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DEVELOPMENT OF A 3-D MICROSCALE TOPOGRAPHY SYSTEM PHASE 1/1

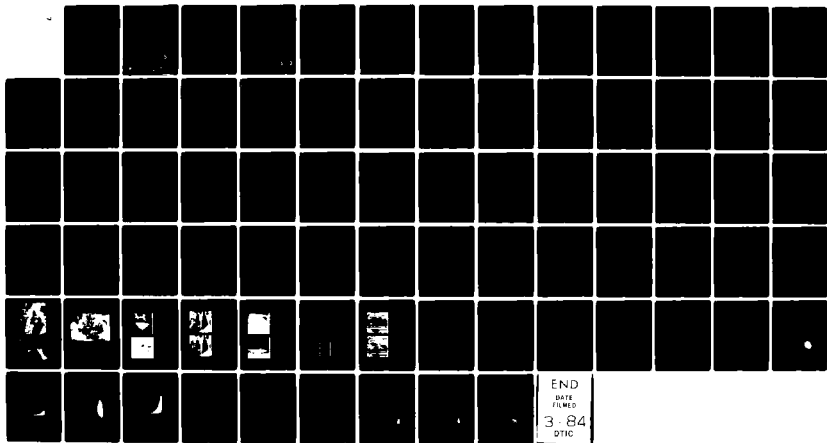
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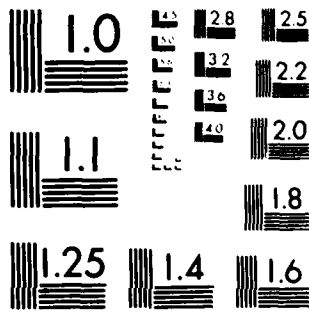
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FEDERAL TECHNICAL REPORT
ON
DEVELOPMENT OF A 3-D MICROSCALE TOPOGRAPHY SYSTEM

PHASE II

B. B. AGGARWAL
R. F. WEHR

SKF REPORT NO. AT83D004

SUBMITTED TO:

OFFICE OF NAVAL RESEARCH
800 N. QUINCY STREET
ARLINGTON, VA 22203

UNDER CONTRACT NO. N00014-80-C-0937

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Project Leader

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FINAL TECHNICAL REPORT
ON
DEVELOPMENT OF A 3-D MICROSACLE TOPOGRAPHY SYSTEM

PHASE II

Dec. '83

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1.0 INTRODUCTION

This report describes the technical work accomplished in the second phase of a program to develop an automated, three-dimensional, quantitative surface topography measurement system using a stereo-pair of scanning electron microscope (SEM) micrographs. The system embodies the disciplines of stereo-microscopy and stereo-photogrammetry. The first phase of the program (ONR Contract N00014-79-C-0792) explored the technical feasibility of making quantitative three-dimensional measurements of surface topography using a stereo-pair of SEM micrographs. The objectives of the second phase of the program (ONR Contract N00014-80-C-0937) were to develop the hardware and software necessary to implement the surface topography measurement system.

1.10 Summary of Work Done in Phase I

Phase I consisted of a comprehensive literature survey to establish the state-of-the-art in the disciplines of stereo-microscopy and stereo-photogrammetry (Task 1) and a set of experiments to establish the feasibility of the proposed surface measurement system (Task 2).

The results of interest from Phase I are summarized below:

- 1) SEM stereology has been used successfully in the biological sciences. Major sources of error have been identified and procedures have been developed to circumvent these problems. Some commercial systems are available for three-dimensional, quantitative, surface topographical measurements using a stereo-pair of SEM micrographs. These systems require the operator to identify the sets of matched points used to calculate surface heights. The results are, therefore, operator dependent.

- 2) Automated digital cartographic systems using a stereo-pair of digitized images have been developed. Development of digital stereo-photogrammetry was motivated by the need to extract topographical information from terrain data obtained from a wide range of sensors. These systems are either general purpose in nature requiring large mainframe computers or have been implemented using special purpose hardware.
- 3) The proof-of-concept tests were successful. Surface heights measurements using a stereo-pair of SEM micrographs were within 10% of the measurements using stylus instruments.

Phase I resulted in the definition of a surface measurements system combining the developments in SEM stereology and digital stereo-photogrammetry. The proposed system consisted of an SEM with a computer controlled scan generator and the hardware to digitize the SEM video signal. To digitize a stereo-pair of SEM images, the specimen to be characterized is oriented in the initial position and the computer is used to scan the specimen and to digitize and store the first image. The specimen is reoriented (tilted, translated or combination) in the second position and the second image is digitized and stored. Scan software is employed to coordinate the sampling of the SEM video signal with the scan generator signal. The digitized stereo-pair of SEM images are then processed by the image matching software to generate a three-dimensional map of the surface.

1.20 Objectives of Phase II

The development of the hardware and software needed to implement the proposed surface measurement system was divided into four tasks:

- Task 1 - Select, procure, and prove the hardware required to digitize SEM images.
- Task 2 - Develop the software necessary to digitize SEM images.
- Task 3 - Develop the image correlation software needed to extract quantitative surface height information from a stereo--pair of digitized SEM images.
- Task 4 - Verify the complete surface measurement system.

1.30 Organization of the Report

This report describes, by task, the work accomplished in the second phase of the program. The selection and shakedown of the system hardware is described in Section 2. The development of the software needed to digitize SEM images is detailed in Section 3. Section 4 contains a description of the image matching software. Tests to verify the performance of the integrated surface measurement system are described in Section 5. Section 6 summarizes the work done in Phase II.

2.0 PROCUREMENT AND SHAKEDOWN OF SYSTEM HARDWARE (TASK 1)

The hardware system needed to digitize SEM images was defined. The specific components of the system were selected, procured, and integrated into one system. The activity in this task is described below.

2.10 Selection of System Hardware

The purpose of this task was to procure and prove the hardware needed to digitize SEM images. Digitizing SEM images required the operation of SEM scan coils under computer control and the ability to digitize the output from the SEM video amplifier. The hardware, and associated software, selected for the purpose included:

- 1) A PDP-11/23 micro-computer system with 128K bytes of memory, two RL02 disc drives with a storage capacity of 10 megabytes per disc, a VT-100 console terminal, and a LA-180 printer. The system is operated using the RT-11 (version 4) operating system. The software is written in FORTRAN IV (version 2.5) and in PDP-11 assembly language using the MACRO-11 (version 4) assembler.
- 2) Tektronix 4662 interactive digital plotter and Tektronix 4010 interactive terminal were selected. The graphics hardware is driven by the Tektronix PLOT-10 software package.
- 3) Real-time clock system. Data translation DT-2769 real-time clock was selected. The clock is fully compatible with the KWV-11 real-time clock made by Digital Equipment Corporation (DEC).
- 4) Analog-to-Digital Converter. Data translation DT-2782 12-bit A/D converter was selected. The converter comes with a self-contained DMA interface for high speed sampling of analog data and storage anywhere within an 18-bit address space of the PDP-11/23 computer system.
- 5) Digital-to-Analog Converter. Data translation DT-2766 4-channel 12-bit D/A converter was selected. The system is software compatible with the AAV11-A converter manufactured by DEC.
- 6) A library of real-time peripheral support software (DTLIB/RT version 2.2) was selected to control the data translation interface board listed above. The library is compatible with RT-11 (version 4) operating system and FORTRAN IV (version 2.5) supplied by DEC.

The graphics hardware and software, the data translation interface boards, and the DTLIB software library were integrated with the computer system. The integrated system was tested to verify the operation of each of the components. In addition, an interface was built to allow the computer system to access and control the SEM scan hardware. A circuit drawing of the interface is included in Appendix A. The interface provides access to the SEM scan coils and the SEM beam blanking signal, and an ability to augment the signal sent from the SEM video amplifier to the SEM cathode ray tube (CRT).

2.20 System for Digitizing SEM Images

A schematic of the system for digitizing SEM images is shown in Figure 1. SEM images are formed by modulated the brightness of spots, referred to as pixels, on the SEM CRT in proportion to the output of the SEM video amplifier. To digitize an image, the voltage signal from the SEM video amplifier at each spot on the specimen is converted into an integer number using an A/D converter; the number is referred to as the gray level of the pixel. A digitized SEM image is the array of gray levels generated as the SEM scans a specimen.

The SEM is operated under computer control to obtain a digitized image. The SEM beam is moved to the desired spot on the specimen using the D/A converter. The real-time clock is then used to trigger the integrator to integrate the SEM video amplifier output for a specified time interval. After completing the integration, the integrator signals the A/D converter to convert the integrated analog signal into an integer number and to store the number in an input buffer. The SEM beam is then moved to the next point to be digitized. The software developed to digitize SEM images is described in Section 3.

3.0 SOFTWARE FOR DIGITIZING SEM IMAGES (TASK 2)

The software for digitizing SEM images consists of a main FORTRAN program which calls a set of assembly language subroutines. Each assembly language subroutine is designed for a specific operation and the main program is used to specify the order in which these operations are performed.

3.10 Description of the Screen Coordinate System

A SEM image is divided into a two-dimensional array of NXSCAN x NYSCAN pixels as shown in Figure 2. A set of pixels with the same Y coordinate (parallel to the X-axis) are referred to as a scan line. Thus, an image has NYSCAN scan lines, with NXSCAN pixels in each scan line. The area to be digitized is defined by specifying the screen coordinates (NXLEFT, NYTOP) of the upper left corner of the area, the number of scan lines to be digitized (NROW), and the number of pixels (NPIXEL) to be digitized in each scan line. The distance d between each pixel along the X axis is given by

$$d = \frac{w}{(\text{MAGNFY}) (\text{NXSCAN}-1) \cos(\text{TILT})} \quad (1)$$

where MAGNFY is the magnification for the SEM image, w the length of traverse for a scan line, and TILT the angle of tilt for the image.

3.20 Digitizing SEM Images

A flow chart for the control program to digitize SEM images is shown in Figure 3. The sequence of operations required for digitizing a SEM image is as follows:

- 1) Input data
- 2) Select area to be digitized
- 3) Set the integration time for integrating the SEM video amplifier signal.

- 4) Digitize and store image
- 5) Obtain screen coordinates of points of interest in the image.
This feature is used to obtain sets of matched points for the image matching software described in Section 4.

The structure of the program permits the user to tailor the sequence of operations for a specific application. For example, if the complete image is to be digitized, operations for area selection can be left out of the sequence. Each of the five operations is described below.

3.21 Input Variables

Program input variables are listed in Table 1, along with the range of acceptable values for the variables. Variables NXSCAN, NYSCAN, NROW, NPIXEL, MAGNFY, and TILT were described in Section 3.10. The values of NPIXEL are restricted to integer multiples of 256 to facilitate data storage and retrieval from random access disc systems used with the PDP-11 series computers. The two remaining input variables are the SEM accelerator voltage (CVOLTS) and the number of samples (NAV) to be averaged at each pixel. The gray level at each pixel is an average of NAV samples of the SEM video amplifier signal at that point. Sample averaging is used to reduce the random noise in the digitized data.

The program assigns default values for the remaining parameters. The values assigned are listed in Table 2. The upper left corner of the area to be digitized (Figure 1) is assigned such that the area is centered in the image. These values are changed when area selection operations are performed (see Section 3.22). The starting value for the integration time (IDWELL) is set at 200 μ s by the program. The actual value for the integration time is set in operations described in Section 3.23. The length of traverse, w, for the ETEC Autoscan SEM is fixed at 88.9mm.

3.22 Selecting the Area to be Digitized

The area to be digitized is delimited by a cursor box as shown in Figure 1. The size and the location of the cursor box can be changed to select the portion of the image to be digitized. The size of the box is changed by increasing or decreasing the number of scan lines (NROW) to be digitized. The number of pixels to be digitized in each line (NPIXEL) cannot be changed. The user is required only to position the cursor box as desired; the program keeps track of the values of all the relevant variables.

3.23 Setting Integration Time

The signal from the SEM video amplifier is integrated to reduce the effect of noise on the digitized gray levels. The magnitude of the integrated analog signal is proportional to the time of integration. The integration time should be long enough to reduce the effect of noise on the SEM video signal but not so long that the magnitude of the integrated signal is outside the range (± 10 volts) of the A/D converter. The selection of the integration time has been automated. The program starts with an integration time of 200 μ s and scans the specimen to check the magnitude of the integrated signal. If more than ten pixels are outside the range of the A/D converter, the time is reduced by 1 μ s and the specimen is scanned again. The process is repeated until there are less than ten points outside the range of the A/D converter.

3.24 Digitizing the Area Selected

The procedure for digitizing a SEM image is shown in Figure 4. After setting the dwell time no additional input is required to digitize the area selected by the user. The contrast and the brightness settings on the SEM should be set so that most of the gray levels are in the range +200 to +2047. This range of gray levels yields the best results (see Appendix A).

3.25 Obtaining Screen Coordinates of Points of Interest

This part of the program is used to obtain the screen coordinates of features of interest. The program displays a cross-hair cursor superposed on the image on the SEM CRT. The cursor is moved to the point of interest and the "C" key on the keyboard is pressed to obtain the coordinates of the point. This facility is used to obtain sets of matched points required to start the image matching algorithm described in Section 4.

3.30 Instructions for Using the Software

Image digitization software starts by typing start up instructions (Figure 5) on the console screen. The instructions for displaying the cursor box may be disregarded if the whole image is to be digitized. After the start up instructions have been complied with, the program requests values for input parameters and the name of the file in which the digitized values are to be stored. The file name can have up to six characters and the file extension up to three characters. If a file with the name and extension specified by the user is already stored on the disc, the program prompts the user to enter a new name. When program input is completed, the function selection menu shown in Figure 6 is displayed on the screen. The user can now choose to perform any of the operations listed in the menu. The menus for each of the operations are described below.

The cursor box menu shown in Figure 7 directs the selection of the area to be digitized. The position and the size of the cursor box are changed using the arrow function keys and the program function (PF) keys. The program does not allow the cursor box to move past the edges of the screen: a bell rings if the user attempts to move the cursor box off the screen and the position or the size of the cursor box is not changed. The integration time menu shown in Figure 8 explains the selection of the integration time and allows the user

to photograph the area to be digitized. The point selection menu shown in Figure 9 explains how the arrow function keys are used to obtain the screen coordinates of the points of interest. The coordinates are typed in the lower left corner of the console screen. There is no menu for image digitization and storage; the prompt "..... DATA COLLECTION IN PROGRESS...." appears on the screen while the image is being digitized. The program returns to the function selection menu after each operation is completed (see Figure 3).

3.40 System Validation

The integrated hardware and software system was tested to verify the repeatability of the digitized image data collected by the system and to devise a procedure that would result in a stereo-pair of digitized SEM images suitable for the image matching software described in Section 4. The tests and the results are detailed in Appendix A. The tests led to several modifications of the software to improve the signal to noise ratio for the digitized data. The tests showed that the SEM brightness and contrast controls should be adjusted so that most pixels have gray levels in the 200 to 2047 range. If the specimen does not permit the above adjustment, sample averaging should be used to reduce the noise in the data.

4.0 IMAGE MATCHING SOFTWARE (TASK 3)

A stereo-pair of digitized SEM images can be used to generate three-dimensional maps of rough surfaces. The first step is to match the independent image of the stereo-pair, referred to as image A, with the dependent image, referred to as image B. The matching process consists of selecting a point on image A and then locating the conjugate point on image B. The matched images are then used to extract micro-topographical data for real surfaces.

The matching algorithm selected for use in this study is a simplified version of the algorithm developed at the U.S. Army

Engineer Topographic Laboratories (UASETL) and used by Control Data Corporation (CDC) to develop a benchmark system to extract topographical information from terrain data obtained from a wide range of sensors. The USAETL algorithm is simplified because the SEM images can be regulated to obtain images with known contrast. This cannot be done with automatic terrain data collection. Therefore, the matching requirements for SEM images are not as severe as those for automated digital cartographic systems. The material in Sections 4.10 to 4.60 has been extracted from the report by Panton et al (1978).

4.10 Coordinate Systems for a Stereo-Pair of SEM Images

A digitized SEM image is a two-dimensional array of pixel gray scale values generated as a SEM specimen is scanned. In this section, a digitized SEM image is represented by N_R rows of pixels spaced at intervals of ΔY , each row having N_P pixels spaced at intervals of ΔX . A digitized SEM image is, therefore, a $N_P \times N_R$ array of pixel gray scale values. A stereo-pair of digitized SEM images is obtained by tilting the specimen about one of the scan directions.

The axes systems chosen to locate points in images A and B are shown in Figure 10. A point (X,Y) in image A maps as point (U,V) in image B. If the stereo-pair of SEM images are obtained by tilting about the Y axis, there is no parallax along the Y direction: the parallax due to surface topography is along the X direction only. Therefore, the Y coordinate of a pixel in image A and the V coordinate of its match point in image B are the same. The matching process for a pixel (X,Y) is reduced to determining the U coordinate of the matching pixel in image B. However, it is not feasible to obtain statistical correlation between individual pixels on the two images. Therefore, the U coordinate of the matching point on image B is calculated by correlating an array of pixels surrounding the point (X,Y) in image A with a set of arrays of pixels centered at the estimated location of the match point in image B.

Image A is divided into a grid of arrays, $N_x \times N_y$ pixels; the arrays are called blocks. A series of blocks with the same X coordinate is called a column while a series of blocks with the same Y coordinate is called a block path. The division of image A into columns and block paths is shown in Figure 10 and a typical block is shown in Figure 11. The matching process requires determination of the match points for the centers of all the blocks in image A.

4.20 Correlation Strategy

To find the match point for a block (I,J) centered at point (X,Y), the estimated location of the match point (\hat{u}) is calculated using coordinate information from previously matched blocks. A set of N_{COR} arrays of $N_u \times N_y$ pixels is centered at the estimated location of the match point in image B; the arrays are called correlation patches. The set of N_{COR} correlation patches is called the correlation search area. The size N_u of a correlation patch is calculated to conform with the surface topography around block (I,J). The calculation of N_u is called patch shaping.

The $N_u \times N_y$ gray scale values in a correlation patch are resampled to obtain an array of $N_x \times N_y$ gray scale values; the resampled array is called a resampled correlation patch. A correlation coefficient, R, is calculated for the block (I,J) and each of the N_{COR} resampled correlation patches in the correlation search area. A parabolic correlation function is calculated using the largest correlation coefficient and values of R for the two adjacent correlation patches. The match point for block (I,J) is then determined to the nearest pixel by locating the maxima of the correlation function.

