

# CALIBRATION OF A SURFACE PLATE

Laser Measurement System  
Application Note **156-2**

REVISED

## INTRODUCTION

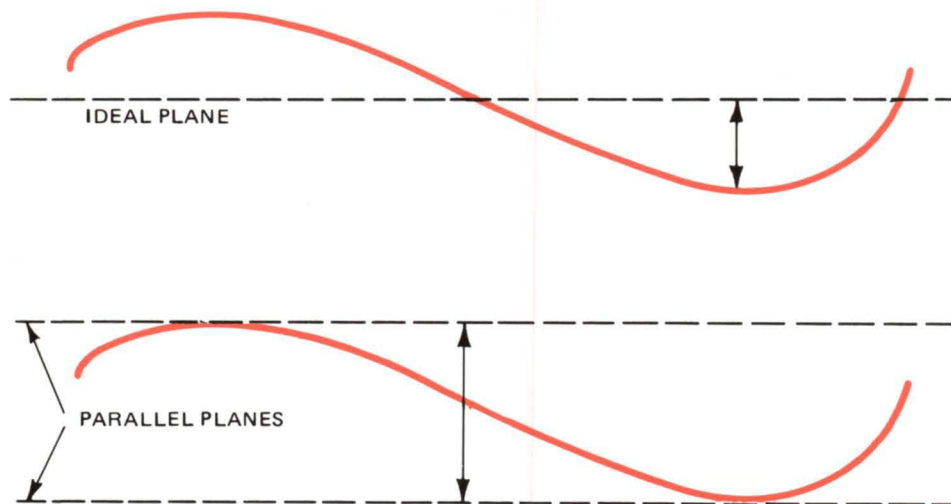
This note describes a surface plate flatness measurement application for the Hewlett-Packard 5526A Laser Measurement System and HP 9820A Programmable Calculator. The Calculator program which is used for this application is an implementation of what is often referred to as the "Moody Method\*" for calibration of surface plates. This is a widely accepted method of measurement and data analysis, but it requires tedious and time-consuming arithmetic calculations to give the final data. (See Appendix B.) The 9820A Programmable Calculator is especially well-suited to this type of data manipulation and can give the inspector the results of the inspection within seconds of when the final data point is taken. Up to 210 total data points can be handled for a given surface plate and the final data can be printed, recorded on magnetic cards, or plotted in one of two formats. The entire procedure from set-up to final data output can easily be accomplished by one person.

\*J.C. Moody, "How to Calibrate Surface Plates in the Plant," The Tool Engineer, October, 1955.

## SURFACE PLATE FLATNESS

The surface plate is used as the datum plane for most measurements in the metrology laboratory or shop inspection station. The accuracy of these measurements is therefore limited by knowledge of the flatness of the surface plate. To keep this knowledge up to date, a calibration is usually performed at least once every 6 months.

Specifications of flatness are normally expressed in one of two ways: the maximum allowable deviation (plus-minus) of any point in the surface from an ideal plane, or the maximum allowable separation of two parallel ideal planes which entirely enclose the surface. Tolerances vary from 0.005 to 0.000050 inches (125 to 1 micrometers) over the usable area of the plate. The calculator program which is used to reduce the surface plate flatness inspection data to final form displays the final data in the format of two parallel ideal planes. The Numeric Data Plot program will display the data in either format.



**FIGURE 1. FLATNESS SPECIFICATIONS**

In either case, one needs an accurate measurement technique to determine the flatness. This note describes the use of the Hewlett-Packard 5526A Laser Measurement System to make these measurements and a Hewlett-Packard 9820A Programmable Calculator and associated accessories to analyze the data and display the final flatness results. Using these instruments provides many advantages over conventional techniques:

- greater accuracy
- much faster procedure
- no eyestrain
- less weight on surface plate
- no heat sources on plate
- digital readout in micrometers (or 0.01 micrometers)
- easy editing of any input line with results of change displayed within seconds, and
- easy-to-read graphical results

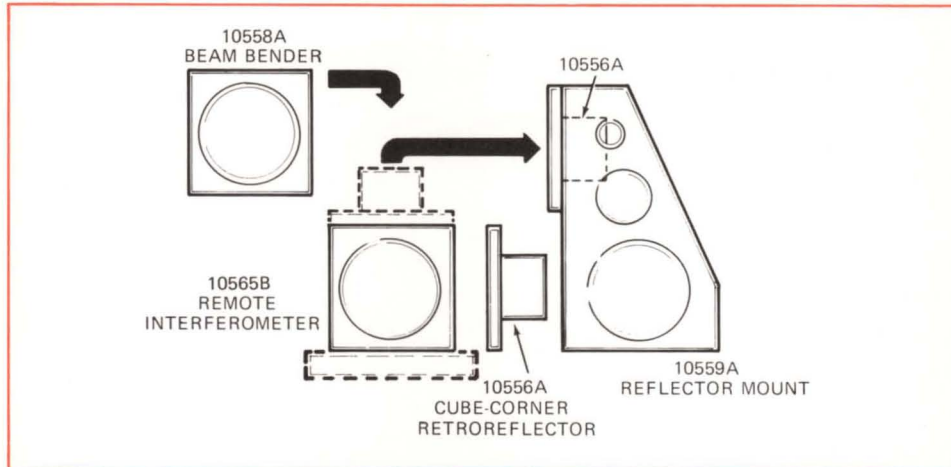


## EQUIPMENT REQUIRED

The following items of standard Hewlett-Packard equipment are required for surface plate calibration as described in this note:

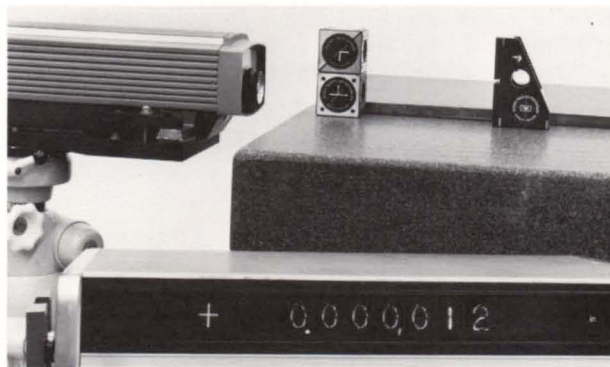
Quantity	Model No.	Description
1	5526A	
1	Opt. 200	Laser Measurement/Calculator System I
	or	
1	Opt. 201	Laser Measurement/Calculator System II
	or	
	Equivalent	Hewlett-Packard Equipment

Four of the accessories are combined into two packages in the following manner (instructions for this procedure are in the appropriate operating manuals, and should be carefully followed):



**FIGURE 2. ARRANGEMENT OF ANGULAR MEASUREMENT ACCESSORIES**

The configuration for measurement is illustrated in this photo (note the read-out directly in microinches of elevation):

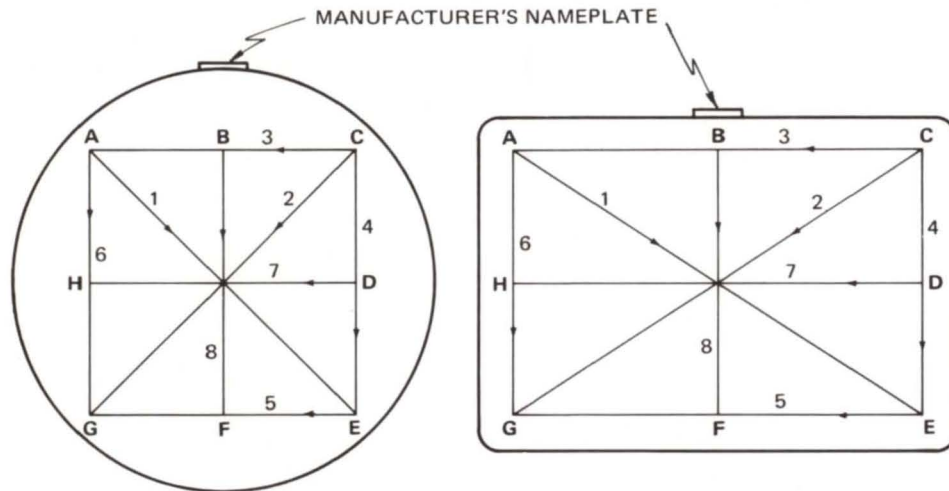


**FIGURE 3. LASER INTERFEROMETER AND ACCESSORIES PREPARED FOR MEASUREMENT**

## PREPARATORY STEPS

Prior to calibration, the surface plate should be cleaned thoroughly and allowed to reach thermal equilibrium with its surroundings (several hours to a full day). Of course, to obtain an understanding of the plate's characteristics while in use, the environment in which it is calibrated should closely approximate the conditions under which it is used — especially temperature. The mechanical accessories to the interferometer should also be cleaned according to instructions provided.

