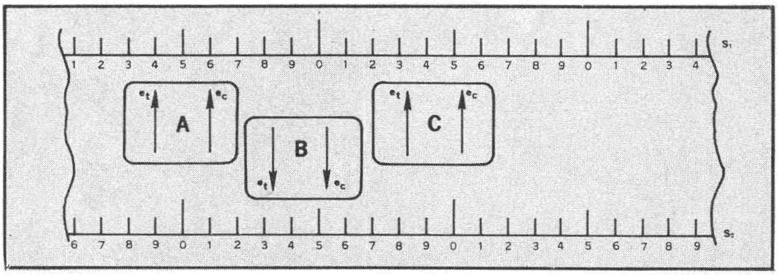

FIG. 13. Table Position Measurement Scales.

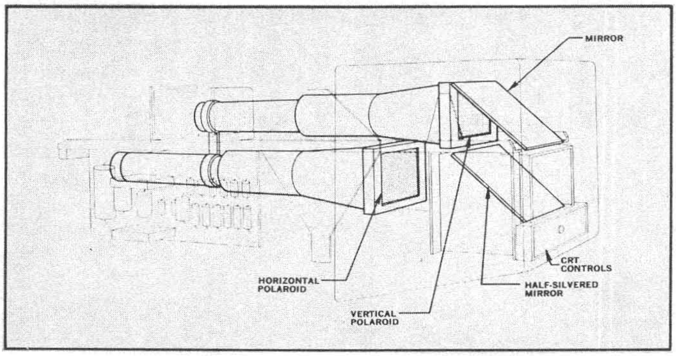

FIG. 14. Stereo Viewer.

used to *S2*, where the readings (with the correct error difference of two units) would be 5.3 and 3.3.

As the system moves to the right, the problem recurs at *C*, where complementing would move the scale used back to *S1*. It is obvious that as long as the real error remains below half the interval (5 units in the diagram), an observed error greater than half the interval must be corrected by the complementing technique. The periodic interval used in the equipment is 4096 microns; operational speeds and accelerations are limited to ranges yielding expected errors that are small with respect to the interval.

AUXILIARY EQUIPMENT

The video signals generated by the photomultipliers at each scanning table are used to drive the correlation circuitry. The signals are also used to recreate images of the scanned area for exposing the orthophoto and to provide a "window" to the operation in the form of an electronic stereoviewer. The viewer is shown in schematic form in Figure 14. It includes two 4-inch, square-faced cathode-ray tubes whose images are superposed using a half-silvered mirror; separation for stereo viewing is achieved through cross-polarized filters in front of the two tubes with correspondingly polarized glasses worn by the operator. An electronically generated floating mark (a bright cross or dot) provides a stereo reference.

The UAMCE incorporates a "reference viewer," which is designed to illuminate a point on a print corresponding to the area under observation on the related diapositive. The viewer, at the upper right of the control console, is designed to take full-size prints. Switches permit the operator to slave the operation to any one of the four tables. The reference viewer permits the operator to locate the observation area in order that he can interpret the image in the stereoviewer. It is also used in certain operations not requiring full equipment accuracy (such as initial calibration and defining potentially troublesome areas).

A control keyboard provides operator selection of computer programs or operating parameters. Keys are provided to select the table to be manually moved, as previously described, and to change the sensitivity of the control. Other keys cause the computer to go through a defined calibration routine, to go into the comparator or compilation operating programs, to take in measured coordinate data, or to allow manually inserted height changes during compilation.

The tables are manually controlled with a position control, which takes the form of a ball whose upper surface protrudes above the table top. Movement of the ball is communicated to the computer by properly coded signals; the computer then commands corresponding motions of the tables. This may take the form of combinations of x and y motions of a selected table during comparator measurements or of Z changes during compilation.

A symbol generator provides video for the generation of symbols on the orthophoto and altitude chart scanners. These are used, under computer control, for marking important features, such as pass-points and map grid-coordinates on the orthophoto and altitude chart. The symbols are generated by a flying-spot scanner, whose light is modulated in accordance with a symbol on a mask. The symbol is computer-selected, from a field of six, by moving the center of the scanning raster. The light modulated by the symbol is sensed by a photomultiplier and the resulting signal amplified for application to the printout tubes.

OPERATING CHARACTERISTICS OF THE UAMCE

The UAMCE permits an unparalleled operating flexibility. This is illustrated in the following description of the principal operations performed with the equipment.

