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A System for Computerized Surface Roughness Measurement

Dennis A. Swyt

Institute for Basic Standards
National Bureau of Standards
Washington, D. C. 20234

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Final Report

U. S. DEPARTMENT OF COMMERCE

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A SYSTEM FOR COMPUTERIZED SURFACE ROUGHNESS MEASUREMENT

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Introduction

Prior to the development of the system to be described, the available basis for calibrations by NBS of roughness specimens for industrial consumers was by means of comparisons with a roughness master. The values assigned to the master involved single displacement calibrations of stylus instruments and hand calculations from planimeter measurements of surface profiles. The overall method has several limitations. Individual calibrations are referred to the historical values of roughness assigned to a unique artifact which is subject to loss, damage and deterioration with ordinary use. AA values, indicated on an integrating meter, are only accurate to 3% of full scale, cannot be displayed digitally, and must be subjectively interpolated between scale divisions. To eliminate these difficulties, a new system has been developed. At present, an Interdata 3 Minicomputer has been fully interfaced with a Talysurf 4 Stylus instrument. The completely operational system offers:

(1) instrument calibration at each use by means of interferometrically measured gage block steps;

(2) considerably more accurate AA values, computer-calculated for arbitrary specimens;

(3) computer-calculated thin film thicknesses;

(4) precise, digital print-out of measurement results in permanent record format;

(5) access to punched tape surface profile data which may be analyzed by a larger, faster computer to yield further information, e.g. peak height and roughness wavelength distributions.

Scheduled to be completed before the end of FY 1973 are:

(1) a complete determination of the dynamic operating characteristics of the entire system;

(2) the development of a range of interferometrically measured thin-film and gage-block steps;

(3) a changeover of surface roughness calibration services from those based on a roughness artifact to the new system;

(4) the introduction of thin-film thicknesses measurement services based in part on the computerized stylus instrument system.

Data Acquisition*

The means by which topographical profiles are converted to surface roughness data is represented by the functional schematic in figure 1. When the stylus is traversed across a surface, the profile is indicated on the strip chart recorder; the signal driving the recorder, amplified and filtered, appears at the analog-to-digital converter (A/D).

At a particular point in the stroke, the stylus arm activates a relay, which in turn generates two pulses. The first pulse, one second long, appears at the common input of the recorder and interface amplifier. (The source of the event pulse is in the information channel only for the duration of the pulse). Coincident with the leading edge of the event pulse is a fifty-microsecond interrupt pulse to the A/D converter. On receipt of the interrupt at the A/D, a programmed one-second delay is executed, and the analog signal at the filter output is converted to binary data points and stored sequentially in computer memory. (Thus the event mark, recorded on the strip chart, does not appear in the digital data). The results of the computer analysis of the stored data are output to the Teletype, Model 33.

Data Analysis of Step Heights

In order to efficiently handle the discontinuity in the trace which comprises the step height and to eliminate restrictions on the alignment of the step artifact, a mathematical model of the step data in the computer memory has been devised. Figure 2a represents a general step profile in which the traces on opposite sides of the discontinuity are wavy and parallel neither to each other nor to the sides of the strip chart.

Linear least-squares curves are fitted to the segments designated by L1 and L2 in figure 2b (appendix A); the segments are located at

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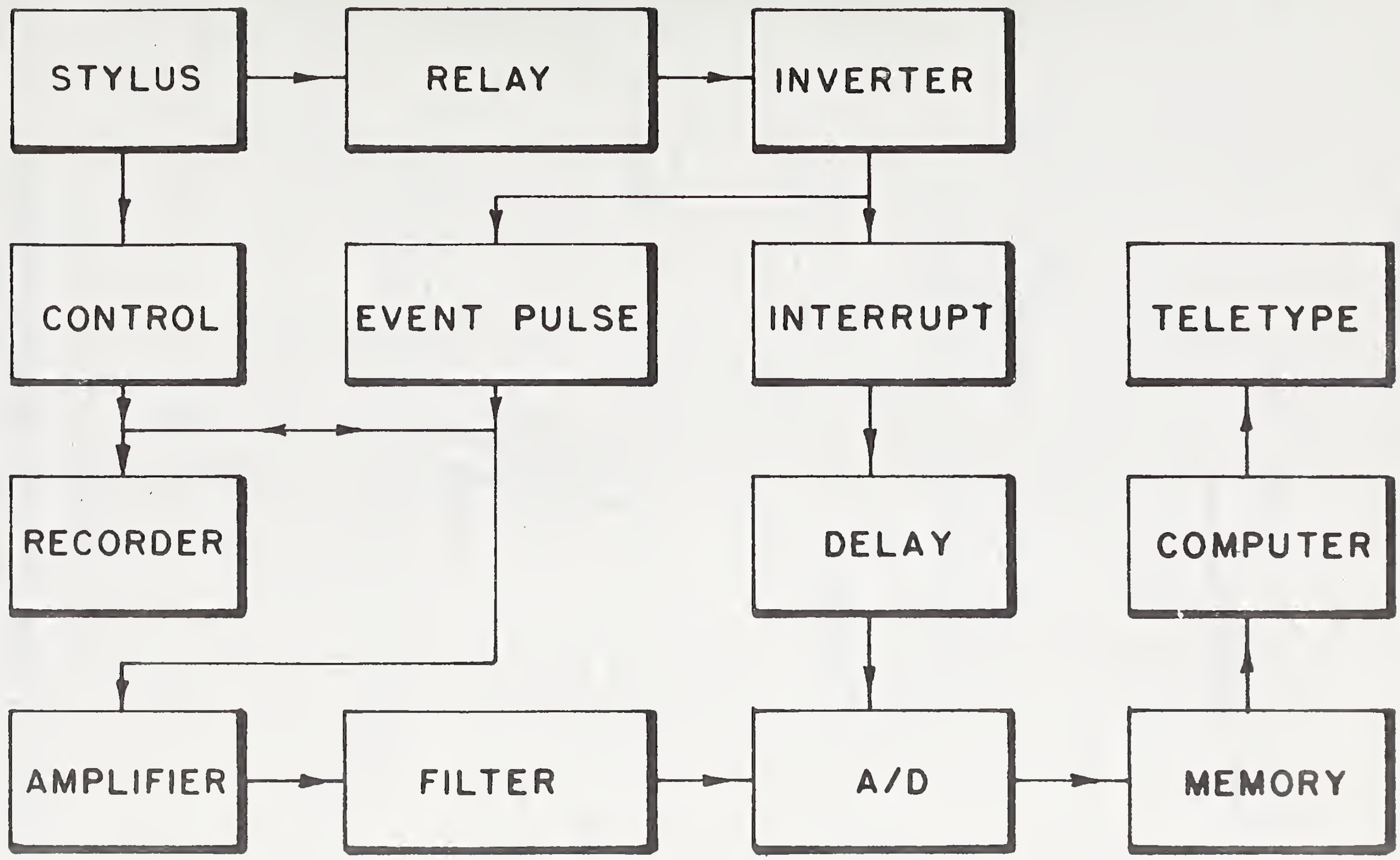
*Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.



FUNCTION DIAGRAM OF TALYSURF/INTERDATA SYSTEM

FIGURE 1

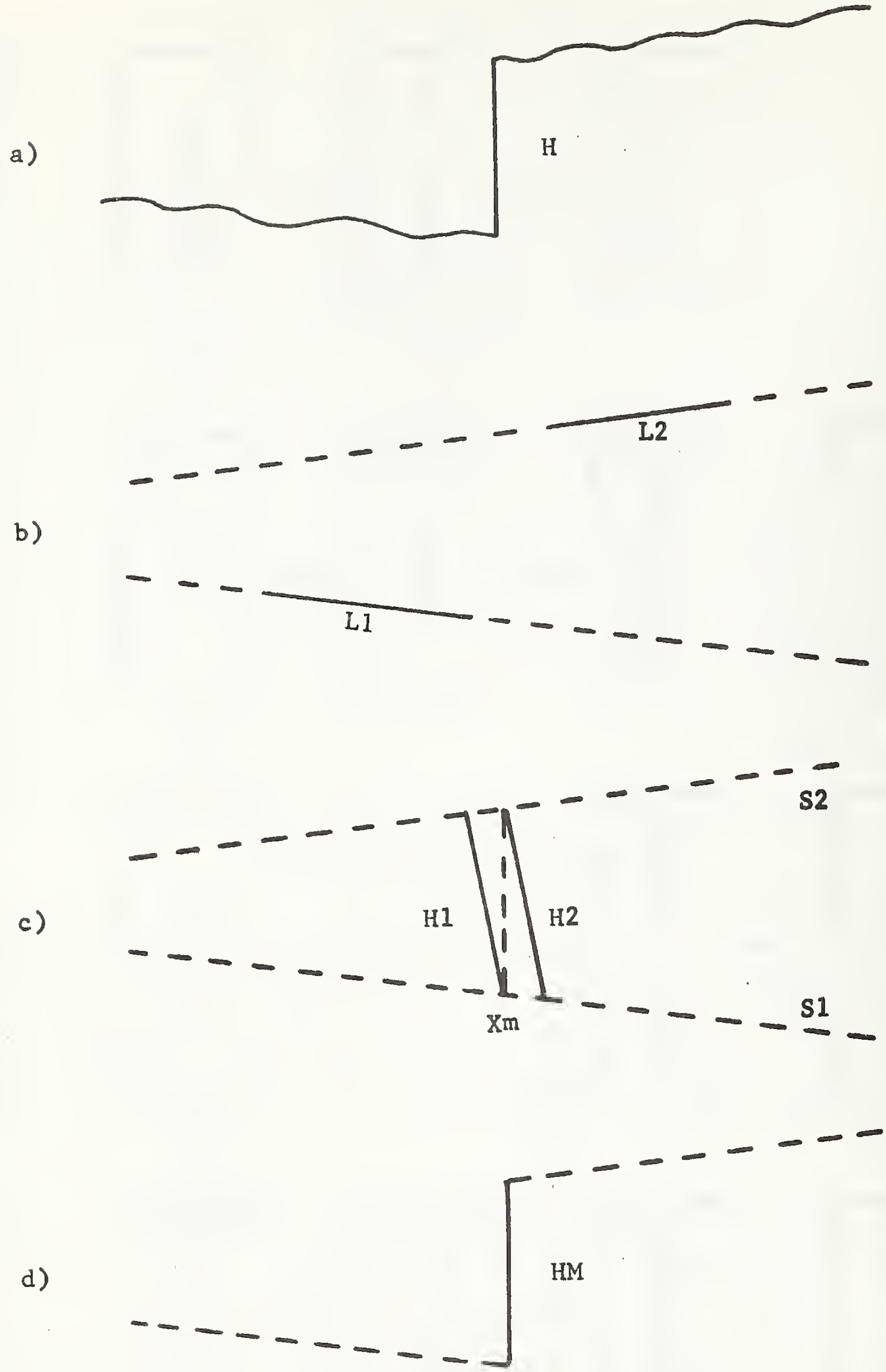


FIGURE 2 . STEP HEIGHT CALCULATION

a) Step Profile Input
b) Linear Least Squares Line Segments
c) Perpendicular Distances at X_m between the Two Lines
d) Mean Distance of Step Height

the operator's discretion relative to the event mark (appendix B), are of equal lengths and constitute one-half of the total trace. From the slopes and intercepts of the two computed lines, S1 and S2 in figure 2c, are calculated the distances H1 and H2 (appendices C and D); the two heights are the perpendicular distances from the points on each line, having the coordinate xm, to the opposite lines. The distance HM in figure 2d is the arithmetic mean of H1 and H2.

