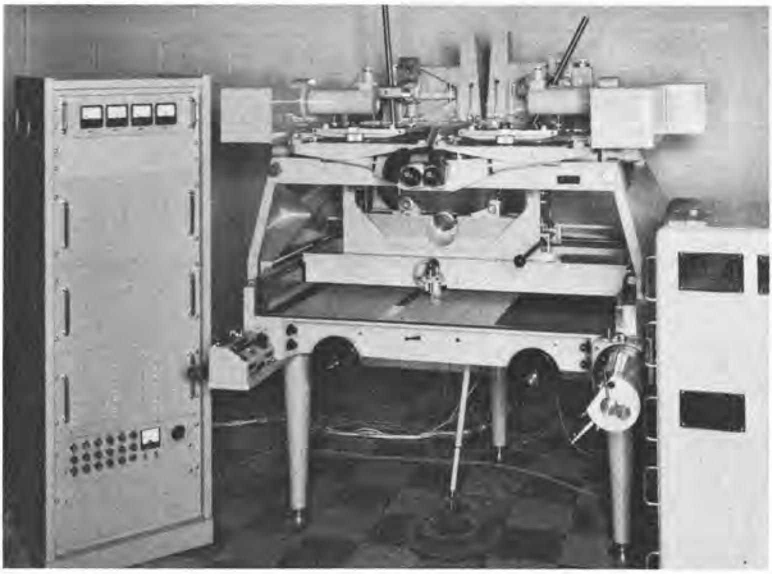

FIG. 1. Carl Zeiss Planimat automated with the ITEK Electronic Correlator.

JOHN W. HARDY, H. RONALD JOHNSTON, JOHN M. GODFREY
Itek Corporation
10 Maguire Road, Lexington, Mass. 02173

Electronic Correlator for the Planimat

The Itek system is designed for the Zeiss stereoplotter to increase speed of profiling through automation.

INTRODUCTION

THE PLANIMAT, a new stereoplotting instrument of second-order has recently been introduced by Carl Zeiss. Provision has been made in this instrument for the installation of an electronic image correlator to allow automation of the stereo profiling operation. This paper describes the design and performance goals of this automation equipment, which is designated the ITEK EC-5 Electronic Correlator.

Even with the most modern instruments, manual stereoplotting is a tedious and time-consuming operation. The time required manually to profile a stereo model is typically between two and four hours, depending on the roughness of the terrain. In the basic profiling operation, using a stereoplotter such as the Planimat, the operator is required to view the diapositives stereoscopically, traverse over the stereo model in a fixed pattern at a fixed or variable speed, and adjust the apparent height of a floating mark by means of a hand wheel or foot wheel so that it follows the terrain profile. When functioning in this way, a human operator becomes part of a closed-loop feedback system and is subject to some basic limitations. For example, his response time (i.e., the time delay between the perception of an error in the height of the floating mark and its subsequent correction by means of the hand wheel) has a definite minimum value making it necessary to slow down the traversing speed in rough terrain.

It is evident that an electrical servo system, given a suitable input, can be made to respond in a much shorter time than a human operator and will have superior ability in following rapid fluctuations of terrain height.

one-half to one hour with the Electronic Correlator. This increase in profiling speed brings the throughput time of the Automated Planimat into line with the time required to print the orthophoto in the GZ-1 Orthoprojector, resulting in better utilization of equipment.

ABSTRACT: *An electronic correlator has been designed to automate the Zeiss Planimat stereoplotter. The equipment consists of two flying-spot scanning units which are integrated with the Planimat optical system, together with a free-standing rack containing the electronics. The correlation system automatically clears X-parallax in the profiling mode by means of a servo motor driving the Z-slide of the Planimat. Reliability and accuracy of the equipment are maximized by the use of an adaptive control system which adjusts the correlation bandwidth, scanning-pattern size, and profiling velocity according to the quality of image correlation. The correlator materially reduces the time required to profile mapping photography without sacrificing the overall accuracy of the system.*

The performance of an electronic correlation system can be improved in two ways over that of a human operator:

1. The accuracy of terrain following can be maximized by the use of sufficiently high loop gain.
2. The speed at which terrain fluctuations can be followed can be maximized by the use of a wide servo bandwidth.

To exploit these possibilities requires an image correlator that is capable of rapidly and accurately detecting small variations in the X-parallax between conjugate stereo images while accommodating residual distortions caused by terrain slope and camera attitude variations. In addition to these qualities, a successfully automated system must have adaptive features which allow it to adjust to varying image quality and other anomalies such as clouds, water areas etc., to minimize the necessity for human intervention. Many adaptive features have been included in the design of the EC-5 correlator, with the aim of reducing to a minimum the necessity for operator intervention.