The output of the matching process is: coordinates (X,Y) in image A, coordinates (U,V) in image B, and the correlation coefficient R which serves as a measure of the reliability of the match. The matching process is outlined in Figures 12 and 13.

4.30 Predicting the Location of the Match Point in Image B

The predicted location of the match point, $U_{I,J}$ is obtained using a rate of change function, $\Delta U/\Delta X$. The rate of change function is the rate at which the U coordinate changes for a unit rate of change in the X coordinate. It is a useful criterion for predicting the location of a match point and for calculating the size N_u of a shaped correlation patch in image B. The rate of change function for a block is a measure of the surface slope near the center of the block. The rate of change function is unity for a flat surface, less than one for an uphill slope, and greater than one for a downhill slope. The effect of surface topography on the rate of change function is shown in Figure 14.

For a block (I,J) on image A, the predicted location of the match point in image B, $\hat{U}_{I,J}$, is estimated using the relation

$$\hat{U}_{I,J} = U_{I-1,J} + [W_1 \left(\frac{\partial U}{\partial X}\right)_J + W_2 \left(\frac{\partial U}{\partial X}\right)_{J-1} + W_3 \left(\frac{\partial U}{\partial X}\right)_{J+1}] \Delta X \quad (2)$$

where $U_{I-1,J}$ is the U coordinate of the previously matched block (I-1,J) in column I-1, W_1 , W_2 and W_3 are weights such that

$$W_1 + W_2 + W_3 = 1.0 \quad (3)$$

and $(\partial U/\partial X)$ terms are the values of the rate of change function given by (see Figure 15)

$$\begin{aligned} \left(\frac{\partial U}{\partial X}\right)_{J-1} &= (U_{I,J-1} - U_{I-1,J-1}) / \Delta X \\ \left(\frac{\partial U}{\partial X}\right)_J &= (U_{I-1,J} - U_{I-2,J}) / \Delta X \\ \left(\frac{\partial U}{\partial X}\right)_{J+1} &= (U_{I-1,J+1} - U_{I-2,J+1}) / \Delta X \end{aligned} \quad (4)$$

The use of a weighted value of the rate of change function in equation (2) to predict the location of the match point $\hat{U}_{I,J}$ couples the topography of block paths J, J-1 and J+1. The extent of coupling can be changed by specifying different weights. The values of the weights for SEM environment will have to be determined by experience.

4.40 Patch Shaping and Resampling

A block of $N_x \times N_y$ pixels in image A will compress or expand in image B depending on the local surface slope. The change in size due to parallax will be along the X axis only. The size N_u of the image B patch is given by

$$N_u = [W_1 \left(\frac{\partial U}{\partial X}\right)_J + W_2 \left(\frac{\partial U}{\partial X}\right)_{J-1} + W_3 \left(\frac{\partial U}{\partial X}\right)_{J+1}] N_x \quad (5)$$

where the variables in equation (5) are the same as in equation (2).

A shaped correlation patch of $N_u \times N_y$ pixels has to be resampled to obtain an array of $N_x \times N_y$ numbers to enable correlation with a block in image A. The resampling is done by linear interpolation between the two adjacent pixels using the relation (see Figure 16)

$$G_R = G_1 (1 - D_x) + G_2 D_x \quad (6)$$

where G_R is the gray scale value of the resampled point, G_1 and G_2 are the gray scale values of the two adjacent pixels, and D_x , the normalized distance of the sampled point from pixel 2.

4.50 Correlation Coefficients

A block (I,J) on image A is correlated with all of the N_{cor} resampled correlation patches centered at the predicted location of the match point on image B. The choice of a particular correlation measure is determined by the type of the digitized images being matched. For stereo matching applications, where one image appears to be different from the other, the linear correlation coefficient is preferred because it acts as a filter: uniform additive and multiplicative gray scale changes do not effect the correlation coefficient. The correlation coefficient R is given by

$$R = \frac{\sum_{i=1}^{N_x} \sum_{j=1}^{N_y} (A_{ij} - \bar{A}) (B_{ij} - \bar{B})}{\left[\sum_{i=1}^{N_x} \sum_{j=1}^{N_y} (A_{ij} - \bar{A})^2 \sum_{i=1}^{N_x} \sum_{j=1}^{N_y} (B_{ij} - \bar{B})^2 \right]^{1/2}} \quad (7)$$

where A_{ij} is the pixel gray scale value for pixel (i,j) in a block in image A; \bar{A} the average of all the pixel gray scale values in the block; B_{ij} the gray scale numbers in a resampled patch in the correlation search area in image B; and \bar{B} the average of all the gray scale numbers in the resampled correlation patch.

After the correlation coefficients for all the resampled correlation patches have been calculated, the patch with the largest correlation coefficient is located. Then, a parabolic correlation function is fitted to the largest correlation coefficient and the values of R for the two patches on either side of the patch with the largest correlation coefficient. The maxima of the correlation function, the point where the slope of the function is zero, gives the location of the match point to the nearest pixel. The scheme described above is shown in Figure 13.

When the patch with the largest correlation coefficient is at either end of the correlation search area, a parabolic correlation function cannot be calculated. The center of the end patch is assumed to be the match point. The point is, however, regarded as suspect and is a candidate for further processing.

4.60 Block Wandering Tolerance

In hard to correlate areas, the match points of some blocks tend to wander with respect to blocks in neighboring block paths. To prevent such artificial bulges in the surface at these match points, the U coordinate of the match point of each block in a column is compared to the average position, U_{av} , of the match points of the two adjacent blocks. If the difference $|U - U_{av}|$ exceeds a prescribed tolerance, U_t , the block is said to wander. The match point for the wandering block is moved towards the neighbor average U_{av} by a weighted amount. The corrected match point is given by

$$U_c = U + W (U_{av} - U) \quad (8)$$

where U_c is the coordinate of the corrected match point and W the weight for wandering block correction. The correcting scheme is shown in Figure 17.

The value of the local rate of change function is updated to reflect the wandering block correction.

4.70 Structure of the Image Matching Software

The matching algorithm, composed of elements described in Sections 4.20 through 4.60, is outlined in the flow chart in Figure 18. The figure shows how the elements are integrated into a software package for automated stereo-photogrammetry using SEM images. Each of the major operations have been divided into simple functional modules to facilitate changes in the computer code in accordance with technological advances in the subject areas of the modules.

The image matching program is set up to match one block path at a time. A complete surface is mapped by matching a series of adjacent strips. The height data for each strip is stored in a file on disc. Instructions for using the software are given in Section 4.80.

The matching program has a few control variables to help guide the program through areas that are hard to match. The two parameters are the maximum and minimum values for the rate of change function. If the local rate of change function at any block is greater than the maximum limit, it is set equal to the maximum; if the rate of change function is less than the minimum limit, it is set equal to the minimum. Flags are set to indicate that the value of the rate of change function was not within the specified limits. The limiting values for the rate of change function should conform with the range of values of surface slopes expected for the surface being mapped (see Section 4.30).

The matching program needs the screen coordinates of one pair of matched points to start matching the block path. The matched point in the independent image is set as the center of the first block in the block path and its conjugate point in image B marks the starting point for the correlation search area in image B.

After a block path has been mapped, the matched points are checked to see if the correlation coefficients are greater than a minimum acceptable value input by the user; a point with the correlation coefficient less than the minimum limit is considered unacceptable. If the number of unacceptable points exceeds a specified value, the block path is matched again to refine the results. During the refining iterations, the coordinates of matched points obtained in the previous iteration are used as the predicted locations of the match points in image B; the rate of change function is not used for prediction (see Section 4.30). The refining iterations are continued until either the number of un-

acceptable points is less than the specified value or the number of iterations equal a user specified limit.

The coordinates of matched points are used to calculate the height of the centers of all the blocks in the block path relative to the height of the first block. For a parallel projection geometry in the SEM, the height of a block i relative to the first block in the path is given by

$$z_i = \frac{d(x_L \cos \alpha_R - x_R \cos \alpha_L)}{\sin (\alpha_R - \alpha_L)} \quad (9)$$

where x_L is the distance between block i and block 1 in image A, x_R the distance between block i and block 1 in image B, d the distance between pixels (see Eq. 1) in image A, α_L the angle of tilt for image A, and α_R the angle of tilt for image B. Lengths x_L and x_R are measured in screen coordinate units.

4.80 Instructions for Use

The program input consists of the variables for the size of blocks and correlation patches, control parameters to guide the matching algorithm, coordinates of the matched points for the block path being matched, and the name of the files in which the digitized SEM images are stored. All the other information, for example the magnification, is read from header blocks in the image files.

The input parameters for blocks and patches are the width of a block along the X axis (NX), the number of scan lines in the block path (NY), number of blocks in the block path (NCOLUM), the distance (in number of pixels) between the centers of adjacent blocks in the path (NDIST), and the number of correlation patches in the search area in image B (INDEX). The control parameters are the minimum acceptable value of the correlation coefficient (CORMIN), the number

of acceptable points allowed (NAXEPT), the maximum number of iterations allowed (NLOOPS), the maximum value of the rate of change function (RATMAX), and the minimum value of the rate of change function (RATMIN). The remaining input data are the names of the data files in which the stereo-pair of images are stored and the screen coordinates of the pair of matched points provided to start the algorithm. The height data for the block path are stored in a file with the same name as the independent image but a file extension HIT. The input variables are listed in Table 3 along with the range of acceptable values for the variables.

5.0 VERIFICATION OF INTEGRATED SYSTEM (TASK 4)

A photograph of the computer SEM system is shown in Figure 19. The procedure for mapping a surface using the surface measurement system is as follows:

- 1) Tilt the specimen at 31.469°
- 2) Digitize the area of interest
- 3) Tilt the specimen at 40.485°
- 4) Relocate the area of interest and digitize the second image.
- 5) Match the stereo-pair of images

The stop-block arrangement to obtain tilt angles of 31.469° and 40.485° was developed in Phase I of the program. The arrangement, shown in Figure 20, was necessary because the tilt angles must be known accurately for calculating the heights of points based on the differences in parallax. The tilt mechanism in the SEM was not accurate enough. The estimated reproducibility of the stop-block arrangement was $\pm 0.1^\circ$ from the average tilt angle. The choice of the two angles was dictated by the physical constraints of the SEM chamber and stage. The difference of 9 degrees between the tilt

angles was selected because it approximates the angle subtended by human eyes when viewing objects at distance of 25 cm.

5.10 Verification of Digitized Images

The quality of the digitized images was verified by displaying a digitized image on the SEM view CRT and photographing the image.

Figure 21 shows a SEM micrograph of a hardness impression and the digitized image for the same surface. Both images were scanned under computer control to obtain images with a resolution of 512 x 256 pixels. Figure 22 shows 512 x 512 pixel images of a corrosion pit. From Figures 21 and 22 it is evident that the digitized images are a faithful reproduction of the usual SEM micrographs. The contrast and brightness levels differ because while the SEM micrographs are processed for the best visual impression, the digitized gray levels are optimized for use with the image matching software. A 512 x 256 pixel digitized image of a low contrast sample is shown in Figure 23 along with a SEM micrograph with a resolution of 1024 scan lines. Again, the digitized image reproduced most of the finer detail on the surface despite the low contrast. For most surfaces, a resolution of 512 x 512 pixels is recommended. A higher resolution should be used only for busy surfaces.

5.20 Verification of the Surface Measurement System

The surface measurement system was verified by matching a stereo-pair of digitized micrographs of the electropolished aluminum specimen used in Phase I for the proof-of-concept tests. A schematic of the specimen is shown in Figure 24 and the stereo-pair of digitized images are shown in Figure 25.

The image matching software was used to obtain heights along grid line 6. The results for two different sets of limits for the rate of change function are shown in Figure 26 along with an actual stylus trace and the results obtained by matching points by eye.

The height measurements using a tight set of restrains on the rate of change function are in good qualitative agreement with the stylus trace and the results from eye measurements. The stylus measurements were made with a stylus having a 25 μm tip radius and will, therefore, underestimate the depth of the groove at grid line 2 because the stylus will not enter the narrow regions of the groove. The trace from the matching software has more noise than the stylus trace. The noise may be due to:

- 1) An artifact of the matching algorithm
- 2) Features not present along the line traced by the stylus but present along grid line 6.
- 3) Features not detected by the stylus.

More experimental work needs to be done to identify the sources of noise in the image matching software. The matching algorithm is purely statistical and fails in areas with very little contrast or areas with too much gray level information. The experimental work should focus on identifying variables that will anticipate the possibility of failure of the matching algorithm. Control strategies can then be devised to guide the matching algorithm through areas that are hard to match.

6.0 SUMMARY AND CONCLUSIONS

The integration of software and hardware for digitizing SEM images has been completed. The system reliability has been verified by experiments designed to check the quality and repeatability of digitized image data. Procedures have been developed to obtain digitized SEM images suitable for matching a stereo-pair of images. The image matching software is designed to process a single strip of an SEM image. The complete surface can be mapped by processing a series of adjacent strips. The integrated system has been used successfully to obtain quantitative height data from a stereo-pair of SEM images. The image digitization system can be regarded as a reliable, mature system. The image matching software is, however, still in the development stage. The major drawback is the reliance on purely statistical measures of correlation to locate the match points. The matching software needs some intelligence in the form of heuristic control algorithms to guide the matching process in areas that are hard to match.

The SEM based system has the following advantages over a typical stylus system:

- 1) The SEM system is non-contacting and can, therefore, be used with soft surfaces (for example, coated surfaces) which may be damaged by a stylus.
- 2) The SEM system has a horizontal resolution at least an order of magnitude greater than the best stylus instruments. The system can, therefore, be used to map surface features which the stylus instruments are not capable of observing. Examples of such surface features are spalls and cracks on bearing surfaces, details of fracture surfaces, etc. The shape of such surfaces provides important information towards identifying the cause of spalls and fractures.
- 3) Output from any of the SEM sensors (x-ray, backscatter

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electrons, secondary electrons, etc.) can be digitized using this system. The system can, therefore, be used to provide a map of surface materials along with the surface topography.

The stereo-pairs surface topography system needs further development to evolve into a handy, reliable surface measurement system. The work should focus on improving the reliability and the stability of the image matching software.

7.0 SCOPE OF FURTHER DEVELOPMENT EFFORT

Image Processing

The image matching software uses gray level differences to locate match points. A number of tribological surfaces yield images with poor contrast. Image enhancement software to improve contrast will improve the performance of the matching software. At the other extreme, too much gray level information in the image can defeat the matching algorithm. Fourier analysis software could be used to filter out the very high frequency variations in the gray level. The filter will be used in the same way as the stylus instruments use filters to separate waviness and roughness.

Image Matching

The current matching software should be used to match a wide range of surfaces to accumulate empirical data on control strategies required to match images. The data can then be used to develop control algorithms to guide the matching program in areas that are hard to match. The lack of adequate general purpose control algorithms is the primary reason for the problems encountered in matching images.

Surface Analysis

Most of the surface analysis software currently available is for two-dimensional surface profiles. Surface analysis software should be developed to exploit the three-dimensional surface height measurement capability of the stereo-pairs surface topography system. The software should include multi-dimensional spectral analysis, multi-dimensional digital filters, identification of surface features of interest (summits, valleys, etc.), surface height distributions, contour maps, etc.

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14. Rosenberg, P. et al, "Digital Mapping System: Mathematical Processing," USAETL Report No. ETL-CR-74-6 (AD-A782-230), May 1974.

TABLE 1 RANGE OF ACCEPTABLE VALUES
FOR THE INPUT VARIABLES

<u>VARIABLE</u>	<u>RANGE OF VALUES</u>
NXSCAN	1 to 1024
NYSCAN	1 to 1024
NROW	1 to 1024 (\leq NYSCAN)
NPIXEL	256, 512, 768, or 1024 (\leq NXSCAN)
MAGNFY	500X to 32,000X
CVOLTS	30,000 Volts Maximum
NAV	1 to 15
TILT	0 to 60 Degree

TABLE 2 DEFAULT VALUES FOR PARAMETERS
NOT INPUT BY THE USER

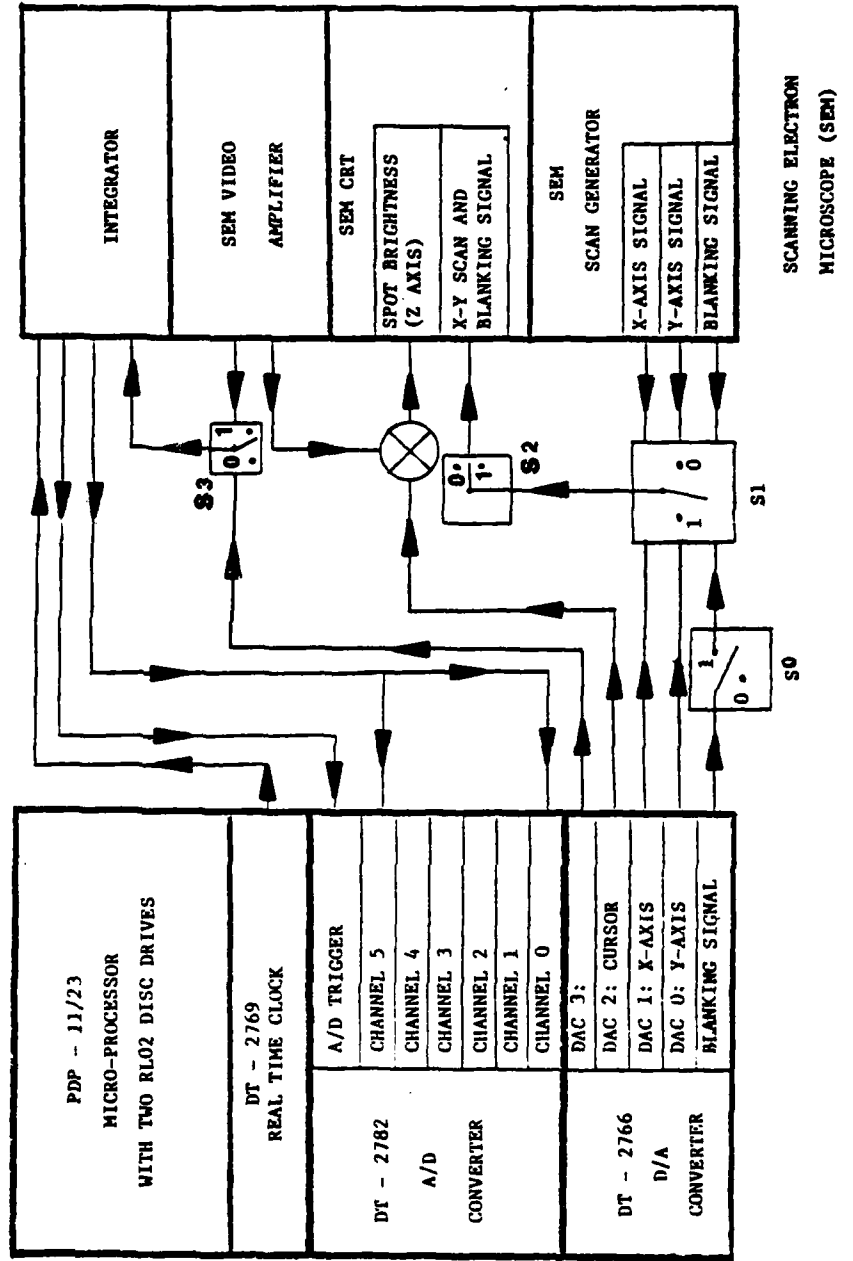
<u>PARAMETER</u>	<u>DEFAULT VALUE</u>
IDWELL	200 μ s
NXLEFT	(NXSCAN - NPIXEL)/2
NYTOP	(NYSCAN - NROW)/2
W	88.9 mm

