Calibration of the areal metrological characteristics of scanning confocal microscopes

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Abstract: The use of areal surface texture measuring instruments has increased significantly over the past ten years as industry starts to embrace the use of surface structuring to affect the function of a component. This increased use has led to a range of areal surface texture measuring instruments being developed and becoming commercially available. One common and versatile measuring instrument, addressed here, is the scanning confocal microscope. For such instruments to be used as part of quality control during production, it is essential for them to be calibrated according to international standards. The ISO 25178 suite of specification standards on areal surface texture measurement presents a series of tests that can be used to calibrate the metrological characteristics of an areal surface texture measuring instrument. This paper will discuss methods to measure the noise levels, flatness and geometrical characteristics, that are simple to apply, and can be used for all types of scanning confocal microscope.

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1. Introduction

A scanning confocal microscope (Minsky 1988) like any other areal surface topography measuring instrument provides a three dimensional (3D) or areal map of a surface (Leach 2011, ISO/FDIS 25178-607: 2011). The 3D areal map is made up of a set of points measured along three orthogonal length scales. According to ISO 25178-601: 2010 the scales of an areal surface topography measuring instrument should be aligned to the axes of a right-handed orthonormal co-ordinate system as described in ISO 25178-601: 2010. The axes are physically realised by various components that are part of the metrological loop of the instrument. Hence the quality and the mutual position of these components partially confer the quality of the co-ordinate measurements. The co-ordinate measurements produced by the areal surface topography measuring instruments are also affected by other influence factors such as ambient temperature, mechanical noise and electrical noise. The effect of a single influence factor, or a combination of influence factors, on the quality of the areal measurements should be quantified by experimentally determining the metrological characteristics of the instrument. The main metrological characteristics of areal surface topography measuring instruments are the noise of the instrument; the linearity, amplification and resolution of the scales; the deviation from flatness of the areal reference and the perpendicularity squareness of the axes. The metrological characteristics of an areal measurement instrument can have different magnitudes for different sizes of measuring area and sampling distance, that is to say the measurement bandwidth. The choice of measurement bandwidth is application dependent and is based on the selection of S-filters and L-filters/F-operators, each having a range of preset values called nesting indexes (see ISO/DIS 25178-3: 2011 and Leach 2010a for information on areal filtering). The S-filter nesting index determines the maximum sampling distance whereas the L-filter, or the F-operator, indicates the minimum size of the measuring area. The calibration of the instrument should be performed using the same conditions as those used on a daily basis.

A way of calibrating the scales of a scanning confocal microscope used as an areal surface topography measuring instruments is presented in this paper. The calibration of the scales consists of a series of relatively simple tasks that allows the evaluation of the magnitude of the uncertainty associated with the metrological characteristics of the instruments whilst assuming well-defined measuring conditions. The calibration process also requires the use of material measures designed for calibrating surface texture measuring instruments. An Olympus LEXT OLS4000 scanning confocal instrument has been used as an example instrument. The instrument fitted with a 50× magnification objective lens (0.95 numerical aperture and working field of view was of 0.26 mm by 0.26 mm) was used to obtain the measurement results presented in this paper. The areal data was analysed using commercially available surface texture analysis software (MountainsMap version 5 – Digital Surf 2011).

2. Calibration steps

The main metrological characteristics that influence the uncertainty associated with the co-ordinate measurements produced by areal surface topography measuring instruments are:

- noise;
- residual flatness;
- amplification coefficient and the linearity of the scales (axial and lateral scales);
- squareness of the axes; and
- resolution.

2.1 Noise

The magnitude of the measurement noise can be estimated by calculating the root mean square (RMS) of the scale limited surface *Sq* on a flat surface of less than or equal to 30 nm peak to valley (VDI/VDE 2617: 2004). The difficulty of the test is in separating the effect of the roughness of the flat surface from the instrument noise. VDI/VDE 2617 presents a method of separating the noise from the flat surface roughness. The method consists of subtracting two repeated measurements from each other. The noise can then be estimated using equation (1),

$$Sq_{noise} = \frac{Sq}{\sqrt{2}} \tag{1}$$

where *Sq* is the calculated RMS of the resulting surface obtained after subtraction of two repeated measurements.

Another technique of noise estimation was developed elsewhere (Haitjema and Morel 2005). This technique is based on the assumption that the instrument noise contribution to the RMS of the average surface obtained from multiple measurements performed at the same location on the flat will decrease by the square root of the number of repeat measurements, so that the noise of the instrument can be estimated using equation (2),

$$Sq_{noise} = \sqrt{\frac{Sq^2 - Sq_n^2}{1 - \frac{1}{n}}} \tag{2}$$

where *Sq* is the measured RMS after one measurement, n is the number of repeated measurements, Sq_n is the measured RMS of the averaged surface and Sq_{noise} is the noise of the instrument.

