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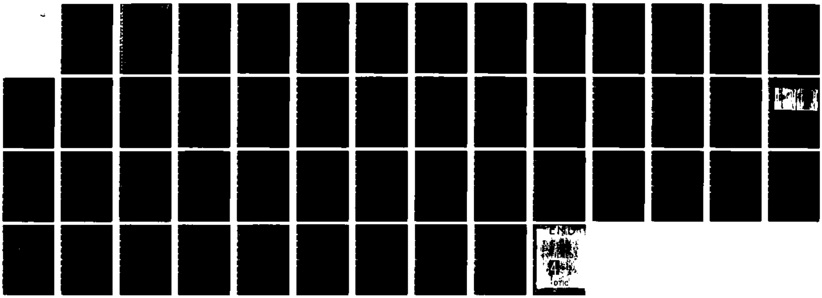

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FINAL TECHNICAL REPORT

ON

DEVELOPMENT OF A 3-D MICROSCALE TOPOGRAPHY SYSTEM

PHASE III

B. B. AGGARWAL

JUNE 1983

SKF REPORT NO. AT83D011

SUBMITTED TO:

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

SUBMITTED UNDER CONTRACT NO. N00014-82-C-0342

SUBMITTED BY:

SKF TECHNOLOGY SERVICES
SKF INDUSTRIES, INC.
KING OF PRUSSIA, PA

SKF TECHNOLOGY SERVICES
SKF INDUSTRIES, INC.

1 March 1984

To: Recipients of Final Technical Reports on "Development of A 3-D Microscale Topography System"

PHASE I SKF REPORT NO. AT83D001
ONR CONTRACT NO. N00014-79-C-0792

PHASE II SKF REPORT NO. AT83D004
ONR CONTRACT NO. N00014-80-C-0937

PHASE III SKF REPORT NO. AT83D011
ONR CONTRACT NO. N00014-82-C-0342

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Sincerely,

SKF INDUSTRIES, INC.

Bharat B. Aggarwal

Bharat B. Aggarwal
Project Leader

BBA/amh

FINAL TECHNICAL REPORT

ON

DEVELOPMENT OF A 3-D MICROSCALE TOPOGRAPHY SYSTEM

PHASE III

JUNE 1983

PREPARED: Bharat B. Aggarwal

SKF REPORT NO. AT83D011

RELEASED: [signature]

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1.0 INTRODUCTION

This report describes the technical work accomplished in the third 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. In the second phase of the program (ONR Contract N00014-80-C-0937), the hardware and the software necessary to implement the surface topography measurement system were developed and the integrated system was tested to verify its performance. The objectives of the third phase of the program were to provide a data display capability for the system and to refine the system to improve its performance.

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]:

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. In limited tests, surface height 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 Summary of Work Done in Phase II [2]

The integration of software and hardware for digitizing SEM images was completed. The system reliability was verified by experiments designed to check the quality and repeatability of digitized image data. Procedures were developed to obtain digitized SEM images suitable for matching a stereo-pair of images. The image matching software was developed to process a single strip of an SEM image. The complete surface is mapped by processing a series of adjacent strips. The integrated system was used successfully to obtain quantitative height data from a stereo-pair of SEM images. The image digitization system was regarded as a reliable, mature system.

The image matching software was however, still in the development stage. The major drawback was the reliance on purely statistical measures of correlation to locate the match points. The matching software needed 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 pro-

vides important information towards identifying the causes of spalls and fractures.

3) Output from any of the SEM sensors (x-ray, backscatter 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.

1.30 Objectives of Phase III (ONR Contract N00014-82-C-0342)

The primary objective of the third phase of the program was to complete the development of the quantitative, three-dimensional surface topography measurement system by adding a data display capability. The work was divided into four tasks:

1) Define, procure, test and verify remaining hardware/software (extended RAM, floating point chip, controller algorithms for DAC and ADC boards) for a data display capability consisting of an interactive graphics terminal, a digital interactive plotter and a PDP-11/23 computer.

2) Provide and verify a software module for computation of physical surface features.

3) Provide and verify a software module for hard copy output of maps and graphs.

In addition to the above tasks, the image matching software developed in Phase II was modified to improve the performance and the reliability of the system.

1.40 Organization of the Report

This report describes the technical work accomplished in Phase III and summarizes the technical status of the complete three-phase program. The hardware and software procured for the data display capability is described in Section 2. The statistical software module for the computation of physical surface features is described in Section 3. Graphics display software to draw surface profiles and contour maps is described in Section 4. Section 5 describes the additional work done in Phase III. The technical status of the program and suggestions for further work are presented in Section 6.

2.0 DATA DISPLAY SOFTWARE AND HARDWARE (TASK 1)

Graphics display hardware procured for the system was described in the final technical report for Phase II. The hardware includes a Tektronix 4662 Digital Intractive Plotter and a Tektronix 4010 Interactive Graphics Terminal. Both devices are driven using Tektronix PLOT-10 graphics software library. Early experience with the development of graphics software accentuated the need for additional memory for the PDP-11/23 computer and the requirement for faster computational rates. As a result, an additional 128 KB of RAM and a floating point processor were procured for the PDP-11/23. The graphics software developed for th system is described in Section 4.

3.0 STATISTICAL SOFTWARE MODULE (TASK 2)

This software module is used for statistical analysis of surface height data generated by the image matching software. The program calculates the following parameters for a two-dimensional surface profile:

- Arithmetic average roughness for the surface profile and the peak heights.
- Root-mean-square roughness for the surface profile and the peak heights.
- Skewness and kurtosis for the surface profile and the peak heights.
- Spectral moments m_0, m_2 and m_4 for the surface profile.
- Maximum peak-to-valley roughness.
- Average spacing of peaks.
- Average peak curvature.
- Histogram of surface heights.
- Histogram of peak heights.

The above parameters can be calculated for unprocessed height data or for a filtered surface profile. A cascaded band pass digital filter is included in the module.

3.10 Definition of Parameters [3,4]

Surface texture is defined in terms of its constituents: roughness, waviness, lay and flaws. Roughness consists of the finer irregularities of the surface texture while waviness is the more widely spaced components of surface texture. The roughness and the waviness are separated by some form of filtering process based on the wavelength of irregularities; the cut-off value is equal to the maximum wavelength to be included in the roughness. Lay is the direction of the predominant surface pattern and flaws are unintentional irregularities on the surface.

The parameters calculated by the statistical analysis program are described below. A discrete surface profile is represented by an array of numbers; the heights of point i in the profile is denoted by h_i. The heights are measured relative to the graphical centerline of the profile. The centerline is a line such that the sums of the areas enclosed between it and those parts of the profile which lie on either side of the line are equal. A point i in the profile is called a peak if height h_i is greater than the heights of adjacent points i-1 and i+1; point i is called a valley if height h_i is less than the heights of adjacent points i-1 and i+1.

Arithmetic Average Roughness, R_a, is given by

$$R_a = \sum_{i=1}^{n} |h_i|/n \tag{1}$$

where n is the number of points in the surface profile, and h_i the height of point i relative to the centerline.

Maximum Peak-to-Valley Roughness, R_{max}, is the distance between two lines parallel to the centerline which contact the extreme outer and inner points in the profile. This value is typically more than three times the average roughness value.

Average spacing of roughness peaks, A_r, is given by

$$A_r = \sum_{i=1}^{m} A_i/(m-1) \tag{2}$$

where A_i is the spacing between peaks i and i+1, and m is the total number of peaks. The average spacing is a measure of the wavelength of the surface irregularities.

Root Mean Square Roughness, R_q, given by

$$R_q = [\sum_{i=1}^{n} h_i{}^2/n]^{1/2} \tag{3}$$

is the square root of the mean of the square of the deviation from the centerline of the profile.

Skewness, R_{SK}, of the surface profile measures the asymmetry of the surface height distribution curve. The skewness is given by

$$R_{SK} = \sum_{i=1}^{n} h_i^3 \, / \, (n \, R_q^3) \qquad (4)$$

Kurtosis, R_K, is a measure of the hump on a distribution curve. A surface with a gaussian height distribution has $R_K = 3$; the distributions with $R_K < 3$ are called Platykurtic while those with $R_K > 3$ are called Leptokurtic. The kurtosis is given by

$$R_K = \sum_{i=1}^{n} h_i^4 \, / \, (n \, R_q^4) \qquad (5)$$

The curvature ρ_i for a peak i is calculated using the central difference relation

$$\rho_i = (h_{i+1} - 2h_i + h_{i-1})/(\Delta x)^2 \qquad (6)$$

where Δx is the spacing between adjacent points in the profile. When point spacing Δx is large, the error can be reduced by calculating the curvature using the relation

$$\rho_i = (-h_{i+2} + 16h_{i+1} - 30h_i + 16h_{i-1} - h_{i-2})/(12 \, \Delta x^2) \qquad (7)$$

The average peak curvature, ρ_a, is given by

$$\rho_a = \sum_{i=1}^{m} \rho_i/m \qquad (8)$$

where m is the number of peaks.

