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Stylus-laser surface calibration system

T. V. Vorburger, J. F. Song, C. H. W. Giauque, T. B. Renegar, E. P. Whitenton, and M. C. Croarkin
National Institute of Standards and Technology, Gaithersburg, MD, USA

A stylus-laser surface calibration system was developed to calibrate the NIST sinusoidal roughness Standard Reference Materials (SRM) 2071–2075. Step height standards are used to calibrate the stylus instrument in the vertical direction, and a laser interferometer is mounted on the traversing unit of the stylus instrument to calibrate the instrument in the horizontal direction. The calibration uncertainty (±2σ) for SRM 2075 is ±1.2% for roughness calibrations (R_a = 1 μm), and ±0.06% for spatial wavelength calibrations (S_m = 800 μm). Published by Elsevier Science Inc., 1996

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Introduction

Both the manufacturing process and engineering function of mechanical parts can be characterized by surface texture measurements. More than 50 parameters have been used for surface texture characterization, the important ones being the roughness average (centerline arithmetic average) R_a in the vertical direction and the mean spacing of profile irregularities S_m in the horizontal direction.[1] At the NIST surface and microform calibration laboratory, customer surface roughness specimens are tested primarily for R_a; some specimens are tested for S_m and other parameters as well. In addition to this service, in 1982 sinusoidal profile precision roughness specimens were developed by the NIST and J. B. Bryan of the Lawrence Livermore National Laboratory using a CNC diamond-turning process.[2,3] These specimens are now NIST Standard Reference Materials (SRM) 2071–2075.[4,5]

An earlier NBS stylus/computer system for measurement of surface roughness was developed in 1976.[6] This was a computerized commercial stylus instrument. The calibration traceability of roughness height parameters, such as R_a, was established by using a set of step height standards for instrument gain calibration. The step heights were interferometrically calibrated and traceable to NIST length standards. These step height masters now range from 0.03 μm to 150 μm. On the other hand, the calibration uncertainty of spacing parameters largely depends on the accuracy of the traversing system of the stylus instrument. The traversing system on most commercial stylus instruments is designed as a mechanical (or motion) system rather than a metrology system. For one instrument, the variation of the traversing speed was measured to be ±0.04 mm/s at a nominal speed of 1.52 mm/s, and ±0.013 mm/s at a nominal speed of 0.3 mm/s.[6] This means about a ±4% uncertainty would be directly included in the measurement of spacing parameters unless a metrology system is added to the stylus instrument for calibrating the horizontal displacement.

To establish calibration traceability for the sinusoidal roughness specimens in both the vertical and horizontal directions, we developed a stylus–laser surface calibration system. A laser interferometer is installed on it to establish the calibration traceability and improve calibration uncertainty of horizontal parameters. The corner cube retroreflector of the laser interferometer is mounted on the traversing unit of the stylus instrument. The horizontal displacement of the stylus is measured by the laser interferometer with traceability to the optical wavelength. The calibration procedure also enables measurement automation. The calibration uncertainty was calculated according to ISO and NIST policy for expressing measurement uncertainties.[7,8]

In this paper, we describe the metrology requirements, instrument setup, calibration and check standards, calibration procedure, calibration traceability and uncertainty procedure, and calibra-

Address reprint requests to Dr. T. V. Vorburger, Surface and Microform Metrology, Precision Engineering Division, National Institute of Standards and Technology, Quince Orchard Boulevard, Gaithersburg, MD 20899, USA.