The other preparatory step is to draw a "map" of the surface plate. This map should be drawn on a sheet of paper with highlights located on the surface plate itself with lead pencil, chalk, or other suitable marking. Take care not to put markings directly on the grid lines, since the equipment must be free to slide on the granite surface along these lines. The grid system must contain the eight basic lines as shown in Figure 4.



**FIGURE 4. GRID MAP OF SURFACE PLATE**

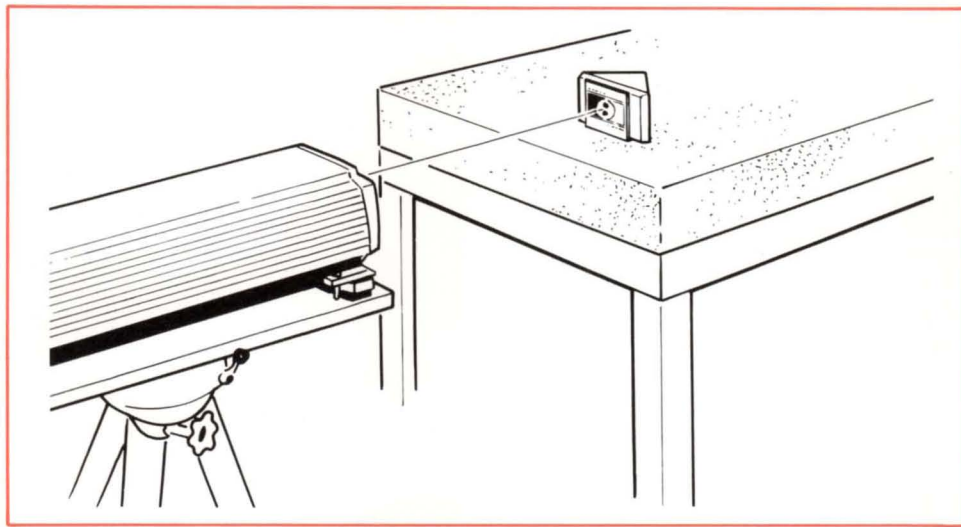
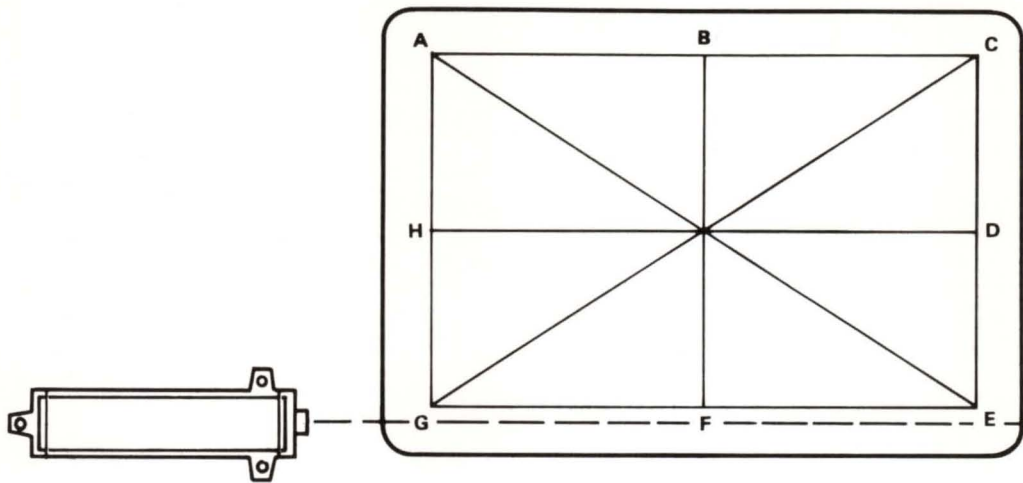
The length of each line in this grid should be an even-integral multiple of the foot spacing of the 10559A Reflector Mount; otherwise, special fixturing may be required to perform the calibration. If special foot spacing fixturing is used, then a simple proportionality factor will convert the readings into true elevation in the calculator program.

## SET-UP FOR THE MEASUREMENT

The Laser Head should be mounted such that the laser beam is pointed approximately parallel to perimeter line GE and at least one inch (25 mm) outside of the grid (see Figure 5).

To ensure that the laser beam is parallel to the surface and at the correct elevation, follow these steps: Take the magnetic template from the 10565B Remote Interferometer and center it on the front of the 10557A Turning Mirror. Next, place the mirror on the surface plate so as to reflect the beam back toward the Laser Head. The beam is correctly aligned when it passes through the top aperture of the template and autoreflects from the Turning Mirror to the output port of the Laser Head (see Figure 6).

**FIGURE 5. LOCATION OF LASER HEAD**



**FIGURE 6. AUTOREFLECTION ALIGNMENT OF LASER BEAM**

## **MEASUREMENT OF A LINE**

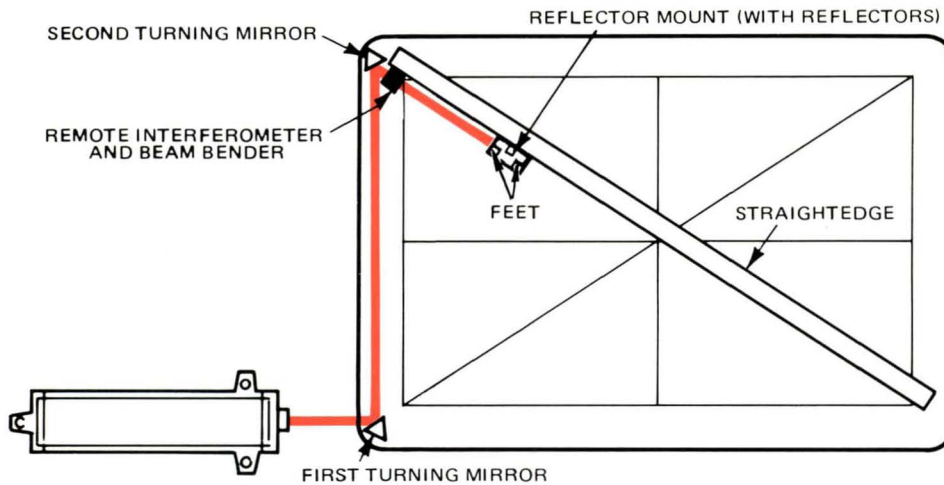
### **Alignment**

Using the two 10557A Turning Mirrors, the laser beam can be directed along any line of the grid pattern, as shown in the diagram in Figure 9. There is no need to move the Laser Head during the calibration. This paragraph will describe in detail the procedure used to take readings on line AE; for succeeding lines, the procedure is identical.

First arrange the accessories on the surface plate as shown in Figure 7.

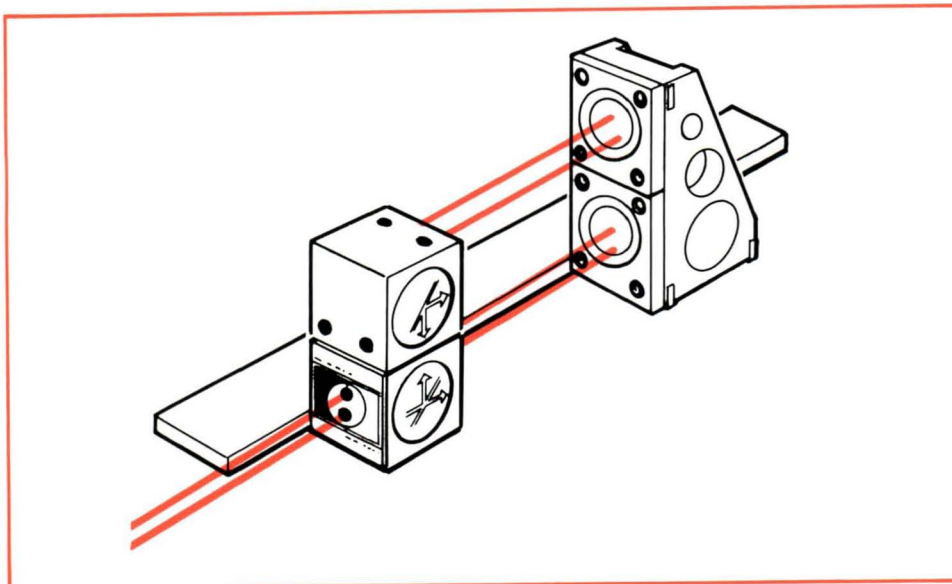
The straightedge may be marked at intervals corresponding to the foot spacing of the Reflector Mount for ease in locating reading positions. It is positioned such that the two feet on the right side of the reflector mount slide along the measurement

line when the Reflector Mount is in contact with the straightedge. Note that the Remote Interferometer is positioned about ½-inch (12 mm) outside the grid and also is in contact with the straightedge.



