It should be easy to arrange for the height scale to be readable from both sides.

(11) The depth of focus should be as large as possible without very adversely affecting the model resolution. This is probably best achieved by employing small apertures and very bright lighting, with, if necessary, silent running fans to effect cooling.

(12) Resolution should be as high as possible. With rotating shutter viewing the considerable loss of resolution which is the worst feature of most projection plotters employing anaglyph viewing would be very substantially avoided. It is considered that a resolution performance should be obtainable which approaches closely that of binocular instruments provided the instrument is worked close to its level of optimum projection. The depth of focus provided should thus be used for accommodating the model relief and not as a means of changing model scale.

(13) An accessory should be provided as an optional extra in the form of a pantograph, or coordinatograph for the purpose of adjusting the plotting scale without introducing plottable error.

*Automatic Stereo Plotting**†

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ABSTRACT: *The mechanical function of detecting and removing X and Y parallax from the stereo model is performed automatically by the instrument described.*

The clearing of parallax between two images requires that corresponding points in the images be identified and located with respect to each other. In the Stereomat, a small area is scanned by a spot of light moving in a random pattern. Fluctuations in the light produced by the scanning spots crossing image boundaries are sensed by a separate photo electric cell for each photograph. Signals from the two photo electric cells are processed electronically and X and Y parallax information is obtained therefrom in the form of separate X and Y error voltages. The "Y error" is used to orient the projectors in the relative orientation operation, and "X error" is used to actuate a Z motion so as to bring the platen or floating mark to the surface of the model.

INTEREST in automation of the tedious process of stereo plotting has increased steadily over the past decade, following the development of electronics computation, information theory and servo techniques.

As a result, various co-ordinate read-out systems have been devised for plotting instruments, and direct coupling to computers has been used to achieve rapid data reduction for highway planning and other engineering applications of photogrammetry.

Two years ago Mr. D. N. Kendall, the president of the Photographic Survey Corporation, Toronto, Canada, gave support to, and provided funds for, a research project aimed at automatizing the basic stereo operations of clearing parallax, and driving the floating mark to produce profiles or contours automatically.

The essential sensing operation to be performed by a stereo perception system (human or mechanical) is that of relating corresponding points in two similar images. In general a fiducial mark or optical axis defines a point in one image; another mark or axis is then positioned by the system to the corresponding point in the other image.

It is essential that the operation of locating

* This publication is made without prejudice to any rights of the author, his associates and licensees concerning subject matter in respect of which patent applications have been and may hereafter be filed in the United States and foreign countries.

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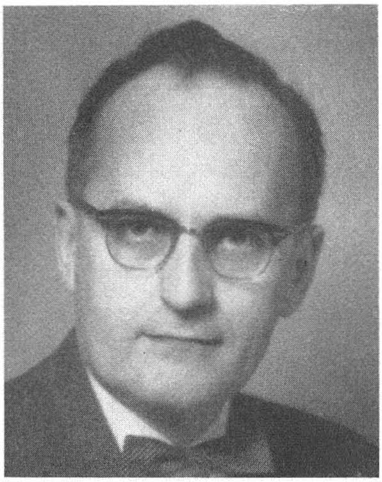


GILBERT LOUIS HOBROUGH

corresponding image points should be as independent as possible of the nature and structure of the image itself, provided of course that there is sufficient image detail properly and unambiguously to define points in the images. In addition, the degree of image similarity required must not be greater than may be expected from stereo pairs having a base sufficiently wide for aerial stereo-photogrammetry. Likewise, the presence of minor image flaws, and film granularity must not inhibit the recognition of corresponding image areas.

Stereomat takes the form of an attachment to a conventional stereo plotter and provides the necessary motions of the projectors and of the floating mark, for relative orientation and location of the terrain surface respectively.

The following is a description of the Stereomat System. Correlation techniques are used to maximize response to similarities in the stereo images.

In order to examine an image, such as a photograph, electronically, it is desirable to reduce the information content of the image to a single valued function with respect to time. This may be accomplished by scanning, i.e. by examining the image, point by point, in some order or pattern (Figure 1) and generating an electrical signal which is simply related to the image density at each point. When the entire image has been examined in this way, all the image information has been extracted and is available as an electrical signal, the amplitude of which is an analogue of the image point densities in order.

