Procedure Title: Interferometric Calibration of Sphere Diameter
Revision/Author: Revision 1.0 / Ralph Veale
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Measurement of Master Balls using the Strang Viewers

Ralph Veale

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1.0 Introduction

There are two Strang Viewers that can be used to make diameter measurements of balls. This procedure will describe both systems; however, the basic principal is the same for both instruments and the differences in use are minor.

The measurement method consists of measuring the distance between two optical flats, one on which the ball is resting and the other on the top supported by the ball. The top flat is held in a fixture so that the flat can be raised and lowered depending on the size of the ball to be measured.

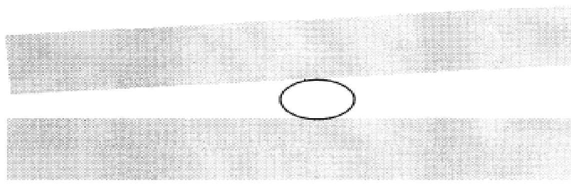


Fig. 1

There must be a wedge between the two flats in order to produce fringes. There also must be provisions for tipping the flat to change the angle between the two flats (wedge angle), and also a provision for tipping the flat in the direction ninety degrees to the wedge angle. The fixtures with the two viewers provide these adjustments.

The setup as shown above is viewed with parallel rays of cadmium light aligned so that the rays are nearly perpendicular to the bottom surface. This setup creates a Fizeau interferometer. Light is reflected off the top of the bottom flat and the bottom of the top flat to create interference fringes. Counting the number of fringes that occur between the two flats gives the distance between the two flats. Because the flats are not parallel, the distance between the flats is different depending where the measurements are made; therefore, one must measure at the point that passes through the center of the ball.

Numerous corrections must be made to the measurement to get the undeformed diameter of the ball. All dimensional measurements are defined at 20 °C, so if the ball is not exactly at that temperature – and it almost never will be – the actual temperature must be determined and a correction applied for the thermal expansion of the material to get the diameter at 20 °C.

The wavelength of the cadmium lines used to make the measurement depend on the density of the air through which they pass. The density can be obtained with sufficient accuracy by measuring the temperature, barometric pressure, and the relative humidity (or dew point). The wavelengths of the four colors of cadmium used in the process are defined at either the vacuum wavelength or at the standard metrological conditions of 20 °C, 760 mm of mercury, and 10 mm of water vapor. A correction must be made for the differences between the actual wavelengths and the standard wavelengths.

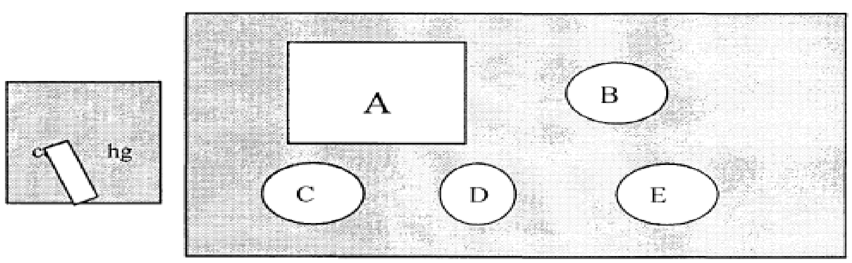
The weight of the flat and the fixture holding the top flat exerts a force on both points where the ball touches the flats. The force on the bottom flat will be larger than at the top because of the weight of the ball. These forces cause deformation to occur at the point of contact. Corrections must be made to get the undeformed diameter of the ball.

Additional corrections must be made for the instrument used to project the cadmium light source creating the fringes. A correction is made because the slit has a finite size (not a point source). An even larger instrument correction is the obliquity correction caused by the fact that the reflected light must return to an opening slightly offset from the point of departure. The instrument corrections are marked on the side of each viewer. They may be verified by measuring a gage block with both the Strang viewer and the Hilger Tyman-Green interferometer using a helium-neon laser as the light source. The difference obtained (assuming negligible uncertainty in the measurement) is the instrument correction of the viewer.

