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National Institute of Standards and Technology

Standard Reference Materials:

A Users' Guide to NIST SRM 2084: CMM Probe Performance Standard

G. W. Caskey, S. D. Phillips, B. R. Borchardt,
D. E. Ward, and D. S. Sawyer

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[1]At Boulder, CO 80303.
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G. W. Caskey
S. D. Phillips
B. R. Borchardt
D. E. Ward
D. S. Sawyer

Precision Engineering Division
National Institute of Standards and Technology
Gaithersburg, MD 20899

U.S. DEPARTMENT OF COMMERCE, Ronald H. Brown, Secretary
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Preface

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Contents

A Users' Guide to NIST SRM 2084: CMM Probe Performance Standard

G.W. Caskey, S.D. Phillips, B.R. Borchardt, D.E. Ward, D.S. Sawyer
Precision Engineering Division
National Institute of Standards and Technology

Introduction

Over the past two decades, the coordinate measuring machine (CMM) has matured as a technology for both shop floor and gage lab three-dimensional coordinate metrology. During this time, national and international committees were organized to address the performance specification and assessment of these machines, their subsystems and accessories. The results were a number of published standards which provide a set of specifications and testing methodologies for the assessment of CMM performance. These tests require the use of various precision artifacts which, in many cases, have been developed to fulfill the demand created by the issuance of these standards.

The CMM Probe Performance Standard, Standard Reference Material (SRM) 2084, developed at the National Institute of Standards and Technology (NIST), is one such precision artifact. It was developed to facilitate point-to-point probing performance evaluation of a coordinate measuring machine (CMM) according to the American National Standard ASME B89.1.12M-1990 "Methods for Performance Evaluation of Coordinate Measuring Machines"[1]. Additionally, this SRM carries a NIST sphere calibration for both roundness and diameter (the diameter calibration is not required by the ASME Standard) which makes it applicable to addressing additional probe performance issues. SRM 2084 consists of (see figure 1) a precision sphere mounted on a stem and a support stand with holes for mounting the sphere stem in either a horizontal, vertical, or 45 degree orientation. The spheres are available in two sizes, the standard 10 mm diameter tungsten carbide sphere which is included as part of SRM 2084 and an optional 25 mm diameter stainless steel sphere designated SRM 2085. Additional 10 mm tungsten carbide spheres can be purchased separately as SRM 2084R. These spheres are interchangeable, with each one mounted on a 3.2 mm (0.125 in) diameter stem. Included with SRM 2084 are:

- 10 mm tungsten carbide sphere on a tungsten carbide stem with a protective vinyl cap and plastic storage vial
- Stainless steel stand
- Wooden storage case
- Mounting hardware for 5/16 in, 3/8 in, 1/2 in, M8, M10, and M12 machine inserts
- Ten (10) brass-tipped #6-32 x 1/4 in set screws in a plastic storage vial
- 1/16 in hex key
- Spare storage vial for optional additional sphere/stem
- Copy of the Standard Reference Material Certificate and roundness traces covering this SRM
- Copy of the ASME B89.1.12M-1990 Standard

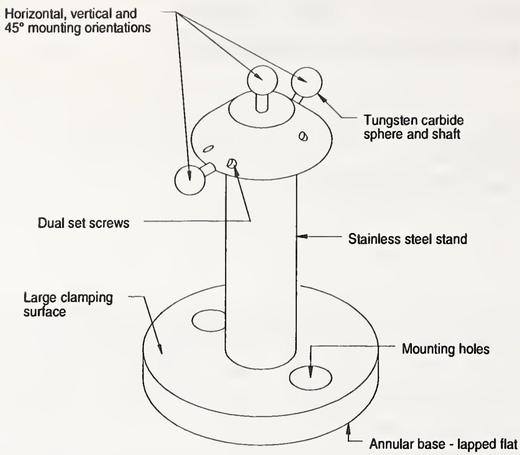

Figure 1. Highlights of SRM 2084. Note: unit shown with two optional 10 mm spheres

