NISTIR 6036

Benchmarking the Length Measurement Capabilities of the National Institute of Standards and Technology

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January 1998

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Abstract

A cross-section of length measurement capabilities from the Precision Engineering Division within the National Institute of Standards and Technology is benchmarked against those of other leading National Measurement Institutes. We present a variety of length-related calibration services and standard reference materials each of which are performed or calibrated by at least one means in the Precision Engineering Division. Measurement capabilities and uncertainties were solicited from the other leading national measurement institutions. These data are compared to NIST work in as equal a presentation as possible. The length traceability chain is identified from the defined speed of light and the cesium clock through the realization of the meter to actual length artifacts. We make comparisons at various stages of the traceability chain and document the dissemination of length in many application specific artifacts and measurement techniques such as photomasks, gage blocks, and roundness. In general, the uncertainties of PED/NIST compare quite favorably as benchmarked against the other leading national measurement institutes. Specific superior capabilities or weaknesses of PED/NIST are noted in the conclusion.

Benchmarking the Length Measurement Capabilities of the National Institute of Standards and Technology

I. **Introduction** (R. M. Silver)

This document is the result of an effort to compare various examples of similar dimensional measurement capabilities and standard artifacts available from different national measurement institutes (NMIs). In preparing this document, information and data were solicited from leading or internationally recognized facilities with measurement capabilities in those areas on which we have reported. The final document was reviewed by participating laboratories to ensure the fidelity of the data. The contributions are primarily from other government run laboratories, including the National Physical Laboratory in the United Kingdom (not a wholly owned and operated government institute), although there are a few results mentioned from private companies. The document focuses on length related or dimensional measurement techniques each of which is performed by at least one means in the Precision Engineering Division (PED) of the National Institute of Standards and Technology (NIST). This includes specialties such as roundness, surface roughness, and laser interferometry.

We first present the method for realization of the meter, which essentially defines the traceability path from the cesium clock (the basis for the definition of frequency), to interferometry techniques. Once the path to a wavelength-based metric is established, we describe a number of specific methods which realize the meter in the form of physical artifacts traceable through interferometry. At NIST and commonly seen throughout measurement laboratories, we have three primary paths of traceability: 1) a single system with a long measurement history is used to transfer the metric to other more complex and sample specific measurement systems, 2) He-Ne lasers which are calibrated to the iodine stabilized He-Ne laser frequency are used in fringe counting interferometry, 3) atomic sources such as Cd spectral lamps are used in static interferometry.

The first traceability path at NIST takes the form of a one-dimensional optical measurement system with an interferometer whose laser source frequency is regularly compared with an iodine stabilized helium-neon laser for stability over time. The instrument also allows for the international comparison of the meter bar in an early stage of length dissemination prior to the more specific artifacts measured in a variety of other systems. The line scale interferometer, the one-dimensional measurement system at NIST, is capable of measuring samples up to one meter in length with an optical sensor which, therefore, makes it capable of measuring a large range of sample sizes and materials. This method enables transfer of the metric via stable artifacts which can also serve as control specimens for monitoring the calibrated systems long term performance. Two- and three-dimensional artifacts can have scales calibrated in each dimension with this instrument although the orthogonality of the axes remains uncalibrated. In this way, a wide variety of artifact dimensions and more complex shapes can be calibrated for dissemination to users with an acceptable traceability chain.

The second and third traceability chains mentioned above are used in a number of calibration systems here at NIST. These methods do not utilize an artifact for the portability of calibration but rather use He-Ne lasers or atomic light sources calibrated to the iodine stabilized He-Ne laser. The calibrated He-Ne lasers are used for displacement interferometry where fringe counting and fringe interpolation yields distance measurements directly traceable to the He-Ne wavelength. The Cd sources are used for static measurements as discussed in the sections on gage blocks and step heights.

In the interest of clarity, the comparisons are presented in the following logical sequence: 1) realization of the meter through the He-Ne laser and its relationship to the cesium clock, 2) precision linear scales and one-dimensional measurements, 3) two-dimensional measurements, and 4) more complex forms, such as angles and step heights. In the comparisons, whenever possible, we have incorporated results from more extensive formal international comparisons although some notable informal international comparisons are also mentioned. The data from the various laboratories are presented in alphabetical order within each section. Each individual section presents a measurement method with an explanation of the technique and particular concerns which arise when comparing similar but not identical methods. There is a limited analysis of the comparison results in each section, but the focus is on an unbiased presentation of the data. It should be noted, however, that NIST does have a measurement or standards program in every section presented.

Whenever possible, we have also made the comparisons of capabilities to include expanded uncertainties with a k=2 coverage factor (approximate 95% confidence level). We have identified the uncertainty calculations as type A or B when possible using the standard ISO guidelines [1,2]. The intent is to compare as identical a measurement technique and uncertainty calculation as possible. However, in some cases it is clear that the uncertainty calculations of a measurement technique are not directly comparable as when one institution does include the uncertainty component due to the artifact or variations in artifact properties. We attempt to point out the discrepancies with possible explanations particularly when they appear obvious.

We have also included measurements which may be performed in a location not necessarily at the national laboratory's site, but rather under the direct control or authorization of that institute. This practice is followed at NIST for a limited number of calibrations within the Precision Engineering Division (PED), a process which is explained more fully in the appropriate section. This is a method of calibration more closely followed by other institutions such as Physikalisch Technische Bündesanstalt (PTB) of Germany.

II. **Realization of the Meter** (J. A. Stone)

Traceability to the definition of the meter

Ideally, all dimensional measurements carried out by the NMIs can be linked, either directly or through a chain of comparisons, back to the internationally agreed upon definition of the meter. This chain of traceability, from measurement of physical artifacts to the cesium clock at the primary standard of time, is described below.

In 1983, an international agreement re-defined the meter in terms of the speed of light: "The meter is the length of path traveled by light in vacuum during a time interval of 1/299792458 of a second" [3]. The definition, by fixing the speed of light at exactly 299 792 458 m/s, ties the unit of length directly to the unit of time— the second. The primary standard for determining the second is the cesium-beam atomic clock; the second is defined as the duration of 9 192 631 770 periods of the radiation from the hyperfine transition in the ground state of a cesium atom. The agreement defining the meter suggests two basic methods by which the definition can be implemented: (1) The time of flight for light to travel a given path provides a direct measure of the length of path, because the speed of light has a precise, defined value. We are aware of only one high-accuracy length measurement (lunar ranging) that employs this method and will not consider it further. (2) If the frequency of a light source is measured, the wavelength (in vacuum) can be determined using the relationship $\lambda=c/f$, where λ is the vacuum wavelength, c is the speed of light, and f is frequency. Of primary importance is the fact that the frequency/wavelength of certain stabilized lasers can be reproduced with high precision, and considerable effort has been directed toward making very accurate measurements of the frequency of these lasers. Along with certain spectral lamps, these lasers constitute the "recommended radiations" for which the accepted value of the wavelength and its uncertainty are set by international agreement.

Of particular importance for length metrology is the 633 nm helium-neon laser stabilized by saturated absorption in iodine vapor. Although several other lasers can potentially provide more accurate standards, the 633 nm iodine stabilized laser is overwhelmingly the most important frequency standard used to establish traceability of length measurements to the definition of the meter. Its importance arises from the fact that its frequency is very close to the working frequency of lasers most commonly used for length measurements; as a consequence, working lasers can be easily calibrated by comparison of their frequency to that of the 633 nm iodine stabilized laser. The accepted value [4] for the relative standard uncertainty of this 633 nm wavelength is 5×10^{-11} (coverage factor k=2 or 2-sigma estimated uncertainty). This uncertainty is roughly three orders of magnitude smaller than the relative uncertainty $\Delta l/l$ achieved in the most accurate measurements of physical artifacts. (Measurements of silicon lattice spacing and some length measurements of long gage blocks claim relative uncertainties of a few parts in 10^8.)

An example of the chain of traceability to the definition of the meter is provided by gage block calibrations at NIST. Customer blocks are measured by mechanical comparison to NIST master blocks. The master blocks are calibrated interferometrically using a laser, and the laser vacuum wavelength has been previously determined by comparison to an iodine stabilized helium neon laser. The reproducibility of iodine stabilized lasers has been studied extensively by many NMIs over the last fifteen years, and the frequency of iodine stabilized lasers has been compared to the cesium clock through a chain of comparisons to intermediate standards, employing harmonic generation and mixing of the outputs of stabilized lasers and oscillators with frequencies bridging the gap between the 473 THz iodine absorption and the 9 GHz cesium clock.

Realization of the Meter

NMIs are involved in a variety of activities related to realization of the meter. Much activity in the NMIs is directed toward development of new lasers with more reproducible wavelengths and toward precision measurements of laser frequency/wavelength. A number of laser wavelengths have been determined to very high accuracy, but most of these lasers have been used only minimally (if at all) for length measurement. As described above, almost all length measurements carried out by NMIs are traceable back to the iodine stabilized helium-neon laser at 633 nm (i.e. stabilized to the iodine saturated absorption, transition 11-5, R(127)). The primary exceptions are length measurements using spectral lamps; although the wavelengths of spectral lamps are more uncertain than laser wavelengths by several orders of magnitude, the uncertainty is sufficiently small that it does not degrade the accuracy of measurement of many types of physical artifacts.

Thus, for purposes of this paper, the iodine stabilized laser is the most important link in establishing traceability to the definition of the meter. The internationally accepted value for the uncertainty of this laser is $\Delta\lambda/\lambda = 5 \times 10^{-11}$ (2-sigma). This uncertainty value was adopted in 1992 by the Comite International des Poids et Mesures (CIPM), the governing body of the Bureau International des Poids et Mesures (BIPM) [4]. The uncertainty reflects both the imperfect reproducibility of the iodine stabilized laser and uncertainties in relating the laser frequency to the cesium clock.

