Uncertainty analysis of roughness standard calibration using stylus instruments

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A stylus instrument was characterized and calibrated, including a dynamic calibration of the probe. This stylus instrument was used to calibrate ten roughness standards for six surface roughness parameters. The sensitivity of each parameter of each standard to such measurement conditions as stylus geometry, measurement force, cut-off wavelength, and so forth was determined experimentally. These results were used for an uncertainty evaluation of each parameter for each roughness standard. It is shown that the manufacturers’ specification for the stylus instrument (2% uncertainty in roughness parameters) is approximately correct for the most commonly used samples and parameters, but the uncertainty may range from 0.03% (for sinusoidal profiles) to 100% (for very fine surfaces), depending upon the standard and parameter to be calibrated. © 1998 Elsevier Science Inc.

Keywords: surface roughness; stylus instrument; uncertainty; dynamic calibration

Introduction
Surface measurement using a stylus instrument is the most widely used surface characterization technique. From a measured profile, roughness parameters can be derived for characterizing the surface. Surface measurements and parameters are standardized in ISO and national standards. In these standards, several measurement conditions are prescribed under which a roughness parameter is to be measured. These conditions include filter characteristics, stylus geometry, measuring force, and so forth. It has long been recognized that deviations in these conditions lead to significant deviations of the measured parameters.

A significant source of differences between measurements is the short-wavelength cut-off, which was not defined for a long time, so roughness measurements tended to scatter because of the probe geometry deviations and the resonance oscillations in the probe. Because of these effects, a rather high scattering of results is usually found in intercomparisons; e.g., in an intercomparison among 28 laboratories in Europe held between 1988 and 1992. The results for commonly used parameters scattered usually in the 2–5% region with a few outliers of over 10%. Since that time, new written standards have appeared that intend to overcome some of these problems by defining phase-correct filters including a bandwidth. The latter standard is included in the standard that describes how to determine surface roughness parameters using a stylus instrument.

This paper describes how a stylus instrument can be calibrated with respect to all properties that affect the uncertainty of a roughness measurement. With an instrument calibrated in this way,
the sensitivity of six roughness parameters to all influencing factors is analyzed for ten characteristic roughness standards and an uncertainty budget is made for each parameter of each standard.

**Calibration of a stylus instrument**

A Rank-Taylor-Hobson (RTH) type Form Talysurf Series (FTS) 120L stylus instrument was used for nearly all measurements. For a further evaluation than the software of the instrument permits, additional software was developed to enable averaging/subtraction of profiles and digital filtering for any bandwidth. Some crosstests have been made using a Perthen-type C5D with a homemade digitizing/evaluation system. Some of the used calibration methods are especially appropriate for the FTS instrument. For instruments using a skid or if the operator has no direct access to the measured profile, not all of the methods used can be applied.

**X-axis calibration**

Calibration of the horizontal axis is important for a proper definition of the cut-off wavelength, the sampling length, and for the calculation of such spacing parameters as \( S_m \) and such hybrid parameters as \( \Delta_x \). The most convenient method proved to be the measurement of a graduated rule: the lines appear as small peaks in a profile measurement. In our case, the deviations were within \( \pm 1 \mu m \) for distances up to 20 mm. Assuming a rectangular-shaped uncertainty distribution, this means that the standard uncertainty in the \( X \)-axis value can be stated as \( 1 \mu m / 3^{1/2} \approx 0.6 \mu m \).

Because the FTS has its own internal \( X \)-scale, a constant traversing speed is not essential for its operation. However, for dynamic calibration purposes, it is significant because we want to calibrate the \( X \)-axis using time-based displacements that correspond to spatial wavelengths. The average traversing speed was measured using an HP 5527A laser interferometer and proved to be 489 \( \mu m / s \) with variations characterized by a standard deviation of 20 \( \mu m / s \). This is sufficiently constant to enable the simulation of defined surface sine waves using a time-based piezo oscillation (see below). For an instrument using a time-based \( X \)-scale, a correct and constant speed is essential to enable a proper definition of cut-off lengths, as well as is the correctness of the horizontal and hybrid roughness parameters.

**Z-axis calibration**

Because the FTS instrument uses an internal laser interferometer for measuring the vertical (\( z \)) displacement, the standard probe has a measurement range of 6 mm with a resolution of 0.01 \( \mu m \). In addition to this, we made a probe with a smaller measuring range (2 mm) and a corresponding smaller resolution (3 nm).

