NIST SURFACE ROUGHNESS AND STEP HEIGHT CALIBRATIONS:
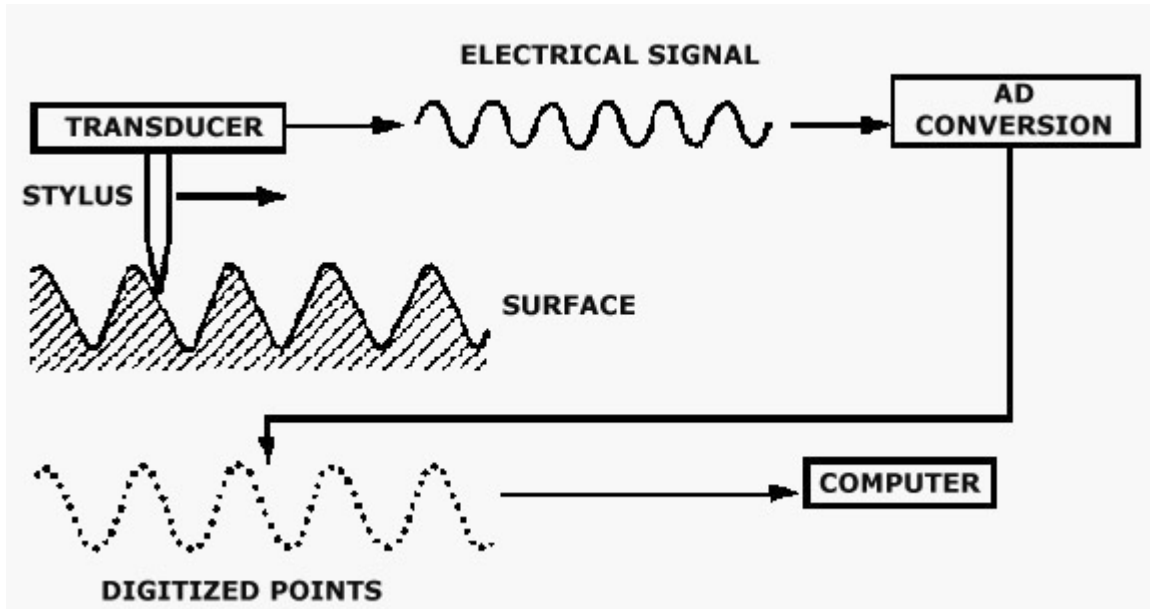## Measurement Conditions and Sources of Uncertainty
T.V. Vorburger, J.F. Song, T.B. Renegar, and A. Zheng
January 23, 2008

The property of surface roughness average *Ra* in the range 75 μm and below and step heights in the range 75 μm and below are currently measured at the NIST by means of a computerized/stylus instrument. We use either an interferometrically measured step or a calibration ball as a master to calibrate the instrument on each value of magnification employed during a measurement. Profiles of the calibrating master and the step or roughness sample under test are stored in a computer using up to a 16-bit analog to digital conversion, depending on the instrument used.

In measurement of roughness, surface profiles are taken with a lateral sampling interval of either 0.25 μm or 0.5 μm over an evaluation length of 4 mm. *Ra* values are then calculated as described in American National Standard ASME B46.1-2002.[1]

Two parameters of the instrumentation are important in the specification of roughness measurements. These are the stylus radius and the roughness (high- pass) filter long wavelength cutoff. The stylus for the Form Talysurf* instrument has a radius of (1.57 ± 0.15) μm, calibrated on 05/17/2007 by measuring a NIST standard wire with a calibrated radius. The stylus for the Federal Surfanalyzer* has a radius of (5 ± 1) μm as profiled by the razor blade trace method [2-4] and calculated by a procedure found in ASME B46.1-2002.[1] The nominal Gaussian filter long wavelength cutoff is 0.8 mm. The filter transmission characteristics are in accordance with the Gaussian filter described in ASME B46.1-2002.[1]

* 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.

The above measurement conditions of evaluation length, sampling interval, stylus radius, and Gaussian filtering are the customary conditions for our roughness measurements.

