*Digitizing Pictorial Information with a Precision Optical Scanner**

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ABSTRACT: *An electromechanical scanner has been developed at the National Bureau of Standards which dissects a nine-inch square aerial photograph into 2.98 million picture elements and assigns one of eight numbers representing possible gray scale values to each element. The numerical representation of a stereo-photo pair is recorded on magnetic tape for subsequent processing in a high speed electronic computer. A variety of matching techniques is being developed to facilitate recognition of conjugate points and permit the calculation of information necessary for a three-dimensional representation of the terrain.*

FIRST, a comment is in order about the term "precision" as used in the title of this talk. The scanner to be described is not a precision instrument in the same sense as when that term is used by the Metrology Division of the National Bureau of Standards. Its precision should only be considered in relation to that normally attainable in purely electronic scanning systems and in this respect it compares favorably.

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The scanner has been developed in connection with a project for the United States Naval Training Device Center at Port Washington, New York. This project is concerned with the development of techniques for automatic processing of aerial photographs. As a result of this processing, we wish to produce the information necessary for a three-dimensional description of the terrain. This information is obtained by measuring the parallax between conjugate points, on two pictures of the same terrain. These pictures must have been taken from two different but known aerial locations. The key to the parallax measurement is the recognition and identification of each point in one picture with its corresponding or conjugate point in the other picture. Once this has been accomplished, standard techniques permit the calculation of the relative position and elevation of each point common to the two pictures.

Our approach to the recognition problem is to employ a scanner to produce numerical representations of these pictures. The numerical patterns obtained from one picture are then compared in an electronic computer with those obtained from the mating stereophoto. A variety of matching techniques is used in an effort to obtain the best possible match between each point and its conjugate.

Any black-and-white picture can be considered to be made up of a very large number of points which are either black or white. To explain this statement, let us consider the smallest element of a picture which we can visually discern. This element may appear to

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be black or white, but it is more likely to appear to be some in-between shade of gray. In this event, let us simply divide that just discernible element into, say, one hundred sub-elements. Each sub-element is now below the limit of visibility. Now, if we make each of these sub-elements either black or white, we can adjust the proportions to make elements which appear to have intermediate shades of gray. This is essentially what happens in a photograph where the number of sub-visible grains of silver compound which have been darkened, determines the shade of gray in a picture element.

A pure black and white, or binary, approach to the numerical representation of all of the information capable of being stored on a square inch of the best film would require approximately 10^9 bits. This is such a formidable quantity of data that it could not be economically processed on even our fastest computers. To keep the data processing task within reasonable bounds we must use a larger picture element size and a coding scheme to represent its average gray scale value. Our scanner dissects a picture into square elements which are approximately one two-hundredth of an inch on a side, and assigns one of eight numbers representing possible gray scale values to each element. Even this relatively coarse quantization produces nearly nine million bits of data from a single 9-by-9-inch photograph. As this amount of data is still considerably in excess of our available computer memory capacity, it must be first recorded on magnetic tape. It can then be read into the computer, a little at a time, for processing.

Description of the Scanner

The scanner is of the lathe type in which the subject copy is mounted on a drum rotated by the spindle, while the optical system is mounted on the carriage and is made to progress parallel to the axis of the drum by means of a screw driven by the spindle through a gear train. Figure 1* is a schematic drawing of the Scanning System. Figure 2 is a photograph of the Scanner. The subject picture is scanned helically, the optical system having advanced along the y coordinate a distance equal to one line of the picture, while the drum rotates once. The scanner is thus similar in principle to a facsimile transmitter.

* All figures appear in numerical order following the text.

The angular position of the drum corresponding to the x coordinate of the picture is sensed by a second optical system, fixed in position, and focused on a striped band (the sync band) permanently mounted on the picture drum. A photomultiplier emits a pulse for every stripe on the sync band and thereby determines the discrete spatial intervals at which density readings are taken from the subject photograph.

