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Comparison of Calibration Methods for a Surface Plate

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1 Abstract

This paper presents equipment and methods that can be used to calibrate the flatness of large surface plates to Federal Specification GGG-P-463c. The flatness calibration requirements in the Federal Specification are discussed. Moody's method for collecting data and calculating flatness for surface plates is presented. Three measurement methods, electronic levels, autocollimator, and laser interferometer, are used to collect data. The instrumentation and measurement procedure for each of the three are presented and the flatness results are compared and discussed.

2 Surface Plate Specifications

Federal Specification GGG-P-463c [1] together with Amendment 1 [2] specify the material, design, and construction requirements of granite surface plates used for precision locating, layout, and inspection work. The specification also includes work surface workmanship, surface texture, tolerances on repeat reading, and flatness. In this paper we focus flatness calibration for granite surface plates.

In the Federal Specification, a flatness tolerance is listed for three different grades, AA, A, and B, for a variety of common surface plate sizes. A portion of this chart, for rectangular surface plates, is repeated in Table 1 and Table 2. For unlisted sizes, the flatness tolerance for Grade AA is calculated by $40+\frac{D^2}{25}$ μin (where D is the diagonal length of the surface plate in inches) or $1+1.6D^2\times10^{-6}$ μm (where D is the diagonal length of the surface plate in millimeters). The flatness tolerance excludes a zone of 1.0-1.5 inches (25-38 mm) along the edge of the plate, depending on size.

[1] Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Table 1: Total Flatness Tolerance in μin [1]

SIZE		GRADE		
Width (in)	**Length (in)**	**AA**	**A**	**B**
12	12	50	100	200
12	18	50	100	200
18	18	50	100	200
18	24	75	150	300
24	24	75	150	300
24	36	100	200	400
24	48	150	300	600
36	36	150	300	600
36	48	200	400	800
36	60	250	500	1000
36	72	300	600	1200
48	48	200	400	800
48	60	300	600	1200
48	72	350	700	1400
48	96	500	1000	2000
48	120	700	1400	2800
60	120	750	1500	3000
72	96	600	1200	2400
72	144	1100	2200	4400

Table 2: Total Flatness Tolerance in µm [2]

SIZE		GRADE		
Width (mm)	**Length (mm)**	**AA**	**A**	**B**
300	300	1.3	2.6	5.2
300	450	1.5	2.9	5.9
450	450	1.6	3.3	6.6
450	600	1.9	3.8	7.6
600	600	2.2	4.3	8.6
600	900	2.9	5.7	11.5
600	1200	3.9	7.8	15.5
900	900	3.6	7.2	14.4
900	1200	4.6	9.2	18.4
900	1500	5.9	11.8	23.6
1500	1800	7.5	15.0	29.9
1200	1200	5.6	11.2	22.4
1200	1500	6.9	13.8	27.6
1200	1800	8.5	17.0	33.9
1200	2400	12.5	25.0	50.0
1200	3000	17.7	35.4	70.8
1500	3000	18.5	36.9	73.9
1800	2400	15.4	30.8	16.6
1800	3600	26.9	53.8	107.7

In the Federal Specification, testing is broken into two groups. Group A covers thickness, stiffness, surface texture, squareness, and seams. Group B covers repeat reading measurement and flatness of work surface. We will only cover the calibration of flatness.

Periodic flatness calibration is recommended with the interval varying depending on the grade of the plate, wear resistance, conditions, and frequency of use. This may be a six month interval for a busy manufacturing shop, or a year or longer in a laboratory environment. No interval is specified in the GGG-P-463c standard. NCSLI RP-1 [3] provides guidance for determining calibration intervals. However, the GGG-P-463c standard recommendeds that the flatness of the surface plate be monitored with a repeat reading gage (shown in Figure 1), and recalibration be performed when the results from the repeat reading gage differ from those found in the previous calibration.

Figure 1: Repeat reading gage

Surface plates must be given sufficient time in the calibration area before calibration to allow the temperature of the surface plate to reach room temperature. The Federal Specification gives guidance on soak-out time. Larger, thicker surface plates and those that have a large initial temperature offset from the calibration area require more soak-out time. An equation that relates the size and initial temperatures to soak-out time is given in the standard. In addition to soak-out time, it is necessary to thoroughly clean and dry the surface plates before testing for flatness.

A flatness calibration test, as stated in the Federal Specification, contains readings in an eight line grid pattern on the surface plate. The eight lines include two diagonal lines, four side lines, and two center lines, as shown in Figure 2.