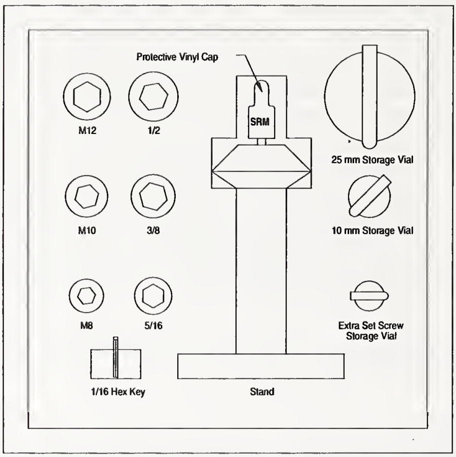

Figure 2. SRM 2084 and accessories in storage case

SRM 2085 consists of:

- 25 mm stainless steel sphere on a tungsten carbide stem with a protective vinyl cap and plastic storage vial
- Copy of the Standard Reference Material Certificate covering this SRM

Design Features

The sphere is constructed from tungsten carbide to provide abrasion and corrosion resistance to withstand repeated probing and handling. The stem is also constructed from tungsten carbide to provide high stiffness, necessary to minimize bending due to probing forces. For the stand, stainless steel was chosen for moderate stiffness and corrosion resistance characteristics. The stand height is sufficient to allow probing access while still maintaining adequate stiffness. The bottom of the stand is relieved to provide an annulus which is lapped flat for a more secure mounting surface. Two holes in the stand base accommodate the various sized mounting screws provided with SRM 2084.

The stand has three sphere/stem mounting holes; horizontal, vertical, and inclined at 45 degrees, to provide greater accessibility for the array of probe configurations available on CMMs today. A sphere/stem is secured in the stand with two brass tipped set screws, which are approximately 120 degrees apart and perpendicular to the stem. The softer brass on tungsten carbide material combination ensures that the set screws will not mar or raise a burr on the stem.

Two sphere sizes were chosen to accommodate different CMM probe testing requirements. The 10 mm diameter sphere is small enough to allow probing points below the equator for most sizes of styli. (For these SRMs no probing points should be taken below 50 degrees from the equator due to uncertainty about the sphere form in the region near the stem (see figure 3).) Alternatively, a 25 mm diameter sphere is better suited for contact scanning tests due to the larger radius of curvature.

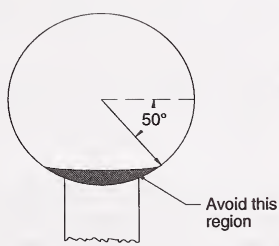

Figure 3. SRM sphere "no measurement zone"

Calibration

The spheres included as part of SRM 2084 and 2085 are calibrated for both form (roundness) and size (diameter). Calibration values are given on the accompanying SRM certificate and can be identified by the serial number engraved on the stem. The uncertainty budgets for these calibrations are given in Appendix A. These spheres were measured over a period of one year with no detectable change in either size or form, establishing the short term stability of the calibration values.

The sphere size is assessed through a two-point (parallel plane) comparison with NIST master spheres of the same nominal diameter. The sphere is compared to tungsten carbide masters using a redundant measurement technique designed to minimize extraneous influences such as operator bias and thermal drift. These comparisons are conducted on a high precision bench micrometer.

The sphere roundness deviations are assessed through a series of five roundness traces made on a roundness measuring instrument. The traces consist of a single equatorial trace and four great circle traces inclined at 45 degrees to the equator. The inclined traces are made in orthogonal pairs with a 90 degree phase difference between the two pairs. (For the above discussion, the equator is defined as the great circle whose normal is parallel to the axis of the stem.)

The out-of-roundness of this SRM was treated differently than a standard out-of-roundness calibration. For the sphere, an upper threshold on any of the out-of-roundness measurements (a total of 5 per sphere) was established as 0.076 µm. Any sphere with a roundness trace greater than this threshold value was rejected. Therefore, the upper limit combined with the out-of-roundness measurement uncertainty provides a worst case out-of-roundness for any of the 5 traces.

