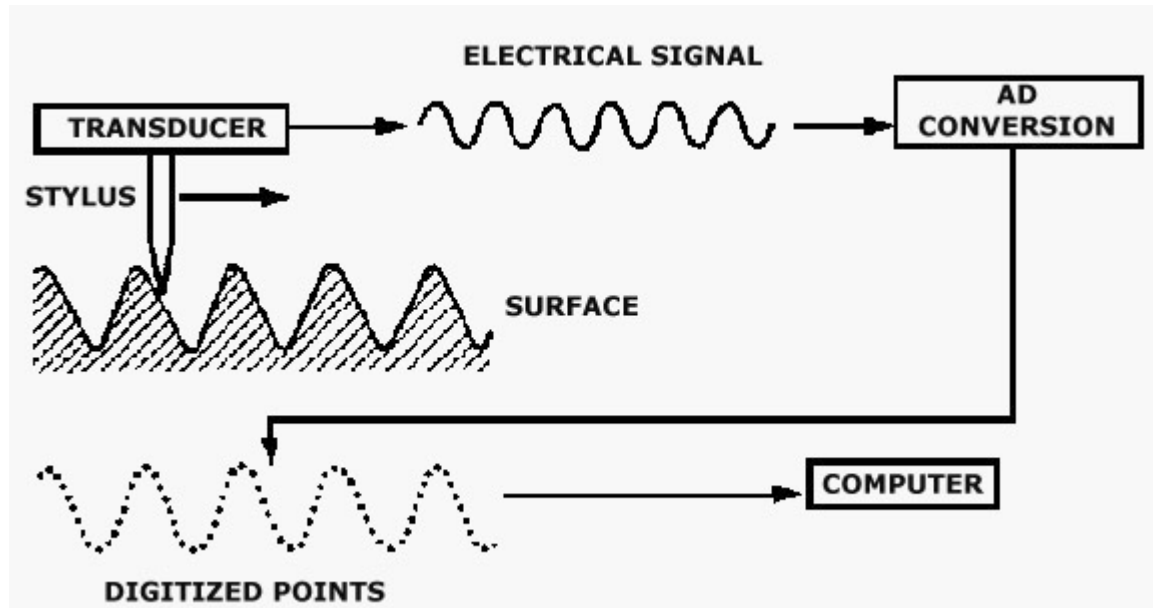# NIST SURFACE ROUGHNESS AND STEP HEIGHT CALIBRATIONS,
Measurement Conditions and Sources of Uncertainty
T.V. Vorburger, T. Brian Renegar, A.X. Zheng, J-F. Song, J.A. Soons, and R.M. Silver

Parameters of surface roughness and step height are currently measured at the National Institute of Standards and Technology (NIST) by means of a computerized/stylus instrument. For roughness height parameters, we use a calibration ball as a master to calibrate the instrument to be employed during a measurement. Profiles of the calibrating master and the roughness sample under test are stored in a computer. For roughness spacing parameters, we use an interferometrically calibrated Standard Reference Material (SRM) to check the calibration of the drive-axis encoder of the stylus instrument.

In measurement of roughness, surface profiles are taken with a lateral sampling interval of 0.125 µm, typically over an evaluation length of 4 mm. Three parameters of the instrumentation are important in the specification of roughness measurements. These are the roughness filter long wavelength cutoff (λc), the roughness filter short wavelength cutoff (λs), and the stylus radius. The nominal filter cutoff λc is 0.8 mm, and the nominal filter cutoff λs is 2.5 µm. These filter transmission characteristics are in accordance with the phase-correct Gaussian filter described in ASME B46.1-2009.[1]

The stylus has a radius of 1.52 µm ± 0.15 µm (with a coverage factor $k = 2$), calibrated by measuring a standard wire with a calibrated radius and by the razor blade trace method[1-6]. An iterative computer algorithm[5,6] is used to calculate the effective radius from the razor blade trace method. Stylus tip correction is then applied to estimate the profile of the mechanical surface[7-9] from the measured profile.

The above measurement conditions of evaluation length, sampling interval, Gaussian filtering, and stylus radius are the customary conditions for our roughness measurements. The parameters of roughness average (*Ra*), root mean square (rms) roughness (*Rq*), average maximum height of the profile (*Rz*), maximum height of the profile (*Rt*), maximum profile peak height (*Rp*), maximum profile valley depth (*Rv*), and mean spacing of profile irregularities (*RSm*) as described in American National Standard ASME B46.1-2009[1] are then calculated.