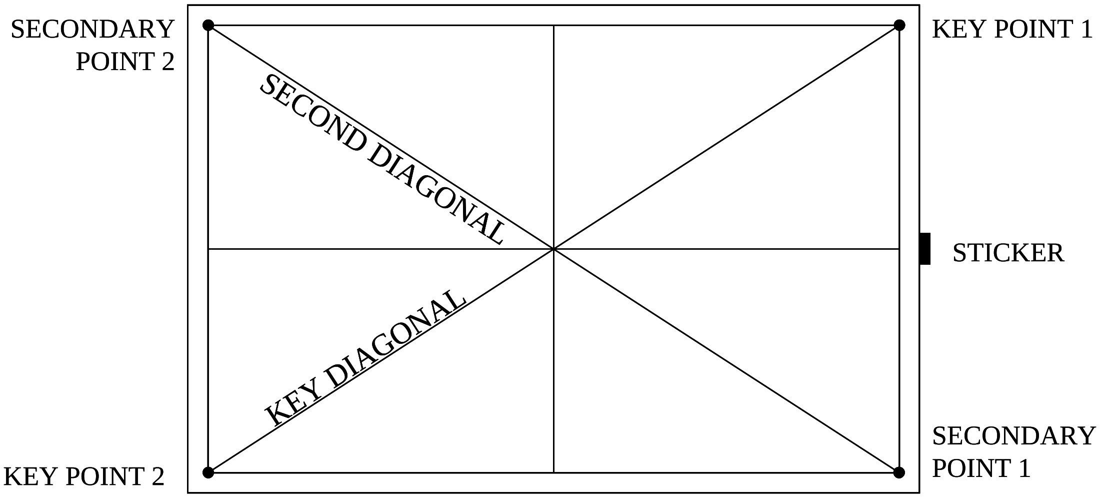

Figure 2: Eight line calibration pattern for rectangular surface plates [1]

Flatness calibration elevation values are stated with respect to the reference plane of the surface plate. The reference plane is defined at the center of the surface plate, and can be found by evaluating the key diagonal profile and the intersection point of the two diagonal profiles. The data points should be equally spaced and selected so that there is a data point in the middle of each measurement line. The maximum vertical displacement above the reference plane locates the roof plane. The roof plane is parallel to the reference plane. Similarly, the maximum vertical displacement below the reference plane locates the base plane. The datum plane is also parallel to the reference plane and located midway between the base plane and the roof plane. These planes are shown in Figure 3 relative to the key diagonal, although the maximum and minimum values that define the base and roof plane do not necessarily lie on the key diagonal. The specification defines flatness as the distance between the roof plane and the base plane.

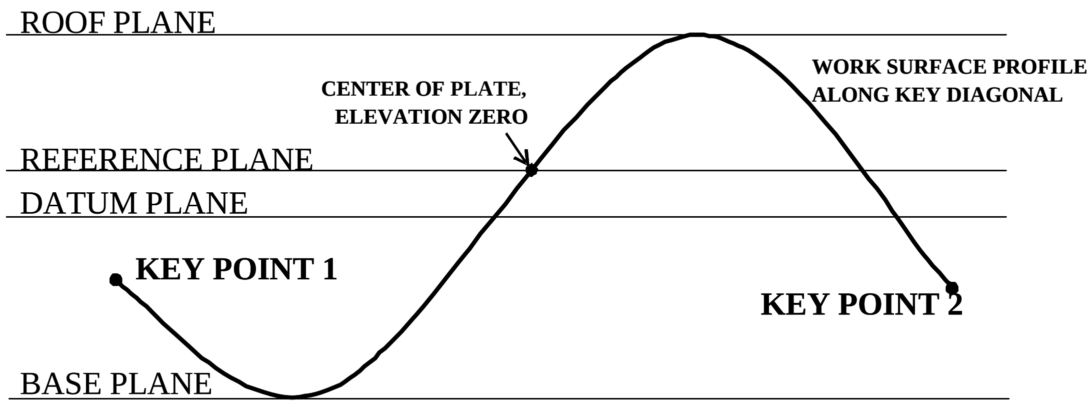

Figure 3: Plane Identification [1]

Several rules govern the selection of measurement points along these grid lines. The data points must be equally spaced along each line, with a maximum spacing of 12 inches (305 mm) and a minimum of 6 data points taken in any one line. The number of steps taken on any line must be an even number (giving an odd number of data points) and the intersection points of all lines must fall within a 0.3 inch (8 mm) diameter circle of each other. In most cases the last requirement necessitates the use of adjustable supports to allow different spacing for the perimeter/center lines and diagonal lines.