Data Analysis of Surface Roughnesses

The AA roughness for a surface profile is computed from the data in memory in a manner analogous to the operation of an integrating meter. Since the profile signal has wavelength cut-off restrictions imposed by analog filtering (appendix E), no digital filtering or signal conditioning is involved. The value corresponding to the center line of the profile is the arithmetic average of all points in the record. The AA value is the arithmetic average of the magnitudes of the deviations of each point from the mean.

Calibration of Step Heights and AA Values

When the binary HM value of the calibration step profile has been computed and the decimal Ho value of the interferometrically measured calibration step entered at the Teletype, a conversion constant, KCAL, is computed:

$$KCAL = Ho\ (\text{decimal})/HM\ (\text{binary}).$$

The calibrated values of unknown steps and surface roughnesses are then of the form:

$$HM\ (decimal) = HM\ (binary) \times KCAL$$

and

$$AA\ (decimal) = AA\ (binary) \times KCAL.$$

Program Operations

An example of a calibration, wherein an unknown step and roughness are measured, may be illustrative. A sample Teletype output is given in figure 3. Further details appear in appendix F.

After an appropriate magnification has been selected, the corresponding gage block step is aligned on the Talysurf and program execution begun. At the proper point in the program, the operator is informed at the teletype to begin the stylus stroke in order to enter the calibration step profile. In this case, a 50 microinch step at 20,000 mangification produces a one-inch displacement on the chart and a one-volt output to the amplifier. The signal is amplified by 10, filtered (appendix E), converted to 512 twelve-bit data points over a 25 second record length and stored in memory. The operator is then instructed to enter HO, the measured value of the gage block step, at the teletype; this four decimal-digit number is converted to binary and stored. The operator now enters the information at the teletype which locates the step discontinuity in the stored data; the information is derived from the chart trace and the step locator chart (appendix B).

The step height is computed, converted to decimal and printed; the printed calibration step height HM should conform within tolerances

```
OE002
      STEP/SURFACE ROUGHNESS CALIBRATION

ENTER DATA/ IN ENTER HO 9014 ENTER UNITS TU ENTER A1 118A ENTER A2 1214
H1       H2       HO       UNITS
00009014 00009014 00009014 TU       MORE? Y H OR R? H
ENTER DATA/ IN ENTER HO  ENTER UNITS TU ENTER A1 118A ENTER A2 1214
H1       H2       HO       UNITS
00008993 00008993 00008993 TU       MORE? Y H OR R? H
ENTER DATA/ IN ENTER HO  ENTER UNITS TU ENTER A1 118A ENTER A2 1214
H1       H2       HO       UNITS
00008998 00008998 00008998 TU       MORE? Y H OR R? H
ENTER DATA/ IN ENTER HO  ENTER UNITS TU ENTER A1 118A ENTER A2 1214
H1       H2       HO       UNITS
00009015 00009015 00009015 TU       MORE? Y H OR R? H
ENTER DATA/ IN ENTER HO  ENTER UNITS TU ENTER A1 118A ENTER A2 1214
H1       H2       HO       UNITS
00009009 00009009 00009009 TU       MORE? Y H OR R? H
ENTER DATA/ IN ENTER HO  ENTER UNITS TU ENTER A1 118A ENTER A2 1214
H1       H2       HO       UNITS
00009013 00009013 00009013 TU       MORE? Y H OR R? R ENTER DATA/ IN
AA       UNITS
00001214 TU
00001217
00001213
00001205
00001211
00001202
                                     MORE? Y H OR R? R ENTER DATA/ IN
AA       UNITS
00001204 TU
00001208
00001210
00001213
00001206
00001208
                                     MORE? Y H OR R? R ENTER DATA/ IN
AA       UNITS
00001202 TU
00001205
00001199
00001201
00001204
00001209
                                     MORE? Y H OR R? R ENTER DATA/ IN
AA       UNITS
00001212 TU
00001201
00001210
00001208
00001207
00001204
                                     MORE? N FINI
```

FIGURE 3

>

the HO previously entered.

The operator now aligns the specimen to be measured on the stylus instrument. On being queried at the Teletype, the operator indicates the type of artifact. If it is a step, an H is entered and the procedure for entering a step profile repeated. If a roughness is to be measured, the proper filter cut-off and stroke speeds are selected, an R entered at the teletype and the stroke begun. The computer calculates either a step height or roughness AA, prints the result, and asks if more measurements are to be made from the same calibration. If more are to be made, a Y is entered at the teletype and the measurement of the unknown as described in this paragraph repeated. If no more measurements or those at a different magnification are to be made, an N is entered and the program is terminated.

A rough timetable for the program operation is given in table 1.

The AA Calculation and the ANSI Standard

The AA roughness value of a surface profile is defined as the arithmetic average deviation from the center line; the center line in turn is defined by the ANSI B46.1 standard as "the line parallel to the general direction of the profile within the limits of the roughness width cut-off, such that the sums of the areas contained between it and those parts which lie on either side of it are equal".

The specific details involved in the implementation of these definitions in the operation of analog or digital devices are not delineated in the standard. While band-pass characteristics in

Time Study of Measurement Procedure: Step

Operator Function:	Machine Function:
Align Calibration Artifact; Begin Program (5 min.)	
	Input Step Data (0.5 min.)
Select A1 and A2 from Chart & Scale, enter (1 min.)	
	Compute Step Height (0.25) min.)
Align Unknown Step (5 min.)	
	Input Step Data (0.5 min.)
Select A1 & A2 from Chart & Scale, enter (1 min.)	
	Compute Unknown; Exit (0.25 min.)
Operator Function Time (12 min.)	Machine Function Time (1.5 min.)

Total Time

13.5 min.

Table 1

Time Study of Measurement Procedure: Roughness

Operator Function	Machine Function
Align Calibration Artifact; Begin Program (5 min.)	
	Input Step Data (0.5 min.)
Select A1 and A2 from Chart & Scale; Enter (1 min.)	
	Compute Step Height (0.25 min)
Align Unknown Roughness (5 min.)	
	Input Roughness Data (0.05 min.)
	Compute AA; Exit (0.25 min.)
Operator Function Time (11 min.)	Machine Function Time (1 min.)

Total Time

12 min.

terms of half-power points and roll-off rates are specified, the exact nature of center-line, to which a profile is instantaneously referenced, is not clearly specified (again see appendix E for filter characteristics).

In the operation of an integrating-meter stylus instrument, the filtered signal represents the surface profile with wavelength cut-off restrictions imposed. The continuous analog computations of the center line and average deviation from the center line are made by integrating circuitry. Specifically, the stylus instrument stroke is begun and the resulting signal integrated to establish a center-line; at a particular point in the stroke, the instantaneous signal is compared to the established center line and the magnitude of the difference integrated for the remaining length of the stroke. Mathematically, the operation corresponds to the integral:

$$AA = \frac{1}{T_3 - T_2} \int_{T_2}^{T_3} \left[\mathrm{Abs}\ \left(f(t) - \frac{1}{t - T_1} \int_{T_1}^{t} f(t')dt'\right) \right] dt.$$

This equation reflects the necessity in an analog device of comparing the instantaneous signal to a center line which does not bracket the signal, but rather represents a segment of the profile of which the signal is the trailing edge.

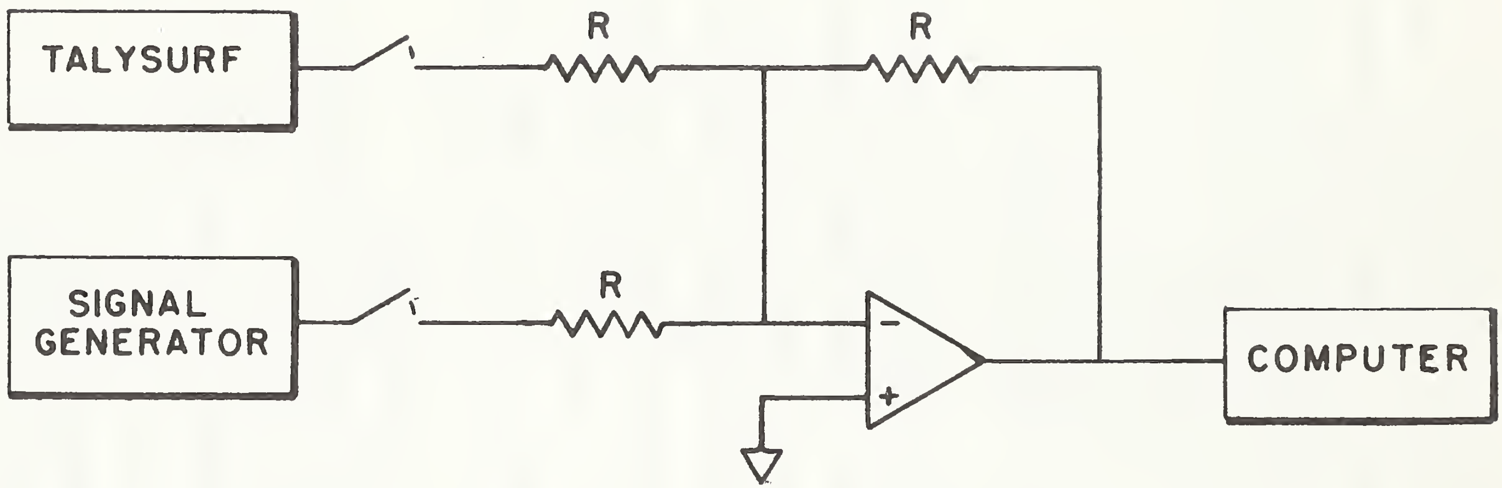
In the operation of the present digital system, the filtered signal is digitized and stored in the computer memory; the conversion rate (1.64 kHZ) is sufficiently high to reproduce the analog information in the filter bandpass (f_c = 300 HZ) with no loss of fidelity. The record length of the data corresponds to five wavelength cut-off widths. Since wavelength cut-off restrictions have been imposed on the signal by filtering, the center line is computed over the record length. Mathematically, the operation corresponds to the integral:

$$AA = \frac{1}{T} \int_0^T \left[\mathrm{Abs}\ \left(f(t) - \frac{1}{T} \int_0^T f(t')dt'\right) \right] dt.$$

Although the mathematical descriptions of the analog and digital computations differ, it is believed that the digital computations are in accord with the present ANSI B46.1 surface texture standard, in terms of the fundamental definitions of AA and the center line. Since the effective center line is computed as the mean over the record length and the record width is five times the cut-off width, the effect of a fractional roughness wavelength in the record length is greatly diminished.