2.0 Fixtures, Viewers and Power Supplies

2.1 Number 6

The instrument most used is model M # 6 currently in B12 (NIST # 151944). The view from the front appears as in fig. 2. The viewer is equipped to use either mercury or a cadmium source. This procedure will describe using cadmium only as the Group no longer has any mercury cells. The level on the left will always be in the cadmium position. It is clearly marked. The eyepiece (A in figure 2) is equipped with a filar eyepiece for measuring distances between fringes. The eyepiece can also be adjusted to focus at the desired distance. The knob labeled "B" has two positions: microscope and telescope. The microscope position is used in locating the reflected image and to properly adjust the prism to give the desired wavelength. The telescope position is used when viewing the fringe pattern. The knob labeled "C" rotates the prism to properly place the desired color in the field of view. The "D" knob is for setting the slit to the desired light source. It should be set to cd. Knob "E" opens and closes the aperture. During setup the knob is usually in the open position, but must be closed when reading the fringes.



Model M #6 Viewer
Fig. 2

The front of the power supply is shown in figure 3. Because we are using only cadmium as a light source, the right hand or mercury portion of the power supply can be ignored. To turn on the system both of the cadmium power switches must be turned on. Adjust the amperage to 1 to 1.5 amps. Wait about sixty seconds, then turn off switch A (the upper switch). Adjust the power to one amp, or lower if the brightness at one amp is not needed. The brightness of the image increases with the amperage. It is important to time the interval with both switches in the "on" position and not leave to do something else. Leaving both switches on for an extended period of time can damage the light source.

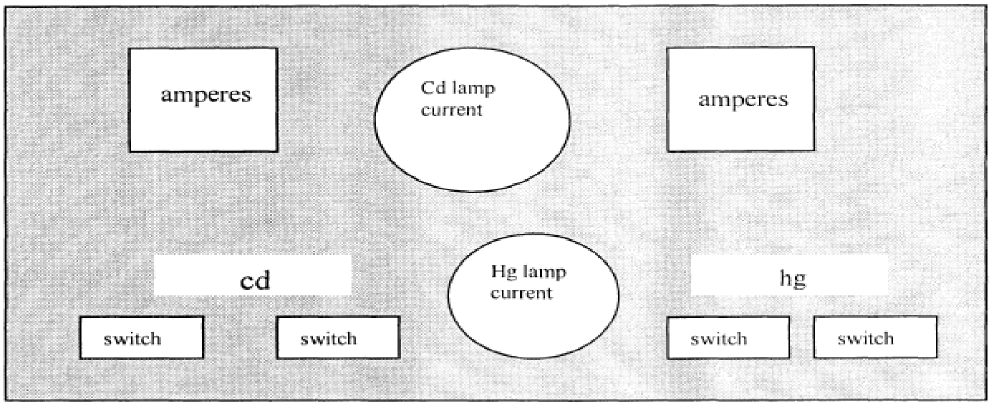


Fig. 3
Power supply with viewer # 6

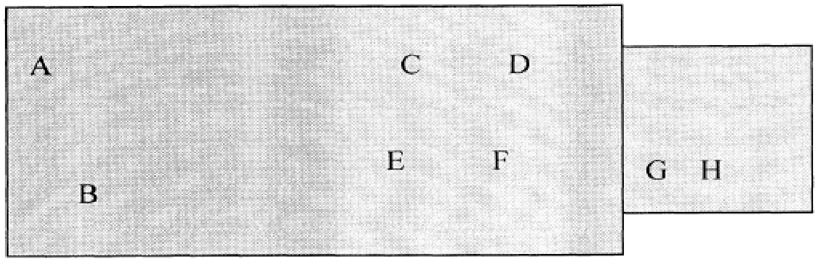
To best prolong the life of the cadmium bulb, the power should be left on during the day while the instrument is being used with the power at the lowest amperage needed. The instrument should be turned off for any extended period of time when not in use. Turn it off at the end of the day and then back on again the next morning if the instrument is being used for more than one day.

2.2 Number 1

Model F12-M #1 (NIST #165922) is currently in room B18. There are some differences between the two instruments. Looking at the instrument from the top, the light source holder can be moved to four locations labeled hg. 198, Ger. Osram, Cenco, with the fourth position blank. The position is set to German Osram when using the cadmium source. The parts of the instrument are listed below with the appropriate letters shown in figure 4.