On the sync band are other markings including a black area where there are no stripes. This area, which is in line with the paper clamp, causes a pause in the data transmission which is recorded on the magnetic tape as an inter-record gap. It can be seen, then, that there is an inter-record gap corresponding to each traverse of the paper clamp. Stated another way, there is a record on the magnetic tape for every line on the photograph.

Optical System

The two separate optical systems—one for sensing the sync bars and the other for sensing the reflection density of elementary areas on the subject photograph—are very nearly alike.

An illuminator of the condenser type floods an area on the paper that includes the small elementary area to be sensed.

The incident angle of the illuminating beam is sufficiently oblique to cause any specular reflection from the photograph to completely escape the objective lens. Thus, the percentage of reflected light entering the objective lens depends only on the diffuse reflection density of the elements on the photograph and is independent of the gloss characteristic of the surface of the paper.

The reflected light from this illuminated area enters an objective lens and is focused on a disc at the image-plane of this objective lens. At the center of the disc is a square aperture of such a size as to admit the light from only that element of the subject photograph that is on the axis of the objective optical system. The light passing through the aperture impinges on the cathode of a photomultiplier whose output circuit delivers a voltage proportional to the luminous flux. These parts are shown in Figure 3.

Digital Data Formats

The electronics systems performs the function of converting the analog signal from the picture photomultiplier to a digital recording on the magnetic tape. An analog-to-digital converter performs a conversion each time a pulse from the sync band photomultiplier arrives at the converter's control. The output of the converter appears on three lines, each having two possible levels of voltage, which are subsequently recorded on three tracks of the magnetic tape, thus forming an octal character whose value is related to the reflectance of the picture element it represents. For example, the binary character 000 (octal 0) corresponds to a black element, 111 (octal 7) to a white and 100 (octal 4) to an intermediate gray, as shown in Figures 4 and 5.

The three remaining information tracks on the magnetic tape are recorded as zeros, while the seventh track, usually reserved for the parity bit, is recorded with an invariable "one." These "ones" record the output of the sync band and therefore mark a tape record by their presence and an inter-record gap by their absence.

Figure 5 shows a picture element of 1/200 inch square, which is approximate. Figure 6 shows a picture element of 1/192 inch square, which is the actual size now employed. This dimension can be modified or made rectangular instead of square if desired.

Figure 6 shows the relationships between the picture format, magnetic tape format, and computer magnetic core word format.

The relationships may be summarized as follows:

1. Each element on the picture is transcribed as a single character on the magnetic tape.
2. The grayness, or reflectance of the element is recorded as a binary coded octal number, 0 corresponding to black and 7 corresponding to white. Intermediate gray tones are recorded as numbers between 0 and 7, the numbers being closely proportional to the reflectance. Provision has been incorporated in the electronics to provide manual adjustment of the slope and datum of the photomultiplier output in order to accommodate the range of densities of a given photograph to the range of the digital output.
3. The grayness information is contained in the three least significant bits of a character. The other three information bits are invariable zeros.
4. Each line on the photograph is a record on the tape.
5. Each scanner run is a file. At present, only one file is permitted on a magnetic tape. Thus a new tape is required for each scanner run. However, where pictures are small, a number of them may be pasted up and mounted on the drum, if the overall size of the montage is less than 10″×10″.

Pictorial Printouts

Figures 7 through 11 show several techniques illustrative of the variety of printouts which can be obtained from the digital computer after various methods of programmed data processing of the scanned inputs.

Figure 7, of Abraham Lincoln, illustrates several points. Because there are more columns to the inch than rows to the inch in a computer printer, it is necessary to compress the vertical dimension to maintain the correct ratio of height to width. This was accomplished by tilting the original picture of Lincoln, and photographing it obliquely to compress the height as shown in the inset of Figure 7. This distorted picture, about the size of a postage stamp, was scanned by the lathe scanner. In this case the computer was used only to convert each octal character into a character selected to correspond roughly in printing density to the original scanned character optical density. Faithful reproduction of the picture demonstrates that the data are properly entered and formatted in the computer memory after passing through the scanner, electronics and magnetic tape into the computer.