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Table 1 Calibration uncertainties of NIST SRM 2071–2075 sinusoidal roughness specimens

	Nominal			Calibration uncertainties			
				R_a		S_m	
	R_a µm	S_m µm	Calibration dates	µm	%	µm	%
SRM 2071	0.3	100	12/89	±0.013 (±3σ)	±4.3%	±0.33 (±3σ)	±0.33%
			10/90	±0.015 (±3σ)	±5%	±0.31 (±3σ)	±0.31%
SRM 2072	1	100	12/89	±0.027 (±3σ)	±2.7%	±0.24 (±3σ)	±0.24%
SRM 2073*	3	100	6/91	±0.08 (±3σ)	±2.7%	±0.12 (±3σ)	±0.12%
			10/94	±0.047 (±2σ)	±1.6%	±0.08 (±2σ)	±0.08%
SRM 2074	1	40	5/92	±0.025 (±3σ)	±2.5%	+0.06 −0.02 (±3σ)	+0.15% −0.05%
SRM 2075	1	800	9/93	±0.012 (±2σ)	±1.2%	±0.47 (±2σ)	±0.06%

* Measurements for the first issue of SRM 2073 were performed in 1984 with a different system and are not shown here.

tion results. The use of the laser interferometer has vastly improved the calibration uncertainty of spacing parameters. The expanded calibration uncertainty (±2σ) for sinusoidal roughness SRM 2075 is ±1.2% for roughness calibrations (R_a nominally = 1 µm), and ±0.06% for spatial wavelength calibrations (S_m nominally = 800 µm).

Calibration requirements for NIST sinusoidal roughness specimens SRM 2071–2075

The sinusoidal roughness specimens SRM 2071–2075 are manufactured by the CNC diamond-turning process,[2,3] with nominal R_a values of 0.3, 1, and 3 µm and nominal spatial wavelength values of 40, 100, or 800 µm (see *Table 1*). For a sinusoidal profile, the S_m parameter is identical to the sinusoidal spatial wavelength. For calibrations of these specimens, several requirements have evolved:

1. Both the roughness height and spatial wavelength calibrations should be directly traceable to accepted length standards with acceptably small calibration uncertainties. The instrument setup, calibration and check standards, and calibration and uncertainty procedures should be established to ensure the calibration traceability and uncertainty.
2. The profile quantization step and profile sampling interval should be small enough for testing the finest structure of the surface texture of SRM 2071–2075 specimens. The horizontal resolution of stylus instruments depends on both the stylus size and the profile sampling interval. The tip sizes of commercial styli often range from 2 to 10 µm;[1,9] therefore, the profile sampling interval should be less than 2 µm. In the vertical direction, the vertical resolution of stylus instruments depends on the transducer, usually a linear variable differential transformer (LVDT), and the instrument gain. The quantization step should be at least 1000 times smaller than the peak-to-valley height.
3. For the instrumentation of the laser interferometer on the stylus instrument, attention should be paid to the Abbe offset error for wavelength measurements. An accurate slide and traversing mechanism of the stylus instrument should be used to minimize the Abbe offset error.
4. The algorithms and software package should conform to the surface texture definitions in ISO and ANSI standards.[1,9] For SRM 2075 with long (800 µm) spatial wavelength, particular attention should be paid to the calculation of the mean line in the wavelength algorithm. Because of the small number of peaks and valleys in the surface profile, the least-squares mean line may not follow the true profile level. We discuss this further in the calibration traceability and uncertainty section.
5. Because of the number of measurements required for the NIST SRM 2071–2075 sinusoidal roughness specimens, it is desirable to automate the measurement.

NIST Stylus-laser surface calibration system

The NIST stylus-laser surface calibration system is shown in *Figure 1*. The stylus instrument (1) is a commercial stylus instrument[10] with 300 mm traversing length. (Certain commercial equipment, instruments, or materials are identified in this paper to specify adequately the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that