For step height measurements, one of several algorithms may be used. 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. 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 and the two results are averaged (Fig. 1a). Alternatively, the ISO algorithm, described in ISO Draft International Standard 5436-1 [2] may be used. If so, it is explicitly stated in the covering report. Our implementation of this algorithm is described in Fig. 1b.

Uncertainty of *Ra* Measurements:
The quoted expanded uncertainty U is equal to the combined standard uncertainty u_c times a coverage factor k (= 2). The combined standard uncertainty u_c is the quadratic sum of the system standard uncertainty $u(I)$ and the statistical variation of the measurements s. The statistical variation of the measurements is mainly derived from the nonuniformity 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. The system standard uncertainty $u(I)$ for *Ra* is the quadratic sum of six uncertainty components. These are derived from:

(1)   Geometrical nonuniformity and surface finish of the step-height or calibration ball master used to calibrate the instrument. This leads to an uncertainty in stylus measurements of the master to obtain the calibration constant(s) for the instrument.

(2)   Variations in the calibration constant(s) due to (a) noise in the stylus instrument transducer, (b) surface topography 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 average height of the step-height master or in the radius of the calibration ball as determined from interferometric and other measurements of those objects.

(5)   Uncertainty in the horizontal resolution of the instrument. This is most often due to uncertainty in the stylus radius.[3, 4] However, for very fine styli with good horizontal resolution, the resolution of the instrument itself may be limited instead by the frequency response of the electronics. Uncertainty in either quantity causes uncertainty in *Ra*. Quoted uncertainties here represent estimates of the difference obtained when a surface is traced with styli of different radii. Two different model surfaces were used to provide entries in Table 1.

(6)   Vertical resolution of the instrument. This component tends to increase the *Ra* value and depends on which instrument is being used. For one instrument in our laboratory, the vertical resolution is determined by the quantization limit of the analog-to-digital converter. For the other two instruments, the vertical resolution is determined by the instrument noise.

Table 1 shows the uncertainty budgets for *Ra* measurements, expressed in accordance with guidelines at NIST.[5] The entries are rounded to two significant digits except for component 6, which only requires one significant digit in some cases. The components depend on the choice of instrument and its magnification and hence on the choice of master used to calibrate the instrument. The six uncertainty components are shown in Table 1 as standard uncertainties. Components 1-3 are type A uncertainties.[5] That is, they are standard deviations calculated by statistical methods. Components 4-6 are type B uncertainties, which are evaluated by other means.[5] These uncertainty components are 1σ estimates calculated from models that estimate biases in the measured *Ra* values based on the identified uncertainty sources. The expressions used for each component depend on the master and the *Ra* value itself, and on whichever instrument in our laboratory is used for the measurement.

The six components are added quadratically to yield the formulas for calculation of the system standard uncertainty $u(I)$.

Uncertainty of Step Height Measurements:
As with *Ra* measurement, the quoted expanded uncertainty *U* for step height is equal to $2u_c$, and u_c is the quadratic sum of $u(I)$ and *s*. System standard uncertainty $u(I)$ for step height 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 of the measurement results *s* about the mean value. The formulas used to calculate the measurement uncertainty depend on the height of the measured step *X* and the height of the calibration step *H* or the radius of the calibration ball and are given in Table 2.

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.

References:
Additional information on the NIST surface measurement system is contained in the following references. References 3-4 and 6-8 may be obtained from us upon request.

[1]   ASME B46.1-2002, *Surface Texture* (American Society of Mechanical Engineers, New York, 2003).

[2]   ISO/DIS 5436-1, *Geometrical Product Specifications (GPS) – Surface Texture: Measurement Standards   Part 1: Material Measures* (International Organization for Standardization, Geneva, 2000).

[3]   T.V. Vorburger, E.C. Teague, F.E. Scire, and F.W. Rosberry, Measurements of Stylus Radii, *Wear* **57**, 39 (1979).

[4]   J.F. Song and T.V. Vorburger, Measurement Comparison of Stylus Radii, *Proceedings of 1997 International Conference on Precision Engineering (ICPE 97)*,   Taipei, 1997.