<u>Noise Effect in AA Measurements</u>

It is known that measurements of ultrafine finishes are limited in accuracy by the inherent noise level of the stylus instrument itself. The specific effect of this noise has been established by a study of the computer measured AA values as a function of the signal-to-noise ratio. The experimental set-up is shown in figure 4. An operational amplifier was employed as an inverting adder without



NOISE EFFECT MEASUREMENT

FIGURE 4

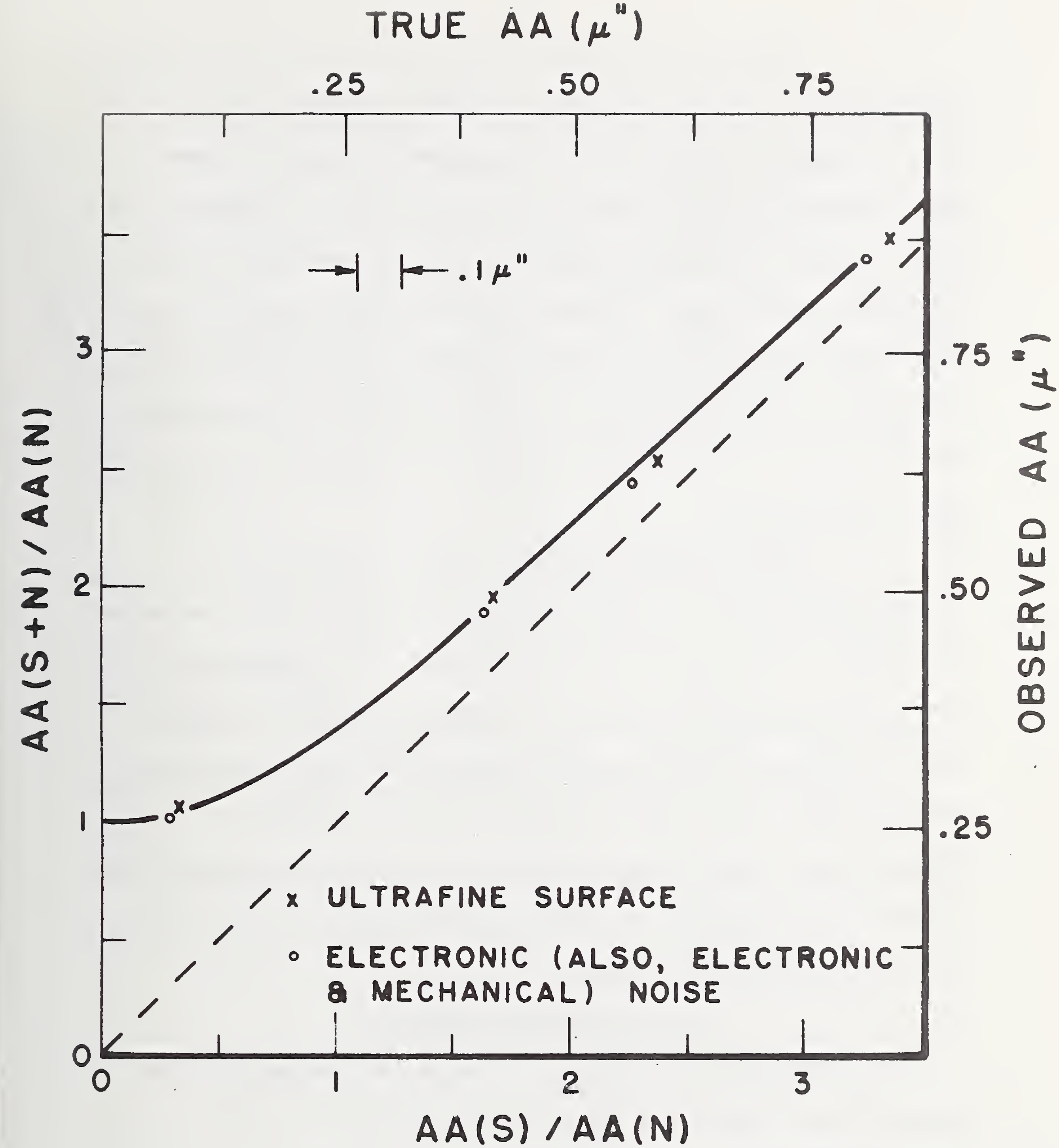

TRUE AA (μ")
.25
.50
.75
$\to| \quad |\leftarrow .1\mu$"
3
2
1
0
.75
.50
.25
OBSERVED AA (μ")
AA(S+N)/AA(N)
x ULTRAFINE SURFACE
o ELECTRONIC (ALSO, ELECTRONIC & MECHANICAL) NOISE
0
1
2
3
AA(S)/AA(N)

FIGURE 5

weighting. The apparatus allowed the stylus instrument output to be measured separately and combined with a measured signal. Measurements were made of the inherent electronic noise in the system (with the stylus stationary), the mechanical and electronic noise (stylus resting on a plane which traversed with the stylus), and the stylus output while traversing an ultrafine surface (a float-formed glass substrate). The results for each case, normalized to the zero signal input level, are indicated in figure 5. The smooth curve represents the equation:

$$\text{Signal Output} = [(\text{Signal Input})^2 + (\text{Noise})^2]^{1/2}.$$

The actual "noise" levels associated with the three cases above indicated: (1) an electronic noise of .13μ", (2) a mechanical and electronic noise of .16μ" and (3) a probable minimum AA reading of .25μ". It has not been determined what portion of the minimum AA reading is due to the highly polished surface. Therefore, it is assumed that the full minimum reading is due to the instrument; thus, the total inherent noise is taken to be .25μ" and its effect on AA readings is also shown in figure 5.

Partial Estimate of Accuracy

The elements which contribute to the overall accuracy of the roughness measurements are manifold; they include the accuracy of the interferometry measurement of the calibration step, the transfer characteristics of the stylus instrument and interface hardware, the computational precision of the software, the suitability of the mathematical models, and the noise levels in the system.

In table 2, the contributions of the operating characteristics of the interface hardware (amplifier, filter and A/D converter) are itemized; the total error in the signal due to the interface is estimated to be .15%. The uncertainty in the computation of the AA values due to the intermediate calculations of the calibration step height, calibration constant and AA values, is considered to be .075%. The sum of the effects of the interface and computation is, therefore, about .25%, as indicated by Δ(comp) in table 2.

The uncertainty in the interferometric measurements of the gage block steps is $\pm$ 1 microinch. The corresponding percentage uncertainties, Δ (cal), range from 5% to .025% for the different magnifications involved.

Finally, a constant noise level of about .25 microinches contributes uncertainties at different magnifications ranging from 170 to 0%.

The effect on the observed AA values of incremental changes in the calibration, computation and noise levels appears as:

$$AA(obs) = (1 + \Delta\ (cal))(1 + \Delta\ (comp))\ \sqrt{AA\ (true)^2 + N^2},$$

which leads to the first order uncertainty in the AA values given by:

$$\Delta AA = AA\ [|\Delta\ (cal)| + |\Delta\ (comp)| + |\Delta\ (N)|]$$

where

$$\Delta N = (1 + (\frac{N}{AA})^2)^{1/2} - 1.$$

The uncertainty of the AA measurements (exclusive of styluspreamplifier response) as indicated in table 3 is shown in the graph of figure 6. The curve indicates accuracies for the standard 20 and 120 microinch patches of $\pm$ .2 and $\pm$ .4 microinches, respectively. These partial estimates of accuracy correspond to uncertainties of $\pm$ 1.2 and $\pm$ 12.0 for integrating meter readings of the stylus instrument and $\pm$ 2.04 and $\pm$ 0.93 for the round-robin determinations of the NBS master artifact; a comparison summary of these results appears in table 4.

Preliminary Results

Trial measurements of the round-robin calibrated artifact, designated NBS-1, have been made on the nominal 20 and 125 microinch patches. The roughnesses were measured at least four times at each of five different locations on each of the two masked regions of the patches. The results, including 3σ values, are given in table 5. A general summary, including the estimate of accuracies of individual readings based on figure 6 and including the results of the round-robin calibration, appear in table 6.

Some interesting effects are indicated in tables 5 and 6. First, the reproducibility of readings at individual scan locations is not significantly different than the reproducibility of readings for the masked regions of the patch; i.e.,

$$3\sigma \text{ (scan)} \approx 3\sigma \text{ (patch)}.$$

This result may indicate an important contribution of stylus response to overall accuracy. Second, the results of the computer AA values and

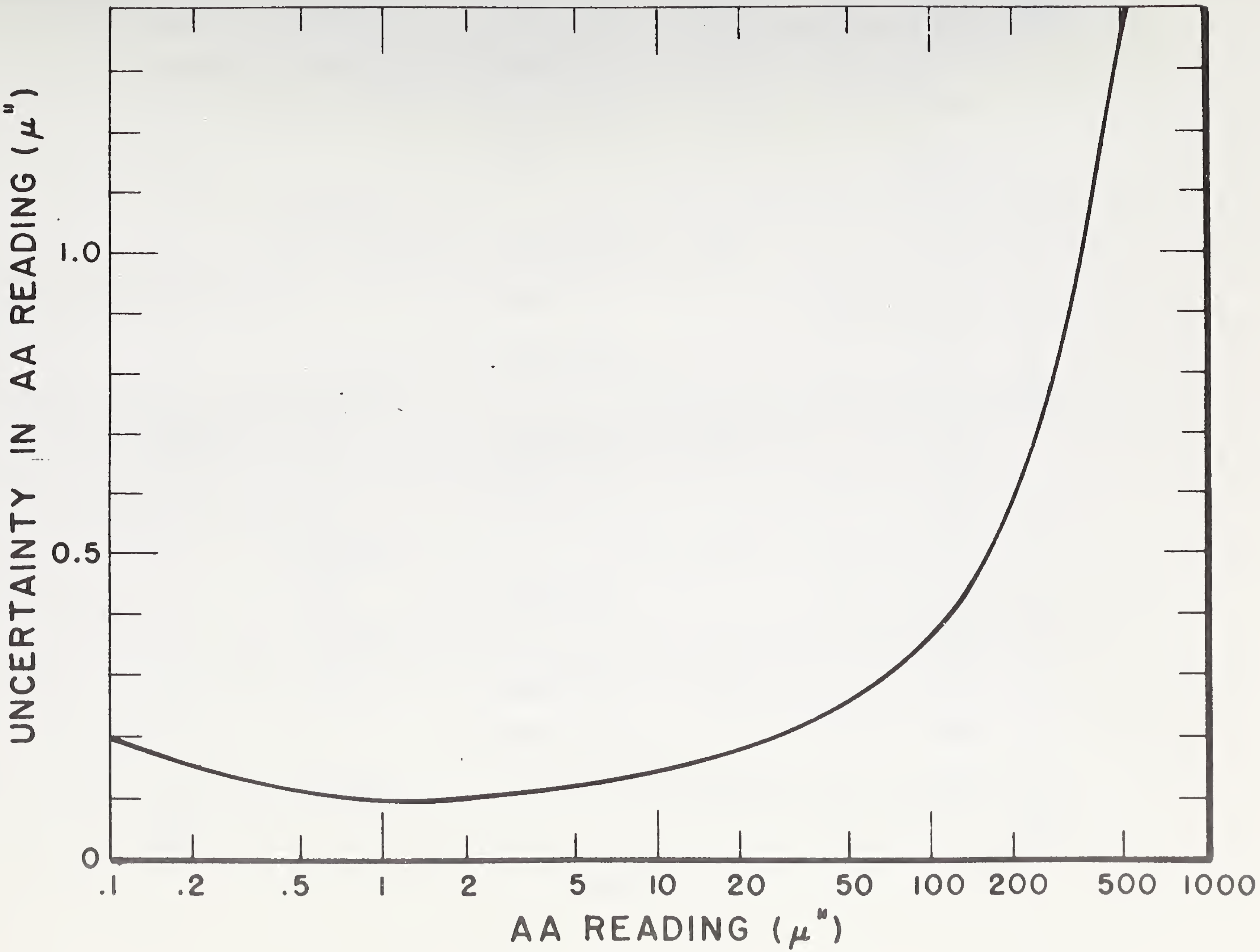

UNCERTAINTY IN AA READING (μ")
1.0
0.5
0
.1
.2
.5
1
2
5
10
20
50
100
200
500
1000
AA READING (μ")

