Procedure Title: **Calibration of Ball Diameter by Mechanical Comparison (11030S)**
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Author: **Eric S. Stanfield**
Approved:

Revision Description:

This procedure was revised to accurately describe the current process for calibration of customer balls by mechanical comparison using the laser interferometer retrofitted SIP550 rather than the Pratt & Whitney LVDT based micrometer.

Purpose: This procedure describes the process for the calibration of balls ranging in diameter from 0.8 mm up to and including 101.8 mm by mechanical comparison.

NOTE! This procedure assumes the operator is familiar with all functions of the NIST AWire@ Software and is familiar with the use of the laser retrofitted SIP550 Bench Style Micrometer. For guidance using the software refer to reference [2]. Additionally, this procedure does not explain the statistical process control theory and calculations performed, for detailed information on this issue refer to reference [1]. The software and statistics are identical to those used for gage block calibration by mechanical comparison, with only slight modifications for balls with significant diameter variation due to out-of-roundness.

References:

[1] NIST Monograph 180, *The Gage Block Handbook*, T. Doiron & J. Beers, June 1995

[2] NISTIR 6387, *The NIST Gage Block Calibration Software System User=s Manual*, J. Zimmerman, January 2000

[3] NIST Technical Note 1297, *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*, B. Taylor & C. Kuyatt, 1994

[4] Journal of Research of the National Institute of Standards and Technology, Volume 102, Number 6, Pages 647 -675, *Uncertainty and Dimensional Calibrations*, T. Doiron & J. Stoup, Nov-Dec 1997

[5] National Standards Laboratory Technical Paper No. 25, *Elastic Compression of Spheres and Cylinders at Point and Line Contact*, M. Puttock and E. Thwaite, Australia 1969

Definitions:

Equipment Required:

- Laser Retrofitted SIP550 Bench Style Micrometer
- X-Y position detector (laser alignment)
- Appropriate AA (Steel), SKF (Steel), and TC (Tungsten Carbide) master balls as

identified in the master file listing. The current listing can be found under "Masters" in the NIST "Wire" Program.

Additional Equipment/Items Needed:

- Ball tongs
- Cotton gloves
- Ball trays
- Ball stands
- Lint free cleaning towels
- Preservative pan and brush (preservative used is Starrett M-1)

General: The calibration of test balls ranging in diameter from 0.8 mm to 101.6 mm is performed by mechanical comparison using the laser retrofitted SIP550 bench style micrometer and six pairs of master balls. The master pairs contain sizes ranging from 1.5875 mm up to and including 25.4 mm, with each pair containing one tungsten carbide master and one steel master. The different material masters ensure that for the majority of our measurements a like material comparison can be performed, thus minimizing the sources of uncertainty. With a long range comparison process, such as this one, temperature corrections and deformation corrections must be made even for like material comparisons due to the significant diameter differences between the masters and the test ball. For all cases, like-material and dissimilar material comparisons, deformation corrections are made according to reference [5]. For sizes less than 25.4 mm, the test ball is compared to the master of similar material and closest in nominal size. However, with the long range of this instrument; remeasures, if desired, can also be done using a completely different master pair.

For large sizes (balls with a diameter greater than 25.4 mm), the test ball is compared to the similar material master from the 25.4 mm master pair. For these sizes, special care must be taken to ensure temperature stability has been achieved and that accurate, as well as, current environmental data is used for wavelength compensation.

For all measurements, the adjustable vertical stage is equipped with a readout that provides the operator with convenient feedback to ensure that all balls are gauged within ± 0.5 mm of the center of the contacts. This minimizes Abbe Error and variations due to the contact geometry flatness and parallelism.

Two measurement schemes from the NIST "Wire" Software have been validated for ball calibration, these include the 3-4 design (2 masters, 1 unknown) and the 4-4 design (2 masters, 2 unknowns). The choice of design is up to the operator; however the 4-4 design is used when possible for efficiency purposes. These least-squares drift eliminating designs are typically appropriate for Grade 10 or

better test balls. If during a series of measurements the operator observes diameter variations greater than 250 nm for the test ball or that the F-test consistently fails due to variability of the test ball measurements, then it is suggested that the "modified" 3-4 measurement scheme be employed. This measurement sequence is described later in this procedure and the Excel worksheet that performs the calculations is provided on the storage device maintained with the "Ball Calibration" documentation binder. This modified design is an average based drift eliminating design where the T-test is calculated for statistical process control (SPC) purposes, and the standard deviation of the test ball data is used in calculating the uncertainty, rather than in the calculation of the F-test.

Refer to Appendix A for a detailed discussion of the uncertainty budget for this measurement process.

1.0 Order Setup:

1.1. Following unpacking and logging in customer ball orders the balls must be allowed to stabilize in the laboratory environment for a minimum of 24 hours. This is typically not a problem because all dimensional items are unpacked and stored in holding drawers in the laboratory environment until the calibration is performed, which is normally several weeks.

1.2. During cleaning and setup, all balls are to be handled using ball tongs to protect the balls from corrosion caused by contact with bare skin. All cleaning is done using 200 proof ethyl alcohol.

NOTE! Cleaning towels used for removing grease or oil from steel balls must be kept separate from towels used to perform the final cleaning of the balls.

1.3. Using the calibration summary sheet complete the customer name, set description, set serial number, number of test balls, material of test balls, internal control number, technical staff initials, filename of "Wire" setup file, start date, and nominal sizes. For the set serial number, list the manufacturer=s serial number and the customer=s property number, if available.

NOTE! Ball identification numbers do not normally exist, except sometimes on the individual ball container. If the individual ball container does have an identification number then record it beside the nominal size on the summary sheet.