The instrument calibration procedure consists of using a sphere standard with a known radius, after which the instrument calculates a polynomial correction for the arcuate movement of the probe. We used this procedure as a base by which various checks were made on other traceable standards: we used a 500-\( \mu m \) gauge block.wrung on a baseplate and a pair of gauge blocks with a length difference of 10 \( \mu m \). These standards were calibrated using standard gauge block interferometry. The deviations measured by the FTS are of the order of 0.05 \( \mu m \) for the 500-\( \mu m \) gauge block and 0.01 \( \mu m \) for the 10-\( \mu m \) gauge block step. A significant deviation from linearity larger than \( 1 \times 10^{-4} \) could not be detected.

A check that better represents the movements that a probe makes during a measurement, is made by using a Queensgate digital piezo translator (DPT)-type DPT-C-S. The calibration and use of this system is described elsewhere.4,5 The DPT moves a gauge block of which the displacement is simultaneously measured using an HP 5527A laser interferometer. The setup is schematically depicted in Figure 1. Because two laser-beams are positioned symmetrically around the probe, the setup fulfills the Abbe principle, apart from a small offset attributable to the probe movement. The laser interferometer measures the displacement with a resolution of 5 nm, a maximum sampling frequency of 33 kHz, and a relative accuracy of better than \( 1 \times 10^{-6} \).

For the linearity check, a sinusoidal signal was fed to the DPT with a frequency of 6.1 Hz (corresponding to a surface wavelength of 80 \( \mu m \)), which was measured by the laser interferometer with the same frequency as the sampling interval of the FTS (0.25 \( \mu m \), corresponding to 1956 Hz). The amplitude was varied between 10 nm and 7 \( \mu m \). A comparison was made between the unfiltered parameter \( P_q \), which is the standard deviation from the mean line, and the standard deviation that is directly calculated in the laser interferometer software. It proved that all deviations were within 2 nm \( \pm \) 0.1 %. Assuming that these deviations can be characterized by a rectangular-shaped distribu-
tion, this means that a standard uncertainty of 1.2 nm + 0.06% can be used in further uncertainty evaluations.

**Straightness datum**

The effect of the quality of the straightness datum on a roughness measurement was checked using an optical flat with an $R_a$ value of about 0.01 $\mu$m. The optical flat was traced several times at the same position. By subtracting two profiles point-by-point, these measurements enable an estimation of the noise in each individual measurement. It proved that this noise can be characterized by a standard deviation $R_q$ of 2 nm and a maximum deviation $R_z$ of 20 nm under common filtering conditions. To achieve this, the measuring unit must be directly mechanically connected to the base where the roughness standard is positioned, in addition to its attachment to a vertical positioning column, in order to shorten the rather large mechanical loop in the instrument. Without this support, the noise doubles.

To investigate the surface roughness of the datum itself, an optical flat was probed at many, randomly distributed, positions, while using exactly the same part of the datum each time. By averaging these measurements point-by-point, the noise as well as the influence of the surface roughness of the optical flat are reduced by averaging, and the datum roughness remains. From the average of 10 measurements, the roughness of the datum proved to be about 3 nm $R_q$ or 8 nm $R_z$ for common filter conditions.

**Filter definition and dynamic probe behavior**

The setup sketched in Figure 1 has also been used to check the filtering and the dynamic behavior of the probe by varying the frequency of the sine signal simulated surface waves with an amplitude of 0.3 $\mu$m and wavelengths between 0.3 $\mu$m and 4 mm. The measured signals have been used unfiltered and filtered with the instrument’s software with short-wavelength cut-offs $\lambda_s$ of 1.25, 2.5, and 8 $\mu$m and long-wavelength cut-offs $\lambda_c$ of 0.08, 0.25, and 0.8 mm. The roughness parameter $R_q$ measured by the FTS was compared to the standard deviation measured by the laser interferometer system. The unfiltered data provide information about the probe behavior itself: ideally the z-displacement should be independent of the surface wavelength. From the filtered data, it can be determined whether the system (probe + software) behaves in accordance with the defined filter characteristics. A graph of the results is given in Figure 2. The graph shows that the nominal filter characteristics are followed very well for the long-wavelength cut-offs and fairly well for the short-wavelength cut-offs. The unfiltered data show a flat response for wavelengths $>4$ $\mu$m. For shorter-wavelengths, deviations occur that become rather dramatic for wavelengths $<1$ $\mu$m. This transfer function is depicted for three probes with different mass and static measuring force in Figure 3. The resonance peak, which is to be expected in any stylus pick-up system, can clearly be observed and is somewhat dependent upon the probe mass and the static measuring force. The figure also shows that the resonance effects are not com-