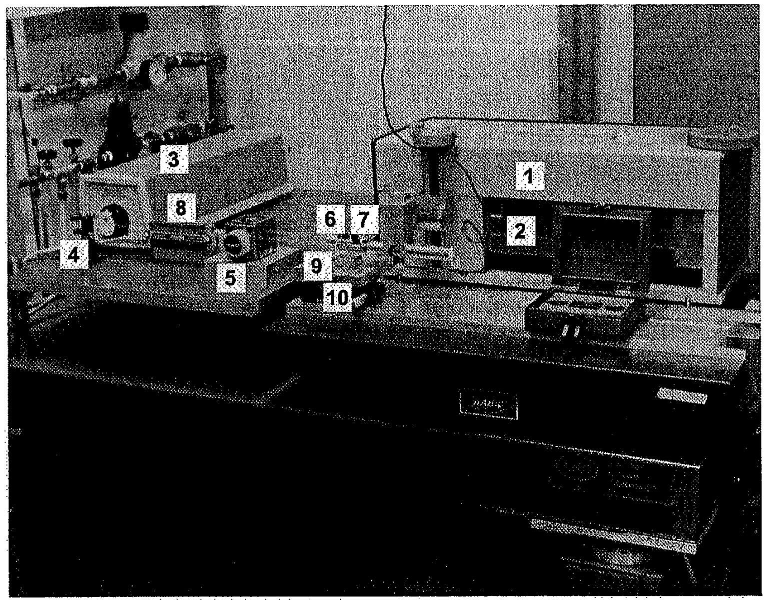

Figure 1 NIST Stylus-laser surface calibration system: (1) stylus instrument housing; (2) 300 mm slide; (3) He–Ne laser; (4) 45° reflecting mirror; (5) interferometer; (6) retroreflecting mirror; (7) traversing unit and LVDT transducer; (8) receiver; (9) SRM specimen; (10) *Y*-stage

the materials or equipment identified are necessarily the best available for the purpose.) The slide (2) and its traversing mechanism were constructed to have a vertical straightness of motion of approximately 0.075 μm over the 300 mm traversing length (*see Figure 2*). The maximum traversing speed is 2.5 mm/s, and the minimum traversing speed is 2.5 μm/s.

In *Figure 1*, the He–Ne laser (3) is mounted perpendicular to the instrument's axis of motion to reduce the space of the instrumentation. A 45° reflecting mirror (4) directs the laser beam through the interferometer (5) to the retroreflecting mirror (6), which is mounted on the stylus traversing unit (7), close to the stylus. The returned laser beam travels back through the interferometer (5) to the receiver (8).

There is a 15 mm Abbe offset between the measurement path defined by the laser beam and the path of motion of the stylus on the surface. However, because of the high accuracy of the slides and the traversing system, the maximum angular deviation measured in the direction of Abbé offset is only 3.4 μR. This angular deviation produces an Abbe offset uncertainty in the traversing length of only 51 nm.

A remote control system has been installed in this stylus instrument, which permits measurement automation in the traversing *X*-direction. For positioning the specimen (9) in the *Y*-direction, we currently use a manual stage (10).

An HP 9836 microcomputer and the control unit of the stylus instrument (not shown in *Figure 1*) are used for controlling the calibration process, calculating the surface parameters and calibration uncertainties, and printing the calibration results. The signal from the interferometer directly triggers the voltmeter to take profile height data points at equal sampling intervals. The sampling interval was 1.009 μm for SRMs 2071–2074 and 2.007 μm and for SRM 2075. Altogether, 4000 datapoints comprise the profile evaluation length, which was then slightly more than 4 and 8 mm, respectively. In the vertical direction, the range-to-least-count ratio of the system voltmeter is about 2400:1. The profile quantization step is about 2 nm when full scale is about 4.8 μm, the conditions used for SRM 2075. We intend to use 8000 points per evaluation length and 16-bit data acquisition in our next surface calibration system.

The software package of the calibration system includes an instrument calibration program that uses one-sided and two-sided step height standards, a calibration program for the SRMs with a semiautomated measurement procedure, a calibration program for step height specimens, the calibration of other surface roughness specimens, and the calibration of uncertainties. The measurement data can also be used for calculating other surface texture parameters in addition to R_a and S_m. Finally, a program for statistical surface texture analysis includes PSD (power spectral density) and ACF (autocorrelation function).