A ext. and mercury set to ext.
B bubble level There is a bubble level for leveling the machine. There is another on top for leveling in the ninety-degree position.
C eyepiece for viewing the reflections and reading the fringes
D knob for setting the slit width for the appropriate source
E knob for setting the slit height for the appropriate source
F knob for switching between microscope and telescope The microscope position is used in locating the reflected image and to properly adjust the prism to give the desired wavelength. The telescope position is used when viewing the fringe pattern.
G knob to rotate prism to get desired color (proper wavelength)
H crank for changing from mirror to prism position. When using cadmium, use prism setting.

The power supply is also slightly different in the two models, but they are interchangeable. The one used with viewer model #1 could be used with viewer model #6 and vice versa.



Model F12-M #1 Viewer
Figure 4

The power supply currently with viewer model # 1 is equipped with two inputs. The output switch shown in figure 4 must be set to the correct cable input to the viewer located on the back of the power supply.

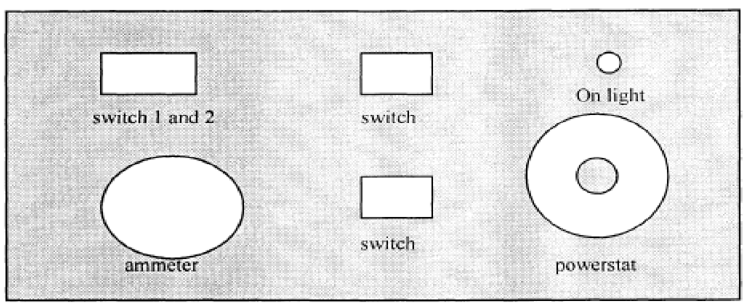


Figure 5
Power supply with viewer # 1

The switches on this power supply are clearly marked. Follow the instruction written on the front of the case when turning on this instrument. Again leave both switches on about sixty seconds and then do not forget to turn off the start switch.

Optical Flat Holding Fixture
The fixture must have a pivot point between the optical flat and a counterbalance to allow for setting the desired force on the top flat. The fixture must be capable of adjustment to make the top flat nearly parallel with the bottom flat. It must also have means of moving the flat up and down in order to measure various sized balls. The fixtures currently available have a 40-pitch thread in the up and down movement. This means that one revolution of the knob raises or lowers the fixture 0.025 inches. When changing from one size to the next counting the number of turns allows one to get almost exactly the correct height for the next ball size.

3.0 Aligning the Instrument

If the instruments are moved they may need realignment. It is necessary for the light rays to be nearly perpendicular to the top of the bottom flat used in making the ball measurements. Start by leveling the table so that it is perpendicular to the gravity vector. (This is not absolutely necessary, but it makes both the alignment and the use of the instrument easier.) Align the instrument using the bubble levels so that it is parallel to the tabletop. Next place a mirror or a steel platen on the top of the table or desk on which the viewer is used. The optical flat used to make the measurements could be used but if the two surfaces are not parallel, two images may be seen. The bottom image can be eliminated by covering the bottom surface with Vaseline or other oil having about the same density as quartz. With the switch in the microscope position and the slit open, look for an image from the reflecting surface. This may take some time, as you must move the X and Y orientations of the instrument to get the proper alignment. If the bottom flat is not supported on the table but rather supported on another device, it makes the alignment even more difficult, but the procedure is the same. The light rays must be perpendicular to the top of the bottom surface.

Next place the fixture holding the top flat as show in figure 1 above the bottom flat and adjust the fixture so that the bottom of the top flat is nearly perpendicular to the light source. In is necessary for the top flat to have a wedge angle between the two surfaces; otherwise, it will not be possible to separate the images from the top of the top flat from the image off the bottom of the top flat.

4.0 Measuring the Force

There are two different methods to measure the force on the ball. Although the initial setup may be a bit more difficult, the most accurate and easiest to use method is to support the bottom flat on a precision scale (balance). With the top flat not touching the bottom flat and nothing on the bottom flat, use the floating zero button to set the reading to zero. Next place the ball to be measured on the flat and measure the weigh of the ball, which is also the force exerted at the bottom of the ball causing some deformation of the ball and flat. Next place the top flat in contact with the top of the ball with the fixture set to exert approximately the desired force. A reading is again taken which gives the combined force of the top force pushing down and the force due to the weight of the ball. This number is used to calculate the deformation at the bottom of the ball. The total force minus the force due to the weight of the ball is used to calculate the deformation at the top of the ball. Four ounces (about one Newton) is a reasonable value for most measurements. A smaller force would be used for very small balls and in some cases one may want to use a larger force for larger balls. The important thing is to remain well below the elastic limit of the ball deformation. The deformation can be determined using the Hertzian equations given in Puttock and Thwait's book *Elastic Compression of Spheres and Cylinders at Point and Line* Contact, NSL Technical Paper No. 25, Commonwealth Scientific and Industrial Research Organization, Australia, 1969. They also can be obtained using Jay Zimmerman's program "Elastic."