Spectral moments m_0, m_2 and m_4 for a surface profile are given by

$$m_0 = \sum_{i=1}^{n} (h_i - \bar{h})^2 / (n-1) \qquad (9)$$

$$m_2 = \sum_{i=1}^{n-1} (h_{i+1} - h_i)^2/[(n-1)\Delta x^2] \qquad (10)$$

$$m_4 = \sum_{i=1}^{n-2} (h_{i+2} - 2h_{i+1} + h_i)^2/[(n-2)\Delta x^4] \qquad (11)$$

where n is the number of points in the profile and $\bar{h}$ the average surface height given by

$$\bar{h} = \sum_{i=1}^{n} h_i/n \qquad (12)$$

3.20 Cascaded Band-Pass Filter [3]

The cascaded band pass filter passes all frequencies over a specified interval defined by the lower and upper cut-off frequencies. The filter coefficients are based on the digital frequencies λ_1 and λ_2 given by

$$\lambda_1 = 2\pi f_1 \Delta x$$

$$\lambda_2 = 2\pi f_2 \Delta x \qquad (13)$$

where f_1 is the lower cut-off frequency, f_2 the upper cut-off frequency, and Δx the distance between adjacent points in the surface profile. A schematic of the filter is shown in Figure 1.

Filter coefficients for the first stage are given by

$$
\begin{aligned}
a_{01} &= 1/(1+\alpha) \\
a_{11} &= 0 \\
a_{21} &= -a_{01} \\
a_{31} &= 0 \\
a_{41} &= 0 \\
b_{11} &= -2\alpha\beta/(1+\alpha) \\
b_{21} &= (\alpha-1)/(1+\alpha) \\
b_{31} &= 0 \\
b_{41} &= 0
\end{aligned}
\tag{14}
$$

where

$$
\begin{aligned}
\alpha &= \cot[(\lambda_2-\lambda_1)/2] \\
\beta &= \sin(\lambda_1 + \lambda_2)/(\sin\lambda_1 + \sin\lambda_2)
\end{aligned}
\tag{15}
$$

The surface profile is processed through the first stage filter to obtain an array F given by

$$F_i = \sum_{j=0}^{4} a_{j1}\, h(i-j) - \sum_{j=1}^{4} b_{j1}\, F(i-j) \quad i=5,6,\ldots n \tag{16}$$

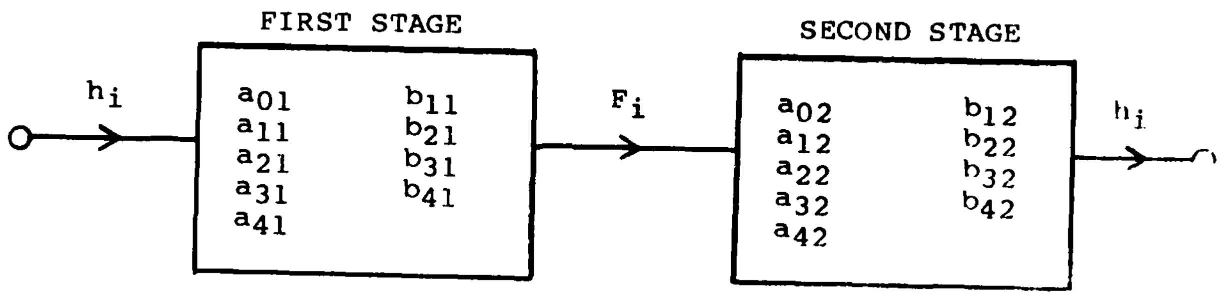


FIGURE 1: CASCADED BAND PASS FILTER

The output from the first stage is processed through the second stage to obtain the filtered profile H given by

$$H_i = \sum_{j=0}^{4} a_{j2}\, F(i-j) - \sum_{j=1}^{4} b_{j2}\, H(i-j) \quad i=5,6,\ldots n \tag{17}$$

where a_{j2} and b_{j2} are coefficients for the second stage filter and are obtained using the relations

$$\begin{aligned}
a_{02} &= 1/k \\
a_{12} &= 0 \\
a_{22} &= -2a_{02} \\
a_{32} &= 0 \\
a_{42} &= a_{02} \\
b_{12} &= -(4\alpha^2 b + 2\alpha\beta)/k \\
b_{22} &= (2\alpha^2 + 4\alpha^2\beta^2 - 2)/k \\
b_{32} &= (4\alpha^2\beta - 2\alpha\beta)/k \\
b_{42} &= (\alpha^2 - \alpha + 1)/k
\end{aligned} \tag{18}$$

where

$$k = \alpha^2 + \alpha + 1 \tag{19}$$

Four known points are required to start calculations for the two stages of the filters. For consistency, the starting values used in equations (16) and (17) are given by

$$H_1 = H_2 = H_3 = H_4 = \overline{h} \tag{20}$$

$$F_1 = F_2 = F_3 = F_4 = \overline{h}$$

The filter described above can be used to separate waviness and roughness.

3.30 Instructions for Use

The input required for the statistical analysis program includes the name of the file in which surface height data are stored by the image matching software and, if an analysis of a filtered profile is required, the upper and lower cut-off frequencies for the filter.

4.0 GRAPHICS SOFTWARE MODULE (TASK 3)

The graphics software module has programs to draw a surface profile using the output from the image matching software and to draw a contour map for a surface. The core program used to draw contour maps is functional but has to be linked to the output from the image matching software.

The primary input required for drawing the surface profile is the name of the file in which the results from the image matching software are stored. The data are scanned to set the maximum and minimum values for the axes. The user can elect to connect data points with straight lines or to fit a cubic spline function through the data points. After drawing the surface profile, the user is prompted to input labels for the x and y axes.

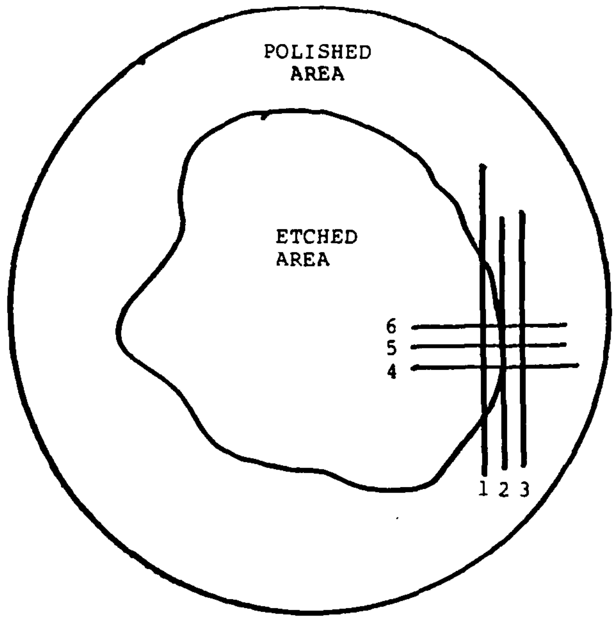
5.0 ADDITIONAL WORK DONE IN PHASE III

At the end of the second phase of the program, it was evident that the image matching software required modifications to enhance the reliability and the stability of the matching algorithm. The results of these changes are described in this section along with additional software developed to augment the capabilities of the surface measurement system.

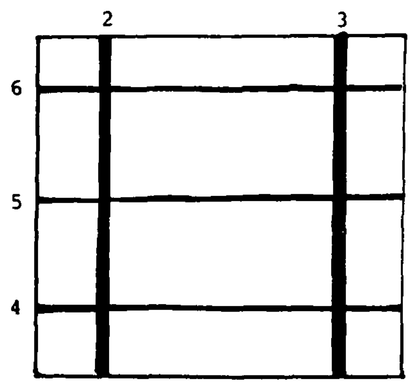
5.10 Improvements In Image Matching Software

The electropolished aluminum specimen used in the first two phases of the program was matched using the modified image matching software. A schematic of the specimen is shown in Figure 2 and the stereo-pair of digitized images are shown in Figure 3. A stylus trace in the region above grid line 6 is shown in Figure 4. The trace was obtained using a lightly loaded stylus with a tip radius of 2.5μm. The trace for the segment of the surface digitized was redrawn in Figure 5 to facilitate comparison with the results from the image matching software.