TABLE 3 INPUT VARIABLES FOR IMAGE MATCHING SOFTWARE

<u>VARIABLE</u>	<u>RANGE OF ACCEPTABLE VALUES</u>
NX	5 to 15
NY	5 to 15
NCOLUM	≤ 128
NDIST	≥ 1
INDEX	5 to 21
CORMIN	0 to 1.0
NAXEPT	≥ 1
RATMAX	≥ 0
RATMIN	≥ 0
NLOOPS	≥ 1

FIGURE 1 A SCHEMATIC OF THE SEM-COMPUTER SYSTEM

S0 (Digital Output 0 in DAC 3): Blanking On/Off Switch
 S1 (Digital Output 1 in DAC 3): Local/Remote Scan Switch
 S2 Record CRT Blanking Switch
 S3 (Digital Output 3 in DAC 3): Integrator Loopback Switch
 A/D Channel 0: Data Collection
 A/D Channel 5: Integrator Saturation Signal



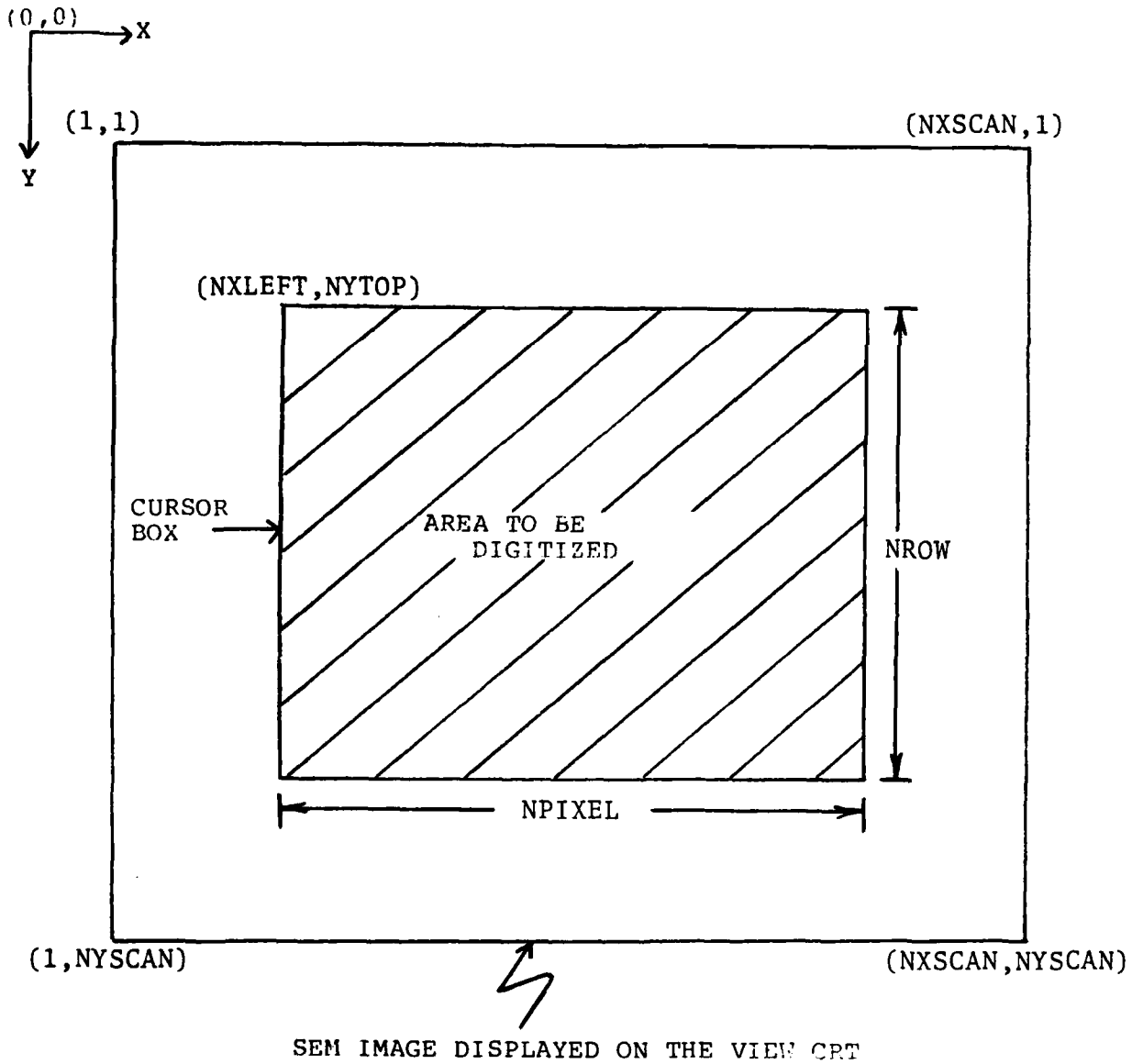


FIGURE 2 SCREEN COORDINATE SYSTEM

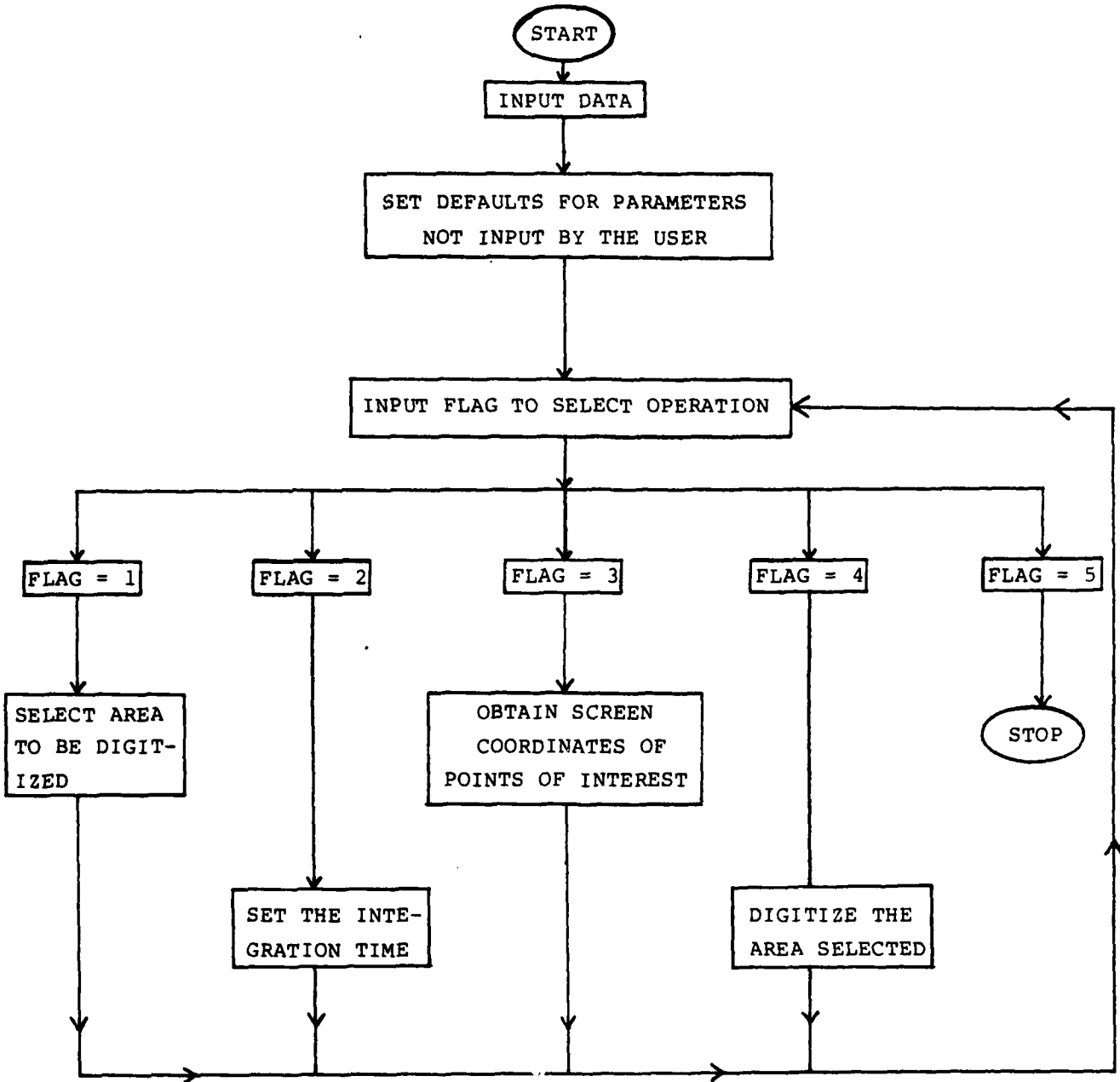


FIGURE 3 FLOW CHART FOR THE MAIN CONTROL PROGRAM

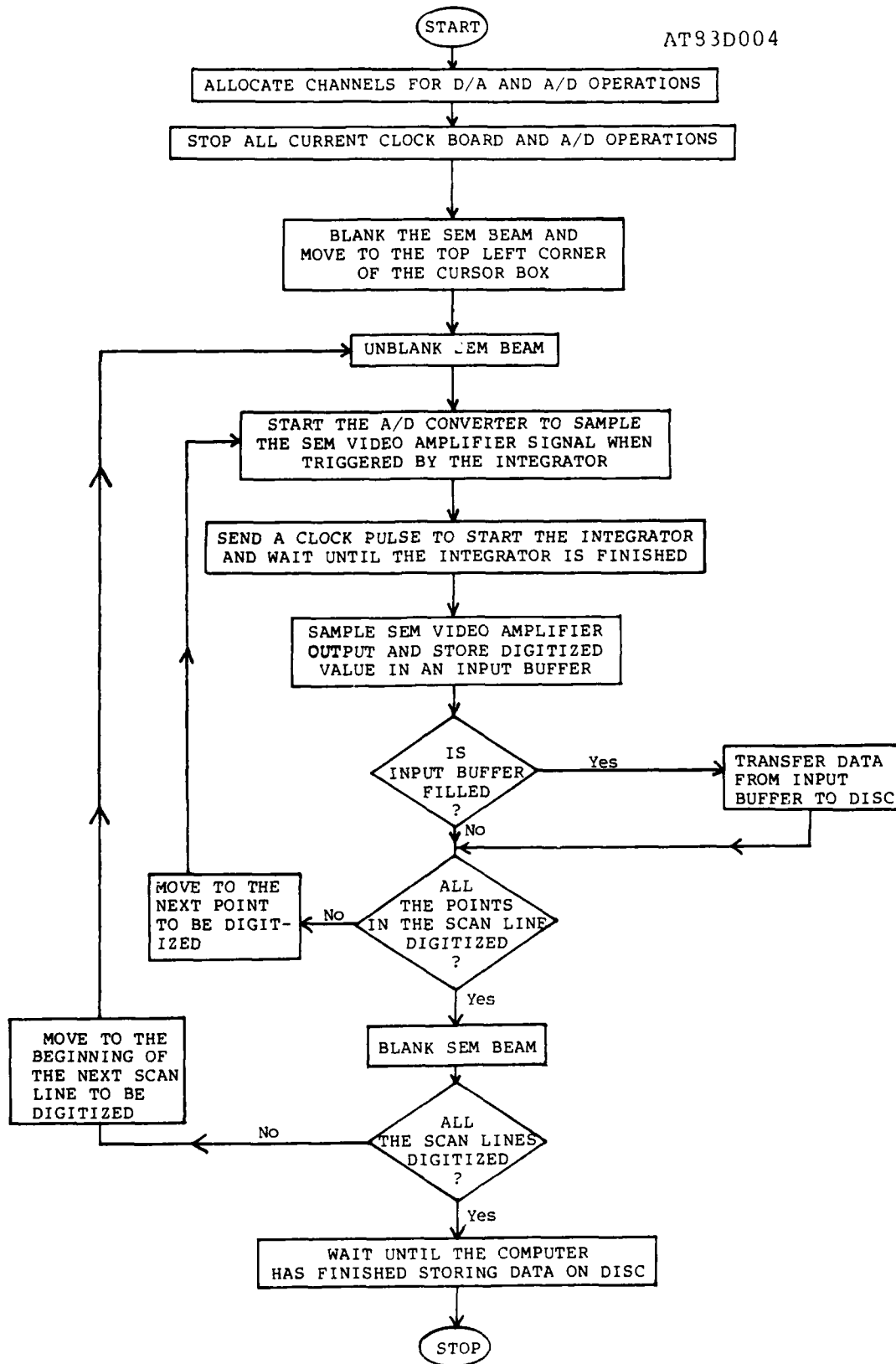


FIGURE 4 FLOW CHART FOR DIGITIZING SEM IMAGES

DATA COLLECTION SOFTWARE

MAKE SURE THAT THE 'CAPS LOCK' KEY IS NOT DEPRESSED
TO DISPLAY THE CURSOR BOX:

- 1) SET THE MANUAL VIDEO AMPLIFIER TO 'SUM'
- 2) SET THE CHANNEL SELECT FOR 'XRAY2'
- 3) REVERSE POLARITY OF SIGNAL
- 4) SET PHOTO CRT FOR 'CHANNEL 2'

PRESS RETURN TO CONTINUE

FIGURE 5 START-UP INSTRUCTIONS

DATA COLLECTION SOFTWARE

<u>NO.</u>	<u>FUNCTION</u>
1	SELECT AREA TO BE DIGITIZED
2	SET INTEGRATION TIME
3	OBTAIN COORDINATES OF POINTS OF INTEREST
4	DIGITIZE AND STORE IMAGE
5	STOP

ENTER FUNCTION NO.:

FIGURE 6 FUNCTION SELECTION MENU

POSITION THE CURSOR BOX

TO MOVE THE BOX:

- 1) PRESS THE PF3 KEY
- 2) USE THE ARROW FUNCTION KEYS TO MOVE THE BOX

TO CHANGE THE SIZE OF THE BOX:

- 1) PRESS THE PF2 KEY
- 2) USE THE ARROW FUNCTION KEYS TO MOVE THE LOWER EDGE OF THE CURSOR BOX UP OR DOWN

PRESS PF4 KEY WHEN FINISHED

FIGURE 7 CURSOR BOX MENU

SET THE INTEGRATION TIME

WHEN THE BELL STOPS RINGING, THE
INTEGRATION TIME IS SET TO YIELD
LESS THAN TEN PIXELS WITH A GRAY
LEVEL OF 2047

PRESS PF1 KEY FOR PHOTO

PRESS PF4 KEY WHEN THE TIME IS SET

FIGURE 8 INTEGRATION TIME MENU

SELECT POINTS OF INTEREST

USE THE ARROW FUNCTION KEYS TO
MOVE THE CROSS-HAIR CURSOR TO
THE POINT OF INTEREST

PRESS C KEY TO GET COORDINATES

PRESS PF4 KEY WHEN FINISHED

FIGURE 9 POINT SELECTION MENU

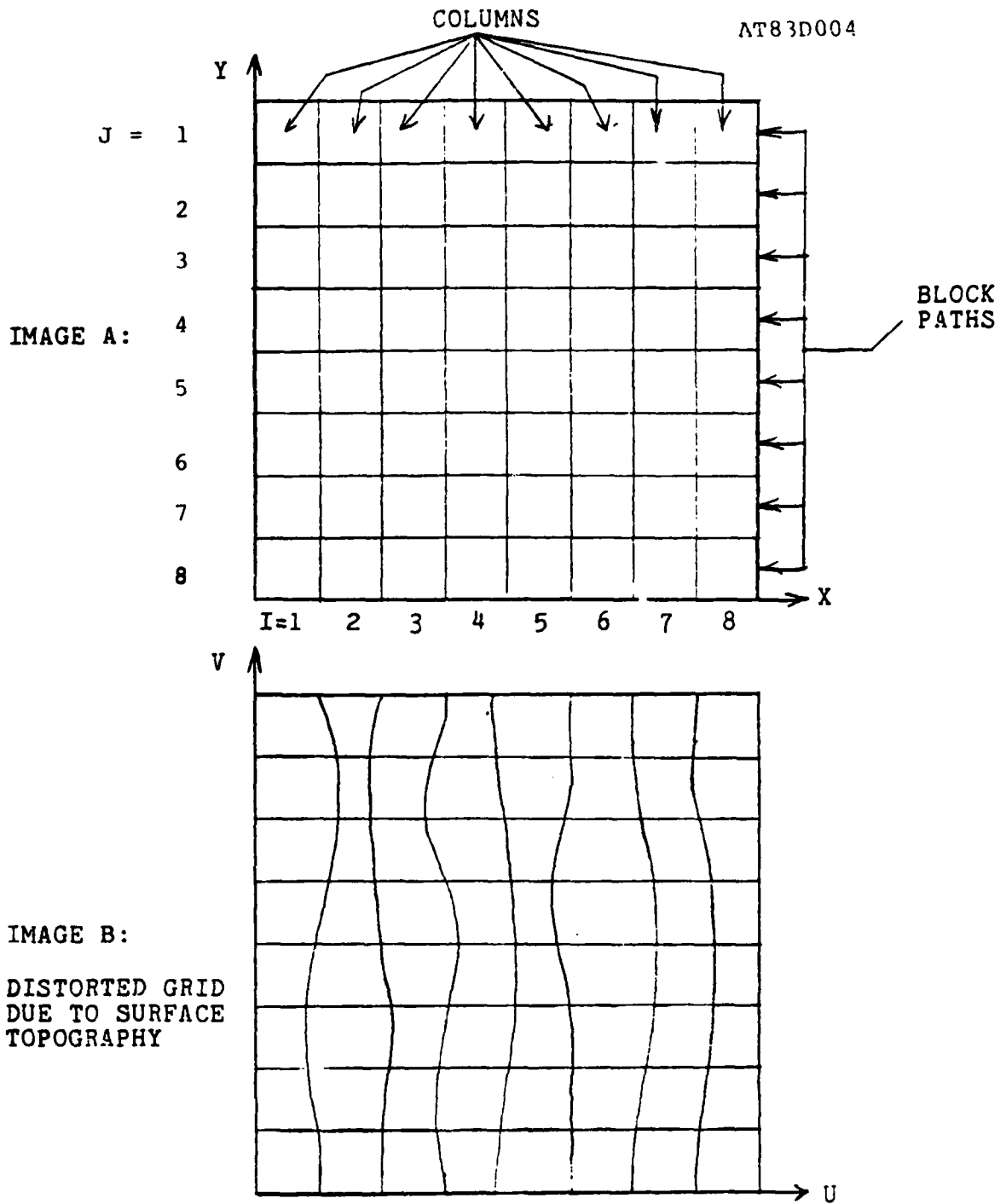
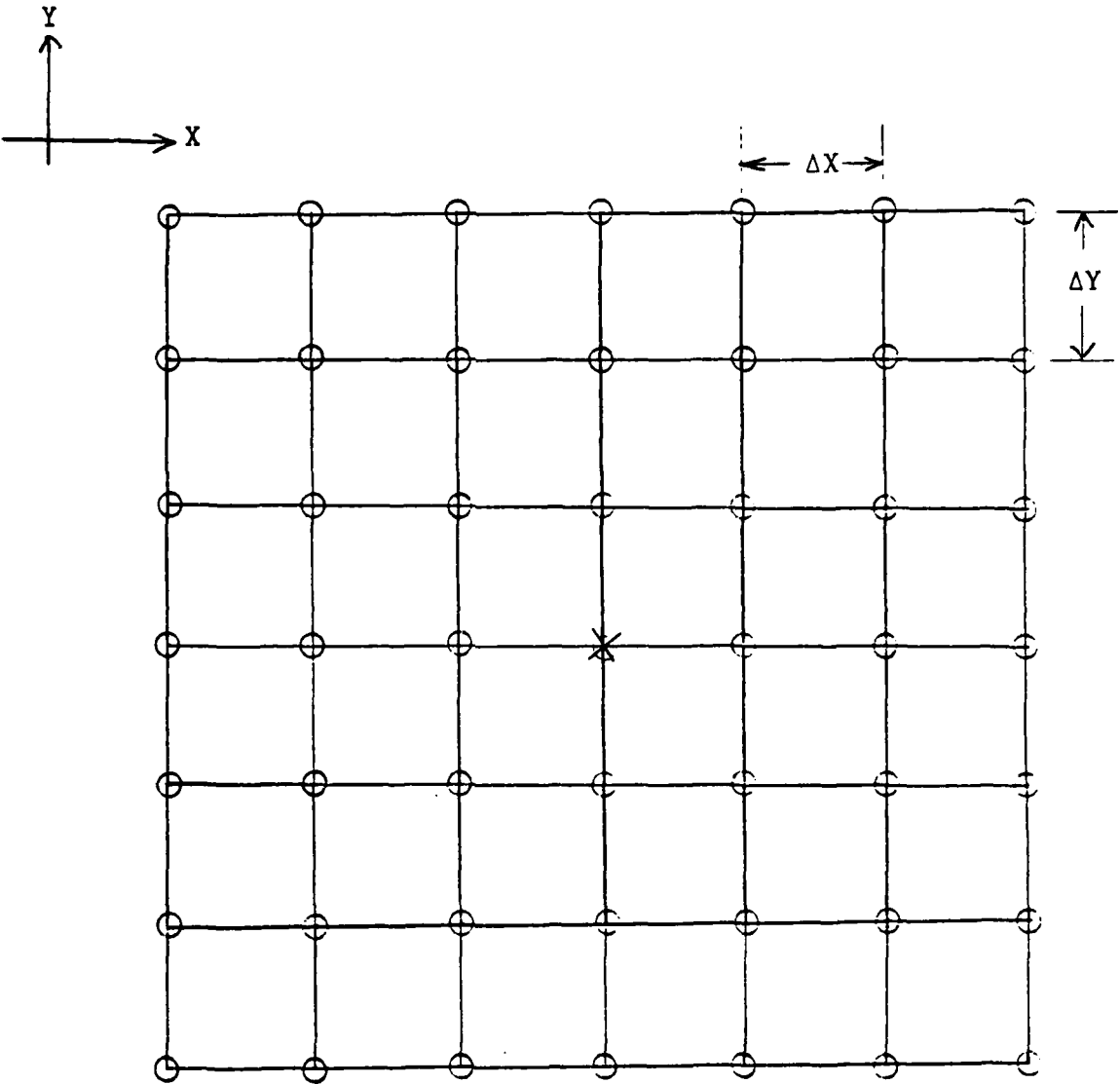


FIGURE 10 DIVISION OF DIGITIZED SEM IMAGES
INTO COLUMNS AND BLOCK PATHS

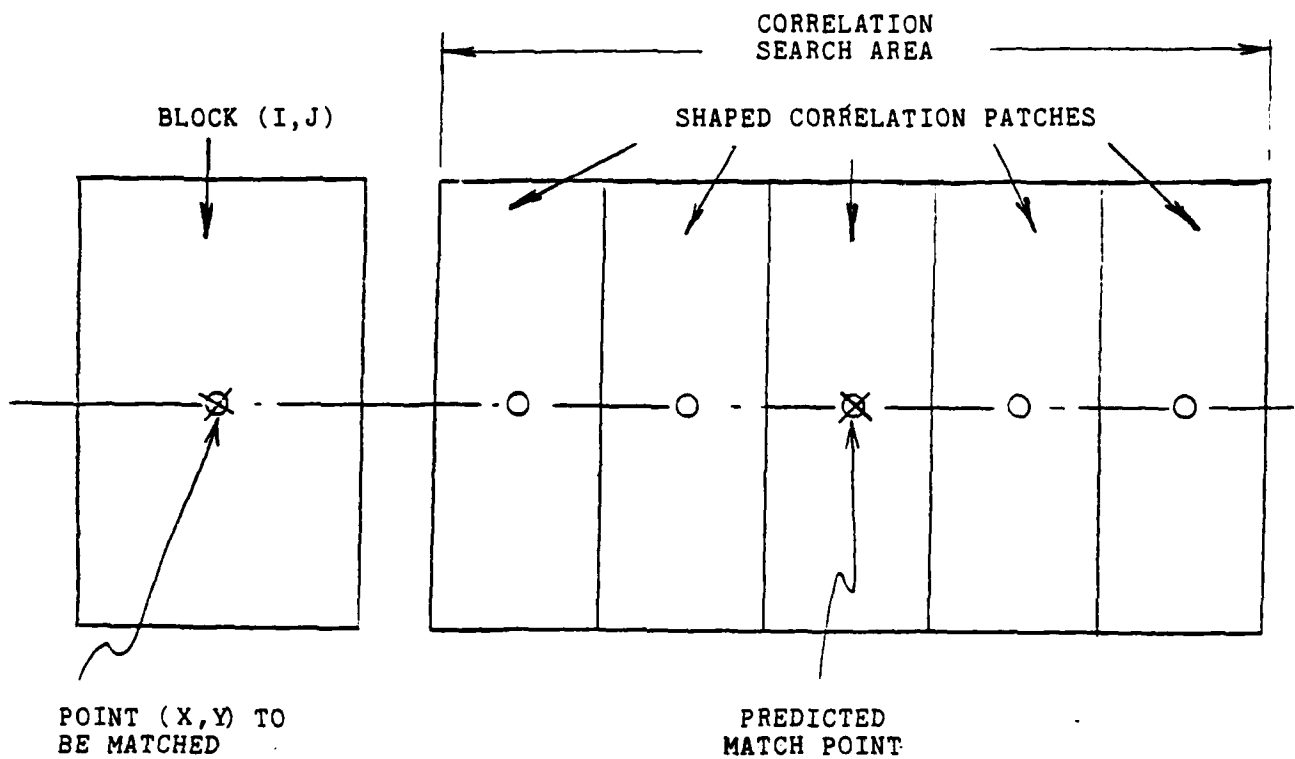


⊗ CENTER OF BLOCK

○ PIXELS

$N_x = N_y = 7$

FIGURE 11 A 7 X 7 PIXEL BLOCK IN IMAGE A



RESULT OF MATCHING IS A 5-TUPLE:

(X, Y, U, V, R)