If the material properties of the ball to be measured are not well known, several measurements can be made at different forces to determine the correction for the undeformed diameter. For measurements of the highest accuracy this method should be employed even if one thinks the properties are known.

The alternate method does not use the scales. The bottom flat is placed directly on top of the table or desk supporting the fixture and viewer. The ball is weighed separately to determine the force it will exert downward. The top force is determined using a dynamometer to measure the downward force on the ball. The problem with this method is that one must measure the force at exactly the point on the flat where the ball will be placed. This can be done by marking a thin line on the top of the flat or by choosing a scratch on the flat in an area near the center of the flat. The ball then must always be positioned under this marking at the spot where the force was measured. The advantage of having the flat directly on the scale is that it allows for the ball to be positioned nearly anywhere within the field of view – although it is best to position it near the center of the field of view.

The force readings using the dynamometer are not accurate unless the dynamometer has been recently calibrated. The calibration can be made using weights suspended on a thin thread. Note that some of the dynamometers read in two directions, each of which would give a different reading. The dynamometer must be used in the same direction that it was calibrated.

5.0 Preparations for making a Measurement

Following the initial alignment of the instrument, the ball to be measured in carefully placed between the two flats. Some adjustment will again be necessary to get fringes. Start using the green line of cadmium, as it is the easiest to see. With the slit open and the top flat nearly parallel to the bottom flat, make the necessary adjustment to get the image from the top of the bottom flat and the bottom of the top flat to overlap. Then make the necessary adjustments so one can see the reflected image when the slit is closed. Next switch to telescope and view the fringes. Additional adjustments will be necessary to get the desired spacing between the fringes and to get the correct orientation of the fringes. Some thought also must be given to the position of the open end of the wedge. It is customary (though not necessary) to have the open end of the wedge at the top of the field of view. The view would look somewhat similar to figure 6.

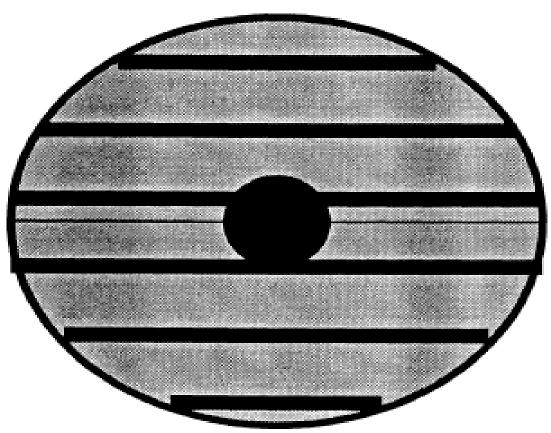


Figure 6
View of fringes

The actual fringes will not be as clear and sharp as shown in the picture. The dark circle in the middle is the ball to be measured. The ratio of the size of the ball to the field of view will be dependent on the ball size. A 50-mm ball will occupy almost the entire field of view. The thin black line is a moveable reticule line. It should be set to the center the ball when estimating the fringe fraction. Rather than estimating the center, a reading may be made with the reticule line at the top of the ball and another at the bottom. Calculate from those readings the position of the centerline. Assuming we have set the open end of the wedge at the top of the field of view, the goal next is to determine the ratio of the distance from the line through the center of the ball to the fringe below the ball divided by the distance between the two fringes (the one above and the one below). For example, in figure 6 the ratio appears to be somewhere between 0.60 to 0.65

If we had placed the open end of the wedge at the bottom of the field of view, the fringe fraction would be taken in the opposite direction, i.e., it would be between 0.35 and 0.40.