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**Figure 1** Setup of dynamic probe calibration system; the gauge block represents a flat surface, the movement of which is measured simultaneously by the laser interferometer and the stylus instrument.
pletely removed by filtering. The “unfiltered” profile is rather unreliable for very fine surfaces and is, in fact, better approximated by the measured profile filtered with $\lambda_c = 1.25 \mu m$. The resonance effect will be most significant if the probe makes sudden “drops” such as with a rectangular-shaped sample. In normal “rough” profiles, the resonance effect is also diminished by the probe radius, which also acts as a low-pass wavelength filter. Note that a correction method has been recently proposed for oscillation effects, based on a probe model from which a filter is designed that is the inverse of the response function. The measurement method presented here enables a direct and accurate determination of the parameters used in this model (gain, effective mass, spring constant). For the purpose of this paper, it is sufficient to note that because of probe resonance effects the short-wavelength cut-off is not well defined.

Another subject of concern is the “stylus flight” effect: the stylus might fly over the surface when the stylus cannot follow very rapid profile slope changes. Experiments showed that this effect occurs in our FTS instrument for a stylus speed of 0.48 mm/s and a static stylus force of 1.0 mN, for amplitudes larger than 1.3 $\mu m$ at a surface wavelength of 5 $\mu m$. At a surface wavelength of 50 $\mu m$, the maximum amplitude will be 130 $\mu m$, so this will not be a problem for normal surfaces.

**Stylus geometry**

The stylus geometry was determined by measuring the tip of an uncoated razor blade. Earlier inves-
tigations have indicated that this is an effective and reliable method where the effective razor blade tip radius is smaller than 0.1 \( \mu m \).\(^9\) The four styli with nominal radii of 2 \( \mu m \) proved to have effective radii of 1.6, 2.1, 2.5, and 3.0 \( \mu m \), respectively; the nominal 5- \( \mu m \) stylus proved to have an effective radius of 5.1 \( \mu m \). The uncertainty in these determinations is about 0.3 \( \mu m \). The stylus angles of nominal 60 and 90° deviate less than 2° from their nominal value. The standards\(^3\) prescribe a 2- \( \mu m \) radius for most cases and a stylus angle of 60°.

**Measuring force**

The static measuring force was measured by probing a balance. The force of all styli proved to be about 1.0 mN; somewhat more than the 0.75 mN prescribed in the standard.\(^3\) The dynamic force that is superimposed on the static force during a measurement can be estimated to be much less than the static force, because we found no evidence of stylus flight, which will occur when the dynamic force becomes −1 mN, when the traversing speed was quadrupled. Another indication for the absence of this effect is that no significant change in the parameters was noticed when the traverse direction of the probe was reversed (The sample was probed in the reverse direction). This was checked in all cases.

**Selected standards and parameters**

Once the stylus instrument is calibrated for the above-mentioned aspects, one must estimate or measure the influence of the deviation (known or unknown) from the standardized measurement conditions. This has been investigated experimentally.

Ten different roughness standards have been selected that can act as roughness standards for the calibration of other stylus instruments and for which calibration is necessary. According to the ISO 5436\(^10\) classification these are:

1. type C1: a sinusoidal standard (Rubert type 6);
2. type C2: a triangular-shaped standard (Rubert type 8);
3. type C3: approximate sine wave (RTH type 112/557); and
4. type D: unidirectional irregular profile that repeats of each 5 cut-off lengths.

An example of a type C3 standard, the RTH standard, is taken with a trapezium-form profile, which is also given as an example in the standard. The type D standards best represent a roughness measurement of a workpiece, but they are manufactured to give uniform parameter values, independent of the profile starting point. The most common form is mostly referred to as PTB standard, because it has been developed there by Häsing,\(^11\) but it is now manufactured by Halle. Some similar standards, which have smaller roughness values, were developed by Song\(^12\) at CIMM (Beijing). These standards are reproduced by an electroforming process by Rubert.\(^13\)

The parameters investigated are\(^14\): \( R_a \), \( R_q \), \( R_s \), and \( R_z \) as amplitude parameters, \( S_m \) as a spacing parameter, and \( \Delta_q \) as a hybrid parameter. It has been proved that \( R_a \) and \( R_q \) and also \( R_s \) and \( R_z \) have a closely identical behavior, so \( R_q \) and \( R_s \) are

