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U.S. DEPARTMENT OF COMMERCE
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Arati Prabhakar, Director

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Introduction

The impetus behind the national ball plate round robin, administrated by the National Institute of Standards and Technology (NIST) in cooperation with the National Conference of Standards Laboratories (NCSL) and the University of North Carolina at Charlotte (UNCC), was to provide a simple method for the assessment of the current state of industrial measurement capability using coordinate measuring machines (CMMs). Historically, round robins (where a single artifact is circulated among the participants for measurement) have been well suited for such a purpose. In particular, this round robin was modelled after the CIRP (International Institution for Production Engineering Research) international round robin for which a similar ball plate was sent to various national laboratories for measurement. This paper presents the interim results of the NIST round robin along with some analysis of these results.

Round Robin Demographics

The round robin participants included various US public and private manufacturing institutions that are engaged in coordinate metrology using coordinate measuring machines. In order to provide a fair comparison, only computer controlled coordinate measuring machines were included in the study. Since the goal of this round robin was to assess industrial measurement practices, manufacturers of CMMs were also excluded because they have the advantage of routinely performing extensive characterizations of their machines.

There were a total of 16 organizations that volunteered to participate in this round robin, representing a substantial portion of the manufacturing spectrum. Most participants are leaders in their fields, which include aerospace, heavy equipment, petroleum equipment and defense facilities. To date, 13 participants have reported results of ball plate measurements on a total 34 CMMs. This sampling of machines represented most of the US and foreign coordinate measuring machine manufacturers and ranged from ultra precision to shop floor accuracy machines with axis lengths up to 2.5 meters.

Ball Plate Description

The ball plate used for this round robin, shown in figure 1, is a two-dimensional array of tool steel balls mounted on a base plate. The plate consists of 16 spheres on an equally spaced grid with a nominal spacing of 80 mm. The nominal coordinates of these spheres and the distance from the plate coordinate system origin are given in table 1. The spheres are 25.4 mm (1 inch) in diameter and are round to better than 0.15 micrometer. The base plate is constructed from mild carbon steel with three semi-kinematic pads ground on the bottom for mounting. It is important that the artifact remain dimensionally stable for the duration of the round robin. Hence in order to avoid damage to the plate (which could change its measurement values), the size of the ball plate was limited to 0.24 m by 0.24 m, and the plate was made quite massive by having a thickness of 25.4 mm (1 inch). Upon completion of the round robin the ball plate will be remeasured by NIST to confirm its dimensional integrity.

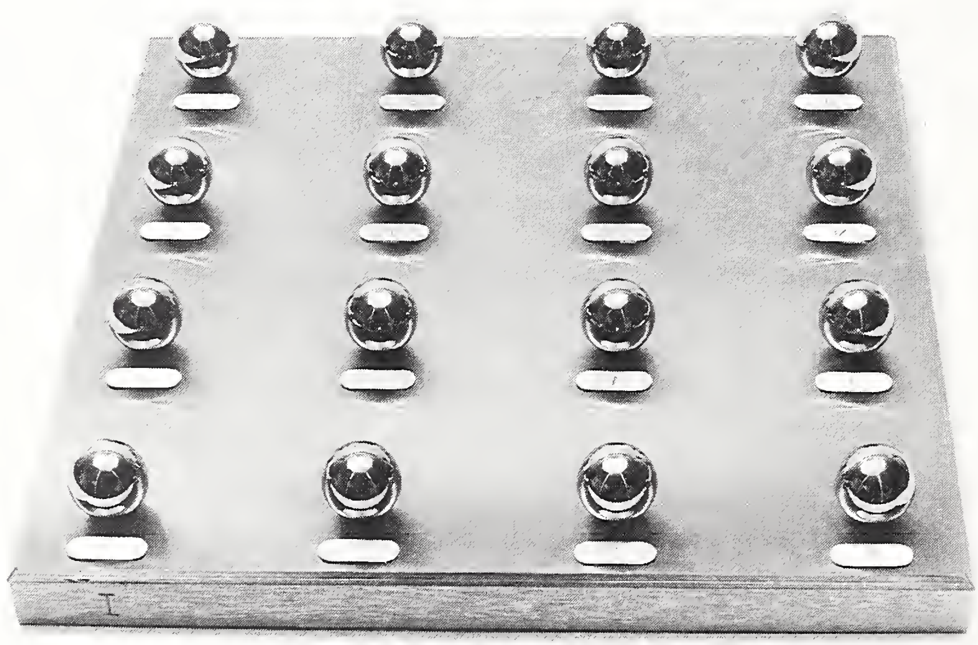

Figure 1. The ball plate used in the round robin. The spheres are numbered sequentially from left to right beginning with number 1 in the lower left corner