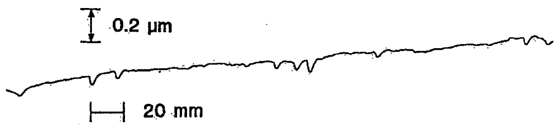

Figure 2 Vertical straightness profile of the traversing unit of the stylus instrument as measured by the manufacturer

Calibration and check standards, calibration procedure

The stylus-laser surface calibration system is calibrated in the vertical direction with step height master standards. Three methods are used to determine their actual step heights independently. These methods include two optical interferometry methods yielding measurements of the step heights directly in terms of a wavelength of light and a ratio method using the stylus instrument itself whereby we compare a smaller, unknown step height with a larger, known step height. These measurement results have shown very good agreement.[11]

At the surface and microform calibration laboratory, check standards also play an important role in establishing measurement quality control and calculating uncertainty in various surface and microform calibrations. The check standards should be as similar as possible to the calibrated specimens, so that the check standards can be used to verify, control, and recheck the calibration conditions for the specimens. Other requirements for the check standards include their geometric uniformity, material stability, and calibration traceability.[12,13] The check standards help us to perceive variations of calibration conditions from day to day.

When calibrating the sinusoidal roughness specimens, we designate one specimen from each batch of specimens as the check standard. Its surface parameters, including roughness average R_a and profile wavelength S_m are measured on each day that the SRM units are measured. We use the calibrated R_a and S_m of the check standard SRM 2075 as a reference to exercise quality control over calibrations for the other specimens in the same issue. A random component of the measurement uncertainty is calculated from the variation of these diurnal measurements.

The check standard is measured for S_m by a second approach to verify the operation of the interferometer. For SRM 2075, that approach consists of comparing on the profile recorder the wavelength of the check specimen with the 40 μm wavelength of SRM 2074. For SRM 2075, we measured the S_m of the check standard to be 800.04 ± 0.47 μm ($\pm 2\sigma$) using the stylus-laser surface calibration system and 800.48 ± 1.9 ($\pm 2\sigma$) using the other approach. The two values agreed within the experimental uncertainty.

These calibration and check standards are used in combination with a standardized calibration procedure. This measurement procedure, combined with a calibration uncertainty calculation procedure, described later, aids in the calculation of uncertainty of our surface and microform calibrations.

Each day that calibrations of the sinusoidal roughness specimens are performed, the instrument is first calibrated using one of the master step height standards. The instrument calibration is then checked by measuring the check standard SRM and comparing the measurement results with a pre-established uncertainty limit.

After that, the SRM specimens are calibrated one after another. For SRM 2071–2073 with spatial wavelength of 100 μm and SRM 2074 with spatial wavelength of 40 μm, nine measurement positions are evenly distributed in three parallel rows, with 4 mm evaluation length and 0.8 mm cutoff using a 2RC filter[1] for each measurement. For SRM 2075 with 800 μm spatial wavelength, 10 measurement positions are evenly distributed in five parallel rows, with 8 mm evaluation length and unfiltered operation for each measurement (see Figure 3). The longer evaluation length is used here to sample a sufficient number of profile wavelengths (10) with each trace. At each measurement row, the measurement process is automated by the computer-driven control system of the stylus instrument. This automated measurement process includes: (1) returning the stylus to its home position (left end), changing its traversing direction and dropping the stylus to contact the measured surface; (2) performing a 4 or 8 mm measurement traverse at position 1; (3) raising the stylus and rapidly moving the stylus to the next position; (4) dropping the stylus to contact the measured surface and proceeding to the next measurement until the two or three measurement positions along the measurement row are completed; and (5) raising the stylus, changing traversing direction, returning the stylus to the home position, and repeating the measurements one more time. At each measurement position, two measurements are made, and the measurement results are averaged for the calibration report. We currently use a manual motion Y-stage to move the SRM specimen in the Y-direction from one row to the next. The entire automated measurement can be realized by using a computer-controlled stepping motor-driven Y-stage.

At the end of each day's SRM specimen calibrations, we check these calibrations by remeasuring the check standard (i.e., the master SRM specimen) and comparing the measurement results with those measured in the beginning of the calibration routine.