For step height measurements, we use either an interferometrically calibrated step height or a calibration ball to calibrate the instrument. Profiles of the calibrating master and the step under test are stored in the computer. One of several algorithms may be used for calculating the step height values. For single-sided steps, a straight line is fitted by the method of least squares to each side of the step transition, and the height is calculated from the relative position of these two lines extrapolated to the step edge. See example feature d1 in Fig. 1a. For double-sided steps, an algorithm developed at NIST is ordinarily used. For the NIST algorithm, the step height transition on each side of the step is measured independently as described above, and the two results (features d1 and d2 in Fig. 1a) are averaged. Alternatively, the ISO algorithm, described in ISO Standard 5436-1:2000 [2] may be used. If so, it is explicitly stated in any calibration reports that we develop. Our implementation of the ISO algorithm is illustrated in Fig. 1b.

Uncertainty of Measurements
For all measurements, the quoted expanded uncertainty U is equal to the combined standard uncertainty u_c times a coverage factor (k) equal to 2. The combined standard uncertainty u_c is the root-sum-of-squares of the measurement system standard uncertainty $u(I)$ and the statistical variation of the measurements s. The statistical variation of the measurements is mainly derived from the non-uniformity of the specimen under test, but it also includes instrumental random variation during the measurement process. It is calculated as one standard deviation (1σ) of the set of values measured at different positions on the measuring area.

Measurement System Uncertainty for *Ra*
The measurement system standard uncertainty $u(I)$ for *Ra* is the root-sum-of-squares of six uncertainty components. These are derived from:

(1) Geometrical non-uniformity and surface finish of the calibration ball master used to calibrate the instrument. This leads to variations in measurements of the master ball to obtain the calibration constants of the stylus instrument and hence, to an uncertainty in the calibration constants.

(2) Variations in the measured calibration constants arising from the instrument: (a) noise in the stylus instrument transducer, (b) surface topography imperfections in the reference datum of the stylus instrument, (c) sampling and digitizing processes in the controller, and (d) round-off in the software computations.

(3) Variations in the measured *Ra* values due to nonlinearity in the instrument transducer.

(4) Uncertainty in the radius of the master ball used to calibrate the instrument.

(5)   Uncertainty in the horizontal resolution of the instrument. The ideal Gaussian filter to attenuate short spatial wavelengths is not perfectly realized by the digital filter used in stylus instruments. In addition, spatial wavelengths of the surface that are smaller than the stylus tip radius are measured with reduced sensitivity by the stylus or not measured at all.   Uncertainty in these influence quantities causes uncertainty in the short wavelength cutoff of the measurements and hence uncertainty in *Ra*.   Quoted uncertainties here represent conservative estimates of the potential biases. The estimates were obtained from variations observed in *Ra* values when a surface is measured with styli of different radii. Measurement results for two different model surfaces were used to estimate this component.

(6)   Vertical resolution of the instrument. This component arises from the instrument noise and tends to increase the *Ra* value.

The top row of Table 1 shows the uncertainty budget for *Ra* measurements, expressed in accordance with guidelines at NIST.[10]   The six uncertainty components are shown there as standard uncertainties. Components 1 to 3 are Type A uncertainties.[10]   That is, they are standard deviations calculated by statistical methods.   Components 4 to 6 are Type B uncertainties, which are evaluated by other means.[10] These uncertainty components are 1σ estimates calculated from models that estimate errors in the measured *Ra* values based on the identified uncertainty sources. The six components are added quadratically to yield the formulas for calculation of the measurement system standard uncertainty $u(I)$.

Measurement System Uncertainty for *Rq* Measurements
The measurement system standard uncertainty for *Rq* measurements arises from the same sources already described for *Ra* measurements, and components 1 to 4 of the uncertainty budget in Table 1 are the same as the entries 1 to 4 for *Ra* in Table 1. Components 5 and 6 are slightly larger because *Rq* is a slightly larger quantity than *Ra*. Component 5 for *Rq* is 25 % larger than component 5 for *Ra*, a factor based on the ratio of *Rq/Ra* for a Gaussian random surface.[11] Component 6 for *Rq* is taken directly from *Rq* measurements of the system noise.