1.4. Visually inspect each test ball for damage. If damage is found, record observations on summary sheet, take pictures if possible, and consult customer before proceeding with the measurement of that ball.

1.5. Using the AWire@ software create a setup file for the calibration and save it with the name assigned in the Step 1.3. When setting up the file choose the appropriate measurement algorithm, either Method 3 "3-4 Design" or Method 5 "4-4 Design." Refer to the table below for the measurement sequence of the appropriate algorithm.

Additional Information: The first number in the design nomenclature stands for the number of different balls in the algorithm and the second number stands for the number of measurements to be made on each ball.

S = Master #1, C = Master #2, 1 = Test Ball

3-4 Design	
S	C
1	S
C	1
C	S
1	C
S	1

4-4 Design	
S	C
1	2
2	S
C	1
C	S
2	1
S	2
1	C

2.0 Measurement Setup

2.1. For balls there is no cleaning process during the order setup, only as needed to visually inspect for damage. Typically, balls are cleaned and setup to measure as needed until the entire set and remeasures are completed.

2.2. Prior to starting the calibration the following initial steps should be performed.

2.2.1. The contacts of the instrument should be cleaned using a lint free towel and ethyl alcohol, and then puffed to remove any remaining dust.

2.2.2. With the target on the laser head rotated into place such that it interferes with the return beam, the carriage of instrument should be translated over ~200 mm of travel while watching the return spot on the target. If you notice movement of the return spot, then the laser alignment is off. Follow the instructions in Section 7.0 to align the laser with the carriage motion.

2.2.3. Ensure that the SIP550 software has the appropriate measurement force setting. Typically for balls between 0.8 mm and 31.75 mm the force setting will be 1.1 N (4 oz). If smaller balls are attempted then a smaller force might be necessary to avoid permanent deformation. For larger balls, a larger force might be more appropriate to ensure stability (seating).

2.2.4. Verify the proper sign of the reading is displayed by the NIST "Wire" Software. This can be verified by checking that the displayed number increases with a positive movement of the carriage (or greater separation between the contacts).

2.2.5. Verify that the material temperature sensor is located on the vertical stage of the instrument in close proximity to the balls to be measured.

2.3. Using the appropriate ball tongs and the ball trays set up the masters and test balls for measurement. All balls setup for measurement should be place on the vertical stage of the instrument. The appropriate master ball can be identified by inspection of the first column of the master file. The S-master is listed first followed by the C-master. Each number in the master identification is the fractional representation of the nominal English size followed by T or TC, AA, and S or SKF. These designations refer to the English tungsten carbide set and the two English steel master ball sets: AA and SKF.

Master Identification Example:
5/32TC1/4S → S = 5/32 English Tungsten Carbide Master and C = ¼ English Steel SKF Master

NOTE! Exercise extreme care when setting up and returning master and test balls, so to avoid mixing them up. Because the entire surface of the ball is the gauging surface and because the balls get rather small it is typical that balls are not individually marked. If any ball is mixed up during the setup phase, the T-test will most likely fail. Unfortunately, when returning the balls there is no such check until the master pair is used for the next customer order.

2.4. It is recommended practice to mark the sizes on a piece of masking tape and attach it to the end of each tray so that it is clear which tray contains which sizes. It is also recommended to place the balls in the ball holes on the trays in the following order: S, C, 1, and 2 ordered from left to right. For smaller balls it is necessary to put a square piece of masking tape over each hole of the ball tray to prevent the ball from falling into the bottom of the hole where it is very difficult to pick up. The piece of masking tape should be centered on the hole then attached by pushing down in the center with your finger or thumb to create a circular dimple that will keep to ball from rolling off.

2.5. There are several ball stands which span the standard size range. One ball stand can be used for several different sizes before needing changed to the next bigger or smaller size. The only requirement is that the width of the ball stand must be smaller than the diameter of the smallest ball you want to measure so that the stand will not interfere with the measurement contacts. The stand used should be large enough that it is easy to put the balls in and out without the ball falling off the stand. The ball stand is designed with a V-shape, the line that forms the bottom of the V should be aligned parallel to the axis of the measurement contacts. With the V parallel to the contacts, this provides the ball freedom to move in the measurement direction but restricts motion in other directions.

NOTE! The smallest ball stand is just a bit smaller than a 1/16 inch ball. This means that a ball stand can not be used for a 1/32 inch or 1 mm measurement. For these measurements, each ball should be placed at approximately the same location between the contacts to minimize the contact geometry error in the measurement results. The ball stand eliminates this concern completely. For these small balls that must be measured with a stand, a towel should be placed under the contacts to prevent losing or damaging the ball if it is dropped while placement or removal. Additionally, the smallest ball tongs can only be used for ball placement down to a ball diameter of 1/8 inch or 4 millimeters. For smaller size balls, a wire with a diameter smaller than the ball you are measuring and small magnet attached to the wire makes a good substitute tool. This also applies to tungsten carbide balls even though they are much less magnetic, but extreme care must be exercised as a slight jolt during relocation can be enough to throw the ball off. This technique can be used to place each ball between the contacts during the measurement.

2.6. The Z-axis zero position should be established using one of the master balls to be measured. This is done by visually positioning the center of the ball stand (with or without the ball whichever is easier) in the center of the contacts from front to back. Place the master ball on the stand, if not already there, gage the ball then tram the ball vertically using the adjustable vertical stage of the instrument to find the Z-coordinate of the top and bottom edge of the contact. The top and bottom edge can be identified by either observing the transition point where the force bars on the SIP550 software begin deviating from the null position and/or dramatic changes in the laser reading occur with very small changes in the vertical position. With these two coordinates, locating the

center is a trivial task. After positioning the ball at the center of the contacts, use the SIP550 software to zero the Z-axis display. The two observed coordinates for the top and bottom of the contacts should be approximately 7.00 mm apart.