The ITEK EC-5 Electronic Correlator can be integrated into a complete orthophoto production system based on the Zeiss Planimat and GZ-1 Orthoprojector. Off-line operation can be secured by means of the SG-1 storage unit in which profile data from the Planimat is stored in analog form on scribed plates. These plates are then placed in the LG-1 Scanning Unit which drives the Orthoprojector. The time required to profile an average stereo model is reduced from two to four hours with manual operation to

A photograph of the Automated Planimat is shown in Figure 1, with the Electronics Rack and Control Box on the left and the SG-1 Storage Unit on the right.

BASIC DESIGN AND PACKAGING

The ITEK EC-5 Electronic Correlator which is shown schematically in Figure 2 consists of two main sections:

- A flying spot scanning system mounted on the Planimat.
- An electronics rack that can be located up to 15 feet from the Planimat.

The scanning system comprises two

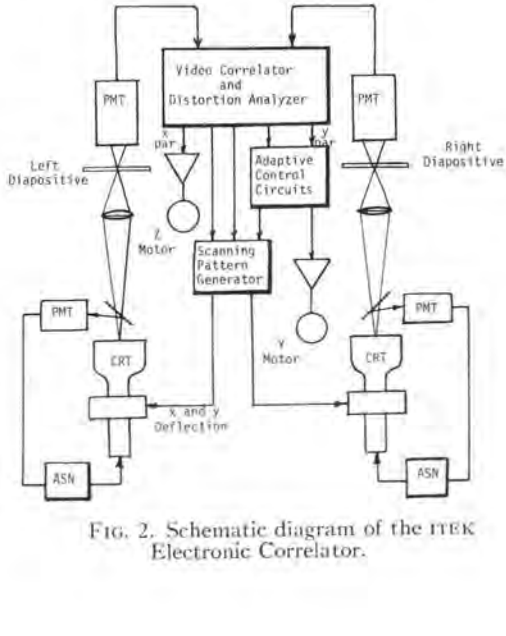

FIG. 2. Schematic diagram of the ITEK Electronic Correlator.

cathode ray tubes which are integrated with the left and right viewing paths on the Planimat. The scanning patterns produced by these tubes are imaged on to the left and right diapositives, and the transmitted light, modulated by the images, is converted into electrical signals by two photomultiplier tubes. The two diapositives can be viewed continuously as a stereo pair through the eyepieces, using the normal Planimat optical system. Dichroic mirrors are used to separate the blue CRT scanning light from the yellow viewing light. The use of this system does not preclude the use of color material, although the blue end of the spectrum is lost. In order to maximize the stability of the system, an optical demagnification of 10 is provided between the CRT scanning pattern and the photographic plates. Alignment errors or disturbances in the scanning pattern are thereby reduced by a factor of 10.

The two video signals from the photomultiplier tubes are fed into the electronics rack. Here the signals are correlated and analyzed into the zero-order and first-order error coefficients: X-parallax, Y-parallax, X-scale, Y-scale, X-skew and Y-skew.

The X-parallax signal, corresponding to the heighting error, is applied to a servo system which drives the motor controlling the height of the Z-carriage in the Planimat, thereby correcting the X-parallax. The presence of terrain slopes causes X-scale and X-skew distortions to be present. These distortions must be removed to maintain good correlation between images, and are corrected in the present system by changing the shape of the scanning rasters by means of feedback to the scanning system. Figure 3 shows the scanning pattern and the method of correcting distortion.

Ideally, no Y-parallaxes are produced in mapping photography, but in practice small amounts of Y-distortion are usually present. In this system, residual Y-parallax, Y-scale and Y-skew distortions are automatically corrected, again by changing the position and shape of the scanning pattern.

Scanning System

The task of the scanning system is to convert the information in the photographic images into time-dependent electrical signals suitable for correlation. A flying spot scanner was chosen as being the best compromise between technical and economic factors.

Each flying spot scanner consists of a cathode ray tube with a short-persistence P16 blue-emitting phosphor upon which a small intense spot produced by the electron beam continuously traces out a scanning pattern. The spot is focused on to the photographic plate by the optical system. The light transmitted through the plate is modulated by the density variations of the imagery and is picked up by a photomultiplier tube which converts the light energy into an electrical signal.