COORDINATES
OF POINT ON
IMAGE A

COORDINATES
OF POINT ON
IMAGE B

RELIABILITY
FACTOR OF
THE MATCH

FIGURE 12 BLOCK (I,J) AND ITS CORRELATION SEARCH AREA ON IMAGE B

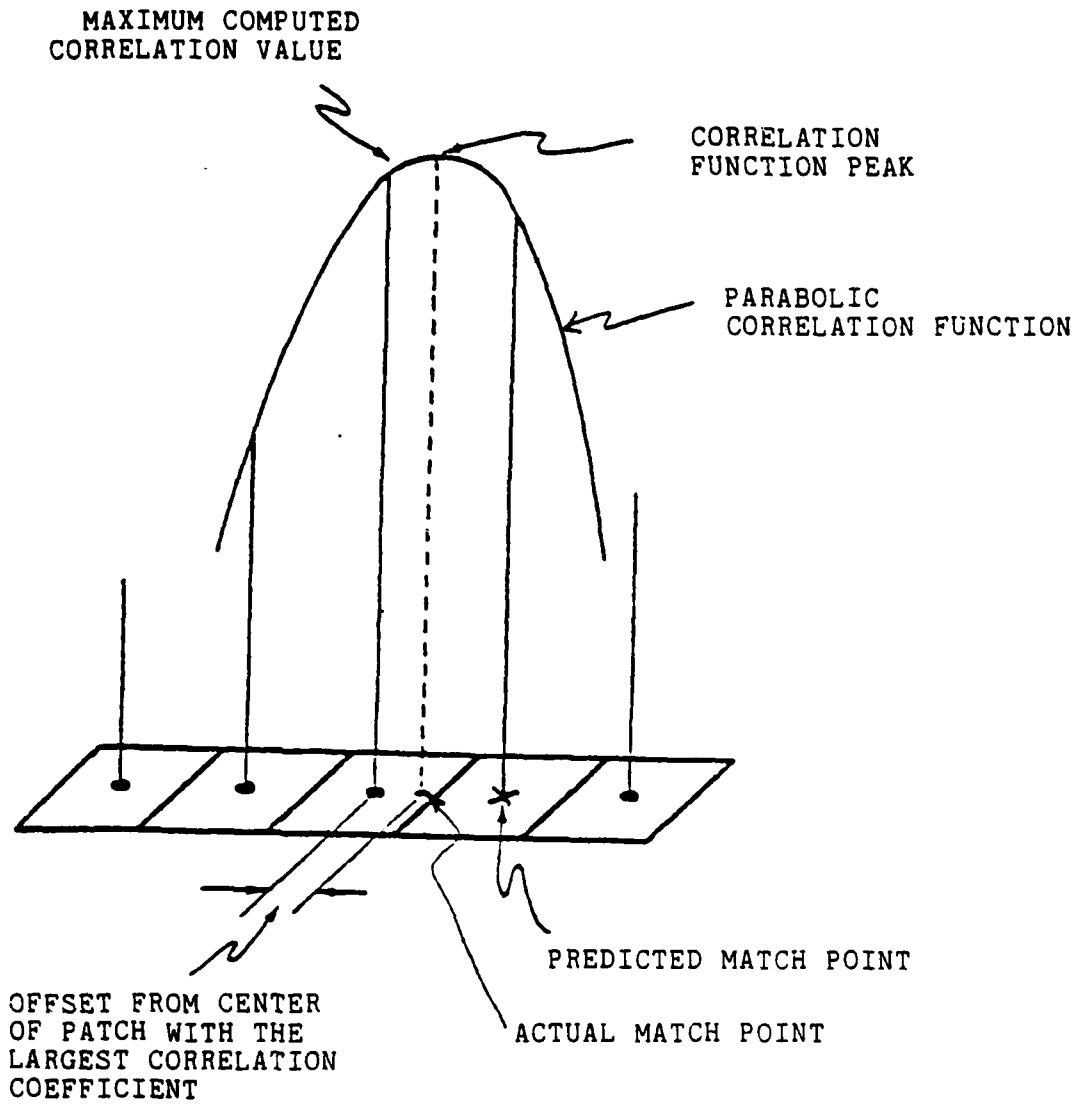


FIGURE 13 DETERMINATION OF THE MATCH POINT

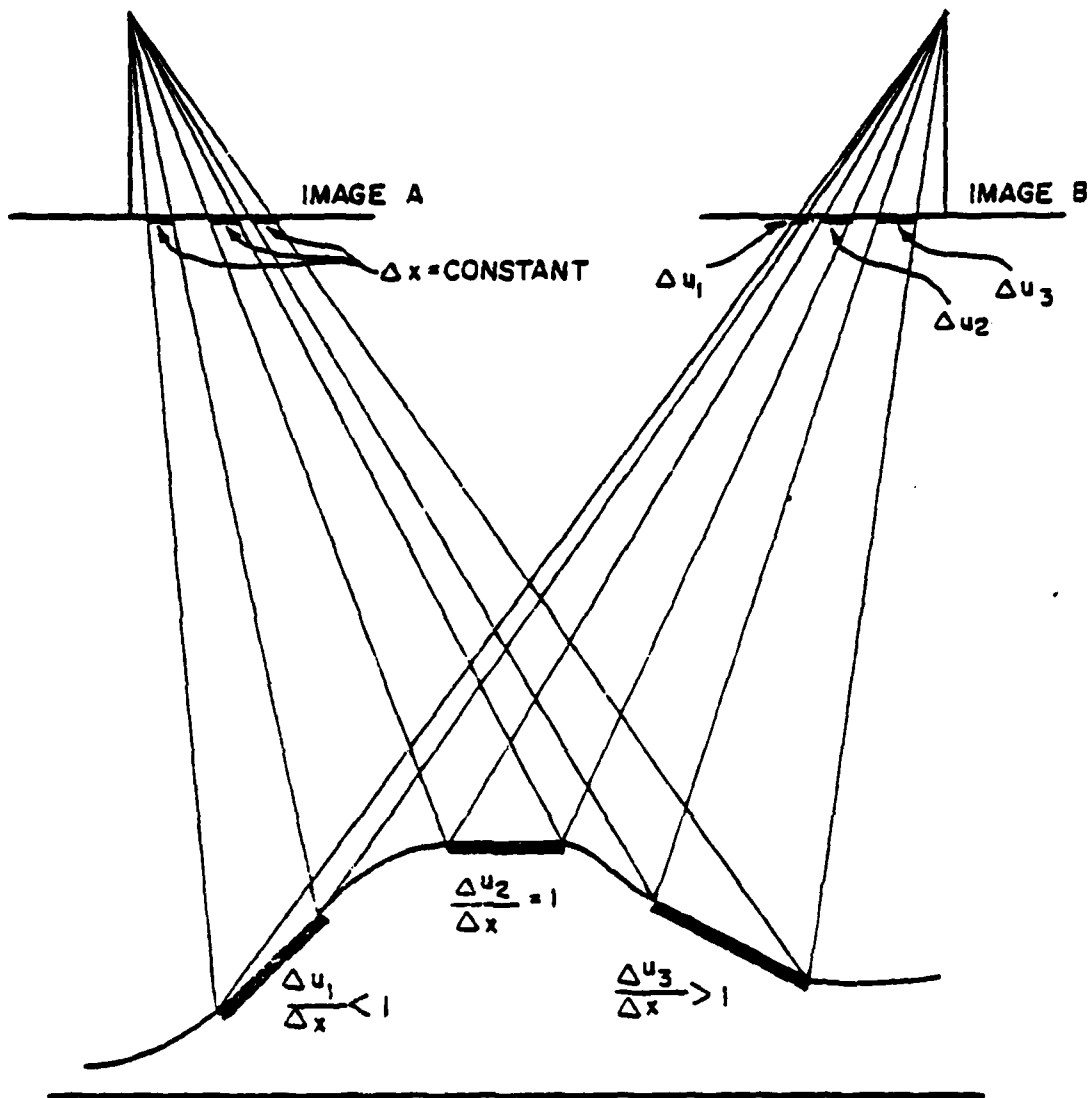


FIGURE 14 EFFECT OF SURFACE TOPOGRAPHY ON THE RATE OF CHANGE FUNCTION

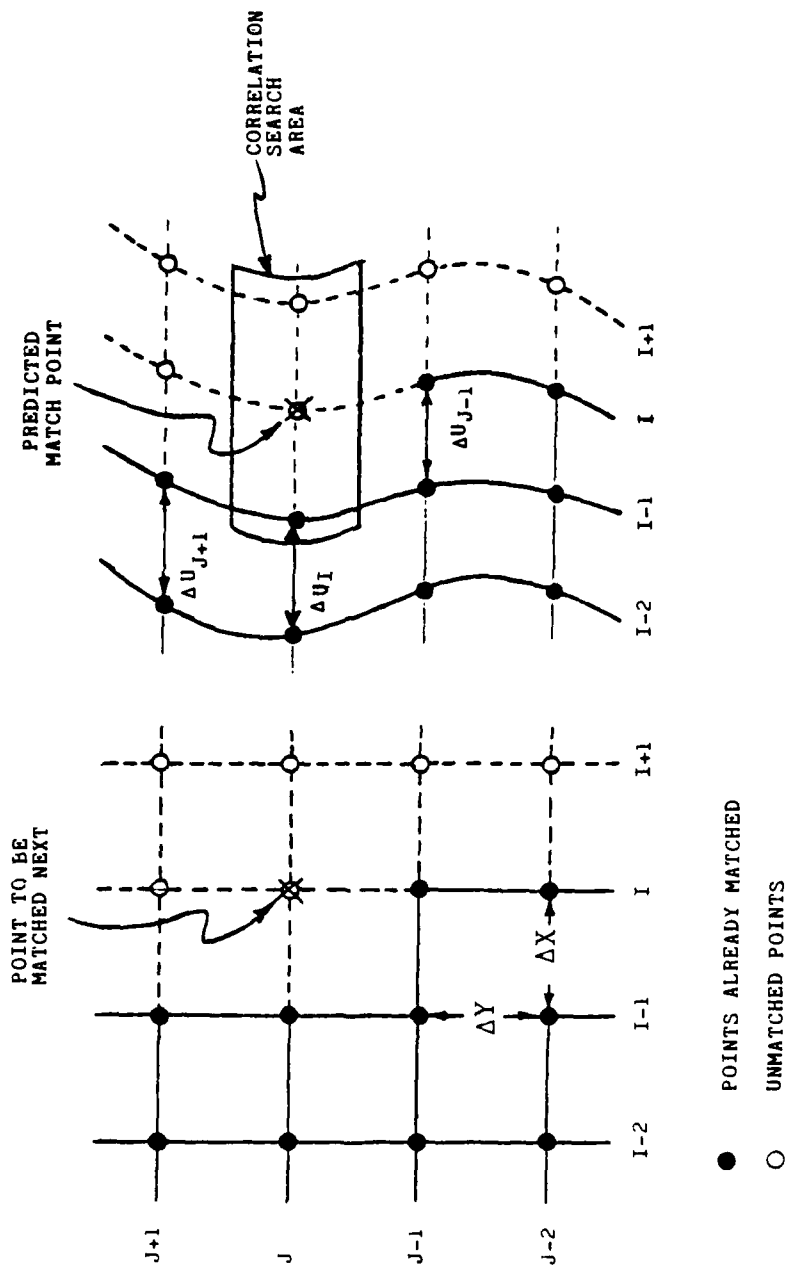
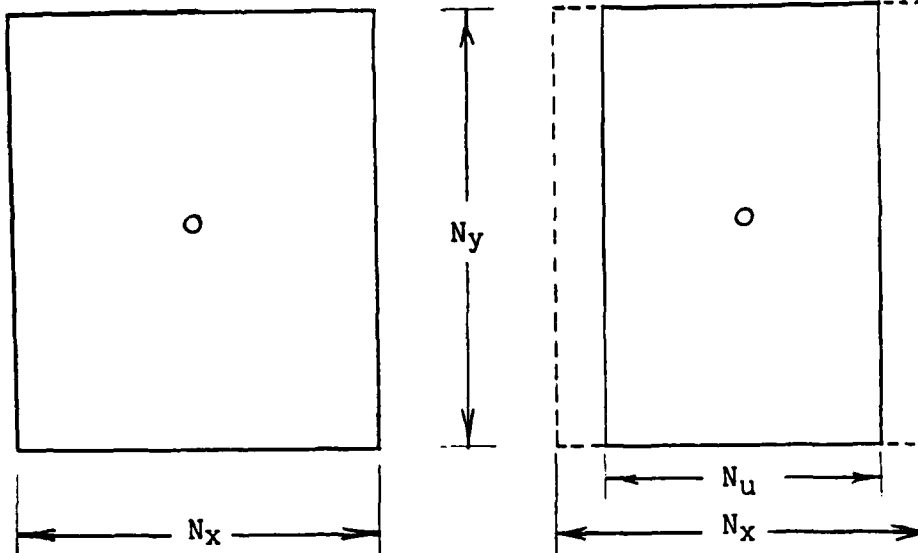


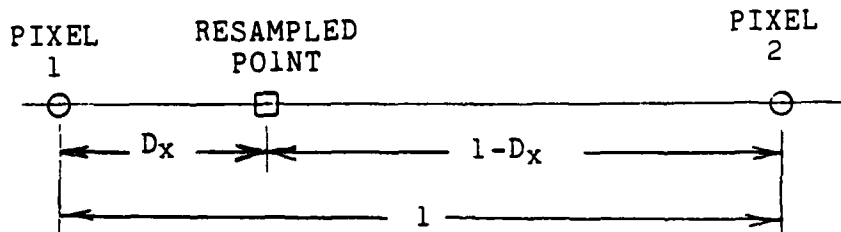
FIGURE 15 GRID FOR CALCULATING THE RATE OF CHANGE FUNCTION

BLOCK (I,J) ON
IMAGE B

SHAPED PATCH ON
IMAGE B

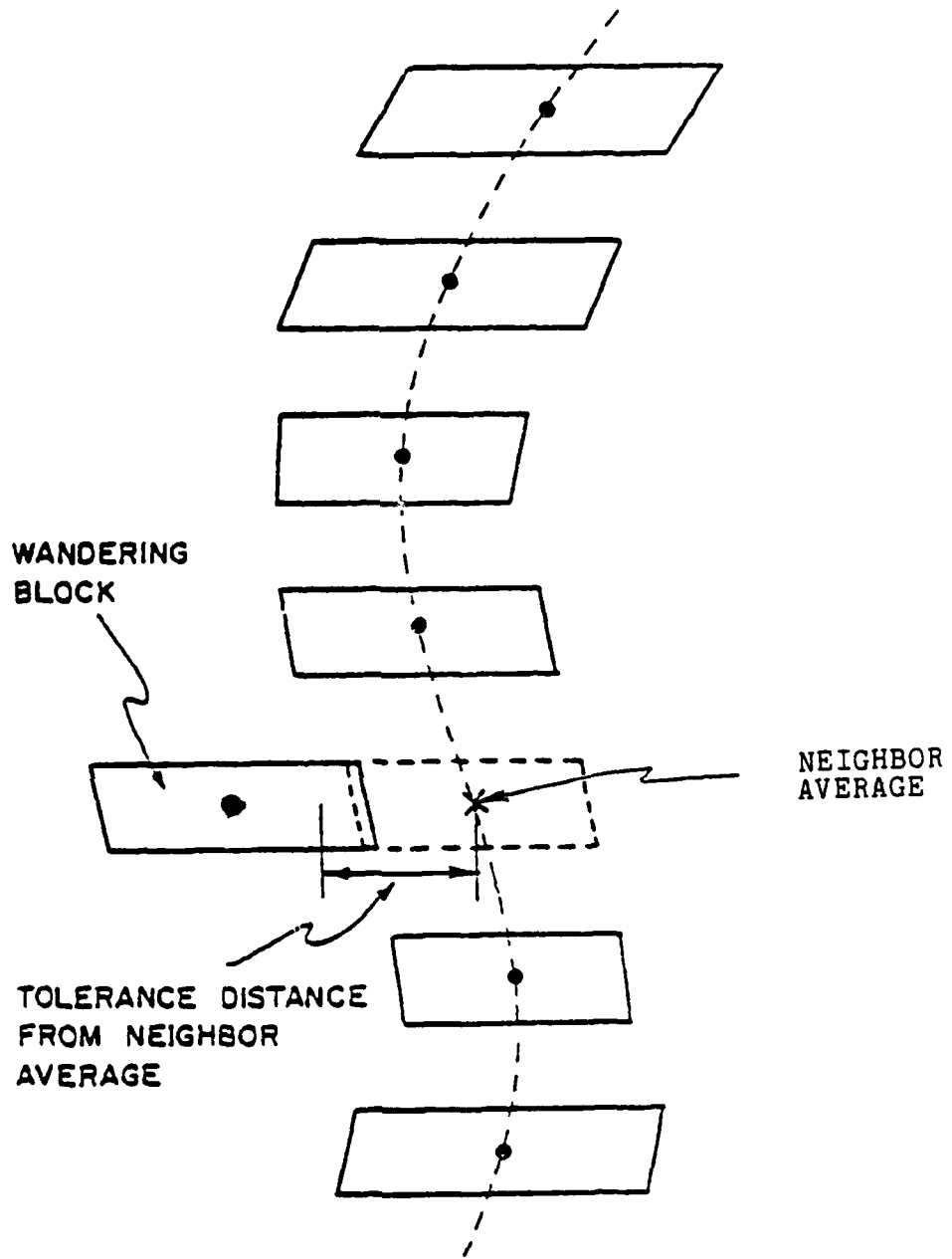


(a) PATCH SHAPING



(b) RESAMPLING

FIGURE 16 PATCH SHAPING AND RESAMPLING



- BLOCK IS CORRECTED TOWARD NEIGHBOR AVERAGE BY A WEIGHTED AMOUNT
- WEIGHT DETERMINED BY TUNING

FIGURE 17 WANDERING BLOCK TOLERANCE

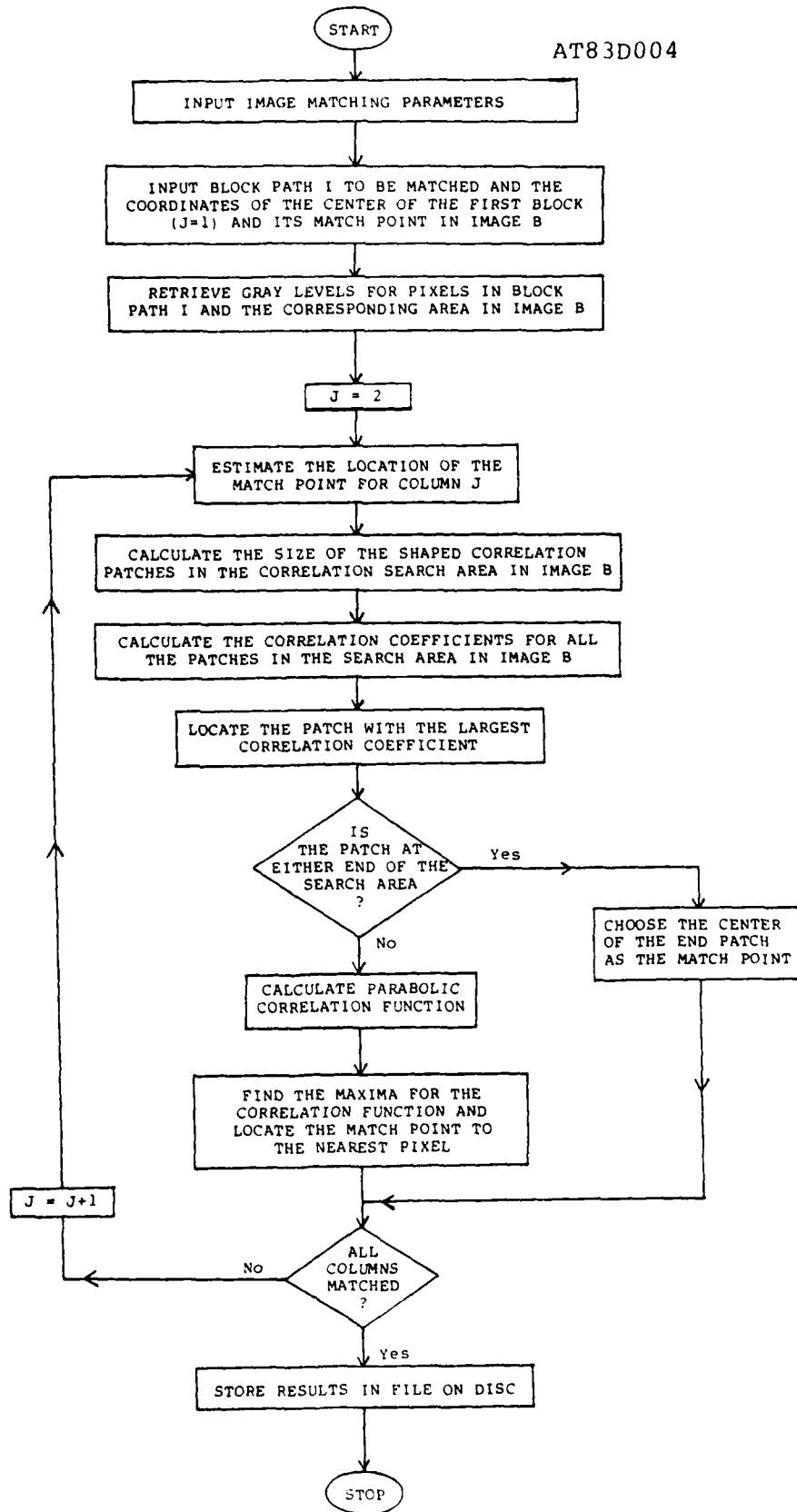
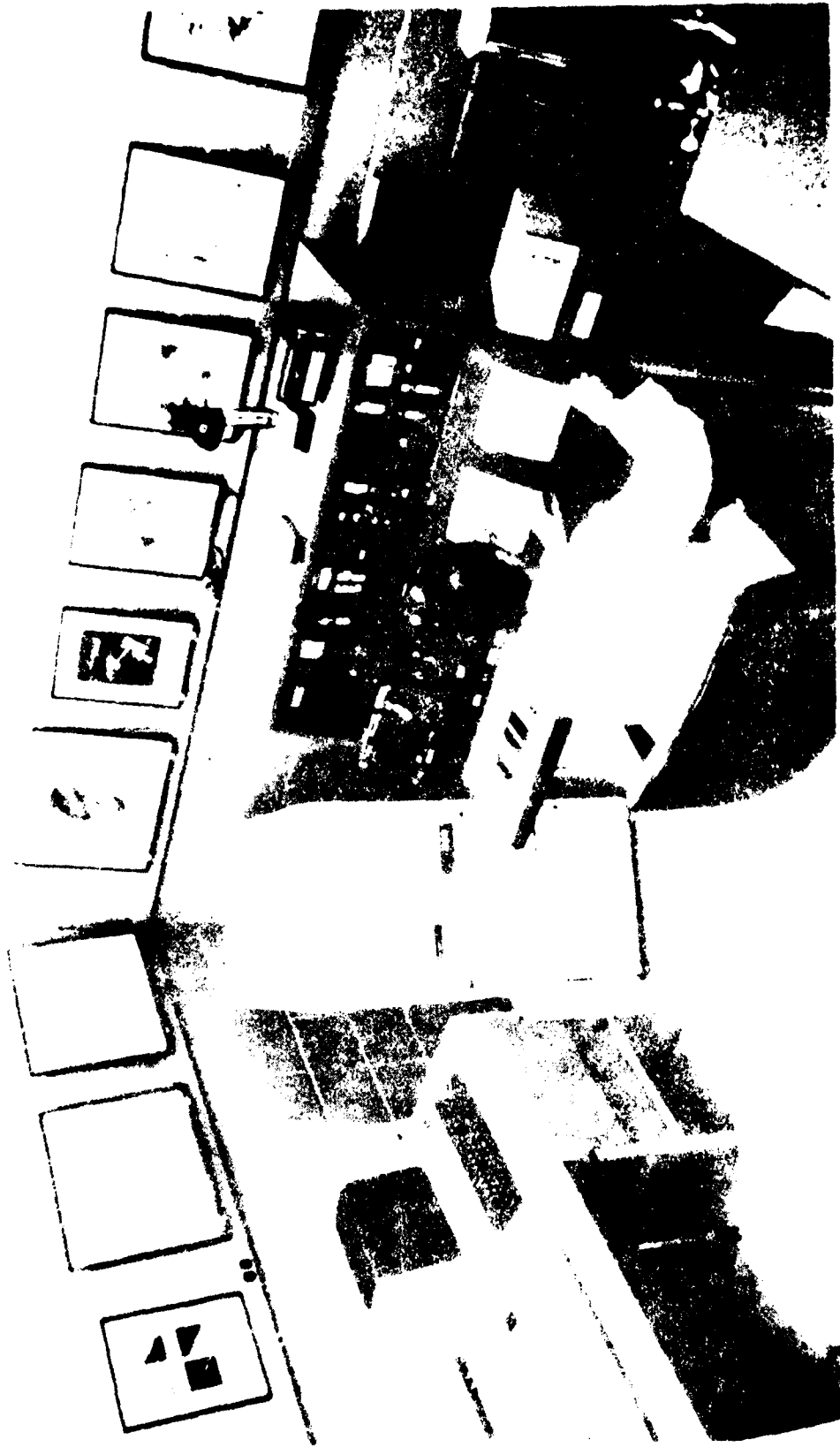


FIGURE 18 FLOW CHART FOR THE IMAGE MATCHING SOFTWARE



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FIGURE 19 - PHOTOGRAPH OF THE COMPUTER-SIM SYSTEM

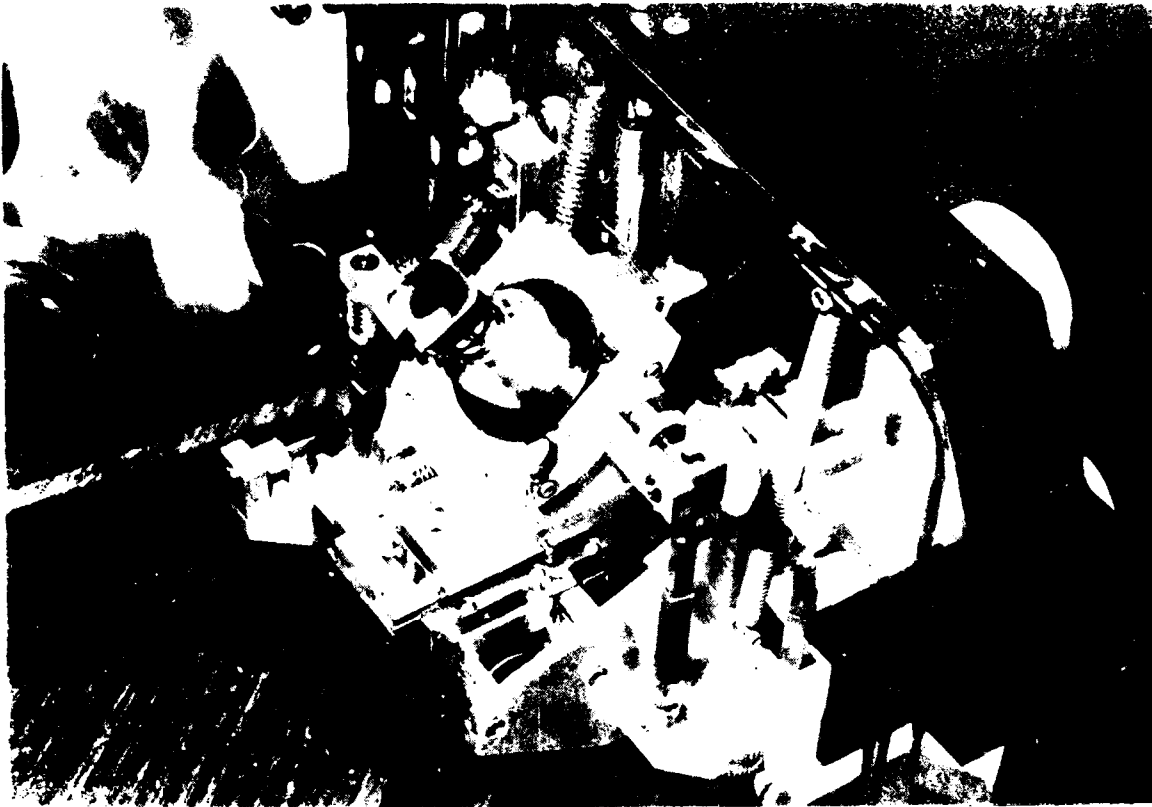
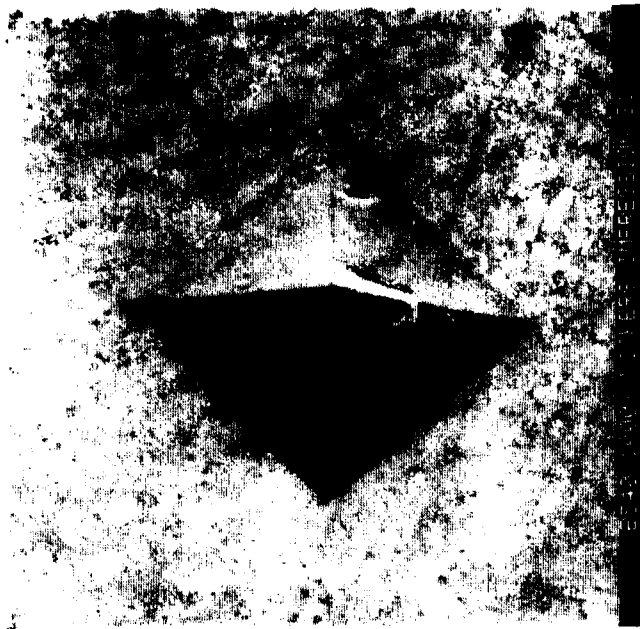