Care and Cleaning

Although the spheres that are part of these SRMs are constructed of a robust material, it should be kept in mind that they are calibrated artifacts and must be treated with reasonable care. A yellow vinyl cap is supplied with each sphere so that it may be covered and protected when not in use. Additionally, during extended periods of nonuse, it is recommended that the sphere be removed from the stand and placed in its storage vial. In the event of damage (or suspected damage) to the sphere, the SRM should be removed from service until the sphere can be recalibrated or replaced.

The sphere may be cleaned by wiping with a clean, soft lint-free cloth or lens paper. A more thorough cleaning can be accomplished by dampening the cloth with a mild uncontaminated solvent, such as methyl alcohol (methanol). Care should be exercised in selecting both the cloth and the solvent as they can leave behind dust and chemical residues which can affect any subsequent measurements. Under no circumstances should an abrasive material or solution be used to clean a sphere as this could invalidate the calibration.

Assembly and Setup

Select a suitable location on the CMM worktable for the placement of the CMM Probe Performance Standard. The concern here is to allow for adequate probing access of the entire sphere, keeping in mind that for some testing configurations offsets of 50 mm or more perpendicular to the probe axis may be required. It may also be desirable to leave the stand permanently fixtured to the worktable, so select an area that will not interfere with routine measurements. Fasten the stand to the CMM using one of the threaded inserts in the machine worktable and the corresponding socket head cap screws supplied with SRM 2084. Next, remove the sphere/stem from the protective vial and insert the stem in the stand hole with the desired orientation. The stem is secured in the stand by tightening the two #6-32 set screws corresponding to that hole. Using the supplied hex key, firmly tighten the set screws (by hand only) to ensure stable mounting. At this point it is a good idea to clean the sphere to remove any dirt or other contaminants that might have collected on the sphere during handling. For high accuracy measurements, a thermal "soak" time of approximately one-half hour (after assembly and cleaning) should be observed to allow the artifact to reach thermal equilibrium with its environment.

In assembling the unit it should be noted that the distance between the bottom of the sphere and the top of the stand is an important consideration. An excessive sphere-to-stand offset can degrade the measurements (depending on the precision desired) through bending of the stem. This is primarily a concern with analog or proportional probes where sustained probe-to-part contact is integral to the measurement process and not so much with a switching probe where the contact is for shorter periods of time (usually less than a second). Stem bending can appear as an apparent sphere form error (sphere out-of-roundness) and/or probe lobing error. To minimize the effects caused by stem bending, it is recommended that the stem be inserted such that there is 5 mm (0.20 in), or less, between the bottom of the sphere and the top of stand as shown in the figure 4.

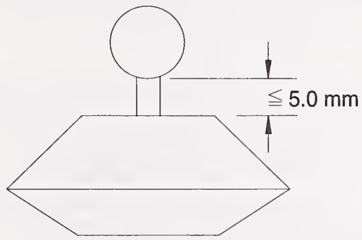

Figure 4. Schematic showing recommended sphere-to-stand offset distance (similarly for the remaining two mounting orientations)

At this distance, stem deflection will be on the order of 0.05 μm (2.0 μin) for 0.1 newton (10 grams) of probing force. For other sphere offset/probing force combinations, the amount of stem bending, δ, can be calculated from the equation:

$$\delta = F[1.09\times10^{-4} \times (L + 8.81)^3 + 0.17]\mu m$$

where, F = Probing force, newtons
L = Distance from bottom of sphere to top of stand, in millimeters

The above equation is an approximation for the average bending, developed from beam theory and empirical data, and is accurate to better than 0.01 μm for SRM 2084 (10 mm sphere) with probing forces up to 0.5 N (50 g). As can be seen from the equation, the stem bending is a function of the sphere offset and probing force. The first term (1.09×10^{-4}) is a combination of the factors that are a function of the material properties and stem diameter. The second term $(L + 8.81)^3$ is the "effective" cantilevered length which includes the distance from the set screws to the top of the stand, the distance from top of the stand to the bottom of the sphere, and the radius of the sphere. The final term (0.17) is the deflection, per newton, of the stainless steel stand determined from experimental observations.