The actual pattern traced out by the scanning spot may be chosen to optimize the extraction of information significant to the problem at hand. The pattern used in the Stereomat System is the Random Scan shown at the lower right of Figure 1.

The random pattern was chosen for the following reasons:

1. The irregular and constantly changing pattern cannot react with a particular image configuration, such as circles, lines, etc. to produce an anomalous reaction.
2. Each image point is subject to scanning in many directions so that the image information is extracted in many permutations.
3. The velocity of the scanning spot varies over wide limits thereby automatically varying the emphasis between the fine and the coarse detail in the images.
4. The random pattern is symmetrical and, when averaged over a period of time, tends to weight the scanning time in favor of the center of the pattern where the reference point is located.
5. The random scan is reasonably simple to produce electronically by means of random noise generators.

In order to examine two similar images, such as a stereo pair, for any comparative purpose, it is usually expedient to scan the images simultaneously with identical scanning-patterns.

Figure 2 illustrates a well-known method, called "flying Spot" scanning, of extracting information from photographic transparencies. A cathode ray tube light-source and photoelectric cell-sensing means are employed. The spot of light produced by the electron beam striking the fluorescent screen in the cathode ray tube, may be moved about the

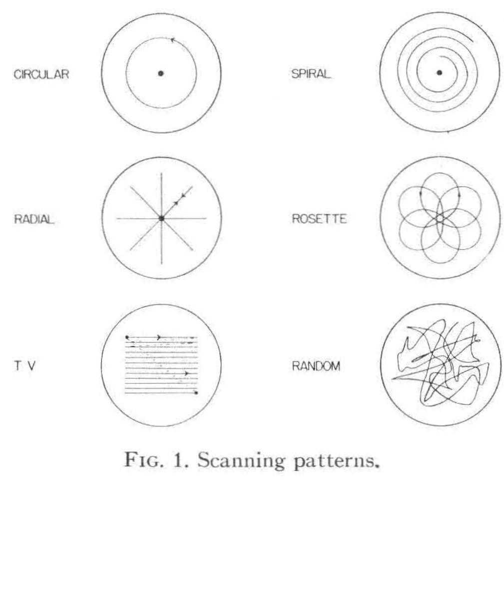


FIG. 1. Scanning patterns.

screen area in response to voltages applied to coils which deflect the electron beam from its normal central position. Separate *X* and *Y* deflection coils are usually employed to give independent control of the spot in mutually perpendicular co-ordinate directions on the face of the tube. Images of the light spot, produced by the objective lenses, execute corresponding movements on the surface of each photograph. The amount of light reaching the photo-cells will be a function of the image densities at any instant. As the spot image moves over the photographs, the light reaching the photo-cells varies, producing thereby electrical signals responsive to the image density variations from point to point.

Separate photo-cells are used to provide separate electrical signals from each photograph.

It can be seen that, when the optical axes intersect corresponding image points in the two photographs, the electrical signals from the two photo-cells will be similar. It is the object of subsequent circuitry to process these two signals, and to extract therefrom information as to the degree and direction of misalignment of the optical axes with respect to corresponding points on the two images.

The Stereomat is at present applied to a plotter of the Kelsh type which provides an optical-mechanical arrangement similar to that shown in Figure 2. The cathode ray tube is installed in place of the usual viewing table, and the photo-electric cells are added to the light projectors normally provided. (See Figure 3.)

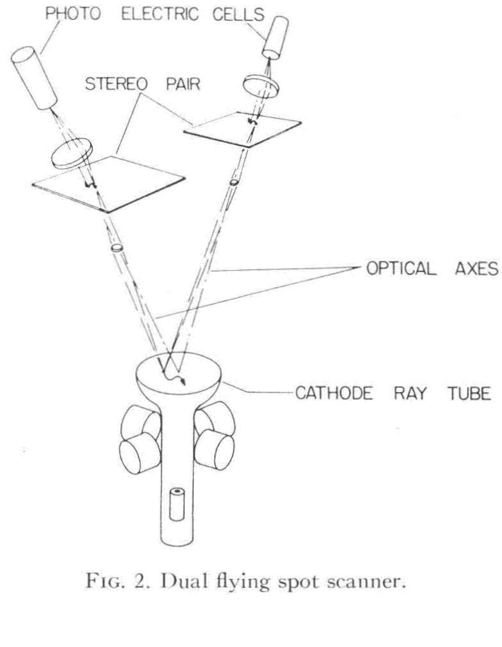


FIG. 2. Dual flying spot scanner.