FIGURE 6

System	Component	Contribution	Factor	Bits	%FS	Total
Hardware	Interface	Linearity	.02%		.020	
		Filter Ripple	.01 db		.100	
		Noise	.5 mv		.005	
	Subtotal		------		.125	
	A/D Converter	Linearity	.010		.010	
		Noise		I 1/2	.005	
		Resolution		1	.025	
	Subtotal		-----		.025	.150
Software	Step	Conformity	.025		.025	
		Computation		32	.000	
	Subtotal		-----		.025	
	KCAL	Computation		14	.025	
	Subtotal		-----		.025	
	AA	Conformity	.025		.025	
		Computation		32	.000	
	Subtotal		-----		.025	.075
Sum						.225

Table 2

Magnification	AA(μ")	Δ (Cal)	Δ (Comp)	Δ (noise)	Δ Total	Δμ"
100,000	0.1	± 5.00	± 0.25	169.25	174.50	.20
100,000	0.2	± 5.0	± 0.25	60.25	65.5	.15
100,000	0.5	± 5.0	± 0.25	11.75	17.00	.10
100,000	1.0	± 5.0	± 0.25	3.25	8.50	.10
100,000	2.0	± 5.0	± 0.25	0.75	6.00	.10
50,000	5.0	± 2.5	± 0.25	0.25	3.00	.125
20,000	10	± 1.0	± 0.25	0.00	1.25	.15
10,000	20	± 0.5	± 0.25	0	0.75	.20
5,000	50	± 0.25	± 0.25	0	0.50	.25
2,000	100	± 0.10	± 0.25	0	0.35	.35
1,000	200	± 0.05	± 0.25	0	0.30	.60
500	500	± 0.025	± 0.25	0	.275	1.35

Table 3

Nominal AA (μ")	Computed AA (μ")	Meter Output (μ")	Round-Robin 35 (μ")
20	$\pm$ 0.2	$\pm$ 1.2	$\pm$ 2.04
120	$\pm$ 0.4	$\pm$ 12.0	$\pm$ 0.93

Table 4. A comparison of the computational accuracy of one reading by the computer method and the integrating meter method with the 3σ of the round-robin determination of the roughness of the NBS master, NBS-1.

Table 5. Preliminary measurements on NBS-1 Caliblock.

Nominal 20 microinch patch

Scan Location	AA(μ")*	3σ(μ")
1	20.74	0.24
2	20.69	0.21
3	20.87	0.24
4	20.77	0.10
5	20.90	0.15

*Average of four readings with an estimated accuracy in each reading of 0.2μ" based on Figure 6.

Nominal 125 microinch patch

Scan Location	AA(μ")†	3σ(μ")
1	121.0	1.4
2	121.1	1.2
3	121.3	1.5
4	121.6	1.2
5	121.6	1.2

†Average of five readings with an estimated accuracy in each reading of 0.4 μ" based on Figure 6.

the round-robin values agree almost within the one σ of either measurement; i.e.,

$$(AA \pm \sigma) \text{ computer} \simeq (AA \pm \sigma) \text{ round-robin.}$$

Further studies into the overall precision and accuracies of the computer calculated surface roughnesses are to be made and may reveal the bases for these results.

Table 6. Summary of Preliminary Results

Nominal AA (μ'')	Calibration Step (μ'')	Calibration Check (μ'')	Average AA (μ'')	3σ (μ'')	Round-Robin (μ'')	3σ (μ'')
125	901.4 $\pm$ 1.0	901.5	121.3	1.5	120.76	2.04
20	75.0 $\pm$ 1.0	74.4	20.79	0.3	20.34	0.93

Appendix A

The Linear Least Squares Curve Fit

For the general case of a linear least squares (LSQ) curve fit of the form:

$$y = a\,x + b,$$

where y is the dependent variable, x the independent, a the slope, and b the intercept, the following formulae apply:

(1) $$b = \frac{1}{N} \Sigma\, y_i - \frac{a}{N} \Sigma\, x_i$$

(2) $$a = \frac{N\,\Sigma\, x_i\, y_i - (\Sigma\, x_i)\,(\Sigma\, y_i)}{N\,\Sigma\, x_i^2 - (\Sigma\, x_i)^2}$$

where Σ indicates the summation over the n index from 1 to N.

For the special case of equally spaced x increments, x_i may be replaced by an integer n corresponding to the value of i and the summations over x_i and x_i^2 evaluated as standard series.

(3) $$\Sigma\, x_i = \Sigma\, n = \frac{N}{2}\,(N + 1)$$

(4) $$\Sigma\, x_i^2 = \Sigma\, n^2 = \frac{N}{6}\,(N + 1)\,(2\,N + 1)$$

Substitution of equations (3) and (4) into equations (1) and (2), with some simplification, leads to:

(5) $$b = \frac{1}{N} \Sigma\, y_i - \frac{a}{2}\,(N + 1)$$

$$(6) \qquad a = \frac{12 \Sigma n y_i - 6 (N + 1) \Sigma y_i}{N(N + 1)(N - 1)}$$

Where N is large, the denominator may be approximated by N^3. (In the case of 128 data points, the subsequent error in the calculated slope is about .005%.) Thus,

$$(7) \qquad a = \frac{1}{N^3} [12 \Sigma n y_n - 6(N + 1) \Sigma y_n].$$

Appendix B

Step Location

At the interrupt signal generated at the appropriate position in the stylus stroke, a one second delay is executed by the computer and data is read into memory for twenty-five seconds at the rate of approximately twenty points per second. Since the event marker is in the information channel, the delay is necessary to avoid reading the event marker as data. The signal which is recorded in those twenty-five seconds is thus entered as 512 data points in memory locations 1000_{16} to 1400_{16}. The memory locations of selected points and the corresponding positions on the strip chart (measured in mm relative to the trailing edge of the event marker as in figure 7) are indicated in figure 8.

Figure 8a represents a properly positioned step, approximately centered within the 40 mm - 110 mm region. A representation of the data recorded im memory is given in figure 8b.

The length of the segment on the chart, corresponding to the 128 points over which a least-squares straight line is computed, is 37.5 mm. The address A_1 (input during program execution) must correspond to a location in the region 40 mm to the step edge; similarly, A_2 must correspond to a location in the region between the step edge and the 110 mm position (see figure 9a). The line segments corresponding to the A_1 and A_2 selected are indicated in figure 9b. Choices for A_1 and A_2 are limited to pairs of points situated equally distant to the left

MM ADDRESS		MM ADDRESS	
0040	1116	0075	1206
0041	111E	0076	120E
0042	1124	0077	1214
0043	112A	0078	121A
0044	1132	0079	1222
0045	1138	0080	1228
0046	1140	0081	1230
0047	1146	0082	1236
0048	114E	0083	123E
0049	1154	0084	1244
0050	115A	0085	124A
0051	1162	0086	1252
0052	1168	0087	1258
0053	1170	0088	1260
0054	1176	0089	1266
0055	117E	0090	126E
0056	1184	0091	1274
0057	118A	0092	127A
0058	1192	0093	1282
0059	1198	0094	1288
0060	11A0	0095	1290
0061	11A6	0096	1296
0062	11AE	0097	129E
0063	11B4	0098	12A4
0064	11BA	0099	12AA
0065	11C2	0100	12B2
0066	11C8	0101	12B8
0067	11D0	0102	12C0
0068	11D6	0103	12C6
0069	11DE	0104	12CE
0070	11E4	0105	12D4
0071	11EA	0106	12DA
0072	11F2	0107	12E2
0073	11F8	0108	12E8
0074	1200	0109	12F0