International comparisons have demonstrated that iodine stabilized lasers usually agree well within the accepted 5×10^{-11} uncertainty [5,6,7]. However, it must be noted that a small but significant number of iodine stabilized lasers exhibit larger errors, primarily due to either contaminated iodine cells or problems with the stabilization electronics, which must correctly identify the center of the iodine transition to very high accuracy. Good accuracy can be guaranteed only if the iodine in the cell is pure, the electronics are carefully designed, and the laser is operated within a range of operating parameters specified by the BIPM. In practice, establishing that an iodine stabilized laser works properly with an uncertainty $\Delta\lambda/\lambda < 5 \times 10^{-11}$ is probably most easily accomplished by comparing the laser directly or indirectly to iodine stabilized lasers from other NMIs.

This comparison process is greatly facilitated through the work of the BIPM, which has sponsored a large number of comparisons. We have recently participated in two BIPM laser comparisons. In a 1993 comparison [5] the average wavelength of NIST and BIPM lasers disagreed by only 1 kHz, or $\Delta\lambda/\lambda = 2 \times 10^{-12}$. A second comparison, including the BIPM and North American Metrology Corporation (NORAMET) lasers from the United States (U.S.), Canada, and Mexico, was carried out in March, 1997. Results will be published in the near future.

Table 1.1 shows the accuracy with which NMIs state that they can realize the meter, using a 633 nm iodine stabilized helium-neon laser. In compiling the table, it has been assumed that, if the NMI has participated in a BIPM-sponsored international comparison and has demonstrated that at least one of their lasers can achieve suitable accuracy, that the uncertainty value as given by the CIPM is appropriate.

III. Calibration of Vacuum Wavelength of Lasers (J. A. Stone)

Practical length measurements of the highest accuracy are usually carried out using an interferometer with a laser light source. The light source is usually not an iodine stabilized laser. Ideally, traceability to the definition of the meter is established by comparing the frequency of the working laser to the frequency of an iodine stabilized laser. Almost all NMIs calibrate their working lasers in this manner and many provide a calibration service for outside customers as well. Stated accuracies for calibration services are shown in the third column of Table 1.1.

The calibration is performed by mixing light from the laser under test with light from an iodine stabilized laser and measuring the resulting beat frequency. This beat is the frequency difference between the two lasers. From the measured frequency difference, the vacuum wavelength of the laser under test can be easily calculated.

If the laser to be calibrated has a stable frequency/vacuum wavelength, the uncertainty of the calibration is dominated by uncertainties in the frequency of the iodine stabilized laser; contributions to the uncertainty arising from imperfect measurement of the beat frequency are much smaller. Therefore, the maximum achievable accuracy that can be attained for the comparison is the uncertainty in the wavelength of the iodine stabilized, $\Delta\lambda/\lambda = 5 \times 10^{-11}$ (2-sigma). However, in practice this uncertainty is only attainable when comparing two iodine stabilized lasers; commercial stabilized lasers typically exhibit large frequency variations, making it impossible to define the test lasers's wavelength with such a small uncertainty. Therefore, some laboratories give a higher uncertainty for laser calibration, or simply state that the calibration accuracy depends on the stability of the laser under test. At NIST, a type-A uncertainty for a calibration is computed based on the dispersion of repeated measurements. This value is typically at least two orders of magnitude greater than the uncertainty of the iodine stabilized laser, essentially reflecting the limited reproducibility of the wavelength of the laser under test.

Some laboratories, such as Bureau National de Métrologie Laboratoire National d' Essais (BNM-LNE), Commonwealth Scientific and Industrial Research Organization (CSIRO), Physikallisch Technische Bundesanstalt (PTB), and National Physical Laboratory (NPL), provide calibration services for other "recommended radiations" such as the 543 nm He-Ne green line or provide interferometric calibration of any laser in a suitable range of wavelengths. At NIST, we currently have no plans to offer this service because it addresses the needs of only a small portion of U.S. customers. (The primary non-red laser in use for length measurement is the green He-Ne, and we are aware of only two stabilized green lasers that are currently employed for length measurement in the U.S.) Although the Precision Engineering Division does not maintain recommended radiations other than the 633 nm He-Ne, some additional recommended radiations are maintained by the Time and Frequency Division within NIST.

Finally, it may be noted that, in practical interferometry, the laser vacuum wavelength is usually a relatively small source of uncertainty. The greatest source of uncertainty associated with interferometry is usually determination of the index of refraction of air. (Even this uncertainty is often small relative to other uncertainties in a measurement process, such as part-temperature measurement, that are not intrinsic to the interferometry itself.) To insure that a commercial interferometer, with built-in sensors for determining index of refraction, is operating properly, it is of interest to calibrate the full interferometer system (including atmospheric sensors). Many NMIs offer this service. At NIST, we do such calibrations as "special tests," but they are not listed as a standard calibration service and, therefore, are beyond the scope of this paper.

Table 1.1 Realization of the Meter and Transfer to Secondary Lasers

Institution	Relative Uncertainty for Realization of Meter ($\Delta\lambda/\lambda$), with 633 nm He-Ne Laser using Coverage Factor K=2**	Quoted Accuracy for Calibration of Secondary Lasers using Coverage Factor K=2
BNM-LNE	5×10^{-11} [5,8,9]	* [8]
CSIRO	5×10^{-11} [5,10]	*
DFM	5×10^{-11} [5,6,7]	
IMGC	5×10^{-11} [5]	* [11]
KRISS	5×10^{-11} [5]	
NIM	5×10^{-11} [12]	
NIST	5×10^{-11} [5]	0
NMI	5×10^{-11} [5]	1×10^{-8} [13]
NPL	5×10^{-11} [5]	2×10^{-9} [14]
NRC	5×10^{-11} [5]	0
NRLM	2×10^{-11} [15]	1×10^{-8} for accreditation lab
OFMET	5×10^{-11} [5]	* [16]
PTB	5×10^{-11} [5,6,17]	

Table 1.1. Accuracy of realization of the meter with the iodine stabilized helium-neon laser, transition 11-5, R(127), and accuracy of transfer to secondary lasers as a calibration service. In compiling the table it has been assumed that, if the NMI has participated in a BIPM-sponsored international comparison, and has demonstrated that at least one of their lasers can achieve suitable accuracy, that the uncertainty value as recommended by the BIPM is appropriate.

* Stated that uncertainty is essentially a function of repeatability of laser under test.

** Uncertainty assigned by international agreement for saturated absorption in iodine, transition 11-5, R(127).

IV. Calibrations of Precision Linear Scales (R. G. Dixson)

One-dimensional gratings or linear scales are used for a variety of applications, such as Moire' encoder scales and stage micrometers, for which dimensional accuracy is often important. Most NMIs, therefore, offer calibration services for such scales. Although the implementation and resultant uncertainties vary significantly, the instruments used for such calibrations normally employ a fixed photoelectric microscope for line center detection and interferometric measurement of stage (i.e. sample) displacement to determine the spacing between lines. Our consideration of this subject will include a comparison of the measurement capabilities and uncertainties of NMIs which provide this type of service and an examination of noteworthy differences between them.

Discussion

The capabilities of the NMIs in the area of line scale measurement vary somewhat, and, when enough detail is available, the important differences in approach/instrumentation will be noted here. A compilation of published or publicly available NMI measurement uncertainties for linear scales in various ranges is given in Tables 4.1, 4.2, and 4.3. Typically, expanded (2σ) uncertainties are given, but where an NMI has chosen to specify a 1σ, 3σ, or 99% confidence interval this is noted. In those cases where an NMI specifies the uncertainty by a formula which has explicit length dependence, this formula is given and evaluated at certain values of length. Although direct comparison of values in the tables is possible and informative, it is potentially misleading since there is not always exact equivalence between these measurements. The remainder of this section is, therefore, devoted to a general consideration of some issues in linear scale calibration and variations in NMI approaches.

Due largely to the less general applicability of the transmission mode illumination and to added instrument complexity, the scale measurement systems of most NMIs use a reflection mode microscope to detect and center upon the lines. It should be noted, however, that NPL researchers have recently developed an instrument that can be operated in both reflection and transmission mode for suitable (transparent) samples [18]. The maximum interval that can be calibrated by a measurement system is usually restricted by the dimensions of the sample carriage and of the waybed on which it is translated. For most NMI's, the maximum measurable interval is one meter. There are, however, noteworthy exceptions. Intervals of up to three meters can be measured by the instrument developed at BNM-LNE [8], and measurement systems developed by both PTB [19] and KRISS [20] measure lengths up to approximately two meters [21].

Precision linear scales are normally fabricated on glass or metal substrates and may consist either of dark lines on a highly reflecting substrate or highly reflecting lines on a dark substrate. The quality and properties of a scale will affect the calibration uncertainty, and most of the NMI uncertainties listed represent best or limiting case values for scales of high quality. Some of the properties of scales which have important effects on calibration are the substrate material, particularly its coefficient of thermal expansion (CTE), and the width and uniformity of the scale lines. The latter can affect the consistency of centering upon the lines, while the former mainly contributes to length dependent uncertainties. For larger intervals, NMI uncertainties are typically dominated by length dependent uncertainties, such as those in the interferometry arising from the refractive index of air and those related to thermal expansion of the scale. At the smallest lengths, the uncertainty of NMI calibrations is usually dominated by the uncertainty in centering on the lines. Length dependent uncertainties in NMI calibration systems typically range from 100 nm to 400 nm per meter of length. The line centering uncertainties commonly range from 10 nm to 100 nm although NIST has demonstrated line centering uncertainties as low as 1 to 2 nm.

Length dependent uncertainties in scale calibrations arise from the scale CTE, scale temperature, air temperature, air pressure, humidity, air CO_2 content, the refractive index of air equation, and the laser (in the interferometer system) vacuum wavelength. These parameters affect the length measurement in one of two ways: (1) by altering the length of the scale, or (2) by altering the effective wavelength of the light used in the displacement interferometry.