<table>
<thead>
<tr>
<th>ISO 5436 type</th>
<th>Ident</th>
<th>( \lambda_r )/( \mu m )</th>
<th>( \lambda_r )/( \mu m )</th>
<th>( R_a )/( \mu m )</th>
<th>( R_q )/( \mu m )</th>
<th>( S_m )/( \mu m )</th>
<th>( \Delta_q )/°</th>
<th>( R_a )/( \mu m )</th>
<th>( R_q )/( \mu m )</th>
<th>( S_m )/( \mu m )</th>
<th>( \Delta_q )/%</th>
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</thead>
<tbody>
<tr>
<td>C1</td>
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<td>2.5</td>
<td>0.8</td>
<td>2.9</td>
<td>9.2</td>
<td>100</td>
<td>12</td>
<td>0.14</td>
<td>0.3</td>
<td>0.01</td>
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<td>0.8</td>
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<td>15</td>
<td>11</td>
<td>1.7</td>
<td>1.3</td>
<td>1.3</td>
<td>1.8</td>
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<tr>
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<td>0.02</td>
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<td>11</td>
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<td>2</td>
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<td>5</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
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<td>0.08</td>
<td>1.0</td>
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<td>6</td>
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<td>3</td>
<td>5</td>
<td>2.3</td>
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<tr>
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<td>Rubert 4</td>
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<td>0.25</td>
<td>0.12</td>
<td>0.8</td>
<td>8</td>
<td>7</td>
<td>2</td>
<td>2.5</td>
<td>4</td>
<td>1.4</td>
</tr>
<tr>
<td>D</td>
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<td>0.8</td>
<td>0.15</td>
<td>1.3</td>
<td>16</td>
<td>4</td>
<td>0.4</td>
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<td>1.0</td>
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<td>0.8</td>
<td>0.6</td>
<td>3.3</td>
<td>81</td>
<td>5</td>
<td>2.5</td>
<td>2.1</td>
<td>6</td>
<td>2.4</td>
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<tr>
<td>D</td>
<td>Halle 3</td>
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<td>0.8</td>
<td>1.5</td>
<td>8.0</td>
<td>124</td>
<td>6</td>
<td>0.2</td>
<td>1.1</td>
<td>6</td>
<td>0.7</td>
</tr>
</tbody>
</table>
not further mentioned, but the results for \( R_a \) and \( R_z \) are also valid for \( R_q \) and \( R_y \), respectively.

The standards used, their approximate parameter values, and their measured homogeneity are summarized in Table 1. The exact standard measurement conditions for which the conventional true parameter values are assumed to be obtained are mentioned in the table; such conditions, which apply for all measurement are the following. The profile length is six cut-off lengths; the profile is leveled according to the least-squares line; after filtering a half cut-off length is neglected at two ends of the profile. The evaluation length \( L \) is equal to five cut-off lengths, the filter has a Gaussian characteristic, the measuring force is 0.75 mN, the stylus radius is 2 \( \mu m \), and the stylus cone angle is 90°. The sample interval is small enough to have no influence.

As a measure for the (in)homogeneity we take the standard deviation of 18 measurements at randomly taken positions within the measurement area. This value is a combination of the instrument’s repeatability and the nonuniformity of the standard, but, in all cases, the repeatability proved to be negligibly small. The \( \lambda_c/\lambda_s \) ratio as it is described in the standard\(^3\) could not be met by the Form Talysurf software for the Rubert type D number 1 standard: at a cut-off wavelength \( \lambda_c = 0.08 \) mm, \( \lambda_s \) is taken as 1.25 \( \mu m \) instead of 2.5 \( \mu m \), as described in the standard.

### Sensitivity of roughness parameters to measurement conditions

The measurement conditions have been varied, partly on the same measured profile (evaluation length, cut-off wavelengths, filter type), partly on the same measured trace (force, sampling frequency, repeatability), and partly on the average of the 18 measurements on one sample (tip radius, cone angle). The aim was to have variations small enough for estimation of a partial derivative but large enough to generate a measurable effect; because of experimental limitations, this could not always be achieved satisfactorily. The sensitivities are expressed as relative numbers \( x \) which mean: a \( q \% \) change in the measurement condition will lead to an \( x \cdot q \% \) change in the measured parameter (%). For example, for \( r_{tip} \), \( x = 0.1 \): a probe radius of 2.2 \( \mu m \) instead of 2 \( \mu m \) \( (q = 10) \), gives a 0.1 \( \times 10 = 1 \% \) change of the given parameter on the given sample.