FIGURE 7

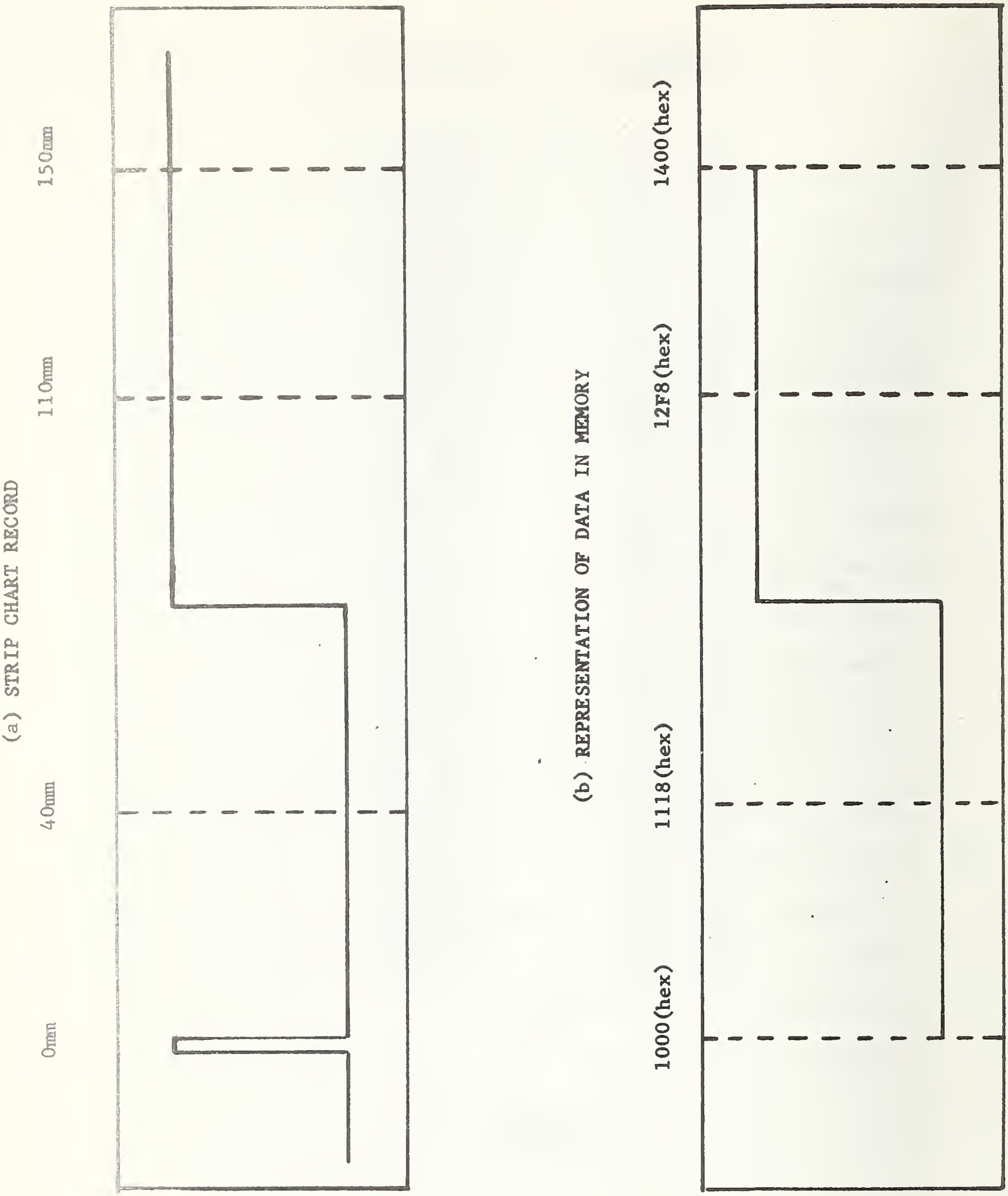


FIGURE 8. PROPER LOCATION OF STEP RELATIVE TO EVENT MARKER

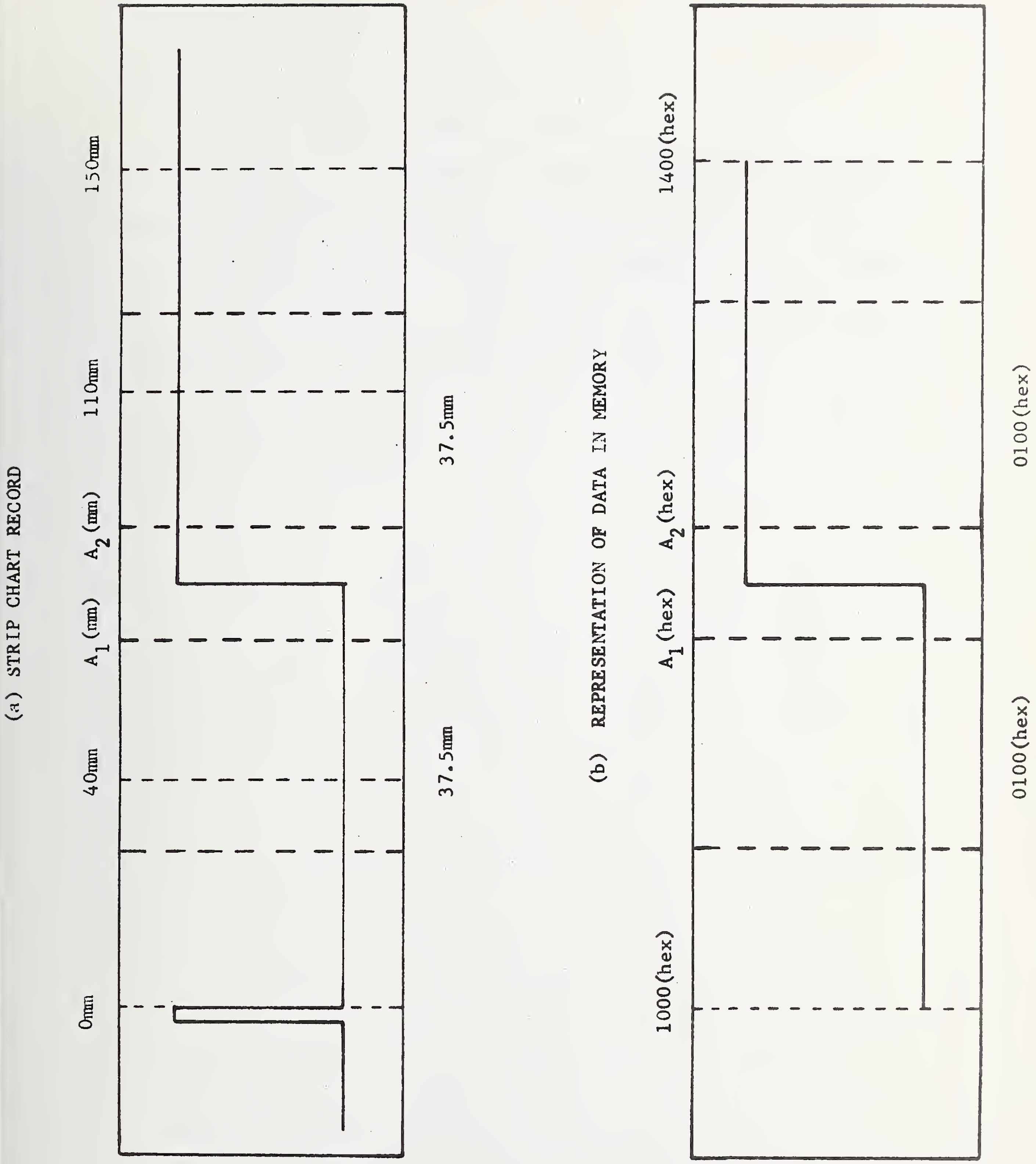


FIGURE 9 . SELECTION OF A_1 AND A_2 LOCATIONS

and right of the step location, S, such that:

$$S(\text{mm}) - A_1(\text{mm}) = A_2(\text{mm}) - S(\text{mm}).$$

A_1 and A_2 determine individually over which segment lines are to be computed; the mean of A_1 and A_2 determines the location at which a step is to be computed from the two lines. The effect on the calculation of the step height of proper (figure 10a) and improper (figure 10b) selection of A_1 and A_2 may be significant.

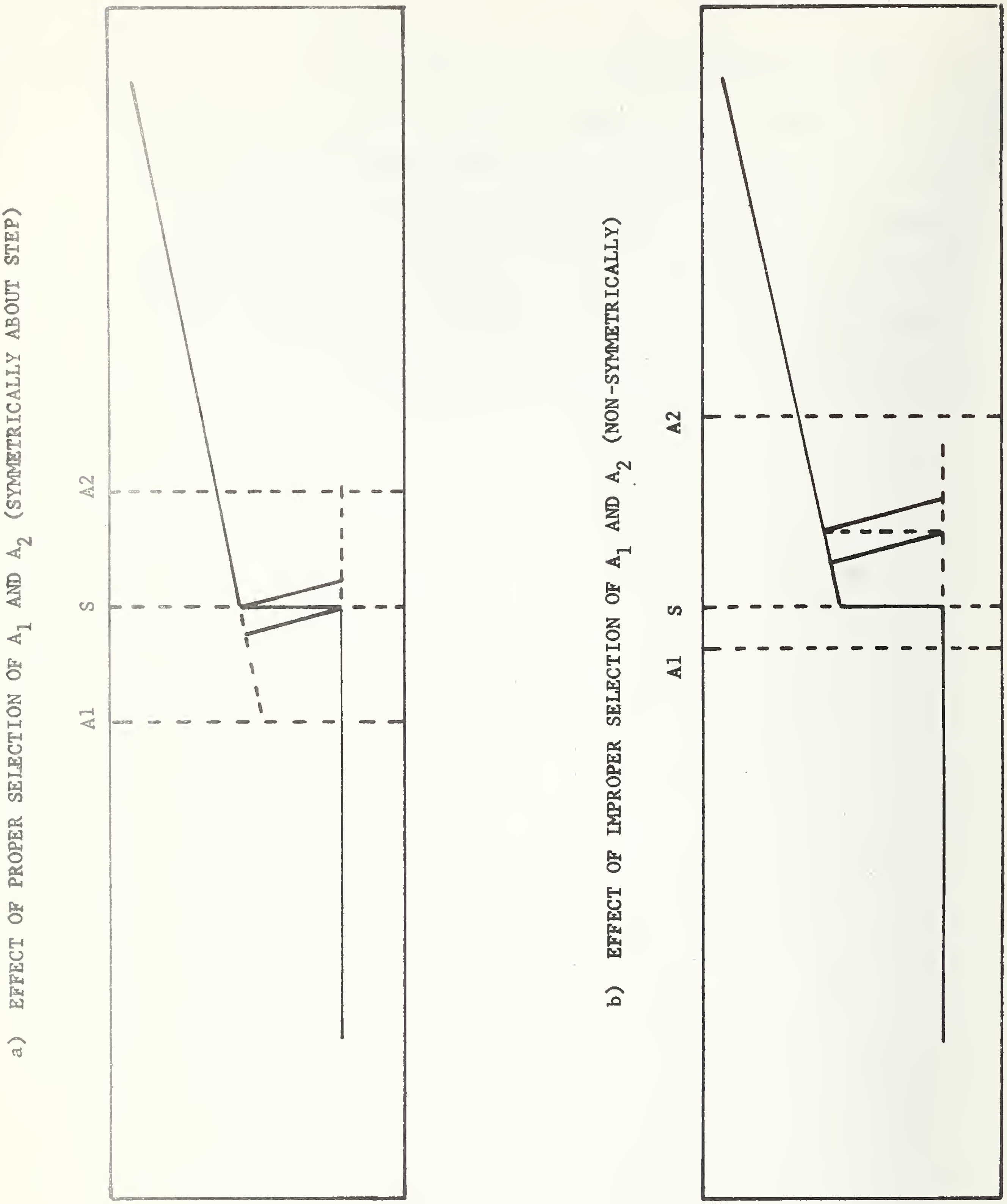


FIGURE 10. PROPER AND IMPROPER SELECTION OF A_1 AND A_2

Appendix C

The Mean Distance Between Two Non-Parallel Lines

The following vector analysis is employed to define the "mean perpendicular distance" between two non-parallel lines at some x coordinate xm. Line L_1 is defined by its slope, a_1, and the point A_1 with x and y coordinates $(0,b_1)$; line L_2 is similarly defined by a_2 and point A_2 at (x, b_2) as in figure 11. The general approach is to define vectors, V_1 and V_2, coincident with lines L_1 and L_2, respectively, and to find the perpendicular distances: h_1 from the point on V_1, with coordinate x_m, to V_2; and h_2 from the point on V_2, with coordinate x_m, to V_1. The mean distance, h_m, is then defined as the arithmetic average of h_1 and h_2.

The vector V_1 is defined as the difference between the vector to the general point P_1 and that to A_1':

(1) $$V_1 = P_1 - A_1'$$

(2) $$= [i\ (x_1) + j\ (a_1\ x_1 + b_1)] - [i\ (0) + j\ (b_1)]$$

(3) $$= (i + a_1\ j)\ x_1.$$

Similarly:

(4) $$V_2 = P_2 - A_2'$$

(5) $V_2 = (i + a_2 j) x_2$.

The general vector between points P_2 and P_1 is:

(6) $H = P_1 - P_2$

(7) $= i (x_1 - x_2) + j (a_1 x_1 - a_2 x_2 + b_1 - b_2')$.

To find the perpendicular distance from point P_1 to the line V_2, the product $H \cdot V_1$ is evaluated, set equal to zero, and the coordinate x_2 determined as a function of x_1.

Thus,

(8) $H \cdot V_1 = x_1 (x_1 - x_2) + a_1 x_1 (a_1 x_1 - a_2 x_2 + b_1 - b_2') = 0$

and

(9) $$x_2 = \frac{x_1 (1 + a_1^2) + a_1 (b_1 - b_2')}{(1 + a_1 a_2)}$$

The magnitude of the perpendicular distance, H_1, is:

(10) $H_1 = [(x_1 - x_2)^2 + (a_1 x_1 - a_2 x_2 + b_1 - b_2')^2]^{1/2}$.

Substitution of equation 9 into equation 10 yields:

(11) $H_1 = [(a_1 - a_2) x_1 + (b_1 - b_2')](1 + a_1^2)^{1/2} (1 + a_1 a_2)^{-1}$.