The reason for determining the fringe fraction is to compute the total number of fringes plus the fringe fraction between the top of the bottom flat and bottom of the top flat. This number will be very large; the distance between the fringes is equal to one half of the wavelength of light, which for the green cadmium line is about 500 nanometers. If we know the approximate size of the ball (within 100 microinches), and if we measure the fringe fraction between the flats for all four of the wavelengths of the cadmium line, we can calculate the number that precedes the fraction for each of the reading of the four colors.

6.0 Measurement Process without Computer Programs

First, the process will be described assuming that the measurements are made when the computer is not available. This section will use the data sheet developed by A. Strang for recording and analyzing the data. The information sheet is given in appendix A. The worksheet is somewhat more complicated than necessary because it was developed for measuring balls between two steel surfaces. At that time it was thought that the elastic deformation was better known for the steel to steel than for steel to quartz. That is the purpose of the 0.1006 in gage block wrung to the top surface. It has later been show that measuring between two quartz flats is considerably more accurate. We are measuring the distance between the two platens at the center of the ball in both types of measurements.

In the top line on the form the fractions .55, .70, .00, .70 are the estimated fractions of the distance from the center of the ball (as indicated by the line) to the fringe below, divided by the distance between the fringes. In this case the fractions were estimated; a more accurate method would have been to use the filar eyepiece. The total distance that we are measuring is the 0.96875 ball plus the 0.1006 block for a total distance of 1.069350 inches. If we knew the total number of fringes (plus the fractional part) of the distance between the flats, only one wavelength would be sufficient. Or, if we knew that the ball was within less than five microinches from its nominal length, one wavelength would be sufficient. In this example we only know that the ball is less than 100 microinches from nominal; therefore, we must use more that one wavelength.

The procedure for interferometric measurements using multiple wavelengths is to compute the total number of fringes for the four wavelengths of the nominal distance – in this case 1.06935inches. The values for the bands (one-half the wavelength) per inch are given on the first page of the attached NBS booklet dated January 12, 1961. The Group also has a 1967 version of a similar document consisting of four volumes that was prepared under contract for the United States Air force Inertial Guidance and Calibration Group at Dayton, Ohio. The latter has some slight differences for the value of the wavelengths which accounts for the fact that the values on the sheet are different than those in the 1961 book. The wavelengths are at the standard metrology conditions of 20 °C, 760 mm of mercury, and 10 mm of water vapor. The values were derived from the vacuum wavelength using the Edlén equation. Improvements have been made in the Edlén equation since 1961.

The number of bands (fringes) is calculated by multiplying the bands per inch times the distance in inches (the Air Force booklet has the values listed for both the metric and inch system). The number of fringes and the fractional part of the calculation are recorded on the worksheet. The fractional part is also recorded on the second line of the work sheet. The goal is to get the difference in the number of fringes between the nominal value and the observed value. We have to make a guess at this stage. If we believe the measured distance is larger than the nominal, we subtract the nominal fraction from the observed fraction, and the reverse if we believe it is smaller. This gives us the values: X.48 for red, X.65 for green, X.63 for blue1, and X.66 for blue 2(violet). Note that again we must guess at the number before the decimal; however, we can tell if we have guessed incorrectly because the deviation from the nominal length must be nearly the same for all four colors. In our example on the worksheet we guessed that the nominal and the actual were almost the same giving us zero before the decimal. Taking the average of the four colors, we find that the observed uncorrected measured distance is 6.2 microinches larger than the nominal. The tables in section 3-1 of the 1961 booklet make it easier for us to estimate the number before the fraction. You find the length where all four fractions are on — or nearly on — the same line. The average deviation from nominal length is recorded in the space provided on the right hand side of the sheet. Fringes were converted to microinches by multiplying each of the observed-nominal band fractions by the band fraction in inches as show on the left hand side of the work sheet. The values for the distance between two fringes are given in the 1961 booklet.

On the right hand side of the sheet the next two spaces below the average deviation are for recording the thermal expansion correction of the ball and the block. They are separated as the ball and block could be of dissimilar materials. When measuring without the block, we will have only the thermal correction for the ball. The thermal expansion correction is obtained by multiplying the length times the deviation of the ball from the nominal temperature times the linear coefficient of thermal expansion. The equation and calculations are shown at the bottom of the sheet.