The thermal expansion of the scale is important because NMI length calibrations are referred to a standard temperature of 20 °C. In a typical measurement system, the temperature of the environment is stabilized and the temperature of the scale is monitored. Uncertainties arise from the stability of the temperature, the accuracy of the thermometry, and the knowledge of the CTE. The relative importance of scale temperature stability and calibration in NMI uncertainties varies somewhat. This contribution to the CSIRO budget, for example, is approximately twice as large as in the NIST budget. Although NMI measurements are usually performed at scale temperatures near 20 °C, the deviation is normally large enough that a correction is necessary in order to report values at the standard temperature. Typically, an accepted value of the scale CTE is used to refer the measurements to the standard temperature. Some NMIs perform measurements of the CTE if it is not known. PTB, for example, has developed an ‘alpha measuring device’ [21] to measure scale CTEs. Alternatively, if an accurate measurement of the CTE is not available, some NMIs, NPL for example, report calibrations with respect to the mean temperature of observation [14].

The effective wavelength of the light used in the interferometry depends upon the vacuum wavelength of the laser and the refractive index of the air in the system. Although these two contributions are usually of similar magnitude, the uncertainty due to the vacuum wavelength is ordinarily smaller. Uncertainty in the refractive index of air arises from imprecise knowledge of the temperature, pressure, humidity, and CO_2 content of the air, and also from the equation which expresses the dependence of the index on these parameters. The largest uncertainty contributions are usually from the refractive index equation and the pressure. In a typical NMI system, the air pressure and humidity are regularly monitored, while CO_2 content, which normally results in a smaller contribution, is checked infrequently.

Other sources of length dependent uncertainties in measurement systems are alignment and motion errors in the carriage translation. If the interferometer measurement axis is not aligned with the scale axis (Abbe offset), then any angular errors in the carriage motion (roll, pitch, yaw) will result in an offset in the measured length (Abbe error) proportional to the angular change. In most systems, great care is taken to reduce Abbe offset to well below one millimeter. The angular errors of the carriage translation are usually characterized, and in some systems the errors are compensated for. This may take the form of closed loop servo control, or it may be a programmed correction for various increments of motion, based upon off line characterization of the errors. The latter approach is presently being developed for future implementation in the line scale measurement system at NIST [22,23], known as the line scale interferometer (LSI).

In a typical NMI calibration system, the edges of a line are 'detected' when the signal from a photo-electric microscope exceeds a certain threshold, and the line center is given by the mean of these two positions. If the illumination, line geometry, and the response of the optical system are symmetric, then no errors should be introduced by this procedure. Even when asymmetries are present, if the lines are uniform the shifts resulting from asymmetries would cancel in the measurement of line spacing. However, if the widths, edge roughness, cross-sectional profile, or material properties of the lines are not uniform across a scale, then centering errors may occur in the measurement of line separation. In many NMI systems, centering errors are more tractable for narrower lines. The CSIRO system, for example, can be operated using a reflective objective when the width of the scale lines does not exceed 10 μm. In this configuration, the uncertainty contribution due to line centering is reduced by a factor of two relative to the centering uncertainty associated with the refractive objective which must be used when the scale lines have a larger width.

Finally, intercomparisons of different NMI measurements on a common scale have been performed for a couple of decades. In most cases, these comparisons have shown differences between NMIs consistent with their estimated uncertainties. One specimen that has been measured by many NMIs is the BIPM meter bar #12924. A 1989 measurement of this specimen using the NIST Line Scale Interferometer (LSI), for example, was within 35 nm of the mean of the measurements of leading NMIs [23]. This was well within the estimated 100 nm uncertainty of the LSI measurement of this specimen. A more recent intercomparison (1992 to 1994) was EUROMET Project 252 "Line Scale Measurement." NIST did not participate in this comparison, which was organized by the BNM-LNE. The participating NMI's were PTB, IMGC, NPL, OFMET, BIPM, SP (Sweden), and the finish metrology laboratory. The specimen used was a nickel plated steel scale which was one meter long and had an H-shaped cross section. The NMIs compared measurements at the decimeter intervals and the standard deviation of the disperson among laboratories from the mean was $0.08\ \mu\text{m} + 2 \times 10^{-6}\ L$.

Summary

The majority of NMIs have developed systems for the calibration of precise linear scales. These systems typically utilize a fixed photoelectric microscope for line center detection and interferometric measurement of carriage displacement to determine line separations. At large length scales, NMI uncertainties are typically dominated by length dependent effects. These uncertainties are typically a few tenths of a micrometer per meter of length. At the smallest lengths, the uncertainty of NMI calibrations is usually dominated by the uncertainties of centering upon the lines, such as those related to the shape of the lines and the homogeneity of the linewidths. This uncertainty is typically a few hundredths of a micrometer. For the longest measurements, those on the order of a meter, the uncertainties of most NMIs are roughly comparable: typically being within a factor of two or three of each other. PTB, the NMI with the smallest uncertainty on a one meter length measurement, has a smaller uncertainty by at most a factor of five relative to the other NMIs. However, for the smallest, deep sub-millimeter scales, a more significant difference exists between NMIs. While some NMIs have limiting uncertainties, due primarily to line centering errors, approaching 100 nm, the NIST LSI has been able to demonstrate a limiting uncertainty of 1 to 2 nm [24]. This surpasses the capability of the other NMIs by more than an order of magnitude.

Table 4.1 NMI Uncertainties for Precision Linear Scale Measurements in 3000 mm to 1000 mm Range

National Laboratory	Precise Linear Scale @ 3000 mm	Precision Linear Scale 3000 mm to 1000 mm	Precision Line Scale @ 1000 mm	Precision Line Scale $\leq$ 1000 mm (See Table 4.2, 4.3 for Breakout)
BNM-LNE [8]	0.97 μm (2σ)	0.07 μm + 0.3 x 10^{-6} L (2σ)	0.37 μm (2σ)	0.07 μm + 0.3 x 10^{-6} L (2σ)
CSIRO [25,26]	Not Performed	Not Performed	0.088 μm (1σ) for Glass Scale and Linewidth (lw) is less than 10 μm (Reflective Objective can be used) 0.095 μm (1σ) for lw is greater than 10 μm and 0.189 μm (1σ) for Brass Scale	$\surd(20^2 + (86\,L)^2)$ nm (1σ) for Glass and lw is less than 10 μm $\surd(40^2 + (185\,L)^2)$ nm (1σ) for Brass and lw is more than 10 μm
IMGC [27]	Not Performed	Not Performed	0.35 μm (2σ)	0.15 μm + 10^{-6} L (2σ)
KRISS [28]	Not Performed	Less than 2 meters Only — $\surd(17076 + 22800\,L^2)$ nm (2σ), L in meters	0.200 μm (2σ)	$\surd(17076 + 22800\,L^2)$ nm (2σ), L in meters
NIM [12]	Not Performed	Not Performed	0.2 μm (1σ)	0.2 μm (1σ)
NIST [24,29]	Not Performed	Not Performed	0.1 μm (2σ)	0.1 μm to 0.001 μm (2σ) (See Breakout)
NPL [14,29,30,31]	Not Performed	Not Performed	Not Currently Performed*	Not Currently Performed*
NRC-INMS [32]	Not Performed	Not Performed	No Length Breakout Available-Limiting Value in Highest Accuracy Operation (Stationary Mode) is not less than 20 nm (2σ)	No Length Breakout Available-Limiting Value in Highest Accuracy Operation (Stationary Mode) is not less than 20 nm (2σ)
NRLM [33]	Not Performed	Not Performed	0.596 μm (2σ)	2x $\surd(16614 + 72351)\,L^2$ nm (2σ)
OFMET [34]	Not Performed	Not Performed	0.16 μm	0.04 μm + 0.12 x 10^{-6} L
PTB [21,29]	Not Performed	0.1 μm +1.2 x 10^{-7} L 95% Confidence Less than 2.3 m Only, and Lower Value Applies for less than 1.2 m	0.07 μm (95% Confidence)	0.02 μm +5 x 10^{-8} L (95% Confidence)

Table 4.2 NMI Uncertainties for Precision Linear Scale Measurements In 1000 mm to 10 mm Range

National Laboratory	Precision Line Scale 1000 mm to 400 mm	Precision Line Scale @ 400 mm	Precision Line Scale 400 mm to 10 mm	Line Scale or Stage Micrometer @ 10 mm
BNM-LNE [8]	0.07 μm + 0.3 x 10^{-6} L (2σ)	0.19 μm (2σ)	0.07 μm + 0.3 x 10^{-6} L (2σ)	0.073 μm (2σ)
CSIRO [25,26]	$\sqrt{(20^2 + (86\,L)^2)}$ nm (1σ) for Glass and lw is less than 10 μm $\sqrt{(40^2 + (185L)^2)}$ nm (1σ) for Brass and lw is more than 10 μm	40 nm (1σ) for Glass and lw is less than 10 μm 84 nm (1σ) for Brass and lw is more than 10 μm	$\sqrt{(20^2 + (86L)^2)}$ nm (1σ) for Glass and lw is less than 10 μm $\sqrt{(40^2 + (185L)^2)}$ nm (1σ) for Brass and lw is more than 10 μm	20 nm (1σ) for lw is less than 10 μm (Limiting Value) 40 nm (1σ) for more than 10 μm (Limiting Value)
IMGC [27]	0.15 μm +10^{-6} L (2σ)	0.23 μm (2σ)	0.15 μm +10^{-6} L (2σ)	No Information Available
KRISS [28]	$\sqrt{(17076 + 22800\,L^2)}$ nm (2σ) L in meters	0.144 μm (2σ)	$\sqrt{(17076 + 22800\,L^2)}$ nm (2σ) L in meters	0.132 μm (2σ)
NIM [12]	0.2 μm (1σ)	0.2 μm (1σ)	0.2 μm (1σ)	0.2 μm (1σ)
NIST [24,29]	~ 10^{-7}L (2σ)	0.040 μm (2σ)	~ 10^{-7} L + Limiting Value (0.005 μm (2σ) or Less, Depending on Scale)	0.005 μm (2σ) or Less, Depending on Scale Type (i.e. near Limiting Value)
NPL [14,29,30,31]	Not Currently Performed	0.1 μm (2σ) * 95% Confidence	0.028 μm + 1.7 x 10^{-7} L	0.03 μm (2σ) 95% Confidence
NRC-INMS [32]	No Length Breakout Available-Limiting Value in Highest Accuracy Operation (Stationary Mode) is not less than 20nm (2σ)	No Length Breakout Available-Limiting Value in Highest Accuracy Operation (Stationary Mode) is not less than 20 nm (2σ)	No Length Breakout Available-Limiting Value in Highest Accuracy Operation (Stationary Mode) is not less than 20 nm (2σ)	No Length Breakout Available-Limiting Value in Highest Accuracy Operation (Stationary Mode) is not less than 20 nm (2σ)
NRLM [33]	2 x$\sqrt{(16614+72351\,L^2)}$ nm (2σ) L in meters	0.336 μm (2σ)	2 x$\sqrt{(16614+72351\,L^2)}$ nm (2σ) L in meters	0.258 μm (2σ)
OFMET [34]	0.04 μm + 12 x 10^{-6} L	0.09 μm	0.04 μm + 0.12 x 10^{-6} L	0.04 μm
PTB [21,29]	0.02 μm +5 10^{-8} L 95% Confidence	0.040 μm (2σ) 95% Confidence	0.02 μm +5 10^{-8} L 95% Confidence	0.020 μm (2σ) 95% Confidence