To find the perpendicular distance, H_2, from point P_2 to the line V_1, the product $H \cdot V_2$ is evaluated similarly, with the result.

$$(12)\quad H_2 = [(a_1 - a_2)x_2 + (b_1 - b_2')](1 + a_2^2)^{1/2}(1 + a_1a_2)^{-1}.$$

Since $b_2' = b_2 - a_2x$ and x_1 and x_2 are chosen to be x_m, the distances h_1 and h_2 as indicated in figure 11 are given by:

$$(13)\quad h_1 = [(a_1 - a_2)x_m + (b_1 - b_2 + a_2x)](1 + a_1^2)^{1/2}(1 + a_1a_2)^{-1}$$

and

$$(14)\quad h_2 = [(a_1 - a_2)x_m + (b_1 - b_2 + a_2x)](1 + a_2^2)^{1/2}(1 + a_1a_2)^{-1}.$$

The mean perpendicular distance is then:

$$(15)\qquad h_m = 1/2\ (h_1 + h_2).$$

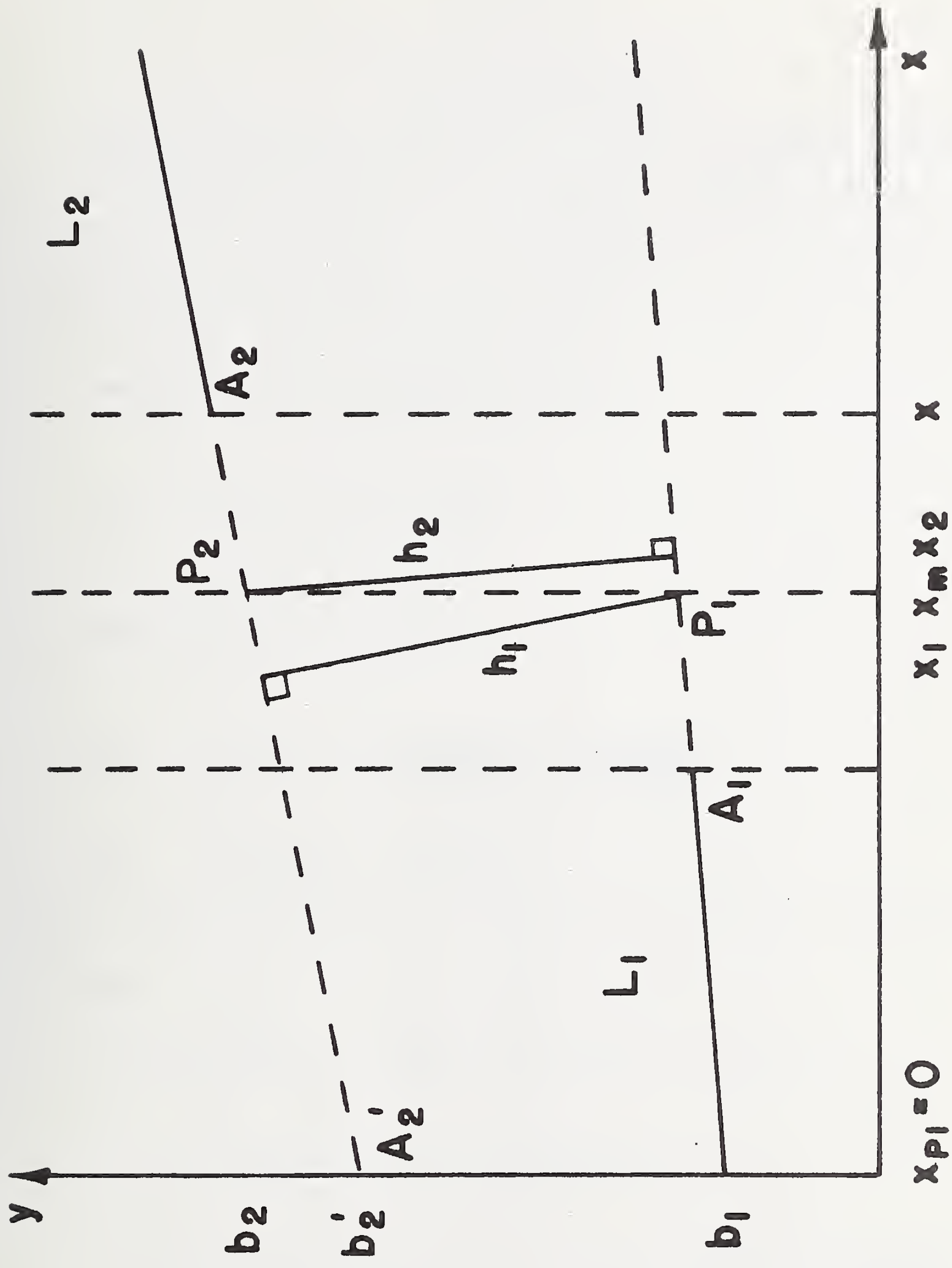


FIGURE 11

Appendix D

Slope Scale Factor

Since the linear least squares curve fit utilizes single precision hexadecimal numbers as y coordinates and hexadecimal memory addresses as x coordinates, it is necessary to scale this coordinate system to that of the chart recorder.

The following transformation applies:

(1) $y(\text{chart}) = k\ y(\text{hex})$

(2) $x(\text{chart}) = x(\text{hex})$

The slopes are then related by:

(3) $$a(\text{chart}) = \frac{dy(\text{chart})}{dx(\text{chart})} = k\ \frac{dy(\text{hex})}{dx(\text{hex})}$$

(4) $a(\text{chart}) = k\ a(\text{hex})$.

Substitution of equations 1, 2 and 4 into equation 11 of appendix C produces:

(5) $$H_1 = [(ka_1 - ka_2)x_1 + (kb_1 - kb_2 + ka_1x)]\ x$$

$$[1 + (ka_1)^2]^{1/2}[1 + (ka_1)(ka_2)]^{-1}$$

$$= k\ [(a_1 - a_2)x_1 + (b_1 - b_2 + a_1x)][1 + (ka_1)^2]^{1/2}[1 + k^2a_1a_2]^{-1}.$$

Since similar equations apply to H_1 and H_2, the relationship between the two is independent of the leading multiplier and it may be omitted to give heights of the form:

$$(6) \quad H_1 = [(a_1 - a_2)x_1 + (b_1 - b_2 + a_1x)][1 + ka_1)^2][1 + (ka_1)(ka_2)]^{-1}$$

Equation 3 may be evaluated using the full scale parameters of the chart and hexadecimal coordinate systems:

$$(5) \qquad 25.4 \text{ mm}/37.5 \text{ mm} = k\ (07ff_{16}/0100_{16})$$

which yields in hexadecimal and decimal values:

$$(6) \qquad k_{10} = 0.08466$$

$$(7) \qquad k_{16} = 0.15ACD.$$

Appendix E

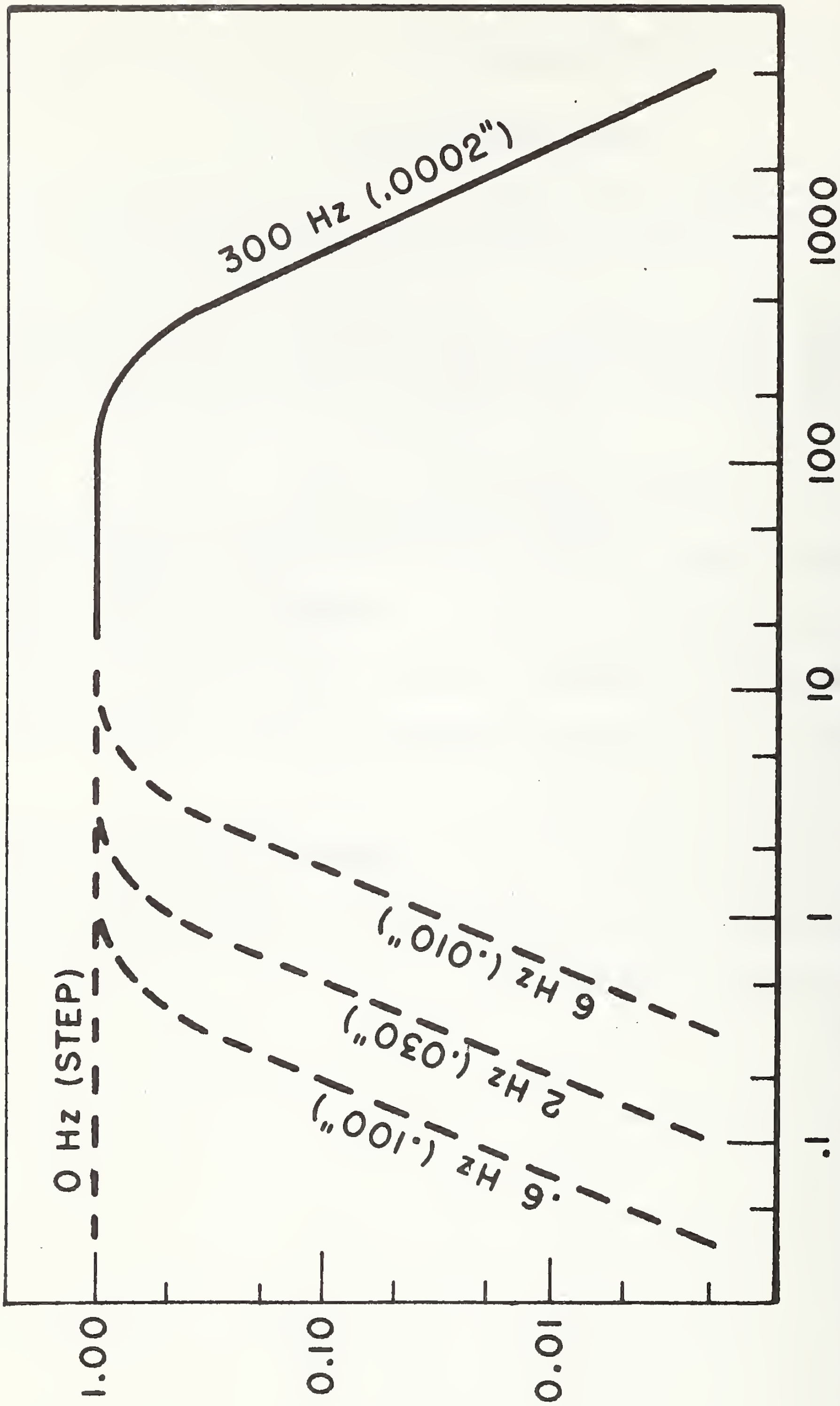
Filter Characteristics

The gain-bandpass characteristics of the filter circuits have been designed to conform with ANSI Standards when the device is used in conjunction with a Talysurf 4. The filter 3 db down points are related to the conventional wavelength cut-offs through the stylus speed:

$$f(\mathrm{Hz}) = .06 \text{ in/sec} \div \lambda_c \text{ (in)}.$$

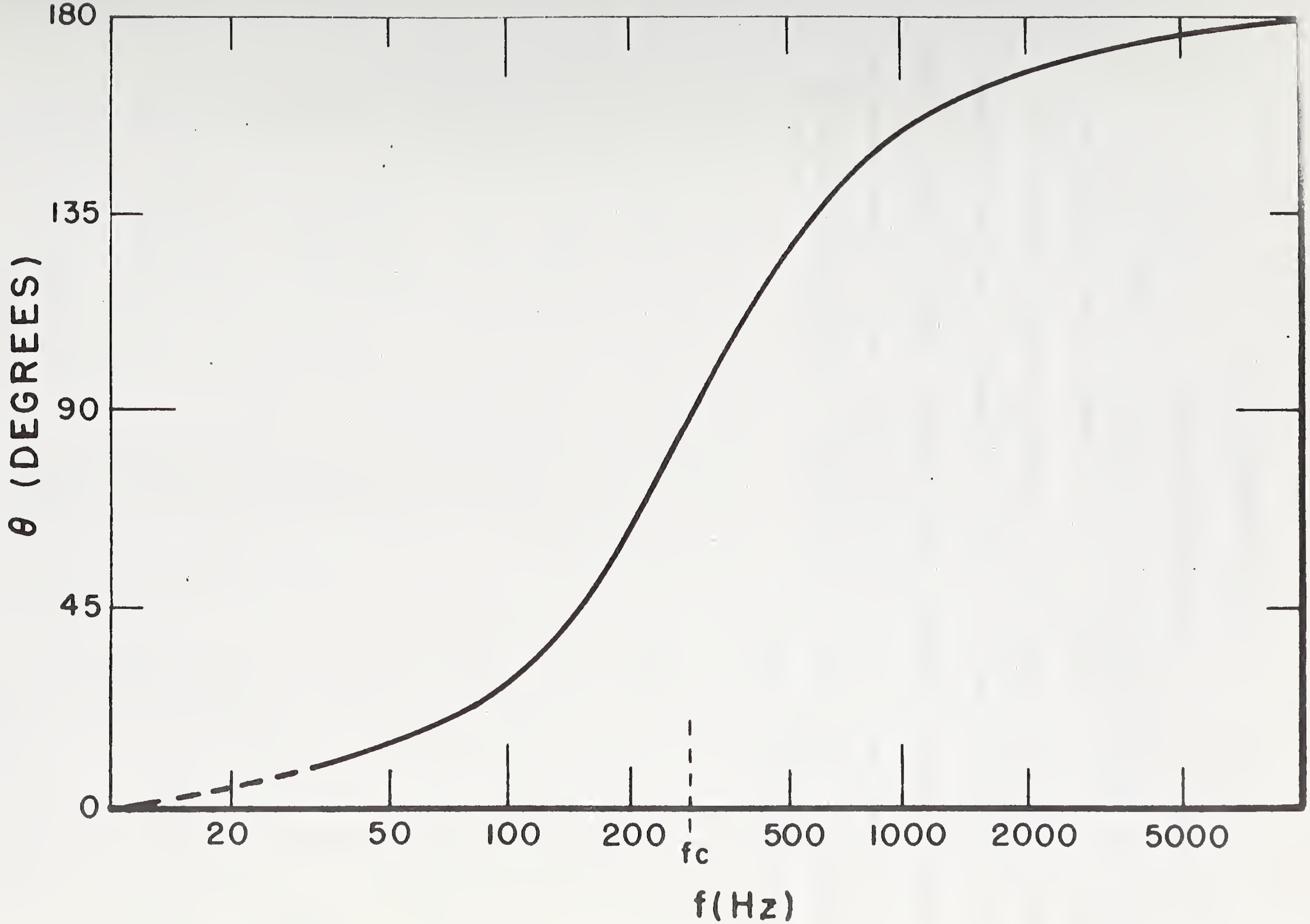
The filters are active Butterworths with selectable high-pass cut-off frequencies as indicated by figure 12. Roughness measurements are made with one of three high-pass filters in series with the single low-pass filter. Step height measurements are made with only the low-pass filter in the circuit.

The conformity of the filters to specified operation is indicated by the band pass curves in figure 12 and the observed phase delay in the low pass filter in figure 13.



FILTER-AMPLIFIER GAIN-BANDPASS CHARACTERISTICS

FIGURE 12



OBSERVED AMPLIFIER-FILTER PHASE DELAY

FIGURE 13

Appendix F

Program Operation

A flow-chart indicating the points in the program operation at which information is input at the A/D converter and Teletype and at which results are output at the eletype is shown in table 7. In table 8 are shown numerical values of parameters involved in a sample program operation in which a fifty microinch calibration step is used in the measurement of an unknown step height and an unknown roughness specimen. A compilation of characteristic parameters of the entire system is given in table 9.

TABLE 7

MASTER PROGRAM LEVEL 0

Program	Input		Output at TTY	
Level 0	ADC	TTY	Format	Data
Clear Flag				
Print			Heading	
Print			Enter Data	
Set Step Parameter				
Wait for Interrupt				
Read Step	Step Data			
Reset AA Parameters				
Print			In	
Print			Enter Ho	
Read 4 (Ho)		Ho		
Print				
Read Units		Units		
Print			Enter A1	
Read 4 (A1)		A1		
Print			Enter A2	
Read 4 (A2)		A2		
Print			H1....Units	
Calculate Step				
Y - Test Flag - N				
Compute KCAL				
Convert/Print-Steps				Steps
Print			Units	
Branch Uncond.				
Interrogate			H or R?	
H - Branch-R		H;R		
Set Flag				
Branch Uncond.				
Print			Enter Data	
Wait				
Read AA	AA Data			
Print			In	

Table 7 cont.

Program	Input		Output at TTY	
Level 0	ADC	TTY	Format	Data
Print			AA Units	
Compute/Print AA				AA
Print			Units	
Interrogate			More?	
Y - Branch - N		Y;N		
Print			Exit	

Table 7

Artifact: type value	Step 50μ"	Step Unknown	Roughness Unknown
Talysurf Magnification	20,000 X	20,000 X	20,000 X
Displacement on chart: low	-0.5"	-0.25"	-1.0" (valley)
high	+0.5"	+0.25"	+1.0" (peak)
Talysurf Profile Out: low	-0.5 V	-0.25 V	-1.0 V
high	+0.5 V	+0.25 V	+1.0 V
Amplifier Gain	10X	10X	10X
A/D Output: low	C010 (•)	E010 (•)	8010 (•)
high	3FF0 (•)	1FF0 (•)	7FF0 (•)
H_c Input at TTY	5000	------	------
H_o in hex.	1388	------	------
Linear least square: slope: low	(•)0000	(•)C000	------
high	03FF(•)	07FF(•)	------
Slope Scale Factor:	(•)15AD	(•)15AD	------
Scaled Slopes:	(•)0000	(•)0000	------
Voltage Step Height	0800(•)	0400(•)	------
KCAL: H_o/8Hm.	(•)4E20	------	------
Calibrated Step Height (8KCAL x Volt. Stage)	1388(•)	09C4(•)	------
Decimal Step Height Printed	5000	2500	------
Computed Voltage AA	------	------	2000(•)
Calibrated AA (KCAL x Voltage AA)	------	------	09C4(•)
Decimal AA Printed	------	------	2500
Artifact Value	50.00μ"	25.00μ"	25.00μ"

Table 8

Table 9

Characteristic Parameters

Talysurf 4

Profile Output (nominal)	± 1V
Relay Output (nominal)	−4V
Magnification (vertical, max.)	10^5
Stylus Speed (4X)	3.6"/min.
(20X)	0.72"/min.
(100X)	0.14"/min.
Scan Distance (.030" cutoff, 4X)	.150"
Chart Speed	14.4"/min.

Filter-Amplifier

Input (limited)	± 1V
Input Impedance	100 kΩ
Gain (nominal)	10X
High Frequency cut-off	300HZ
Low Frequency cut-off	6HZ
	2HZ
	.6HZ
Filter Roll-Off	-12 db/octave
Flatness	±.02 db
Overall Linearity	.02%
Output (nominal)	±10V
Noise Output	≤5 mv.

Interface Circuitry

Inverter Output	+4V
Event Marker Output	±1.35V (1 sec.)
Interrupt Signal Output	3V (50 µsec)

Data Input: Step Mode

Record length (time)	25 sec.
(chart)	5.9" (150 min).
(surface, 100X)	.060"
(surface, 20X)	.300"
Number of data points	512
Time per data point	50 msec
Horizontal Resolution (100X)	120μ"
(20X)	600μ"
Vertical Resolution (A/D resolution at highest Talysurf gain).	.02μ"

Data Input: AA Mode

Record length (time)	2.5 sec
(chart)	.6"
(surface, 4X)	.150"
Number of data points	4096
Time per data point	600 μsec
Horizontal resolution (4X)	37μ"
Vertical resolution (at 10^5 X)	.005μ "
Short Wavelength cut-off	200 μ"
Long wavelength cut-off	.010"
	.030"
	.100"

A/D Converter

Input Voltage	$\pm$ 10V
Input Impedance	100 MΩ
Output (including sign)	12 bit
Resolution (voltage)	5 mv
(relative)	.025% FS
Linearity	.010% FS

Appendix G

Operator's Instructions: Interdata 3/Talysurf 4 System

I. Preliminary Set-up

A. Instrumentation: the following connections are necessary:

1. those on the Talysurf for normal operation as indicated by the Talysurf Operating Instructions manual;

2. those internal to the A/D converter as shown in figure 14;

3. the power cord of the interface electronics as in figure 15 (N.B. Disconnect main power line to computer when connecting this line).

4. The external leads between the Talysurf, interface electronics and A/D converter as in figure 16.

B. Software: the following programs must reside in memory:

1. the hexadecimal monitor (3A80-3FFF);

2. the arithmetic subroutines (3010-35FF);

3. the master program (0080-1000).

II. General System Operation

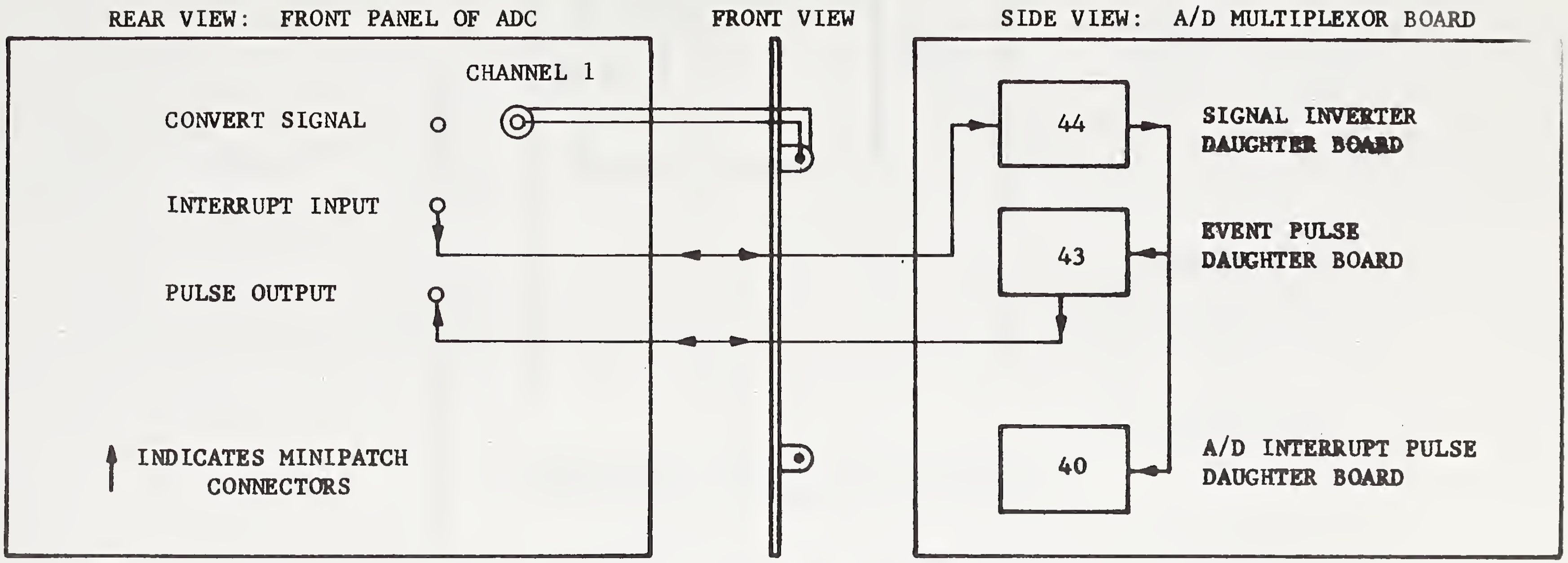
A. Calibration of Stylus Instrument

1. Magnification Selection

(a) Align unknown specimen on Talysurf;

(b) traverse stylus with chart recorder on and select magnification on Talysurf electronic unit to obtain approximately three-quarters of maximum on-scale deflection of recorder pen;