CMM Testing Considerations

A properly selected measurement/data analysis strategy for SRM 2084 can reveal a significant amount of useful information about the CMM and probe subsystem (i.e., probe, indexable probe head, probe changer, multiple stylus configurations). Table 1 shows the range of machine and probe errors that can be detected when measuring a calibrated sphere.

Table 1. - CMM Errors Revealed Through Calibrated Sphere Measurements [2]

Radial Deviations	• CMM Repeatability • Probe Repeatability • Probe Lobing • Stylus Ball Form, *i.e.,* out-of-roundness • Stylus Bending • CMM Dynamics (Vibrations) • Probe Head Repeatability • Probe Offset Vector Errors (multiple styli/probes) • Probe Changer Repeatability • Short-Range Scale Errors
Ball Diameter Deviations	• Effective Stylus Diameter (probe calibration)

These errors, although not all independently quantifiable, can be realized through machine testing in accordance with a national or international standard governing the performance verification and accuracy specification of CMMs or any other well designed performance test. For the latter, several principles are important to note.

When testing the machine probing system, using the same artifact for both probe calibration (sometimes referred to as probe qualification) and performance testing should be avoided (in some Standards it is expressly forbidden). For performance testing which uses the sphere size in the analysis, it is essential that a calibrated sphere other than the one used for probe calibration be employed. If sphere form is the quantity being used in the performance assessment, a second sphere is also recommended. However, for this case a single sphere can be used for calibration and performance testing, if as a minimum, the sphere is reoriented. This will help to reveal the errors that can be masked when using the same sphere for both tasks. Additionally, the dimensional accuracy of the test sphere (form and in some cases size) should be some fraction of the magnitude of the error that is under assessment. For example, a 1-to-5 ratio is recommended in the ANSI/ASME B89.1.12M-1990 Standard.

In order to accurately assess the probe performance, the tests should be carried out as close as possible to normal part measuring conditions, i.e., in the same environment, with representative probe configurations (same probe, stylus length, stylus orientation, number of styli, etc.), and similar machine motion parameters (probing velocity, probe approach distance, etc.). These variables can have a significant impact on machine performance and testing with different parameter combinations can reveal the extent of these effects. It is therefore advisable, where practical, to test all probe combinations that are of interest. For all tests, the probe configurations relevant to that test should be calibrated using the manufacturer's specified procedures.

The sampling strategy (number of probing points and distribution of these points) is another important consideration when making the sphere measurement(s). The strategy chosen will depend on whether sphere size, form, or center location is being assessed. Generally, more points with a greater distribution are required when measuring form. For example, the probe performance tests found in published Standards require 25 to 49 points where form is to be evaluated. In the absence of other guidance, eight or more points uniformly distributed over at least a hemisphere can be a quick, although less thorough, probe performance test.

Finally, it is worth restating that both the test sphere and the probe stylus should be clean and free from dust (see section on Care and Cleaning). Many films (skin oils, chemical residues) and common dust particles can be many micrometers thick. A "bump" of this magnitude can be detected by many CMMs and can, therefore, adversely affect test results.

Performance Tests

The first two tests, probing performance and repeatability, were taken from the American National Standard B89.1.12M-1990 and are therefore only outlined in this document (the user is referred to the Standard for more detailed information). The remaining two tests, multi-tip probing and scanning performance, do not appear in the Standard and will be treated in more detail. In general, the tests presented here were developed for the purpose of verifying a machine's conformance to a published standard. If the intent is to establish the limits of a CMM's performance, it is suggested that the test be repeated several times to provide a more accurate picture of a machine's range of variability for that test.

Point-to-Point Probing Performance

The probe performance test, B89.1.12M Section 6.1, is designed to evaluate the probing error (pretravel variation) for several different probe configurations. For this test, 49 points consisting of one point on the pole and 12 points on 4 levels with polar angles of 30, 60, 90, and 100 degrees, are measured. Between levels the 12 point pattern is rotated 10 degrees to provide more coverage of the sphere and variability in the probe approach vectors. This test is then repeated with a minimum of three different stylus configurations. The probing performance is defined as the range of the radii to each measurement point calculated from the least squares sphere center for each stylus configuration. If the CMM software has the capability to assess sphericity (based on a least squares center), the value obtained from this data analysis is equal to the range of the radial residuals and therefore may be used interchangeably. Although this test does not require a calibrated sphere diameter, this information can be used in conjunction with this test to verify the probe calibration (effective probe diameter) by comparing the calibrated value with the measured value. This later test is analogous to the B89.1.12M Bi-directional Length Measurement Capability (section 5.6) which uses a gage block for similar purposes.