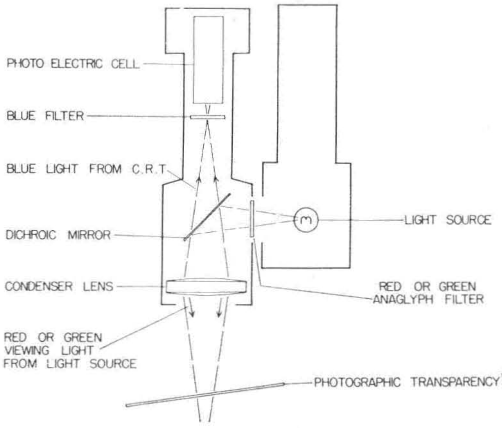


FIG. 3. Optical duplexer.

Viewing of the model by the operator is accomplished by means of an auxiliary illumination system optically separated from the photo-cells by means of dichroic mirrors and colored filters. The terrain model is visible on the face of the cathode ray tube.

Figure 3 is a detail of the illumination system and photo-cell assembly which we call an optical duplexer. The cathode ray tube emits blue light which passes up through the photograph and dichroic mirror to the photo-cell, while the viewing light is reflected downward

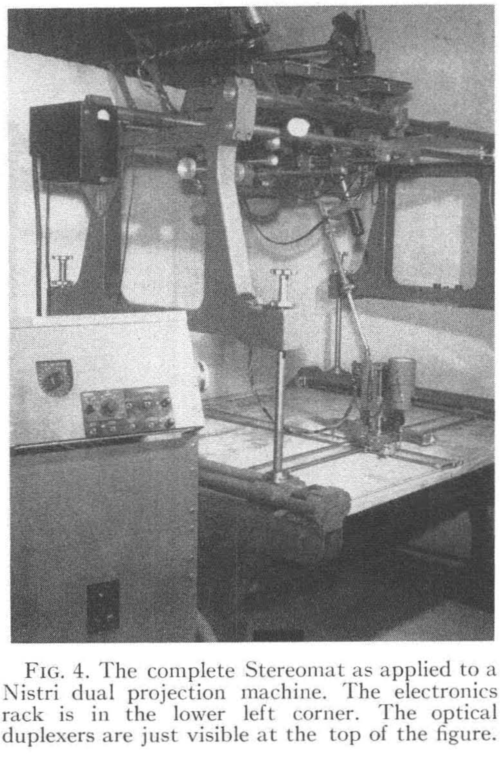


FIG. 4. The complete Stereomat as applied to a Nistri dual projection machine. The electronics rack is in the lower left corner. The optical duplexers are just visible at the top of the figure.

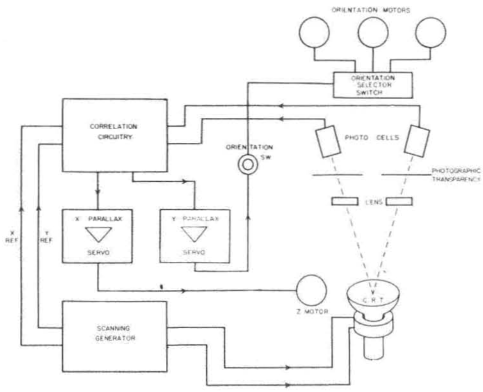


FIG. 5. Stereomat system block diagram.

through the photograph to form an image on the C.R.T. face for monitoring by the operator.