The image matching software was used to obtain the heights along grid lines 4, 5, and 6. The results for grid line 6 are shown in Figure 6. The heights are relative to the first point,

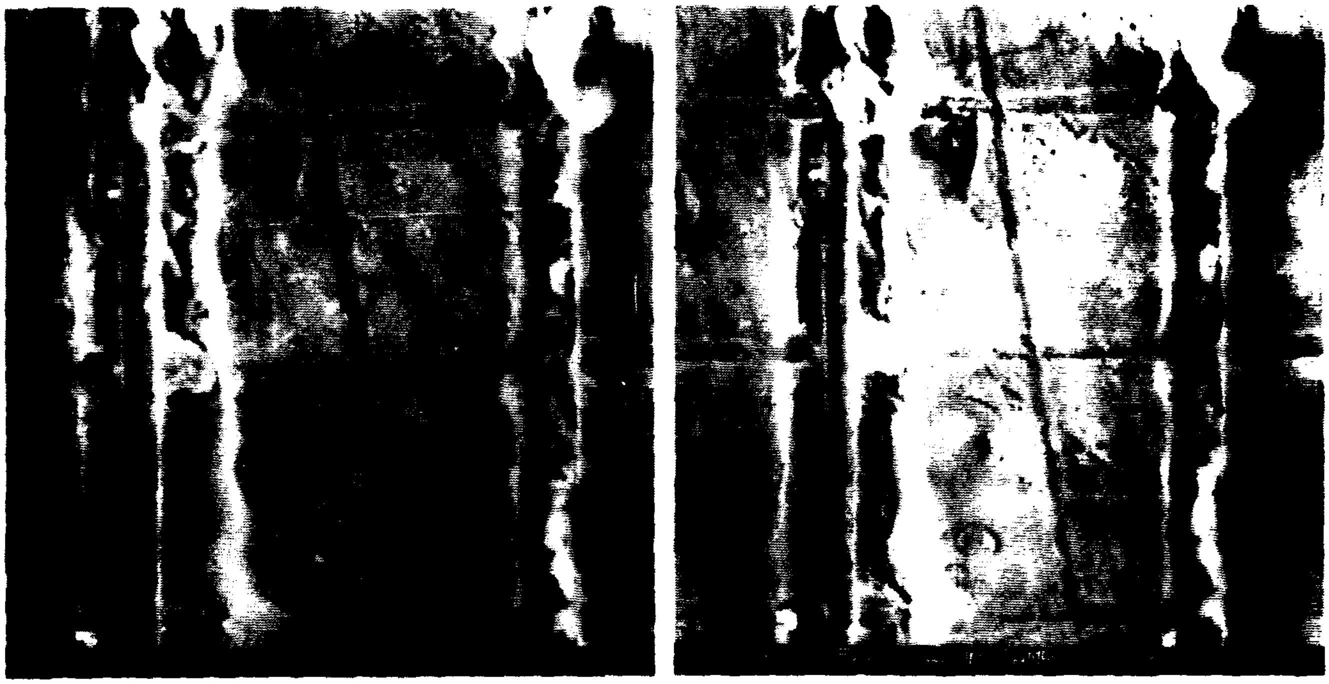


(a) Top View of Specimen



(b) Area Digitized

FIGURE 2: ELECTROPOLISHED ALUMINUM SPECIMEN



31.469° Tilt 40.485° Tilt

512 x 256 Pixels

FIGURE 3: STEREO PAIR OF DIGITIZED SEM IMAGES OF ELECTROPOLISHED ALUMINUM SPECIMEN

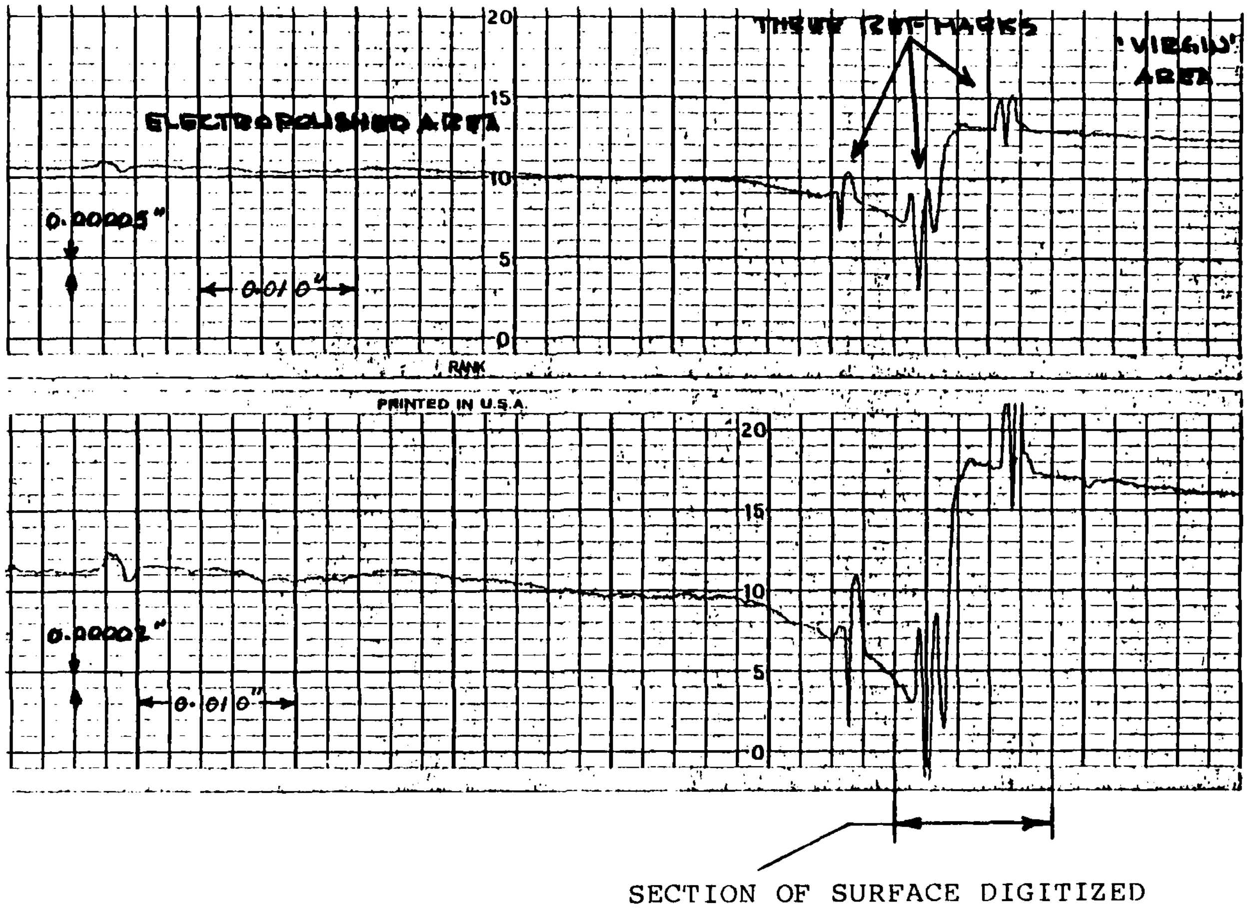


FIGURE 4: STYLUS TRACE USING TALYSURF IV
AND A 2.5 μm STYLUS

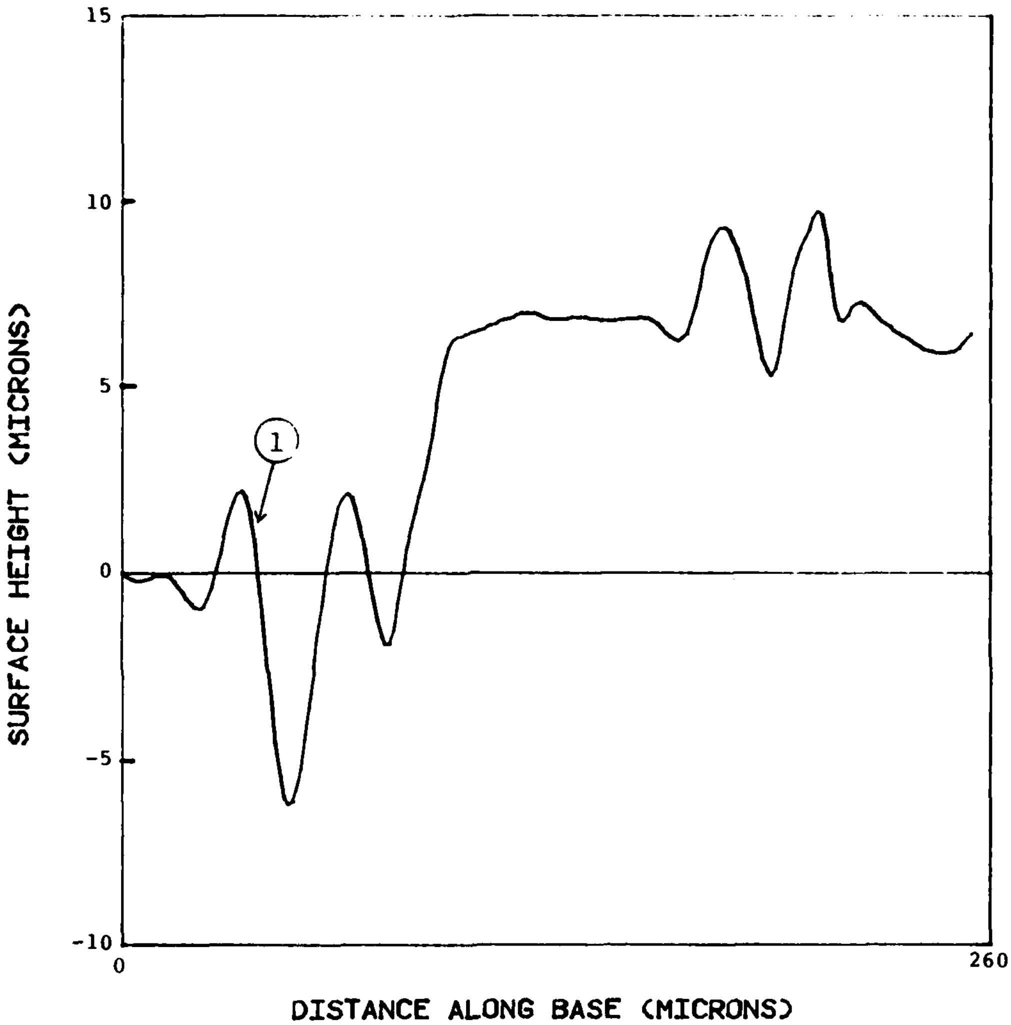


FIGURE 5: STYLUS TRACE REDRAWN FOR COMPARISON
WITH RESULTS FROM IMAGE MATCHING SOFTWARE

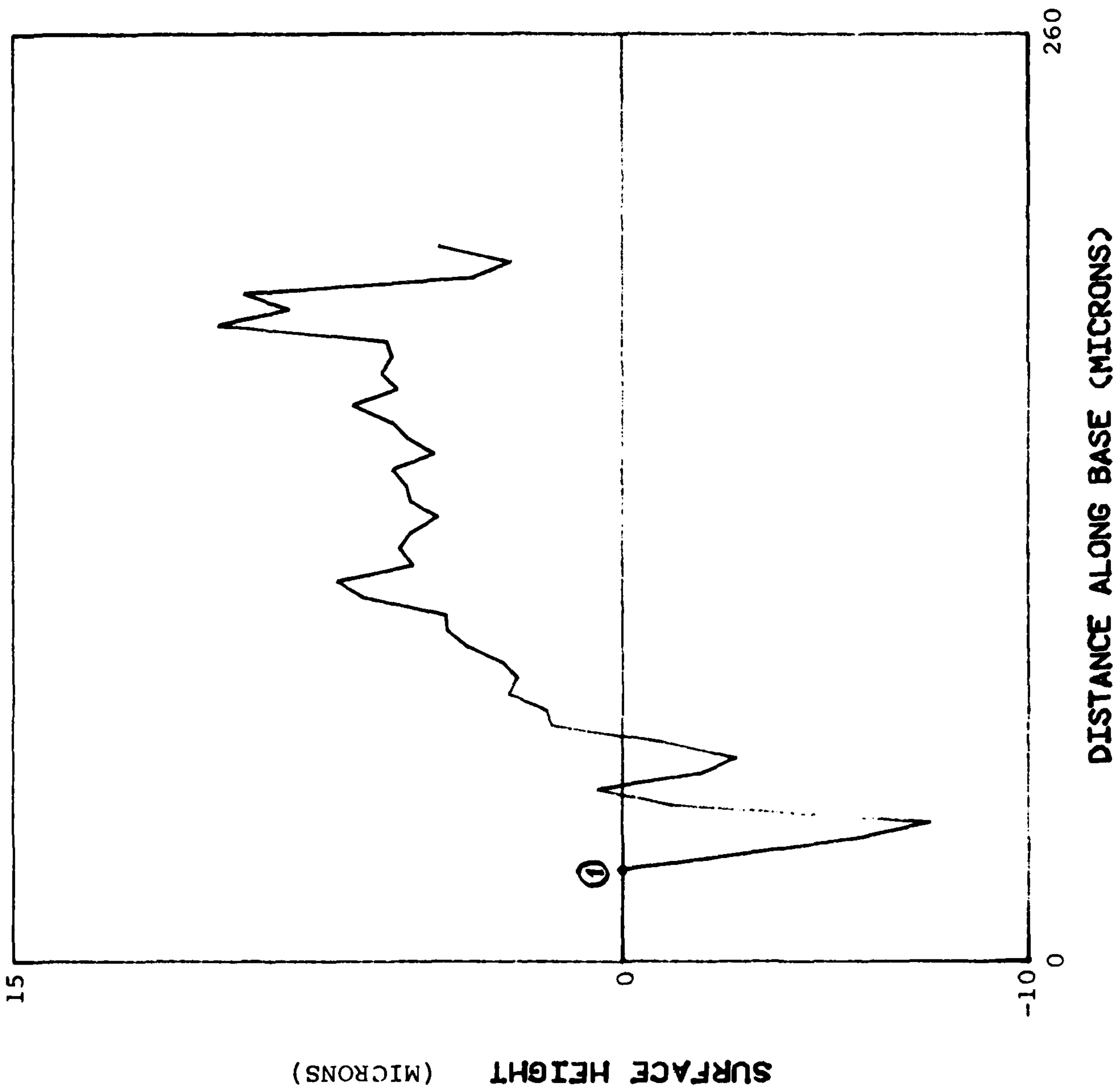


FIGURE 6: RESULTS FOR GRID LINE 6

labelled (1), matched by the software. When the traces in Figures 5 and 6 are overlaid with point (1) coincident, the results from the matching software are in good qualitative agreement with the stylus trace. 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.

The height measurements for grid lines 4 and 5 are shown in Figures 7 and 8, respectively.

The results for points along grid line 6 obtained at the end of Phase II are shown in Figure 9. The improvements in the performance of the image matching software are accentuated by a comparison between Figures 5, 6, and 9. The height of the electropolished step as measured in Phase I is compared in Table 1 with the results from image matching software. The results are in good agreement. The heights measured with the 25μm stylus are smaller than the other results because the stylus does not penetrate the narrow valleys on the surface and, hence, underestimates the peak-to-valley height of the step.

TABLE 1

COMPARISON OF HEIGHT MEASUREMENTS FROM PHASES I, II AND III

GRID LINE	STEP HEIGHT (μm)			
	HAND MEASUREMENTS*	25μm† STYLUS	2.5μm STYLUS	IMAGE MATCHING SOFTWARE
4	9.47	8.64	--	12.6
5	8.24	8.47	--	13.0
6	7.39	7.94	11.9	11.8

* Results from Phase I

† Results from Phase I using a heavily loaded stylus.