Table 4.3 NMI Uncertainties for Precision Linear Scale Measurements In 10 mm To ≤ 0.1 mm Range

National Laboratory	Precision Line Scale 10 mm to 1 mm	Precision Line Scale @1 mm	Precision Line Scale 1 mm to 0.1 mm	Precision Line Scale ≤ 0.1 mm
BNM-LNE [8]	0.073 μm to 0.07 μm (2σ)	0.07 μm (2σ) (Limiting Value)	0.07 μm (2σ) (Limiting Value)	0.07 μm (2σ) (Limiting Value)
CSIRO [25,26]	20 nm (1σ) for lw is less than 10 μm (Limiting Value) 40 nm (1σ) for lw is more than 10 μm (Limiting Value)	20 nm (1σ) for lw is less than 10 μm (Limiting Value) 40 nm (1σ) for lw is more than 10 μm (Limiting Value)	20 nm (1σ) for Lw is less than 10 μm (Limiting Value) 40 nm (1σ) for Lw is more than 10 μm (Limiting Value)	20 nm (1σ) for Lw is less than 10 μm (Limiting Value) 40 nm (1σ) for Lw is more than 10 μm (Limiting Value)
IMGC [27]	No Information Available	No Information Available	No Information Available	No Information Available
KRISS [28]	0.132 μm (2σ) (Limiting Value)	0.132 μm (2σ) (Limiting Value)	0.132 μm (2σ) (Limiting Value)	0.132 μm (2σ) (Limiting Value)
NIM [12]	0.2 μm (1σ)	0.2 μm (1σ)	0.2 μm (1σ)	0.2 μm (1σ)
NIST [24,29]	0.005 μm (2σ)-Down to Limiting Value of 0.002 μm (2σ) or Less, Depending on Scale	0.002 μm (2σ) or Below, Depending on Scale (i.e. near Limiting Value)	0.002 μm (2σ) or Below, Depending on Scale (i.e. near Limiting Value)	0.001 μm (2σ) (Limiting Value, for Highest Quality Scales)
NPL [14,29,30,31]	0.028 μm + 1.7 x 10^{-7}	0.03 μm (2σ) 95% Confidence	0.028 μm + 1.7 x 10^{-7}	0.03 μm (2σ) 95% Confidence
NRC-INMS [32]	No Length Breakout Available-Limiting Value in Highest Accuracy Operation (Stationary Mode) is not less than 20 nm (2σ)	No Length Breakout Available-Limiting Value in Highest Accuracy Operation (Stationary Mode) is not less than 20 nm (2σ)	No Length Breakout Available-Limiting Value in Highest Accuracy Operation (Stationary Mode) is not less than 20 nm (2σ)	No Length Breakout Available-Limiting Value in Highest Accuracy Operation (Stationary Mode) is not less than 20 nm (2σ)
NRLM [33]	0.258 μm (2σ) (Limiting Value)	0.258 μm (2σ) (Limiting Value)	0.258 μm (2σ) (Limiting Value)	0.258 μm (2σ) (Limiting Value)
OFMET [34]	0.04 μm + 12 x 10^{-6} L	0.04 μm	0.025 μm	0.05 μm
PTB [21,29]	0.020 μm 95% Confidence (Limiting Value)	0.020 μm 95% Confidence (Limiting Value)	0.020 μm 95% Confidence (Limiting Value)	0.020 μm 95% Confidence (Limiting Value)

V. **Gage Blocks** (B. S. Faust)

The gage block comparisons are shown in two separate tables: interferometry (Table 5.1) and mechanical (Table 5.2). This is a result of the fact that some labs only perform interferometry. In addition, where possible, listings will be presented in short block (L < 100 mm) and long block (100 mm < L) size ranges. Stated uncertainties are expressed in μm and reflect the 95% confidence level (k=2). Any stated uncertainties which have been converted to the k=2 level are denoted by an asterisk (*).

Table 5.1 Interferometry

National Laboratory	Size Range (mm)	Uncertainty Statement (k=2) in μm and L in m	Uncertainty Value of 100 mm Steel Block (μm)	Measurement Method
BNE-LNE [8]	$0.1 \leq L \leq 300$	0.016 μm + 0.12 x 10^{-6} L	0.028	Red/Green Interferometry
CSIRO [26]	Special Cases Only	Calibration to Class 1 or Class 2	Not Specified	Interferometry Red/Green/Orange He-Ne Laser [35]
DFM [36]	$0.5 \leq L \leq 100$	± 0.02 μm + 0.2 x 10^{-6} L	0.040	Interferometry
IMGC [11]	$0.5 \leq L \leq 100$	± 0.02 μm +0.03 x 10^{-6} L	0.023	Interferometry
KRISS [28]	$L < 250$	0.02 μm + 0.2 x 10^{-6} L	0.038	Interferometry
NIM [12]	$0.5 \leq L \leq 100$ $150 \leq L \leq 1000$	0.02 μm + 0.2 x 10^{-6} L 0.033 μm + 0.333 x 10^{-6} L	0.040	Not Specified
NIST [37]	$L \leq 500$	± 0.022 μm + 0.16 x 10^{-6} L	0.038	Interferometry
NMi [38]	$L \leq 100$ $100 < L \leq 1000$	0.02 μm + 0.4 x 10^{-6} L 0.02 μm + 0.2 x 10^{-6} L	0.060	Interferometry
NPL [14]	0.5 < L< 100 mm $100 < L < 1000$	± 0.025 ± 0.42 x 10^{-6} L [39] ± 0.049 ± 0.083 x 10^{-6} L [40]	0.050	Interferometry
NRC http://www.cisti.nrc.ca/ inms/dsdme.html P.2 [41]	$L \leq 100$	0.02 μm + 0.4 x 10^{-6} L * (Commensurate with Gage Quality)	0.060	Interferometry Using at Least 5 Wavelengths and 2 Radiation Sources
NRLM [42]	$L \leq 250$	$\sqrt{[2.39 * 10^{-14} L^2 + 136 \text{ nm}^2]}$ (1σ Uncertainty Level, with L in nm)	0.039 μm	Interferometry
OFMET [34]	$L \leq 100$ $100 \leq L \leq 1000$	0.016 μm + 0.16 x 10^{-6} L* 0.04 μm +12 x 10^{-6} L*	0.031 μm	Length Comparator with Laser and White Light Interferometry
PTB [43]	$0.1 \leq L \leq 100$ $0.5 \leq L \leq 100$ $100 \leq L \leq 1000$	0.013 μm + 0.133 x 10^{-6} L* (Steel, T.C.) 0.02 μm + 0.133 x 10^{-6} L* Ceramics 0.01 μm + 0.1 x 10^{-6} L to 0.01 μm + 0.05 x 10^{-6} L (Depending on Surface Quality)	0.026	Interferometry

Discussion

Interferometry at NIST is most commonly performed using a Fizeau-type NPL Hilger interferometer and a calibrated stabilized He-Ne laser light source. Fringe fractions are manually read by eye as a percent of a total fringe, a process which can be repeated to better than five percent of the wavelength (note that this is not a limiting factor in the measurement process). Recent technological advances in interferometer design have all but eliminated the manufacture of manual optical interferometers. Manufacturers now produce interferometers with charge coupled device (CCD) camera technology and software algorithms to perform the function of interpreting fringe fractions.

The NIST gage block calibration process is described in detail in NIST Monograph 180 [44]. It is interesting to note, however, that a mechanical comparison value for the deviation of a gage block is still necessary for an interferometric value to be determined. The mechanical value is used to determine the correct fringe order of the fringe fraction being estimated.

A separate process also performed at NIST, four-color interferometry, uses an atomic light source that disperses into different colors. Fringes are read in the various colors, each with its associated distinct wavelength, and after software calculation the fringe fraction readings converge on some common deviation. The problems with the four-color interferometry process are two-fold. First, it is time-intensive and second, the cadmium light source is also a significant heat source. Coupled with the time factor for reading a single block in multiple colors is the fact that fringes of the spectral lamp can be very difficult to read. They become fuzzy and dim due to low intensity (compared to the laser). The longer it takes to read the fringe, the longer the lamp has been heating the entire instrument.

Analysis of Table Results

Although NIST's uncertainty for interferometric measurements of gage blocks may be slightly reduced in the near future as a result of research into the phase shift phenomenon, currently, the phase shift correction is the largest component of the NIST interferometry uncertainty budget. Wringing problems (the process of contacting the gage block to the mounting surface) will always be inherent to this measurement process and may at some future time become the largest uncertainty component. If wringing effects become the limiting factor in the uncertainty budget, this would be unfortunate since they are correlated directly to the mechanical comparison uncertainty as well.

Although the German laboratory (PTB) specifies material dependence in their uncertainty statement, Denmark and Australia both specify geometry/surface finish grades. This is not surprising because differing mechanical properties, block geometries and surface finishes each contribute to the uncertainty. The coefficient of thermal expansion (CTE), phase shift correction, mechanical and optical material properties must be determined for each gage block material. In addition, artifact geometry and surface finish also have substantial effects which are often difficult to understand.