[5]   B.N. Taylor and C.E. Kuyatt, *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*,   NIST Technical Note 1297 (National Institute of Standards and Technology, Gaithersburg, MD, 1993).

[6]   T.V. Vorburger and J. Raja, *Surface Finish Metrology Tutorial*, NISTIR 89-4088 (National Institute of Standards and Technology, Gaithersburg, MD, 1990).

[7]   J.F. Song and T.V. Vorburger, Standard Reference Specimens in Quality Control of Engineering Surfaces, *J. Res. NIST* **96**, 271 (1991).

[8]   J.F. Song and T.V. Vorburger, Stylus Profiling At High Resolution and Low Force, *Applied Optics* **30**, 42 (1991).

Table 1: Uncertainty Budgets for NIST Roughness Measurements
(R = measured Ra value, H = NIST step height master)

H (µm)	**Standard Uncertainty Components**						**System Standard Uncertainty, $u(I)$** $= [(u^2(1) + ... + u^2(6)]^{1/2}$
	1	**2**	**3**	**4**	**5** (nm)	**6** (nm)	
0.02937 (A)	0.021 R	0.0064 R	0.0018 R	0.0073 R	0.13	0.08	$[(0.023\,R)^2+(0.15\text{ nm})^2]^{1/2}$
0.04481 (A)	0.0022 R	0.0008 R	0.0018 R	0.0037 R	0.13	0.08	$[(0.0048R)^2+(0.15\text{nm})^2]^{1/2}$
0.09065 (A)	0.0035 R	0.0030 R	0.0018 R	0.0024 R	0.13	0.08	$[(0.0055R)^2+(0.15\text{nm})^2]^{1/2}$
0.3024 (A)	0.00085 R	0.0015 R	0.0012 R	0.0041 R	3.5	0.08	$[(0.0046\,R)^2+(3.5\text{ nm})^2]^{1/2}$
	1 and 2 Combined						
1.0157 (B)	0.0054 R		0.0012 R	0.0012 R	3.5	4.4 (E)	$[(0.0057\,R)^2+(5.6\text{ nm})^2]^{1/2}$
3.0289 (B)	0.0054 R		0.0012 R	0.0064 R	3.5	4.4 (E)	$[(0.0085\,R)^2+(5.6\text{ nm})^2]^{1/2}$
9.9813 (B)	0.0054 R		0.0020 R	0.0026 R	3.5	4.4 (E)	$[(0.0063\,R)^2+(5.6\text{ nm})^2]^{1/2}$
12.668 (B)	0.0054 R		0.0020 R	0.0047 R	3.5	4.4 (E)	$[(0.0074\,R)^2+(5.6\text{ nm})^2]^{1/2}$
22.90 (B)	0.0054 R		0.0020 R	0.00087 R	3.5	4.4 (E)	$[(0.0058\,R)^2+(5.6\text{ nm})^2]^{1/2}$
152.37 (B)	0.0054 R		0.0020 R	0.00066 R	3.5	4.4 (E)	$[(0.0058\,R)^2+(5.6\text{ nm})^2]^{1/2}$
21.9999 mm Radius Ball (C)	$4.8\times10^{-6}\,R$	0.00099R	0.00087R	$6.1\times10^{-6}\,R$	3.5	2.6	$[(0.0013\,R)^2+(4.4\text{ nm})^2]^{1/2}$

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 Federal Surfanalyzer 2000 is being used
(C) Assumes that the Form Talysurf 120L is being used
(E) Given by the smooth surface Ra value measured on 16 May 03 for the SIM 4.8 comparison