Six repeated measurements have been performed in the same location on a transparent glass flat. The noise results using the subtraction method are presented in table 1 and the results using the Haitjema method are presented in table 2.

Both methods of measuring the noise of the instrument provide similar results such that either method can be used to estimate the noise of the instrument. The relative instability of the measurement results presented in table 1 and table 2 could be an indication of the presence of non-stationary noise.

Table 1 Noise results – subtraction method.

Subtracted measurements	Sq_{noise} / nm
1 – 2	1.4
2 – 3	1.9
3 – 4	1.7
4 – 5	1.4
5 – 6	1.5
Average	1.6
Standard deviation	0.2

Table 2 Noise results – Haitjema method.

Number of repeated measurements	Sq_{noise} / nm
2	1.9
3	2.2
4	1.7
5	1.4
6	1.5

2.2 Residual flatness

An important quality of any areal surface topography measuring instrument is the flatness of its areal reference. Similarly to the measurement noise test, the flatness test is performed on a flat surface but the parameter that quantifies the magnitude of the flatness effect is the maximum height of the scale limited surface (*Sz*). Unlike *Sq*, the value of *Sz* is highly sensitive to the local height variations such as scratches or dirt. It is, therefore, difficult to completely separate the contribution of the instrument from that of the flat and other spurious measurement data. One way to overcome these issues is to measure the topography of the flat at different locations (VDI/VDE 2617: 2004) without changing the instrument setup and to average the height measurement of each point of the topography. The contribution of the flat and any spurious data should diminish whereas the quality of the areal reference should be preserved. It is difficult to recommend the exact number of repeated measurements because the number depends on the rate at which the value of *Sz* stabilises. The measurements should be repeated until the value of *Sz* stabilises. An example of flatness measurement results is presented in table 3.

Table 3 Residual flatness of the areal reference.

Number of repeated measurements	*Sz* / nm
2	32
4	73
6	53
8	42
10	44

Sz is 44 nm after averaging ten measurements. The magnitude of *Sz* is dominated by the residual flatness error present at right hand side of the areal reference of the instrument (see fig. 1).

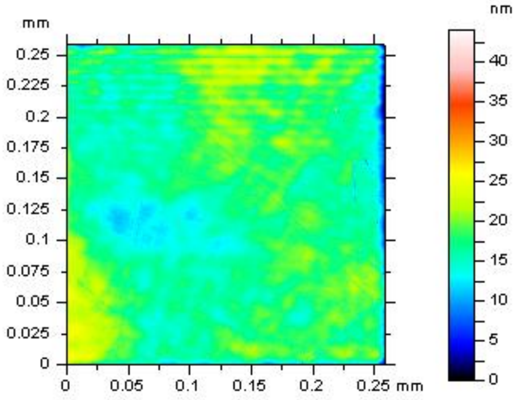

Fig. 1 Residual flatness of the full field of view (0.26 mm by 0.26 mm) - result after ten repeated and averaged measurements.

A simple digital zoom will produce a better quality areal reference (see fig. 2). The value of *Sz* drops to 29 nm (more than 25 %) only by using a restricted measurement window of 0.25 mm by 0.25 mm.

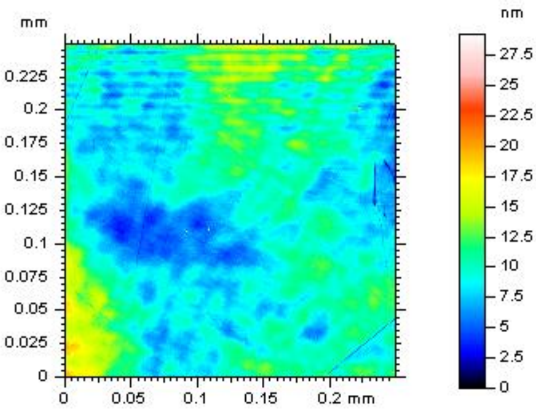

Fig. 2 Residual flatness of the restricted field of view (0.25 mm by 0.25 mm) - result after ten repeated and averaged measurements.

2.3 Calibration of the *z* scale

The *z* scale calibration consists of a series of measurements of a range of step height artefacts with various depths to establish the relationship between the ideal response curve and the instrument response curve. This calibration provides information about the *z* axis linearity and amplification coefficient. Fig. 3 shows a typical example of a linear scale response curve. The linearity of the *z* axis is given by the maximum deviation of the instrument response curve from the linear curve where the slope is the amplification coefficient.