Most instruments do not work close enough to the edge (within 1-1.5 inches (25-38 mm), depending on size) to meet requirements. If this is the case, the eight line pattern may be reduced in size but the edge profile needs to be tied to the pattern using other instrumentation, such as a master straight edge with an indicator.

3 Moody method of Calibration

J.C. Moody developed a method, including data analysis, for the calibration of surface plates [4]. This method meets the requirements of Federal Specification GGG-P-463c. The Moody method is common in industry; frequently referenced in technical papers on the subject and used in commercial software designed for surface plate calibration.

3.1 Methodology

The general procedure for surface plate calibration, as dictated by the Moody method [4], is as follows:

1. Collect readings from two diagonals, four perimeter lines, and two center lines as specified in Federal Standard GGG-P-463c. These measurements are angular deviations from one

reading to the next. Sum the angular deviations cumulatively along each line in order to get the angular displacement from the first point. This process is diagrammed in a later section (Figure 6).

2. Adjust slope and height of the deviations on the diagonal lines to get zero displacement in the center of each line and equal deviation at either end.
3. Adjust slope and height of each perimeter line to maintain consistency with the appropriate corner point deviations on the diagonal lines (found in step 2).
4. Adjust slope and height of center lines to get consistency with the appropriate middle points of the perimeter lines. The middle value for the center lines should be zero if everything is done perfectly. This is unlikely due to the effect of slight errors in reading the instrumentation. A certain amount of error, called closure error, should be permitted, Moody specifies 0.0001 inch (2.5 μm) in [4]. The center lines can be shifted so the center point is zero, and the error is propagated away from the center.
5. Convert the angular deviations to linear displacements by multiplying the sine of the angular deviation by the distance between points. The maximum vertical displacement upward locates the roof plane and the maximum vertical displacement downward locates the base plane.

4 Calibration Methods

In this paper, three methods were used to acquire angular measurement data along the eight prescribed lines. These measurement methods use: an autocollimator, a laser interferometer [5], or electronic levels [6].

4.1 Electronic Levels

Electronic levels can be used to measure flatness by the Moody method. The electronic level sensing head shown in Figure 4, operates on the pendulum principle. In the case of the electronic level, a pendulum is attached to an extension block by two flexures (reed springs). Tilting the level causes the shading loop to move away from the center of the core. This movement causes an imbalance in the induced magnetic field between the primary and secondary coils, delivering a signal proportional to the displacement of the pendulum. The signal is translated into an angle and displayed on the amplifier meter.

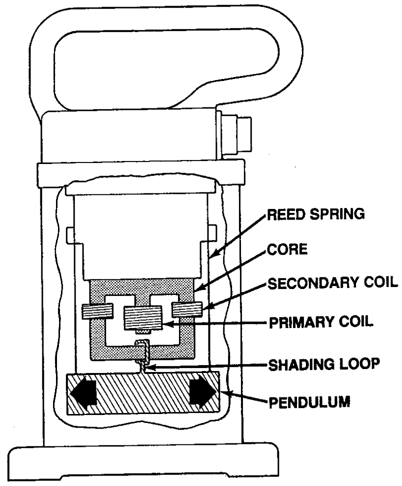

Figure 4: Electronic Level [6]

For measurement of flatness by electronic levels, at least one electronic level with readout, a straightedge, and clamps are needed. The equipment used for the flatness measurement by electronic levels presented in this paper is shown in Figure 5.

