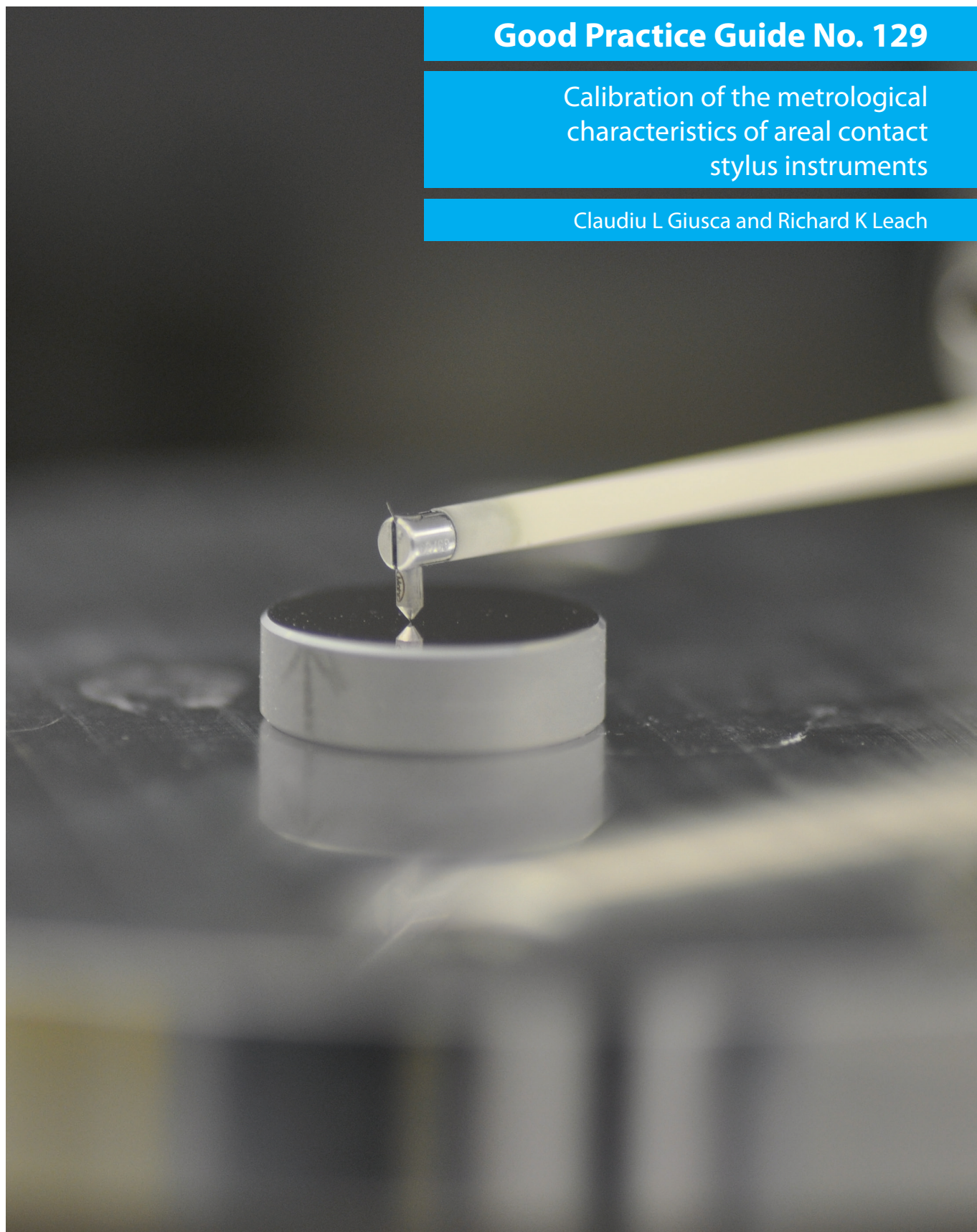


Good Practice Guide No. 129

Calibration of the metrological
characteristics of areal contact
stylus instruments

Claudiu L Giusca and Richard K Leach



Measurement Good Practice Guide No. 129

Calibration of the metrological characteristics of areal contact stylus instruments

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ABSTRACT

This document is a guide to the calibration of contact stylus instruments. Methods for determining the measurement noise, flatness deviation, amplification coefficient, linearity and perpendicularity of the axes of areal surface topography measuring instruments are presented.