The range of different step height artefacts should cover the entire *z* axis range of the instrument or at least they should cover the range from the minimum to the maximum height of interest. The linearity and amplification coefficient can be extracted from the measurement results of multiple calibrated step heights of different values by fitting a straight line to the data.

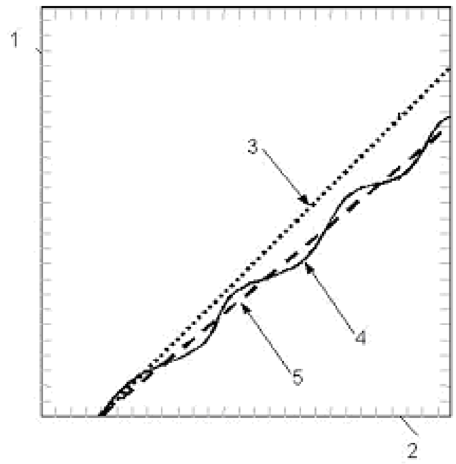

Fig. 3 (ISO 25178–601: 2010) Example of an instrument response curve, where: 1 measured quantities, 2 input quantities, 3 ideal response curve, 4 response curve, 5 linear curve whose slope is the amplification coefficient

Often the *z* axis calibration is performed using a single step artefact that is also used to adjust a software parameter. This situation is potentially very dangerous because it could only shift the response curve in such a way that it crosses the ideal response curve only at that measured point. Unless the response curve is perfectly linear one calibration artefact does not provide sufficient information about the quality of the instrument's *z* axis scale and it will underestimate its contribution into the uncertainty calculations. The *z* axis scale should be calibrated at regular intervals because the instrument characteristics could change over time. An example of *z* scale calibration results with the confocal microscope using three step heights is presented in table 4.

Table 4 Calibration of the *z* scale using three step heights.

Nominal value	Certified value	Uncer-tainty	Measured value	Standard deviation	Error
/ nm					
3000	3030.7	3.7	3037	11	6.3
350	343.4	1.5	337.6	2.4	5.8
19	18.3	1.5	18.0	0.9	- 0.3

The results presented in table 4 indicate that the linearity errors are 0.3 nm in the 0 to 18 nm range and 6.3 nm in the 18 nm to 3 µm range.

The squareness between the areal reference and the *z* axis can be determined by measuring the pitch of a periodic structure mounted at different angles relative to the instrument's areal reference (Xu 2008). If the *z* axis is not perpendicular to the areal reference the pitch will change according to the angle between the areal reference and the step height surface. On the other hand the calibration of the *z* scale with multiple step height standards can correct for the squareness problems. The cosine error that is introduced by the *z* axis scale squareness behaves as an amplification error.

2.4 Calibration of the *xy* scale

Traditionally the calibration of the lateral axis of surface topography measuring instruments is performed using a grating with a known pitch. The pitch measuring technique can be applied to calibrate instruments that measure areal topography but the analysis has to be performed in profile mode. The drawback of pitch measurements is that they only estimate the local characteristic of the instrument's scale and do not give information about the instrument response curve. Areal material measures such as cross gratings (Leach *et al.* 2006) or pyramidal structures (Ritter *et al.* 2007) are better suited for calibration of the lateral scales of areal topography measuring instruments.

The *x* and *y* axes amplification and the squareness can be measured using a calibrated cross grating artefact (see fig. 4). By measuring the positions of the centre of gravity of the cross grating's squares with a traceable areal surface topography measuring instrument (for example Leach *et al.* 2009, Thomsen-Schmidt and Krüger-Sehm 2008) provides traceable length measurements along the *x* and *y* axes. In addition, the squareness of the *x* and *y* axes can be measured by measuring the angle between two nominally orthogonal rows of square holes whose squareness is known. The orientation of each row of squares can be calculated by fitting a line though the centre of gravity of the corresponding squares. Note that at the time of writing, results for the *x* and *y* axes of the confocal microscope are not available.

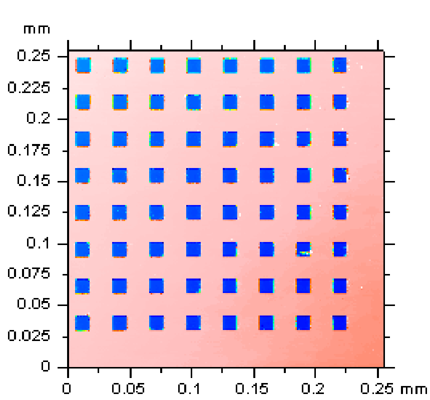

Fig. 4 Measurement of a cross grating of 30 µm pitch and 1 µm depth.