Note! Each time the ball stand is changed to accommodate different sizes; the zero position will need to be re-established.

2.7. As a part of the setup, the Z-position for each ball should be determined in advance so that you can quickly determine the setting between measurements. As a simple rule to ensure a ball of different diameter than was used to find the zero position is positioned at the zero position (center of the contacts), simply take the diameter difference between the zero position ball diameter size and the ball of interest and multiply it by 0.542 mm (0.542 mm/mm). If the ball of interest is smaller, then the Z-stage will need to be increased to the resulting calculated setting or decreased to the calculated setting if larger. If the support stand was a flat surface the height difference would simply be the radius difference between the two balls, however for a V-stand, the ball sits slightly deeper or shallower depending on the size. The above factor takes this into consideration.

2.8. Recommended practice is to start with the largest ball and work your way down in size. Smaller sizes are more difficult to handle and position, thus working your way down in size helps you to get the feel for the smaller sizes in an incremental manner.

3.0 Measurement

3.1. **Measurement (Ball Diameter 0.8 mm to 31.75 mm)**

3.1.1. Once the balls and the instrument have thermally stabilized, normally about an hour or two after initial setup, the operator should complete the measurement process for each test ball in a timely manner.

3.1.2. Using the "Wire" program, load the setup file for the order and follow the software prompts. The material temperature and environmental readings with calibration corrections applied should be entered when prompted.

Note! As of the time this procedure was written there is no scale correction or force correction to be applied, if corrections are to be applied this procedure should be revised to reflect current practices. Scale corrections are not needed if the laser is calibrated on some predetermined interval, currently every five years unless the SPC indicates a problem, and the vacuum wavelength value from the calibration report used to update the configuration file. The force correction factor is not needed as long as the force setting when checked with a calibrated force gauge is within ± 10 %. This ± 10 % potential error is factored into the uncertainty budget.

3.1.3. To make a single measurement, adjust the vertical stage to the proper height, use the ball tongs to place the ball between the contacts, then use the course and fine carriage control to engage the ball until the force setting is achieved (as indicated by observing the null indicator on the SIP550 computer screen and by the audible beep). This process should be repeated for each ball throughout the measurement sequence, as directed by software. Each ball should be rotated between measurements to ensure that four random diameters have been sampled and to ensure the result is a good estimate of the average diameter.

NOTE! The following guidelines should be followed to ensure that the measurement results are within the limits specified in the uncertainty budget:
(1) Ideally, the measurements should be performed no more than 30 to 60 seconds apart with no interruptions or stopping during the measurement sequence.
(2) The corrected material temperature should be entered for each measurement.
(3) The corrected air temperature reading does not need to be updated between measurements, unless it differs from entered value by more than 0.25 ºC.
(4) The corrected relative humidity reading does not need updated unless it differs from the entered value by more than 10 %.
(5) The corrected atmospheric pressure reading does not need updated unless it differs from the enter value by more than 133 Pa (1 mm of Hg).

3.1.4. Repeat Steps 3.2 and 3.3 for each ball.

NOTE! The number of measurements made back-to-back is limited to the indicated material temperature being within ∀0.25E of 20 EC, as specified in the uncertainty budget.

3.1.5. If a ball fails the same test or tests after one remeasure investigate the following typical reasons measurements fail statistics: (1) dirty ball, can cause the F or T test to fail, (2) measurements made in the incorrect sequence, can cause both F and T tests to fail, (3) wrong size is being measured, causes T-test to fail, and (4) balls were setup in the wrong order, causes T-test to fail. Remeasure any one ball only two times, if the measurement does not pass after the second remeasure contact lab manager to assist in determining the cause of the failure and to aid in resolving it.

3.2. **Measurement (Ball Diameter > 31.75 mm ≤ 101.6 mm)**

3.2.1. The measurement of larger balls is done by comparison to the 25.4 mm tungsten and steel master ball pair. As the test ball size increases, so does the measured difference between the masters and the unknown. Due to this increased sensitivity the following steps should be strictly adhered to:

(1) Visually check the laser alignment as described in 2.2.2, prior to performing any measurements. If there is any suspicion with regards to the alignment, the X-Y position detector should be used as described in Section 7.0 to check the alignment more accurately.
(2) The adjustable vertical stage of the instrument has an adjustment for tilt in the measurement direction (refer to SIP550 operation manual to identify this knob if you are not sure which one it is). Using this adjustment, the table should be leveled using a simple bubble level prior to measurement.
(3) Due to the significant weight of these larger balls and a tendency for this weight to cause noticeable bending in body of the micrometer, it is essential that the test ball be located on the adjustable vertical stage of the micrometer during all measurements. The variation in the position on the stage at any given time causes no noticeable difference in the measurement results, as occurs when the ball is in the measurement position versus the setup position.
(4) Although variation in the environmental parameters used for wavelength compensation is permitted within the limits set forth in the uncertainty budget, it is considered best measurement practice to enter current readings for atmospheric pressure, air temperature, and relative humidity prior to each measurement sequence.
(5) Manipulation of the ball should be done using either large insulated tongs or gloves.

3.2.2. For most large sizes the V-stand and the measurement process described in 3.1.3 should be followed, however for sizes larger than 75 mm this may not prove to be adequate. If the standard procedure does not prove adequate refer to the following steps for guidance.