Red-Green rather than Red-Blue anaglyph spectacles are used in order to mask the blue scanning-pattern produced by the C.R.T. During normal operation, the area of image scanned is sufficiently small (12 millimeters) to allow the operator to monitor the operation through the spectacles. Should precise positioning be required for reading spot heights, the flying spot on the cathode ray tube can be stopped by depressing a button; the resulting dot then becomes the floating mark, which the operator can position precisely in the place required. Upon release of the button, the dot commences scanning the area again. Mechanical details of the C.R.T. assembly can be seen in Figure 4.

Figure 5 is a block diagram of the complete Stereomat and shows the relationship between the various functional units. The scanning generator in the lower left corner provides signals to the deflection coils as shown. X and Y reference voltages are also supplied to the correlation circuitry. These reference voltages are a measure of the position of the scanning spot at any instant in the X and Y co-ordinate directions.

The signals from the two photo-cells are processed by the correlation circuitry so as to provide an X and Y parallax signal. These signals are amplified and used to excite servo-motors to execute the corrective movements required.

The X parallax signal is shown operating the Z servo-motor which moves the C.R.T. in a vertical direction as required to locate the surface of the stereo model. The Y parallax signal is used to effect relative orientation. When the orientation switch is pressed by the operator the signal from the Y parallax amplifier is passed to the appropriate orientation motor. Selection of the orientation motor to be energized is automatic and depends upon the parallaxing station being scanned. The selector switch consists of a series of mercury tilt switches attached to the machine linkage.

Figure 6 shows the scanning generator in detail. Separate X and Y noise generators are employed so that the X and Y motions of the scanning-spot are completely independent of each other. The band pass networks limit the portion of the noise spectrum utilized. After further amplification the noise signals pass through two separate potentiometers which control the amplitude of the signals, and thereby the size of the scanning pattern. These potentiometers are controlled automatically by a pattern size servo-motor in response to signals from the correlation circuitry. In this way the pattern size is *always* as small as the detail of the image will allow.

Figure 7 shows a breakdown of the correlation circuitry into functional units. The signals from the photo-cells are processed by a registration discriminator to be described. There are two outputs from this discriminator. The sum output is a measure of the aver-

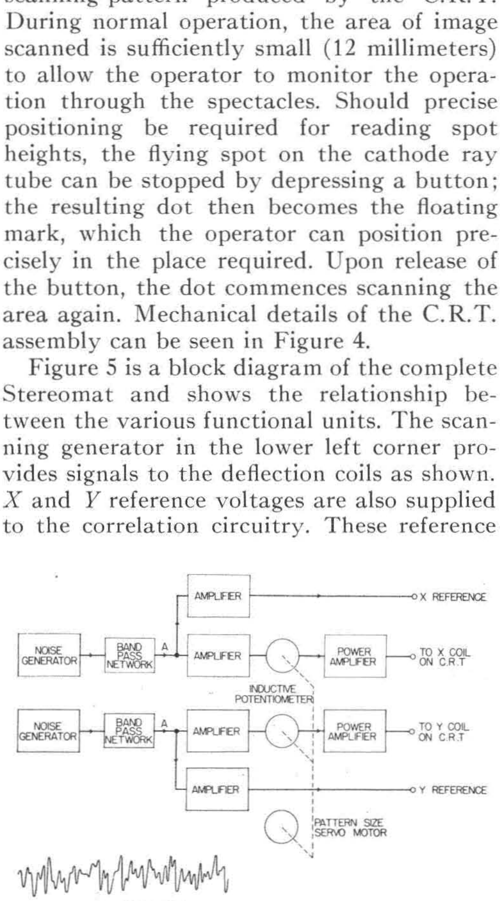


FIG. 6. Random scanning generator.

