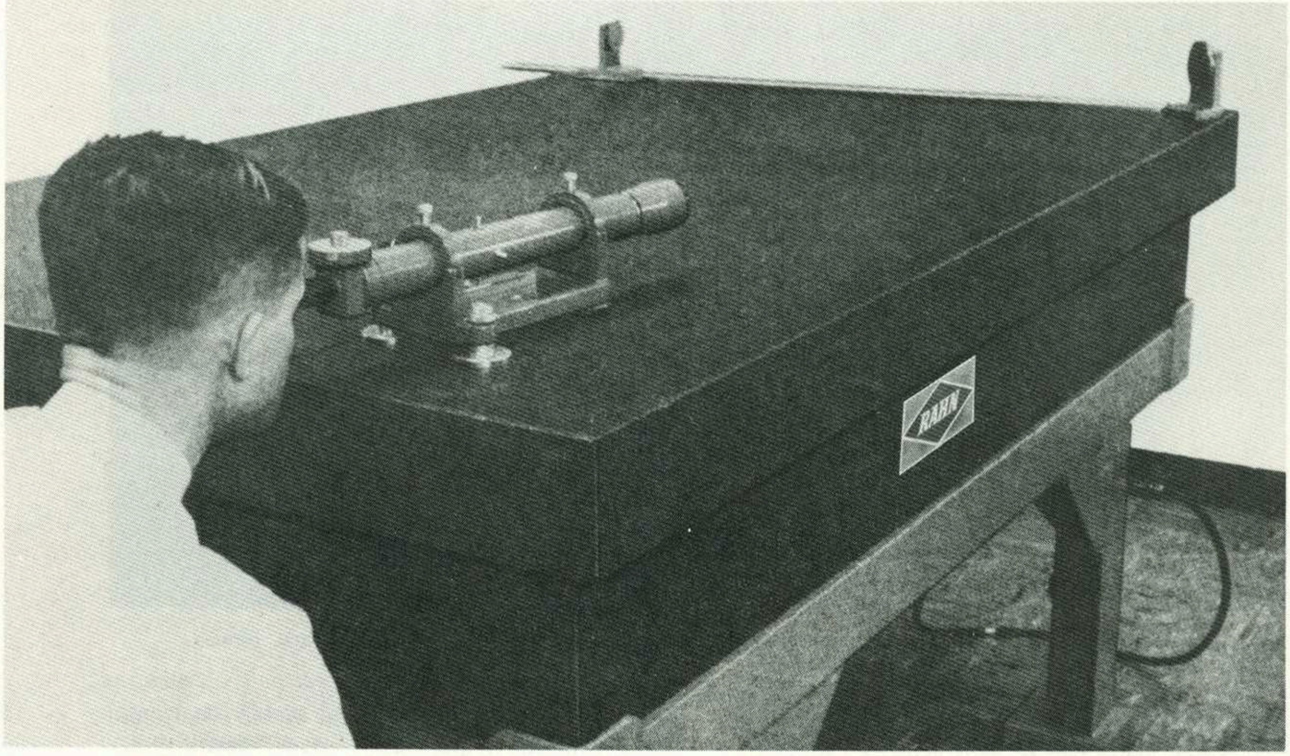


Fig. 1. Typical calibration setup showing the autocollimator, optical flat attached to mount on extreme left-hand corner, mirror mount on extreme right-hand corner and straight edge on end of surface plate.

how to calibrate surface plates in the plant

By J. C. Moody

Physical and Electrical Standards Dept.
Sandia Corp.
Albuquerque, N. M.

SINCE MEASUREMENTS are no more reliable than the surface plate on which they are referenced, it is important to know exactly the accuracy of the plate being used. Surface plates are manufactured to accuracies varying from 0.002 to 0.00005 inch of deviation from a true plane. The user should check each plate after it is installed to determine whether it meets specifications and from time to time thereafter to learn the effect of wear and environment. The check measurements must, for practical purposes, be done in the work environment.

Fortunately, a practicable method of accurately calibrating surface plates is available to industry. The method used in the metrology laboratory at Sandia Corp. is highly accurate yet can be performed by semiskilled personnel using instruments available to any industrial laboratory. This method is an application and extension of procedures developed by K. J. Hume (British metrologist) and involves no new principles.