Table 2: Uncertainty Budgets for NIST Step Height Measurements
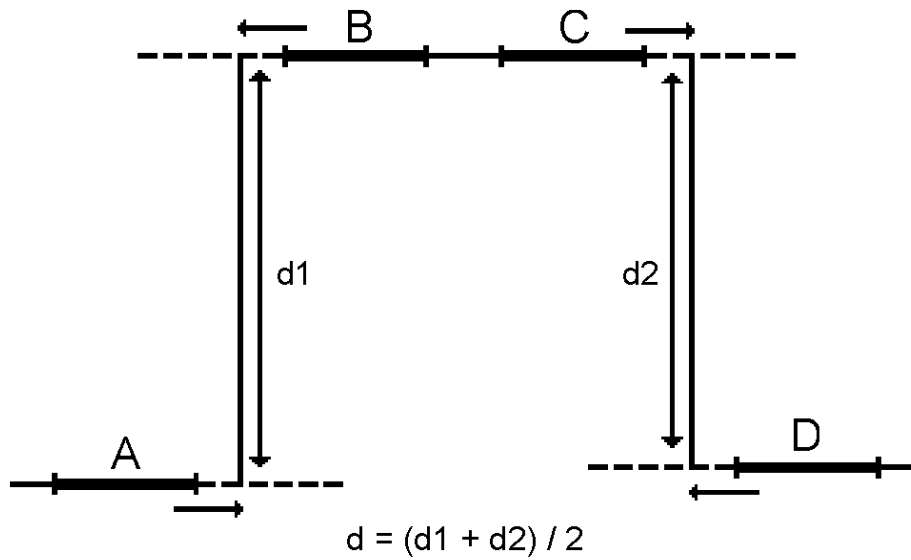(X = measured step height value, H = NIST step height master)

H (μm)	Standard Uncertainty Components 1	2	3	4	System Standard Uncertainty, $u(I)$ $= [(u^2(1) + ... + u^2(4)]^{1/2}$
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
9.9813 (B)	0.0014 X	0.0012 X	$[(0.0020\ X)^2+(8.7\ \text{nm})^2]^{1/2}$	0.0026 X	$[(0.0038\ X)^2+(8.7\ \text{nm})^2]^{1/2}$
22.90 (B)	0.0013 X	0.00079 X	$[(0.0020\ X)^2+(8.7\ \text{nm})^2]^{1/2}$	0.00087 X	$[(0.0027\ X)^2+(8.7\ \text{nm})^2]^{1/2}$
152.37 (B)	0.00073 X	0.00053 X	$[(0.0020\ X)^2+(8.7\ \text{nm})^2]^{1/2}$	0.00066 X	$[(0.0023\ X)^2+(8.7\ \text{nm})^2]^{1/2}$
21.9999 mm Radius Ball (C)	$4.8\times10^{-6}\ X$	0.00099 X	0.00087 X	$6.1\times10^{-6}\ X$	0.0013 X

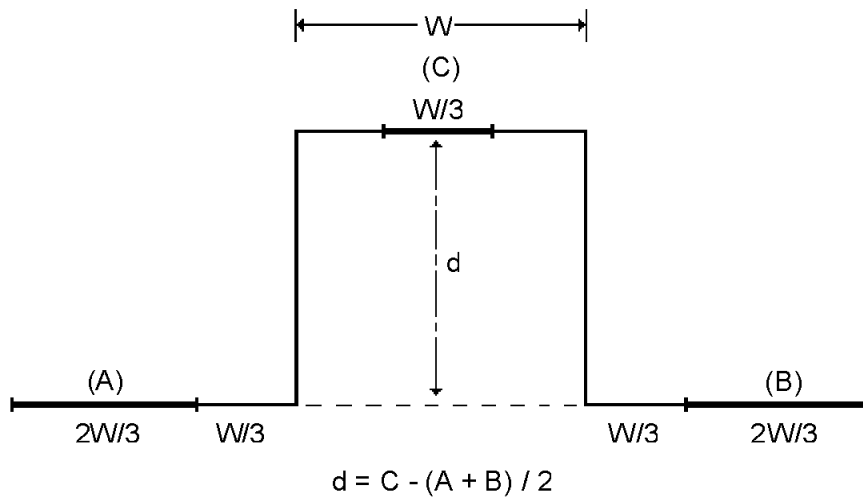**Combined Standard Uncertainty,** $u_{\mathrm{c}} = [(u^2(I) + s^2]^{1/2}$
Expanded Uncertainty, $U = 2u_{\mathrm{c}}$

(A) Assumes that the Talystep is being used.
(B) Assumes that the Federal Surfanalyzer 2000 is being used
(C) Assumes that the Form Talysurf 120L is being used

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.