The ball plate was chosen as the measurement artifact for this round robin due to its simple design and ease of measurement. Most coordinate measuring machine users are familiar with the measurement of spheres due to their widespread use as probe calibration artifacts. Although a more complicated artifact could have been chosen to better represent manufactured parts, it was felt that this type of artifact was a suitable choice for the broad spectrum of round robin participants. We point out that ball plate measurements provide only limited information about the CMM. In particular, since this plate was designed to be measured in the plane of the CMM table no information is determined regarding the vertical axis of the CMM, *e.g.*, Z axis squareness or Z axis roll etc. Furthermore, since only the center to center distances between the spheres are reported, many effects such as probe lobing or repeatability problems which occur at each probing point are averaged out in the sphere fitting process. Finally the center to center distances are insensitive to errors in the effective size of the stylus, which will appear in actual size measurements such as the length of a gage block. Consequently, the ball plate results should be viewed as representing only a fraction of the potential errors which could occur in an actual part measurement.

Table 1. - Nominal Sphere Coordinates and Distances from Ball #1.

Ball Number	X Coordinate (mm)	Y Coordinate (mm)	Distance from Ball Number 1 (mm)
1	0	0	0
2	80	0	80
4	160	0	160
4	240	0	240
5	0	80	80
9	80	80	113
7	160	80	178
9	240	80	252
9	0	160	160
10	80	160	178
1[illegible]	160	160	226
12	240	160	288
14	0	240	240
14	80	240	252
15	160	240	2[illegible]0
16	240	240	339

Measurement Procedures

The participants were asked to measure the plate and report the X and Y ball center coordinates along with the estimated errors in these coordinates. The participants were given the option of measuring the plate on multiple machines (if applicable) as long as each measurement was independently reported. The only instructions pertained to the reporting of the data which stated that the center of ball number one was to be defined as the origin of the plate coordinate system, that the center of ball number four was to be defined to be on the plate X axis, and that the X and Y ball center coordinates were to be reported referenced at standard temperature 20 °C (the nominal coefficient of thermal expansion was supplied for this plate as 11.6 ppm/°C). The latter requirement was left to the discretion of the individual participants because correction for the thermal expansion of the part and the CMM scales is part of the measurement plan and is therefore included in the overall assessment. There were no other instructions on how the plate was to be measured - simply that the plate be treated as a precision part. The measurement plan, such as the number of points per sphere, number of times each sphere was to be measured, the location and orientation of the plate measurement(s) within the machine measurement volume, probing parameters (probe approach rate, probe approach distance), etc., were also left to the discretion of the individual participants.

Results and Data Analysis

The coordinate deviations reported in this paper are with respect to the mean of baseline measurements made by NIST and UNCC on their respective coordinate measuring machines. These results were chosen as the calibrated ball center coordinates based on an intercomparison between the two institutions. The worst case difference from the mean of the baseline measurements was 0.5 micrometer with typical agreement better than 0.25 micrometer. These measurements were made on two completely different standard production accuracy coordinate measuring machines. Both organizations used redundant measurement techniques [1,2] which effectively eliminate most of the residual CMM errors which would affect the measurement results for this ball plate.

The results of the ball plate round robin are shown below in figures 2 through 6. Figure 2 shows the deviations in distance from ball number 1 for all of the participants. It is also instructive to view the distance deviations as parts per million (ppm) of error. Figure 3 is a plot of this data as a function of distance from ball number 1. This gives an indication of how well the individual machines could measure two-dimensional features of various lengths. The majority of the machines are within ± 50 ppm which translates to ± 50 micrometers per meter of feature length. However, it is apparent from this data that over short distances some of the machines could not do better than 100 micrometers per meter.