Figure 8 shows the ability to process line pictures in a similar manner, and Figure 9 shows a tabular printout of the same type of data after considerable data reduction within the computer.

Figures 10 and 11 show printouts of corresponding pairs of sections of aerial photographs, each about postage stamp size when entered into the scanner. In these the density characters are used to emphasize changes in optical density. Study indicated that the pictures are displaced two lines relative to each other, and the lines encircled correspond.

Instead of the printing characters used, eight digits could have been used, so that quantitative optical density could be read directly at each point. Of interest in connection with this, IBM has provided to the Weather Bureau a 1403 printer with a special numerical font whose printing density is proportional to the digit printed. This satisfies the eye in a gross sense and provides direct quantitative readout at any point in the picture.

Computer Programming

A critical part of the project is the actual matching of conjugate points in the two stereophotographs. We do not pretend to have mastered this problem but there follows an explanation of how we are trying to proceed. The left photo can be represented by a plot of the density (8 levels designated 0 to 7) as the ordinate and the x-distance along the photograph as the abscissa. The right photo can be represented in the same way. For the moment we are comparing one scan line of the left photo with one scan line of the right. We have previously interceded by deciding visually and manually which left line corresponds to which right line. This was done by carefully studying a stereo pair of two-dimensional visual printouts like two of the figures we have seen (the stereo pair of maps).

Thus two lines are ready to be compared for the selection and mating of corresponding stereo points. Figure 12 shows a stretched out, very small portion of line 298 on the left vs. line 300 on the right.

How can a computer be made to judge these curves and to relate corresponding features? We find ourselves getting into an area of research known as image processing—a subject not covered in the traditional textbooks on photogrammetry, but which is receiving attention currently from researchers in several fields of endeavor utilizing scanner-computer applications.

Our procedure is as follows: First, the computer goes through the data and extracts significant information. In effect a list is made of all the describable features in the left line and another list for the right line. A feature is a break or a change in density. We have classified the features according to their nature and have devised a set of our own names for them. We have what we call up-hills, up-shoulders and up-peaks and the opposite, down-hills, down-shoulders, and down-peaks. Each extracted feature is described in some detail including type, intensity, extent and what is immediately before and immediately after.

The computer program, after being told where to start, proceeds through the two lists of features endeavoring to find matches. The program will make three passes through the lists. The first time it will seek out major features (arbitrarily defined as a change of at least three levels). As respective major features are related which seem unmistakable matches, these are established as major reference points. The second pass will look for remaining lesser features between the established major points. Similarly, the third pass will dig still deeper between the previously matched points trying to match what is left.

It is interesting to notice that the computer goes about its task of matching points on the two similar charts in essentially the same manner as would a human being. A person would first look for the sharp breaks, latch onto those, and then try to carry out the matching between those points and continue the matching process in this manner down to the least noticeable features.

The computer matching that we have described so far is essentially a one-dimensional analysis, each line being considered separately. For the more marked features, it is believed this may be enough. However, for the final matching of the less marked features, it is expected that it will be advisable, if not necessary, to consider adjacent lines simultaneously. Figure 13 shows two adjacent lines on the same photograph. As would be expected, the features demonstrate a marked continuity as they are carried over from one scan line to the next. If two slices of the subject matter were made 1/200th inch apart, the cuts would certainly be expected to have similarity, and indeed they do.

One interesting plan with which we will experiment is to use a 3-by-3, or even a 5-by-5, unit mask centered on the point under analysis. Using the left point surrounded by its mask as the reference, a prospective matching right point similarly masked would be compared. Each element of the left mask would be compared with the corresponding element of the right mask. The respective differences would then be squared and summed to provide a correlation score. The process would be repeated for all plausible right-hand points. The best correlation score would then suggest which right-hand point was best matched to the left point used as reference. The computations to do even this portion of the total job would obviously be so tedious and lengthy that without a computer the method would be out of the question.