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Introduction

1

The aim of this guide is to allow the user to provide surface texture measurement results with associated uncertainties that are derived from the instrument calibration process. The purpose of this good practice guide is to assist users in calibrating contact stylus based areal surface topography measuring instruments. To make best use of this guide users should first familiarise themselves with the content of NPL GPG 37¹, and operating manuals and application notes supplied by the instrument manufacturers.

The contact stylus scanning measurement is defined in ISO 25178 part 6 (2010) as:

“surface topography measurement method whereby the probing system uses a contacting stylus whose motion is converted into a signal as a function of position”.

In 2002, the International Organization for Standardization (ISO) Technical Committee, dealing with Dimensional and Geometrical Product Specifications and Verifications (TC213), formed Working Group 16 to address standardization of areal (three dimensional) surface topography measurement methods. Working Group 16 is developing a number of draft standards (the ISO 25178 series) encompassing definitions of terms and parameters, calibration methods, file formats and characteristics of instruments. Under this process, a project team is developing specification standards for areal surface topography measurement including calibration techniques. This guide is intended to be compliant with this standardisation process.

Current industrial demand is for areal surface topography measuring instruments that provide traceable measurement results, but traceability in areal surface texture cannot be supplied by most National Measurement Institutes. According to the *International vocabulary of metrology — Basic and general concepts and associated terms* (VIM), metrological traceability is the “*property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty*”.

A complete traceability route for areal surface texture measurements requires the following elements:

- calibrated areal physical measurement standards (ISO/FDIS 25178 part 70, 2012) or standard artefacts for calibrating areal surface topography measuring instruments or means for calibrating the geometric deviations of the x and y axes and the probe movement;
- software measurement standards for calculating areal surface texture parameters; and
- methods for calculating the uncertainties associated with areal surface topography measuring instruments and surface texture parameters.

Commonly the term calibration is misused, which has led to confusion in understanding the aim of the calibration process. The frequent misuse of the term calibration is when it is used instead of adjustment:

VIM 2.39 Note 1 – “*Calibration should not be confused with adjustment of a measuring system, often mistakenly called “self-calibration”, nor with verification of calibration.*”

¹ Leach R K 2001 The measurement of surface texture using stylus instruments *Good Practice Guide No. 37* (National Physical Laboratory)

Instrument adjustment

The adjustment process physically changes some parameters of a metrological tool (it can be a mechanical adjustment or it could be the result of changing the value of a software constant) to provide an indication that is closer to a known value. The adjustment process does not provide information about measurement uncertainty. Similar results could be obtained by correcting the measurement result using the results from a calibration certificate. A meaningful measurement result can be presented without adjustment, but it must have an associated uncertainty.

An example of adjustment of a stylus instrument is the physical adjustment that is performed using a calibrated step height standard artefact or a sinusoid with a known Ra . These physical measurement standards reproduce a height value known with an associated uncertainty. Generally, during the adjustment of the instrument, the response curve (see chapter 4, figure 11) is changed according to the result of a single measurement. The adjustment cannot account for the uncertainty associated with the measurement result, it only uses a value from the range of possible values that are within the limits given by the measurement uncertainty. After adjustment, the measurement of the same step height can provide a different result as we shall see in chapter 4.

There are situations in which the measurement after adjustment matches closely the value reproduced by the physical measurement standard but, unfortunately, the response curve could be changed in such way that it crosses the ideal response curve only at that measured point. The closeness between the measurement result and value reproduced by the physical measurement standard could be attributed to good measurement reproducibility but it does not indicate anything about systematic effects. The advantage of a good instrument adjustment is that the measurement results could be used without correction.

If the user decides that the adjustment operation is required, the measurements before adjustment should be recorded and calibration of the instrument should be performed after adjustment.

Instrument calibration

Areal surface texture measurements involve the simple task of measuring a set of points across the surface of a component. The difficulty in calibration lies in the assessment of the effect of a multitude of influence factors that contribute to the measurement uncertainty. First of all, it is necessary to establish the measurement conditions (that is to say sampling interval, environmental conditions, *etc.*) for a particular surface or, ideally, the measurement conditions that are directly related to a particular function of the surface. The next step is to choose the appropriate set-up parameters of the instrument suitable for the spatial bandwidth of the surface such as scanning speed, range, and the geometry and dimensions of the stylus tip. The measured topography data is then analysed using software and this process adds to the complexity. This software is used for data processing such as filtering, parameter calculation and visual representation.