Ideally, the calibration should be performed in a room in which the temperature of the plate can be kept in equilibrium and from which thermal currents can be excluded. However, industry uses

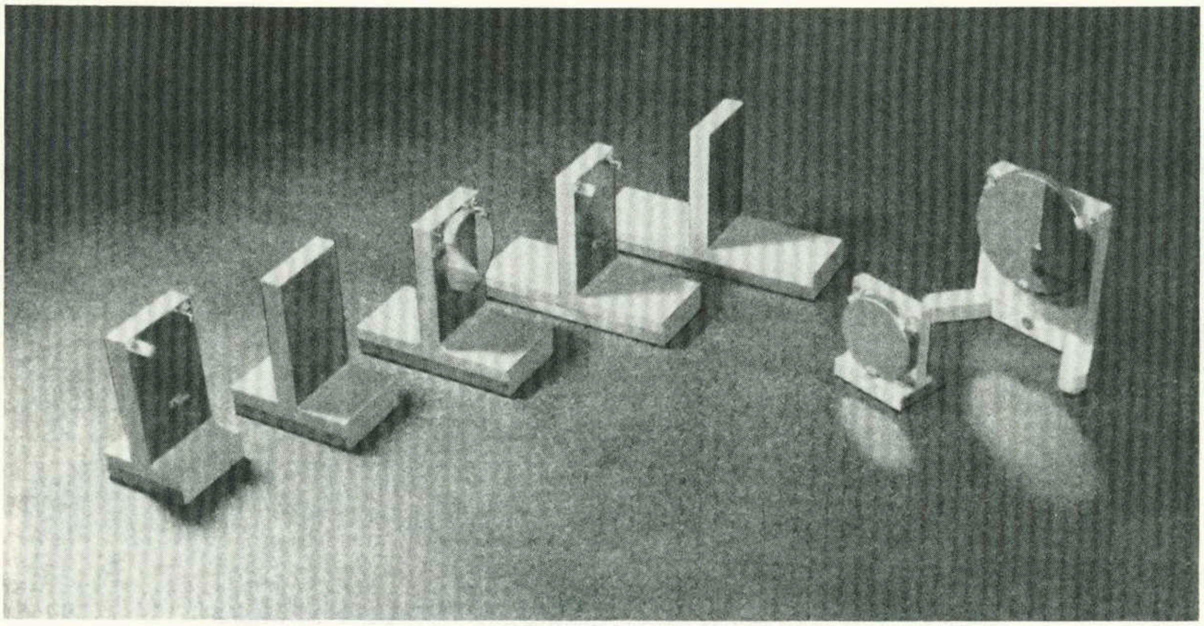


Fig. 2. Mirror mount, reflector mounts and optical flats used for calibrating surface plates.

surface plates under conditions that are less than ideal. These plates can be satisfactorily calibrated under the same conditions. Extremes of temperature changes, thermal currents, and vibration are obviously to be avoided.

Calibration Method: Equipment needed for this method is shown in *Fig.* 1. The autocollimator is essentially an optical lens system from which parallel rays are emitted. These rays strike the surface of a steel optical flat and are reflected back into the autocollimator. The reflected rays produce an image at the focal plane of the autocollimator from which angular displacements can be accurately determined.

The reflector is mounted on a bracket, the support pads of which are separated by a distance arbitrarily chosen so that it will divide evenly into the dimensions of the surface plate. This distance should be about 8 percent of the length of the short side of the plate. Various reflector mounts needed for different size plates are shown in *Fig.* 2. The mirror mounting bracket is so designed that the mirror mounting is normal to the surface plate. Steel optical flats, the faces of which do not deviate from a plane by more than 0.000003 inch, are used for both the mirror and reflector. In addition, a straight edge, graduated in increments equal to the distance between the support pads of the reflector stand, is used.

A total of eight lines of readings are taken: four perimeter lines, two diagonal lines, and two center lines, *Fig.* 3. The perimeter lines are laid out one increment from the edge of the plate. The precise stations at which readings along all eight lines are taken are measured off in steps equal to the increments on the straight edge. Many more readings could be taken, but a reasonable compromise between accuracy and economy is achieved by this method.