In the Automated Planimat an optical duplexing system is used to enable image scanning to be carried out without interference to the normal viewing of the photographic plates through the eyepieces of the instrument. This is achieved by means of the system shown schematically in Figure 4 which represents one of the two optical paths in the instrument. The viewing path originates with the illuminating lamp and condenser system L. A dichroic mirror M that transmits yellow light and reflects blue light is mounted at a 45° angle between the condenser and the photographic plate P. An objective lens O produces a magnified image of the plate at the eyepiece focal plane where it is viewed by the eyepieces in the normal manner.

A second dichroic mirror N, again transmitting yellow light and reflecting blue light, is placed between the objective and the eye-

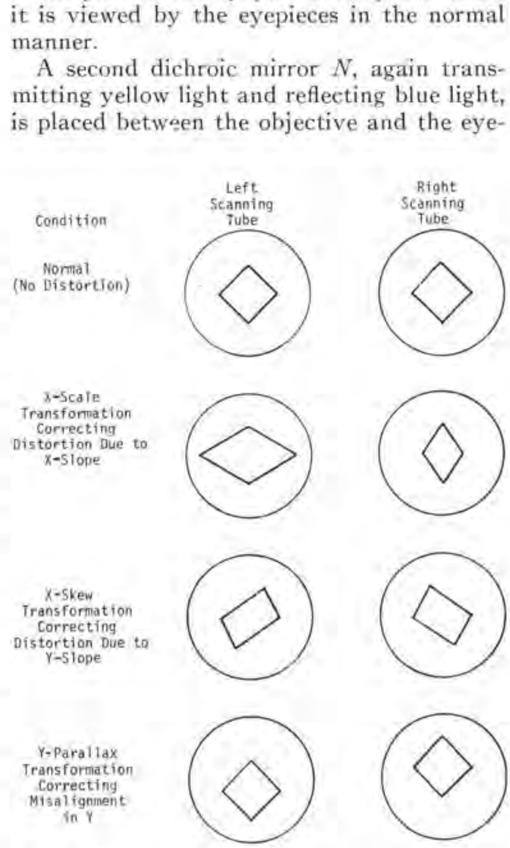

FIG. 3. Scanning pattern and method of correcting image distortion.

piece. An auxiliary lens Q and a beam-splitter S provides the duplex optical path in which the blue light from the CRT travels through the optical path in the reverse direction to the viewing light. The spot on the face of the CRT is thereby sharply focused on the emulsion of the photographic plate. Blue light from the CRT spot transmitted through the photographic emulsion is reflected by the dichroic mirror M into the photomultiplier tube. Sensitivity of the photomultiplier tube to room light and to light emitted from the illuminating lamp L and scattered off surfaces in the optical path is minimized by inserting a blue filter in front of the photomultiplier and a yellow filter in front of the illuminating lamp.

The problems associated with a flying-spot scanner in this application are: (1) the stability of the scanning pattern, (2) the light output of the phosphor.

Scanning Pattern Stability

Any error in the position of the scanning patterns on the left and right CRT's will be interpreted by the correlator as a parallax error between the photographic plates. Errors in the Y-direction are corrected electrically and are unimportant, but in the case of an error in the X-direction, the system would adjust the Z-carriage of the Planimat to restore the relationship between the left and right raster, thus producing a heighting error. The sensitivity of the system to this source of error is considerably reduced by using a demagnification ratio of 10:1 between CRT and film.

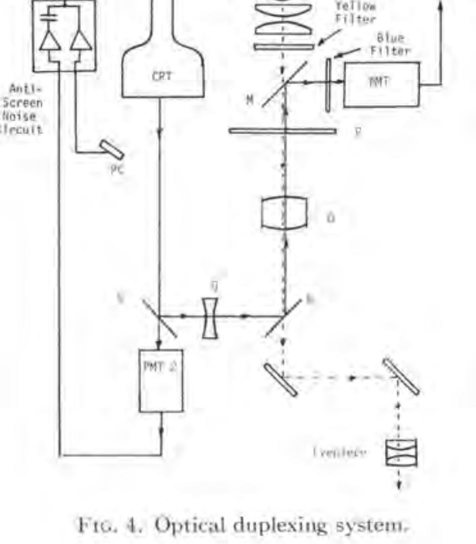

Fig. 4. Optical duplexing system.

Factors causing scanning pattern position errors are: (a) External magnetic fields, (b) Internal magnetic fields, (c) Variations in the electrical deflection system of the CRT.

(a) In many environments strong magnetic fields are common. The electron beam in a CRT is deflected by passing through any magnetic field. Even the variations of the earth's field would be noticeable in the present application. To avoid this source of error the cathode ray tubes have two layers of magnetic shielding. The inner layer surrounds only the neck of the tube where the electron beam velocity is slowest and hence most sensitive to magnetic fields. The outer layer covers the entire tube. Measurements showed that this system eliminates the effect of all magnetic fields likely to be encountered in practice.