The evaluation length \( L \) was varied by excluding 1\% of the profile for a filtered profile and recalculating the parameters. The shorter-wavelength cut-off \( \lambda_c \) and the long-wavelength cut-off \( \lambda_s \) have been varied 10\% around their nominal values, while keeping the evaluation length constant. As a separate item, the difference between the long-wavelength Gaussian filter characteristics and the simulated analog 2RC-characteristics have been evaluated. The static measuring force of 1 mN was varied by adding a weight to the probe to double the force to 2 mN.

The sample interval was varied between 0.25 and 1 \( \mu m \). At the latter density, the lateral speed of the probe quadruples. So, simultaneously the oscillation wavelength becomes 2.4 instead of 0.6 \( \mu m \) and will be transmitted by the low-wavelength filters. This proved to have effect on the two smoothest Rubert samples. For this reason, these have also been tested on the Perthen system for which the sample interval could be varied at a constant lateral probe velocity. From measurements taken on the Perthen system, it proved that the dependence of parameters on the sample interval goes rapidly to zero for sampling intervals

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Sensitivity of ( R_a ) to measurement conditions</th>
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</thead>
<tbody>
<tr>
<td>SO 5436</td>
<td>2RC—Gaussian ( \lambda_c/% ), Sampling deviation/%</td>
</tr>
<tr>
<td>type</td>
<td>Idnet</td>
</tr>
<tr>
<td>C1</td>
<td>Rubert 6</td>
</tr>
<tr>
<td>C2</td>
<td>Rubert 8</td>
</tr>
<tr>
<td>C3</td>
<td>RTH</td>
</tr>
<tr>
<td>D</td>
<td>Rubert 1</td>
</tr>
<tr>
<td>D</td>
<td>Rubert 2</td>
</tr>
<tr>
<td>D</td>
<td>Rubert 3</td>
</tr>
<tr>
<td>D</td>
<td>Rubert 4</td>
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<td>Halle 1</td>
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<td>D</td>
<td>Halle 2</td>
</tr>
<tr>
<td>D</td>
<td>Halle 3</td>
</tr>
</tbody>
</table>
smaller than the cut-off length. To estimate the deviation that a sampling length of 0.25 m gives, compare it with a “zero” sampling length; to approximate the measured “rapidly going to zero,” it is assumed that the parameter values depend quadratically on the sampling density. So the deviation caused by the departure of the 0.25 m sampling length from “zero” is taken as 1/16 of the difference between the parameters obtained at 0.25 and 1 m sampling lengths. Because of the changing lateral speed to obtain a different sample interval, some dynamic force effects and stylus flight are also implicitly included in the measurements on the sampling density and measurement force. The tip radius and the cone angle were varied by using probes with different styli.

Results of these tests are shown in Tables 2–5. Although the values given should be considered as estimates, they give a good insight into both high sensitivities (e.g., $\Delta_q$ to $\lambda$) and low sensitivities (e.g., $\Delta_q$ to $\lambda$) with a quantitative estimate. For example: consider the sensitivity of the $Ra$ value of the Rubert 1 sample to the low-wavelength cut-off $\lambda$. The 0.40 in Table 2 means if $\lambda$ has a standard uncertainty of 20%, the uncertainty in $Ra$ will be $0.40 \cdot 20\% = 8\%$. This relation will hold only in the vicinity of the nominal value.

**Filter type effects**

The filter type (2RC or Gaussian) has been added as a check whether the filter type has a negligible effect, as stated in annex A to ISO 3274: “Differences between instruments using 2RC filters and instruments using Gaussian filters measuring $Ra$ and $Rz$ are normally negligible”. According to our results, this is not at all the case; the differences range up to 9%. For trapezium or rectangular formed standards like the RTH specimens, strong effects on the $Rz$ can be anticipated, but Table 2 also shows strong effects on the $Ra$ of the Halle