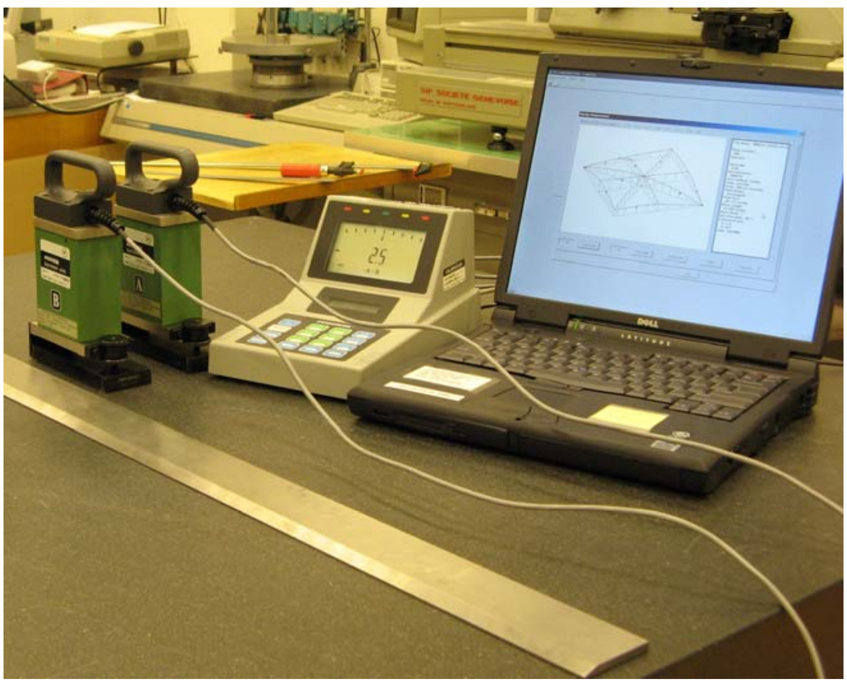

Figure 5: Equipment used for measurement by electronic levels

To operate the electronic level, the level is first adjusted so the meter reads zero at the starting position (at the beginning of each line for evaluation). The electronic level is then translated along a straight edge, which acts as guide. Measurements are taken at evenly spaced distances along the line to be evaluated. The distance between measurements is determined by distance between the feet on the base of the electronic level. A diagram of the measurement process is shown in Figure 6.

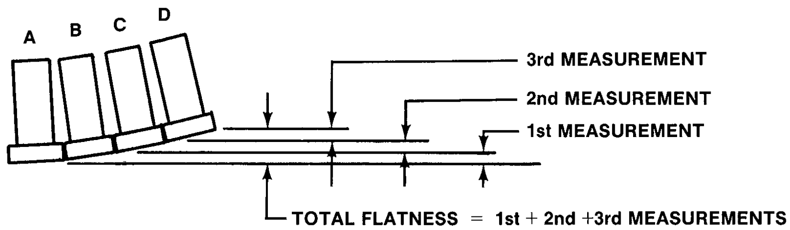

Figure 6: Flatness measurements [6]

For our measurements, two electronic levels are used. The first level remains stationary and the second is translated along the straight edge. The difference between the two measurements recorded. If the surface plate tilts due to the weight of the translating level, the differential measurement will not be effected, while an absolute measurement made with a single level would be effected. The foot spacing of the base of the electronic levels used is 5.125 inches (130 mm). The foot spacing on our levels is not adjustable. The level is moved along the straight edge a distance of 5.125 inches (130 mm) for each reading. The flatness measurement is taken along the center of the width of the level. The set-up used is shown in Figure 7.

Figure 7: Electronic level set-up

4.2 Autocollimator

Autocollimators project a beam of collimated light. An external reflector reflects all or part of the beam back into the instrument where the beam is focused and detected by a photodetector. Changes in the inclination angle of the reflector cause changes in the position of the reflected image, as seen in Figure 8. The angular deviation is determined by measuring the offset between the initial reflected mage and the current reflected image.

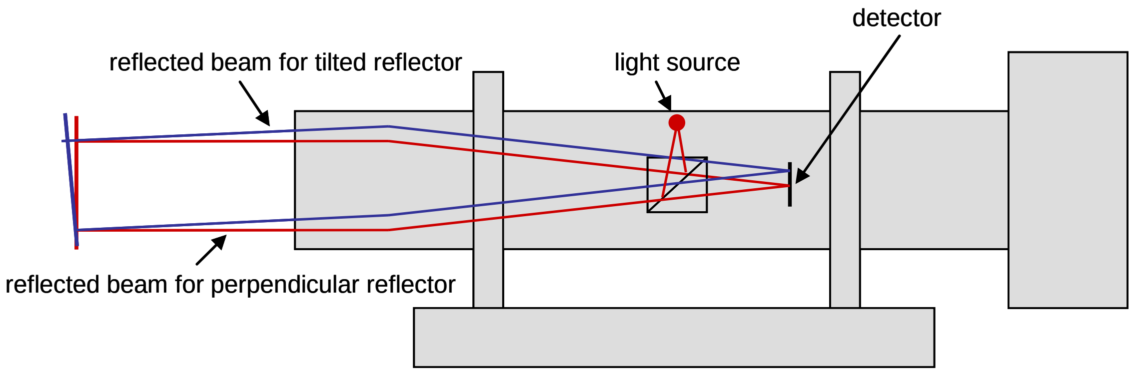

Figure 8: Autocollimator diagram

Figure 9: Autocollimator set-up

For measurement with our autocollimator, a zero value is established by reading the micrometer drum with the mirror at the starting position (at the beginning of each line for evaluation). The mirror and mirror mount are then translated in the same manner as the electronic level, with measurements taken at intervals equal to the foot spacing of the mirror mount.