2.5 Resolution

It is difficult to design material measures suitable for testing the *z* axis resolution. In almost all situations the *z* axis resolution is small compared to other contributors to the uncertainty such as scale linearity, amplification errors and noise.

The resolution of the lateral scales is defined as the smallest lateral separation between two points that can be distinguished. This is a useful definition of the lateral resolution for a 2D microscope or when making lateral measurements. However, for areal surface topography measurements, the distance between two adjacent points could affect their relative measured height difference, this definition becomes impracticable. The width limit for full height transmission has been defined (ISO 25178-601: 2010) to overcome the problem with the lateral resolution definition but is still under debate. Experimentally the width limit for full height transmission is measured on gratings or crossed gratings with the pitch value close to the resolution of the instrument. A 3D star pattern (Leach *et al.* 2006, Weckenman *et al.* 2009), see fig. 5, can be used to find the approximate value of the width limit for full height transmission before measuring a grating with a predefined pitch.

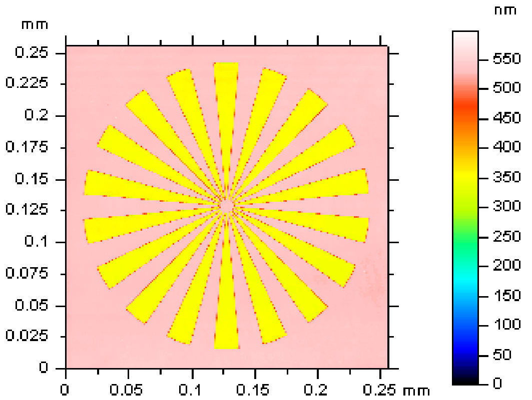

Fig. 5 Measurement of a star pattern

Other definitions of lateral resolution could be used where the width limit for full height transmission is not appropriate for a specific application. ISO/TC213-WG16 is looking to introduce an umbrella term, spatial height resolution, defined as the ability of a surface topography measuring instrument to distinguish closely spaced surface features (ISO/DIS 25178-603: 2011). Note that at the time of writing, results for the resolution of the confocal microscope are not available.

3. Uncertainty

The calculation of uncertainties for surface topography measuring instruments is a very complex task that is often only carried out at NMIs. It is often possible to calculate the instrument uncertainty, that is to say the uncertainty in measuring (*x*, *y*, *z*), but when the effect of the surface is taken into account this uncertainty value may significantly increase, often in an unpredictable manner. Where possible the guidelines in the GUM (BIPM 2008) should be applied to calculate instrument uncertainties and the effect of the surface should be considered in as pragmatic a manner as possible. Examples of methods to calculate the uncertainty in a profile measurement using a stylus instrument are given in (Leach 1999) and (Krüger-Sehm and Krystek 2000), but the methods are far from mathematically rigorous or applicable in all circumstances. A rigorous uncertainty is calculated (Krystek 2000), using the GUM approach, for the use of a Gaussian profile filter but little work has been carried out for the uncertainty associated with areal parameters (Morel and Haitjema 2001).

When the instrument uncertainty has been calculated it is then often necessary to find the uncertainty in a parameter calculation. Once again this is far from trivial and often the guidelines in the GUM cannot be easily applied (Harris *et al.* 2010). The problem is that for roughness parameters, some characteristics of a roughness measuring instrument have an obvious influence on a roughness parameter, but for others this is highly unclear (Haitjema 1998).

To conclude, it is not straightforward to calculate a rigorous uncertainty value for an instrument for all surfaces and for all parameters. Only a pragmatic approach can be applied for a given measurement scenario. At the very least repeated measurements should always be carried out and the standard deviation or the standards deviation of the mean quoted.

4. Conclusions

This paper presents a simple way of calibrating the scales of a scanning confocal microscope used as an areal surface topography measuring instrument. The calibration consists of measuring the noise and flatness of the instrument, amplification coefficients, linearity and squareness of the scales.

It is important to point out that measuring the above metrological characteristics is not enough to qualify an areal instrument for the measurement of complex, rough surfaces. For this, the spatial frequency response of the instrument needs to be calibrated and such methods are still in their infancy (see for example Yashchuk *et al.* 2008, Polodhi *et al.* 2010, Leach and Haitjema 2010b). The effect of the filters employed for a specific application also has to be studied. For example the OLS4000 used in this paper can accurately measure very small step heights because the mathematical algorithm used to estimate the step value reduces significantly the effect of the noise and flatness errors.

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