(b) No amount of shielding will eliminate the effect of fields originating within the space shielded. In fact, the shield could easily worsen the situation. To cure this problem it is necessary to exclude all magnetic materials from within the shield. The deflection yoke cannot be excluded of course, and to keep a field from building up, a degaussing circuit is incorporated in the design. This circuit automatically operates each time the machine is turned on, and can also be operated by push button if so desired.

(c) The electrical circuits controlling positioning of the raster have been designed to give a stability of better than 0.1 percent in order to prevent unwanted drift.

Light Output Variations

Two main causes of variations occur in the light output of a phosphor:

- Granularity
- Fatigue and Aging.

Granularity produces relatively high-frequency variations in light output. If these are not corrected at the source, there is no way of distinguishing them from variations produced by the photographic images. When the scanning pattern is varying in size and shape as in the present system, phosphor fatigue can likewise produce variations in light intensity within the scanned area, which can cause false correlation. To reduce these effects to acceptable levels an anti screen noise circuit is used, consisting of a photomultiplier tube PMT2 and high frequency amplifier as shown in Figure 4. This circuit monitors the intensity of the CRT spot and provides a bias to the grid of the CRT to maintain the intensity constant.

In addition to the short-term intensity variations described above, the CRT gradually loses emission over a period of a few thousand hours. To stabilize against this variation

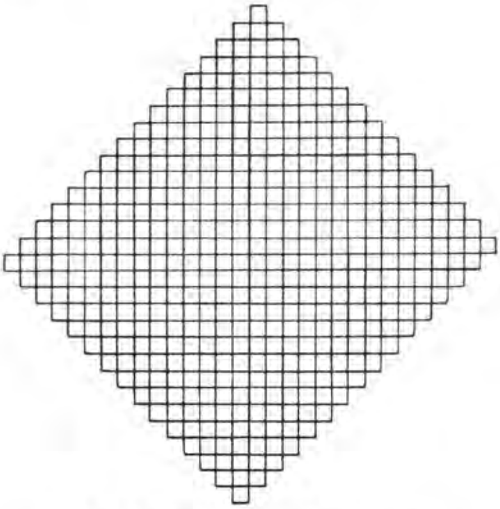

FIG. 5. Diamond scanning pattern.

which would affect the efficiency of correlation, a stable photocell PC is used to control the grid voltage of the CRT. This circuit enables the CRT's to be replaced if necessary, without any further adjustment to the circuit.

Scanning Pattern

To provide uniform scanning over conjugate image areas, a Lissajous scanning pattern is used. This pattern is normally produced by two triangular waveforms for x- and y-deflection, which differ in frequency by the required frame frequency. It is necessary for the frame frequency to be substantially higher than the bandwidth of the correlation servo loop to enable frame frequency components to be filtered out. Furthermore, the number of scanning lines does not need to be large in order to detect zero and first-order distortion. In the present case, a scanning pattern with 31 lines across the diagonal is used, the frame frequency being 560 Hz.

Some advantages can be gained by orientating the scanning pattern in the form of a diamond as shown in Figure 5. This pattern can be generated by merely rotating the deflection system through 45°, or by maintaining alignment of the deflection coils with the x- and y-axes and using a more complex scanning waveform. The diamond pattern has the advantage that the scanning spot always moves in either the x- or y-direction, enabling the quality of correlation in these directions to be evaluated separately. Separate monitoring of x- and y-correlation quality allows image areas of poor correlation to be covered with greater reliability.

Correlation

The video signals from the photo multipliers are fed through video amplifiers to the correlator where they are split into several frequency bands, the purpose of which is to allow the low spatial frequencies to be correlated first, progressing to higher frequencies as the accuracy of alignment is improved. The correlation process consists of multiplying the two inputs in a balanced, linear, four-quadrant multiplier. Two outputs are produced from the correlator as shown in Figure 6. One output consists of the normal correlation function which peaks at the point of maximum correlation. This output is used as an indication of correlation quality. The second output is obtained by phase-shifting the signals before multiplication, resulting in the orthogonal correlation function which passes through zero with a change of polarity at the point of maximum correlation. This output contains the desired information on the magnitude and direction of image displacements between the scanned images.