This set-up requires an autocollimator with readout, a mirror attached to a traveling mirror mount, a straightedge and clamps. A mirror mount with 4 inch (101 mm) foot spacing was used.

A small surface plate mounted on a cart was used to minimize vertical drift. The set-up is shown in Figure 9.

4.3 Laser Interferometer

The laser emits a single beam with two frequencies. The angular interferometer has a splitter to separate the beam into two paths having different frequencies. One beam, through a beam bender (turning mirror), is sent to the upper part of the angular reflector. The second beam is sent to the lower part of the angular reflector. These beams return and are combined. The difference in length between the two beam paths can be determined from the combined signal. The difference in path length is directly related to the inclination angle of the angular reflector. A diagram of the angular interferometer is shown in Figure 10.

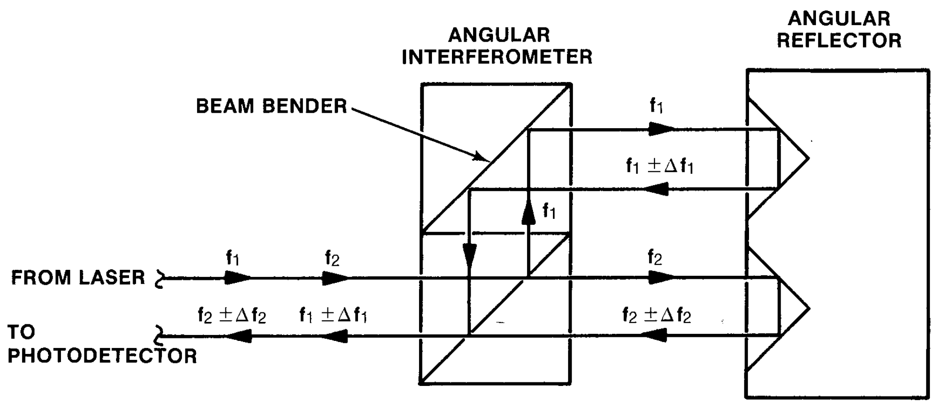

Figure 10: Angular interferometer optics [5]

Like the electronic levels, the laser interferometer is zeroed at the beginning of each grid line to be measured. The angular interferometer remains stationary and the angular reflector is translated in the same manner as the electronic level and autocollimator, with measurements taken at intervals equal to the foot spacing of the reflector mount.

This set-up requires a laser, an angular interferometer, and angular reflector and optics to alter the beam path. The angular reflector mount with 4 inch (101 mm) foot spacing was used. The laser was mounted on a tripod and remained stationary for the entire calibration. Turning mirrors mounted on a base were used to keep the beam path in line with the movement of the angular reflector. The set-up is shown in Figure 11.

Figure 11: Set-up for laser interferometer calibration

4.4 Resolution and Accuracy

The resolution and accuracy of the three systems used in this paper are given in Table 3. The three methods have similar resolution (the resolution of the autocollimator is at least one half of the resolution of the divisions on the micrometer scale). Note that the accuracy specification of the instrument is a tolerance, and does not indicate the actual measurement uncertainty of the individual data points or the combined uncertainty in the analysis of flatness. Other sources of measurement uncertainty include cleanliness, geometry of the foot pads, and geometry of the contact between foot pad and surface plate.

Table 3: Resolution and accuracy of instruments used (per manufacturer specification or instrument calibration)

Method	Resolution	Accuracy
Electronic Levels	0.1 arcsec (0.5 μrad)	±2 arcsec
Autocollimator	0.1 arcsec (0.5 μrad)	±0.2 arcsec
Laser Interferometer	0.1 arcsec (0.5 μrad)	±(0.2% of reading + 0.05 arcsec/m of travel)

5 Results

A 48 x 72 inches (1219 x 1829 mm) granite surface plate was measured by all three methods. The flatness specification for grade AA, from Table 1, is 350 μin (8.9 μm). Computing the flatness from the equation (when the size is not listed in the GGG-P-463c specification), one obtains 340 μin (8.6 μm). Since this plate size is in the table, we use 350 μin (8.9 μm) as the flatness specification for grade AA. The data from both the electronic levels and from the laser interferometer were entered in commercial software in order to calculate the flatness of the surface plate. According to their documentation, these software programs use the Moody method for calculations. The software used with the laser interferometer uses the base plane as the reference plane, unlike the other two software systems which locate the reference plane in accordance with the standard. The data from the autocollimators were collected and analyzed using software developed in-house for this specific task. This software uses the method Moody established in [4], with slight changes in location of the reference plane in order to comply with the Federal Specification. The software reports data in microinches.