3.2.2.1. Find a used ring gage with a diameter small enough so that when the ball is seated in the ring it supports the ball in a stable manner without letting the ball touch the table surface. Place masking tape around the outside edge of the ring gage and mark vertical lines denoting a specific diameter. Position the ring gage and ball, with ball centered front-to-back between the instrument contacts and the diameter marks lined up approximately parallel to the measurement axis. Using a marker, transfer the vertical marks on the ring gage to the top of the adjustable vertical stage of the instrument. Unlock the clamp knob that allows the stage to float freely in the measurement direction (refer to SIP550 operation manual to identify this knob if you are not sure which one it is). Tram the ball up and down between the contacts as described in Step 2.6 to find the Z-coordinate of the center of the contacts. Record this coordinate value for use during measurement.

3.2.2.2. Lock the free motion of the stage in the measurement direction, then slide the ring and test ball out from between the contacts to a holding position

elsewhere on the vertical stage of the micrometer. Position the V-stand of appropriate size for the 25.4 mm masters into place between the contacts. Adjust vertical stage and the V-stand/base with one of the master balls so that the ball is centered between the contacts from front-to-back. Using a marker, create some alignment marks on the vertical stage so that the V-stand and base can be repositioned consistently between measurements. Tram the master ball up and down between the contacts as described in Step 2.6 to find the Z-coordinate of the center of the contacts. Again, record this value for use during measurement.

3.2.2.3. The measurement should be performed as described in Step 3.1.3; however the balls and their associated fixture will be interchanged between each measurement. For the master measurements, the gauging process will be performed as normal; however the test ball will be gauged in a slightly different manner. Once the test ball is positioned between the contacts, with the markings aligned and the ball not quite touching the fixed measurement contact, the stage motion in the measurement direction should be unlocked. This allows almost frictionless movement of the stage, ball, and ring as a unit in the measurement direction. Now gauge the ball as normal. *NOTE! Lock the stage motion prior to moving the test ball out from between the contacts.*

3.2.2.4. If the measurements are not repeatable, it may be necessary to increase the applied measurement force to 2.2 N (8 oz). A greater force is certainly permissible but should not be required.

3.3. Measurement (Balls with a large variation-in-diameter)

3.3.1. Occasionally, we will find a test ball with an observed diameter variation that is large enough (typically > 250 nm) that will cause the F-test to fail more often than not. In deed, if we continue to remeasure the ball, sooner or later it will pass; unfortunately it will be due to coincidence and quite possibly the answer could be more incorrect than a result of a failing test. This situation needs to be identified immediately and the alternative measurement scheme and analysis that uses averaging rather than least-squares regression needs to be employed.

3.3.2. Whether it is a standard size ball or a large ball, the data collection process and analysis is the same. In either case, the physical procedure for making the measurements is the same as previously described, however the measurement scheme is a modified order of the 3-4 Design (see below) and the analysis is done using the Excel worksheet titled “SIP550 Large Dia Variation Avg Method Analysis”, located on the storage device in the ball calibration binder.

3.3.3. Use the NIST “Wire” program to collect the data using the program’s standard 3-

4 Design, however perform and collect the measurements in the order defined in the modified 3-4 Design shown in Step 3.3. Print the data then use the Excel worksheet to calculate the results.

NOTE! Remove and replace the S master between the second and third measurements, as these must be two different measurements.

S = Master #1, C = Master #2, 1 = Test Ball

Modified 3-4 Design	
1	C
S	1
C	S
S	C
1	S
C	1

3.3.4. For this worksheet, the material temperature, nominal size, the thermal expansion coefficients for each ball, the deformation corrections for each ball calculated using NIST "Elastic" Program, the master values from the master file, and the expected S-C value from the master file must be entered.

3.3.5. If the T-test passes the sheet should be printed for inclusion in the calibration envelop. The modified measurement uncertainty is listed on the result page as well, reflecting an increase due to the observed diameter variation. The uncertainty is calculated by substituting the standard deviation of the average of the test ball measurements in place of the reproducibility figure in the standard uncertainty budget. Refer to the attached example result sheet at the end of this procedure.

3.4. Measurement (CMM Spheres)

3.4.1. Typically, CMM spheres can be identified by an attached stem and are commonly referenced as such on the customer purchase order. CMM spheres are measured using the procedure identified in Section 3.1 and on rare occasions, using the procedure in Section 3.3, if the variation-in-diameter is excessive.

3.4.2. The only variations to these procedures are defined as follows.

3.4.2.1. Some CMM spheres come with either a magnetic base or a removeable stem extension. In either case, use a wrench to remove as much of the stem / base assembly as possible. In most cases you will be left with a fixed portion of the stem with a length of somewhere between 50 and 150 mm long, the less the better. Remember to reassemble all pieces before returning the item to the customer.

3.4.2.2. CMM sphere measurement orientations.

3.4.2.2.1. The first two of the four measurements are made with the stem vertical (balanced) with sphere seated in the V-stand. The second measurement orientation is obtained by rotating the sphere about the axis of the stem approximately 90º from the first. These two measurements represent a sampling of the diameter at the equator.

3.4.2.2.2. The second two measurements are made by laying the stem down on a cylinder located towards the front of the adjustable vertical stage with the sphere still seated in the V-stand. The stem should be approximately perpendicular to the measurement axis. *This cylinder provides support for the stem while hopefully providing a small contact point so that the stem will slide when the sphere is engage to ensure self seating. If the sphere doesn't seem to seat properly when gauged, the top of the adjustable vertical stage can be unlocked as described in 3.2.* The first of the two final measurements can be made by rotating the stem 45º towards the fixed anvil or the moveable carriage from the perpendicular starting position. The second orientation can be achieved by rotating the stem 45º in the opposite direction relative to the perpendicular starting position (the 45º angle is the angle between the stem and the measurement axis). This assumes the measurements are made in the same diametrical plane. The same results can be accomplished by measurement in the same 45º orientation for both of the final measurements, however rotating the sphere 90º about the stem axis between measurements.