The geometrical imperfections of an instrument are inherited from the flatness of the areal reference, the translational degrees of freedom and the perpendicularity of the axis of operation and the quality of the optical probing system. The effect of the influence factors on

the quality of the areal measurements can be quantified by experimentally determining the metrological characteristics of the instrument; these characteristics are listed in ISO/CD 25178 part 600 (note that ISO/CD 25178 part 600 is a committee draft and subject to change). The main metrological characteristics of areal surface topography measuring instruments are:

- measurement noise;
- flatness deviation;
- linearity errors;
- amplification coefficient;
- perpendicularity of the axes; and
- resolution of the measurements along the axis of operation.

In this guide a method is presented for calibrating the metrological characteristics of stylus instruments that is based on calibrated physical measurement standards and is compliant with the guidelines of the relevant draft ISO documents. The calibration process consists of a series of relatively simple tasks that can be used to evaluate the uncertainty contribution associated with the metrological characteristics.

It is recommended that the effects of the metrological characteristics of the stylus should be studied separately from the effects of the probe-sample interaction, for example measurement of slopes and different materials. Furthermore, calibrating an instrument for all possible measuring conditions is a difficult and lengthy task. The solution is, therefore, to calibrate the instrument for task specific applications. For instance, the physical measurement standards and the measurement spatial bandwidth required by the calibration process are set according to the surface features to be measured. Other measurement conditions that need to be adhered to, such as environmental conditions and sample cleanliness, are given in NPL GPG 37.

During the calibration of an instrument, the environmental conditions should be similar to the environmental working conditions, otherwise the calibration process will not assess the true performance of the instrument.

Structure of the guide

This guide is structured in the following manner. The next chapter describes briefly the stylus configuration as in ISO 25178 part 601; the physical measurement standards that are recommended by the draft ISO/FDIS 25178 part 70 to calibrate areal surface topography measuring instruments; and the nesting indices that are recommended by ISO 25178 part 3. Methods for determining the metrological characteristics are given in chapters 3 and 4, and methods of calculating the measurement uncertainties are presented in chapter 5. The final chapter presents examples of measurement uncertainty calculations for two common types of areal surface texture measurements.

The methods and artefacts described in this guide are designed to aid a user in determining the metrological characteristics of an instrument. However, it must be noted that there are a

large number of alternative methods and artefacts that can also be applied. Often the instrument manufacturers may have proprietary methods and artefacts that are supplied with the instrument and these should be used as directed by the manufacturer. Also, the method for achieving traceability *via* a primary instrument may not always be appropriate, and may lead to larger measurement uncertainties than are acceptable (the measurement of smooth optical surfaces is an example here). A pragmatic and informed approach is always recommended, and the user is encouraged to gain as much information about the subject as possible.

This guide gives an overview of the published and draft standards. The user should always make reference to the latest issues of the published standards.

General

2

Stylus instruments configuration

In this guide contact stylus instruments that measure areal surface topography will be referred to as stylus instruments. Figure 1 shows a schema of an areal surface topography measuring instrument.

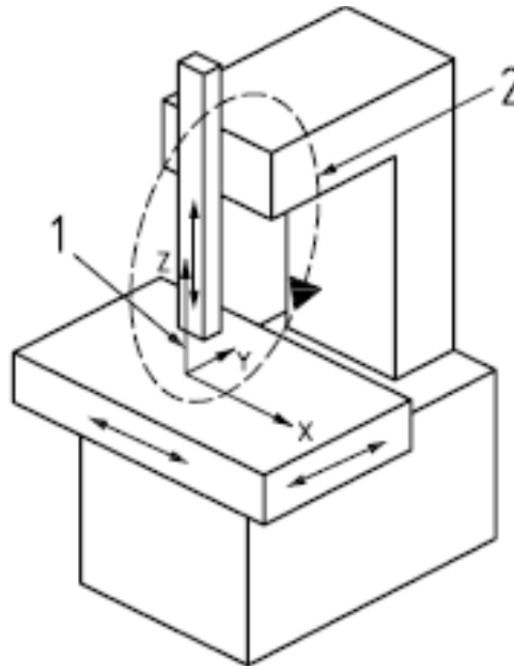


Figure 1 Coordinate system and measurement loop of the instrument (ISO25178-601:2010). 1 coordinate system of the instrument and 2 measurement loop

Stylus instruments scan the surface in a raster fashion by moving the probing system in the x direction in long strokes with the motion of the component in the y direction being moved in small increments. The probing system characteristics of areal stylus instruments are identical to the probing system characteristics for contact stylus instruments that measure surface profile. The probing system is described in detail in NPL GPG No 37.