Most of the reported uncertainties are reasonable in view of the preceding discussion. There are, however, uncertainties reported which are apparently derived for a "perfect block." Those laboratories which report such "perfect block" uncertainties may not have identified all possible error sources or may have underestimated some effects.

NIST offers interferometry calibrations for customer blocks and the corresponding uncertainty is slightly higher than for the NIST masters, due to the unmeasured CTE and phase shifts. Although NIST does not specify tolerance restrictions on artifact geometry and surface finish, NIST does have the option to not calibrate by interferometry based on inspection of the customer block.

Table 5.2 Gage Block Mechanical Comparison

National Laboratory	Size Range (mm)	Stated Uncertainty (k=2) in μm and L in m	Uncertainty Value of 100 mm Steel Block (μm)	Measurement Method
BNM-LNE [8]	$0 < 100$	0.04 μm + 0.6 x 10^{-6} L	0.10	Mechanical Comparison
	$L \leq 3000$	0.3 μm + 0.7 x 10^{-6} L	0.370	Horizontal Comparator using 3 Laser Beams
CSIRO [26]	$L < 10$	0.050 μm	0.100	Mechanical Comparison
	$10 \leq L < 25$	0.060 μm		
	$25 \leq L < 50$	0.070 μm		
	$50 \leq L < 75$	0.080 μm		
	$75 \leq L \leq 100$	0.100 μm		
DFM [36]	$L \leq 0.1$	± 0.015 μm	Not Specified	Length Difference Calibration, Not Specified
KRISS [28]	$L < 500$	0.03 μm + 0.5 x 10^{-6} L	0.080	Electro-mechanical Comparison
NIST [37]	$L < 1$	0.040 μm	0.065	Mechanical Comparison
	$1 \leq L \leq 100$	0.03 μm + 0.35 x 10^{-6} L		
	$100 < L \leq 500$	0.055 μm + 0.2 x 10^{-6} L		
NMi [38]	$100 \leq L \leq 1200$	0.1 μm + 1 x 10^{-6} L	0.200	Horizontal Comparison
	$1200 < L \leq 4000$	0.2 μm + 2 x 10^{-6} L		
OFMET [34]	$L \leq 100$	0.04 μm + 0.4 x 10^{-6} L*	0.08 μm	Mechanical Comparison
	$100 < L \leq 3000$	0.04 μm + 0.12 x 10^{-6} L*		Length Measuring Machine with Laser and mechanical contacting
PTB [43]	$0.1 \leq L \leq 100$	0.01 μm *	0.010	Difference in Length Based on DKD Guideline
	$100 \leq L \leq 1000$	0.013 μm + 0.133 x 10^{-6} L*	0.026	Comparison

Most of the gage block calibrations performed at NIST involve mechanical comparisons of customer blocks with respect to NIST masters and check-standards. The process is documented in NIST Monograph 180 [44]. Gage blocks are measured in the vertical orientation at the defined gage point. The gage block comparators have two diamond probes, each with a nominal radius of 3.175 mm (0.125"), contacting the gage block, one from above and the other from below. The lower probe is coupled to a linear variable differential transformer (LVDT) with the output connected to a digital voltmeter. There are several manufacturers of gage block comparators and most use a design similar to the one described. Measurements are made following an intercomparison test series which is designed to eliminate linear thermal drift. Readings are triggered by a foot-switch and the voltmeter output is directly imported into the computer via an analog-to-digital board with an 8 bit input yielding a nominal resolution of 0.127 nm. Results from the test, after software analysis for both NIST masters and the customer block, are evaluated statistically and compared to historical values. The statistical process control monitors three types of effects: 1) penetration using applied force and probe calibration; 2) temperature gradients using thermocouples and software statistical checks; and 3) all random effects using differences between the expected and observed master block values and repeatability in the customer block values.

Analysis of Table Results

Typical gage block customer calibrations at NIST result in uncertainties of approximately 30 nm for sizes ranging from 1 mm to 25 mm, with increasing uncertainties to about 66 nm at lengths of 100 mm. Thin blocks, less than 1 mm, are assigned a 40 nm uncertainty.

PTB in Germany and DFM in Denmark have very low uncertainties. They also specify a “difference in length calibration” which may be different than comparison to a master block(s). PTB states a 26 nm uncertainty on their “comparison” calibration. Laboratoire National D’Essais in France lists their uncertainty at 370 nm for a 100 mm block. This is probably a result of the measurement process at LNE. The information they supplied listed a horizontal comparator using three laser beams. This type of instrument may have systematic effects which limit their ability during comparison calibrations. The other laboratories listed have comparable uncertainty statements. The range is from roughly 100 nm to 65 nm which is a difference of 35 nm at 100 mm in length which implies that a 100 mm long gage block measured by the majority of laboratories listed agree within 35 nm, which is good agreement.

VI. **Photomask Linewidth Standards** (R. M. Silver and J. E. Potzick)

Linewidth measurement is fundamentally different in nature from linear scale (line-to-line spacing, or pitch) measurements because line edge effects become more important. Linewidth is the difference in position of the left edge of a line from the position of the right edge, while pitch is the position of the line center (left edge plus right edge divided by 2) relative to another line center. Linewidth measurements, therefore, require a specific definition of the line edge as represented by the data acquired from the optical signal transition at the edge. Errors can arise from artifact edge imperfections, from different methods of defining the edge, and in interpreting the different images of the line edges in different measuring instruments [45]. These errors add in the linewidth measurement and subtract in the linear scale measurement because of their symmetrical nature. It is because of this and the fact that the instrument images of the artifact depend strongly on their topography and materials properties that linewidth standards are currently feasible only for simple cases like photomasks, where lines and substrates on different artifacts are similar in these respects and only a few artifact parameters affect the instrument image.

Photomask linewidth standards serve as primary standards for the calibration of photomask metrology tools and are available from the national standards organizations of several countries. These standards are usually in the form of chrome-on-quartz photomasks with a variety of linewidth, spacewidth, and pitch patterns. The primary tool used in industry for photomask linewidth metrology is the optical microscope in either transmission or reflection mode. SEMs are also a popular tool, even though the results are not NIST traceable because the measurements are not modeled. In addition, problems may arise from specimen charging or the application of a conductive coating can affect the results. NIST in the United States has performed an optical comparison of linewidth measurements with NPL in the United Kingdom and PTB in Germany [46]. There is an additional effort underway in the EC, led by NPL.

In Table 6.1, we have presented the specific results of comparisons of the NIST, NPL, and PTB calibration facilities. All values are in micrometers.

Table 6.1 International Comparison of Photomask Linewidth Standards

Linewidth						Spacewidth					
	Measured Values			Differences			Measured Values			Differences	
Nominal Value	NIST	NPL	PTB	NPL-NIST	PTB-NIST	Nominal Value	NIST	NPL	PTB	NPL-NIST	PTB-NIST
0.5	0.493	0.53	0.4963	0.037	0.003	0.5	0.460	0.459	0.4607	-0.001	0.001
0.6	0.597	0.622	0.5923	0.025	-0.008	0.6	0.576	0.577	0.5747	0.001	-0.001
0.7	0.71	0.706	0.7017	-0.004	-0.008	0.7	0.677	0.674	0.6697	-0.003	-0.007
0.8	0.805	0.803	0.8053	-0.002	0.000	0.8	0.774	0.763	0.7770	-0.011	0.003
0.9	0.902	0.893	0.8947	-0.004	-0.007	0.9	0.877	0.852	0.8717	-0.025	-0.005
1	1.011	1.009	1.0060	-0.002	-0.005	1	0.969	0.956	0.9737	-0.018	0.005
1.5	1.501	1.495	1.5017	-0.006	[illegible]	1.5	1.482	1.46	1.4747	-0.022	-0.007
2	1.97	1.973	1.9730	0.003	[illegible]	2	1.977	1.969	1.9717	-0.009	-0.005
5	5.005	4.992	4.9957	-0.013	-0.008	5	4.996	4.996	4.9973	0.000	0.001
10	10.005	10.001	10.0043	-0.004	-0.001	10	9.985	9.976	9.9850	-0.009	0.001
20	19.995	20.012	20.0013	0.017	0.006	20	20.008	20.009	20.0030	0.001	-0.005
30	29.98	29.988	29.9840	0.008	0.004	30	30.004	29.986	29.9930	-0.018	-0.011
Maximum Difference				**+0.037**	**+0.006**	**Maximum Difference**				**+0.001**	**+0.005**
Minimum Difference				**-0.013**	**-0.009**	**Minimum Difference**				**-0.025**	**-0.011**

All of the opaque linewidth and clear spacewidth features on the standard NIST photomask (SRM 473) were measured at all three laboratories. The nominal values are shown in the left column of each half of the table, followed by the NIST, NPL, and PTB measurements, and the differences NPL - NIST and PTB - NIST in the last two columns. The NIST measurements were taken from routine linewidth calibration results [47].

Analysis of the Data

NIST linewidth measurement uncertainty was 36 nm. The largest component was from the imperfections in the etched chrome edges and the reproducibility component was 10 nm. The NPL uncertainty was 50 nm for linewidths less than 10 μm and 100 nm for larger linewidths. The PTB measurement uncertainty is not known. All measurements were made in transmitted light, as recommended. The PTB data are the averages of measurements made at three different wavelengths. All of the measurement differences differ from zero by an amount well within the combined uncertainties. No significant trends were observed.

Discussion

A study of photomask linewidth measurements was also performed in Japan [48] between the NRLM and a number of Japanese semiconductor metrology facilities. Transmitted and reflected light optical techniques and SEM techniques were used to measure features on a photomask which covered a linewidth range of 1 μm to 10 μm. Among the optical measurements of one specimen in this Japanese study, the maximum and minimum measurements differed from the overall mean by +0.020 μm and -0.070 μm. The largest difference between maximum and minimum values over all of the data (optical and SEM) was 0.967 μm. These figures are all measures of reproducibility; the measurement uncertainties were not published. Although this was not a comparison of national laboratories, these results are mentioned here only to provide some information on linewidth measurement reproducibility in Japanese industry.