Repeatability

The second test addresses the repeatability of the CMM (B89.1.12M-1990 section 5.3), machine and probe subsystem. For this test, a sphere is rapidly measured (to preclude thermal drift) ten times using four probing points. The range of the ten sphere center coordinates provides a measure of the machine repeatability on an axis-by-axis basis.

Probe/Stylus Changer Repeatability

If the CMM is equipped with an automatic probe or stylus changer, a variation of the above repeatability test that integrates either of these devices can be performed. This would be done by putting a single probe/stylus into the changer and immediately retrieving it between each of the ten measurements. The range of the sphere center coordinates from this test could be compared with a results obtained from the repeatability test above to establish the repeatability of the probe/stylus changer.

Multi-Tip Probing Performance

Multi-tip probing encompasses the use of multiple styli ("star" or cluster probes) on a single probe, an indexable probe in more than one orientation, or a combination of the two during the course of a measurement. The purpose of this test is to assess the error induced when multiple probe configurations are used in a single feature measurement. These errors arise from three sources: the accuracy of the effective stylus diameter (probe calibration), the ability of the probe head to repeatedly index to a given position(s) (probe head "lock-up" repeatability) and the accuracy of the probe tip's position with respect to the CMM coordinate system (probe offset vector accuracy). Although the multi-tip probing performance test is similar in procedure to the point-to-point probing performance test, the two are distinct and necessary because they address different errors.

An interesting test situation exists for the indexable probe heads. Because these devices typically have more than five hundred different indexable positions, incorporating all of these positions in a single performance test would be highly impractical. However, due to the probe head's construction only a limited number of unique "lock-up" positions exist. It is therefore possible to assess all of these discrete positions in a single test, thus providing a full evaluation of the probe head performance. Table 2 shows an example of one probe head's discrete positions with a largest axis angular travel of 360 degrees in 7.5 degree increments.

Table 2. - Example Probe Head Indexing Positions

Position	Vert. Axis (deg.)	Horiz.Axis (deg.)	Position	Vert Axis (deg.)	Horiz Axis (deg.)
4	0.0	0.0	9	90.0	-60.0
2	7.5	127.5	10	67.5	67.5
4	15.0	-105.0	11	75.0	-165.0
4	22.5	22.5	12	82.5	-37.5
5	30.0	150.0	13	90.0	90.0
6	37.5	-82.5	14	97.5	-142.5
7	45.0	45.0	15	105.0	-15.0
8	52.5	172.5	16	0.0	112.5

In preparation for this test, a number of representative probe configurations are identified and calibrated (qualified). The sphere is then measured using each of the different probe configurations to sample a minimum of one point. A total of 49 points are required at locations equivalent to those used for the point-to-point probing test. These points are then used to construct a sphere using the CMM sphere fit algorithm. The multi-tip probing performance is the form of the substitute sphere as calculated by the CMM sphericity algorithm.

Contact Scanning Performance

The scanning test is aimed at assessing the performance of CMMs with the capability of measuring parts in a contact stylus scanning mode. This test applies regardless of whether the scan data is to be used to evaluate the form or size of the surface/feature. For this test, the scanning parameters such as speed and data density should be consistent with normal (or intended) measuring practices for that machine. The user should be aware that exceeding manufacturer's suggested measurement parameters may cause erratic results. Additionally, any probe configuration may be used for this test with the above provisos.