Stylus instruments have their axes physically realised by a combination of reference guides (linear or areal), which allow the probing system of the instrument to move relative to the surface of a component along known paths. The device responsible for the relative movement of the probing system to the surface is called the drive unit and the relative displacements along the areal reference guide are measured using lateral position sensors. Both these latter two components are part of the instrument scanning system. Based on the type of lateral scanning and probing system, ISO 25178 part 601 identifies ten possible configurations of stylus instruments (see table 1).

Either the probe and/or the component can be driven laterally during the measurement of surface topography such that it becomes possible to have five lateral scanning system combinations: probing system moving along a linear reference guide and component moving along another linear reference guide (PX or CY), probing system moving along two linear

reference guides ($PX \circ PY$), component moving along two linear reference guides ($CX \circ CY$), probing system moving across an areal reference guide (PXY) and component moving across an areal reference guide (CXY).

Table 1 Possible different configurations for reference guides (x and y) (ISO 25178: 601)

		Drive Unit				
		Two reference guides (X and Y)			One areal reference guide	
		$PX \circ CY^a$	$PX \circ PY$	$CX \circ CY$	PXY	CXY
Probing System	A: without arcuate error correction	$PX \circ CY-A$	$PX \circ PY-A$	$CX \circ CY-A$	$PXY-A$	$CXY-A$
	S: without arcuate error or with arcuate error corrected	$PX \circ CY-S$	$PX \circ PY-S$	$CX \circ CY-S$	$PXY-S$	$CXY-S$
For two given functions f and g, f o g is the combination of these functions a PX = probing systems moving along the X-axis PY = probing systems moving along the Y-axis CX = component moving along the X-axis CY = component moving along the Y-axis						

In the most common configurations of stylus instruments, the probing system is based on a design with the tip situated at the end of an arm that pivots in a vertical plane around a fixed axis. The arcuate motion of the stylus can be corrected or not such that the probing system has two variants in ISO 25178 part 601 (Annex A): without arcuate error correction (*A*) and without arcuate error, or corrected arcuate error (*S*). The second variant of the probing system also includes those instruments that are not based on a pivoting arm (for example, linear probes based on a flexure guide).

The contact stylus instrument used to obtain the measurement data presented in this guide was an instrument equipped with a 2 µm radius conical stylus tip arranged in a $PX \circ CY - S$ configuration, where S means with arcuate error corrected.

Surface texture filters

Filtering characteristics and parameters required for surface texture profile analysis have been developed over many years with specifications already defined within a number of ISO documents (ISO 4287, ISO 16610-21)². Profile measurement filtering is discussed and summarized in NPL GPG 37, and the reader should refer to that guide for further information.

Whilst profile characterization requires three groups or classes of surface description (*primary profile*, *roughness* and *waviness*), areal surface characterisation does not. The meaning of the majority of the areal parameters depends on the type of scale-limited surface used. ISO 25178 part 3 defines two categories of filter: the S-filter and the L-filter (see figure 2). The S-filter is defined as a filter that removes unwanted small-scale lateral components of the measured surface, such as measurement noise, spikes or functionally irrelevant small features. The L-filter is used to remove unwanted large-scale lateral components of the surface. Nominal form removal (defined as an F-operator) is achieved typically by using a least-squares method.

The scale at which the filters operate is controlled by the nesting index. The nesting index is an extension of the cut-off wavelength used in profile analysis and is suitable for all types of filters. For example, for a Gaussian filter the nesting index is equivalent to the cut-off wavelength, and for a morphological filter with a spherical structuring element, the nesting index is the radius of the spherical element. These filters are used in combination to create S-F and S-L surfaces.