VII. **Scanning Electron Microscope Length Standards** (M. T. Postek and J. Fu)

The scanning electron microscope (SEM) is used extensively in many disciplines and phases of scientific research. The SEM is also used extensively in the manufacturing environment especially in the production of semiconductor devices. This instrument has been targeted by the SIA National Technology Roadmap for Semiconductors as the production tool of choice for submicrometer metrology into the first part of the next century [49]. The calibration of the magnification of the SEM is imperative if useful information is to be obtained from this instrument. SRM 484 [50] is the current traceable SEM magnification standard available from NIST. Since NIST is the only NMI with a traceable SEM magnification standard we will present this data first followed by other related NIST SEM standards work. This will be followed by a discussion of magnification and linewidth availability from private industry standards laboratories and then relevant standards work of the other NMIs.

NIST SEM Standards

SRM 484 is useful for many current laboratory applications of the SEM, but does have limitations for many newer design instruments and many semiconductor manufacturers' applications both inside and outside the wafer fabrication process [51]. To meet that need NIST began the development of a new SRM [52]. This SRM was identified as SRM 2090 and is currently in the final phases of development. Prototypes of this standard are currently available as RM 8090 [53].

SRM 484 is a NIST certified SEM magnification standard. It is composed of alternating electro-deposited gold and nickel layers. The bulk artifact is sectioned and carefully oriented so that the layers are aligned perpendicular to the surface. The artifact is then sealed (potted) in a metallurgical mount. The sample is then highly polished. Because of the polishing, very little topographic contrast is present in the sample and the contrast mechanism for SEM is mainly based on atomic number differences between the gold and nickel layers (lines). The spacing of the gold lines from SRM 484 is certified with a specially designed metrological microscope using laser interferometry [54]. SRM 484g has spacings of 0.5, 1, 2, 5, and 10μm, but earlier issuances had a minimum spacing of 1.0μm [50]. This standard has calibrated structures in only one dimension thus, physical rotation of the artifact is necessary to achieve both X and Y scan calibration. With this standard, the magnification scale of the instrument can be calibrated from about 1000x to 30,000x. Since little topographic contrast is present on the sample, instrument calibration below about 3-5 keV accelerating voltage is difficult but can be made easier by wet etching [51].

Reference Material (RM) 8090 and Standard Reference Material (SRM) 2090 are intended primarily for use in calibrating the magnification scale of a scanning electron microscope (SEM) over a wide range of magnifications, from less than 100x to greater than 300 000x. RM 8090 contains structures in both X and Y dimensions, ranging in nominal pitch from 0.2 μm to 3000 μm and is useful at both high and low accelerating voltages. RM 8090 is the thickness of a silicon wafer and thus, can be inserted in the modern automated measurement systems. Like SRM 484, SRM 2090 will be certified with an SEM designed specifically for this purpose [51]. Most laboratory SEMs and many of the dedicated in-line metrology SEM-based instruments require a range of calibration structures to cover the full range of magnification. RM 8090/SRM 2090 is specifically designed to meet that need. The value of this standard and SEM magnification standards in general was demonstrated in an Interlaboratory Study [55].

Table 7.1 SEM Magnification Calibration Standards

National Laboratory	Standard	Pitch Range	Uncertainty
JQA [56]	Micro Scale	.24 μm	± 0.001 μm
NIST [50]	SRM 484f	0.5 μm 1.0 μm 3.0 μm 5.0 μm	± 0.021 μm ± 0.026 μm ± 0.035 μm ± 0.052 μm
NIST [53]	RM 8090	0.2 μm-3000 μm	NA
NIST [51]	SRM 2090	0.2 μm-3000 μm	NA
NRC [57]	Diffraction Grating	.833 μm	± 0.0005 μm

Other Traceable SEM Standards

At the time of the preparation of this report, Geller MicroAnalytical Laboratory is the only U.S. supplier producing an SEM standard traceable to national or international standards of length. This standard is MRS-3 [58]. A diffraction grating-type sample has been used for the calibration of the SEM by NRC and another magnification calibration standard for the SEM is marketed by Hitachi; both of these are included in the table.

MRS-3 (Magnification Reference Standard) produced by Geller MicroAnalytical Laboratory is a NIST traceable magnification reference standard with pitch dimensions of 2 μm, 50 μm and 500 μm. However, only the 2 μm spacing is NIST traceable [58]. The useful magnification range of the entire standard is from 10x to 50,000x. The patterns consist of a series of nested square boxes such that X and Y magnification calibration can be set, and scan distortion can be measured without rotation. The optically transparent standard is photolithographically patterned with anti-reflective chromium structures on a fused silica substrate. The substrate has an optically transparent but electrically conductive thin film applied for conductivity. Other patterns on the standard aid in astigmatism correction and measurement of photographic recording system performance. This standard is claimed to be useful at both high and low accelerating voltages.

Standard Microscale available from Nissei Sangyo America has a line and space pattern of 0.240 ± 0.001 μm (3σ) based on the average pitch of a 4 x 4 mm^2 area [59]. The material is etched silicon on a silicon substrate. The material has been cross-checked by the Japan Quality Assurance Organization (JQA) and the National Research Laboratory of Metrology of Japan. The traceability is determined through optical diffraction calibration using an HeCd laser under the supervision of the National Research Laboratory of Metrology of Japan.

Diffraction gratings have been used to calibrate SEMs for several years [60,61]. The Physics Division of the National Research Council of Canada (NRC) optically measured a number of diffraction replica samples with the average spacing of 0.83298 μm with a standard deviation of 0.0005 μm based on a 1σ type A uncertainty. These gratings have been used by a commercial instrument company to calibrate their instruments [62].

Discussion

NIST SEM magnification standards are calibrated under nearly the same conditions for which they are used. The SEM is a point scanning instrument. Generally, the electron beam (point) scans across the specimen in the “X” direction in a single raster line, then moves down some increment in the “Y” direction and repeats the “X” scan. Together the X and Y scans form the square raster pattern. This is done multiple times depending on the number of “Y” increments. Then the system repeats this scan a number of times. The length of the “X” scan and the length of the “Y” scan are the entities that require calibration. The signal composing the image is collected as the beam is scanned and is composed of a modulated flux of electrons. Since no artifact is perfect, irregularities can be found on any magnification standard. These irregularities increase the measurement uncertainty. NIST certifies SRM 484 in a similar manner to the way it is used with specially designed scanning electron microscopes [51,54]. Therefore, any irregularities in the artifact are resolved and included in the uncertainty statement. To summarize NIST efforts, SRM 484 and eventually SRM 2090 are SEM magnification standards traceable to the national standards of length. These standards are certified by an SEM similar to the way they are used as magnification standards.

VIII. Two-Dimensional Grid Measurements and Standards (R. M. Silver)

Two-dimensional grid measurements and standard artifacts are used extensively in a variety of manufacturing environments. The semiconductor, flat panel display, automobile, aerospace and other industries that rely on accurate, position-sensitive instruments such as lithography steppers and machine tools require accurate two-dimensional mapping and calibration of the tools. In the semiconductor fabrication and production arena, the grid sizes of interest are primarily for calibration of photolithography tools, photomask inspection equipment and a wide variety of metrology tools for wafer and defect inspection. The flat panel industry and hard disk drive manufacturers use instrumentation very similar to that used in semiconductor manufacturing and have similar calibration requirements. The specimen size or exposure field is typically 150 to 300 mm with very stringent uncertainty requirements. Currently, PTB and NPL are the only NMIs offering calibration services that meet the required sample size range and uncertainties. PTB uses a modified commercial instrument that combines interferometry with an optical scanner [63]. This metrology tool is capable of measuring samples from 150 mm to 200 mm with a nominal uncertainty in the range of 30 to 40 nm. More details are presented in the table below. Due to the extreme expense of ownership of such a state-of-the-art metrology system, there are only a limited number in use globally throughout the private sector. However, artifacts calibrated in one dimension can be used to calibrate a two-dimensional tool with a sequence of rotations and/or translations. These techniques are known as self-calibration but still require a one-dimensional calibrated standard to obtain a traceable metric on the tool being calibrated. In addition, these methods require some complex error analysis to properly understand the propagation of errors.

For the industries using larger scale coordinate measurement systems, NIST offers a new calibration service also using a modified commercial instrument [64]. This tool is capable of measuring samples in the 300 to 750 mm range. Dimensions smaller than 300 mm may also be measured with a nominal accuracy in the 0.5 micrometer range. This tool calibrates grid plates for several industries that manufacture discrete parts requiring high precision positioning stages. The aerospace industry and automotive manufacturing comprise the main customer base for this service although there is some overlap with flat panel display manufacturing. The large grid size can be a significant contributor to the uncertainty due to glass flex, feature inhomogeneity in materials and geometry, and long term stability. These grid plates are typically made of glass and not quartz as commonly used in semiconductor manufacturing. NPL offers two-dimensional grid standards and calibration services for 150 mm x 150 mm and 175 mm x 175 mm optical plates. NPL uses a modified commercial instrument in conjunction with the NPL 400 mm linear measuring machine. The measurement uncertainty is 60 nm [65].

Table 8.1 Two-dimensional Grid Calibrations

Nominal (Grid Size)	NIST (Uncertainty)	NPL (Uncertainty)	PTB (Uncertainty)
800 mm x 800 mm			1 μm [66]
450 mm x 600 mm	± 0.5 μm [67]		
300 mm x 300 mm	± 0.5 μm [67]		
175 mm x 175 mm		± 60 nm [43]	± 50 nm [68]
150 mm x 150 mm		± 60 nm [43]	± 40 nm [68]

The table above shows a comparison of measurement results from very different tool sizes and sample sizes. As explained earlier, the two calibration services support different industrial sectors and the uncertainties reflect the significant difference in required uncertainties. The uncertainties quoted for the NIST measurement service are calculated using the expanded standard uncertainty. The uncertainties quoted above are from actual NIST calibrations and, in general, can be strongly affected by the measured specimen, its geometry and rigidity.

IX. **Step Gages** (D. S. Sawyer)

In this section, a comparison of the uncertainty of step gage calibrations is made. Step gages are one-dimensional length artifacts which consist of a series of lapped parallel surfaces which are located at nominally equal intervals along the axis of the gage. The calibrated dimensions are the distances from a reference surface, usually located at one end of the gage, to each of the remaining parallel surfaces. The reported uncertainty value is typically the deviation of each of the parallel surfaces from the nominal distance.