Calibration traceability and uncertainty

A definition of traceability proposed at NIST in 1986 is as follows.[14,15]

> Traceability as a measurement implies an unbroken pathway from the measurement to the definition of the accepted unit(s) used to express the results of the measurement. A measurement quality assurance system is required to ensure that the accuracy of the measurement is within stated limits of uncertainty.

The definition of traceability stated in the *International Vocabulary of Basic and General Terms in Metrology* is:[16]

> Property of the result of a measurement or the value of a standard whereby it can be related to a stated reference, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties.

The calibration traceability of NIST sinusoidal roughness SRMs 2071–2075 was established with calibration and check standards, calibration procedures, and uncertainty calculation procedures. We have discussed the calibration and check standards and the calibration procedure above. We now introduce the uncertainty calculation procedure.

The uncertainty calculation procedure for the recently issued SRM 2075 follows NIST and ISO requirements for expressing measurement uncertainties.[7,8] The expanded calibration uncertainty U_c is expressed as:

$$U_c = ku_c \tag{1}$$

where k is a coverage factor ranging between 2 and 3, depending on the confidence level, and u_c is the combined standard calibration uncertainty. The NIST policy recommends $k = 2$, which corresponds to about a 95% confidence level. For measurements of R_a, the quantity u_c is a quadratic sum of four components: (1) specimen nonuniformity mixed with instrument repeatability during the measurement of each specimen; (2) day-to-day variation of the instrument calibration; (3) possible nonlinearities in the overall instrument response; and (4) the uncertainty of the height of the calibrating step.[6,17]

The first three uncertainty components are type A components.[7,8] That is, they have been obtained from statistical methods. The fourth component is type B. Its uncertainty has been calculated by other than statistical methods, in this case, a model.

We normally add uncertainty in the stylus tip radius as a fifth source of uncertainty, because the stylus tip radius affects the spatial resolution of the instrument and, thus, the measured R_a value. For SRM 2075, however, the spatial wavelength of the specimen is so long that uncertainty in the stylus tip radius (5 μm nominal) is negligible as a source of uncertainty in the R_a result.

The combined standard calibration uncertainty u_c for SRM spatial wavelength calibrations is the quadratic sum of nine components of uncertainty. The first three components (type A) are: (1) instrument repeatability mixed with any specimen nonuniformity along the profiling direction; (2) specimen nonuniformity across the profiling direction; and (3) variation in the instrument response from day to day.

The other six components (type B) come from uncertainties in the interferometric measurements of displacement and were evaluated using models. They are: (4) uncertainty in the vacuum wavelength of the He–Ne laser; (5) uncertainty in the wavelength of the He–Ne laser beam propagating in air due to uncertainties in the temperature, pressure, and humidity of the lab environment; (6) uncertainty in the length of the specimen due to uncertainty in its temperature; (7) variation in the path length of the laser beam caused by temperature fluctuations within a single measurement; (8) uncertainty attributable to "cosine error" between the direction of the laser beam and the specimen axis; and (9) uncertainty discussed previously, arising from the Abbe offset between the specimen surface and the laser beam.

Another potential source of uncertainty affecting both the R_a and S_m values is the finite record length used to measure the periodic profiles. This can result in the calculation of a least-squares mean line with varying slope.[18] It has been shown that for a large number of periods (n) in the record length, the three standard deviation (3σ) variation of the rms roughness (R_q) value caused by such a varying mean line is given by $3/(8\pi n)$.[18] This implies a 3σ uncertainty of only ±0.08% in the measurement of R_q for SRM 2074, where the record length of 4 mm includes 100 spatial wavelengths, but an uncertainty of 0.8% for SRM 2075, where the record length of 8 mm includes only 10 spatial wavelengths. The percentage measurement uncertainty for R_a is expected to be about the same.

The finite record length mentioned above could also affect the S_m measurements if a least-squares mean line is used as the reference line at which profile crossings are counted. Any tilt in the least-squares fitted mean line results in a smaller S_m value for a sinusoidal surface.