Detailed instructions for using an autocollimator are supplied with the instrument and should be studied carefully. The position of the autocollimator for each line of readings is shown in *Fig.* 3. The readings along the north perimeter line, for example, are taken with the autocollimator in the southwest corner of the plate. The reflector is moved along the line and readings are taken at each station. These readings are entered directly on the properly identified work sheet, *Fig.* 4. After each line is completed, the reflector is moved back to the first station on that line and another reading taken. If this does not agree within ± 0.3 sec. of

Fig. 3. Positions of autocollimator during readings for the eight principal lines.

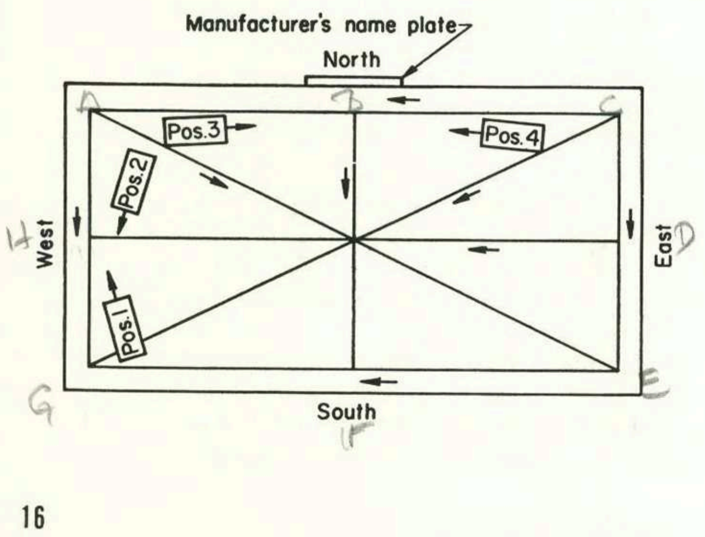
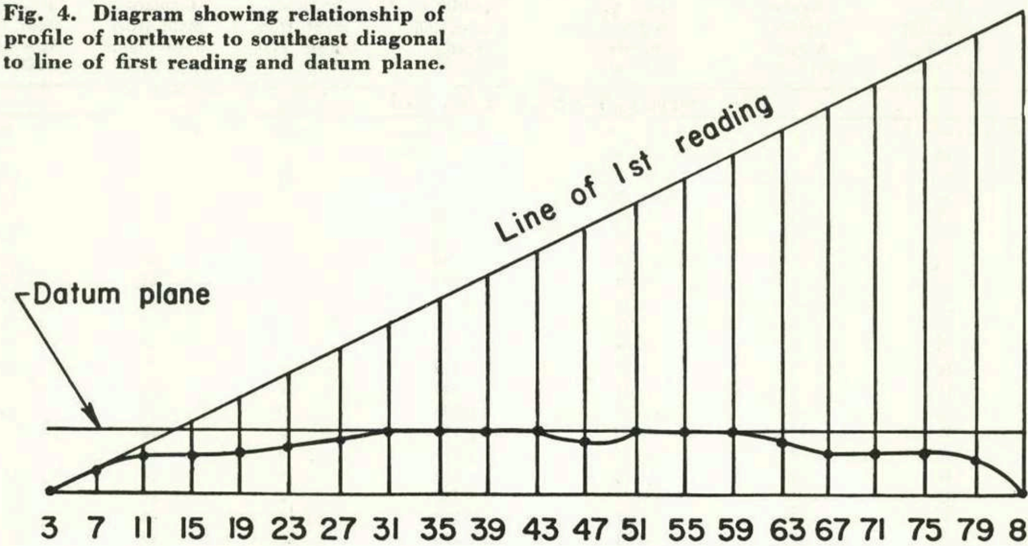


Fig. 4. Diagram showing relationship of profile of northwest to southeast diagonal to line of first reading and datum plane.



arc with the first reading taken at the same station, the operation must be repeated.

Autocollimator readings entered on the work sheet show only angular displacement in tenths of a second of arc in relation to the line of first reading. To be readily meaningful, these must be converted to linear deviations from a base plane. The procedure for these conversions and their presentation will be discussed in the following paragraphs.

Though care must be exercised in each step, the conversion is not a formidable task. Readings can be made in about two hours; an intelligent, properly instructed clerk can reduce the data to an accurate profile of the surface plate in an equal time.