**FIGURE 7. ARRANGEMENT OF ACCESSORIES FOR MEASUREMENT**

Next, attach the magnetic template to the entrance face of the Remote Interferometer. By adjusting the two Turning Mirrors direct the laser beam through the top aperture of the template and observe the two beams exiting. Slide the Reflector Mount to the far end of the line and adjust the Turning Mirrors slightly so that the laser beam enters the top aperture of the template and the exiting beams are directed toward the center line of the reflector mount. A white card is useful for observing the position of the beams.



**FIGURE 8. ALIGNING THE ACCESSORIES**



Now remove the template and observe the return red spot on the turret of the Laser Head. By making small adjustments of the second Turning Mirror, this spot may be directed into the lower port of the turret; further small adjustments will maximize the reading of the BEAM ALIGNMENT Meter on the Laser Display.

The Calculator program expects the inspection lines to be numbered exactly as in Figure 4. Also, the lines are to be inspected by moving the reflector mount in the direction shown by the arrows on each line of Figure 4. It is possible to set up the Remote Interferometer at either end of any of the lines (Figures 9A and 9B) and care must be taken that the direction of motion of the reflector mount corresponds to the direction indicated by the arrows on each of the inspection lines of Figure 4. This requirement is necessary for the Calculator program to know which ends of the lines to connect to each other and to know the sense (+/-) of the readings. For positive (+) line numbers, the back foot is on the measurement point and a positive (+) reading indicates a positive flatness deviation; but, for negative (-) line numbers, the front foot is on the measurement point and a negative (-) reading indicates a positive flatness deviation. (Note: With the 5505A Laser Display sense switch set in the Forward position and the Laser and optical components aligned to make a measurement, tilt the 10559A Reflector Mount so that the back foot is higher than the front foot. The 5505A Laser Display should read a positive deviation. If it does not, reverse the sense switch and perform the same check.) To handle these possibilities in the program, the message "+/- LINE NUMBER?" will be displayed on the Calculator. The +/- sign will be determined by this guideline:

"Enter + line number if the reflector mount moves away from the interferometer and enter - line number if the reflector mount moves toward the interferometer."

### Ensuring Reproducibility

A build-up of dirt particles or flakes of granite under the feet of the reflector mount can introduce error during the measurement. To ensure that this is not the case, first slide the Reflector Mount to the center of the line and reset the Laser Display to a zero reading. Then slide the Reflector Mount from one end of the line to the other several times, observing the readings of the Laser Display at both ends and the middle. These readings of the Laser Display will be reproducible within several microinches (several 0.01 micrometers) on a clean surface plate of good quality.

### Taking the Readings

Place the direction sense switch on the front panel of the 5505A Display in the correct position to give a positive deviation when the rear foot is elevated and position the Reflector Mount for the first measurement point as shown in Figure 10. Reset the display to zero and place the Print switch on the front panel of the 5505A Display in the Manual position. Start the program in the 9820A Programmable Calculator and make all the preliminary entries which initialize the program (see Appendix A). The program will automatically assign a value of zero to the end point of the line and when the program is ready to accept the measurement data, activate the Manual Print Switch. Each time the Print Switch is depressed one reading will be transmitted from the 5505A Display to the 9820A Calculator which will store the data and print it on the Calculator Printer.

After each reading is entered, move the reflector mount to the next position and depress the Print Switch. This procedure is continued until the Reflector Mount has reached the end of the line as shown in Figure 10. When the final reading has been transmitted and the Calculator program commanded that the final reading for



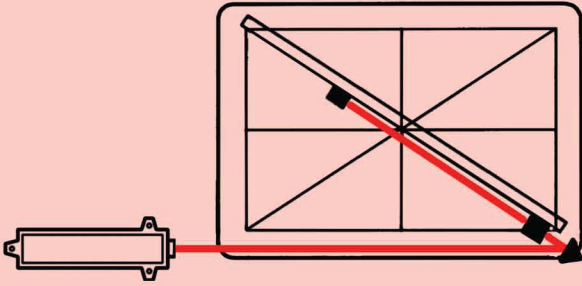
## MEASUREMENT SEQUENCE FOR - LINE NUMBER

**FIGURE 9A**

The following eight drawings illustrate the arrangement of the mechanical accessories for calibrating the eight basic lines of the surface plate grid.

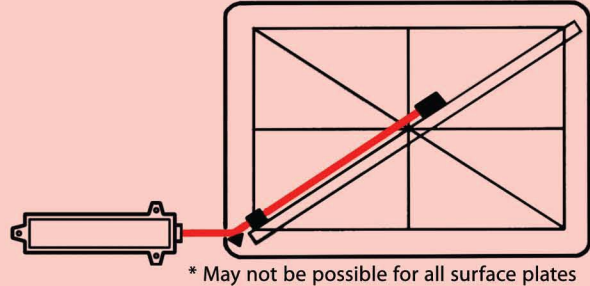
**9A.1**

**DIAGONAL LINE AE**



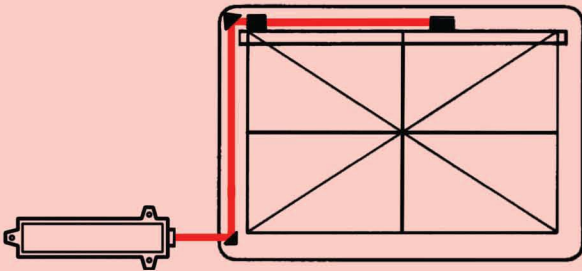
**9A.2\***

**DIAGONAL LINE CG**



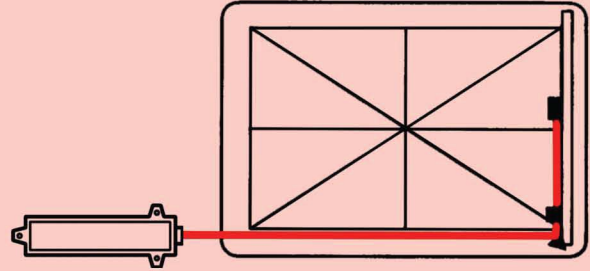
**9A.3**

**PERIMETER LINE CA**



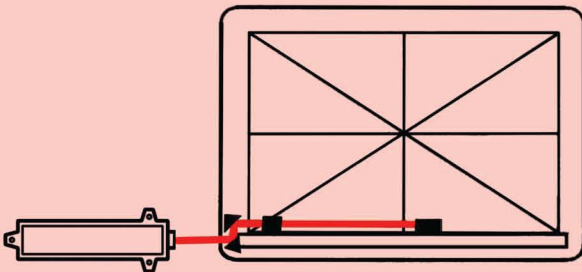
**9A.4**

**PERIMETER LINE CE**



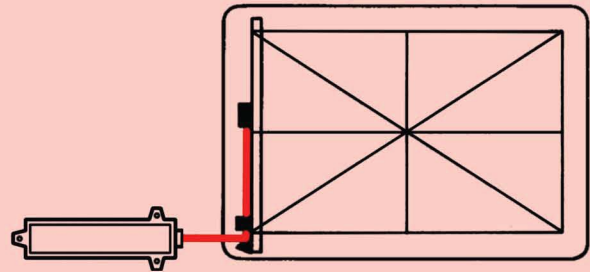
**9A.5**

**PERIMETER LINE EG**



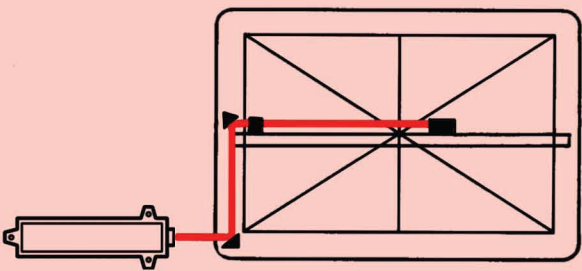
**9A.6**

**PERIMETER LINE AG**



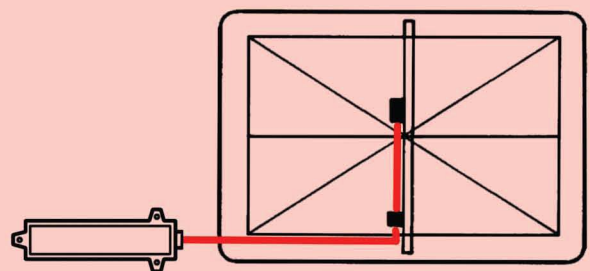
**9A.7**

**CENTER LINE DH**



**9A.8**

**CENTER LINE BF**



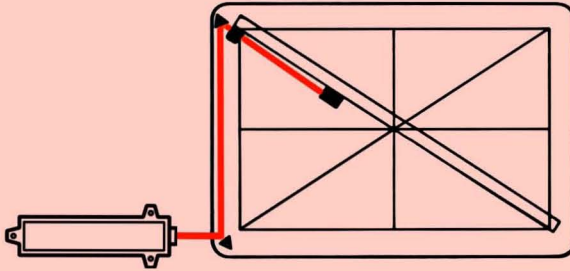
## MEASUREMENT SEQUENCE FOR + LINE NUMBER

**FIGURE 9B**

The following eight drawings illustrate the arrangement of the mechanical accessories for calibrating the eight basic lines of the surface plate grid.