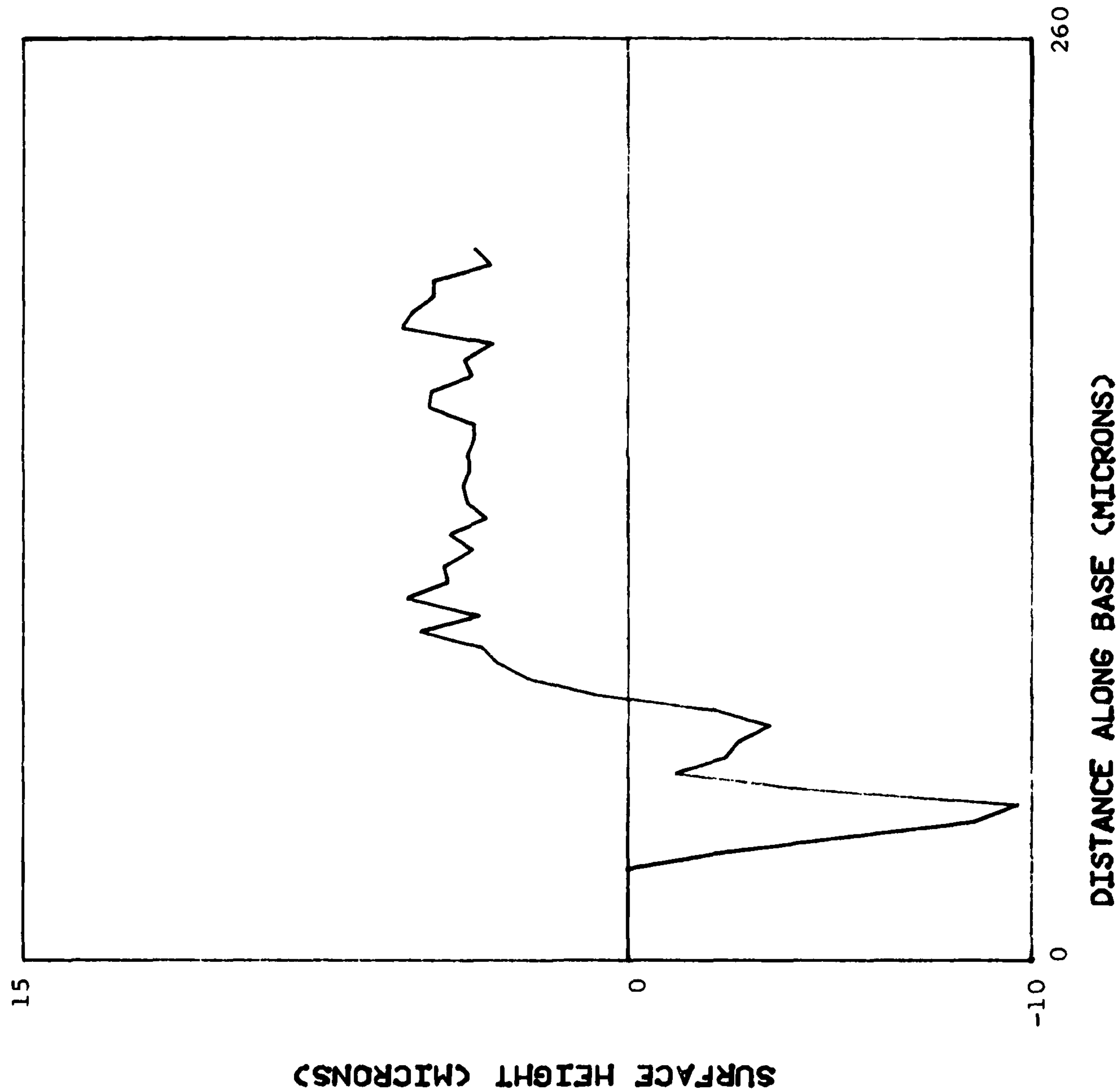


FIGURE 7: RESULTS FOR GRID LINE 4

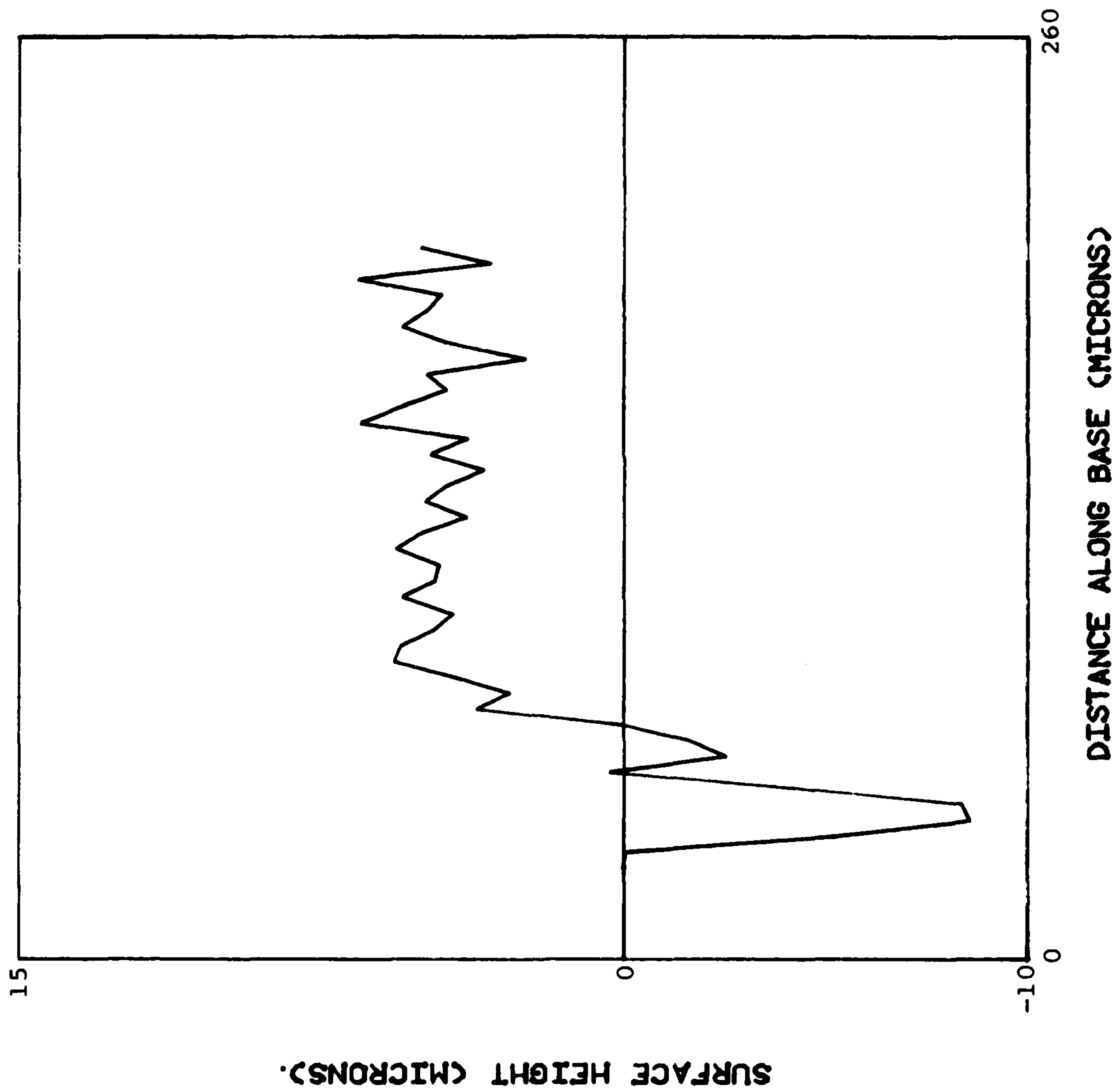
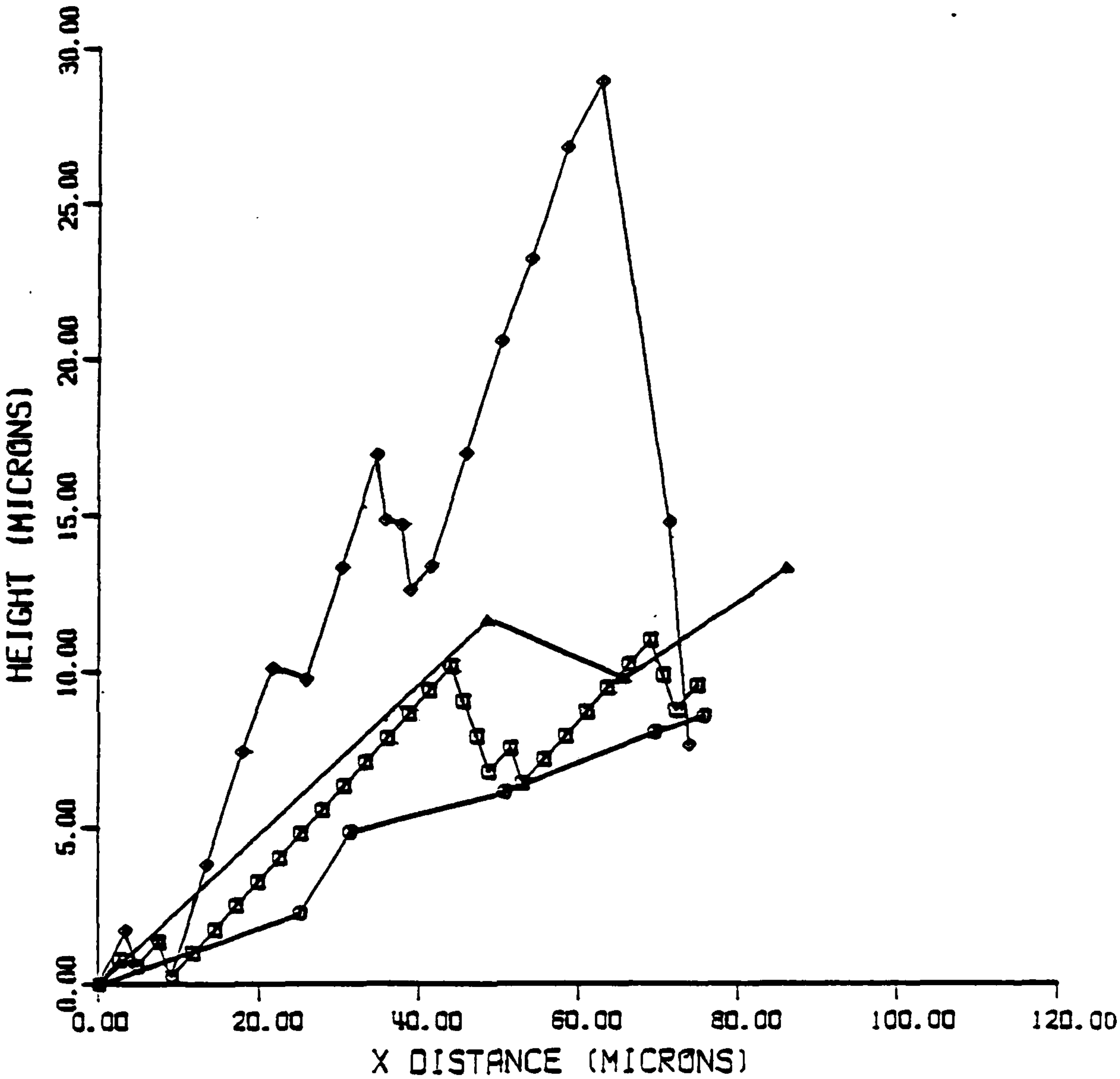


FIGURE 8: RESULTS FOR GRID LINE 5



⊙ - STYLUS MEASUREMENTS
▲ - HAND MEASUREMENTS
◇ - LINEAR CORRELATION $.6 < \partial u/\partial x < 1.4$
⊡ - LINEAR CORRELATION $.85 \leq \partial u/\partial x \leq 1.0$

FIGURE 9: RESULTS FOR GRID LINE 6 AT THE END OF PHASE II

5.20 Additional Capabilities

Use of the surface measurement system highlighted the need for some additional capabilities for the system. Some of these capabilities are described below.