Simplified Data Conversion Procedure: Directions for converting autocollimator readings into linear displacement in hundred-thousandths of an inch are given without any attempt at theoretical justification. One line of each class will be explained in detail. The reader who is interested in the theoretical considerations should read K. J. Hume's *Engineering Metrology* or the author's paper, *The Metrology of Surface Plates*, copies of which are available upon request.

The person who is to reduce the data is given a work sheet for each of the eight lines, TABLE 1. On these, the stations at which readings were taken are indicated in Column 1 in terms of inches from the edge of the plate in the direction in which the line was read. The autocollimator readings are entered in Column 2. No reading is entered for the first station on the line.

CONVERSION FOR DIAGONALS: To process the Northwest to Southeast diagonal line data, the following steps should be taken in order:

1. Convert the autocollimator readings into angular displacement by determining the amount by which each value in Column 2 is greater or less than the first value in Column 2. Do this at each station; enter the result in Column 3, paying attention to the sign.
2. Next, determine the algebraic sum of the angular displacement at each station and enter this value in Column 4. To do this, add the values in Column 3 down to and including each station.
3. Divide the last value in Column 4 by the total number minus one of the stations on the line to determine the correction factor. (In the example shown there are 21 stations. Hence, $-280/20 = -14$.)
4. Set up an arithmetic progression in Column 5. Reverse the sign of the value in Column 4 opposite the midstation and enter it opposite the same station in Column 5. Working up Column 5 from the midstation, add the correction factor cumulatively at each station. Return to the midstation and subtract the correction factor cumulatively at each station to the bottom of the column. The resulting arithmetical progression is the cumulative correction factor for each station.
5. At each station, add algebraically the values in Columns 4 and 5. Enter the sum which is the angular displacement from the datum plane in Column 6. (The datum plane, *Fig.* 4, is that plane in which the center point of the surface plate lies and is parallel to the lines containing the end points of each diagonal.) Proceed with the other diagonal in exactly the same way to this point. Before the last two columns for the diagonal can be completed, computations for the perimeter and center lines must be carried to this point. Do the perimeter lines next.

CONVERSION FOR NORTH PERIMETER LINE:

1. Proceed exactly as with the diagonals through Column 4 for each of the perimeter lines.
2. Prepare a chart of the surface plate as illustrated in *Fig.* 5. Enter the physical center, 0, and the values found for the ends of the diagonals from