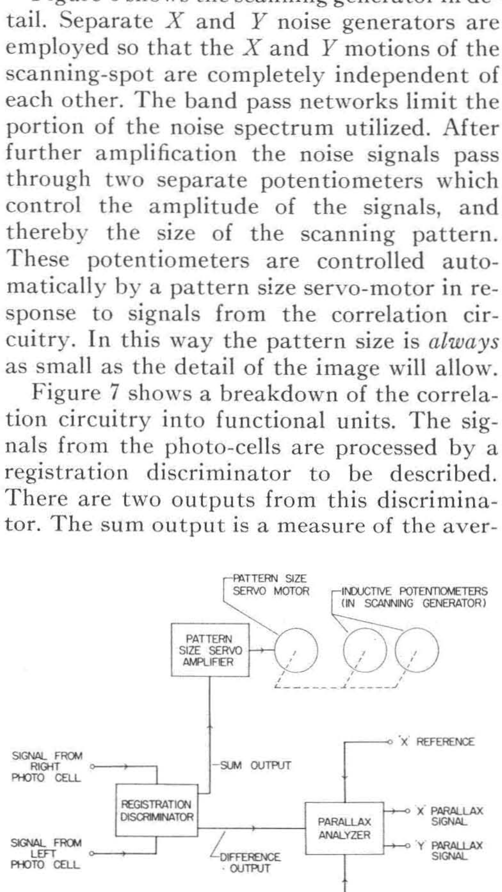


FIG. 7. Block diagram of correlation circuitry.

age correlation or similarity of the images. This signal is used to control the size of the pattern through the pattern size servo previously described. The difference output signal is a measure of the registration error or total parallax between the images. The difference signal is combined with the X and Y reference signals in the parallax analyzer, to be described, to produce the desired X and Y parallax signals.

Before the continuing with the details of the registration discriminator, let us consider the nature of the signals from the photo-cells.

The first curve in Figure 8 shows an ideal wave-form, such as would be produced by an infinitely small scanning-spot traversing perfectly sharp boundaries. The vertical height of the wave-form is of course a measure of the difference in light level across the boundaries. Any image is made up of areas of differing density separated by boundaries, and it is these boundaries which contain information useful for alignment purposes. Transient signals as shown here are produced whenever the scanning spot traverses a boundary.

The second curve shows the smoothing effect of a finite dot size which, of course, must be used in practice. In the Stereomat the spot size has been set equal to the resolution of the film, to avoid loss of detail.

The signals from the photo-cell are filtered to reduce the effect of the random noise generated by photo-cells operating at low light levels. The effect of the filters is shown in the third curve. It will be noticed that the filter produces further smoothing of the wave-form

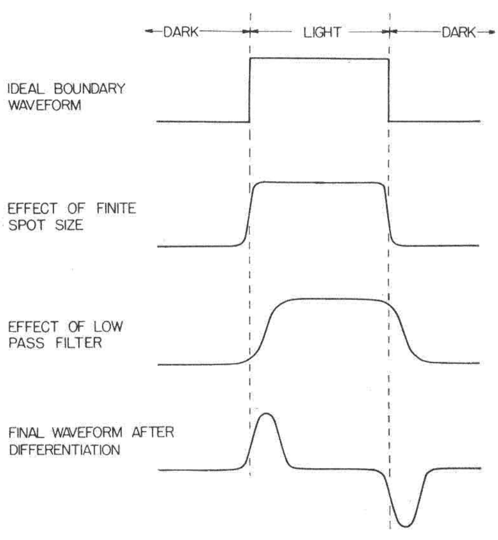


FIG. 8. Wave-forms associated with the boundaries in the image being scanned.

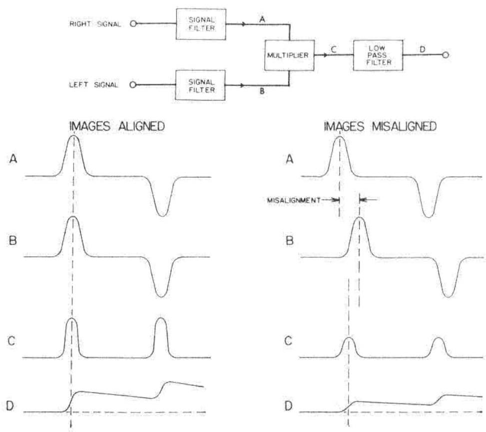


FIG. 9. A simple multiplying correlator.

and also introduces a delay in the response.

The last wave-form shows the effect of differentiating the boundary signal. Differentiation is used to facilitate the alignment sensing.