FIGURE 20 STOP BLOCK ARRANGEMENT FOR [unclear]



SEM Micrograph with Computer Controlled Scan



Digitized Image

512 x 256 Pixels

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FIGURE 21 DIGITIZED IMAGE WITH 512 x 256 PIXEL RESOLUTION



Digitized Image



SEM Micrograph with Computer
Controlled Scan

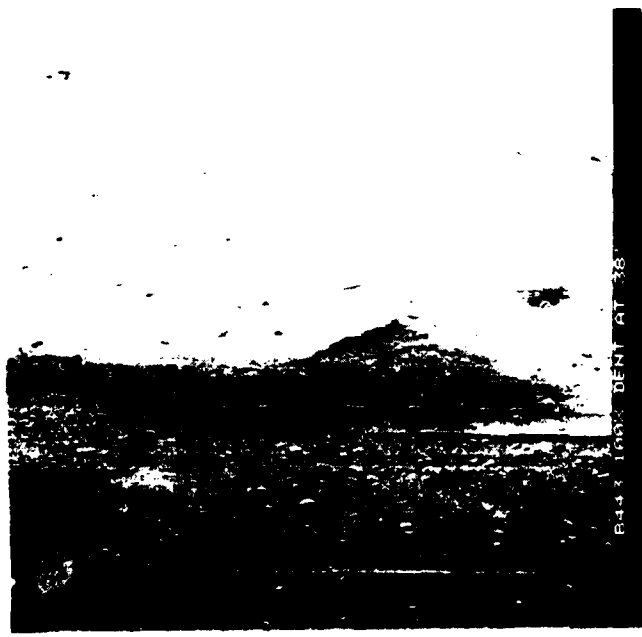
512 x 512 Pixels

FIGURE 22 DIGITIZED IMAGE WITH 512 x 512 PIXEL
RESOLUTION

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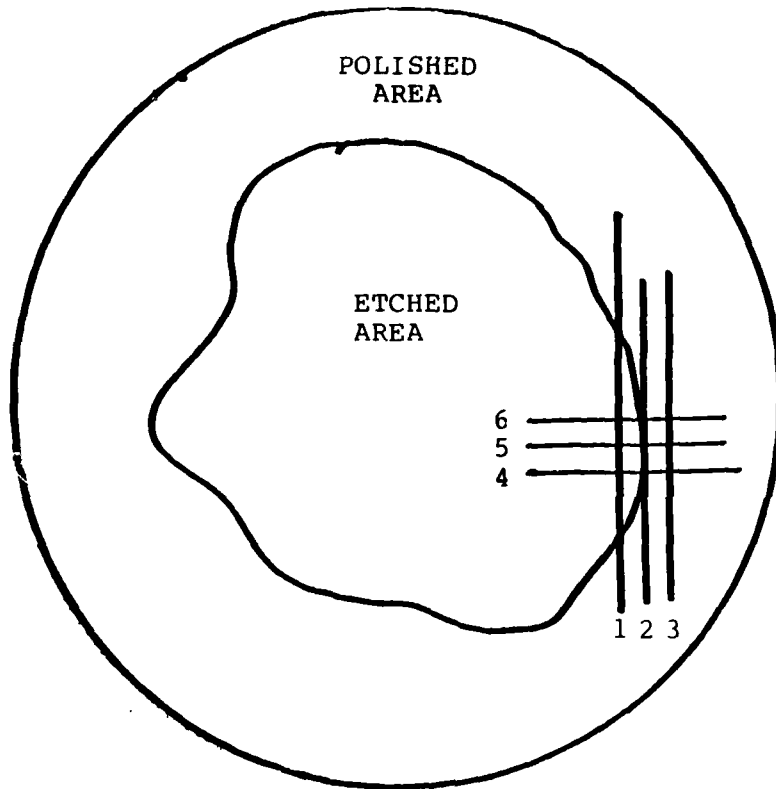


512 x 256 Pixel Digitized Image

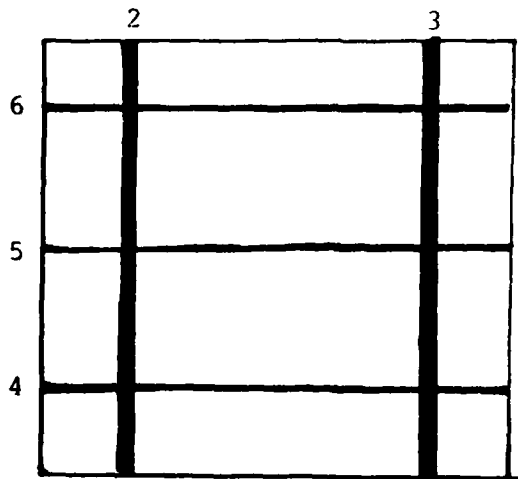


Regular SEM Micrograph

FIGURE 23 COMPARISON OF A REGULAR SEM MICROGRAPH WITH A 512 x 256 PIXEL DIGITIZED IMAGE



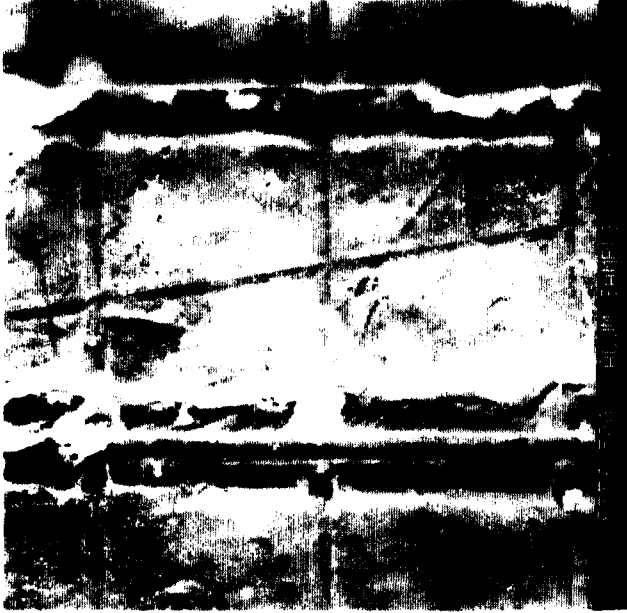
(a) Top View of Specimen



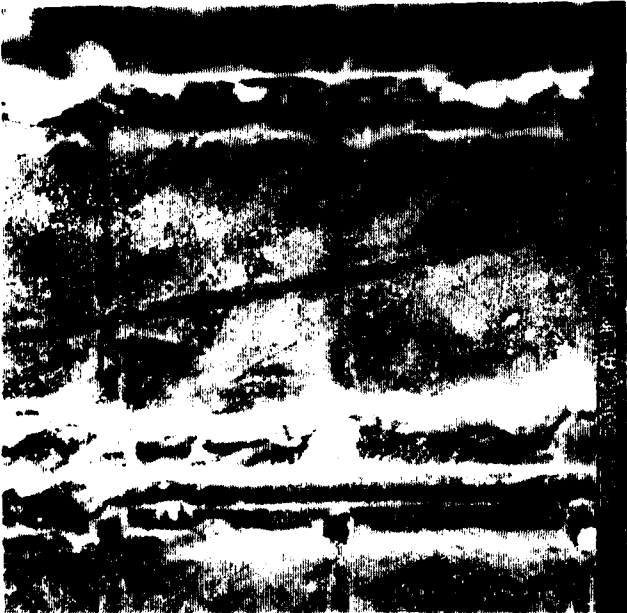
(b) Area Digitized

FIGURE 24 ELECTROPOLISHED ALUMINUM SPECIMEN

AT8 3D004



40.485° Tilt

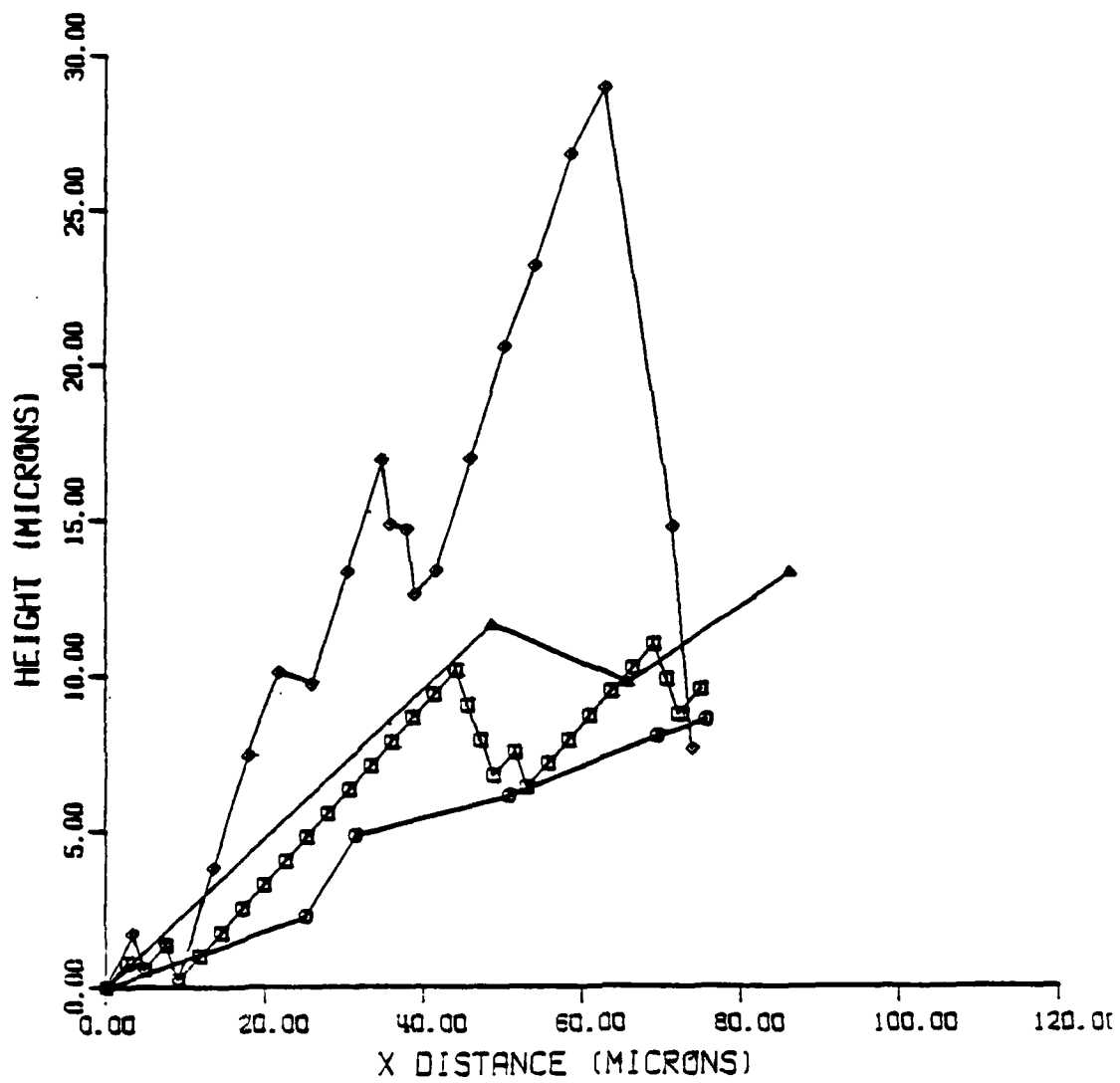


31.469° Tilt

512 x 256 Pixels

FIGURE 25 STEREO-PAIR OF DIGITIZED SEM IMAGES OF ELECTROPOLISHED ALUMINUM SPECIMEN

SK3 10000



- - STYLUS MEASUREMENTS
- ▲ - HAND MEASUREMENTS
- ◇ - LINEAR CORRELATION
- - LINEAR CORRELATION

$$.6 < \frac{\partial u}{\partial x} < 1.4$$

$$.95 \leq \frac{\partial u}{\partial x} \leq 1.0$$

FIGURE 26 COMPARISON OF STYLUS TRACE (GRID LINE 6) WITH HEIGHTS FROM MATCHED STEREO PAIR

E-4185C-1 9-79

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APPENDIX A

VALIDATION OF SOFTWARE USED TO
DIGITIZE SEM IMAGES

APPENDIX A

1.0 INTRODUCTION

Early attempts to match a stereo-pair of digitized SEM images yielded very poor correlation between the two images. An examination of the digitized image data revealed substantial differences in the digitized values for the stereo-pair of images. Subsequently, the same area on a specimen was digitized twice to check the repeatability of the data collection system. The results showed very poor repeatability. A series of tests were designed to identify the causes of the errors and to develop a procedure that would result in a stereo-pair of digitized SEM images optimized for the image matching software.

Appendix C describes the tests conducted to verify the repeatability of digitized image data collected using DATCOL software package described in Section 3 of the report. The tests showed that the lack of repeatability was primarily due to dynamic instabilities in the X-Y scan coils of the SEM. The problem was corrected by waiting long enough for the beam to stabilize at each point before the signal is digitized. The tests led to a definition of a procedure to obtain digitized SEM images suitable for matching a stereo-pair of digitized images.

2.0 TEST PROCEDURE

The same area on a specimen was digitized five times. Each of the five digitized images was an array of 512 X 20 pixels. The five images were used to calculate the standard deviation σ and the average gray level s at each of the 10,240 pixels in an image. The standard deviation was used as a measure of the noise at each point and used to calculate the noise-to-signal ratio, N/S, given by

$$N/S = \sigma/s \quad (1)$$

The results are presented as plots of N/S versus s for each of the 10,240 points in the image.

3.0 TEST RESULTS

3.1 Base-line Results

The base-line results were obtained using the old procedure for integration times of 20 μ s (Figures 1 and 2) and 100 μ s (Figures 3 and 4). Figures 1 and 3 showed that the noise in the data was essentially independent of the magnitude of the signal. The dwell time determined the range of gray levels in the data but did not effect the distribution of noise. For gray levels between -200 and +200, the N/S ratio was greater than 50 percent (Figures 2 and 4).

The noise in the data was attributed primarily to two causes:

1. Dynamic instability in the X-Y scan coils of the SEM resulting in small deviations in the position of the beam. For images in the test (magnification = 1000X), the probe diameter is less than the distance between pixels. Therefore, a deviation in beam position will result in errors because a different part of the specimen is sampled.
2. The SEM signal is generated by the interaction of the electrons in the beam and the specimen material. The beam-specimen interaction is a random process and therefore, some noise is inherent in the signal.

3.2 Remedies Examined

The following procedures were tested to reduce the N/S ratio and to improve the repeatability of the data:

1. Digitize images such that the gray levels are greater than 200.
2. Allow more time for the beam to settle at each point before integrating and digitizing the signal.
3. Scan each line in the image repeatedly to calculate an average gray level at each point in the line. The number of samples at each pixel in the image will be selected to yield the minimum N/S ratio. The average will help to attenuate the random noise in the signal.

4. Increase the signal-to-noise ratio of the SEM signal by increasing the beam current. This is achieved by decreasing the current in the condenser coils from the usual 2.0 amps to 1.7 amps. The result is an enhanced SEM signal and a larger probe diameter. The larger probe diameter provides some overlap between pixels and helps reduce the magnitude of change in gray levels caused by small deviations in the position of the beam due to X-Y scan coil instabilities. The probe diameter should, however, be less than 1.5 times the distance between pixels to avoid introducing new errors.

3.3 Results of Modifications

Figure 5 shows the effect of increasing the beam setting time between scan lines. The N/S ratio is reduced to half of the values in Figure 4. The N/S ratio is improved significantly when each gray level is an average of five samples (Figure 6) but begins to degrade when ten samples are averaged (Figure 7). The existence of an optimum number of samples per pixel was confirmed by repeating the tests using other samples. The results suggested that some systemic causes other than random noise were contributing to the variation in gray levels. Further tests showed that the specimen needs time to recover from the effects of the electron beam. If the same spot on the specimen is sampled repeatedly without allowing sufficient time between samples, the cumulative effects of the beam-specimen interaction result in a decrease in gray level. The level begins to stabilize after 40 to 50 samples. Therefore, multiple samples for calculating average gray levels should be taken such that there is sufficient time between samples for the effects of beam-specimen interaction to dissipate.

Figures 8, 9, and 10 show the effect of increasing the beam signal by reducing the current in the condenser coils and further changes in scan procedure to reduce dynamic instabilities in X-Y scan coils. There is a significant reduction in the N/S ratio. The degradation in data for 10 samples per pixels is present because the modifications discussed above had not yet been incorporated.