As previously stated, the wavelength of the light is a function of the density of the air. The correction to the wavelength can be calculated using the Edlén equation. A simplified version of the Edlén equation is shown at the bottom of the page to calculate the wavelength correction from the nominal metrology conditions. The equation is $K = 0.36\,(760\text{-}P) + 0.05\,(e\text{-}10) + 0.93\,(T\text{-}20)$ where P is in mm hg., e is mm of water vapor, and T is the air temperature in degrees Celsius. The saturated vapor pressure of the air at 20° C is approximately 17.5 mm of hg. If the relative humidity is measured rather than vapor pressure, the vapor pressure can be obtained by multiplying the relative humidity by 17.5 and dividing by 100. This will give an approximation that is sufficiently accurate in most cases. If greater accuracy is needed, the barometric pressure, the actual temperature and the distance above sea level of the instrument should be taken into account.

Next we calculate the elastic deformation at both the top and bottom of the ball. The force at the top is the force pushing down on the ball caused by the weight of the optical flat and fixture less the counter-balance on the other side of the pivot point. The force can be determined using a calibrated dynamometer. Note that the force must be computed at the point exactly where the ball will be positioned. The force at the bottom is the top force plus the additional force caused by the weight of the ball. The calculations are made independently for each contact surface. The equation for calculating the deformation is given at bottom of the work sheet on the right hand side. Addition information on deformation can be found in the attached technical paper *Elastic Compression of Spheres and Cylinders at Point and Line Contact* by M.J. Puttock and E.G. Thwaite. It is Technical Paper No 25 published by the Commonwealth Scientific and Industrial Research Organization, Australia, 1969. Addition information on measuring the force was given in section 4.0.

The two spaces below the space for recording the deformation need not be used when measuring between two optical flats. Obviously there is no block correction, and the phase correction is zero as both surfaces are fused quartz.

Additional corrections must be made for the instrument used to project the cadmium light source creating the fringes. A discussion of the instrument correction was given in the introduction. A correction is made for both the slit correction and the obliquity correction. The correction for this instrument was 1.13 microinches per inch (micrometers per meter). The instrument corrections are marked on the side of each viewer.

The undeformed diameter of the ball is the sum of the nominal length plus all of the corrections.

7.0 Measurements using Wavelength and Elastic Programs

It is simpler and more accurate to use the computer programs to compute the corrections to be applied to the observed readings.

There needs to be an adequate warm up time after turning on the lamp prior to the measurement. Thirty minutes should be adequate. The ball should also be in the fixture with the proper orientation of the fringes for an hour or more prior to measurement. The waiting period depends on the size of the ball and what was handled in the setup process. A waiting period of a few hours may be necessary for a 25-mm ball and less than an hour for a one-mm ball if the fixture and flat were not touched during the setup process. The center of the ball can be measured following the setup to avoid having to do it again during the actual measurement process. The forces should also be determined prior to the actual measurement.

Begin by measuring the pressure, humidity, and the air and ball temperature. Next, using the filar eyepiece, determine the readings of the fringe above and below the centerline. Do this for all four wavelengths.

It is a good practice to first estimate the fringe fractions before making the above measurements. This can be done quickly and it allows the technician to catch mistakes that might be made in misreading the filar eyepiece.

Again read and record the temperatures and the atmospheric pressure. One reading of the humidity is adequate as it doesn't change quickly, and its effect on the wavelength is small compared to the atmospheric pressure and the air temperature.

The fringe fraction is determined by dividing the distance from the center of the ball to the bottom fringe by the distance between the two fringes. This assumes that the open end of the wedge is at the top of the field of view.

On one of the Group's computers in the menu program select "Gage." From "Gage" select "Branch." Then select "Spectrum" from the program "Branch." Follow the instructions given in the program and type in all of the required data. After checking to ensure that the input data are correct, select "Compute and Report." This gives a picture of the fringe lineup. Use the F7 key to get the programs results. The program wants the lineup to occur on the zero order so it may be necessary to go back to the data input and put in new value for the "best know deviation from nominal" input line. That value is obtained from the deviation numbers at the bottom of the screen at the point where all four colors are nearly in a line. Put this value into the program and try again until the reports say you have a good lineup and the measured values are approximately the same for all four colors. Record this value on the data sheet.