Stereocomparator operations can be performed simultaneously on four diapositives. Before the plates are inserted, a tape is prepared which lists the pertinent data for the plates. This includes the nominal orientation data, camera station, and type of camera (frame or panoramic). In addition, rough positions of desirable pass points are entered. A program sheet that defines the task of the operator is also prepared, listing the measurements to be performed.

With the tape entered into the computer, the diapositives inserted, and an appropriately marked print on the reference viewer, the operator presses the appropriate control key to start the operation. The computer then commands all tables having diapositives showing the first pass-point to move to the designated coordinates. It also adjusts the shape of the scans at the diapositives in accordance with the nominal orientation data, in order to present a virtually undistorted vertical view at the stereoviewer (even with panoramic photos). Following the instructions on the program sheet, the operator switches the stereoviewer to a selected diapositive and proceeds to center the pass-point on the crosshair, using the position control. One image of the stereoviewer is then switched to a second diapositive and the position control used to center the pass-point in the field of view. Two alternatives are available for the final centering:

(1) The operator may take advantage of the expanded picture, 90-degree rotation, and interchange of left and right images to manually center the second image to coincide with the first.
(2) The operator, through the keyboard control, can command the correlation circuitry to make the final centering adjustment.

The second alternative is obviously the more desirable. However, it is not always possible; for example, if the area in the field of view has an appreciable variation in altitude, it will be necessary for the operator to adjust the coincidence for the desired point. The stereoviewer is then used with the third and fourth diapositives (or as many as include the pass-point) and the process repeated. When the operator decides that the centering on all diapositives is satisfactory, he depresses the "store data" button, causing the computer to place the measured coordinates in an appropriate store. The operation is then repeated for the next pass-point.

When the measurements have been completed, the data (together with geodetic control) will be used to calculate the orientation parameters required for compilation.

Compilation operations require the orientation data (including lens and film distortion characteristics) and measurement of the machine coordinates of two reference points (e.g., two fiducial points) to establish the interior orientation; of course, the measurement is not required if the diapositives have just been measured in the comparator mode. The inputs also include the coordinates of the corners of the area to be compiled, the desired scale for the output, and the coordinates of points to be marked. The geographic position corresponding to the center of the output film sheets is also defined.

Using a print of one of the diapositives on the reference viewer, the operator next moves the point of light around areas he judges to be potentially troublesome. After an area has been outlined, the operator presses a button to select the program to be used when the area is being compiled. The program includes the following instructions:

(1) Hold altitude (as over a water area)
(2) Take smaller profiling increments
(3) Move across the area, then stop for the operator to determine the altitude
(4) Proceed slowly under operator control of altitude.

When the instructions have been completed, the film sheets are inserted into the output tables (if the compilation is to be one of a mosaic set, the film might already be in the tables). The control and map grid-points are then suitably marked under computer command and, finally, the computer moves the tables to the compilation start position.

The operator then uses the position control to find the altitude of the start point. With this accomplished he can depress the "start" button to begin the compilation mode, after which his job is to monitor the operation through the stereoviewer until manual action is required. Operator action will be required only in very difficult terrains; the operator can mark these for attention before the compilation.

FUTURE OF AUTOMATIC MAP COMPILATION

The success of the Automatic Map Compilation System demonstrated the feasibility of such equipment and ensured the success of the UAMCE. The new equipment has many features, not present in the original, that make it useful as a precision comparator and enhance its potential as a compilation instrument. However, it cannot be claimed that the UAMCE is the ultimate instrument. Until the time that automatic equipment will be able to produce fully annotated, properly colored maps without the attention of an operator, improvements will be sought. It is useful to examine the potential in various areas of the operation.

The UAMCE allows 10 milliseconds for each altitude measurement—about a third of that required by the earlier system. The improvement is a result of (1) the higher intensity flying-spot scanners, which result in a significant improvement in the signal-to-noise ratio and (2) a more effective scanning pattern that provides a good averaging over the area in a few scan lines, permitting higher gain in the height-error loop before localized image detail can cause an undesired count. The improvement would be greater, except that only information in the central part of the scan is used for correlation, resulting in a significant time loss. The larger area provides the operator enough of a picture to be useful, while correlation is limited to a smaller area to obtain a more meaningful measurement of the altitude for the central point.