4.0 CONCLUSIONS

The reduction in N/S ratio due to improved X-Y scan coil stability are sufficient to avoid having to adjust the condenser

current to obtain good digitized data. For most surfaces, the following procedure will yield acceptable images:

1. Ensure that the minimum gray level is above +200. The data collection software was modified to set the dwell time automatically to ensure that the data are spread over the full positive range of gray levels (max. 2047). If the SEM contrast/brightness controls are adjusted to keep the waveform above the zero level, the digitized data are in the 200 - 2047 range.
2. The default is only one sample per pixel. For most specimens, averaging will not be required if the gray levels are between 200 - 2047. When it is not possible to satisfy the above requirement, five samples per pixel should be used.
3. Condenser coil current adjustment should be used only as a last resort.

Images collected using the above criteria were consistently of good quality. Digitized data obtained from the same surface varied by less 5 percent. Preliminary attempts to match stereo-pairs collected using the new procedure yielded dramatic improvements in correlation between the two images.

DWELL TIME = 20 μ s
NUMBER OF ROWS = 20
PIXELS PER ROW = 512
NUMBER OF IMAGES = 5
SAMPLES PER POINT = 1
CONDENSER COIL CURRENT = 2 amps

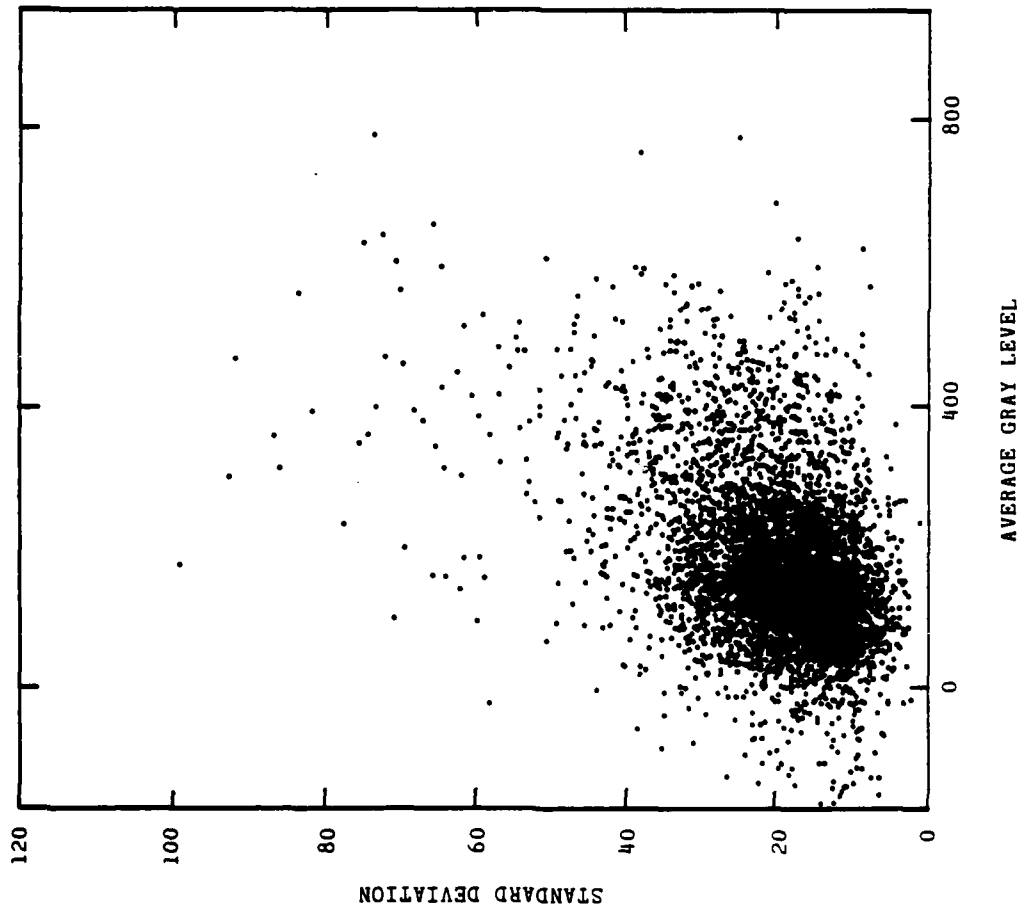


FIGURE 1

DWELL TIME = 20 μ s
NUMBER OF ROWS = 20
PIXELS PER ROW = 512
NUMBER OF IMAGES = 5
SAMPLES PER POINT = 1
CONDENSER COIL CURRENT = 2 amps

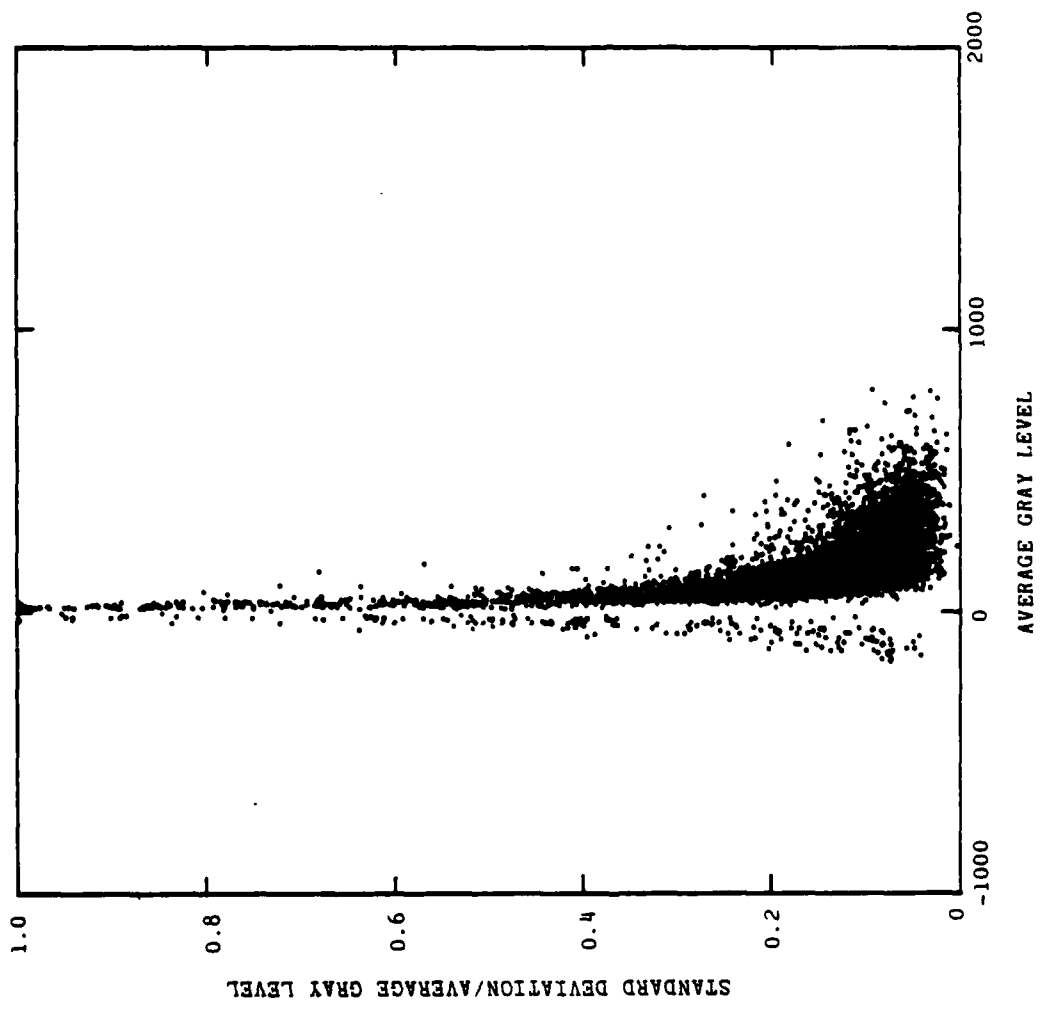


FIGURE 2

DWELL TIME = 100 μ s
NUMBER OF ROWS = 20
PIXELS PER ROW = 512
NUMBER OF IMAGES = 5
SAMPLES PER POINT = 1
CONDENSER COIL CURRENT = 2 amps

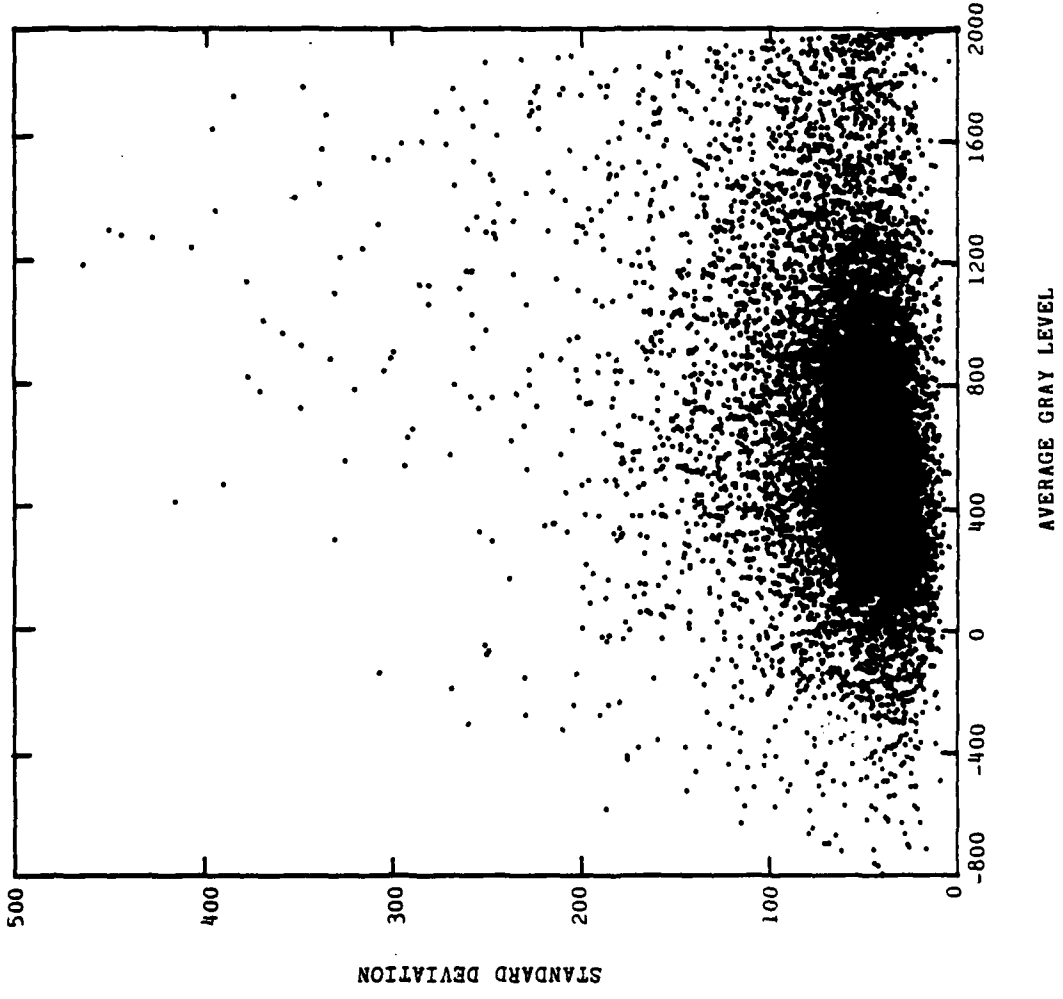


FIGURE 3

DWELL TIME = 100 μ s
NUMBER OF ROWS = 20
PIXELS PER ROW = 512
NUMBER OF IMAGES = 5
SAMPLES PER POINT = 1
CONDENSER COIL CURRENT = 2 amps

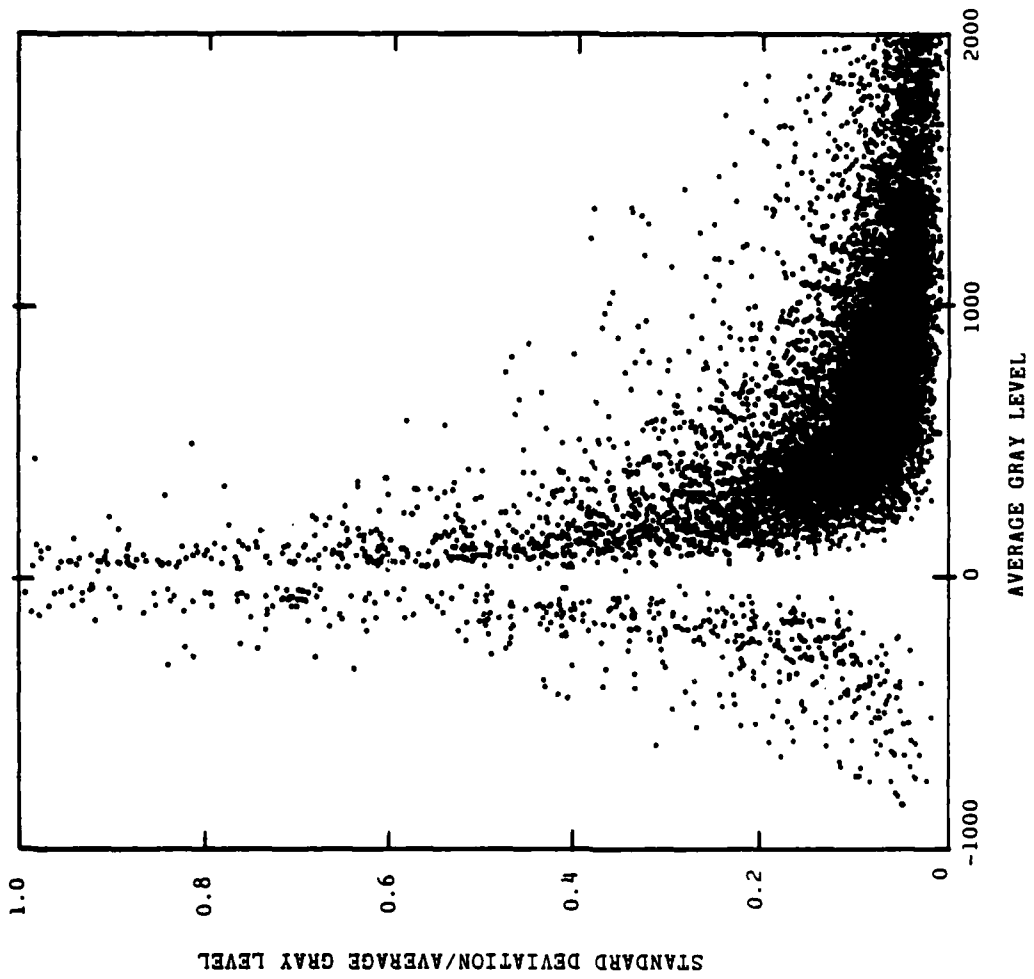


Figure 4

Dwell Time = 75 μ s
Number of Rows = 20
Pixels per Row = 512
Number of Images = 5
Samples per Point = 1
Condenser coil current = 2 amps

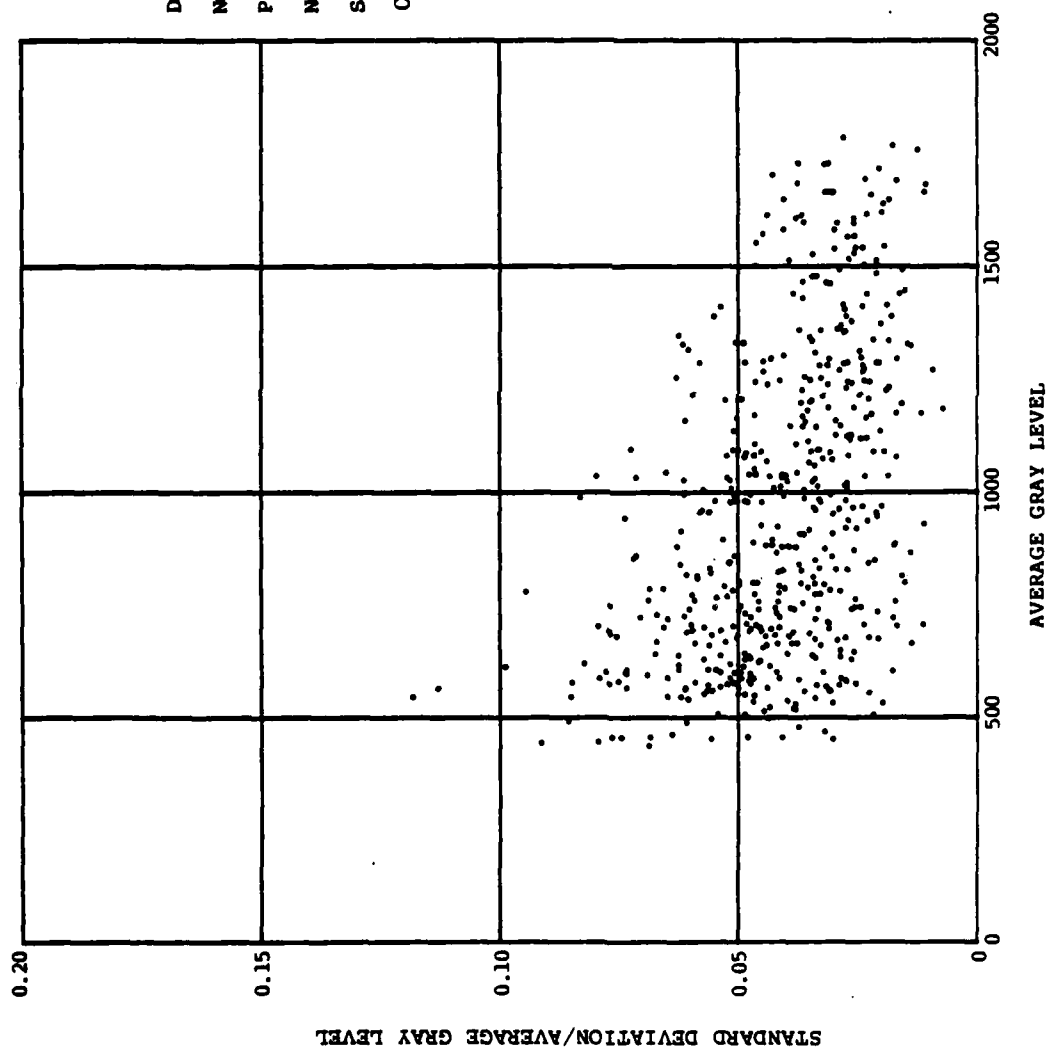


FIGURE 5

Dwell Time = 75 μ s
Number of Rows = 20
Pixels per Row = 512
Number of Images = 5
Samples per Point = 5
Condenser coil current = 2 amps