The results from these three methods are displayed both as a plot of numerical deviations (Figure 12, Figure 13, Figure 14) and as a graphical representation of the numerical deviations (Figure 15, Figure 16, Figure 17). These plots are not necessarily to scale.

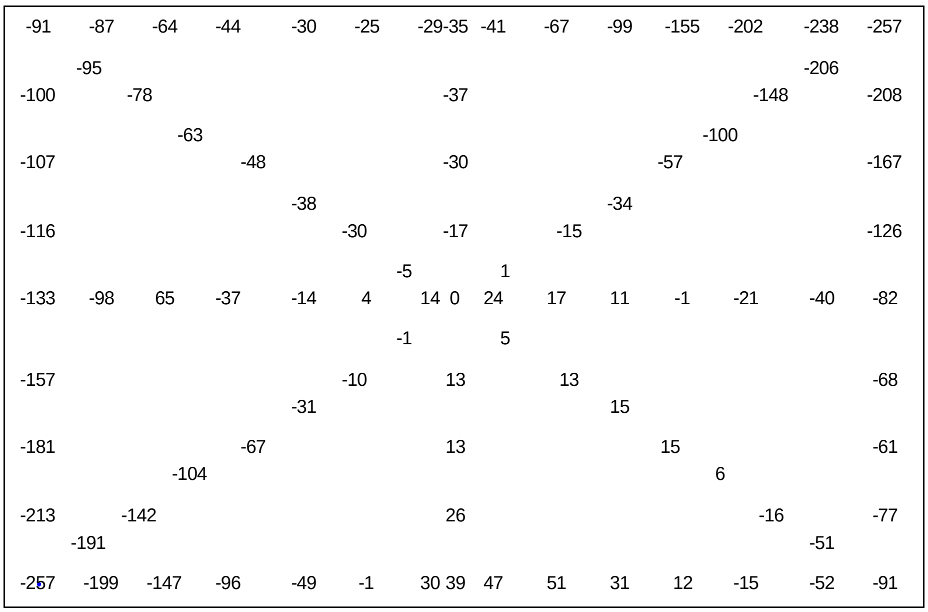

Figure 12: Results from electronic levels measurement (in μin)

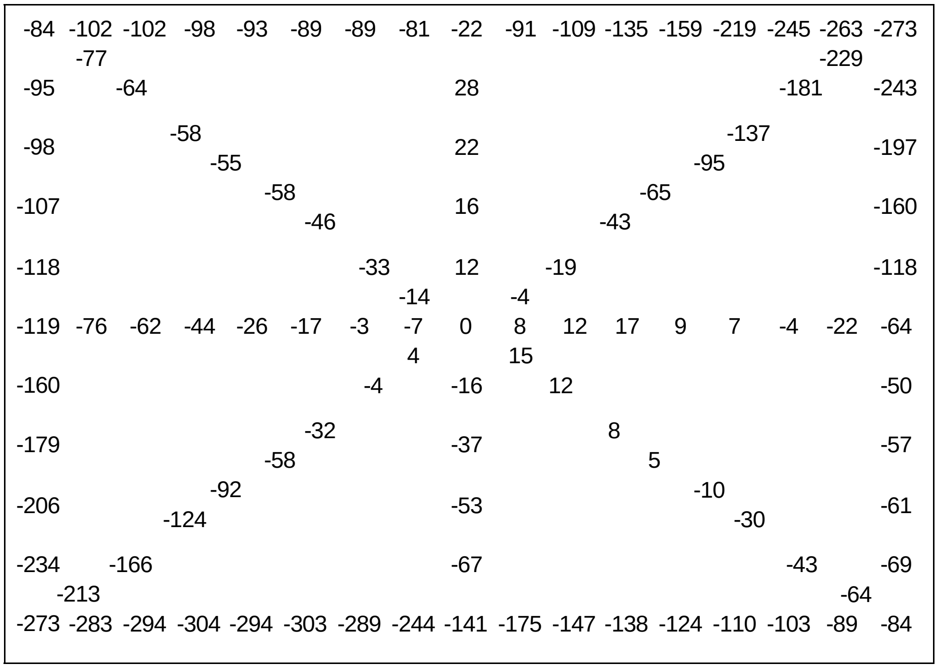

Figure 13: Results from autocollimator measurement (in µin)