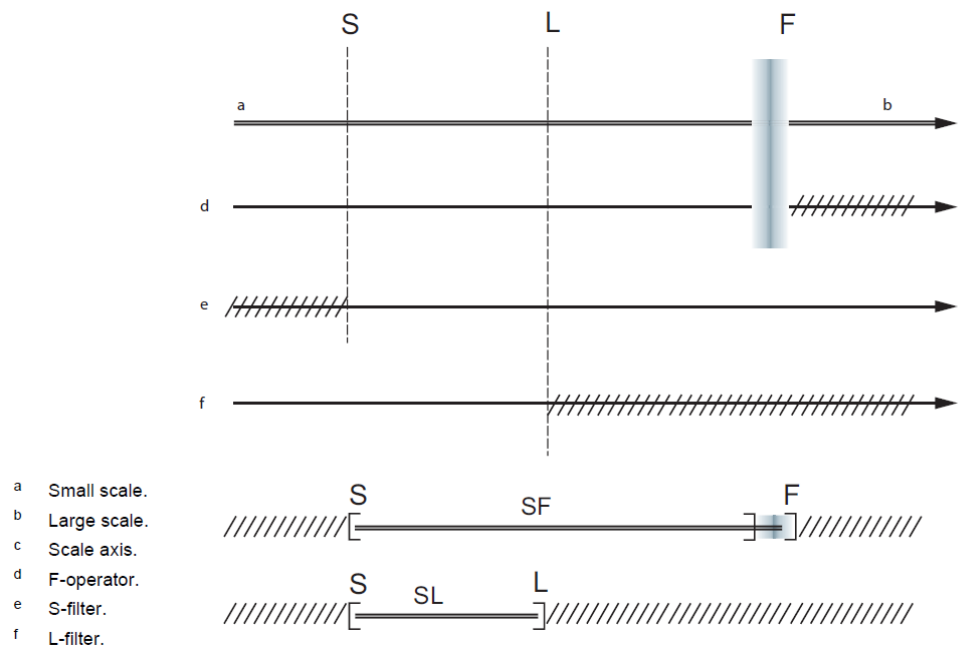


Figure 2 (BS EN ISO 25178 – 2: 2012) – relationships between the S-filter, L-filter, F-operator and S-F and S-L surfaces

² Note that many areal surface topography measuring instruments still use profile filtering methods.

Significant development of filter types and systems has been occurring for areal dataset applications. It has been necessary to produce a standardised framework for filters, which gives a mathematical foundation for filtration, together with a toolbox of different filters. This framework runs parallel to, and cross-references into, the ISO 25178 specifications. Information concerning these filters has been published as a series of technical specifications (ISO/TS 16610 series) with further parts still in development, to allow metrologists to assess the utility of the recommended filters according to applications. When fully published, the technical specifications will contain the classes of filters listed below.

- Linear filters - the mean line filters (M-system) belong to this class and include the Gaussian filter, spline filter and the spline-wavelet filter.
- Morphological filters - the envelope filters (E-system) belong to this class and include closing and opening filters using either a disk or a horizontal line.
- Robust filters - filters that are robust with respect to specific phenomena such as spikes, scratches and steps. These filters include the robust Gaussian filter and the robust spline filter.
- Segmentation filters - filters that partition a profile into portions according to specific rules. The motif approach belongs to this class and has now been put on a firm mathematical basis.

The Gaussian filter has become the routine standardized filter of choice for filtering of line profiles for 2D parameter generation, with both roughness and waviness surfaces acquired from a single filtering procedure with minimal phase distortion. This approach has been extended through the development of the areal Gaussian filter (and robust versions), now used by many instrument manufacturers, and again this approach is being formalized in ISO 16610.

The relevance of the description of areal filtering given here is dependent on the instrument being used. Users should familiarize themselves with the options provided by the instrument software, although many of the newer developments expressed in developing standards (ISO 16610 and ISO 25178) have yet to migrate to full application within analysis software.

The user should consider filtering options on a case-by-case basis with the guiding principle that, if you want to compare two surface measurements, it is important that both sets use the same filtering methods and nesting indices.

Stylus nesting index combinations

The S-filter nesting index (equivalent to λ_s filter in the profile case) allows the selection of the maximum sampling distance (the sampling distance is at least three times the S-filter nesting index). The selection of the S-filter nesting index should be based on the instrument lateral resolution and the lower limit of the measurement spatial bandwidth of interest. The L-filter (equivalent to λ_c filter in the profile case) or the F-operator nesting index could be based on the size of the measured area and their values should be smaller than the upper limit of the measurement bandwidth of interest and at least five times the scale of the coarsest structure of interest. Table 2 reproduces proposed recommended sets of nesting indices from ISO 25178 part 3.