3.4.2.3. Material Issues:

3.4.2.3.1. Most CMM spheres are Alumina or Aluminum Oxide (Al_2O_3) which is the typical ceramic used for this application, they can however be steel, stainless steel, or even in one case I had Zirconia (gage block ceramic).

3.4.2.3.2. Analysis: For all cases other than Al_2O_3 use the material properties found in the NIST software. For Al_2O_3 use the following material properties: Thermal Expansion Coefficient (α) of 8.2×10^{-6}/ ºC, Young's or Elastic Modulus (E) of 377 GPa, and Poisson's Ratio (σ) of 0.24.

3.4.2.3.3. Analysis: After entering the material properties for Al_2O_3 in the NIST "Wire" software you will be prompted for the restraint. The proper entry will be "SC" meaning both S & C. When Zirconia is selected the restraint will automatically be "S" as this is the appropriate choice to the similarity in elastic properties.

3.4.2.3.4. Reporting: We should report the elastic properties for all measurements, however currently we only do this in ball calibrations for Al_2O_3. Typically, the diameter and roundness are measured for CMM spheres thus the final report will include results of both types of measurement. Either way, the following should be included in the report after the diameter data:

"Material properties used for calculating the deformation corrections include:

Young's Modulus, E 37.7×10^{10} N/m^2 (377 GPa)
Poisson's Ratio, Φ 0.24

This sphere was assumed to be alumina (Al_2O_3), which is a type of ceramic material used for dimensional artifacts. The thermal expansion coefficient, Young's Modulus, and Poisson's Ratio reported above were based on available data for alumina (Al_2O_3). Typically, ceramic spheres have different colors, such as, white, almond (cream or bone), and grey. The available data suggests that different colors may have different material properties although they are all considered alumina. The variability in color is based on the percentage of Al_2O_3 and a specific color only suggests a different range of property values. The properties above represent an average of the properties for 99.5 % to 99.9% Al_2O_3. The user is responsible for verifying the accuracy of the material property information."

Note! This data was compiled from the review of numerous sources that include but are not limited to: Swip Tarbell (a common manufacturer of CMM spheres for Zeiss and Brown & Sharpe CMM's in the 1990's, as well as, Coors Ceramic Company and Spheric.)

4.0 **History Analysis:**

4.1. Using the NIST AWire@ Software and the AHistory@ Program analyze the new test results against the history for the set, if applicable. Otherwise, archive your data in the appropriate directory on the server, then go to Section 5.0, Report Generation.

4.2. If there is history, use the tools provided in the AHistory@ Program to analyze the new data. The difference between the new data and the last data point should not be greater than the most current uncertainty, if there is no statistically significant linear trend to the data. This can be determined by using the plot function of the AHistory@ Program. If a significant trend exists, either the ball is growing or shrinking, the difference between the new data point and the trend line should not be greater than the uncertainty. A significant trend can be identified using the plot function then the difference between the most recent result and the trend line can be determined using the APlot Latest Offset To@ function in the AHistory@ Program.

4.3. Any balls that do not meet these criteria should be set up for a remeasure using the master pair from the initial comparison.

4.3.1. If the result of the remeasure does not meet the criteria, yet is consistent to the original result then set up for a second remeasure using a different master pair.

4.3.2. If the second remeasure using the different master pair is consistent with the original result and the remeasure for the first master pair, then this is sufficient proof that the current data is valid.

4.3.3. If this result agrees with history, but is significantly different than the original result and the first remeasure then contact the lab manager for further guidance.

NOTE! Typically, the lab manager will verify that no significant changes have occurred for that master size between this calibration and the previous calibration of the test ball. If no significant changes are found, then the lab manager will contact the customer to verify whether or not the test ball was replaced between calibrations, as this is a typical reason for disagreement with history since the balls are not serialized. If this does not explain the disagreement then the test ball should be scheduled for measurement by interferometry. If the interferometric result for the test ball disagrees significantly with the mechanical result the masters should then be remeasured to determine what has changed. If a significant master change has occurred, the appropriate corrective action should be initiated.

4.4. When this process is completed, remeasures are resolved, and the data file populated with the correct data, use the AHistory@ Program to archive the new data with the old and archive the history to the server.

5.0 Report Generation:

5.1 Using the AFolder@ and AReport@ Programs of the NIST AWire@ Software and the data file generate the calibration report.

6.0 Packing Order:

6.1 During the packing process the balls should be handled with rubber gloves or ball tongs. Steel balls should be coated with a rust preservative before being packed and small balls that may have become magnetized during the measurement process with the wire - magnet tool should be demagnetized.

6.2 Balls maintained together in a set container should be secured so that they do not come in contact with each other during transportation. If after closing the case it is determined the balls are not secure add appropriate packing materials to secure them.

6.3 Tape the case shut to prevent it from opening if the latch fails.

7.0 Laser Alignment

7.1. The laser alignment must be within 0.25 mm when the moveable carriage of the instrument is displaced ~ 220 mm. This can only be achieved using X-Y position detector, typically 0.5 mm can be detected by eye.

NOTE! The 220 mm is the maximum displacement of the carriage without contacting the interferometer and mirror stage mounted on the end of the micrometer bed. Use extreme caution to prevent the carriage from ramming these items as the carriage has more travel range than needed.

7.2. This procedure assumes the operator is familiar with the use of the X-Y position detector and is familiar with the procedure for aligning a laser interferometer. The X-Y position detector is a "calibrate on use" device, as such the displacement in X & Y should be verified and this data recorded documented in the instrument maintenance log maintained with the machine.