This contact scanning test utilizes a 25 mm stainless steel ball (SRM 2085) and makes use of both the form and size calibrations. For this test the sphere is inclined at 45 degrees to the probe (ram) axis to include all of the machine's axes. The procedure is to scan four progressively more difficult paths along the sphere. These paths consist of a scan along the equator, a scan in a plane parallel to and offset 8 mm from the equator, a hemisphere scan beginning and ending at the equator and passing through the pole, and a similar path perpendicular to the previous scan but offset 8 mm from the pole (see figure 5). The data can be analyzed as in the point-to-point probing test above, with the data from all four scan lines used to calculate a substitute diameter and sphericity using the CMM's standard algorithm. The degree of agreement between the calculated and calibrated diameter values provides an assessment of the CMM's ability to accurately resolve features of size when used in scanning mode. Similarly, the calculated sphericity is a measure of the machine's capability to assess features of form. (Although the SRMs are not explicitly calibrated for sphericity, the maximum allowable out-of-roundness deviations, coupled with the extensive coverage of the sphere using five roundness traces, assures to a high degree of certainty, that the deviations can be attributed to the performance of the probe and CMM.)

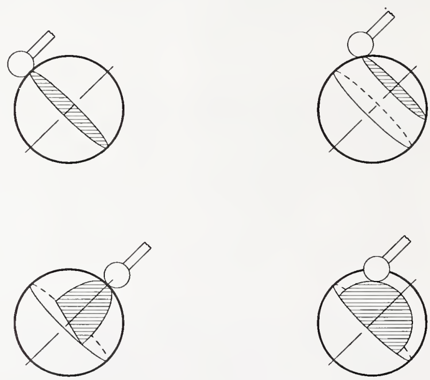

Figure 5. Contact scanning test scan lines

Although this test provides a useful picture of a CMM's scanning performance, it is important to point out several limitations. Like most of the other performance tests, the results depend on the conditions (including measurement parameters, and type and quality of the artifact) that were prevalent during the test. For example, the surface finish spatial wavelength can excite a resonance in some machines and/or probes. This test also does not demonstrate the behavior of the measurement system when drastic part transitions, such as corners and edges are encountered. Additionally, the sphere probe dynamics are strongly affected by both the finish and the lubricity of the surface.

Acknowledgements

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Appendix A: SRM 2084 Uncertainty Analysis

The uncertainty of the sphere calibration values was calculated in accordance with the current NIST [3] policy which establishes the measurement uncertainty as the root-sum-square of the contributing sources multiplied by a coverage factor k=2. This analysis recognizes two components of uncertainty, those evaluated through statistical means (Type A), and those evaluated by other means (Type B). For this assessment, Type B uncertainties were assumed to be from a rectangular (uniform) distribution. The sources of the uncertainties and the associated calculations (standard uncertainties, 1σ) are detailed below and summarized in tables A2 and A3.

Out-of-roundness Calibration

The uncertainty budget for the out-of-roundness of these SRMs is composed of three terms: measurement instrument spindle error, operator interpolation error, and measurement repeatability. The roundness measuring instrument spindle error was assessed using a quasi closure technique [4] which allows the isolation and quantification of the spindle out-of-roundness. Under this technique, a series of roundness traces were made on a single cylinder (with low order and amplitude form error), indexing the artifact through an angle of 30 degrees between traces. The traces are made on nominally the same circular cross section with different starting positions on the circle. For this angular rotation, a total of 12 traces were used (360÷30) to deconvolve the spindle error. This procedure was repeated 9 times and the range of the values was used as the ± limits of a uniform distribution for the purposes of assigning the uncertainty due to spindle error.

$$\text{Standard Uncertainty} = 0.041\,\mu\text{m}/\sqrt{3} = 0.024\ \mu\text{m}$$

Operator interpolation uncertainty results from the calibration technician's finite ability to accurately subdivide the scale divisions on the roundness charts. For the roundness charts associated with these SRMs, values uniformly distributed between ± 1/10 of a scale division were established as a conservative estimate of the operator's interpolation uncertainty. The actual uncertainty also depends on the chart magnification which, in this case, was 0.127 μm/div. Therefore the standard uncertainty due to operator interpolation is:

$$\text{Standard Uncertainty} = (0.127\ \mu\text{m/div})/(10\times\sqrt{3}) = 0.007\ \mu\text{m}$$