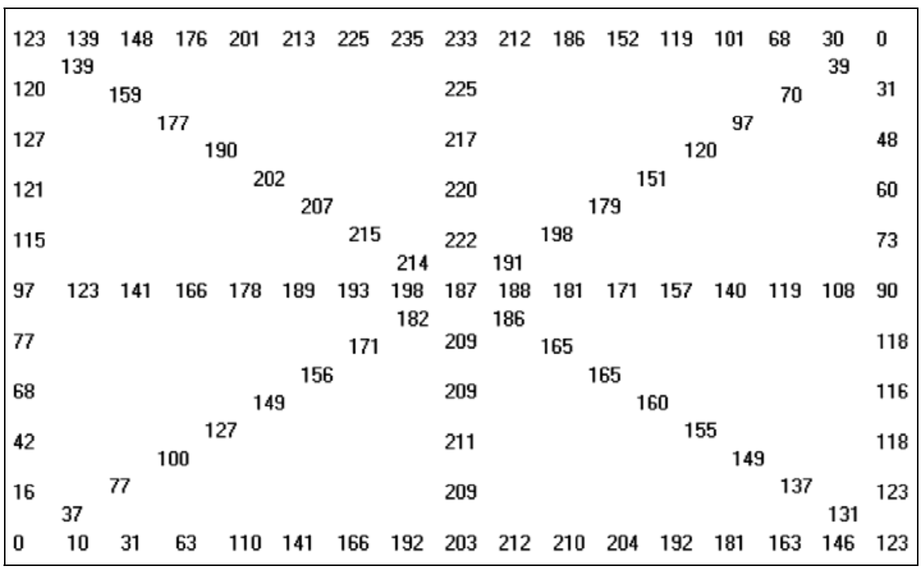

Figure 14: Results from laser interferometer measurement (in µin)