5.21 Simulated Stylus Traces

The finite size of the tip of a stylus distorts the representation of the actual surface topography as shown in Figure 10. The extent of distortion is a function of the size of the stylus tip relative to the surface features being represented. A computer program was written to simulate the stylus trace which would result if a stylus of specified tip radius traversed a surface profile obtained from the image matching software. The program is based on the computer program SKARESIM [3] developed at SKF Industries to assess errors resulting from the finite size of the stylus tip and from the speed of the stylus.

The height of a point i in a discretized surface profile is denoted by h_i. The ordinate z_i of a simulated stylus trace at a point i in the profile is obtained by a search over the $(2n_R+1)$ points in the profile spanned by the tip of a stylus of radius R, where

$$n_R = \text{INTEGER}\ (R/\Delta x) \qquad (21)$$

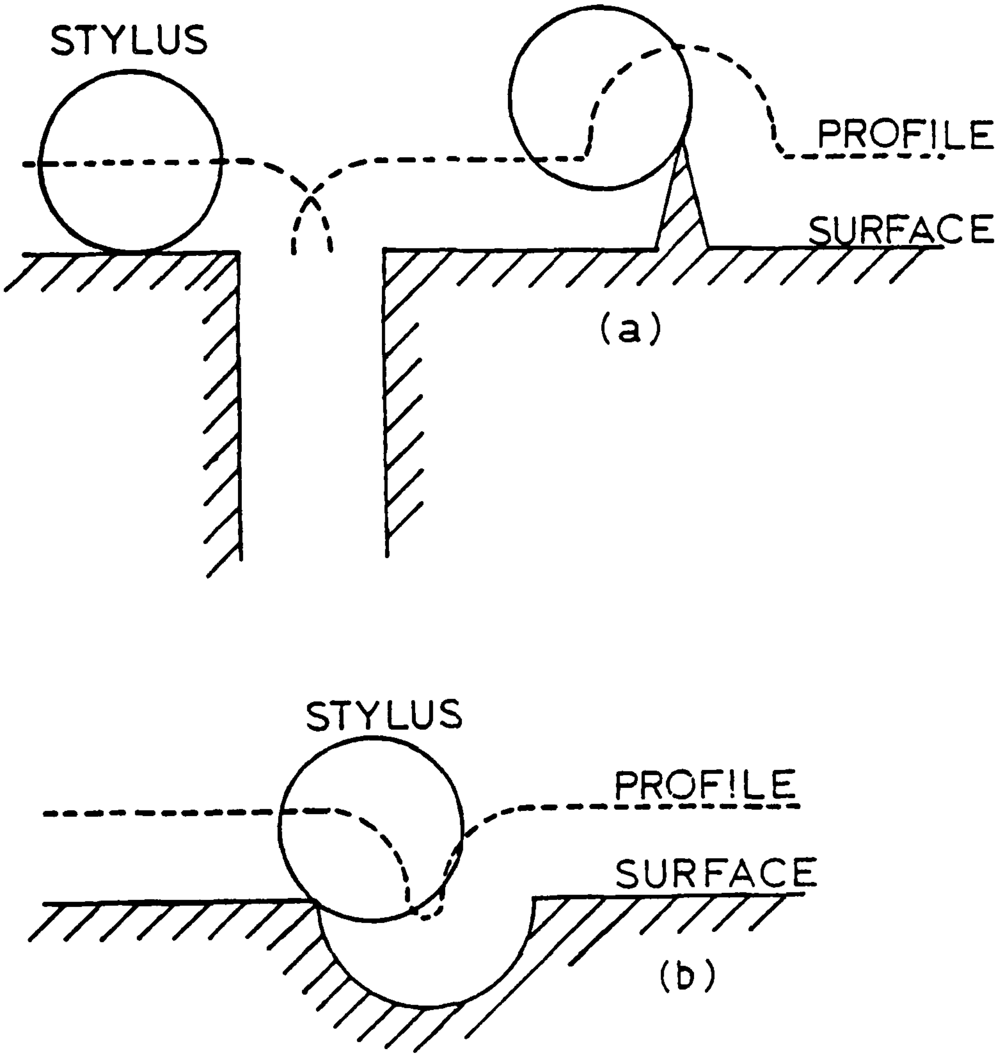


FIGURE 10: EFFECT OF FINITE SIZE OF THE STYLUS

(a) SHOWS THE RESPONSE TO A CRACK AND A SPIKE.

(b) SHOWS THE RESPONSE TO A VALLEY INTO WHICH THE STYLUS CAN PENETRATE.

and Δx is the distance between adjacent points in the profile. The ordinate z_i is the largest element in an array H_k given by

$$H_k = h_i + [R^2 - ((k-i)\Delta x)^2]^{1/2} \tag{22}$$

where the index k varies between the limits

$$i - n_R < k < i + n_R \tag{23}$$

The search is repeated at all points in the profile.

Simulated stylus traces for stylus tip radii of 5 and 10 µm are shown in Figure 11 and 12, respectively, along with the surface profile from the image matching software shown in Figure 6. The traces show clearly the reduction in the peak-to-valley height for the electropolished step as the stylus tip radius is increased.