The final out-of-roundness uncertainty contribution is the repeatability of the measurement. This was assessed from the same data as the spindle out-of-roundness uncertainty, by calculating the pooled variance of the spindle out-of-roundness measurements, i.e., combining the variances of the 9 estimates of the spindle error assessed at 12 points. The standard deviation obtained from the pooled variance provided an estimate of the measurement repeatability. In this case the value was calculated as

$$\text{Standard Uncertainty} = \sqrt{\frac{\sum_{i}^{n} s_i^2}{n}} = \sqrt{\frac{(4.37\times10^{-4}\mu m^2)}{12}} = 0.006\ \mu m$$

Diameter Calibration

The diameter calibration uncertainty is composed of master sphere uncertainty, differential thermal expansion, differential deformation, measurement repeatability, sensor linearity, as well as contributions from the measurement sphere out-of-roundness and uncertainty in measurement sphere out-of-roundness. The uncertainty in the size of the master sphere constitutes a separate and unique error budget. There are many factors which contribute to master sphere uncertainty which can be grouped into five categories; those quantities which are associated with four color interferometry, thermal expansion of the master sphere, contact deformation, geometry (both master sphere and flat/platen), and measurement repeatability. All of these terms were estimated from known measurement system/process variables (see table A1 below), with the exception of master sphere out-of-roundness. The uncertainty due to master sphere out-of-roundness was assessed from 200 random diameter measurements of the master sphere. Because the measurements were made in 40 groups of 5 measurements each, the variances of the 40 groups were calculated and pooled to determine the standard deviation of the process. This value also included the repeatability of the measurement which was subsequently quantified in a similar manner and removed (see comparator repeatability below).

$$\text{Standard Uncertainty} = \sqrt{\frac{\sum_{i}^{n} s_{f_i}^2}{n} - \frac{\sum_{i}^{n} s_{r_i}^2}{n}} = \sqrt{(1.31\times10^{-3} - 3.71\times10^{-4})\mu m^2} = 0.031\ \mu m$$

where

s_f^2 = variance of the master sphere diameter
s_r^2 = variance of the check standard diameter

Table A1. - Master Sphere Uncertainty

Source	Standard Uncertainty (1σ) (μm)
Interferometry	
Phase shift correction	0.002
Uncertainty in cadmium light wavelength	< 0.001
Pressure correction	< 0.001
Temperature correction	< 0.001
Humidity correction	0.002
Slit and obliquity correction	0.001
Thermal	
UNE	0.012
Temperature correction	< 0.001
Deformation Correction	
Force correction	0.002
Force variations due to location	0.002
Material property variations	0.010
Geometry	
Flat/platen geometry	0.007
Master sphere out-of-roundness	0.031
Repeatability	
Measurement repeatability	0.005
Fringe fraction estimation	0.010
Combined Standard Uncertainty	0.035

A temperature difference between the two spheres (master and measurement) during the comparison process can cause a relative expansion of one sphere with respect to the other. It is hard to correct for this differential expansion because it is impractical to directly monitor the temperatures of the individual spheres. Therefore, an estimate of this effect on the uncertainty of the diameter calibration must be made. There is also a component of differential expansion that results from a lack of accurate knowledge of the sphere's coefficient of thermal expansion. For most materials an uncertainty of ± 10% from nominal is the accepted value which results in a worse case when the master and measurement spheres are at the extremes (one sphere at + 10%, the other at - 10 %). For the facilities and procedures used in this calibration, a temperature difference of ± 0.1 °C between the spheres is a conservative estimate for both calculations.

$$\text{Standard Uncertainty} = (0.1\ ^\circ\text{C} \times 5.0\ \text{ppm}/^\circ\text{C} \times 0.01\ \text{mm})/\sqrt{3} = 0.003\ \mu\text{m}$$

$$\text{Standard Uncertainty} = (0.1\ ^\circ\text{C} \times 1.0\ \text{ppm}/^\circ\text{C} \times 0.01\ \text{mm})/\sqrt{3} = 0.001\ \mu\text{m}$$