7.3. The SIP550 is fitted with a vertical stage attached to the end of the micrometer bed. This stage has two mirrors, one of which is adjustable, that allow the operator to easily intercept the return beam and direct it to the photo-sensor mounted on the table beside the micrometer. The vertical stage should be raised only enough to intercept the return beam, otherwise the back of the mirror may block to source beam.

7.4. Once the alignment has been completed, lower the vertical stage so that the laser beam is unobstructed.

7.5. Document the remaining alignment information in the instrument maintenance log. In addition to the calibration information for the X-Y position sensor, record that the laser alignment was performed along with the date and identification of technical staff

member who performed the procedure.

8.0 Instrument Maintenance

8.1. On a yearly basis, clean and oil the lapped surfaces of the micrometer bed where the carriage bearings travel. These surfaces consist of two sides of the vee-groove towards the front of the machine and the horizontal surface towards the back of the machine. The carriage with need to be moved along with the fixed head stock and adjustable vertical stage in order to access all portions of the contact surfaces. Use 200 proof ethyl alcohol for cleaning surfaces and a non-drying instrument oil to protect them.

8.2. Again on a yearly basis, use a force gauge to verify that the typical force settings are within ± 10 %. Our force gauges are considered "Calibrate on Use," therefore locate one of our calibrated weight sets to verify the gauge is reading correctly before using it to check the micrometer force.

8.3. Record all service information in the instrument maintenance log. Minimally, document the type of service or check performed accompanied by the date and identification of technical staff member who performed the procedure. Record all data pertaining to the calibration of "Calibrate on Use" devices along with appropriate identification of the references used.

Example "Modified" 3-4 Design for Large Diameter Variation Balls Excel Worksheet Analysis

Nominal Size (mm)		**101.6**	
Material		**Steel**	
Date		**12/14/2005**	
Serial Number		None	
Material Temperature		19.97	
	S (mm)	C (mm)	1 (mm)
	-0.00021	-0.00051	76.20435
	-0.00021	-0.00046	76.20437
	0.00007	-0.00027	76.20439
	-0.00004	-0.00025	76.20491
CTE	0.0000046	0.0000115	0.0000115
Avg	-0.000098	-0.000373	76.204505
SD	0.000137	0.000132	0.000270
SD Avg			0.000135
SD Avg (Range)			0.000081
Deformation (mm)	0.000142	0.000244	0.000152
Temp Correction	0.000004	0.000009	0.000035
Act Mstr Size (mm)	25.399977	25.399746	
Corrected	0.000048	-0.000120	76.204692
S-C	0.000168		
Act Control	0.000231		
T-Test	2.11	*Pass < 3.00*	
		Actual (mm)	Deviation (mm)
Unknown v. S	TC	101.604621	0.004621
Unknown v. C	ST	101.604558	0.004558
Expanded Uncertianty (k=2)	308	nm	

NOTE! Highlighted entries are user accessible data that must be entered by the user for each analysis. The deviation from nominal is provided versus each master; however the result from the master of material most closely matching the material of the test ball should be used. If not, the answer used should be clearly identified accompanied by an explanation.

Appendix A

Uncertainty Budget

Uncertainty Budget for
Ball Diameter by Mechanical Comparison
Using the Laser Interferometer Retrofitted SIP550 Bench Micrometer
Rev 0 ESS 9-30-2005

This comparison process uses six pairs of master balls to measure test balls ranging in size from

0.8 mm up to 101.6 mm. The laser interferometer retrofitted bench micrometer provides for a large measurement range; however uncertainty contributions typically associated only with absolute measurements must now be incorporated in the uncertainty budget, in addition to those typically addressed in comparison methods. The maximum difference between the test ball and master for test balls smaller than 31.75 mm is 6.35 mm; as such this figure is commonly used to calculate length-dependent, length-difference uncertainty components (typical absolute measurement uncertainty components). All test balls larger than 25.4 mm are compared to the 25.4 mm master pair; thus the length-difference length-dependent components for these larger sizes are calculated individually and are based on the actual difference. Other length dependent components are calculated using the nominal size of the test ball.

In the following explanations, the actual calculation of the standard uncertainty when a rectangular distribution is assumed in not shown, rather it is assumed that the half-width is divided by the square-root of 3 and the full-width is divided by 2 times the square-root of 3.

Master Ball Calibration, u_1 = 19 nm

This component represents the uncertainty associated with the calibration of the master balls. The master balls are measured using static interferometry and many have a history that spans over 30 years. The component here represents a pooled standard deviation derived from the historical data for all the master balls. This figure samples: stability, operators, calibrations of all environmental recording equipment, various light sources, different interferometers, and different operators.

Reproducibility, u_2 = 42 nm

The reproducibility component was derived from approximately 1 ½ years of master pair difference data (S-C) for each of the six master pairs. This data showed no obvious length dependence; therefore one figure was calculated by pooling standard deviations from each master pair.

Scale Components (length-difference, length-dependent), u_s

Wavelength, u_{s1} = 0.10 L nm (L is the length difference in mm)

This figure is simple the standard uncertainty from the laser wavelength calibration as determined against the NIST Iodine-stabilized reference laser.

Index of Refraction, u_{s2} = 0.02 L nm (L is the length difference in mm)

This is simply the standard uncertainty in the Edlen Equation.

Atmospheric Pressure (Reading), u_{s3} = 0.01 L nm
(L is the length difference in mm)

This represents the standard length uncertainty due to the uncertainty of the atmospheric pressure reading obtained from the Paroscientific Pressure Sensor Model #....., which is used in the Edlen Equation to make the wavelength correction. The combined standard uncertainty of the pressure reading for this instrument is 0.03 mm of Hg (4 Pa), thus the corresponding standard uncertainty in length is (0.03 mm / 0.3 mm) × (1×10^{-7}) = 0.01×10^{-6} L.