Measurement System Uncertainty for *Rz, Rt, Rp,* and *Rv* Measurements
The measurement system standard uncertainty for these parameters arises from the same sources already described for *Ra* measurements, and the formulas for components 1 to 4 of the uncertainty budgets are the same for all roughness height parameters.

Components 5 and 6 are different. Because the *Rz* and *Rt* parameters are approximately five to ten times larger than the *Ra* parameter for a Gaussian random surface, we estimate the uncertainty of *Rz* and *Rt* due to uncertainty in stylus radius to be 7.5 times as large as component 5 for *Ra* in Table 1. The parameters *Rp* and *Rv* are treated differently. Because of the identity,

$$Rt = Rp + Rv,$$

one might take the uncertainties for component 5 for *Rp* and *Rv* each to be smaller than the uncertainties for component 5 quoted for *Rz* and *Rt*. However, for a stylus instrument,

uncertainty in the stylus tip size affects the measurement of valleys more than peaks. The value for *Rp* is only affected by a change in the measured mean line when the stylus radius changes. The value for *Rv* is directly affected by changes in horizontal resolution. Therefore, we indicate a smaller uncertainty for *Rp* than for *Rv* due to lateral resolution.

Component 6 is uncertainty due to vertical noise, which tends to increase roughness height values systematically. The values for uncertainty shown in Table 1 for the extreme value parameters *Rz, Rt, Rp,* and *Rv* are derived from the values measured for these quantities on a smooth optical flat, whose roughness is much smaller than the noise of the instrument. Therefore, the value of *Rz* due to instrument noise was measured to be 10.7 nm. Analogously, the value of *Rt*(noise) was measured to be 14.6 nm, the value of *Rp*(noise), 8.6 nm, and the value of *Rv*(noise), 6.0 nm. These values represent conservative estimates for the possible errors that might be obtained when measuring a rough surface using our instrument. We take these values to be equal to the standard uncertainties for those quantities.

The estimated standard uncertainties for all six components and for all six roughness height parameters are shown in Table 1.

Measurement System Uncertainty for *RSm* Measurements:
The measurement system standard uncertainty for *RSm* arises from seven sources:

(1)   The measurement of *RSm* uses the *x*-axis encoder of the instrument to measure the distance travelled by a stylus scanning over the surface. An interferometrically measured physical calibration standard, NIST SRM 2073 Sinusoidal Roughness Specimen, is then used as a check of the encoder calibration. The uncertainty in the spatial wavelength of this standard is therefore a source of uncertainty in *RSm*.

(2)   The current method of *RSm* measurement is different from a previous method we used to calibrate the SRM 2073 standard, which relied on a direct measurement of displacement with a laser interferometer. The potential offset between the two methods was estimated by measurement of the SRM 2073 by the new method and comparison of that value with previous measurements by the laser interferometer method.

(3)   Uncertainty in the temperature of the laboratory causes a proportional uncertainty in any lateral spacings being measured across the surface. The temperature of the laboratory is controlled to 0.1 K. An extreme variation of ± 2 K, assumed here, produces a modest contribution to the uncertainty of *RSm*.

(4)   Possible misalignment of the measured sample axis with respect to the *x*-axis of the encoder of the instrument results in a possible cosine error in the *RSm* measurement.

(5)   Possible error in the measured *RSm* values can arise from the Abbe offset between the encoder axis and the measured surface when combined with potential error in the angular pitch motion of the *x*-axis drive.

(6)   Potential nonlinearity in the x-axis encoder leads to possible variations in measured values of RSm as a function of position along the traversing direction. This component was estimated by measuring the same lateral spacing of SRM 2073 at different positions along the x-axis of the encoder and calculating the standard deviation of the measured values.

(7)   Possible day-to-day variations in the encoder calibration were estimated by measuring the RSm values of SRM 2073 over ten days and taking the standard deviation of the results.

The formulas used to calculate the measurement uncertainty of RSm are given in Table 2. The first five components are Type B. The sixth and seventh components are Type A.

Measurement System Uncertainty for Step Height Measurements
Measurement system standard uncertainty $u(I)$ for step height measurements arises from the same sources already described for roughness, with the exception that components 5 and 6 are eliminated. Neither the horizontal resolution nor the instrumental noise causes offsets in the step height measurements. Instrumental noise, however, contributes to the random variation (s) of the measurement results about the mean value. The formula used to calculate the measurement uncertainty depends on the height of the measured step X and on either the height of the calibration step master H or the radius of the calibration ball and are given in Table 3.