Summary

This is in the nature of a progress report because our project is certainly far from completed. It is a primary rule of progress reporting not to spend too much time on what one expects or would like to do but rather to tell what has been done.

In summary, then, we have constructed a scanner system that will look at a resolution element 1/200 inch on a side, that will assign one of eight gray levels of light density to each element, and that will put the information in a systematic way on a standard magnetic tape. We have computer programs that will then manipulate the information contained on the tape. We can display it by means of a pictorial printout; we can list the actual density values for any area of interest. We can take averages; we can take median values; we can take line totals to measure overall density levels.

We have a matching program which will go through the first level of matching and, for those points, will compute the parallax, the true x and y position and the elevation. We are still working on the programming for the second and third levels.

An interesting by-product is the use of our system to read oscillograms. The basic system and housekeeping programs to read and digest scanned data are such that with only a little additional programming it was possible to tabulate detailed x and y values from an oscillogram which would ordinarily have been read by a time-consuming and error-prone manual process.

We are gaining in our objective of effectively utilizing stereo data. It is a characteristic of specialized computer applications that, while it can take a couple of years of programming and equipment construction and adaptation to do a task right once, the task can then be done a thousand more times in the next few minutes.

Other groups have been working on various phases of automatic mapping and have made great strides. For an insight into these developments the reader is referred to an article by Edward R. DeMeter, "Latest Advances in Automatic Mapping," in the November 1963 issue of PHOTOGRAMMETRIC ENGINEERING and to an article by Hugh F. Dodge, "Automatic Mapping System Design," in the March 1964 issue.

SCANNING SYSTEM

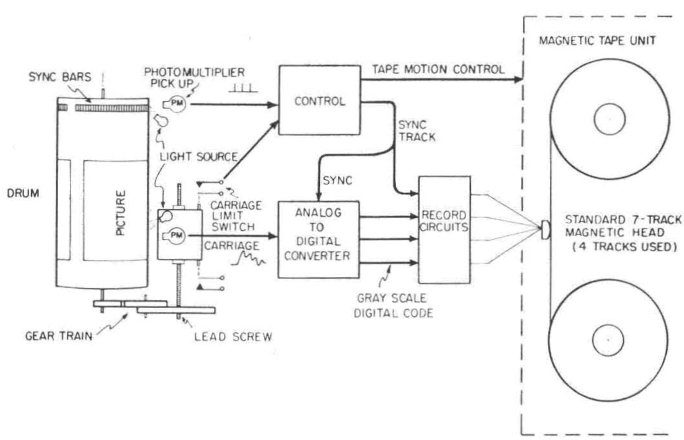

FIG. 1. Scanning system.

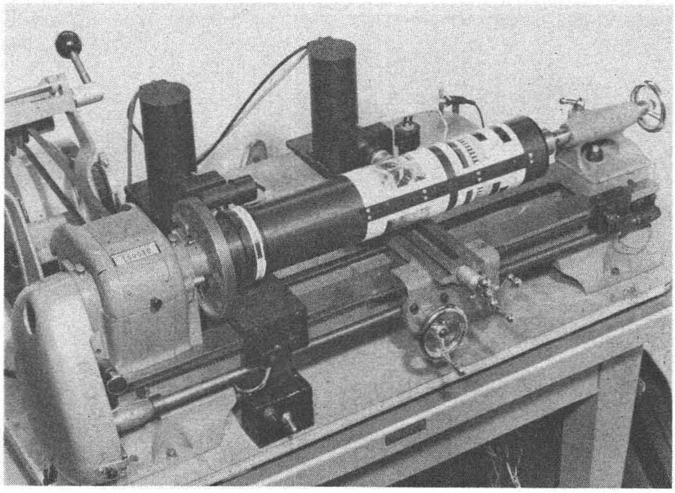

FIG. 2. Photograph of the NBS scanner.