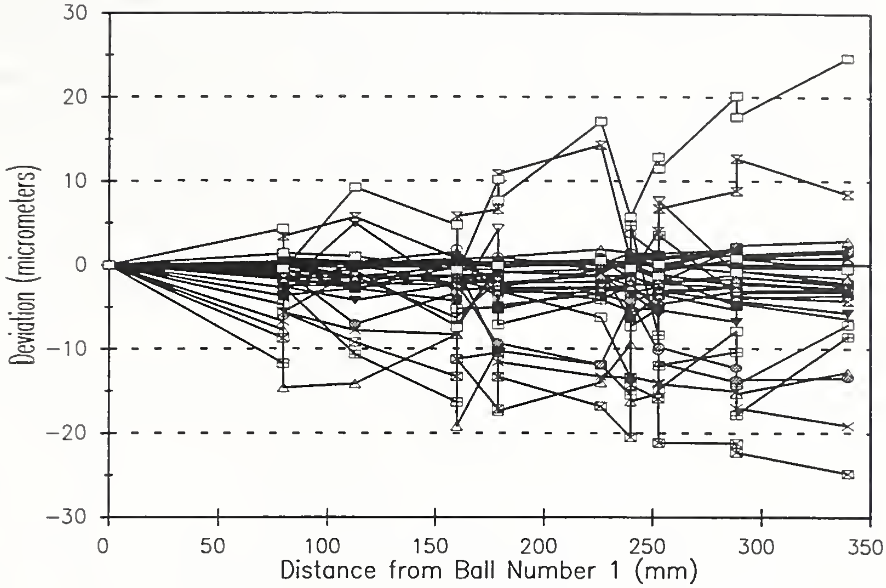

Figure 2. Distance deviations from ball # 1

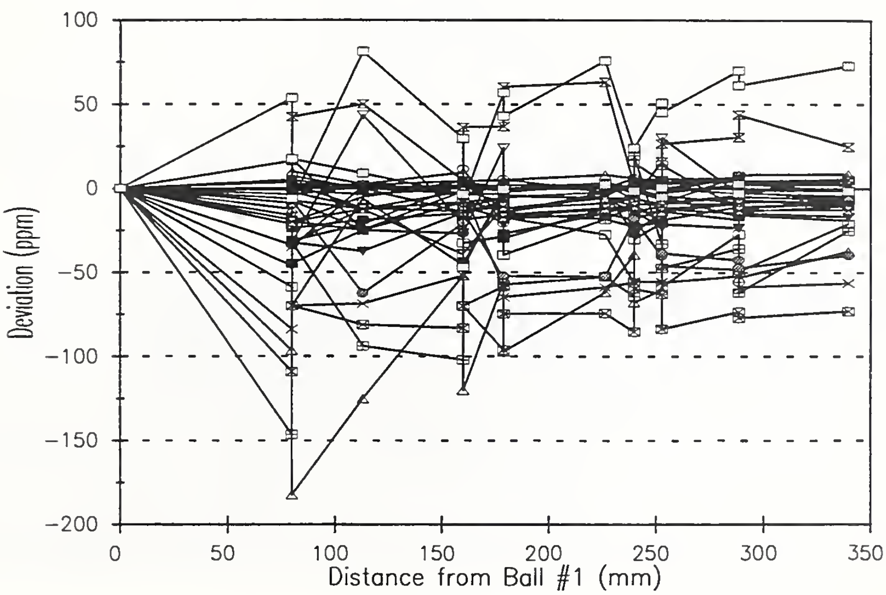

Figure 3. The same distance deviations as in figure 2, expressed on a part per million basis

Data reporting for this round robin was to include an estimate of the measurement error stated as three (3) standard deviations plus any estimated systematic errors.[1] Providing this error estimate proved to be difficult for many of the participants, and varied from the estimates as requested to no estimates at all. Figure 4 shows the error estimates (±) plotted around the maximum coordinate deviation, from the baseline coordinates, for each participant. These deviations were chosen without regard to ball number or coordinate (X or Y).