Note:
The uncertainty reported by NIST represents only the estimated uncertainty in the NIST calibration of the customer's specimen. Additional uncertainties arising in the customer's use of the specimen (e.g., to transfer a calibrated value to another device) should be evaluated by the customer considering all the influence quantities in the customer's measurement system, including calibration and check standard(s), instrument, environment, operators, and other factors.

References:
Additional information may be found in the following references. References 3, 4, 6-8, 12, and 13 may be obtained from us upon request.

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Table 1: Uncertainty Budgets for NIST Measurements of Roughness Height Parameters

Roughness Average – Ra Root Mean Square (rms) Roughness – Rq

Average Maximum Height of the Profile – Rz Maximum Height of the Profile – Rt

Maximum Profile Peak Height – Rp Maximum Profile Valley Depth – Rv

| Parameter | Standard Uncertainty Components | | | | | | Measurement System Standard Uncertainty $u(I)$ $= [(u^2(1) + ... + u^2(6)]^{1/2}$ |
	1	**2**	**3**	**4**	**5** (nm)	**6** (nm)	
Ra	$4.8\times10^{-6}\,Ra$	$0.0016\,Ra$	$0.00020\,Ra$	$6.1\times10^{-6}\,Ra$	3.5	1.3	$[(0.0016\,Ra)^2+(3.7\text{ nm})^2]^{1/2}$
Rq	$4.8\times10^{-6}\,Rq$	$0.0016\,Rq$	$0.00020\,Rq$	$6.1\times10^{-6}\,Rq$	4.4	1.6	$[(0.0016\,Rq)^2+(4.7\text{ nm})^2]^{1/2}$
Rz	$4.8\times10^{-6}\,Rz$	$0.0016\,Rz$	$0.00020\,Rz$	$6.1\times10^{-6}\,Rz$	26	10.7	$[(0.0016\,Rz)^2+(28\text{ nm})^2]^{1/2}$
Rt	$4.8\times10^{-6}\,Rt$	$0.0016\,Rt$	$0.00020\,Rt$	$6.1\times10^{-6}\,Rt$	26	14.6	$[(0.0016\,Rt)^2+(30\text{ nm})^2]^{1/2}$
Rp	$4.8\times10^{-6}\,Rp$	$0.0016\,Rp$	$0.00020\,Rp$	$6.1\times10^{-6}\,Rp$	13	8.6	$[(0.0016\,Rp)^2+(16\text{ nm})^2]^{1/2}$
Rv	$4.8\times10^{-6}\,Rv$	$0.0016\,Rv$	$0.00020\,Rv$	$6.1\times10^{-6}\,Rv$	26	6.0	$[(0.0016\,Rv)^2+(27\text{ nm})^2]^{1/2}$

Combined Standard Uncertainty, $u_c = [(u^2(I) + s^2]^{1/2}$

Expanded Uncertainty, $U = 2u_c$

Table 2: Uncertainty Budget for NIST Wavelength Measurements

Mean Spacing of Profile Irregularities - RSm

| Standard Uncertainty Components $W = RSm$ | | | | | | | Measurement System Standard Uncertainty, $u(I)$ $=[(u^2(1)+...+u^2(7)]^{1/2}$ |
1	**2**	**3**	**4**	**5**	**6**	**7**	
$0.00020\,W$	$0.00015\,W$	$1.4\times10^{-5}\,W$	$1.6\times10^{-6}\,W$	$2.0\times10^{-5}\,W$	$7.9\times10^{-5}\,W$	$5.7\times10^{-5}\,W$	$0.00027\,W$

Combined Standard Uncertainty, $u_c = [(u^2(I) + s^2]^{1/2}$

Expanded Uncertainty, $U = 2u_c$

Table 3: Uncertainty Budgets for NIST Step Height Measurements

(X = measured step height value, H = NIST step height master)