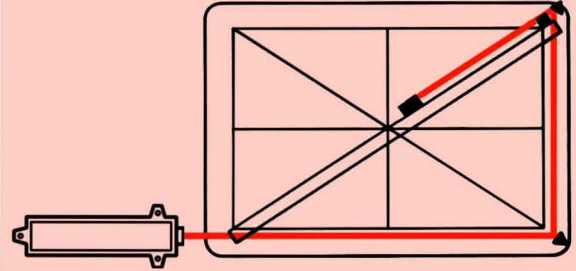
**9B.1**

**DIAGONAL LINE AE**



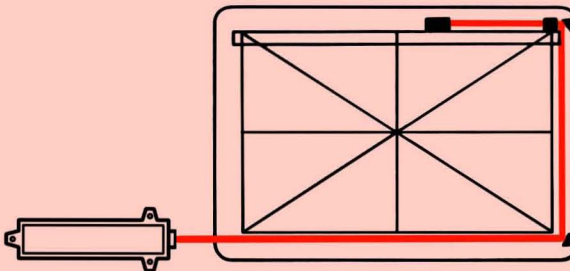
**9B.2**

**DIAGONAL LINE CG**



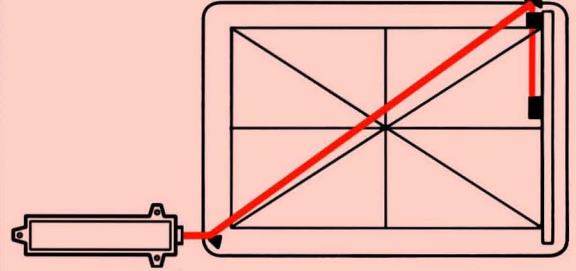
**9B.3**

**PERIMETER LINE CA**



**9B.4\***

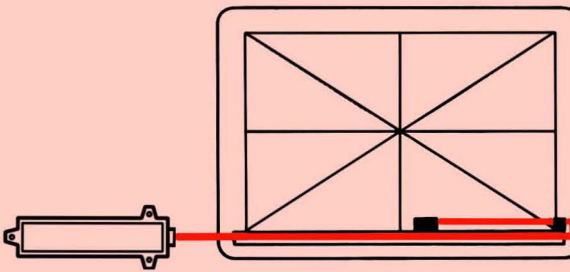
**PERIMETER LINE CE**



\* May not be possible for all surface plates

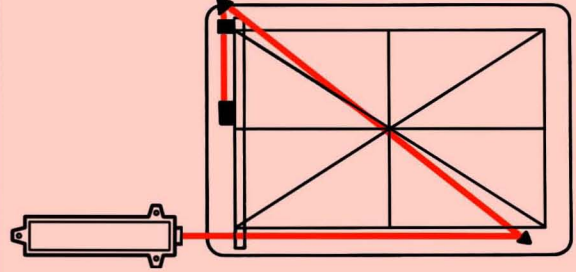
**9B.5**

**PERIMETER LINE EG**



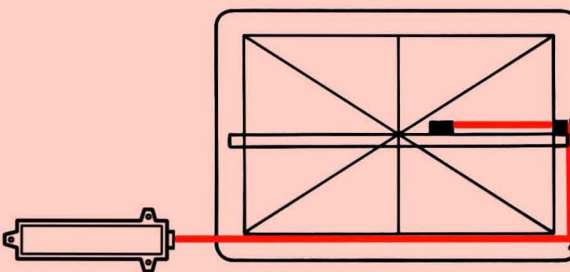
**9B.6**

**PERIMETER LINE AG**



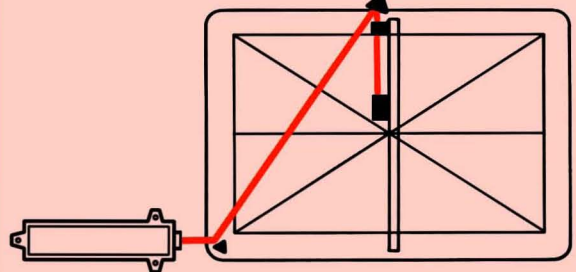
**9B.7**

**CENTER LINE DH**



**9B.8**

**CENTER LINE BF**



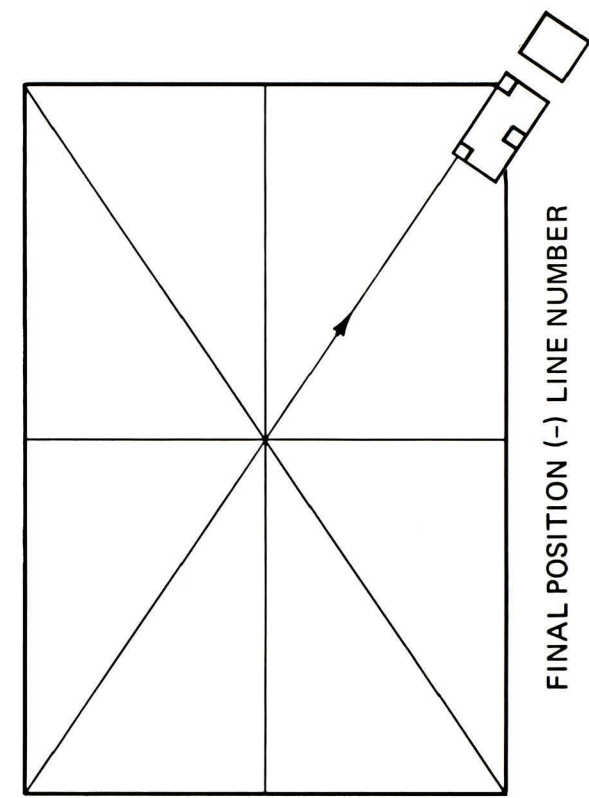
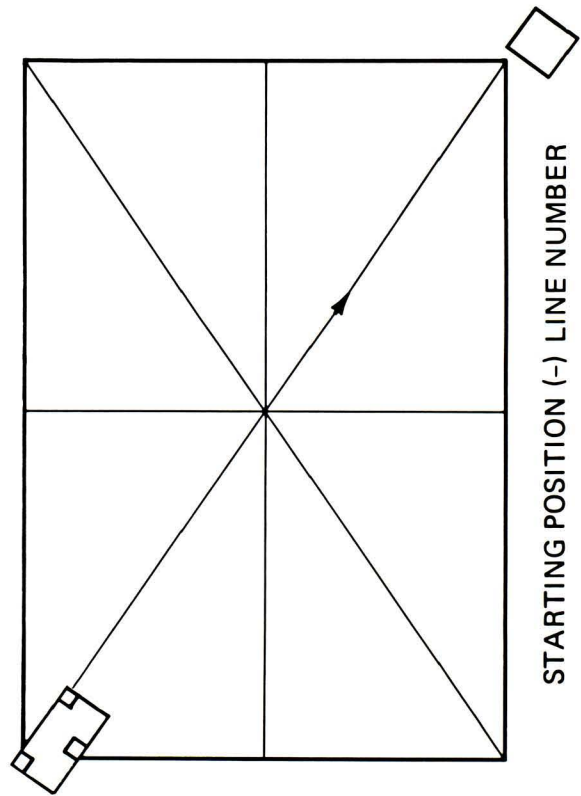
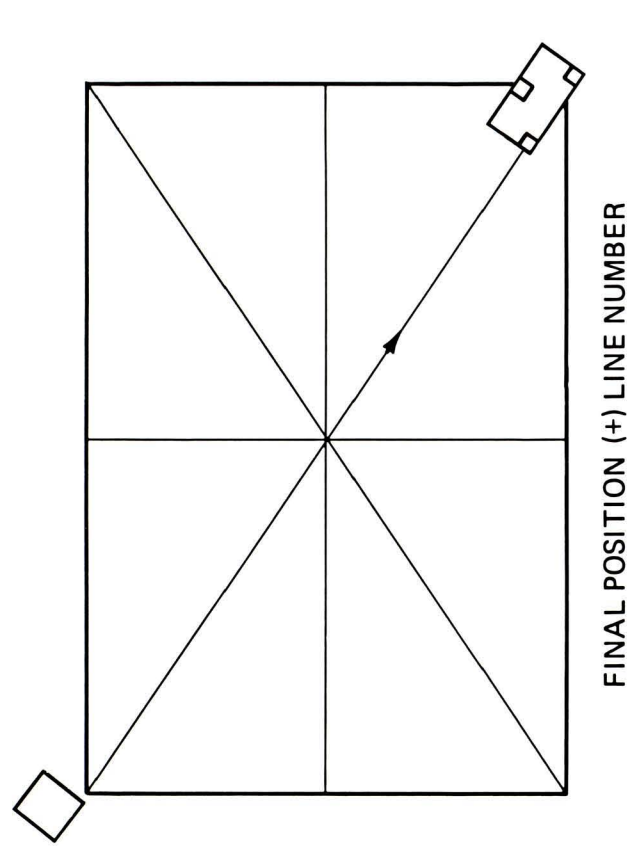
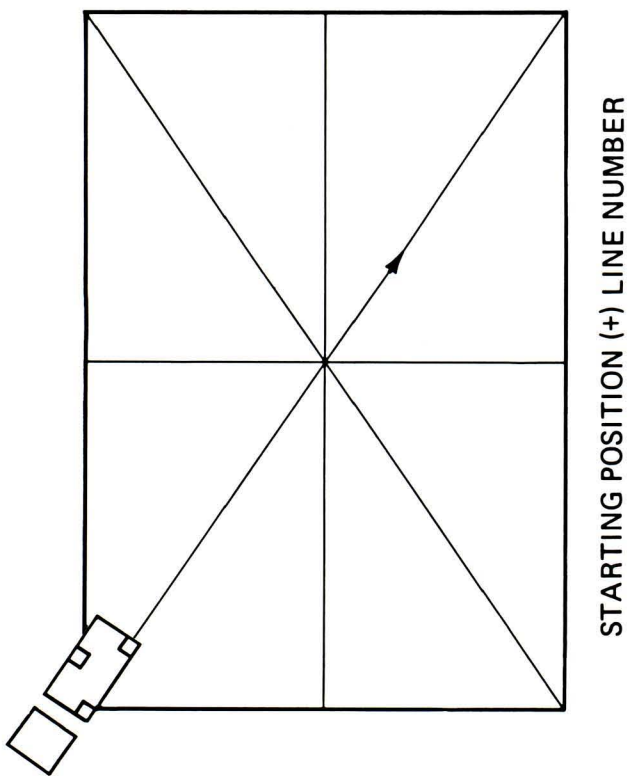