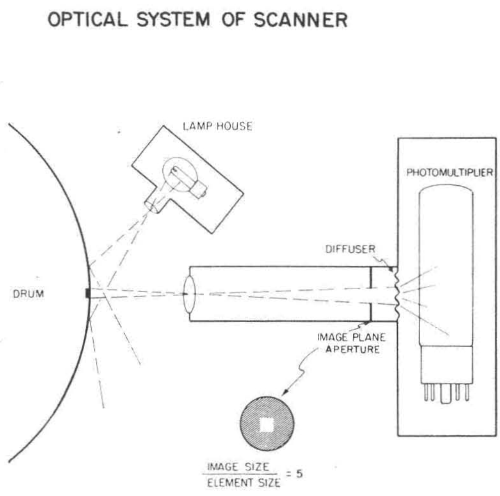

FIG. 3. Optical system of scanner.

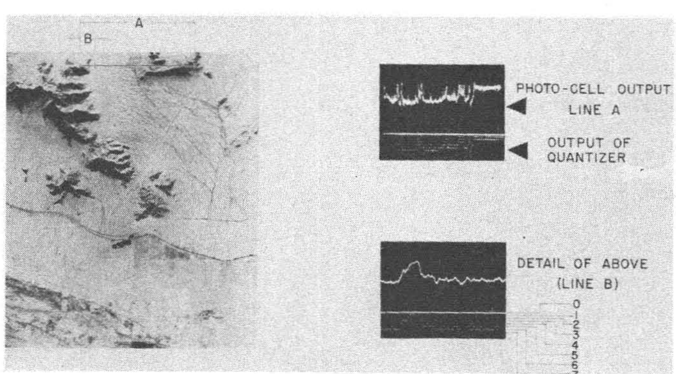

FIG. 4. Conversion of picture to quantized gray scale.

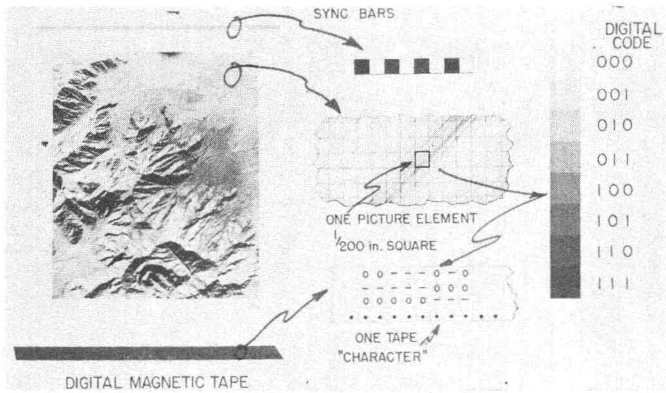

FIG. 5. Recording pictorial information on digital mag. tape.