The measurement uncertainties for step gage calibrations for two National Measurement Institutes are reported in the table below. The uncertainty is reported in μm and reflects a confidence level of 95% (k=2).

Table 9.1 Measurement Uncertainty for Step Gage Calibrations

National Measurement Institute	Range of Measurement	Uncertainty
NIST [37]	Not Specified	(0.4 + 0.3 L) μm where L is in Meters
PTB [68]	< 2.5 m	0.2 μm to 2 μm

Discussion

NIST calibrates step gages at the Y12 site of the Department of Energy (DOE) in Oak Ridge, Tennessee using Y12 staff and equipment under NIST administrative and metrological control. The gages are calibrated using a Moore M-60 Coordinate Measuring Machine. The measurement assurance program was designed by NIST and the calibration procedures were developed jointly by NIST and Y-12. Measurement process control is enforced with a number of check standards which include 500 mm to 1000 mm end standards of steel and Zerodur, which are calibrated by NIST at the Gaithersburg, Maryland site.

All step gage calibrations are performed under the metrological control of the NIST Precision Engineering Division at the Y-12 site. The unique relationship between the Y-12 and NIST sites enables the use of state-of-the-art instrumentation at the Y-12 site in conjunction with the measurement expertise and supervision of the NIST staff.

X. **Step Heights** (T. V. Vorburger)

Introduction

Step heights serve as calibration standards for profiling instruments for measuring surface topography. These include stylus instruments, scanned probe microscopes, and phase measuring interferometers. Step heights are useful for characterizing the vertical magnification of both contacting and noncontacting instruments that operate over a wide range of horizontal magnification. That is, the same step can be used to calibrate both an atomic force microscope with a field of view of a few micrometers squared or a stylus instrument with a stroke of 100 mm. However, each step height standard is only useful over a narrow range of vertical magnification. Therefore, a series of steps of different heights are required to calibrate or check the calibration of a profiling instrument over its vertical range.

This comparison for step height is based primarily on a laboratory intercomparison of five step height specimens performed as a Euromet project between April 1994 and April 1996 in which nine laboratories participated, including NIST, PTB, NMi, IMGC, and OFMET. The report of that project by Haitjema [69] gives an overview of the measuring instruments, the measured step height values, the quoted uncertainties, and traceability considerations. We also obtained information from the NRC concerning its step height calibrations in its Directory of Calibration Services [70]. Table10.1 shows quoted uncertainties by NIST, PTB, NMi, IMGC, and OFMET based on their measurements of three of the steps in the intercomparison. The results for the other two steps in the intercomparison are consistent with these and are not shown. We also show uncertainty estimates for hypothetical NRC measurements of the same three steps based on the information in their Directory [70].

Table 10.1 Estimates of Uncertainties for Step Height Measurements by Several National Laboratories. The values are expressed in percent and represent expanded uncertainties with a coverage factor of 2.

Laboratory		**IMGC [69]**	**NIST [69]**	**NMi [69]**	**NRC [70]**	**OFMET [69]**	**PTB [69]**
Type of Instrument		Stylus	Stylus	Stylus, Interference Microscope	Stylus	Interference Microscope	Stylus, Interference Microscope
Nominal Step Height	**40 nm**	11.9%	3.4%	2.6%	11.4%	8.9%	7.0%
	150 nm	7.0%	1.0%	1.0%	4.6%	3.3%	2.0%
	950 nm	1.6%	0.5%	0.4%	2.4%	1.2%	0.8%

Analysis

The three artifacts were all measured by IMGC, NIST, NMi, OFMET, and PTB and the uncertainties were reported by them as part of the laboratory intercomparison [69]. Because these uncertainties were obtained from actual measurements rather than a laboratory's uncertainty budget, we assume that the quoted uncertainties include both the uncertainties arising from the instruments as well as the nonuniformity arising from the specimen itself. The uncertainty shown for the NRC, on the other hand, is based on a formula for uncertainty contained in the NRC Directory, which seems to take into account the uncertainties arising from the measurement system alone. To this component we added quadratically an estimate of uncertainty due to the measured nonuniformity of the specimens. We used the nonuniformities measured by NIST during the laboratory intercomparison.

Summary

The NMi laboratory reports the lowest uncertainties for these step height specimens and NIST is a close second. More importantly the NMi and NIST results for the step height values themselves agree very closely with one another and lie very close to the mean of the results of all the laboratories in the Euromet intercomparison. There were four other laboratories contributing to that intercomparison whose results are not shown here.

The preceding data were obtained with stylus instruments and interference microscopes. New calibration systems have recently come into operation which are based on scanned probe microscopes either directly coupled to laser interferometers [71,72,73] or intermittently calibrated by them [73,74,75]. Whether use of these new systems will lead to significantly improved uncertainties for step height measurements remains to be seen.

XI. Surface Roughness (T. V. Vorburger)

Introduction

Surface roughness standards serve nearly the same function as step height standards. They are used to check the calibration of stylus instruments for measuring roughness average (R_a) and other roughness height parameters. These standards are primarily used with stylus instruments but have been used with scanned probe microscopes and optical profiling instruments as well. Roughness standards are particularly useful for testing not only the vertical gain of the instrument, but also its dynamic response for measuring roughness, as well as the software for calculating roughness quantities. Therefore, these specimens are useful for checking the complete response of the instrument for measuring specific roughness parameters such as R_a.

The uncertainties reported in Table 11.1 for the Netherlands, UK, Italy, and Switzerland are based on their participation in an intercomparison [76] of 29 laboratories in 13 countries held between 1989 and 1992. The intercomparison focused on measurements of three highly uniform roughness specimens originally developed by PTB and available from a company in Germany [77]. The table shows the uncertainty reported for each specimen by laboratories in each of the four above mentioned countries. The laboratories were not identified in the report. Because the report discusses measurements from more than one laboratory in the Netherlands and the UK, we used the results showing the lowest uncertainties in those countries. Although PTB led the intercomparison, we use more recent information [78] obtained directly from them concerning their measurement uncertainties, which supersedes the results reported for the inter-comparison. In addition, we include information from the NIST roughness measurement laboratory [79] as well as information received from three other laboratories that did not participate in the comparison: NRC [70], KRISS [80], and NIM [81].

Table 11.1 Examples of Uncertainties for Roughness Measurements by Several Laboratories. The values are expressed in percent and represent expanded uncertainties with a coverage factor of 2.

Nominal Roughness Value	Italy [76]	KRISS [80]	Nether-lands [76]	NIM China [81]	NIST [79]	NRC [70]	PTB [78]	UK [76]	Switzerland [76]
200 nm	3.0%	5.0%	3.9%	6.5%	5.4%	5.7%	5.0%	4.5%	3.9%
500 nm	3.9%	3.0%	2.9%	3.9%	2.3%	3.3%	4.0%	3.6%	4.0%
1500 nm	5.1%	2.0%	2.9%	2.5%	1.7%	2.7%	3.0%	3.7%	4.0%

Analysis

For the four laboratories shown in the intercomparison [76], the uncertainties are assumed to represent combined expanded measurement uncertainties including components due both to the instrument and to the specimen. For comparison purposes, the quoted uncertainties for NIST represent estimates of the laboratory's instrumental uncertainties as reported by NIST [79], quadratically added to the nonuniformity of the specimens as measured by NIST on a set of PTB specimens similar to the set used in the intercomparison.

Based on the information we received, we then assumed that the uncertainties quoted by KRISS already included the sample nonuniformity, whereas those quoted by NRC and NIM did not. Therefore, we entered the KRISS uncertainties directly into Table 11.1 whereas we quadratically added the sample nonuniformity we had measured to the NRC and NIM uncertainties, and entered the quadratic sums in Table 11.1. In addition, KRISS, NRC, and NIM quote a range of uncertainties for a range of measured R_a that encompasses the range in Table 11.1 of 200 nm - 1500 nm. For example, NIM stated that their measurement uncertainty for R_a was 2%-5% over the R_a range 0.1 μm - 10 μm. We therefore chose specific uncertainty values within the 2% - 5% range to produce the numbers in Table 11.1. In particular, we used the highest percent uncertainty (5%) for the 200 nm R_a nominal value, and the lowest percent uncertainty (2%) for the 1500 nm R_a nominal value.

Summary

There is a factor of 3 between the highest and lowest quoted uncertainties for the smoothest specimen shown in Table 11.1. The source of the differences in the quoted or estimated uncertainties is not known. In some cases the differences may arise from a conservative approach taken by some of the laboratories in modeling certain systematic components of uncertainty in roughness measurement.

The various laboratories also have different specialties for roughness measurement. Many European laboratories routinely measure the maximum peak-to-valley height R_{max} and average peak-to-valley height R_z(DIN), whereas R_a and rms roughness R_q are emphasized in the United States. In addition, PTB was the pioneer in producing highly uniform random roughness standards [77]. NIST, however, was the pioneer in producing sinusoidal profile standard reference materials [82,83,84].

XII. Angle Blocks (B. S. Faust)

Angle blocks are used in the calibration of instruments that either measure angles or require high accuracy angular positioning. Standard angle block sets include 45, 30, 15, 5, 3, 1 sizes in degrees, and 30, 20, 5, 3, 1 sizes in both minutes and seconds, totaling 16 blocks. Standard physical dimensions are approximately 5.08 cm in length and 2.54 cm high on the gaging faces, with allowances made for the hypotenuse lengths of the larger-angle blocks. The above mentioned set is non-standard in the U.K. The most common set seen in the U.K. is the NPL type include 41, 27, 9, 3, 1 sizes in degrees, 27, 9, 3, 1 sizes in minutes, and 0.05, 0.1, 0.3, and 0.5 sizes in minutes, plus a square block [85].