Atmospheric Pressure (Variation), u_{s4} = 0.19 L nm
(L is the length difference in mm)

This component has been added because in the process of measuring a set of test balls, it is not appropriate to have the operator enter the pressure for each comparison. Rather our measurement procedure allows the operator to continue measuring as long as the pressure remains within ± 1 mm of Hg (133 Pa) of the pressure reading currently be used in the NIST software. Taking 1 mm as the half-width of a rectangular distribution, the standard uncertainty in length due to this allowable variation is (0.58 mm / 0.3 mm) × (1×10^{-7}) = 0.19×10^{-6} L.

Humidity (Reading), u_{s5} = 0.03 L nm
(L is the length difference in mm)

This represents the standard length uncertainty due to the uncertainty of the humidity pressure reading obtained from the Vasilla Humdity Sensor Model #....., which is used in the Edlen Equation to make the wavelength correction. The combined standard uncertainty of the humidity reading for this instrument is 3 %, thus the corresponding standard uncertainty in length is (3 % / 12 %) × (1×10^{-7}) = 0.03×10^{-6} L.

Humidity (Variation), u_{s6} = 0.05 L nm
(L is the length difference in mm)

This component has been added because in the process of measuring a set of test balls, it is not appropriate to have the operator enter the humidity for each comparison. Rather our measurement procedure allows the operator to continue measuring as long as the pressure remains within ± 10 % of the humidity reading currently be used in the NIST software. Taking 10 % as the half-width of a rectangular distribution, the standard uncertainty in length due to this allowable variation is (6 % / 12 %) × (1×10^{-7}) = 0.05×10^{-6} L.

Air Temperature (Reading & Variation), u_{s7} = 0.15 L nm
(L is the length difference in mm)

Our measurement procedure assumes we are using a air temperature measurement device with a combined standard uncertainty of the reading of less than 0.04 ºC. Again because it is not appropriate to have the operator enter the air temperature for each comparison, we allow the operator to continue measuring as long as the air temperature remains within ± 0.25 ºC of the temperature reading currently being used in the NIST software. If the temperature indicator meets the above requirement, then the reading uncertainty is negligible in comparison to the allowed variability; thus the standard uncertainty in length, using 0.25 ºC as the half-width of a rectangular distribution, is (0.15 ºC / 1 ºC) × (1×10^{-6}) = 0.15×10^{-6} L.

Interferometer Alignment, u_{s8} = 0.16 L nm
(L is the length difference in mm)

Misalignment of the interferometer in relation to the carriage motion of micrometer results in a cosine error. With our configuration the carriage can be translated approximately 219 mm, which results in a path length change of 438 mm for alignment purposes. Our procedure requires the laser be aligned with the measurement axis to within 0.25 mm over 438 mm (corresponding to angle of 0.0327º) with the aid of x-y photo-detector. As a result, the cosine error associated with this potential misalignment is (1 – COS (0.0327)) = 0.16×10^{-6} L.

Artifact Temperature

Material Temperature (Reading), u_{T9} = 0.12 L nm
(L is the length difference in mm)

Material temperature of the artifact in a comparison process is typically negligible due to comparison of almost identical sizes; however in a long range comparison this component is not negligible. Our procedure assumes we are using a temperature indicator with a combined standard uncertainty of reading of 0.01 ºC or better. Using the thermal expansion coefficient of steel (11.5 um/(m·ºC) as the worst case the standard uncertainty is 0.01 ºC × 11.5 um/(m·ºC) = 0.12×10^{-6} L.

Thermal Expansion Coefficient, u_{T10} = 0.08 L nm
(L is the nominal diameter of test ball)

The uncertainty stated in literature for the thermal expansion coefficient values for well characterized materials is typically 5 %. This means that the further off from the standard temperature of 20 ºC measurements are made, the larger the potential error is with regards to the temperature correction. Using the thermal expansion coefficient of steel as worst case, 0.25 ºC as the largest allowable deviation from 20 ºC, and assuming a rectangular distribution due to the unknown format of the literature specification the standard uncertainty is(((0.05 × (11.5×10^{-6})/ ºC)) / √3)*0.25 ºC = 0.08×10^{-6} L.

Thermal Gradients, u_{T11} = 0.20 L nm
(L is the nominal diameter of test ball)

The comparison process involves three balls, two masters and one test, each of which can be at slightly different temperatures. Based on temperature measurements in our laboratory that is controlled to ± 0.1 ºC we found the maximum temperature difference to be approximately 0.03 ºC between any two balls as typically arranged on the comparator. The instrument is now located in better laboratory controlled to ± 0.01 ºC, however until this experiment can be repeated we will continue to use the conservative figure. Again using the thermal expansion coefficient of steel as the worst case and assuming a rectangular distribution, the standard uncertainty is 0.017 ºC × (11.5×10^{-6} / ºC) = 0.20×10^{-6} L.

Elastic Deformation, u_{12} = 23 nm

There are two sources of uncertainty with regards to differential elastic deformation correction applied between the master and test balls: (1) the uncertainty in the elastic properties of the balls and (2) the uncertainty associated with the applied force setting that is used in the calculation. With our measurement process each master pair consists of one chrome steel master and one tungsten carbide master, therefore the majority of the customer measurements performed result in a comparison of like materials. Unfortunately, with a long range comparator a differential deformation between the master and test ball of the same material must still be made due to the significant difference in size. For this uncertainty contribution we want a conservative estimate, thus we choose the worst case where a 0.8 mm steel ball is measured against the 1.6 mm master for both error sources. These sizes are the approximate metric equivalent of the standard nominal English sizes 1/32 inch and 1/16 inch.