FIGURE 10



the line has been entered, the Calculator will take the data which have been stored for the line, will normalize them, and print the result on the Calculator Printer. The normalized line of data has the slope removed and is adjusted to give the end points a value of zero. The line can then be repeated by using the editing features of the program or the equipment can be set up to measure the next line.

When all of the data have been entered, and the Calculator program has been commanded that all of the data have been entered, the closure errors for Lines 7 and 8 will be printed along with the maximum elevation. These closure errors are a measure of the repeatability of the measurements and denote the mismatch of the center point where the diagonals and Lines 7 and 8 cross. If there were no errors in any measurements, the closure error for each center line would be zero. Since each error is reflected at the center point where the diagonals and lines 7 and 8 cross, the closure error will usually be non-zero. In most cases if the magnitude of the closure error is less than 100 microinches (2.5 micrometers), the calibration would be considered satisfactory, but the acceptable magnitude is a function of the surface plate flatness tolerance. If the magnitude of the error is greater than an acceptable value, then the inspection should be repeated.

The Data in Lines 7 and 8 are left in the format that displays the closure errors at the intersection of the two diagonals and the center lines. The printout and the plots are in this format.

The maximum elevation which is printed is the largest value of the data after all of the data have been adjusted to a base plane of zero. This procedure gives the lowest data point a value of zero. The maximum elevation then gives the distance between two parallel planes which enclose the data.

After the maximum elevation and the closure errors are printed, the program will give the option of receiving a complete printout of the final data or not, and the option of recording the final data on magnetic cards or not. The program will then return to the start and will accept a complete new set of data or the data stored in the Calculator can be edited. If the edit option is chosen, any individual line of data may be re-entered. Care must be taken to ensure that the number of data points entered for a line during editing does not exceed the original number of data points. If too many points are entered, then two lines of data will be overlapping and the final results will be erroneous. If the non-edit, or complete new set of data option is chosen, all of the existing data in the Calculator will be cleared.

The edit feature of the program is very useful because it allows any line to be re-inspected and new closure errors computed and printed within minutes. This can save much time in the total inspection and allows a higher utilization of both the inspector and the equipment.

### **Display of Results**

There are two plot programs for displaying the final data, and the operating instructions for these are located in Appendix A. One plot which is most commonly used is the Numeric Data Plot which is shown in Figures 11 and 12. This type of display is most often used for certification data from surface plate manufacturers and gives the final value of each inspection point. The second type of display is the Isometric Plot as shown in Figure 13. This technique is not intended for certification, but rather to give an overall view of the topography of the surface plate. The Isometric Plot can be used to determine rework areas easily and to determine the best areas of the plate for critical inspection setups.

Figures 11, 12, and 13 were generated by the Calculator program using the raw data from the example in Appendix B as input data.