Next select "Elastic" from the "Branch" program menu. Compute the deformation separately for both the top and the bottom deformations. Record on data sheet.

The algebraic sum of the values for the elastic and spectrum programs gives the measured deviation from the selected nominal value.

A form for recording the data is given as Appendix B.

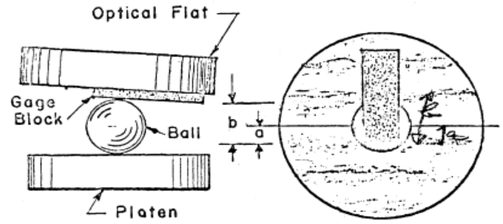
An uncertainty budget developed by John Stoup for interferometric ball measurements is included as Appendix C.

APPENDIX A

Interferometric Measurement of Ball Diameter

Ball size 31/32 (.96875) Ball composition STEEL Top contact composition STEEL
Bottom contact composition STEEL Load on top of ball 4 oz. Load on bottom of ball 6.2 oz Block size .1006

	Red	Green	Blue 1	Blue 2
Obs. fract. $(\frac{a}{b})$	.55	.70	.00	.70
(NF) Nom. fract. for nom. ball dia. + block	.07	.05	.37	.04
Obs.-nom, + $\left(\frac{a_i}{b_i}\right)$	.48	.65	.63	.66
Nom.-obs, − $\left(\frac{a_i}{b_i}\right)$	.	.	.	.



Nominal fraction computation for cadmium

color	bands per inch	NL in	orders (N)	NF
red	78,900.332	x 1.06935	= 84,372	.07
green	99,885.021	x "	= 106,812	.05
blue 1	105,834.73-	x "	= 113,174	.37
blue 2	108,589.37-	x "	= 116,120	.04

Conversion of order and fraction wavelength to inch

Cd	$\frac{\lambda i}{2}$ (+ or −	$N_i + \frac{a_i}{b_i}$)		micro-inch
R	.0000127"	x 0.48	=	+ 6.1
G	.0000100"	x 0.65	=	+ 6.5
B1	.0000094"	x 0.63	=	+ 5.9
B2	.0000092"	x 0.66	=	+ 6.1
		Sum	=	+ 24.6
	Average deviation from nominal length		=	+ 6.2
		Spread	=	0.6

Nominal length (Ball+block) (NL)	1.069350[0]
Average deviation from nominal length	+.000006[2]
Thermal exp. corr. (Ball)	.
Thermal exp. corr. (Block)	+.000001[8]
Wavelength corr.	+.000004[5]
Elastic deform. corr.	+.000015[3]
graph: Top of ball + 6.7	.
graph: Bottom of ball + 8.6	.
Block, calibrated lgth.	.100601[7]
Phase corr. on platten	−.000002[5]
(Slit & Obliq. corr.) 1.13 X NL	+.000001[2]
Undeformed ball dia.	.968775

Elastic deformation in inch between ball and plane.

$$D_\lambda = K \times 10^{-6} \sqrt[3]{\frac{P^2}{D}}$$

where
K=16.31 for steel to steel, 12.65 for tungsten carbide to steel, 8.34 for tungsten carbide to tungsten carbide.
P=load in pounds
D=diameter of ball in inches

AMBIENT CONDITION

	reading	corr.	corr. reading	
temp.	19.852 °C −.025	+.067	19.854	°C (T)
barom.	750.4 mm	−3.1	747.3	mm (P)
vapor pressure	— °C wet, — °C dry		6.0	mm (e)

T_c=Coeff. of linear thermal exp. = 11.5μ"/in/°C for steel; 6.5μ"/in/°C for tungsten carbide

Thermal expansion corr. = (T_c)X(NS)X(20°C − T) = 11.5 x .146 x 1.06932 = +1.8 μ"

Wavelength corr. = (K) times (NS) = 1.06935 x 4.20 = +4.5 μ"

K = 0.36 (760−P) + 0.05 (e − 10) + 0.93 (T − 20)