The multiband correlator provides both wide-range pull-in and high accuracy; an electronic channel selector is used to select the optimum channel, depending on the degree of correlation between the two images. The correlator outputs are then analyzed to determine the magnitudes of each of the various distortion components. A schematic

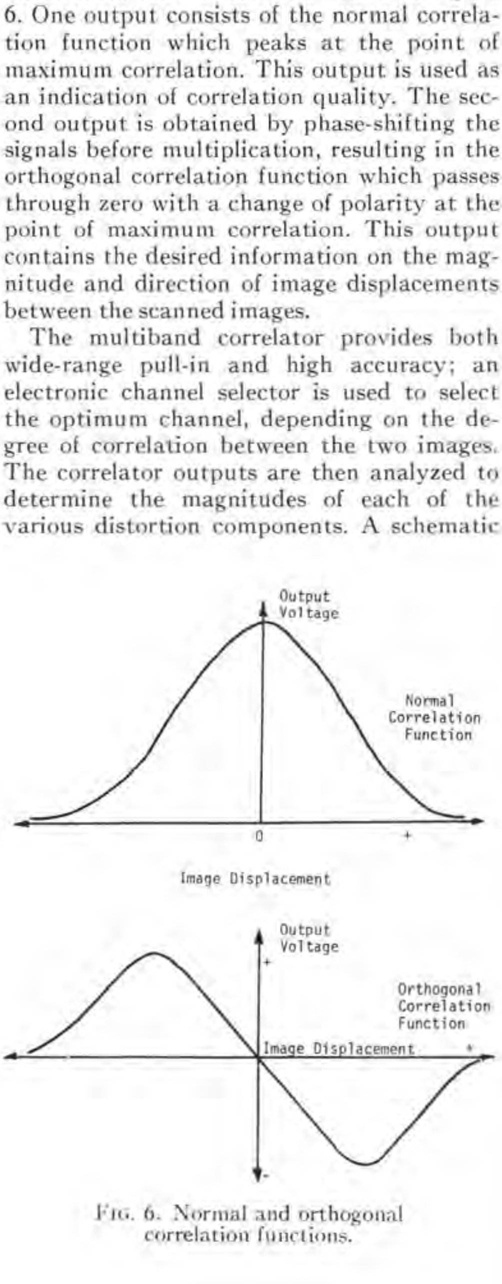

FIG. 6. Normal and orthogonal correlation functions.

diagram of the correlator and analyzer is shown in Figure 7.

Distortion Analysis

The orthogonal correlator outputs are combined and multiplied by $\dot{x}$- and $\dot{y}$-reference waveforms whose instantaneous amplitudes specify the directions of the scanning spot at any instant. The integrated outputs of these multipliers represent the average x- and y-parallaxes between the two inputs.

The x-scale, x-skew, y-scale and y-skew distortion analyzers use multiplier circuits similar to the parallax analyzers; in this case, however, the reference signals are integrated $\dot{x}$- and $\dot{y}$-waveforms.

The two zero-order and the four first-order error signals are fed to x- and y-integrators in order to provide sufficient gain for closed loop corrections. The integrators also incorporate a hold mode where error signals can be stored for a short time in the event a loss of either x- or y-information occurs.

The x-parallax error signal is applied to the Z-servo on the stereo plotter. The y-parallax error signal, on the other hand, is applied directly to the y-deflection amplifier of one CRT to provide electronic correction of y-parallax.

The first-order error signals from the integrators are applied to the modulator to cause appropriate transformations to the

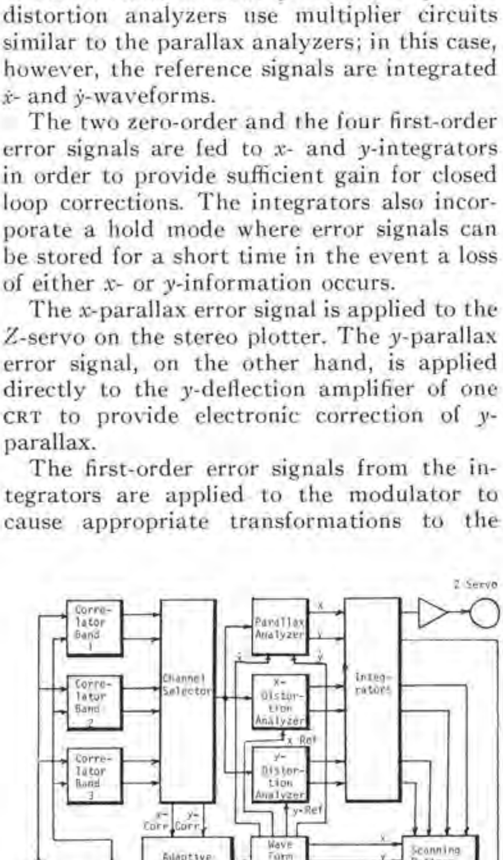

Fig. 7. Schematic diagram of the multiband correlator and the distortion analyzer.

scanning raster waveform. The modified scanning waveforms are added algebraically in the sum and difference circuit to provide equal but opposite transformations to the left and right rasters.