The signal filters in Figure 9 perform the low pass and differentiating functions just described. When the left and right images are in alignment, the scanning-spot crosses image boundaries simultaneously to produce the conditions shown in the first set of curves. The product wave-form at C consists of a positive pulse whenever a boundary is crossed by the scanning-spot. Since the polarity of the pulses is always the same in both input channels, the multiplied output is always positive. The low pass filter smooths the output to provide a more or less steady signal.

Misalignment of the images results in the left and right boundary signals reaching their maximum values at different times. The product wave-form is therefore small as shown.

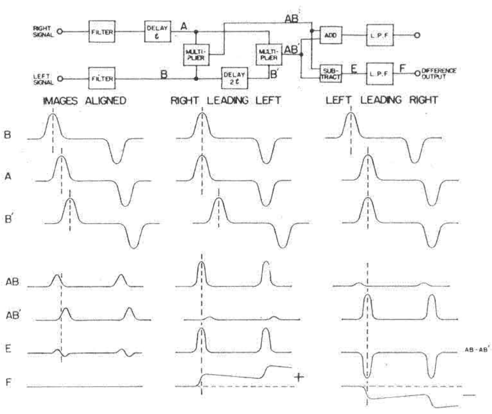


FIG. 10. Wave-forms associated with the registration discriminator.

Since the output of a multiplier is zero when either input factor is zero, a greater displacement than that shown could produce zero output.

A simplified registration discriminator circuit is shown in Figure 10. It contains, in addition to signal filters and multipliers, two delay lines, the purpose of which is to retard signals by a fixed amount. The delay line operating on the right signal introduces a delay equal to approximately $\frac{1}{2}$ the width of a boundary pulse; the delay in the left signal channel is twice this amount. In practice a more elaborate arrangement of constant phase and dispersive networks is used rather than the simple delay lines shown, in order to improve the efficiency of the correlating process.

With perfect image alignment, Signal A will be delayed with respect to B as shown. Also Signal B will be delayed with respect to A by the same amount. The product Signal AB will therefore be somewhat less than the maximum value that would occur if the Signals A and B were simultaneous. Likewise the product AB' will also be less than the maximum and in fact equal to the product AB, since the timing differences in each case are equal. The Signal E is the difference between the products AB and AB' which after smoothing is zero as shown.

The second column of curves shows the result of a misalignment such that the right signal is leading the left signal. The delay in left signal has reduced the time difference between Signals A and B and increased the time

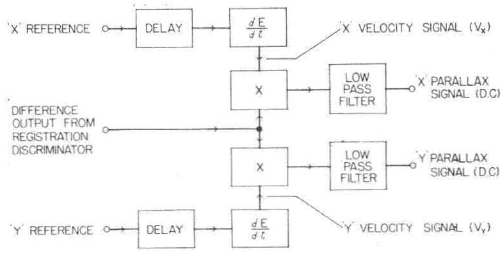


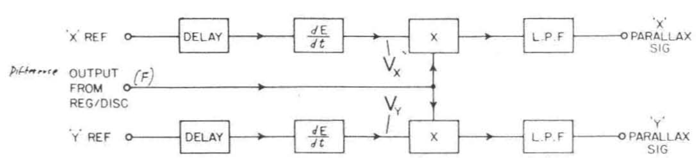
FIG. 11. Block diagram of parallax analyzer.

difference between Signals A and B'. The AB product is therefore increased and the AB' product is reduced to produce a net positive output after smoothing.

The third column of curves shows the reverse condition of the left signal leading the right signal. Since in this case AB' is greater than AB, the resulting output is negative.

To summarize the action of the registration discriminator:

1. With perfect alignment of the optical axes with corresponding image-points, the output is zero.
2. With moderate misalignment, the out-



ASSUME MISALIGNMENT IN 'X' DIRECTION SUCH THAT REGISTRATION DISCRIMINATOR OUTPUT IS POSITIVE WHEN SCANNING FROM LEFT TO RIGHT

DIRECTION OF SCAN	REG/DISC OUTPUT	V_X	V_Y	'X' PARALLAX SIG	'Y' PARALLAX SIG
+'X' (LEFT TO RIGHT)	+	+	O	+	O
−'X' (RIGHT TO LEFT)	−	−	O	+	O
+'Y' (UPWARD)	O	O	+	O	O
−'Y' (DOWNWARD)	O	O	−	O	O