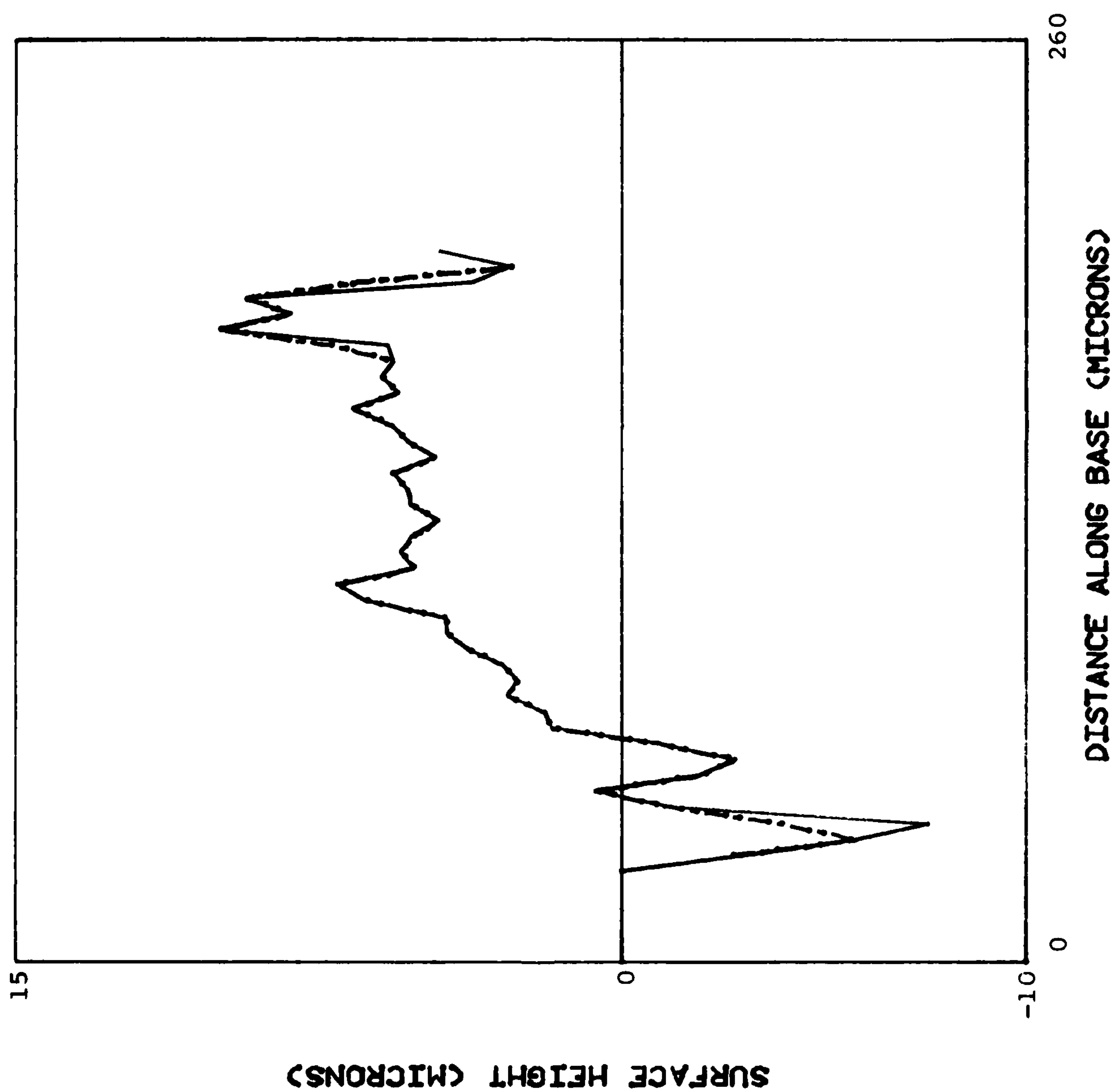


FIGURE 11: SIMULATED STYLUS TRACE FOR A 5μm STYLUS

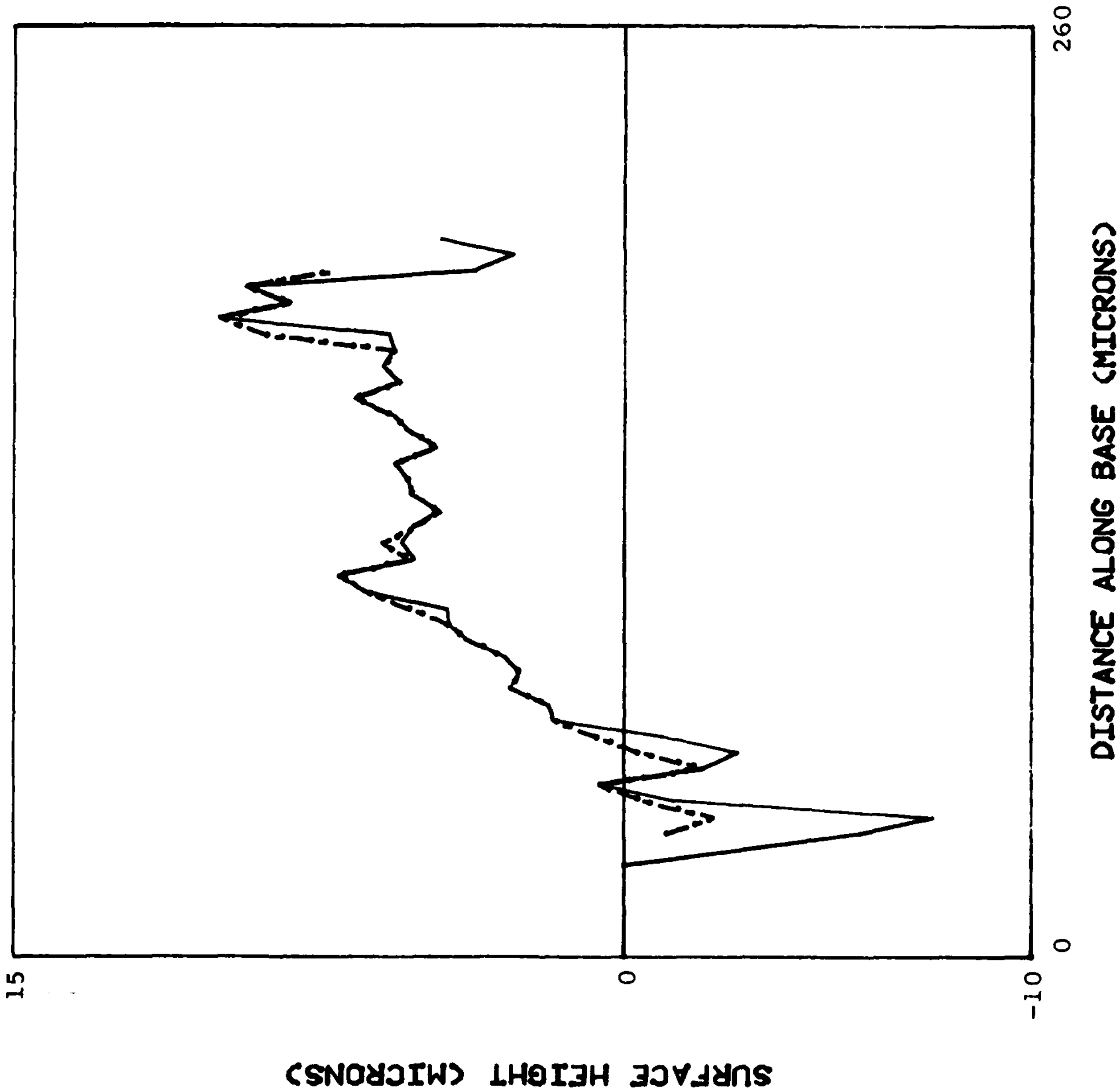


FIGURE 12: SIMULATED STYLUS TRACE FOR A 10 μm STYLUS

5.22 Stereo-Image Display Software

Program STEREO displays a pair of digitized SEM images on the same SEM view CRT and calculates the difference between the heights of a pair of points selected by the user. The images are displayed in a succession of strips; the size of each strip is determined by the computer memory available to the program. A cross-hair cursor is superimposed on each strip and is moved over the strip using the arrow function keys. The current location of the cursor is sent to the computer using the PF keys and is used to calculate the relative hight of the points selected. This section describes the rationale for the program and gives instructions for using the program.

A stereo-pair of digitized SEM images are obtained by tilting about the Y axis (see Figure 13). Therefore, the parallax due to surface topography is along the X axis only; the distances along the Y axis do not change. Calculation of the difference between the heights of two points on a line of contant Y requires the X coordinates of the points in both images of the stereo-pair. These points are labeled LEFT1, LEFT2, RIGHT1 and RIGHT2 in Figure 14. The height difference h_{12} is given by

$$h_{1-2} = C \frac{X_L \cos\alpha_R - X_R \cos\alpha_L}{\sin(\alpha_R - \alpha_L)} \ \mu m \qquad (24)$$

α_L is the angle of tilt for the left image, α_R the angle of tilt for the right image, X_L the distance between the points in the