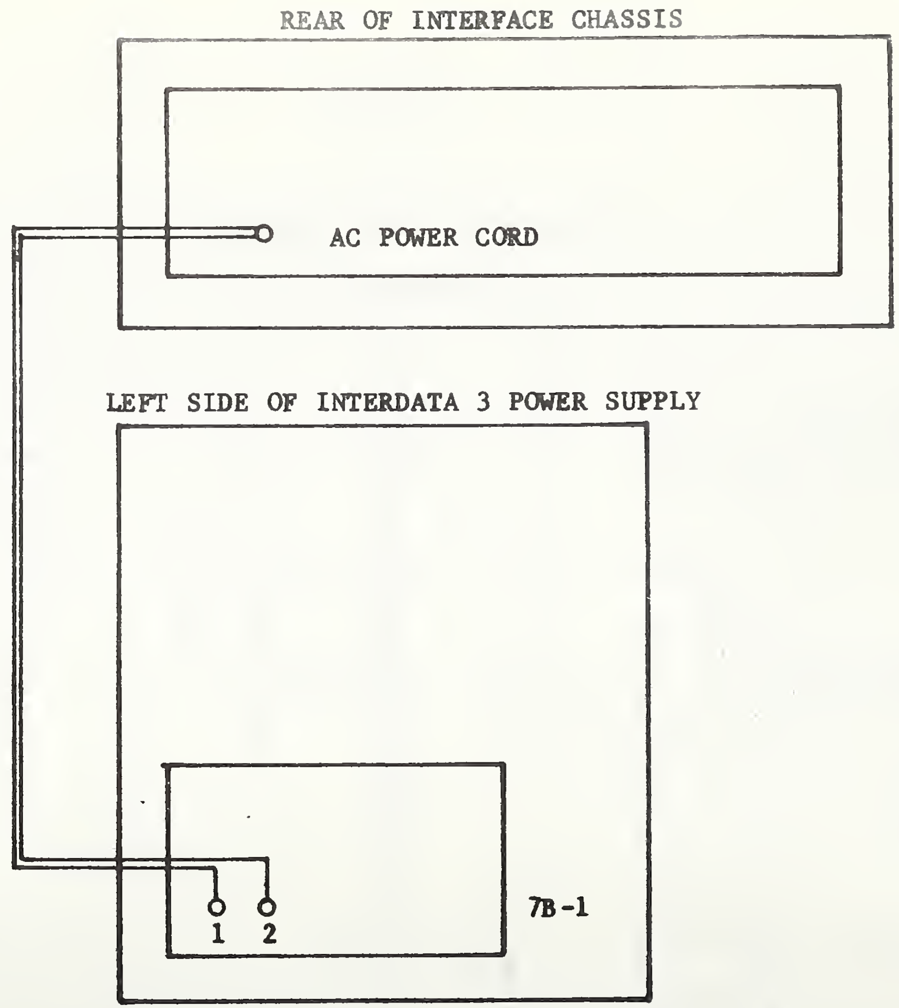
(c) turn off recorder and select calibration step



A/D CONVERTER BOARD

INTERNAL LEAD CONNECTIONS

FIGURE 14



INTERFACE ELECTRONICS: AC POWER CONNECTION

FIGURE I5

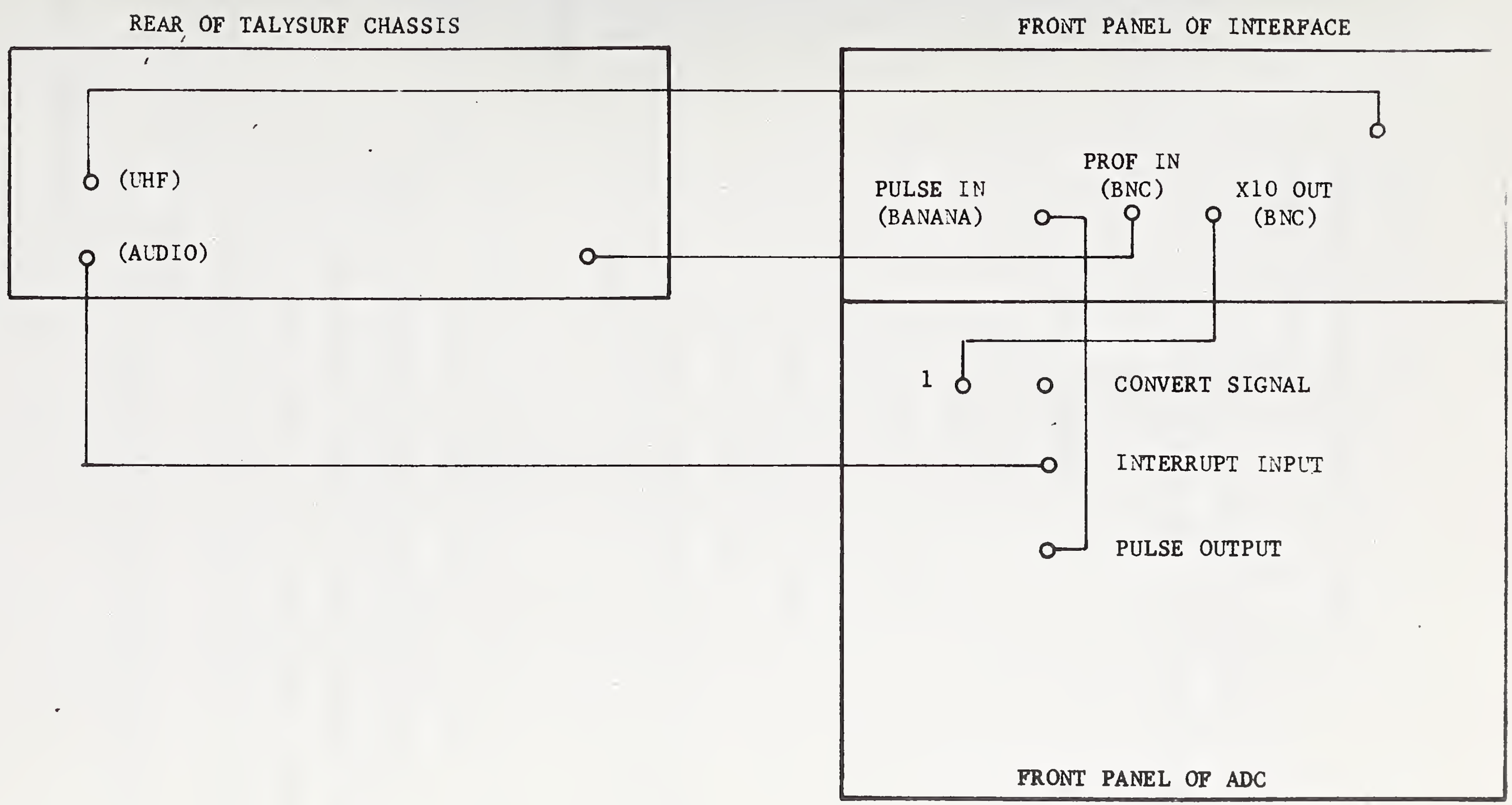

REAR OF TALYSURF CHASSIS
(UHF)
(AUDIO)
FRONT PANEL OF INTERFACE
PULSE IN
(BANANA)
PROF IN
(BNC)
X10 OUT
(BNC)
1
CONVERT SIGNAL
INTERRUPT INPUT
PULSE OUTPUT
FRONT PANEL OF ADC

FIGURE 16

artifact of appropriate size.

2. Input of Calibration Step: Set-up

(a) Set switches

(1) Talysurf Electronic Control Unit

(1) Magnification: as determined in

(2) Cut-off: K

(3) Operation: N

(2) Talysurf Gear Box

(1) Stroke knob: L

(2) Speed knob: X20

(3) Interface Electronics

(1) Mode Select: 10X

(2) Cut-off: Step

(b) Align artifact and traverse stylus to obtain trace with step edge in proper position relative to the event mark (see appendix B).

(c) Rotate the Talysurf Setting Lever at the left (CCN) position (see p. 4 of Talysurf Manual and Note 1 below).

3. Input of Calibration Step: Program Execution

(a) Begin program executive from TTY Control (OEOOG)

(b) At "enter data": turn on the chart recorder and gently move the Setting Lever to the right (OW); data will be read for twenty-five seconds.

(c) At In: shut off the chart recorder and tear off the recorded trace;

(d) A1 and A2 selection:

(1) with the "Step Locator Scale", determine the position in mm of the step edge relative to the trailing edge of the event mark (see appendix B);

(2) select A1 and A2 symmetrically about the step edge.

(3) Decord on the strip chart the mm and address locations of A1 and A2;

(e) At "Enter HO": type in the step height value as four digits and depress the space bar on the TTY;

(f) At "Enter Units": type in a two character unit symbol (do not press the space bar);

(g) At "Enter A1"; type in the four-digit address A1 and depress the space bar;

(h) at "Enter A2"; either A2 as above; the computer will now print out the computed step heights H1, H2 and HM with units.

(i) At "More?":

(1) If the computed step heights are unsatisfactory, type N and repeat the procedure from step 3a;

(2) If the heights are satisfactory, type Y.

B. Calibration of Unknown Specimen

1. Align the specimen on the Talysurf and traverse the stylus to obtain a properly centered trace.

2. Calibration of a Step

(a) Repeat procedure in IIA2, b and c;

(b) At "H or R?": type in H;

(c) At "Enter Data", follow procedure from IIA3, b thru h;

3. Calibration of a Roughness

(a) Select filter cut-off on interface; select X4 stroke speed on Talysurf; type R.

(b) At "Enter Data", rotate the Setting Lever to right position (CW); data will be read for 3.5 seconds.

(c) The computed AA and units will now be printed.

4. At "More?":

(a) If a step is to be calibrated, type Y; then at "H or R?", type H.

(b) If a roughness is to be calibrated, type Y, then at "H or R?", type R.

(c) If no more measurements are to be made, exit from program by typing N.

Note 1. The Event Marker appears on the chart recorder at the "Start of cut-off average" position in the stroke. With the stroke knob on the gear box at position L, the event mark appears when the marks on the gear box window are aligned as indicated below. Therefore, in returning the Setting Lever to the left (CCW) position, it is necessary only for L mark to be to the left of the rightmost mark on the upper scale.

Appendix H

Checklist for Proper Electrical Operation

Talysurf Outputs

(1) The profile Output should produce a voltage of nominally +1 volt when the pen is at the 2 inch mark on the strip chart and -1 volt at the zero inch mark.

(2) The relay output should be a negative - going step of four volts at the "Start of cut-off average" position of the stylus stroke (see Talysurf Manual).

A/D Outputs

(1) With the Talysurf relay output connected to the Interrupt Input terminal on the A/D converter front panel, the A/D output at the Pulse Output terminal should be a zero to volts pulse of about one second duration; (simultaneously the computer interrupt should trigger internally).

Interface Electronics Outputs

(1) With the system fully wired (figure 16), the output at the X10 OUT should be the amplified, filtered Profile Out Signal;

(2) A one-second pulse of nominally one volt should be present at the "PROFILE IN" terminal (and a similar one recorded on the chart recorder) at the "Start of cut-off average" stroke position.

Internal A/D Signals (A/D Multiplex or Board).

With the Talysurf relay signal at the Interrupt Input:

(1) the output of the signal inverter (daughter board 44) should be a positive-going step of four volts;

(2) the output of the A/D Interrupt pulse (daughter board 40) should be a 50 microsecond positive-going pulse of about four volts.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

An overall system for computerized surface roughness measurements, involving a commercial stylus profile instrument and a minicomputer, is described. The method allows: direct displacement calibration of the stylus instrument by means of interferometrically measured gage block steps; the elimination of roughness artifacts as calibration standards; and access to punched-tape surface profile data which may be given detailed analysis on a larger, faster computer. Details of system operation and precision are included.

17. KEY WORDS (Alphabetical order, separated by semicolons)
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