Table 2 Relationships between nesting index value F-operator/L-filter, S-filter nesting index, and bandwidth ratio. n is a positive or negative integer

Nesting index value (F-operator/L-filter) / 10^n mm	S-filter nesting index / 10^n μ m	Bandwidth ratio between F-operator/L-filter and S-filter nesting index
1	10	100:1
	5	200:1
	2	500:1
	1	1000:1
2	20	100:1
	10	200:1
	5	400:1
	2	1000:1
2.5	25	100:1
	8	300:1*
	2.5	1000:1
5	50	100:1
	20	250:1
	10	500:1
	5	1000:1
8	80	100:1
	25	300:1*
	8	1000:1

* Rounded value

Physical measurement standards

The calibration process relies on calibrated physical measurement standards (also known as standard artefacts). A range of physical measurement standards suitable for calibrating instruments that measure areal surface topography is given in the draft standard document ISO/FDIS 25178 part 70. This document identifies thirteen types of profile physical measurement standards (see table 3) and nine types of areal physical measurement standards (see table 4). Optical flats are also used during the calibration process.

Table 3 Type of uni-dimensional (profile) physical measurement standards

Type	Name
PPS	Periodic sinusoidal shape
PPT	Periodic triangular shape
PPR	Periodic rectangular shape
PPA	Periodic arcuate shape
PGR	Groove, rectangular
PGC	Groove, circular
PRO	Roughness profile
PCR	Circular roughness profile
PRI	Prism
PRB	Razor blade
PAS	Approximated sinusoidal shape
PCS	Contour standard
PDG	Double groove

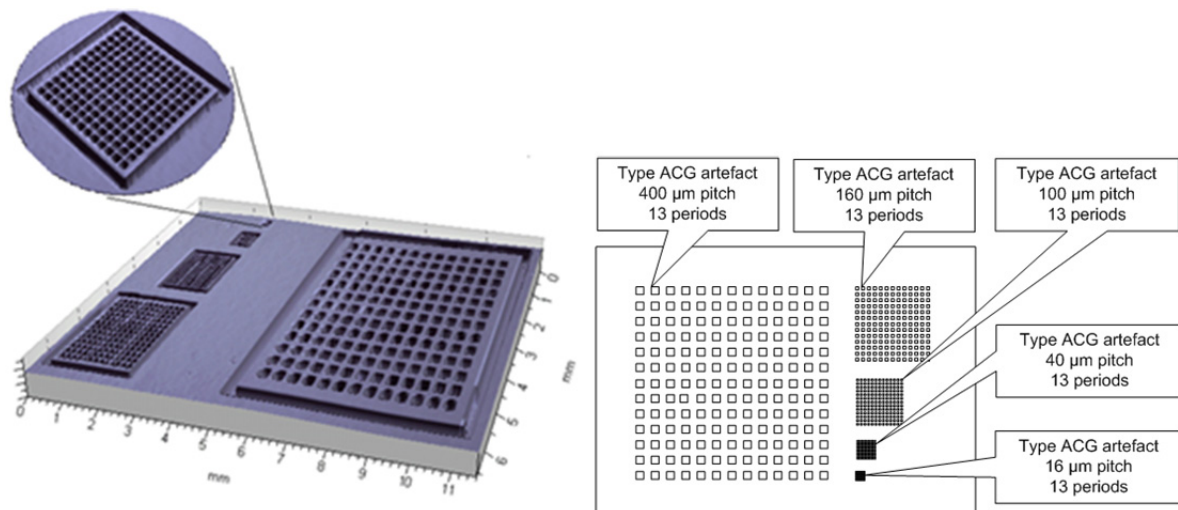
Table 4 Type of bi-dimensional (areal) physical measurement standards

Type	Name
AGP	Grooves, perpendicular
AGC	Groove, circular
ASP	Sphere
APS	Plane – sphere
ACG	Cross grating
ACS	Cross sinusoidal
ARS	Radial, sinusoidal
ASG	Star-shape grooves
AIR	Irregular

Although ISO/FDIS 25178–70 contains details of a large number of physical measurement standards it does not mean that there is a need to use all of them to calibrate an instrument. The choice of physical measurement standards should be based on a selection that is sufficient for a full geometrical calibration of the instrument.