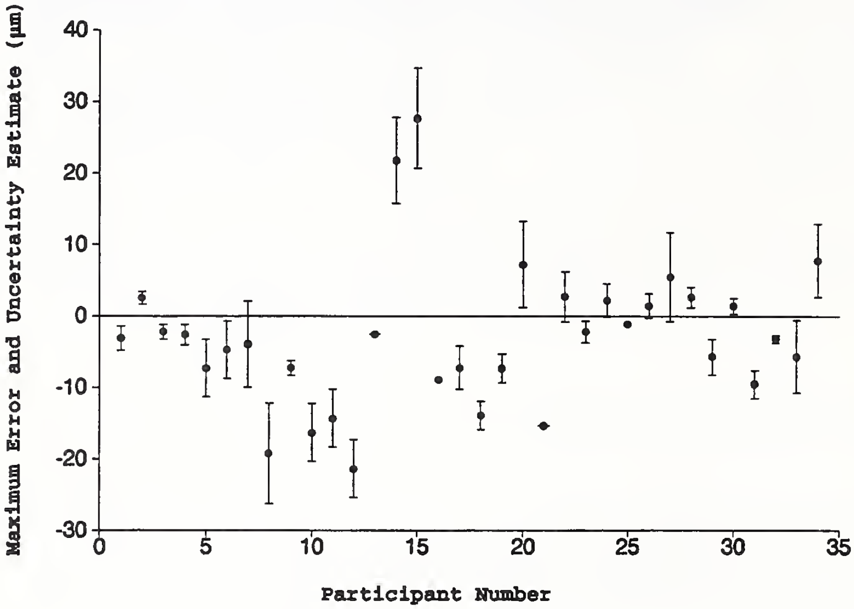

Figure 4. Measurement deviations and error estimates. The deviations are represented by the solid circles and the error estimates by the error bars. Note that there were several participants who did not provide an error estimate.

It can be seen from this plot that the maximum deviations for a majority of the participants are within ± 5 micrometers (± 0.0002 inch) of the baseline coordinates. Using a typical gaging ratio of 10:1 (*i.e.*, the "gage maker's rule") or 4:1 (as suggested by MIL STD 45662A) of part tolerance to measurement error indicates that most participates can inspect parts with tolerances as tight as ± 50 micrometers (± 0.002 inch) using the 10:1 rule or ± 20 micrometers (± 0.0008 inch) using the 4:1 rule. However, as previously discussed, there may be additional errors not detected by the ball plate results which further degrade CMM performance. Perhaps more disturbing is that over 90 percent of the participants failed to correctly estimate the measurement

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[1] "Measurement error" is different from "expanded uncertainty" which, as defined by NIST policy [3], usually reports two standard deviations. This method was used to be consistent with previous CIRP round robin results.

error on at least one of the balls on the plate. (Figure 4 does not necessarily represent the worst case result regarding error estimation because the maximum deviation and the poorest error estimates need not be the same.) This strongly suggests that realistic CMM error estimation techniques must be developed by the CMM community as a whole.

Ball plates have historically been used for the periodic performance evaluation and/or calibration of coordinate measuring machines [2,4]. The amount of information about the CMM that may be obtained from measurements of this type of artifact depends on the number and location of ball plate measurements, the suitability of the plate to be mounted in horizontal and vertical planes (as well as at oblique angles) and whether the ball plate is calibrated.

Without imposing a rigorous and well planned measurement strategy on the participants, it would be difficult to deconvolve all of the individual errors for a series of independent ball plate measurements such as this round robin data. This is due to the highly interdependent nature of the these errors. However, we may examine the individual X and Y coordinate deviations looking for structure in the data. As can be seen from figures 5 and 6, much of this data display a systematic structure, and in some cases, it is possible to identify one or more of the dominant errors from this data. For instance, by comparing the X and Y deviations for a single set of measurements it is possible to identify relative scale errors and/or thermal errors. By rearranging the X and Y deviations in groups of nominally equal Y and X coordinates, respectively, these errors become apparent.