Adaptive Controls

The main adaptive controls are: (1) the channel selector which controls the correlator frequency bands in use; (2) the scanning pattern size control; (3) the profiling speed or Y-velocity; (4) X-axis transformation loop gain; (5) Y-axis transformation loop gain.

Correlation is initially established using image detail of low spatial frequency to secure a good pull-in capability, progressing to higher spatial frequencies to obtain higher accuracy. The size of the scanning pattern is similarly reduced as correlation quality improves, and the profiling speed is increased.

A sudden drop in correlation quality produces a rapid shift to correlation of lower spatial frequencies, to a larger scanning pattern and to a lower scanning rate. In extreme cases the Y-servo will cause the machine to stop profiling, or even to back up, while correlation is restored. A unique feature of the correlation system is that while the scanning pattern is completely amorphous in its ability to detect image displacements, the quality of correlation can be monitored separately in the X- and Y-directions. Loss of correlation in either axis separately does not produce failure, but merely results in the relevant transformations being *held* at their existing values until correlation in that axis is reestablished.

Simultaneous loss of correlation on both axes, such as might be encountered when entering a body of water, results in *conditional failure* in which the size of the scanning patterns are maximized and the instrument is driven at a fixed rate until correlation is reestablished, or until a specified distance has been covered.

Servo System

The Z-servo system consists of a servo amplifier, DC torque motor and a tachometer generator. The tachometer generator provides the rate feedback which stabilizes the servo system in conjunction with the proper compensation network. Two DC signals are provided to the input summing points on the servo amplifier. They are the tachometer rate feedback signal, and the varying X-parallax error signal which produces the requisite Z-motion in the stereoplotter. The torque motor, tachometer generator and servo amplifier used in the Y servo system are identical to those used in the Z-servo.

CONTROLS

Controls for operating the Automated Planimat are mounted in the control box to the left of the operator.

Four mode-selection push buttons are provided, enabling the following modes of operation:

- Standby/Manual
- Orientation
- Manual Check
- Automatic.

A momentary push button is provided to enable connection of the correlation loop to clear X-parallax during the orientation procedure. A switch is provided to raise or lower the profile-recording stylus in the SG-1 storage unit. This switch provides a manual override for the stylus which is normally raised and lowered automatically in AUTOMATIC operation. Indicator lights are provided on the control box to monitor operation of the equipment. In addition to the above, controls normally associated with the Planimat such as, the start push button, the Y-Y^1 lever, the reset switch, and the Y-speed control potentiometer are also mounted on the control box. Setting up adjustments for pointing and centering the CRT scanning patterns are also contained in the control box. These controls are preset and are used infrequently in normal operation.

CORRELATOR PERFORMANCE FACTORS—RANGE OF IMAGE DISTORTION

In order accurately to clear x-parallaxes, the correlation system must accommodate the x-scale and x-skew distortions produced by terrain slope, and the y-scale and y-skew distortions produced by aircraft roll and pitch.

x-scale distortion is produced by terrain sloped in the x-direction and is given by

$$\frac{dx_1}{dx_2} = \frac{1 - (\chi/H)\cdot(dH/d\chi)}{1 - [(\chi/H) - (B/H)](dH/d\chi)}$$

where $dH/d\chi$ is the tangent of the terrain slope χ in the x-direction. The maximum relative scale ratios occur for slopes at the mid point of the base and for acquisition systems giving the largest base-height ratio, B/H. The largest B/H ratio for vertical photography is found in super-wide angle systems. Using $B/H = 1$, we obtain,

$$\frac{dx_1}{dx_2} = \frac{1 - 0.5(dH/dx)}{1 + 0.5(dH/dx)}$$

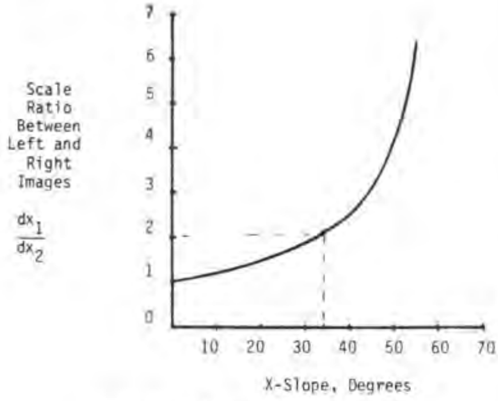

FIG. 8. Relative scale ratio due to X-slopes.