Combining the two values in quadrature and assuming a uniform distribution, the estimated uncertainty is:

$$\text{Combined Standard Uncertainty} = \sqrt{(0.003\ \mu\text{m})^2 + (0.001\ \mu\text{m})^2} = 0.003\ \mu\text{m}$$

Similarly, if the material properties differ from their nominal values for the master and/or measurement spheres (modulus of elasticity, Poisson's ratio) then an uncertainty in the contact deformation correction is introduced. Because for this comparison the master and measurement spheres are of the same material, there is no nominal deformation correction required and the uncertainty arises from an uncompensated differential deformation. Because the range of material properties is often reported as ± 10% from nominal, therefore, the value was calculated as the difference of the extreme values (one sphere at + 10%, the other at - 10 %). (Due to their complexity, the contact deformation equations will not be presented here and the user is referred to sources which treat this topic in greater detail [5,6].) This range was assumed to be the half width of a rectangular distribution and was calculated as:

$$\text{Standard Uncertainty} = \frac{\Delta\delta_{max} + \Delta\delta_{min}}{2 \cdot \sqrt{3}} = \frac{(0.013 + 0.016)\mu\text{m}}{2 \cdot \sqrt{3}} = 0.008\ \mu\text{m}$$

The repeatability of the comparator is another contributor to the uncertainty of the diameter calibration. To assess the magnitude of this term, the pooled variance of the 5 measurements each of 40 different spheres was calculated. It is important to point out that for the 5 measurements of a single sphere, the same diameter was gaged each time which removed any apparent non-repeatability due to sphere form. The resulting standard deviation was used as an estimate of the comparison process repeatability.

$$\text{Standard Uncertainty} = \sqrt{\frac{\sum_{i}^{n} s_i^2}{n}} = \sqrt{\frac{(0.011\mu m^2)}{40}} = 0.017\ \mu m$$

The final terms in the uncertainty analysis are the out-of-roundness of the measurement sphere and the uncertainty in the out-of-roundness value. The out-of-roundness uncertainty propagates directly into the diameter uncertainty. The measurement sphere out-of-roundness value is assumed to be the half width of a uniform distribution centered about the calibrated diameter. The contribution is:

$$\text{Standard Uncertainty} = (0.076)/\sqrt{3} = 0.044\ \mu m$$

Table A2. - Diameter Calibration Measurement Uncertainty

Source	Type	Standard Uncertainty (1σ) (μm)	
Master Sphere Uncertainty	B	0.035	
Transfer Uncertainty			
Differential thermal expansion	B	0.003	
Differential deformation	B	0.009	
Repeatability of comparison	A	0.017	
Transducer linearity	B	< 0.001	
Geometry Conversion			
Sphere out-of-roundness	B	0.044	
Uncertainty in out-of-roundness	A	0.026	
Combined Standard Uncertainty		0.065	
Expanded Uncertainty - Coverage Factor k=2			0.130

Table A3. - Out-of-Roundness Calibration Measurement Uncertainty

Source	Type	Standard Uncertainty (1σ) (μm)	
Spindle Out-of-roundness	B	0.024	
Operator Interpolation	B	0.007	
Measurement Repeatability	A	0.006	
Combined Standard Uncertainty		0.026	
Expanded Uncertainty - Coverage Factor k=2			0.051

Appendix B: SRM 2084/2085 Relevant Material Properties

The user should be aware that these are average material property values obtained from various sources. It is known that these properties can vary as much as ± 10 % from the accepted values.

Tungsten Carbide (10 mm spheres, all stems):

Modulus of Elasticity	650 GPa
Poisson's Ratio	0.22
Coefficient of Thermal Expansion	5.0 ppm/°C

440C Stainless Steel (25 mm spheres):

Modulus of Elasticity	200 GPa
Poisson's Ratio	0.30
Coefficient of Thermal Expansion	10.2 ppm/°C

303 Stainless Steel (stands):

Modulus of Elasticity	193 GPa
Poisson's Ratio	0.30
Coefficient of Thermal Expansion	17.0 ppm/°C

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