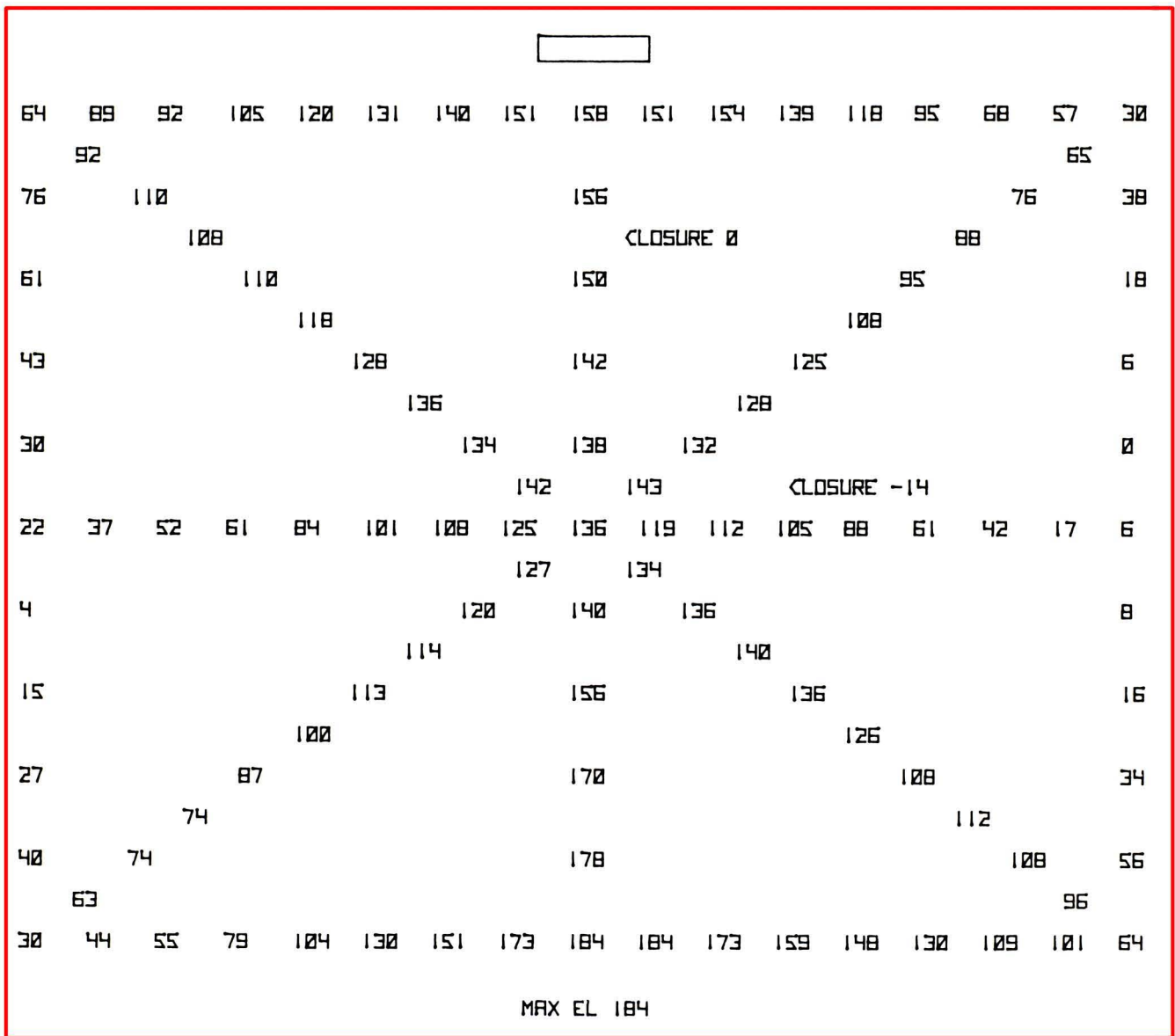


FIGURE 11. NUMERIC DATA PLOT BASE PLANE REFERENCE

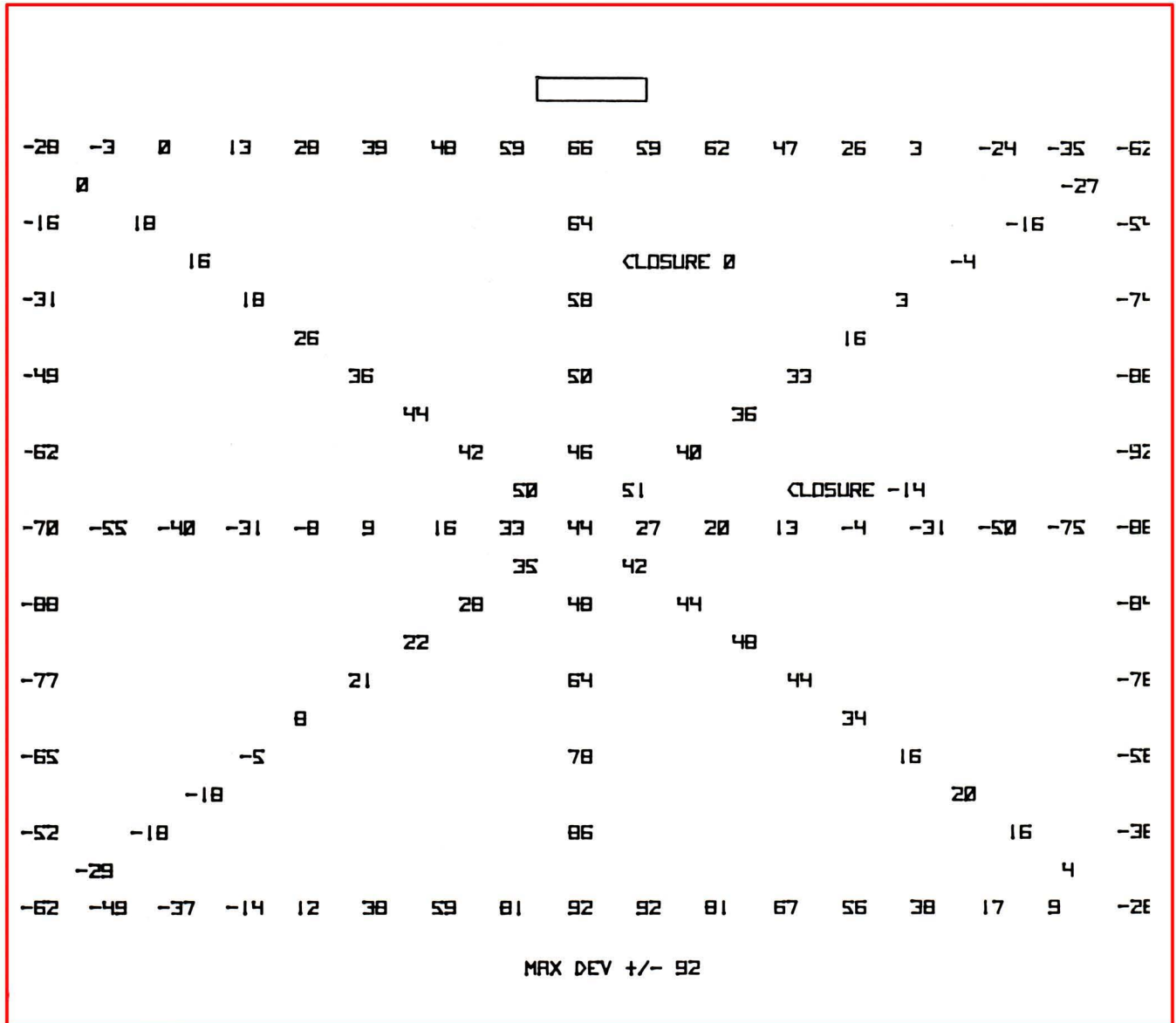


FIGURE 12 NUMERIC DATA PLOT MIDPLANE REFERENCE



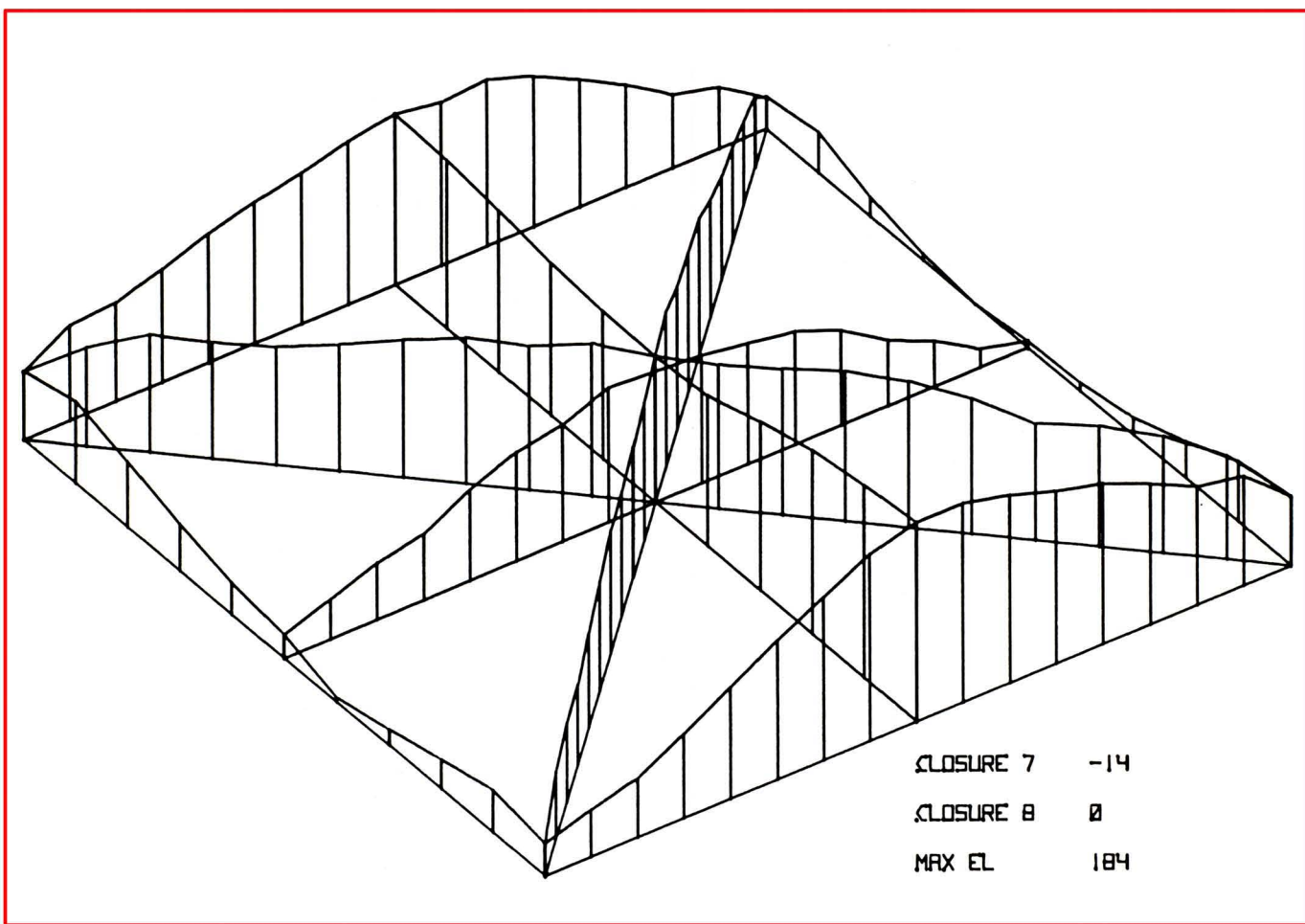


FIGURE 13. ISOMETRIC DATA PLOT

## APPENDIX A

### SURFACE PLATE CALIBRATION 9820A CALCULATOR PROGRAM

#### Main Program

1. Turn the Calculator ON.
2. The Display must be: "O: END |- ". If this is not displayed, check the Calculator handbook for diagnostic techniques.
3. Press: END ; LOAD EXECUTE. Then insert main program card side 1 into the card reader. The card will be read and "NOTE 14" will appear in the display. Press EXECUTE and insert card side 2 into the card reader and repeat the procedure for card side 3.
4. If it is desired to enter data from magnetic cards, press EXECUTE and load the card sides sequentially as in Step 3.
5. Press: END RUN PROGRAM. "METRIC?" will be displayed. If metric system data are to be entered, press O RUN PROGRAM. If English system data are to be entered, press RUN PROGRAM without any entry.
6. "EDIT DATA?" will be displayed. If the data in the calculator are to be modified, press O RUN PROGRAM and the data registers will be saved. OR if an entire set of new data is to be entered, press RUN PROGRAM and the data registers will be cleared.
7. "+/- LINE NO?" will be displayed. If all data have been entered, press RUN PROGRAM and go to Step 16. OR if more data are to be entered, enter LINE NUMBER (an integer between 1 and 8) if the retroreflector moves away from the interferometer, and enter -LINE NUMBER (an integer between -1 and -8) if the retroreflector moves toward the interferometer. (NOTE: See Figure 9 and accompanying explanation to determine +/- LINE NUMBER.)
8. "FOOT SPACING?" will be displayed. Enter FOOT SPACING in either the English or Metric System and press RUN PROGRAM. If no foot spacing is entered, the spacing (2.0625 inches or 52.3875 millimeters) of the 10559A Reflector Mount is automatically used.
9. "KEYBOARD INPUT?" will be displayed. Press O RUN PROGRAM for keyboard entry of data OR press RUN PROGRAM for direct entry of data from 5505A Display. If direct input is chosen, go to Step 13.
10. If keyboard input is chosen, "DATA?" will be displayed. Enter the data point value and press RUN PROGRAM. (NOTE: Input data with same sign as is displayed by the 5505A.)
11. The entry will be printed, "DATA?" will be displayed again, and the next data point is then entered. Repeat this procedure until all the data for the current line number have been entered. When the last data point has been entered, printed, and "DATA?" is being displayed, press RUN PROGRAM.
12. The input data will be normalized and printed. Return to Step 7.

13. For direct input, position the equipment for the first input data point. When the data are ready to be transmitted from the 5505A Display to the Calculator, press the Manual Print switch on the 5505A Display, or actuate this function through the AUX connector on the 5505A. The data will be transmitted, printed, and the Calculator will be ready for the next data point.
14. Move the Retroreflector to the next point and repeat step 13. When the last data point has been transmitted and printed, press the STOP key and press O RUN PROGRAM.
15. The input data will be normalized and printed. Return to Step 7.
16. When all the data have been entered and processed, the closure errors and the maximum elevation will be printed. "PRINTOUT?" will be displayed. If a complete listing is desired, press O RUN PROGRAM and the listing will be generated. If no listing is necessary, press RUN PROGRAM. (NOTE: Allow approximately 10 seconds computation time per 100 data points.)
17. "RECORD DATA?" will be displayed. If it is desired to record the normalized data on magnetic cards, press O RUN PROGRAM. Load side one into the magnetic card unit, and if "NOTE 14" appears in the display, press EXECUTE and repeat for side 2. Repeat this procedure until all the data have been recorded. If no record is desired on magnetic cards, press RUN PROGRAM. If more data calculations are desired, go to Step 5. If not, go to Step 18.
18. If no further data analysis is required, press STOP EXECUTE.

## **NUMERIC DATA PLOT FOR SURFACE PLATE CALIBRATION DATA 9820A CALCULATOR**

This program can be used to generate a numeric data plot of the normalized data from the Surface Plate Calibration Program onto the 9862A Plotter. It can be loaded into the Calculator immediately after processing the surface plate data without destroying any data or the data can be loaded from magnetic cards.

1. Turn the Calculator ON.
2. The display must be: "O:END |-". If this is not displayed, check the Calculator handbook for diagnostic techniques.
3. Press: END ; LOAD EXECUTE. Then load numeric data plot side 1 into the magnetic card reader. The card will be read and "NOTE 14" will appear in the display. Press EXECUTE and insert card side 2 into the reader.
4. If it is desired to enter data from magnetic cards, press EXECUTE and load the card sides sequentially as in Step 3.
5. Press: END RUN PROGRAM. "POSITIVE DATA?" will be displayed. If it is desired to display the data referenced to a base plane through the minimum value of the data, press O RUN PROGRAM. If it is desired to display the data referenced to a base plane through the midpoint of the maximum and minimum values, press RUN PROGRAM without any entry.