### Table 3  Sensitivity of $R_s$ to measurement conditions

<table>
<thead>
<tr>
<th>ISO 5436 type</th>
<th>Ident</th>
<th>2RC—Gaussian $\lambda$/%</th>
<th>Sampling deviation/%</th>
<th>Change in $R_s$/change in parameter (%/%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\lambda$ /%</td>
<td></td>
<td>$\lambda_s$ $\lambda_c$ $F$ $r_{tip}$ $\phi_{tip}$ $L$</td>
</tr>
<tr>
<td>C1</td>
<td>Rubert 6</td>
<td>0.3</td>
<td>0.012</td>
<td>0.003 0.02 0.00008 0.0004 0.0007 0.10</td>
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<td>C2</td>
<td>Rubert 8</td>
<td>1.2</td>
<td>0.19</td>
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<td>Rubert 1</td>
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<td>0.18</td>
<td>0.041 0.008 0.0014 0.007 0.0009 0.15</td>
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<td>D</td>
<td>Rubert 2</td>
<td>5.4</td>
<td>0.50</td>
<td>0.40 0.002 0.03 0.06 0.04 0.10</td>
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<tr>
<td>D</td>
<td>Rubert 3</td>
<td>0.3</td>
<td>1.2</td>
<td>0.19 0.004 0.005 0.11 0.003 0.02</td>
</tr>
<tr>
<td>D</td>
<td>Rubert 4</td>
<td>3.8</td>
<td>0.4</td>
<td>0.15 0.004 0.026 0.11 0.009 0.02</td>
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<td>D</td>
<td>Halle 1</td>
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<td>0.2</td>
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<td>Halle 2</td>
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<td>0.12</td>
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<tr>
<td>D</td>
<td>Halle 3</td>
<td>4.7</td>
<td>0.09</td>
<td>0.011 0.08 0.00007 0.006 0.01 0.07</td>
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### Table 4  Sensitivity of $Sm$ to measurement conditions

<table>
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<tr>
<th>ISO 5436 type</th>
<th>Ident</th>
<th>2RC—Gaussian $\lambda$/%</th>
<th>Sampling deviation/%</th>
<th>Change in $Sm$/change in parameter (%/%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\lambda$ /%</td>
<td></td>
<td>$\lambda_s$ $\lambda_c$ $F$ $r_{tip}$ $\phi_{tip}$ $L$</td>
</tr>
<tr>
<td>C1</td>
<td>Rubert 6</td>
<td>0.007</td>
<td>0.0007</td>
<td>0.00006 0.00003 0.00001 0.00011 0.0003 0</td>
</tr>
<tr>
<td>C2</td>
<td>Rubert 8</td>
<td>0.007</td>
<td>0.0009</td>
<td>0.00007 0.0001 0.0001 0.0010 0.0005 0.02</td>
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<tr>
<td>C3</td>
<td>RTH</td>
<td>0.06</td>
<td>0.002</td>
<td>0.00002 0.00004 0.00005 0.004 0.010 0.0005</td>
</tr>
<tr>
<td>D</td>
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<td>0.13</td>
<td>2</td>
<td>1.1 0.11 0.10 0.11 0.15 0.17</td>
</tr>
<tr>
<td>D</td>
<td>Rubert 2</td>
<td>9.8</td>
<td>2</td>
<td>0.6 0.018 0.04 0.04 0.08 0.7</td>
</tr>
<tr>
<td>D</td>
<td>Rubert 3</td>
<td>1.9</td>
<td>1.2</td>
<td>0.3 0.001 0.010 0.11 0.03 0.2</td>
</tr>
<tr>
<td>D</td>
<td>Rubert 4</td>
<td>3.4</td>
<td>1.4</td>
<td>0.5 0.04 0.014 0.09 0.003 0.6</td>
</tr>
<tr>
<td>D</td>
<td>Halle 1</td>
<td>5.7</td>
<td>0.5</td>
<td>0.4 0.04 0.03 0.03 0.02 1</td>
</tr>
<tr>
<td>D</td>
<td>Halle 2</td>
<td>15</td>
<td>0.5</td>
<td>0.3 0.3 0.02 0.05 0.004 1</td>
</tr>
<tr>
<td>D</td>
<td>Halle 3</td>
<td>19</td>
<td>2</td>
<td>0.11 0.2 0.03 0.10 0.14 1</td>
</tr>
</tbody>
</table>
standards. This must be attributed to a considerable content of spatial wavelengths about and below the cut-off wavelength in the sample.

This effect must be counted as an additional uncertainty contribution when calibrating instruments based on (analog) 2RC filters using standards that are calibrated using the Gaussian filter. Also, when carrying out measurements with 2RC-based instruments, the deviation of the measured parameters from those as defined in ISO 32743 can be considerable.

Uncertainty in measured parameters

In the preceding sections, it is shown how all the information needed for an uncertainty evaluation according to the ISO guide\textsuperscript{15} has been obtained. To evaluate the uncertainty in measured parameters, the following standard uncertainties, based upon one standard deviation, have been assumed:

a. calibration of \( x \)-axis: 0.6 \( \mu \)m;
b. calibration of \( z \)-axis: 1.2 nm + 0.06%;
c. repeatability: as measured;
d. noise/roughness of datum: combines with measured value (except for \( S_m \));
e. short-wavelength cut-off \( \lambda_s \) : 40\% for 1.25 \( \mu \)m, 20\% for 2.5 \( \mu \)m;
f. long-wavelength cut-off \( \lambda_c \) : 2\%;
g. static measuring force \( F \) : 20\%;
h. stylus tip radius \( r_{tip} \) : 30\%;
i. stylus tip angle \( \phi_{tip} \) : 3\%;
j. sampling: assumed deviation from 0; and
k. sample homogeneity: as measured.