A plot of this equation is shown in Figure 8.

x-skew distortion is produced by terrain slopes in the y-direction, and is given by,

$$\frac{dx_1}{dy} = \frac{(\chi/H)\cdot(dH/d\psi)}{1 - (\psi/H)\cdot(dH/d\psi)}$$

where $dH/d\psi$ is the tangent of the terrain slope ψ in the Y-direction.

A plot of this equation is shown in Figure 9, for $Y/H = 1.3$.

An analysis of the Y-distortions produced by roll and pitch angle of up to $\pm 5°$ showed that the worst case occurred when the left and right photographs were obtained with the vehicle rolled and pitched 5° in opposite directions, producing a y-scale error of 1.4 and a skew angle of 10°.

To determine the distribution of terrain slopes likely to be found in practice, an analysis was made of 1:24,000 map sheets covering rugged terrain, broken into 1-inch square sampling areas. Maximum slope in each sample area was determined. The results are shown in Figure 10. The most frequent slope

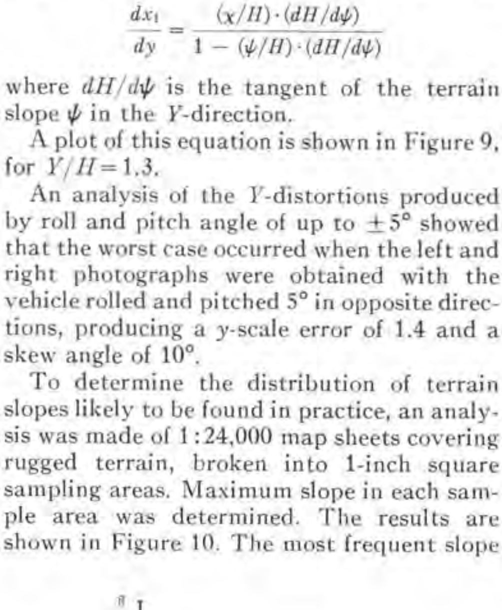

FIG. 9. Relative skew angle due to Y-slopes.

was between 20° and 25°, and no slopes were found in excess of 35°.

The maximum slope of 35 degrees was then referred back to Figures 8 and 9 from which it was found that the maximum x-scale ratio was 2:1 between left and right photographs and the maximum x-skew angle was 76° between photographs.

As scale and skew corrections are shared between the two scanning tubes, the required corrections on each tube are therefore: X-scale, 1.4:1; X-skew, 38°; Y-scale, 1.2:1 Y-skew, 5°.

Accuracy

The static accuracy of the Planimat lies between ±3.5 and ±5.1 microns depending on the focal length used. The correlation system has been designed to detect and clear parallaxes as small as 3 microns. Its ability to perform this task depends not only on the design of the correlation system itself but also depends on the presence of correlatable detail in the photographs. The limiting resolution of mapping photography is normally in the region of 20 cycles per millimeter and will not exceed 30 cycles per millimeter. Using a spatial frequency of 30 cycles per millimeter, the length of 1 cycle on the film is 33 microns; the correlation is therefore required to clear parallaxes to within about 1/10 of the highest spatial frequency on the film. The feasibility of this task depends largely on the signal-to-noise ratio of the electrical video signals presented to the correlator by the scanning system. The total noise is the sum of (1) fixed noise due to differences in the two stereoscopic images scanned, and (2) temporal noise due to electronic fluctuations in the photomultiplier tube and electrical circuits. An ideal correlator improves the signal-to-noise of the video system approximately in the ratio of its input bandwidth to its output bandwidth. However, it is important that the input bandwidth of the correlator be matched to the spatial-frequency content of the image and to the task the correlator has to perform. During initial lock-on for example, when considerable misalignment may be present between the two images, low spatial frequencies only can be correlated. At the other extreme, when the maximum accuracy of correlation is required, the highest spatial frequencies present on the photographs must be used. This is the reason for using a multiband correlator with adaptive control in which the band in use and the size of the area scanned are controlled by the degree of correlation between images.

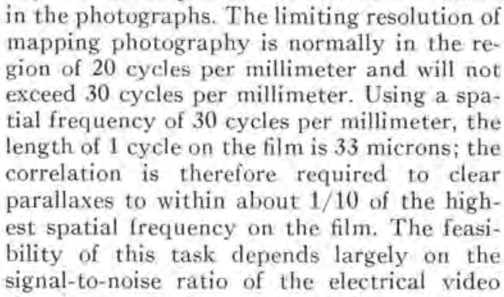

FIG. 10. Frequency of occurrence of terrain slopes. Source: 1:24,000 map sheets; contour interval 40 feet; 128 sampling areas each 1 by 1 inch; maximum slope in each sample determined.