6. "LINES?" will be displayed. If the baselines are desired, press O RUN PROGRAM. If the baselines are not desired, press RUN PROGRAM.
7. "CHANGE PEN?" will be displayed. A different color pen can then be loaded on the plotter to give more contrast in the plot.
8. Press RUN PROGRAM and the numeric data plot will be generated.
9. Press: STOP EXECUTE.

### **ISOMETRIC PLOT FOR SURFACE PLATE DATA 9820A CALCULATOR PROGRAM**

This program is designed to isometrically plot the normalized data from the Surface Plate Calibration Program onto the 9862A Plotter. It can be loaded into the calculator immediately after processing the surface plate data without destroying any data or the data can be loaded from magnetic cards.

1. Turn the Calculator ON.
2. The display must be: "O:END |-". If this is not displayed, check the calculator handbook for diagnostic techniques.
3. Press:END ; LOAD EXECUTE. Then load isometric plot card side 1 into the magnetic card reader. The card will be read and "NOTE 14" will appear in the display. Press EXECUTE and insert card side 2 into the reader.
4. If it is desired to enter data from magnetic cards, press EXECUTE and load the card sides sequentially as in Step 3.
5. Press: END RUN PROGRAM.
6. "TILT ANGLE" will be displayed. If a tilt angle other than 10° is desired, enter the angle and press RUN PROGRAM. If a 10° tilt angle is appropriate, do not make an entry, and press RUN PROGRAM.
7. "ROT. ANGLE?" will be displayed. If a rotation angle other than 35° is desired, enter the angle and press RUN PROGRAM. If a 30° rotation angle is appropriate, do not make an entry and press RUN PROGRAM.
8. The baselines of the plot will be drawn and "CHANGE PEN?" will be displayed. A different color pen can then be loaded on the plotter to give more contrast in the plot.
9. Press: RUN PROGRAM and the isometric plot will be generated.
10. Press: STOP EXECUTE.

## APPENDIX B

### General

The procedure outlined in this Appendix manually converts readings to a complete description of the surface plate. It is quite helpful to draw a sketch of the surface grid and be prepared to label the elevations of points A through H (Figure B-1).

Readings in microinches or 0.01 microns are recorded in worksheet form according to the format in Table B-1 (Step #1 below). Each reading describes the elevation of the rear foot of the Reflector Mount with respect to the previous point. Note that the number recorded for station one on each line is zero, since the rear foot is on station #2 for the initial reading and station one becomes a zero reference.

In order to interpret these readings as elevation above a datum plane, they must be referenced to station #1, defined as elevation zero (Step #2)).

Next lines must be tilted so that their endpoints coincide. This is accomplished via the "correction factor" (Step #3). For the diagonal lines, AE and CG, the midpoints are also constrained to meet at the new zero elevation (Step #4 for diagonal lines).

The center lines, BF and DH provide a check on the reproducibility of the calibration. See Step #7 for center lines.

Finally, all points are elevated so that all readings are positive.

### Diagonal Lines (example: AE)

1. Record all readings in order in column 2. The first reading is opposite station #2.
2. Enter in column 3 the algebraic sum of all readings in column 2 down to and including each station. This sum is the elevation of the station with respect to station #1.
3. Calculate the correction factor by dividing the last value in column 3 by the total number of stations on the line minus one. For line AE, there are 21 stations, so  $C.F. = 120/20 = 6$ .
4. Entries in column 4: First, reverse the sign of the value in column 3 opposite the midstation and enter it at the same station in column 4. Calculate the other entries in column 4 by successively adding the correction factor to each station above the midpoint, and by successively subtracting below the midpoint.
5. For each station, add algebraically the values in columns 3 and 4 and enter the sum in column 5. The first and last stations should now have the same elevation, and the midstation should have a zero elevation.
6. Record the elevations of points A, E, C, and G from column 5 on the sketch as shown in Figure B-1. Also label the centerpoint zero.

### Perimeter Lines (example: CA)

- 1-2. Same as 1-2 in Diagonal Lines.
3. Enter the elevations of the endpoints in column 5. For line CA, enter the elevation of point C(-106) opposite station #1 and point A(-72) opposite station #17.

4. Calculate the correction factor: First, subtract the value opposite the last station in column 3 from the corresponding value in column 5, and enter the difference in column 4. (For line CA,  $-72 - [-78] = 6$ ).

Next, copy the first value in column 5 into column 4. (For line CA,  $-106$ ). For the correction factor, subtract the last value in column 4 from the first and divide by the number of stations minus one. For line CA.,

$$CF. = \frac{-106-6}{17-1} = \frac{-112}{16} = -7$$

5. Add the correction factor successively to each station in column 4, working up from the last station.
6. As above, algebraically add values in columns 3 and 4 and enter the sum in column 5 for each station.
7. Record the elevations of points B, D, F, and H on the sketch.