Table 1—Work Sheets for Calibrating a 48 x 78-Inch Surface Plate*

1	2	3	4	5	6	7	8
Station (inches from edge) (No.)	Auto-collimator Readings (0.1″ arc)	Angular Displacements (0.1″ arc)	Sum of Displacements (0.1″ arc)	Cumulative Correction Factor (0.1″ arc)	Displacement from Datum Plane (0.1″ arc)	Displacement from Base Plane (0.1″ arc)	Displacement from Base Plane (0.00001 in.)
			Diagonal, Northwest to Southeast		AE		
3	—	—	—	−36	−36	32	6
7	65	0	0	−22	−22	46	9
11	60	−5	−5	−8	−13	55	11
15	50	−15	−20	+6	−14	54	11
19	52	−13	−33	+20	−13	55	11
23	55	−10	−43	+34	−9	59	12
27	56	−9	−52	+48	−4	64	13
31	55	−10	−62	+62	0	68	14
35	50	−15	−77	+76	−1	67	14
39	55	−10	−87	+90	+3	71	14
43	48	−17	−104	+104	0	68	14
47	50	−15	−119	+118	−1	67	13
51	52	−13	−132	+132	0	68	14
55	53	−12	−144	+146	+2	70	14
59	49	−16	−160	+160	0	68	14
63	46	−19	−179	+174	−5	63	13
67	42	−23	−202	+188	−14	54	11
71	53	−12	−214	+202	−12	56	11
75	49	−16	−230	+216	−14	54	11
79	45	−20	−250	+230	−20	48	10
83	35	−30	−280	+244	−36	32	6
			Diagonal, Northeast to Southwest		CG		
3	—	—	—	−53	−53	15	3
7	66	0	0	−35	−35	33	6
11	54	−12	−12	−18	−30	38	7
15	54	−12	−24	0	−24	44	8
19	52	−14	−38	+17	−21	47	9
23	55	−11	−49	+35	−14	54	11
27	57	−9	−58	+53	−5	63	12
31	50	−16	−74	+70	−4	64	13
35	50	−16	−90	+88	−2	66	13
39	54	−12	−102	+105	+3	71	14
43	45	−21	−123	+123	0	68	14
47	44	−22	−145	+141	−4	64	13
51	45	−21	−166	+158	−8	60	12
55	45	−21	−187	+176	−11	57	11
59	48	−18	−205	+193	−12	56	11
63	42	−24	−229	+211	−18	50	10
67	42	−24	−253	+229	−24	44	9
71	42	−24	−277	+246	−31	37	8
75	48	−18	−295	+264	−31	37	7
79	42	−23	−318	+281	−37	31	6
83	32	−34	−352	+299	−53	15	3
			North Perimeter Line East to West		CA		
4	—	—	—	−53	−53	15	3
8	205	0	0	−40	−40	28	6
12	197	−8	−8	−26	−34	34	7
16	205	0	−8	−13	−21	47	9
20	203	−2	−10	+1	−9	59	12
24	202	−3	−13	+14	+1	69	14
28	199	−6	−19	+28	+9	77	15
32	190	−15	−34	+41	+7	75	15
35	195	−10	−44	+55	+11	79	16
40	183	−17	−61	+69	+8	76	15
44	186	−19	−80	+82	+2	70	14
48	187	−18	−98	+96	−2	66	13
52	186	−19	−117	+109	−8	60	12
56	184	−21	−138	+123	−15	53	11
60	185	−20	−158	+136	−22	46	9
64	190	−15	−173	+150	−23	45	9
68	179	−26	−199	+163	−36	32	6
			East Perimeter Line North to South		CE		
4	—	—	—	−53	−53	15	3
8	35	0	0	−49	−49	19	4
12	21	−14	−14	−45	−60	8	2
16	25	−10	−24	−41	−65	3	1
20	28	−7	−31	−37	−68	0	0
24	34	−1	−32	−33	−65	3	1
28	32	−3	−35	−29	−64	4	1
32	35	0	−35	−25	−60	8	2
36	40	+5	−30	−21	−51	17	3
40	42	+7	−23	−17	−40	28	5
44	35	0	−23	−13	−36	32	6

*All values except Columns 1 & 8 are in tenths of a second of arc.

Table 1 (Continued)*

1	2	3	4	5	6	6a	7	8	
Station (inches from edge) (No.)	Auto-collimator Readings (0.1″ arc)	Angular Displacements (0.1″ arc)	Sum of Displacements (0.1″ arc)	Cumulative Correction Factor (0.1″ arc)	Displacement from Datum Plane (0.1″ arc)		Displacement from Base Plane (0.1″ arc)	Displacement from Base Plane (0.00001 in.)	
				South Perimeter Line East to West EG					
4	—	—	—	— 36	—36		32	6	E
8	164	0	0	— 18	—18		50	10	
12	150	—14	— 14	0	—14		54	11	
16	156	— 8	— 22	+ 19	— 3		65	13	
20	155	— 9	— 31	+ 37	+ 6		74	15	
24	151	—13	— 44	+ 55	+11		79	16	
28	153	—11	— 55	+ 73	+18		86	17	
32	151	—13	— 68	+ 92	+24		92	18	
36	146	—18	— 86	+110	+24		92	18	
40	140	—24	—110	+128	+18		86	17	
44	135	—29	—139	+147	+ 8		76	15	
48	135	—29	—168	+165	— 3		65	13	
52	133	—31	—199	+183	—16		52	11	
56	133	—31	—230	+201	—29		39	8	
60	134	—30	—260	+220	—40		28	6	
64	140	—24	—284	+238	—46		22	4	
68	139	—25	—309	+256	—53		15	3	G
				West Perimeter Line North to South AG					
4	—	—	—	—36	—36		32	6	A
8	60	0	0	—30	—30		38	~~8~~ 7	
12	46	—14	—14	—24	—38		30	6	
16	45	—15	—29	—17	—46		22	4	
20	47	—13	—42	—11	—53		15	3	
24	50	—10	—52	— 5	—57		11	2	
28	45	—15	—67	+ 1	—66		2	0	
32	59	— 1	—68	+ 7	—61		7	1	
36	60	0	—68	+14	—54		14	3	
40	60	0	—68	+20	—48		20	4	
44	49	—11	—79	+26	—53		15	3	G
				Center Line East to West					
4	—	—	—	—65	—65	—58	10	2	
8	117	0	0	—59	—59	—52	16	3	D
12	124	+ 7	+ 7	—53	—46	—39	29	6	
16	121	+ 4	+11	—47	—36	—29	39	8	
20	125	+ 8	+19	—42	—23	—16	52	10	
24	120	+ 3	+22	—36	—14	— 7	61	12	
28	115	— 2	+20	—31	—11	— 4	64	13	
32	115	— 2	+18	—26	— 8	— 1	67	13	
36	113	— 4	+14	—21	— 7	0	68	14	
40	113	— 4	+10	—15	— 5	+ 2	70	14	
44	103	—14	— 4	—10	—14	— 7	61	12	
48	108	— 9	—13	— 4	—17	—10	58	12	
52	103	—14	—27	+ 1	—26	—19	49	10	
56	100	—17	—44	+ 7	—37	—30	38	8	
60	107	—10	—54	+12	—42	—35	33	7	
64	104	—13	—67	+18	—49	—42	26	5	H
68	104	—13	—80	+23	—57	—50	18	3	
				Center Line North to South					
4	—	—	—	+11	+11		79	16	B
8	66	0	0	+10	+10		78	16	
12	64	—2	— 2	+ 9	+ 7		75	15	
16	63	—3	— 5	+ 8	+ 3		71	14	
20	65	—1	— 6	+ 7	+ 1		69	14	
24	66	0	— 6	+ 6	0		68	14	
28	69	+3	— 3	+ 5	+ 2		70	14	
32	75	+9	+ 6	+ 4	+10		78	16	
36	74	+8	+14	+ 3	+17		85	17	
40	71	+5	+19	+ 2	+21		89	18	F
44	70	+4	+23	+ 1	+24		92	18	