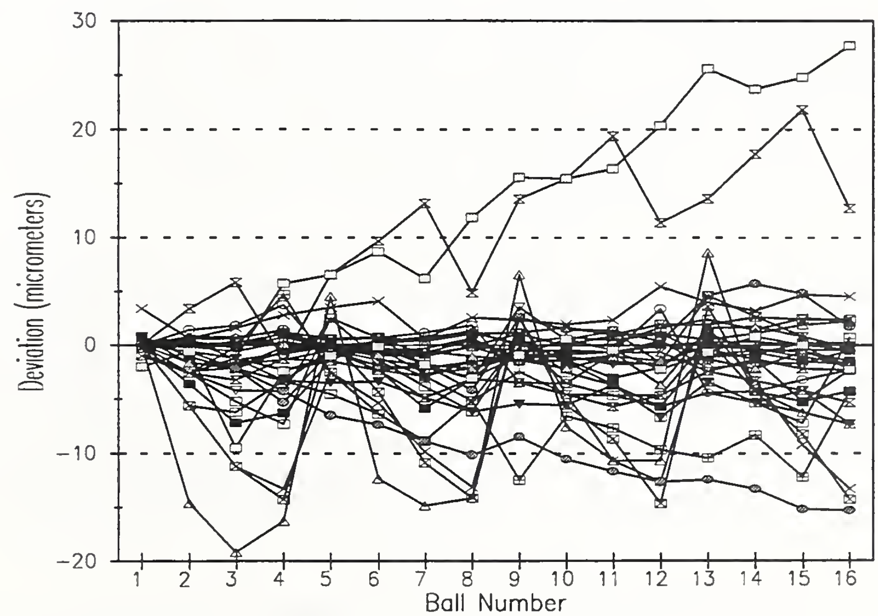

Figure 5. X coordinate deviations

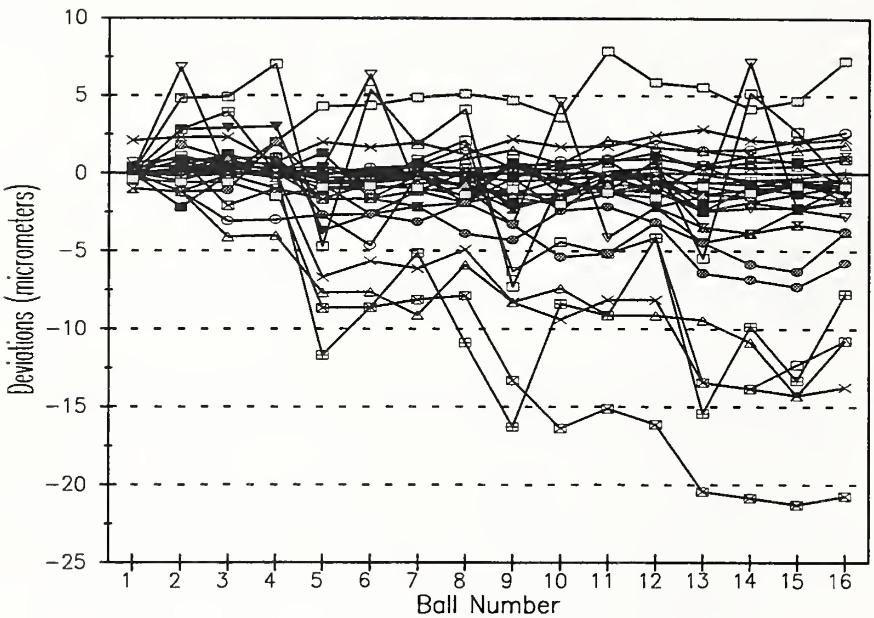

Figure 6. Y coordinate deviations

For example, if the deviations of the X and Y individual ball coordinates are nominally equal, as in figure 7, then a thermal error is suspect. This type of error could result from measurements made at a temperature different from 20 °C or from improper correction for making such measurements due to the lack of accurate temperature and/or accurate coefficient of thermal expansion (CMM scales and/or plate) data. It may also be an artifact of the machine scales resulting from an equal scale error or scales compensated at a temperature different from 20 °C.

Another identifiable error is the out-of-squareness between the two measurement axes. Since the X axis of the ball plate was defined by the plate coordinate system, any squareness error would appear as an out-of-squareness of the Y axis with respect to the X axis. (The assignment of out-of-squareness to either of the axes is purely arbitrary as long as the magnitude, direction and effect on the measured coordinates is understood.) Therefore, by reordering the X deviation data in groups of nominally equal X, any out-of-squareness between the X and Y axes will become evident. Figure 8 shows evidence of a classical out-of-squareness error for one participant's CMM. In this case the out-of-squareness is calculated as 45 microradians (approximately 9 arc seconds) of error.

Although we have presented the results from particular CMMs to illustrate these errors, they were frequently found among the participants. The presence of such systematic errors indicates that more frequent testing of CMMs, i.e. statistical process control, maybe needed.