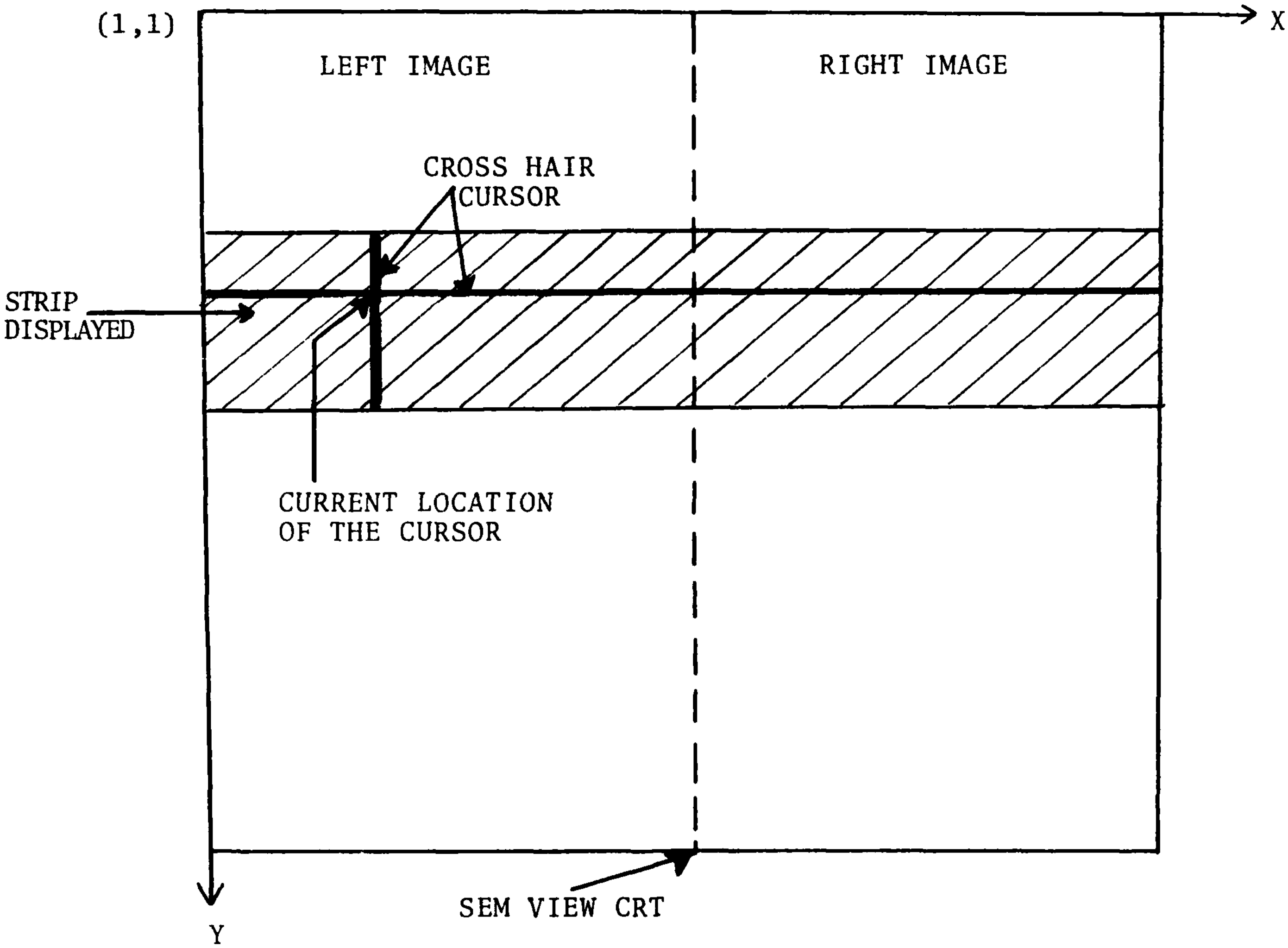


FIGURE 13: COORDINATE SYSTEM FOR THE IMAGES DISPLAYED ON THE SCREEN

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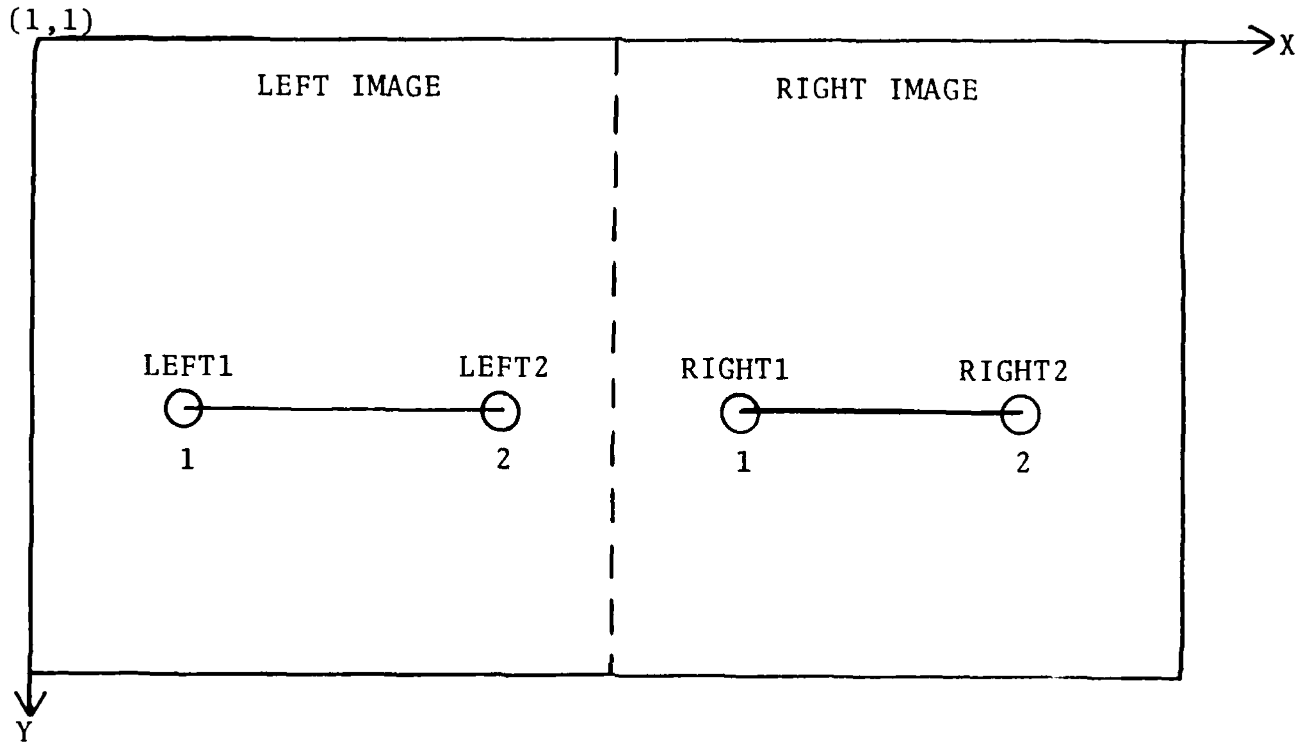

FIGURE 14: COORDINATES USED IN THE HEIGHT CALCULATIONS

left image, X_R the distance between the points in the right image, and C a conversion factor given by

$$C = \frac{88900}{M(N_x - 1)\cos\alpha_L} \ \mu m \tag{25}$$

where M is the magnification and N_x the number of pixels per row of the digitized image. Lengths X_L and X_R are given by

$$\begin{aligned} X_L &= XLEFT2 - XLEFT1 \\ X_R &= XRIGHT2 - XRIGHT1 \end{aligned} \tag{26}$$

Program STEREO calculates the height difference between pairs of points selected by the user. The procedure for using the program is described below.

The program prompts the user to input the names of the data files in which the digitized images are stored. This is the only input required of the user. After a short interval during which the data is read from the files, the menu shown in Figure 15 appears on the screen. The procedure to calculate the height difference between any two points, designated 1 and 2 (see Figure 14):

1) Use the arrow function keys to move the cursor to point 1 in the left image. Save the X coordinate location of the point by pressing the PF1 key. The coordinate of the point will be printed in the lower left hand corner of the screen for all PF keys.

USE THE ARROW FUNCTION KEYS TO MOVE THE CROSS-HAIR CURSOR
PRESS PF1 KEY TO SAVE LEFT1
PRESS PF2 KEY TO SAVE LEFT2
PRESS PF3 KEY TO SAVE RIGHT1
PRESS PF4 KEY TO SAVE RIGHT2
PRESS H KEY TO CALCULATE HEIGHT
PRESS N KEY TO DISPLAY THE NEXT STRIP

FIGURE 15: MENU FOR HEIGHT CALCULATIONS

2) Move the cursor to point 2 in the left image. Save the X coordinate of the point by pressing the PF2 key.

3) Move the cursor to point 1 in the right image and press the PF3 key to save the X coordinate of the point.

4) Move the cursor to point 2 in the right image and press the PF4 key to save the X coordinate of the point.

5) Press the H key to calculate the height difference between points 1 and 2. The height (in microns) of point 2 relative to point 1 will be printed in the lower left corner of the screen below the line in which the X coordinate is printed.

6) When all the points of interest in the strip being displayed have been measured, the next strip of the image is displayed by pressing the N key.

6.0 SUMMARY

The overall technical status of the three-phase program to develop a three-dimensional surface topography measurement system is summarized below. Suggestions for further development of the system are also provided.

6.10 Technical Status of the Program

The integration of software and hardware for digitizing SEM images has been completed. The integrated system reliability has been verified by experiments designed to check the quality and repeatability of digitized images. Procedures have been developed to obtain a stereo-pair of digitized SEM images suitable for processing by the image matching software. The system has the facilities for providing photographic reproductions of the digitized images stored on disc.

Image matching software has been developed to process a single strip from a stereo-pair of digitized SEM images. The complete surface can be mapped by processing a series of adjacent strips. At present, the matching algorithm is purely statistical and may falter in areas with very little contrast on areas with too much gray level information.

A statistical software module has been developed to calculate the following parameters for each strip matched by the image matching software:

- Arithmetic average roughness for the surface profile and the peak heights
- Root-mean-square roughness for the surface profile and the peak heights
- Skewness and kurtosis for the surface profile and the peak heights
- Maximum peak-to-valley roughness
- Average spacing of peaks
- Average peak curvature
- Histogram of surface heights
- Histogram of peak heights

The above parameters can be calculated for unprocessed height data or for a filtered surface profile. A cascaded band pass digital filter is included in the module.

Graphics software is available to draw the surface profile for the strip matched by the image matching software and to draw the stylus trace which would result if a stylus of specified radius traversed the surface. Software for drawing a contour map for a complete surface has been developed but has not been interfaced to the output from the image matching software.

6.20 Suggestions for Further Development

The three-dimensional surface measurement system developed in this program requires further development to be fashioned into a handy, reliable research instrument. The goal of the effort should be to quantitate the resolution and accuracy of the system and to develop adequate control algorithms to guide the image matching software through areas that are hard to match. The system should be used to match well defined specimens to determine its resolution and accuracy. A wide range of engineering surfaces should then be matched to accumulate empirical data on control strategies required to match images: the data base can then be used to develop control algorithms for the image matching software.

Some effort should also be directed towards the development of image processing software for the system. A number of engineering surfaces yield SEM images with poor contrast. Contrast enhancement software could be used to improve contrast and improve the performance of the image matching software. At the other extreme, too much gray level information in the image can defeat the image matching algorithm. Fourier analysis could be used to filter out the high frequency variations in the gray level in a manner similar to the filters used in stylus instruments to separate waviness and roughness.

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