Slit & Obliquity Factor +1.13 μ"/in

Appendix B

INTERFEROMETRIC MEASUREMENT OF BALL DIAMETER

Ball Size (fract)________ Ball Size (decimal)____________ Material___________

Date ___________ Observer _________ Company/lot number________________

Start: T_A _________ T_B _________ Barometer__________ Humidity_________

Finish: T_A _________ T_B _________ Barometer__________ Humidity_________

Ave. T_A _________ T_B _________ Barometer__________ Humidity_________

Ball wt. ________ Total wt. (bottom force) _______ Computed top force _________

Top of ball reading_____________________

Top of ball reading_____________________

Calculated center of ball ________________

	Red	Green	Blue	Violet
Estimated fringe readings	_________	_________	_________	_________
Top fringe readings	_________	_________	_________	_________
Center of ball	_________	_________	_________	_________
Bottom fringe readings	_________	_________	_________	_________
Estimated fringe readings	_________	_________	_________	_________
Observed fraction	_________	_________	_________	_________

Deviation from nominal (Spectrum program) ____________________

Deformation correction (Elastic program) ____________________

Deviation from Nominal ____________________

APPENDIX C

Absolute Measurement: Sphere Diameter by Interferometry

Absolute measurement of sphere diameter at NIST is performed using a Strang monochromatic fringe viewer fitted with a Gaertner vernier scale attached to the eyepiece of the instrument. The instrument is combined with a unique apparatus designed by NIST. The apparatus consists of a set of optics, a frictionless 1-D motion air bearing, a precision scale, and fine adjustments that produce interference fringes between two optical flat surfaces in direct contact with a sphere between them. Using cadmium spectral lamps as the light source, the sphere diameter can be directly measured by measuring the absolute distance between the optical flat surfaces.

The uncertainty budget for absolute measurement of sphere diameter along with short description of each line is included below.

Error Source	Standard Uncertainty (k=1)	Description
Wavelength	0.07 L	Uncertainty of the four wavelengths from (1) and verified by results comparison to stabilized HeNe laser system.
Index of refraction	0.03 L	Uncertainty in the Edlen Equation.
Air Pressure	0.049 L	Rectangular distribution of ± 0.25 mm barometer calibration uncertainty.
Vapor Pressure	0.01 L	Rectangular distribution of ± 2% uncertainty in humidity measurement.
Air Temperature	0.058 L	Rectangular distribution 0.1 deg C. uncertainty in air temperature measurement.
Thermometer Uncertainty	0.133 L	Rectangular distribution of ± 0.02 deg C. thermometer calibration uncertainty * 11.5 ppm steel CTE.
Artifact CTE	0.116 L	Rectangular distribution of 0.5 ppm * 0.2 deg C. Measurement range of 20.0 ± 0.2 deg C.
Artifact Geometry	0.008	From typical high end artifact.
Thermal Gradients	0.133 L	Temperature difference between Temp. probe and artifact: Rectangular distribution of 0.02 deg C. * 11.5 ppm steel CTE.

Elastic Deformation	0.0025	Extrapolation to zero force from measurements using multiple applied forces. Methods documented in (2).
Flatness of reference surfaces	0.005	Estimated from multiple measurements of a spherical contact fixed to the upper flat and using random reference (bottom) flat positions.
Optics and alignment	0.002	Slit & obliquity worst case estimate: (0.05 ppm)(25.4 mm)
Fringe Fraction Repeatability	0.0025	Calculated from repeated measurements of small sphere diameters. Documented in (2).

These components combined by RSS yields a combined standard uncertainty of

$u_c = 10.3 + 0.246 L$ where L is in millimeters

The expanded uncertainty, U, with k=2, is: $\mathbf{U = 20.6 + .492 L}$

The NIST results published in the report of EUROMET 413, The Comparison of Phase Correction Measurements in Gauge Block Metrology, validates critical portions of this measurement process. Although the NIST technique used fixed spherical contacts to determine phase change differences between fused silica platens and steel gage blocks, the methods for fringe fraction reading and, most importantly, the methods for correction of elastic deformations were shown to be valid. Strong supporting documentation can also be found in (2).

References.

1. Interferometric Measurements – Tables for Cadmium 114, USCOMM-NBS-DC, National Bureau of Standards, Washington D.C., (1967).
2. J. Stoup, B. Faust, T. Doiron, Minimizing Errors in Phase Change Correction Measurements for Gage Blocks Using a Spherical Contact Technique, Proceedings of SPIE Vol. 3477 – Recent Developments in Optical Gauge Block Metrology, 161-172 (1998).