*All values except Columns 1 & 8 are in tenths of a second of arc.

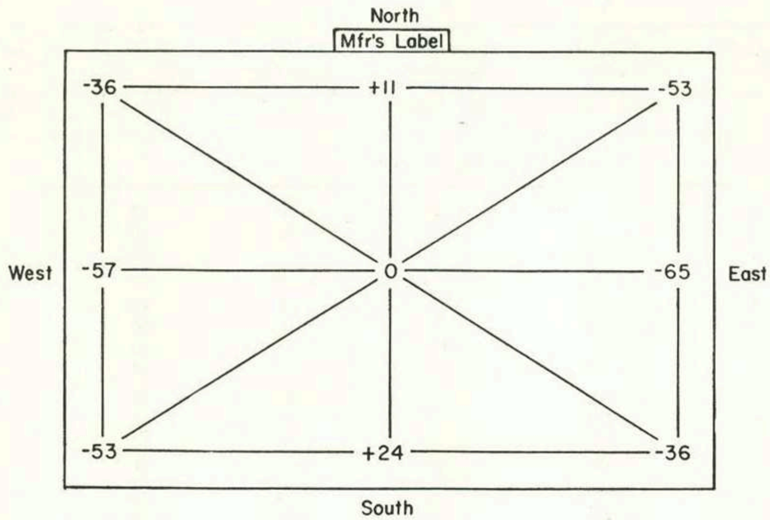


Fig. 5. Data reduction work sketch for determining correction factors and displacements from datum plane.

Column 6 in the work sheets as shown. This chart is important as without it there is danger of confusing the figures.

3. Enter the value for the NE end of the NE-SW diagonal in Columns 5 and 6 opposite the first station. Enter the value of the NW end of the NW-SE diagonal opposite the last station in Column 6 only.
4. Next, find the correction factor. Subtract the value opposite the last station in Column 4 from the value opposite the same station in Column 6 [$-36 -(-199) = 163$]. Enter this value opposite the last station in Column 5. Subtract this value from that opposite the first station in Column 5 ($-53 -163 = -216$) and divide the result by the total number of stations on the line minus one ($-216/16 = -13.5$). The result is the correction factor.
5. Beginning at the last station in Column 5, add the correction factor cumulatively up the column at each station. (Since the correction factor in the example is -13.5 to avoid decimals -13 and -14 are used alternately.)
6. To find the angular displacement from the datum plane, algebraically add the values opposite each station in Columns 4 and 5 and enter the results in Column 6.

Complete the conversion for each of the perimeter lines to this point and enter the values at the midpoints in *Fig.* 5. Now proceed with the center lines.