ASSUME MISALIGNMENT IN 'Y' DIRECTION SUCH THAT REGISTRATION DISCRIMINATOR OUTPUT IS POSITIVE WHEN SCANNING UPWARD

DIRECTION OF SCAN	REG/DISC OUTPUT	V_X	V_Y	'X' PARALLAX SIG	'Y' PARALLAX SIG
+'X' (LEFT TO RIGHT)	O	+	O	O	O
−'X' (RIGHT TO LEFT)	O	−	O	O	O
+'Y' (UPWARD)	+	O	+	O	+
−'Y' (DOWNWARD)	−	O	−	O	+

FIG. 12. Summary of signs.

put will be positive or negative depending upon the direction of misalignment.

3. Reversal of the scanning direction will reverse the sign of the output, since the leading channel now becomes the lagging channel and vice versa.
4. Misalignment in a direction at right angles to the direction of scan will not produce timing differences in boundary wave-forms and will therefore give zero output.

Since the direction of scan using a random pattern is constantly reversing, the output from the registration discriminator will also reverse or become zero, even in the presence of a constant alignment error. It is the purpose of the parallax analyzer (Figure 11) to sort out the fluctuating signal from the registration discriminator into steady X and Y parallax signals. The output from the registration discriminator is separately multiplied with the differentiated X and Y reference signals. Since the X and Y reference signals are a measure of the scanning-spot position, the differentiated signals will be a measure of the spot velocities in the X and Y directions respectively.

The purpose of the delays shown is to compensate for the delays already introduced by the registration discriminator, thereby to assure that the reference signals and the discriminator signals will arrive at the multipliers coincidentally. The low pass filters are to smooth the output signals.

Figure 12 summarizes the effect of misalignment in the different scanning situations which occur in rapid successions with random scanning. The X and Y parallax signals so obtained are utilized as previously outlined.

By driving the scanning head steadily in a straight line, the Z motion of the head, as the X parallax is cleared, may be coupled to an external recorder to produce a profile of the terrain. Alternatively, using the X parallax signal in a different manner, XY steering for the scanning head is obtained so that contours may be drawn for each setting of the Z axis.

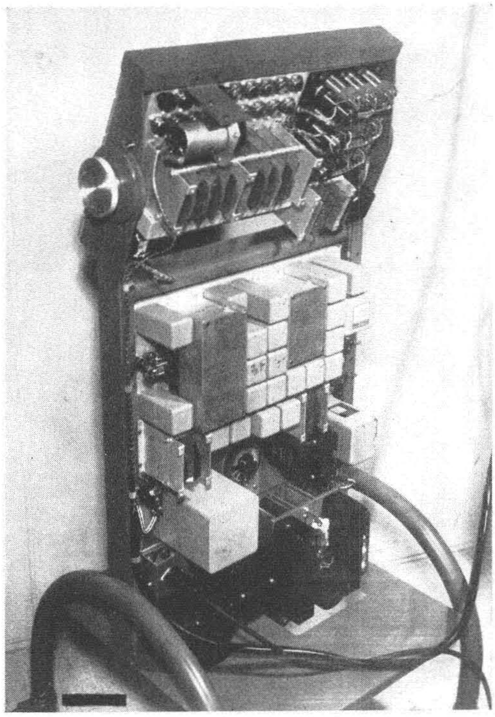


FIG. 13. Rear of the electronics rack. The rack also contains contouring circuitry in addition to that described in the text. On the front of the rack are the five operating controls and the servo adjustments.

Stereomat is applicable to stereo plotters of other types, including first-order machines, and the accuracy of a machine is not affected thereby. The fitting of Stereomat to a plotting instrument involves considerable engineering, and will require close liaison between the manufacturer and ourselves. We expect that a number of machines will be available with Stereomat in the near future and hope that the Stereomat principle will benefit the industry in one of its most difficult areas.

Production and marketing rights to the Stereomat system have been assigned to the Benson-Lehner Corporation of Los Angeles. Requests for further information should be directed to the licensee rather than to the author or to the Photographic Survey Corporation Ltd.