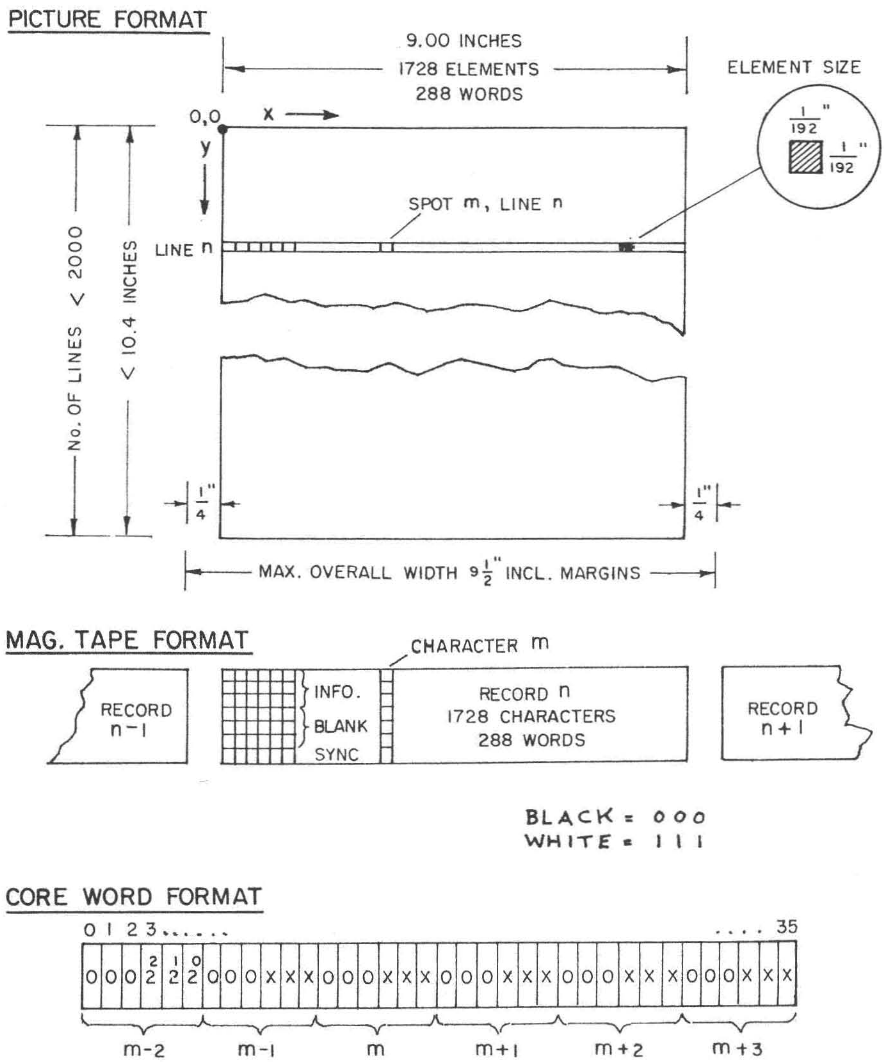

FIG. 6. Relationships between picture and digital data formats.

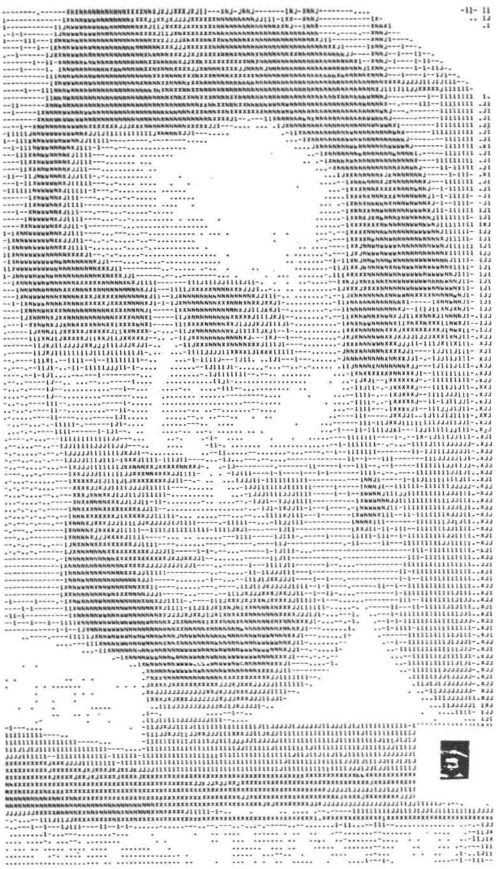

FIG. 7. Abraham Lincoln.