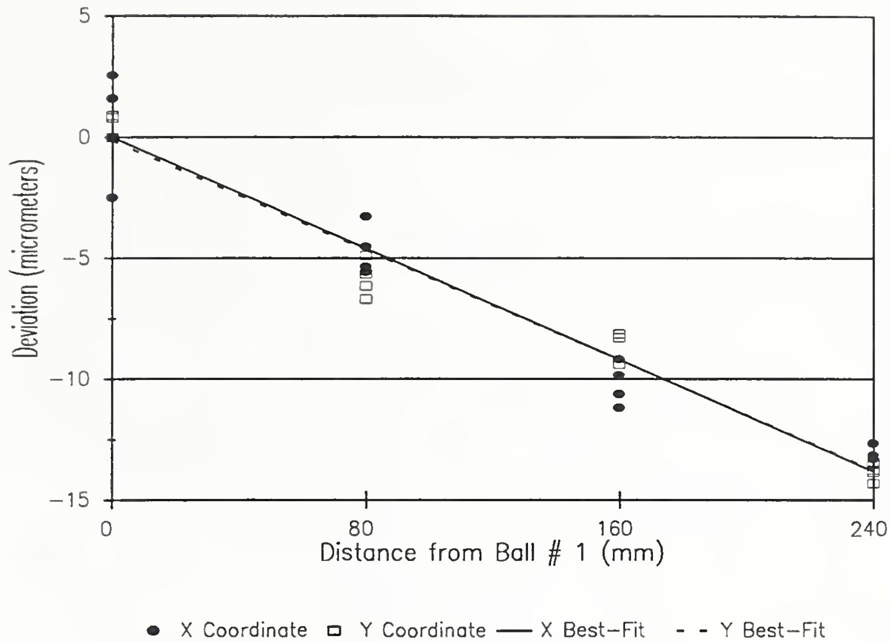

Figure 7. An example of thermal error for one participant's machine

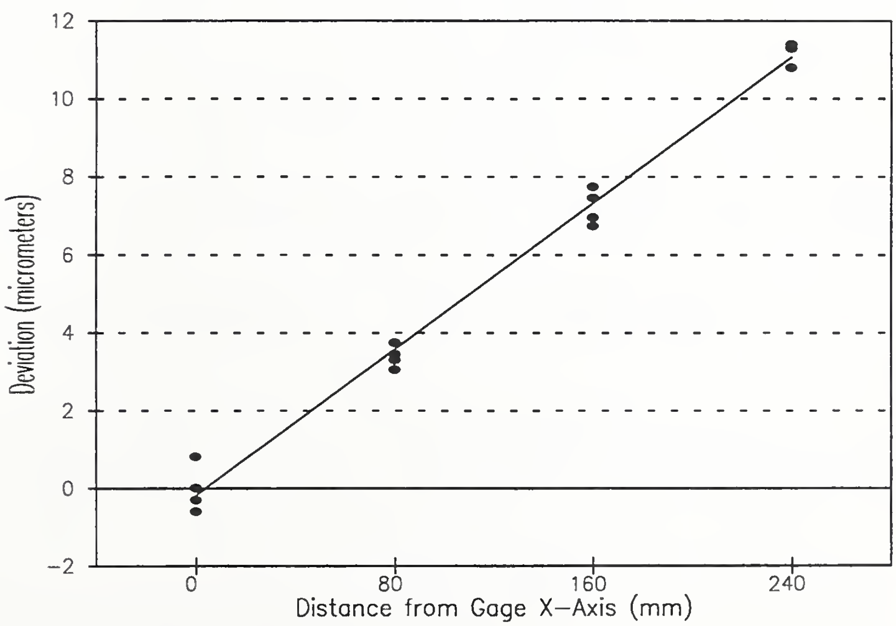

Figure 8. One participant's data showing an out-of-squareness error; in this case the error is 45 microradians (approximately 9 arcseconds)

Summary

We have presented the available results of the NIST/NCSL/UNCC ball plate round robin which is currently in progress. Data for 34 coordinate measuring machines, from 13 different organizations, have thus far been analyzed. The ball plate results are indicative of the level of precision that might be obtained on small (< 250 mm) precision parts. Typical results were within 5 micrometers of the baseline measurements; however, errors exceeding 20 micrometers were present. Expressed on a parts per million basis, the majority of these deviations were less than 25 ppm, but in some cases exceeded 100 ppm. A brief discussion of the data presented some of the possible sources of error that contributed to these deviations. Examples of temperature and squareness errors, taken from actual round robin data, were described. Of the participants that estimated their measurement errors, over 90 percent exceeded this estimate on one or more of the spheres. This suggests that a higher level of measurement process control, e.g., regular interim testing of coordinate measuring machines may be needed to provide statistical process control for industrial measurement practices.

Acknowledgements

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