Table 5  Sensitivity of \( \Delta_i \) to measurement conditions

<table>
<thead>
<tr>
<th>ISO 5436 type</th>
<th>Ident</th>
<th>2RC—Gaussian ( \lambda_c/% )</th>
<th>Sampling deviation/%</th>
<th>Change in ( \Delta_i )/Change in parameter (%/%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( \lambda_s )</td>
<td>( \lambda_c )</td>
<td>( F )</td>
</tr>
<tr>
<td>C1 Rubert 6</td>
<td>0.6</td>
<td>0.22</td>
<td></td>
<td>0.05</td>
</tr>
<tr>
<td>C2 Rubert 8</td>
<td>0.3</td>
<td>0.4</td>
<td></td>
<td>0.04</td>
</tr>
<tr>
<td>C3 RTH</td>
<td>0.3</td>
<td>0.18</td>
<td></td>
<td>0.04</td>
</tr>
<tr>
<td>D Rubert 1</td>
<td>0.04</td>
<td>2</td>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>D Rubert 2</td>
<td>0.09</td>
<td>2.7</td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td>D Rubert 3</td>
<td>0.05</td>
<td>1.6</td>
<td></td>
<td>0.6</td>
</tr>
<tr>
<td>D Rubert 4</td>
<td>0.04</td>
<td>1.8</td>
<td></td>
<td>0.6</td>
</tr>
<tr>
<td>D Halle 1</td>
<td>0.05</td>
<td>0.8</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>D Halle 2</td>
<td>0.9</td>
<td>0.7</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>D Halle 3</td>
<td>0.3</td>
<td>1.1</td>
<td></td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 6  Uncertainty calculation of \( R_s \) for sample Halle 1

<table>
<thead>
<tr>
<th>Influencing factor</th>
<th>Magnitude</th>
<th>Sensitivity %/%</th>
<th>Effect on ( R_s )/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. ( x )-axis calibration (( L ))</td>
<td>0.6 ( \mu )m</td>
<td>0.5</td>
<td>0.0008</td>
</tr>
<tr>
<td>b. ( z )-axis calibration</td>
<td>1.3 nm</td>
<td>1</td>
<td>0.9</td>
</tr>
<tr>
<td>c. repeatability</td>
<td>0.2 nm</td>
<td>1</td>
<td>0.14</td>
</tr>
<tr>
<td>d. datum/noise</td>
<td>0.003 ( \mu )m</td>
<td>—</td>
<td>0.02</td>
</tr>
<tr>
<td>e. ( \lambda_s )</td>
<td>20%</td>
<td>0.04</td>
<td>0.8</td>
</tr>
<tr>
<td>f. ( \lambda_c )</td>
<td>2%</td>
<td>0.08</td>
<td>0.16</td>
</tr>
<tr>
<td>g. ( F )</td>
<td>20%</td>
<td>0.004</td>
<td>0.08</td>
</tr>
<tr>
<td>h. ( r_{tip} )</td>
<td>30%</td>
<td>0.02</td>
<td>0.6</td>
</tr>
<tr>
<td>i. ( \phi_{tip} )</td>
<td>3%</td>
<td>0.006</td>
<td>0.018</td>
</tr>
<tr>
<td>j. sampling</td>
<td>0.08%</td>
<td>1</td>
<td>0.08</td>
</tr>
<tr>
<td>Measurement capability (quadratic sum, 1s)</td>
<td></td>
<td></td>
<td>1.35</td>
</tr>
<tr>
<td>k. sample homogeneity</td>
<td>0.4%</td>
<td>1/( \sqrt{18} )</td>
<td>0.09</td>
</tr>
<tr>
<td>Calibration result, 2s</td>
<td></td>
<td></td>
<td>2.7</td>
</tr>
</tbody>
</table>

Note: The datum roughness is considered to combine with the roughness of the surface to a measured \( R_s \) value that is the quadratic sum of the surface and the datum. For this case, the expected deviation is 0.03 nm, which corresponds to 0.02\% in \( R_s \). Because this effect is not linear with the datum roughness, no sensitivity factor is given.
For example, the uncertainty budget of $R_a$ of the Halle 1 sample is given in Table 6, which shows that the uncertainty, based on 2σ, in the calibration result (the average $R_a$ value of the standard) is 2.7%. The results of all uncertainty calculations, carried out in a way analogous to Table 6, are presented in Table 7. This table shows that the uncertainty of measured parameters may vary between 0.03 and 100%, depending upon the sample and the parameter. In general, the most critical measurement conditions are those that refer to the low-wavelength side of the power spectrum; i.e., the short-wavelength cut-off and the stylus tip radius. For these (steel) standards, the roughness parameters are rather insensitive to the measuring force and the stylus cone angle when these conditions are close to nominal conditions.