X	CURVE 1 Ymin	Ymax	2 Ymin	Ymax	3 Ymin	Ymax	4 Ymin	Ymax
0184	0104	0108	0283	0294	0795	0798	0953	0956
0185	0104	0108	0285	0298	0795	0798	0952	0955
0186	0104	0108	0287	0303	0795	0798	0951	0955
0187	0104	0109	0292	0309	0795	0798	0950	0954
0188	0105	0111	0297	0315	0796	0798	0949	0953
0189	0105	0114	0302	0322	0796	0798	0947	0952
0190	0107	0118	0309	0328	0796	0798	0945	0951
0191	0109	0123	0315	0334	0796	0799	0943	0949
0192	0113	0127	0319	0338	0797	0799	0941	0947
0193	0117	0133	0324	0342	0797	0799	0939	0944
0194	0122	0139	0329	0344	0797	0800	0937	0942
0195	0130	0144	0333	0345	0798	0800	0936	0941
0196	0135	0151	0337	0345	0798	0800	0934	0938
0197	0143	0160	0340	0345	0799	0801	0933	0937
0198	0150	0166	0339	0346	0799	0801	0931	0936
0199	0157	0174	0337	0346	0799	0802	0930	0934
0200	0165	0180	0335	0345	0800	0802	0929	0933
0201	0172	0187	0332	0344	0800	0802	0928	0932
0202	0177	0193	0329	0342	0800	0802	0927	0931
0203	0183	0197	0327	0340	0800	0803	0927	0930
0204	0187	0200	0325	0337	0801	0803	0927	0929
0205	0191	0204	0323	0335	0801	0803	0926	0929
0206	0195	0207	0321	0332	0801	0804	0926	0929
0207	0200	0210	0319	0330	0801	0804	0926	0928
0208	0203	0212	0317	0327	0802	0804	0926	0928
0209	0206	0215	0315	0325	0802	0804	0926	0928
0210	0209	0216	0313	0323	0803	0805	0926	0928
0211	0211	0218	0310	0321	0803	0805	0926	0929
0212	0213	0218	0307	0319	0803	0805	0926	0929
0213	0214	0219	0304	0316	0803	0805	0926	0930

FIG. 9. Tabular printout of coordinates of four curves.

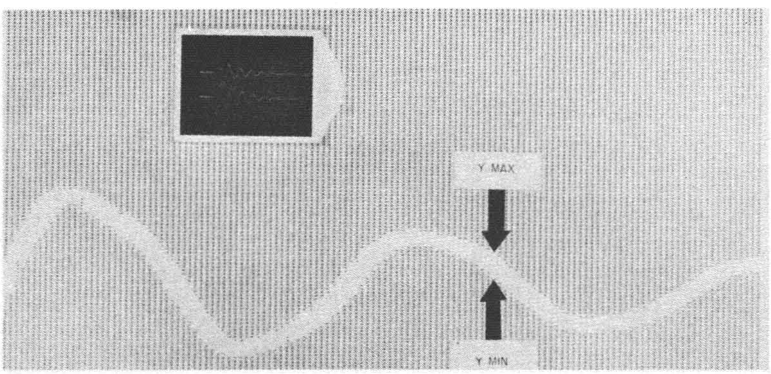

FIG. 8. Printout of image stores in computer memory.

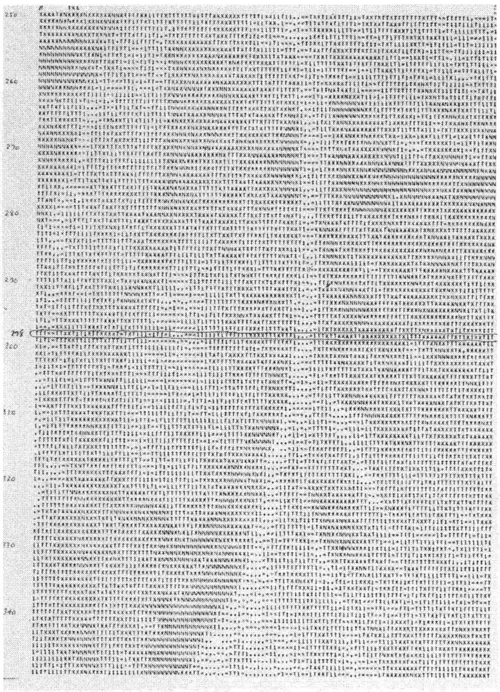

FIG. 10. Printout of aerial photograph—left.