Numerous sources for the elastic properties of well characterized materials state an uncertainty of ± 5 % for the elastic modulus (or Young's Modulus). Our measurement process uses the same elastic modulus for each steel ball in the test, however let us assume that the elastic modulus of one ball is high and one is low by 5% for one calculation of the differential deformation correction and the opposite for the second calculation. This results in corrections that differ by 71 nm, representing the full-width of a rectangular distribution because our process

actually uses the average elastic modulus and we do not know the statistical nature of the stated uncertainty. Converting this potential error to standard uncertainty form, we get 21 nm.

The second source of uncertainty is a result of the inaccuracy of the applied force, which is used in the calculation of the differential deformation corrections. The bench micrometer used in our measurement process applies the force of ± 10 % and we periodically verify that the instrument force is within these limits using a secondary force gauge. For all ball measurements between 0.8 mm and 25.4 mm we use an applied force of 1.11 N (4 ounces), therefore we will calculate the worst case difference in corrections assuming the force is high by 10 % (1.25 N) in one case and low by 10 % (0.97 N) in the other case. Here we assume that the majority of the error in the force setting is systematic and that random error is negligible. The difference in the differential elastic deformation correction is 26 nm. Here again because we are actually using the average force setting and because we do not know the statistical nature of the stated uncertainty we treat the potential error between extremes as the full-width of a rectangular distribution. This results in a standard uncertainty of 8 nm.

Finally, the combined standard uncertainty for the differential elastic deformation correction can be obtained by squaring the individual components (21 nm and 8 nm), adding them together, and then taking the square root. This results in a worst-case fixed component of 23 nm. For cases where a dissimilar comparison between master and test ball is done, the calculations are performed using the actual situation to ensure this uncertainty component adequately covers the potential error.

Instrument Geometry

Abbe Error, $u_{I\,13}$ = 0.76 L nm
(L is the length difference in mm)

The first of two final sources of uncertainty is identified as an instrument geometry error and is a result of Abbe Error caused by the interaction of pitch errors in the carriage of the movable contact and the vertical misalignment of the laser displacement measurement axis and the physical line of contact through the contacts and ball. This results from physical orientation of the center of the retro-reflector versus the center of the contacts and operators ability to gage the balls at the center of the contacts. The instrument has a nice feature were the vertical stage is equipped with a z-axis readout thus allowing precise location of each ball relative to the center of the contacts. However, because each measurement comparison potentially involves three significantly different diameter balls and considering time constraints we assume the operator can conservatively position the ball to within ± 0.5 mm of the contact center. To estimate this error we devised an experiment using the 25.4 mm master pair to measure a 12.7 mm test ball at the top, center, and bottom of the contacts. This provided for a vertical height change of approximately 4 mm over the contact area. The results revealed that the diameter of the 12.7 mm varied linearly from top to bottom and that the diameter measurement at the center of the contacts compared best with the interferometric reference value. The linear variation confirms that the error we are seeing is due to Abbe Error and the comparison with the interfermetric

value reveals that the measurement axis and the contact axis are in very close agreement at the center, as expected. From the comparison of the center results we estimated that the laser axis and the center of the contacts are aligned to within 0.32 mm. Converting the ± 0.5 mm operator positioning inaccuracy to standard uncertainty form by treating the 0.5 mm as the half-width of a rectangular distribution we get 0.3 mm. Combining these two displacement uncertainties by squaring them, adding them, and taking the square-root we get a displacement standard uncertainty of 0.44 mm. Using this term along with the variation of 88 nm over the 4 mm of vertical displacement and the difference in nominal size of the masters and unknown of 12.7 mm we get a standard uncertainty in diameter of ((88nm / 4mm) × 0.44mm) / 12.7 mm = 0.76×10^{-6} L.

Contact Geometry, $u_{I\,14}$ = 6 nm

The final source of instrument geometry error is caused by variation in contact position between the master and unknown during the comparison process. As stated previously, the operator is expected to be able to position the ball within ± 0.5 mm of the center of the contacts. To estimate the error associated with contact geometry we simply displaced the specific diameter of a ball over a 1 mm diameter circular area about the center of the contacts numerous times recording the maximum variation in the observed reading. From this experiment the contact geometry error was estimated to be 20 nm. Treating the 20 nm as the full-width of a rectangular distribution we get 6 nm as the standard uncertainty.

Source of Uncertianty	Standard Uncertainty, u		
	Fixed (nm)	*Length-Difference Length-Dependent (nm)	**Length-Dependent (nm)
Master Ball Calibration, u_1	19		
Reproducibility, u_2	42		
Scale Components			
Laser Wavelength, u_{S1}		0.10 L	
Index of Refraction, u_{S2}		0.02 L	
Pressure - Reading, u_{S3}		0.01 L	
Pressure - Variability, u_{S4}		0.19 L	
Humidity – Reading, u_{S5}		0.03 L	

Humidity – Variability, u_{S6}		0.05 L	
Air Temperatur – Reading and Variability, u_{S7}		0.15 L	
Interferometer Alignment, u_8		0.16 L	
Artifact Temperature Components			
Material Temperature, u_{T9}		0.12 L	
Thermal Expansion Coefficient, u_{T10}			0.08 L
Thermal Gradients, u_{T11}			0.20 L
Elastic Deformation, u_{12}	23		
Instrument Geometry Components			
Abbe Error, u_{I13}		0.76 L	
Contact Geometry, u_{I14}	6		

***L is diameter difference between master and test ball in mm.**
****L is the nominal diameter of the test ball in mm.**

Expanded Uncertainty Summary
Ball Diameter (0.8 mm to 31.75 mm)
U(k=2) = 105 nm
Ball Diameter > 31.75 mm ≤ 101.6 mm
U(k=2) = (76 nm + 0.93 (nm/mm) L), L is the nominal diameter in mm