For the most common cases; i.e., parameter $R_a$, standard type C3, or Halle, the uncertainty can be expressed as $u(2\sigma) = 2 \text{ nm} + 2\%$ of the measured value. This is somewhat better than usually quoted (3–10%), but it is of the same order of magnitude. When other parameters or sinusoidal samples are considered, the uncertainty may be very different.

### Discussion

Considering the uncertainties in the parameters obtained, it may seem that a sinusoidal sample, type C1, with a surface wavelength in the center of the instrument’s bandwidth is preferable for calibrating purposes. From the view of the uncertainty in this standard, this may be true, on the other hand, a sinusoidal sample of this kind will give little information on the performance of a stylus instrument, because it is insensitive to many measurement conditions. For this reason, its use is limited to the $z$-axis calibration, comparable to the application of ISO 5436 type A standards. It has an advantage over these standards of easier use, some software check, and the possibility of an $x$-axis calibration. These standards can also be designed to check cut-off wavelengths; in fact the probe-calibration set-up, as it depicted in Figure 1 and as it is used in this paper, replaces some 40 type C1 standards that cannot all be physically realized. The type C2 standard is designed to be sensitive for the stylus tip, but it is not more sensitive than some of the type D standards. The type D standards, although they cannot be so accurately calibrated, should be preferred for overall calibration of stylus instruments, because they are sensitive to many influencing factors.

For the near future it will still be a problem that many instruments on shop floors are based on 2RC filter characteristics. As shown in this paper, the filter characteristics can have a considerable influence on a measurement result. This problem will be hidden as long as type C1 or C3 standards are used for checking/adjusting these instruments and will only appear in intercomparisons when irregular-shaped samples are used.

For finer surfaces (Rubert), the main factors determining the uncertainty are the short-wavelength cut-off, the stylus radius, and the sample interval. These factors are related to the shorter-wavelength side of the bandwidth of the measured surface undulation. For this reason, it is no surprise that widely scattering results were found in intercomparisons in the past when no short-wavelength cut-off was defined. The Rubert type D #1 standard is at the edge of what can be measured usefuly using our stylus instruments and probably many others; for this and even finer surfaces, a

<table>
<thead>
<tr>
<th>ISO 5436 type</th>
<th>Measured parameter values</th>
<th>Uncertainty (2σ)/%; main factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 Rubert 6</td>
<td>$R_a/\mu m$</td>
<td>2.927</td>
</tr>
<tr>
<td>C2 Rubert 8</td>
<td>0.410</td>
<td>1.66</td>
</tr>
<tr>
<td>C3 Rubert</td>
<td>0.795</td>
<td>2.14</td>
</tr>
<tr>
<td>D Rubert 1</td>
<td>0.015</td>
<td>0.136</td>
</tr>
<tr>
<td>D Rubert 2</td>
<td>0.033</td>
<td>0.21</td>
</tr>
<tr>
<td>D Rubert 3</td>
<td>0.077</td>
<td>0.77</td>
</tr>
<tr>
<td>D Rubert 4</td>
<td>0.115</td>
<td>0.84</td>
</tr>
<tr>
<td>D Halle 1</td>
<td>0.144</td>
<td>1.28</td>
</tr>
<tr>
<td>D Halle 2</td>
<td>0.594</td>
<td>3.33</td>
</tr>
<tr>
<td>D Halle 3</td>
<td>1.453</td>
<td>8.00</td>
</tr>
</tbody>
</table>

The major uncertainty contribution, as listed in the text and given in Table 6, is indicated with the uncertainty in the right four columns.
stylus tip radius of 2 µm is probably too large, and other instruments are preferred, such as a Talystep or scanning probe (STM/AFM) instruments.

Acknowledgments
The Van Swinden Laboratory (NMi-VSL) made its Form Talysurf instrument available, and it was used in this research. Onno van den Akker wrote the software for further profile manipulations. This work was supported by the Dutch Ministry of Economic Affairs.

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