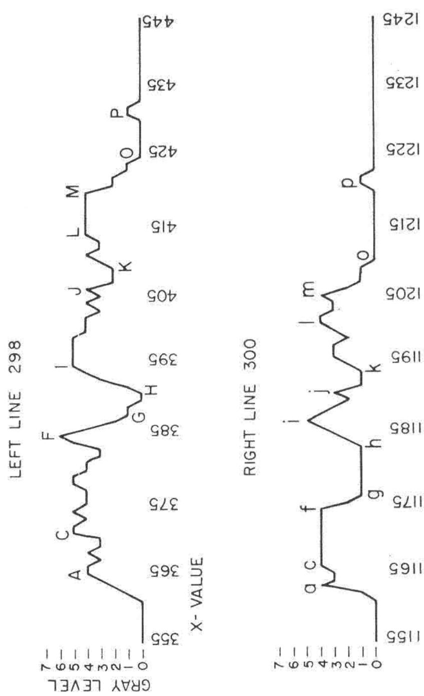

FIG. 12. Comparison of two lines to be matched.

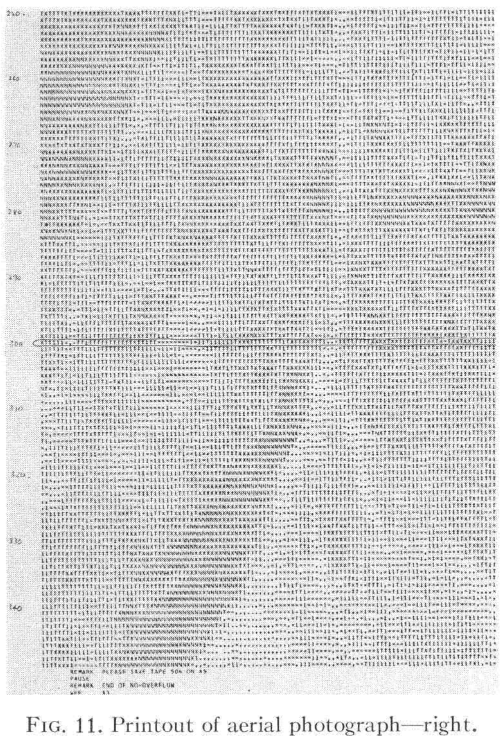

FIG. 11. Printout of aerial photograph—right.

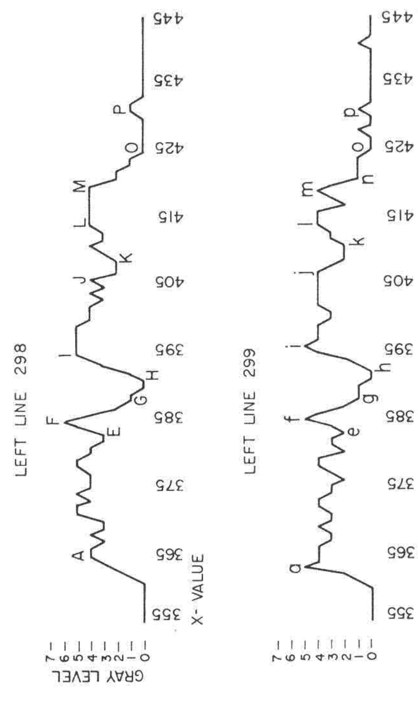

FIG. 13. Comparison to two adjacent lines.