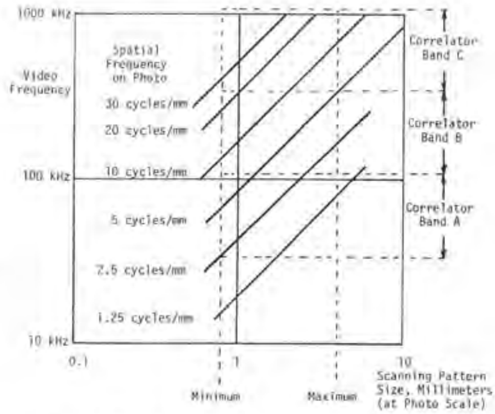

FIG. 11. Relationship between video frequency and scanning-pattern size for various spatial frequencies on a photograph.

The video frequency generated by scanning the image is,

$$f_v = 2a \cdot f_L \cdot f_x \text{ Hz}$$

where

a is the x-dimension of the square scanning pattern in millimeters,

f_L is the effective line scanning rate Hz,

f_x is the spatial frequency on the photograph in the x-direction in cycles per millimeter.

Figure 11 shows the relationship between video frequency and the size of the scanning pattern for various spatial frequencies on the photograph, the line scanning frequency being 8600 Hz. The three correlation bands used on this equipment are also shown.

The pull in range of the orthogonal correlator, i.e., the displacement of the positive and negative peaks from the null, is

$$d = \pm 1/4f_x \text{ millimeters.}$$

If N is defined as the ratio between the maximum error signal voltage and the RMS noise at the correlator output, and provided that the spatial frequency is within the correlator passband, the RMS accuracy with which parallax can be cleared is

$$\delta = d/N \text{ millimeters.}$$

In practical correlation systems with an output bandwidth in the region of 100 Hz, the output signal-to-noise ratio N with typical photographs is usually at least 5:1.

It can be seen from Figure 11 that a spatial frequency of 20 cycles per millimeter is within the correlation bandwidth for scanning patterns less than 3×3 millimeters in size. The RMS accuracy to be expected with $N=5$ is therefore, $\delta = 1/(4f_x \cdot N) = 2.5$ microns RMS.

Operation of the Automated Planimat

There are four operating modes controlled by push buttons. Four indicator lights are provided, to show the mode in use. The buttons are normally operated in the following sequence:

1. *Standby-Manual.* In this mode, the correlation system is inoperative and the servos are not connected. The manual Z-drive is coupled to the Z-carriage and Y-speed is controlled by the Y-speed potentiometer. The X-step mechanism operates normally. In this condition the Planimat may be operated manually in the normal manner, utilizing the floating mark and operator control of Z.

2. *Orientation.* The electronic correlator is activated in the orientation mode to assist the operator in clearing X- and Y-parallaxes. It does this in two ways: (a) X- and Y-parallaxes are displayed on center-zero meters visible to the operator, (b) the X-parallax may be cleared automatically by pushing the correlate button which connects the correlation loop and Z-servo.

3. *Check Mode.* In this mode the correlation loop is closed and all distortions are automatically corrected. The X- and Y-drives are not connected, however, enabling the operator to move around on the model by directly moving the X- and Y-carriages. This mode is useful for checking the performance of the correlator in doubtful areas and for manual override in areas where image detail is not adequate for automatic operation.

4. *Automatic Mode.* After checking the model, the X-carriage is located in the starting position on the model and the AUTOMATIC button is pressed. The carriage is then automatically driven in the Y-direction under control of the correlator adaptive circuit, and steps automatically in X at the end of each strip. If correlation is lost in this mode, the system goes into the conditional-fail state where the scanning patterns go to the maximum size, pattern distortions are zeroed and profiling continues at a preset velocity. While in the conditional-fail state, the scriber in the storage unit is inactivated and the pencil mounted on the X-carriage of the Planimat is lowered onto the manuscript. If correlation is reestablished before the machine has completed one full profile following the profile in which correlation was lost, the system reverts to automatic operation. If correlation is not detected in this interval, the machine goes into fail condition and automatically switches to the CHECK mode. Lines drawn by the Planimat manuscript pencil show the positions where manual fill-in is required.

At the end of the last strip, the system automatically returns to the STANDBY condition.

Conclusion

This paper has described the general design, principles of operation and performance goals of the ITEK EC-5 Electronic Correlator. It is hoped to describe the combined performance of the Zeiss Planimat and the EC-5 Electronic Correlator in a subsequent paper.

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