Conversion for East to West Center Line:

1. Carry the conversion through Column 4. The procedure for the center lines is exactly the same as for the diagonal and perimeter lines to this point.
2. From *Fig.* 5, enter the value for the midpoint of the east perimeter line opposite the first station in Columns 5 and 6. Enter the value for the midpoint of the west perimeter line opposite the last station in Column 6 only.
3. Subtract the value opposite the last station in Column 4 from the value opposite the same station in Column 6 and enter this value at the last station in Column 5.
4. Subtract the last value in Column 5 from the first and divide the result by the total number of stations on the line minus one. The result is the correction factor.
5. Beginning at the last station in Column 5, add the correction factor up the Column in an arithmetic progression to find the cumulative correction factor for each station.
6. At each station, algebraically add the values in Columns 4 and 5 and enter the result in Column 6. This is the angular displacement from the datum plane.
7. Change the sign of the value opposite the midstation in Column 6 and add it to the value opposite each station in Column 6. Enter the sums in Column 6a.

A word of explanation is necessary at this point. The center line check is the criterion of accuracy for the entire operation. The value at the point at which the center lines and diagonals intersect is physically zero. If everything were done perfectly, the value opposite the center station would be zero. But this is not possible because each slight error in reading the instrument is reflected at the midstation of the center lines. If the magnitude of this error is under 0.0001, the calibration may be regarded as satisfactory; if not, the job must be done over.

Column 6a, which appears only in the work sheets for the center lines, is used to move the error away from the center, which is known to be zero, out to the perimeter.

Final Steps in Conversion: The work sheets for the eight lines are now completed through Column 6, including Column 6a for the center lines. The procedure for Columns 7 and 8 is identical for all work sheets and must be done together.

1. Seach through Column 6 for all work sheets, Column 6a of the center lines, for the lowest value in all of the 8 columns. Add this value to the value opposite each station in Column 6 (6a for the center lines) and enter the sums in Column 7. This

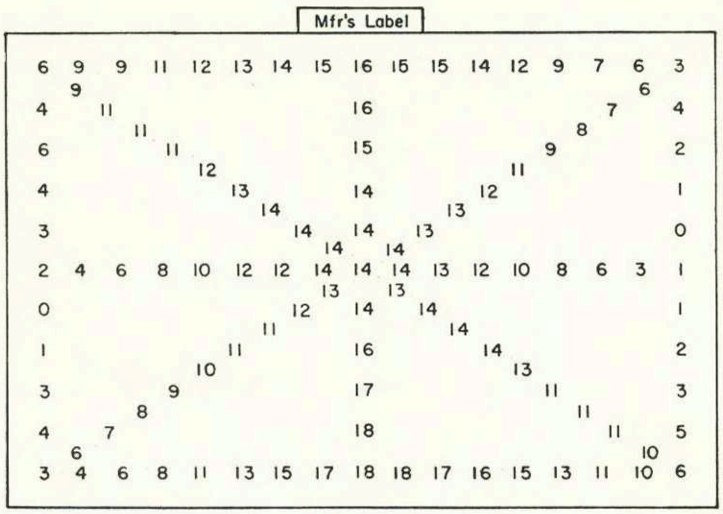


Fig. 6. Linear deviations from base plane indicated along the eight principal lines of a 48 x 72-inch granite surface plate. Figures represent height from base plane in 0.00001 inch units. All points lie between two parallel planes 0.00018 inch apart.

figure is the displacement from the true base plane. This is defined as that plane containing the point of lowest reading and parallel to the datum plane.

2. Next, convert the values in Column 7 to linear values in 0.00001 inch. To do this, multiply the product of the sine of 1 second (0.000005) times the distance between the center lines of the mirror mounts (4 inches in the example) ($0.000005 \times 4 = 0.00002$) by the values in Column 7 at each station. Since the values in Column 7 are in tenths of a second of arc, it is necessary to divide the product at each station by 10 to get the decimal point in the right place. Round out the answer to the nearest hundred-thousandth of an inch, drop out the decimal point, and enter the value in Column 8.

Conclusion: The data from Column 8, when reported on the form shown in *Fig.* 6, allows the user to see at a glance the features of the surface plate he is using. It shows not only the extremes of variation, but also the best areas on the plate.

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