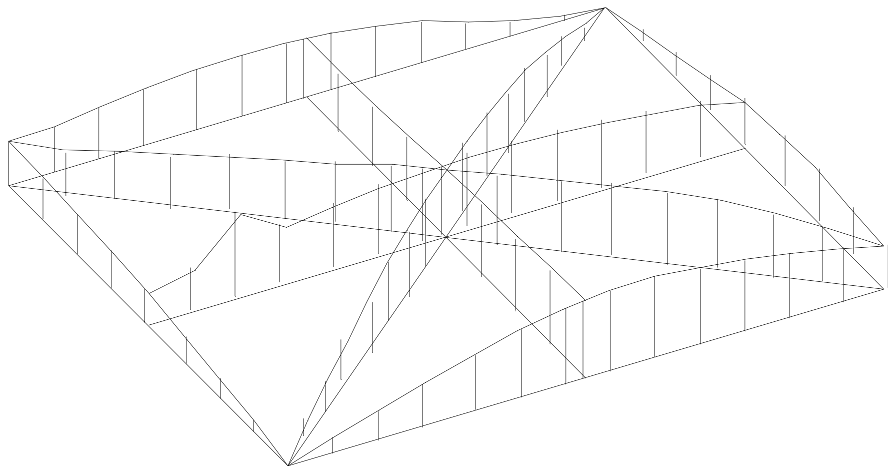

Figure 15: Plot of deviations from measurement with electronic levels

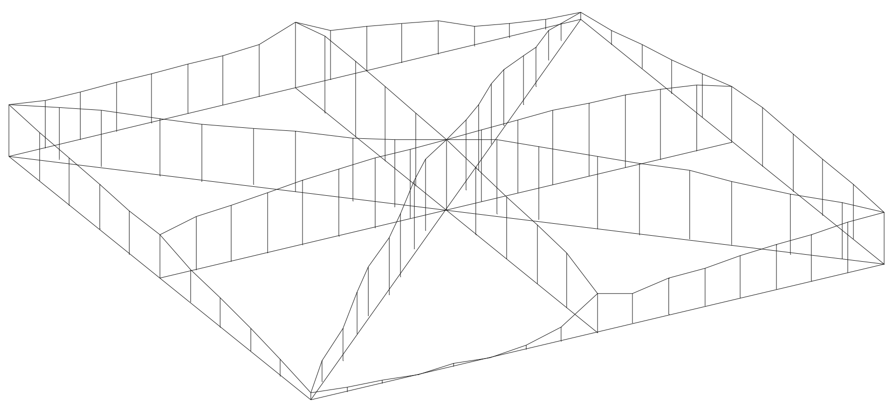

Figure 16: Plot of deviations from measurement with autocollimator

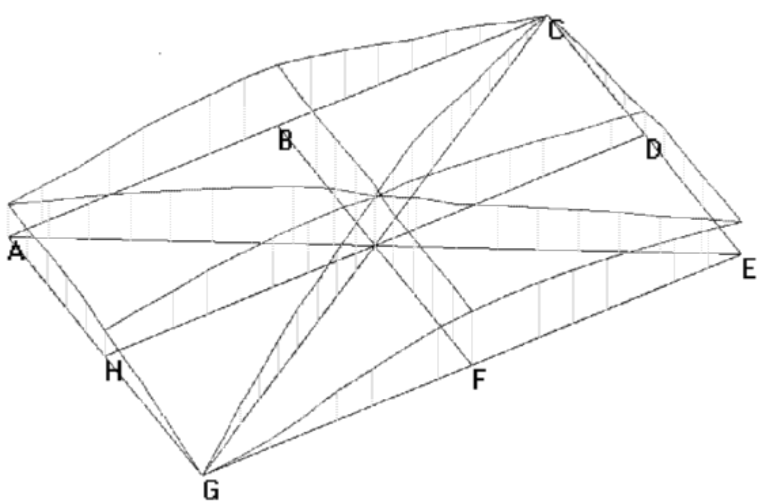

Figure 17: Plot of deviations from measurement with laser interferometer

The flatness measurements from the three methods are reported in Table 4. The flatness is defined as the distance between the base plane and the roof plane. Closure error is the difference between the center point calculated from the diagonal measurements (CG and AE on Figure 17) and the center points calculated from the two center lines (north-south and east-west, or DH and BF on Figure 17).

Table 4: Flatness and closure errors

Measurement Method	Flatness	Closure Error (NS)	Closure Error (EW)
Electronic Levels	308 µin (7.8 µm)	19 µin (0.5 µm)	2 µin (0.05 µm)
Autocollimator	332 µin (8.4 µm)	123 µin (3.1 µm)	40 µin (1.0 µm)
Laser Interferometer	235 µin (6.0 µm)	43 µin (1.1 µm)	3 µin (0.07 µm)

It is possible to see from the results that the overall shape of the surface plate is consistent between the three measurement methods. The flatness values vary from 235 µin (6.0 µm) to 332 µin (8.4 µm) - all meeting the AA flatness specification for a surface plate of this size. The variation in flatness values between measurement methods can most likely be attributed to the differences in the geometries of the equipment and the fact that the data points were taken in slightly different locations for each of the measurement methods.

Moody [4] specifies a satisfactory calibration as having closure error less than 100 µin (2.5 µm). Based on this, both the laser interferometer calibration and the electronic levels calibration can be considered satisfactory. In the autocollimator calibration, the closure error for the north-south center line is slightly higher than what can be considered satisfactory (123 µin, 3.1 µm). This calibration would need to be repeated according the Moody's criteria.

6 Conclusions

It is not possible to recommend a method based on the presented results. All three measurement tools have similar resolution. Their measurement uncertainties are all similar. However, based on ease of use, the electronic levels can be recommended. The levels do not require alignment of optics like the other two methods. Minimal set-up time is required and an experienced operator can perform the calibration in approximately one hour.

The autocollimator needs to be repositioned and re-aligned several times in order to measure all of the required lines. In addition, the autocollimator requires the operator to view the microscope and adjust the micrometer drum in order to determine the angular displacements. This is more time consuming than the other two methods which simply display the angular displacement. In addition, the autocollimator is sensitive to air currents passing between it and the reflector. A knowledgeable operator can complete the measurement by autocollimator in approximately 5 hours.

Like the autocollimator, the laser interferometer requires repositioning and alignment of optics between runs. The operator must also be careful not to break the beam path during measurement. This measurement takes approximately 5 hours with an experienced operator.

This paper presents the Federal Specification for surface plate flatness calibration. A methodology for collecting and analyzing data in accordance with the Federal Specification, Moody's method, is discussed. The results from the three different tools, electronic levels, an autocollimator, and a laser interferometer, used to collect the necessary data for analysis do not indicate any one tool as being better than the others. However, the electronic levels provide the calibration data in one hour as opposed to 5 hours for the other methods.

7 Acknowledgements

Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

8 References

1. Federal Specification GGG-P-463c, 'Federal Specification: Plate, Surface, (Granite),' September 1973.
2. Federal Specification GGG-P-463c Amendment -1, 'Federal Specification: Plate, Surface, (Granite) (Inch and Metric)', June 1977.
3. NCSLI, "Establishment and Adjustment of Calibration Intervals," Recommended Practice RP-1, January 1996.
4. J.C. Moody, "How to Calibrate Surface Plates in the Plant," reprint from The Tool Engineer, October 1955.
5. Hewlett Packard 5528A Laser Measurement System User's Guide, 1986 (Part No. 00528-90014)
6. Federal Electronic Gaging Products Catalog 190.