#### Center Lines (examples: DH)

- 1-6. Same as 1-6 for Perimeter Lines. For line DH, the elevation of the first station in column 5 will be that of point D ( $-130$ ), and the last station that of point H ( $-114$ ). The correction factor is:

$$C.F. = \frac{-130 - (-82)}{17-1} = \frac{-48}{16} = -3$$

7. Ideally, the midpoints of the two center lines should now read zero so that they will intersect the diagonal lines at the center of the plate. In practice, these midpoint values will be non-zero due to an accumulation of random errors such as the influence of temperature changes and dust settlement. The differences between the diagonal midpoint and the midpoint of each center line are referred to as closure errors. The magnitude of these two elevations provides us with a check on the reproducibility of the calibration. In the example, the midpoint of the line DH is  $-14$  and the midpoint of the line BF is  $-2$ ; this is a good calibration. Criteria for accepting or rejecting a calibration run at this point depend on the reproducibility required to test the plate's specification. For most purposes, a reproducibility or closure error of less than 100 microinches (2.5 micrometers) is required. The check may be applied at this stage of the procedure.
8. Change the sign of the value of the midstation in column 5 (for line DH,  $-14$ ) and add it to each entry of column 5, recording each result in column 6. This forces the center lines to intersect the diagonals at the center of the plate (elevation zero), moving the reproducibility errors to the edges. (NOTE: Column 6 has entries for only the two center lines.)

#### Final Step

Search through all entries in column 5 (column 6 for center lines) and find the largest negative number. In our example, the number is  $-136$ , station #5 of line CE. Change the sign of this number and add it to every column 5 entry (column 6 for center lines) recording the result in column 7. The calibration is now complete, with all numbers in the grid having a positive value.



1	2	3	4	5	6	7
Station	Reading	Gross Elevation	Correction Factor	Elevation Above Datum	Revised Center Line	Elevation Final
Diagonal Line AE						
1	0	0	-72	-72		64
2	34	34	-78	-44		92
3	24	58	-84	-26		110
4	4	62	-90	-28		108
5	8	70	-96	-26		110
6	14	84	-102	-18		118
7	16	100	-108	-8		128
8	14	114	-114	0		136
9	4	118	-120	-2		134
10	14	132	-126	6		142
11	0	132	-132	0		136
12	4	136	-138	-2		134
13	8	144	-144	0		136
14	10	154	-150	4		140
15	2	156	-156	0		136
16	-4	152	-162	-10		126
17	-12	140	-168	-28		108
18	10	150	-174	-24		112
19	2	152	-180	-28		108
20	-6	146	-186	-40		96
21	-26	120	-192	-72		64
Diagonal Line CG						
1	0	0	-106	-106		30
2	42	42	-112	-70		66
3	18	60	-119	-59		77
4	18	78	-126	-48		88
5	14	92	-133	-41		95
6	20	112	-140	-28		108
7	24	136	-146	-10		126
8	10	146	-153	-7		129
9	10	156	-160	-4		132
10	18	174	-167	7		143
11	0	174	-174	0		136
12	-2	172	-181	-9		127
13	0	172	-188	-16		120
14	0	172	-194	-22		114
15	6	178	-201	-23		113
16	-6	172	-208	-36		100
17	-6	166	-215	-49		87
18	-6	160	-222	-62		74
19	6	166	-228	-62		74
20	-4	162	-235	-73		63
21	-26	136	-242	-106		30
Perimeter Line CA						
1	0	0	-106	-106		30
2	20	20	-99	-79		57
3	4	24	-92	-68		68
4	20	44	-85	-41		95
5	16	60	-78	-18		118
6	14	74	-71	3		139
7	8	82	-64	18		154
8	-10	72	-57	15		151
9	0	72	-50	22		158
10	-14	58	-43	15		151
11	-18	40	-36	4		140
12	-16	24	-29	-5		131
13	-18	6	-22	-16		120
14	-22	-16	-15	-31		105
15	-20	-36	-8	-44		92
16	-10	-46	-1	-47		89
17	-32	-78	+6	-72		64
Perimeter Line CE						
1	0	0	-106	-106		30
2	2	2	-100	-98		38
3	-26	-24	-94	-118		18
4	-18	-42	-88	-130		6
5	-12	-54	-82	-136		0
6	0	-54	-76	-130		6
7	-4	-58	-70	-128		8
8	2	-56	-64	-120		16
9	12	-44	-58	-102		34
10	16	-28	-52	-80		56
11	2	-26	-46	-72		64

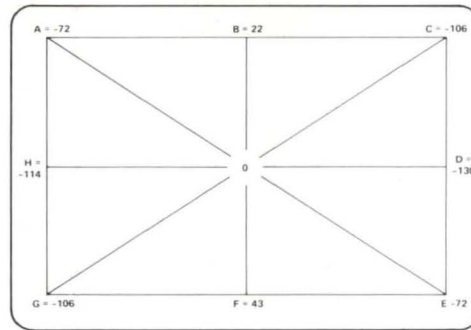
TABLE B-1. SURFACE PLATE FLATNESS WORKSHEET

1	2	3	4	5	6	7
Station	Reading	Gross Elevation	Correction Factor	Elevation Above Datum	Revised Center Line	Elevation Final
Perimeter Line EG						
1	0	0	-72	-72		64
2	36	36	-71	-35		101
3	8	44	-70	-26		110
4	20	64	-69	-5		131
5	18	82	-68	14		150
6	10	82	-66	16		152
7	14	96	-65	31		167
8	10	106	-64	42		178
9	0	106	-63	43		179
10	-12	94	-62	32		168
11	-22	72	-61	11		147
12	-22	50	-60	-10		126
13	-26	24	-59	-35		101
14	-26	-2	-57	-59		77
15	-24	-26	-56	-82		54
16	-12	-38	-55	-93		43
17	-14	-52	-54	-106		30
Perimeter Line AG						
1	0	0	-72	-72		64
2	20	20	-80	-60		76
3	-8	12	-87	-75		61
4	-10	2	-95	-93		43
5	-6	-4	-102	-106		30
6	0	-4	-110	-114		22
7	-10	-14	-118	-132		4
8	18	4	-125	-121		15
9	20	24	-133	-109		27
10	20	44	-140	-96		40
11	-2	42	-148	-106		30
Center Line DH						
1	0	0	-130	-130	-116	20
2	8	8	-127	-119	-105	31
3	22	30	-124	-94	-80	56
4	16	46	-121	-75	-61	75
5	24	70	-118	-48	-34	102
6	14	84	-115	-31	-17	119
7	4	88	-112	-24	-10	126
8	4	92	-109	-17	-3	133
9	0	92	-106	-14	0	136
10	0	92	-103	-11	3	139
11	-20	72	-100	-28	-14	122
12	-10	62	-97	-35	-21	115
13	-20	42	-94	-52	-38	98
14	-26	16	-91	-75	-61	75
15	-12	4	-88	-84	-70	66
16	-18	-14	-85	-99	-85	51
17	-18	-32	-82	-114	-100	36
Center Line BF						
1	0	0	22	22	24	160
2	0	0	20	20	22	158
3	-4	-4	17	13	15	151
4	-6	-10	15	5	7	143
5	-2	-12	12	0	2	138
6	0	-12	10	-2	0	136
7	6	-6	7	1	3	139
8	18	12	5	17	19	155
9	16	28	2	30	32	168
10	10	38	-1	37	39	175
11	8	46	-3	43	45	181

TABLE B-1. SURFACE PLATE FLATNESS WORKSHEET (Cont'd)

### Display of Results

The data in column 7 may be expressed by manually plotting the data in any of a variety of graphical forms. The most common form is that of Figure 11, where elevations are located on a plan view of the surface plate. Another method is the isometric plot, as in Figure 13. Still more sophisticated presentations are possible, such as contour graphs.



**FIGURE B-1. WORKING SKETCH**



For more information, call your local HP Sales Office or nearest Regional Office: **Eastern** (201) 265-5000; **Midwestern** (312) 255-9800; **Southern** (404) 955-1500; **Western** (213) 970-7500; **Canadian** (416) 678-9430. Ask the operator for instrument sales. Or write Hewlett-Packard, 1501 Page Mill Road, Palo Alto, CA 94304. In Europe: Hewlett-Packard S.A., 7, rue du Bois-du-Lan, P.O. Box, CH 1217 Meyrin 2, Geneva, Switzerland. In Japan: Yokogawa-Hewlett-Packard Ltd., 29-21, Takaido-Higashi 3-chome, Suginami-ku, Tokyo 168.

02-5952-0820

PRINTED IN U.S.A.