Routine customer calibrations at NIST use two calibrated dual-axis automatic autocollimators with a 12 second range and a fixturing device allowing each autocollimator to sample a single angle block gaging face. The system is a comparator where differences in angle are measured, rather than absolute deviations. Customer blocks are compared to NIST standard and check-standard angle blocks in an intercomparison test designed to eliminate drift. The angle blocks are measured in “top-up” and “bottom-up” positions, sampling artifact geometry. Error sources and the uncertainty budget for this process is discussed elsewhere [37]. Consistent “top-up” and “bottom-up” values indicate good artifact geometry. The standard block values have been determined by various self-calibration techniques and are periodically recalibrated. Angle deviations for both standard and customer blocks are compared to respective historical values with each customer calibration, comprising an on-line process control check. In-house software generates the customer report of calibration, which contains the deviations of each block from the nominal angle.

The comparison table for angle gage blocks is shown below. Stated uncertainties are expressed in seconds and reflect the 95% confidence level (k=2). Laboratories’ stated uncertainties that have been converted to the k=2 level are denoted by an asterisk (*).

Table 12. 1 Angle Block Comparison

National Laboratory	Size Range	Stated Uncertainty (k=2) in Seconds	Measurement Method
CSIRO [26]	Not Specified, Assuming All Standard Sizes	0.7	Not Specified
IMGC [11]	Not Specified, Assuming All Standard Sizes	± 0.2	Indexing Table and Autocollimator
KRISS [28]	All Standard Sizes	0.2	Indexing Table and Autocollimator
NIM [12]	Plain Angle 360° Small Angle < 1° Small Angle < 5°	< 0.133 * 0.033 * 0.067 *	Not Specified
NIST [37]	All Standard Sizes	± 0.18 Dependant on Block Quality and Physical Size ± 0.35 Dependant on Block Quality and Physical Size	Autocollimator Comparator Autocollimator with Precision Indexing Device
NMi [38]	< 1' < 1° > 1°	0.15 0.3 0.3	Not Specified
NPL [14]	Not Specified, Assuming all standard sizes	± 0.3 (for Gages having Flatness Deviations of less than 0.0002 mm across the Face	Autocollimator with Precision Indexing Device and the NPL Small Angle Generator
NRC http://www.cisti.nrc.ca/inms/dsdme.html P. 6 of [41]	Not Specified, Assuming All Standard Sizes	Not less than 0.1 (Commensurate with Gage Quality)	Interferometric Optical Sine Bar
OFMET [34]	All Standard Sizes	≥ 0.1 Dependant on Block Quality	Rotary Table and Autocollimator
PTB [43]	All Standard Sizes ≤ 30"	0.05 ≤ 0.05	Angle Comparator with Autocollimator PTB Angular Device (Supported by BCR)

Analysis

Most of the laboratories listed are using autocollimators and indexing tables to perform calibrations, with the exceptions being NRC's interferometric optical sine bar and NPL's small angle generator. With NPL and CSIRO on the higher side , and NIM and NRC on the lower side of the stated uncertainty range, the labs are similar in their angle block measuring capabilities. NRC uses an interferometric optical sine bar and achieves their stated uncertainty through increased resolution, good long-term reproducibility values and low systematic effects. In general, higher uncertainties in the table seem to be associated with using one autocollimator and an indexing device. This is particularly the case with indexing devices of limited angular increment. Angle blocks of non-standard dimensions are measured this way as part of the NIST calibration service. Allowances are then made in the calibration for increased and redundant data taking. Angle blocks of non-standard size have a higher incidence of poor geometry and surface flatness; therefore, the extra precautions are required. It is important to note that uncertainties are affected by artifact geometry, and in some cases the geometry becomes the largest error source. When this occurs, the measurement is not limited by the autocollimator resolution. It is, therefore, critical to have artifacts of good geometry and surface finish and less important to have artifacts with minimal deviation from nominal angle.

XIII. **Roundness** (D. S. Sawyer)

In this section, a comparison of the measurement capabilities for roundness (actually out-of-roundness) calibrations is made. The quantity determined, out-of-roundness, is the radial deviation of the actual profile from ideal roundness. Quantitatively, the out-of-roundness value is expressed as the difference between the largest radius and the smallest radius of a measured profile in dimensions of length. For ease of comparison, out-of-roundness is reported in nanometers in the table below. Whenever possible, the published uncertainties have been converted to reflect expanded uncertainties with a coverage factor of k=2.

Table 13.1 Measurement Uncertainty for Roundness Measurements

National Measurement Institute	Range of Measurement	Uncertainty
BNM-LNE [8]	Not Specified	50 nm
IMGC [86]	Diameter < 150 mm	20 nm
NIM [12]	Diameter ≤ 300 mm	6 nm
NIST [37]	Not Specified	16 nm
NRC [30]	Diameter ≤ 355 mm	>10 nm
OFMET [34]	Diameter ≤ 300 mm	6 nm
PTB [68]	Not Specified	10 nm

Analysis

There are two primary types of instruments used for performing high-precision roundness measurements. One instrument uses an accurate spindle to rotate a displacement transducer and stylus probe relative to a fixed artifact. The other instrument rotates the artifact while holding the transducer fixed. In both cases, the measured quantity is the radial deviation of the stylus from some initial position. The output of this measurement is typically a polar graph of the radial deviations.

In order to graphically display the deviations, the measured displacements must be magnified. Therefore, the recorded displacements are proportional to the actual displacement of the transducer stylus in contact with the part. If the deviation of a particular part is known to be within some small range, a larger magnification can be used. Consequently, the ability to perform high precision roundness measurements is, in part, a function of the artifact. It follows that the range of measurement specified in the table is related to the measurement volume of the inspection instrument used to determine roundness.

XIV. Conclusion

A discussion of the calibration methods used at NIST and other national measurement institutes was presented. In addition, a number of application specific artifacts and measurement techniques were presented and compared. The analysis and comparisons are presented in an unbiased manner in table format with some explanations of measurement differences. The results show that some types of measurements are performed by a limited number of institutions and other types are routinely performed by most of the international institutions. There was no intentional effort to not report specific measurements performed within PED simply due to poor internal measurement capabilities. However, there are certainly some internationally leading edge measurements performed at other NMIs which are not performed within the PED, and consequently not reported here. This document does however, give a quantitative comparison of the majority of documented calibration services and standard reference materials of the PED within NIST, and provides a format for the comparison of measurement uncertainties between national measurement institutes and other measurement laboratories.

In general, the uncertainties of the PED of NIST compare quite favorably against the other NMIs in most circumstances. As stated in text, there is good agreement between the various international institutions regarding the vacuum wavelengths of lasers as defined by internationally agreed upon values and methods. There is also basic parity between NIST and several of the laboratories in the majority of measurement areas described in this paper. The comparison of gage blocks in section 5 shows NIST to be near the median of the reported uncertainties with PTB and IMGC to have the best reported values. The photomask linewidth data of section 6 are from a formal comparison on the same sample with the 36 nm uncertainty reported by NIST better than that of NPL while PTB did not report their measurement uncertainties. The linewidth values of this comparison do agree however, within the reported uncertainties. The formal comparison results shown in section 11 for surface roughness again show nominal parity between the contributing laboratories with NIST values on the better side of those reported. Similar results are obtained for both the angle block comparisons and the roundness uncertainties. In both cases, NIST uncertainties are within the extremes of the reported values tending toward the better reported numbers.

In three of the measurement techniques reported here, NIST has the best uncertainties reported or is the only national measurement institute worldwide offering these calibration services or standard reference materials. Although NIST does not perform linear linescale measurements on precision scales longer than one meter, table 4.1 shows that three institutions do perform the longer measurements. NIST does, however, surpass the capabilities of the other NMIs by more than an order of magnitude for the smallest deep sub-millimeter scales. NIST is the only government institute offering traceable SEM magnification standards. And although we do not offer desperately needed SEM linewidth standards, NIST is the only NMI currently offering SEM standard reference materials for scale calibrations. In addition, NIST is the only NMI with two-dimensional grid calibration services having an uncertainty of 0.5 μm for sample sizes greater than 300 mm. The NIST apparatus is capable of measuring samples as large as 750 mm with uncertainties in the 500 nm range.

The NIST two-dimensional grid calibration service can measure samples smaller than 200 mm as well although the uncertainties in this sample range are typically unacceptably large. These values should be compared with the reported uncertainties of the PTB calibration service which can measure samples in the 150 mm to 200 mm range (photomasks and silicon wafers) with uncertainties as small as 40 nm. These two calibration services use instruments manufactured for different purposes. For NIST to offer comparable uncertainties on the smaller samples a new calibration service will have to be developed.

XV. Acknowledgments

The authors thank Dennis Swyt for initiating and motivating the preparation of this document. The authors are also grateful to Jay Zimmerman for assisting with the editing and production of the document and Tyler Estler for initiating contacts with a number of the national measurement institutes. This work was funded by the Precision Engineering Division within the Manufacturing Engineering Laboratory. We extend gratitude for the rapid and complete response provided by the laboratories whose results are presented in this document.

XVI. List of Acronyms

BIPM	Bureau International des Poids et Mesures
BNM-LNE	Bureau National de Metrologie Laboratoire National d' Essais
CCD	Charge coupled device
CIPM	Comite International des Poids et Mesures
CSIRO	Commonwealth Scientific and Industrial Research Organization
CTE	coefficient of thermal expansion
DFM	Danish Institute of Fundamental Metrology
DOE	Department of Energy
EC	European Community
IMGC	Instituto di Metrologia G. Colonnetti
ISO	International Organizations for Standards
KRISS	Korea Research Institute of Standards and Science
LSI	Line Scale Interferometer
LVDT	Linear variable differential transformer
MRS	Magnification Reference Standard
NIM	National Institute of Metrology-China
NIST	National Institute of Standards and Technology
NMi	Nederlands Meetinstituut
NMIs	national measurement institutes
NORAMET	North American Metrology Corporation
NPL	National Physical Laboratory
NRC	National Research Council
NRLM	National Research Laboratory of Metrology (Japan)
OFMET	Swiss Federal Office of Metrology
ONL	Other national laboratories
PED	Precision Engineering Division
PTB	Physikalisch Technische Bundesanstalt

RM	Reference Materials
SEMs	scanning electron microscopes
SIA	Semiconductor Industry Association
SRM	Standard Reference Material
UK	United Kingdom

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