Because the effectiveness of the UAMCE operational cycle remains to be verified, it is not too useful to speculate on how much shorter the time can become. If the equipment were improved to a point where operator attention was not required, the scan could be confined to the area used for correlation. This might permit a factor of two improvement. Faster scanning would require a higher bandwidth and, consequently, brighter scanners; some gain might be obtained in this way, but it would be at the cost of poorer resolution and perhaps less life from the scanner tubes.

It is anticipated that significant improvements in the UAMCE will result from programming modifications that will permit the density of the measurements to adapt to the terrain. To obtain altitude information in conformance with usual map standards, it will be necessary to have at least two measurements per contour interval. In flat areas the measurement interval can be large, allowing such areas to be covered quickly; in areas of high relief, the density of measurement must be very high (unless it is not important to maintain the accuracy). It has been estimated that the UAMCE will compile 9- by 18-inch, 100% lap diapositives in about 3 hours using (at nominal scale) 250-micron (0.01-inch) spacing along the profile, and 500-micron (0.02-inch) spacing between profiles. For very flat areas this could be changed to, say, 1,000 microns between profiles and, with modification of the computer programs, an equal spacing along the profile; this would permit a 9- by 18-inch, 100% lap pair to be compiled in less than half an hour. The program should be made to adapt to the terrain to minimize the time required for each model, while maintaining the required accuracy.

The UAMCE will be improved gradually as other new computer programs are written. These will permit manual measurement of spot heights with hard-copy printout, so that the data can be added to the map. It will probably be desirable to write a program to allow the operator to contour manually in selected areas (as in a forest, where the operator can use judgment to extend whatever stereo coverage of the ground is available); the program would print out the altitude chart on the basis of the manually made measurements, but print out the orthophoto on the basis of machine-made measurements, preserving the dominant imagery on the orthophoto. Undoubtedly, still other programs will be found desirable to optimize the operation and minimize the demands on the operator.

Of course, it would be desirable to print out contour lines, rather than the present rotary sequence of three gray tones. However, until annotated contour lines (not requiring manual touchup) can be automatically drawn, the product would not be as useful as the present output. The three-tone sequence is very easy to follow and easily smoothed to obtain the final product.

The UAMCE should print orthophotos at up to 40-line/mm. resolution without any noticeable joint between the individual small areas making up the composite output. The high resolution permits outputs at reduced scale, so that high quality mosaics from contiguous stereo pairs can be made. While orthophotos may be adequate and desirable for large-scale maps, they are not useful for small-scale maps. Continued efforts will be required to automatically abstract the desired planimetric detail from the orthophotos.

Many groups are working on the problem of recognizing important details in photographs. The compilation problem demands attention to a new class of recognition problems (such as, in an area under examination, can the structure of the area be discerned from the resulting electrical signals?). The stereo signals should make recognition easier (assuming the scale of the photography is such as to reveal height variation in the features to be identified). It may be useful to be able to place upper and lower limits for the altitude variations within an area rather than being constrained to use the weighted-average altitude where the weighting favors the high information content signals.

In the series of equipment developed thus far, no attempt has been made to store any significant amount of the altitude data, except through the altitude chart. It should be realized that the compilation process requires that the measured height of each elementary area be available in digital form at some time. It would be a trivial task to store these data on magnetic tape, making them available for later use for many applications. For example, the data might be used for cutting relief models, for calculations required for cut-and-fill operations, or for calculating the expected coverage of a radar as a function of possible sites.

CONCLUSION

The development of the Automatic Map Compilation Equipment at Bunker-Ramo has been sponsored by the U. S. Army Engineer Geodesy, Intelligence and Mapping Research and Development Agency. Bunker-Ramo is proud to be associated with this organization in bringing about a significant improvement in the art of map compilation.

However, the application of automatic map compilation need not be limited to military applications. Its use will be practical wherever the mapping problem is sufficient to warrant the initial investment. The initial cost, when amortized over any reasonable estimate of the production, should show a much lower cost per model than can be achieved with conventional instruments.

ACKNOWLEDGMENT

The mapping programs at The Bunker-Ramo Corporation have been carried on by a project team encompassing many talents and skills. Mr. Melvin L. Baker, project engineer on the UAMCE, and Mr. George P. Miller, senior mechanical engineer, have contributed greatly to the different programs. Mr. Glenn S. Kimball, electrical engineer, and Mr. Floyd Smith, research assistant, were particularly helpful in the successful demonstration of the Automatic Map Compilation System which made it practical to undertake the UAMCE program.