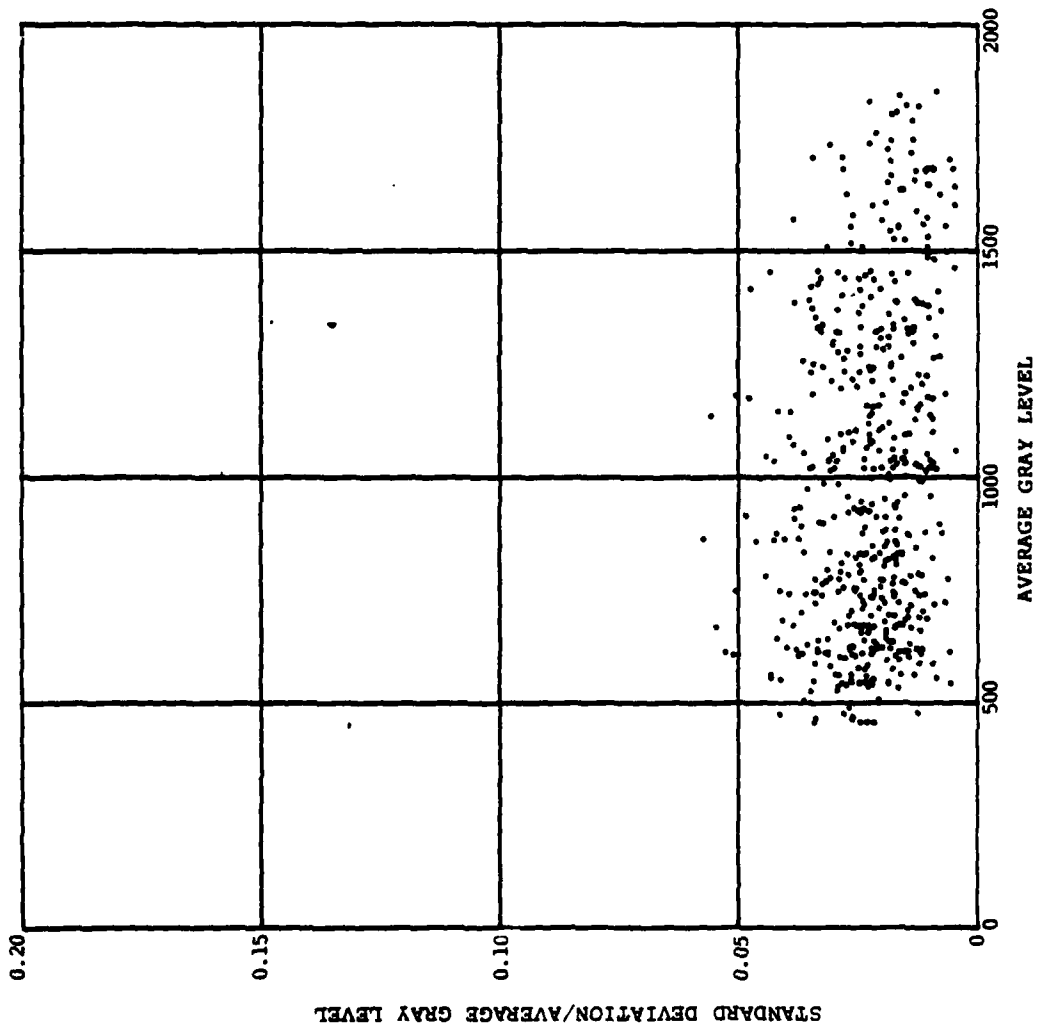


FIGURE 6

Dwell Time = 75 μ s
Number of Rows = 20
Pixels per Row = 512
Number of Images = 5
Samples per Point = 10
Condenser coil current = 2 amps

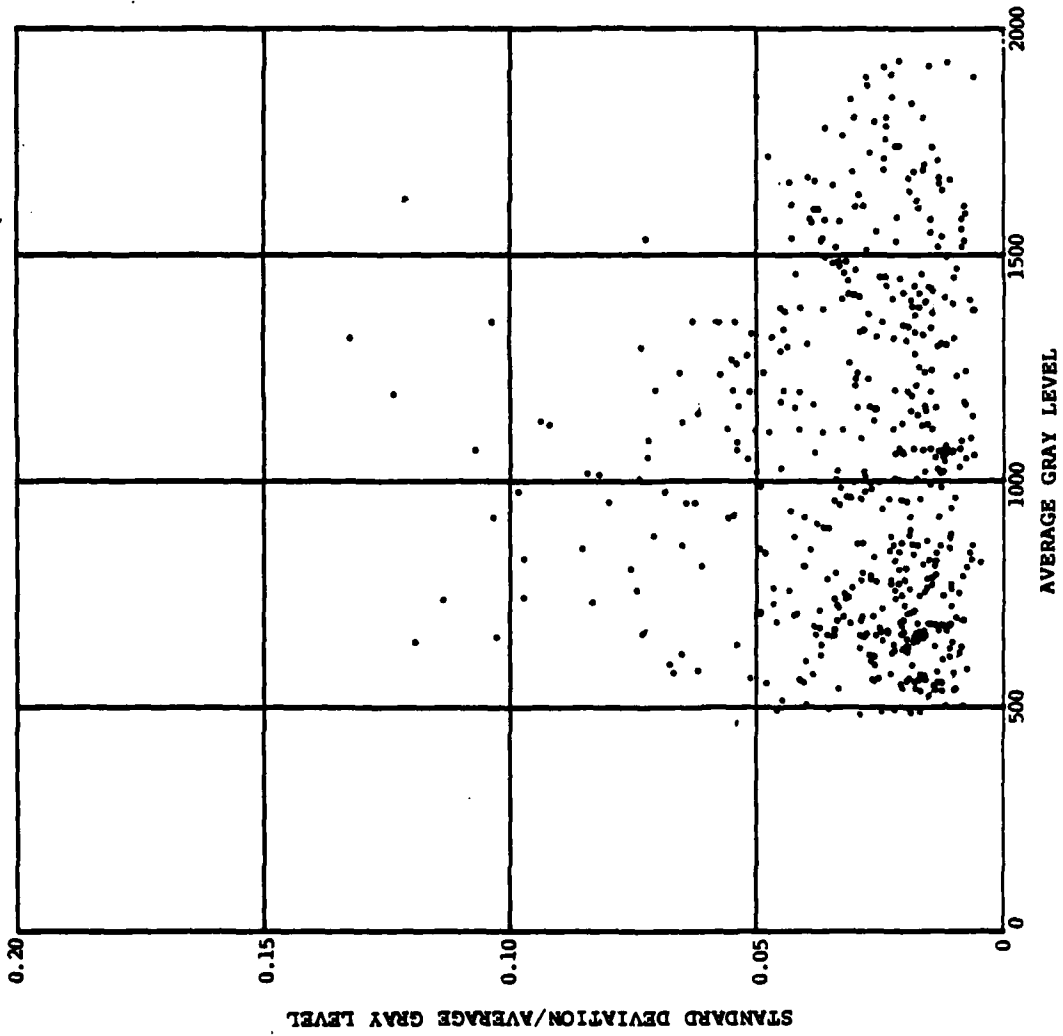


FIGURE 7

Dwell Time = 75 μ s
Number of Rows = 20
Pixels per Row = 512
Number of Images = 5
Samples per Point = 1
Condenser Coil Current = 11.7 amps

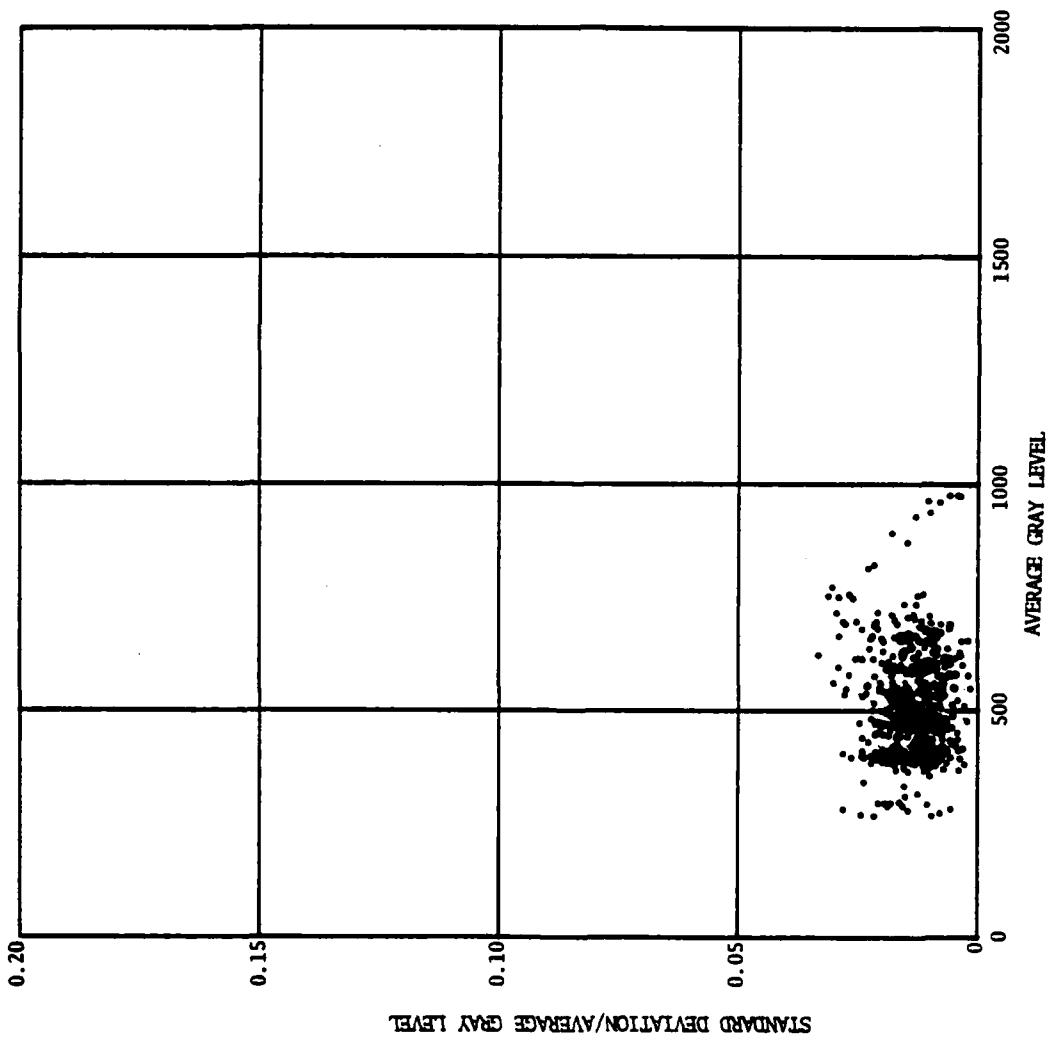


FIGURE 8

Dwell Time = 75 μ s
Number of Rows = 20
Pixels per Row = 512
Number of Images = 5
Samples per point = 5
Condenser Coil Current = 1.7 amp

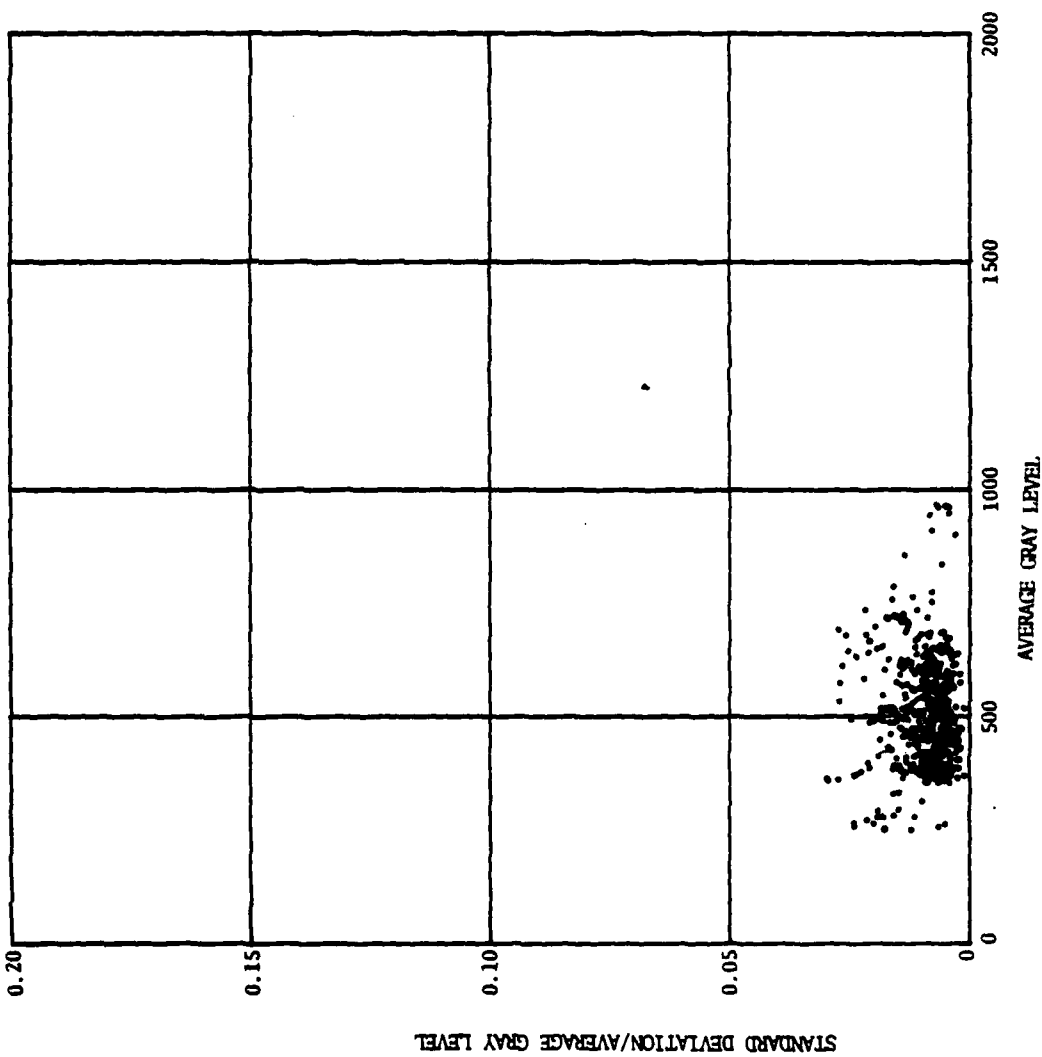


FIGURE 9

Dwell Time = 75 μ s
Number of Rows = 20
Pixels per Row = 512
Number of Images = 5
Samples per Point = 10
Condenser Coil Current = 1.7 amps

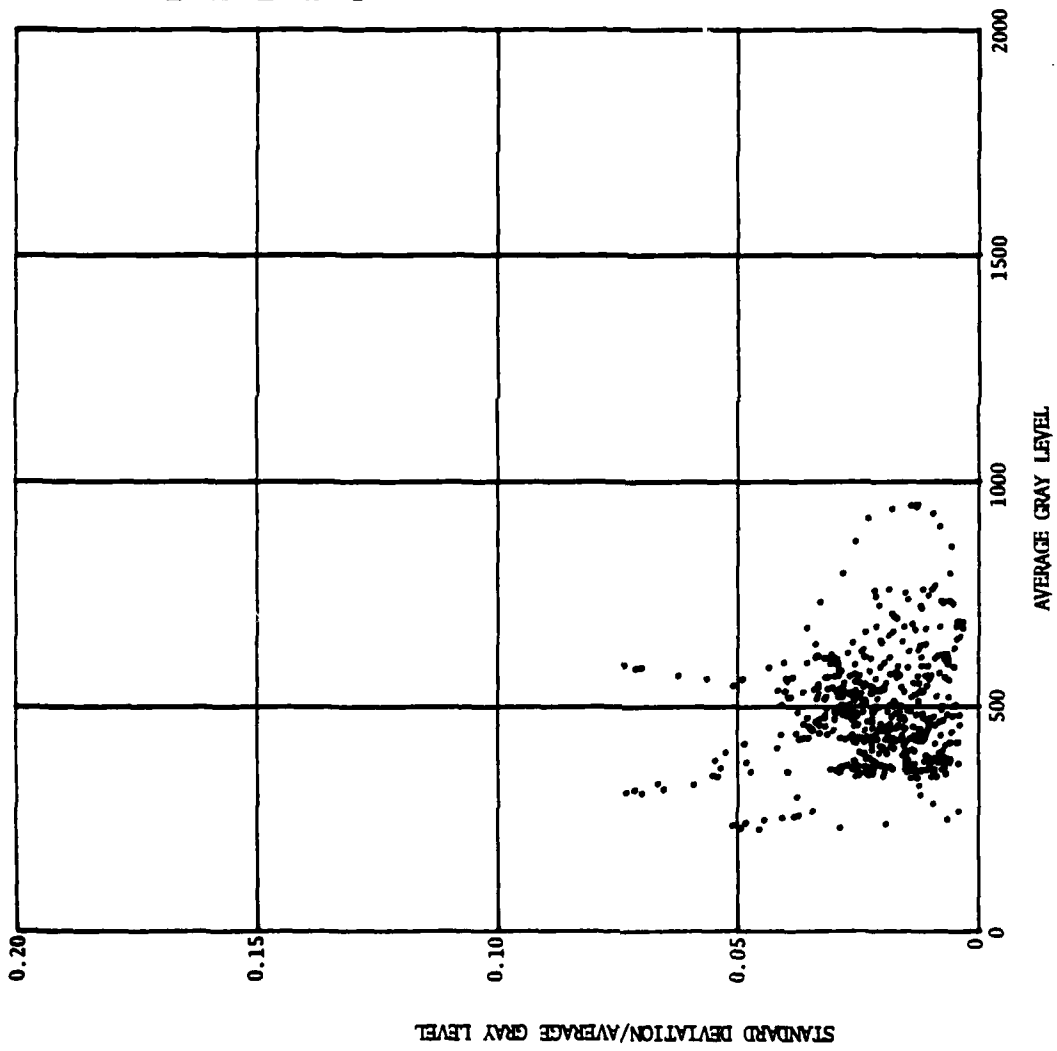


FIGURE 10