H (µm)	Standard Uncertainty Components				Measurement System Standard Uncertainty, $u(I)$ $= [(u^2(1) + ... + u^2(4)]^{1/2}$
	1	**2**	**3**	**4**	
0.02937 [A]	0.021 X	0.0064 X	0.0018 X	0.0073 X	0.023 X
0.04481 [A]	0.0022 X	0.0008 X	0.0018 X	0.0037 X	0.0048 X
0.09065 [A]	0.0035 X	0.0030 X	0.0018 X	0.0024 X	0.0055 X
0.3024 [A]	0.00085 X	0.0015 X	0.0012 X	0.0041 X	0.0046 X
1.0157 [A]	0.0010 X	0.0015 X	0.0012 X	0.0012 X	0.0025 X
21.9999 mm Radius Ball [B]	$4.8 \times 10^{-6}\, X$	0.00099 X	0.00087 X	$6.1 \times 10^{-6}\, X$	0.0013 X

Combined Standard Uncertainty, $u_c = [(u^2(I) + s^2]^{1/2}$
**Expanded Uncertainty,** $U = 2u_c$

(A) Assumes that the Talystep* is being used.
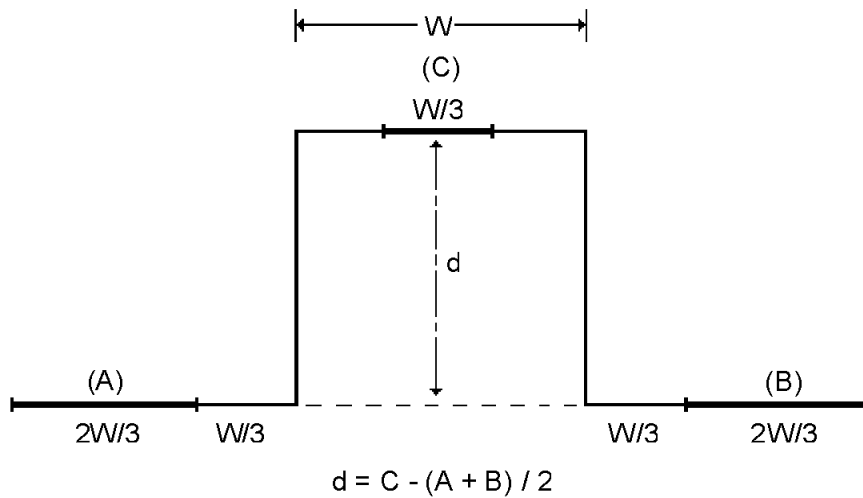(B) Assumes that the Form Talysurf PGI 1240 is being used.

* Certain commercial equipment, instruments, or materials are identified in this document. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products identified are necessarily the best available for the purpose.

Step Height Algorithm Diagrams

d = (d1 + d2) / 2
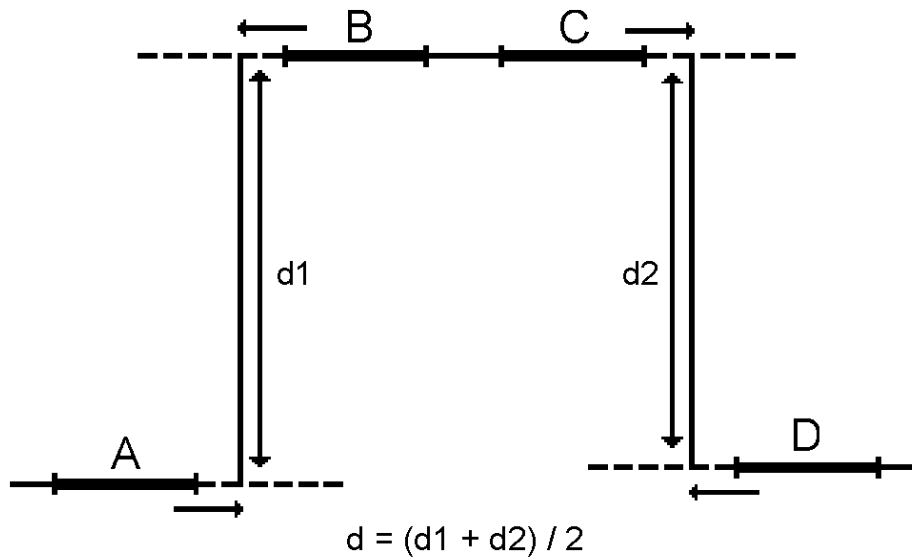
Fig. 1a: NIST algorithm for step height measurement.
The fitted straight lines, A, B, C, and D, are extrapolated to the step edges
to produce edge values d1 and d2, which are then averaged.

d = C - (A + B) / 2

Fig. 1b: ISO algorithm.