To avoid these uncertainties for the SRM 2075 specimens with long spatial wavelength (S_m = 800 μm), the profiles were unfiltered, and we used the trend in the profile peaks and valleys to determine the profile mean line instead of using a least-squares fit. Furthermore, we increased the evaluation length from 4 to 8 mm, so that 10 periods of the profile were included.

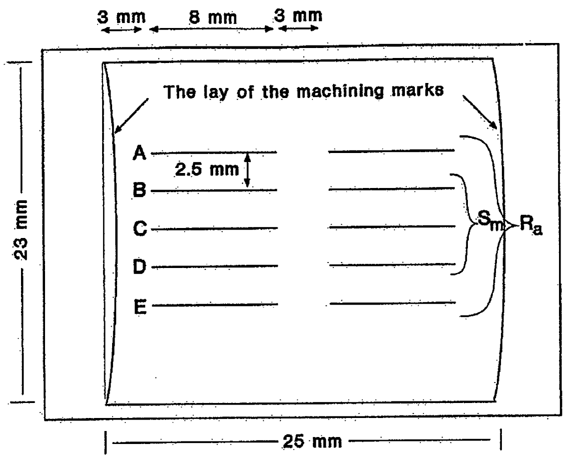

Figure 3 Measurement positions of SRM 2075: 2 positions in each of five rows (A–E)

Calibration results

Since the establishment of the stylus-laser surface calibration system in 1989, hundreds of SRM sinusoidal roughness specimens have been calibrated. The calibration period for one SRM specimen, including 9 and 10 measurement positions at 3–5 sections, each measured twice, takes about 25–30 minutes.

Table 1 shows the calibration uncertainties for the roughness R_a and spatial wavelength S_m calibration of NIST SRM 2071–2075 sinusoidal roughness specimens. The calibration uncertainties were expressed by $\pm 3\sigma$ using an arithmetic sum before 1992, and by $\pm 2\sigma$ using a quadratic sum since 1993. The uncertainty components, as well as the combined calibration uncertainties, are subject to review and modification from issue to issue. The use of laser interferometry is the basis for the tight horizontal calibration uncertainty. Most of the expanded calibration uncertainties for S_m ($\pm 2\sigma$) are less than $\pm 0.2\%$ (see *Table 1*).

Because the surface grooves produced by the CNC diamond facing process are curved (see *Figure 3*), the profile traverse lines are only perpendicular to the machining marks of SRM 2075 in the center section (row C). Hence, the measured spatial wavelength of the outside rows (i.e., rows A and E) is slightly longer than that measured in the center section. The stylus-laser system can measure these small wavelength differences. A statistical analysis of 87 units of the SRM 2075 specimen calibration data is shown in *Table 2*. The wavelength measured in the outside sections (rows A and E, *Table 2*) of the SRM 2075 specimens is systematically larger than those measured in the center section (row C) by about 0.4 μm (see *Table 2*). Therefore, only data rows B, C, and D are used for the spatial wavelength certification. In addition, the small remaining differences between these rows are used to calculate component two in our uncertainty calculation for S_m.

Table 2 Wavelengths and standard deviations (μm) of 87 SRM 2075 sinusoidal roughness specimens versus five measurement rows from A to E

Row	Average	Standard deviation	Degrees of freedom
A	800.40	0.12	87
B	800.11	0.11	87
C	800.01	0.11	87
D	800.11	0.12	87
E	800.41	0.14	87

Summary

The NIST stylus-laser surface calibration system has established the traceability for both R_a and S_m calibrations of NIST SRM 2071–2075 sinusoidal roughness specimens. The expanded calibration uncertainty ($\pm 2\sigma$) for the most recent issue (SRM 2075) is ±1.2% for roughness calibrations (R_a = 1 μm), and ±0.06% for spatial wavelength calibrations (S_m = 800 μm). The calibration process is semiautomated. This system can also be used to calibrate other step height standards, surface roughness specimens, and engineering surfaces, and to perform statistical analysis of engineering surface texture.

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