A typical example of a good selection of physical measurement standards is a calibration set that is limited to a flat, type ACG, type ASG and type AIR. These four types of physical measurement standards form the basis of the NPL areal calibration set. The calibration set is used to determine the metrological characteristics of the instrument (flat, ACG and ASG) and the quality of areal surface texture measurements (AIR).

The type ACG standard is used to calibrate the linearity errors, amplification coefficient and squareness of the x and y axis. The design of the type ACG standard includes five cross gratings with differing pitches, ranging from 16 μm to 400 μm , allowing determination of the amplification, linearity and squareness of the x and y axes of the instruments (see figure 3) for different measurement windows (nesting indices). The patterns are produced at different heights typically 0.5 μm , 1 μm and 2 μm , allowing for z measurement calibration.



**Figure 3 NPL type ACG physical measurement standard:
measured (left) and design (right)**

The type ASG standard is used to calibrate the lateral resolution of the instruments. The NPL design of the resolution measurement standard is a combination of two type ASG standards of 70 μm and 20 μm radius and thirteen type ACG standards with different pitches ranging from 600 nm to 20 μm (see figure 4).

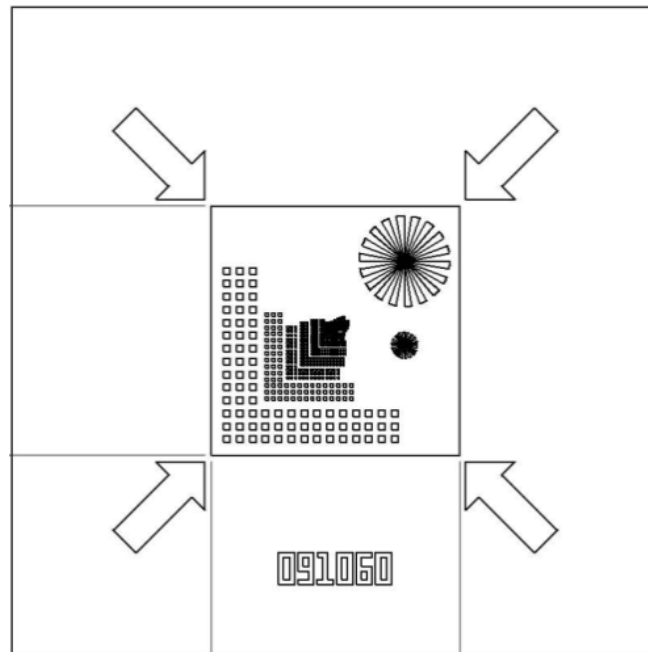


Figure 4 NPL resolution standard artefact

The type AIR standard has a useful working area of 1.5 mm by 1.5 mm (see figure 5) and has a pseudo-random distribution of heights.

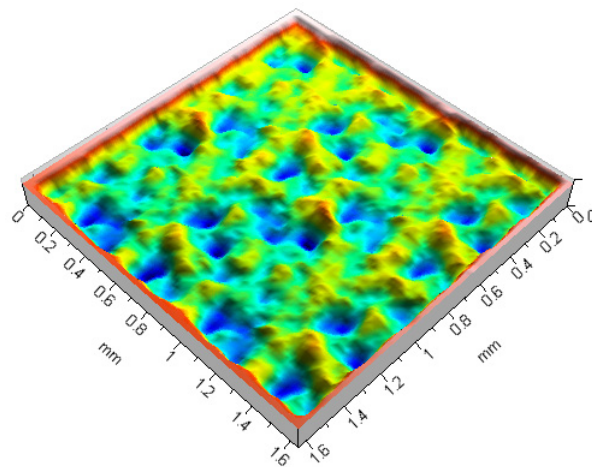


Figure 5 NPL type AIR standard artefact – NPL Areal Instruments measurement

A flat, type ACG, type ASG and type AIR physical measurement standards are contained in the NPL areal calibration set.

Measurement noise and flatness deviation

3

This section of the good practice guide aims to address the measurement challenges and provides measurement methodologies for two of the metrological characteristics: measurement noise, defined as *noise added to the output signal occurring during the normal use of the instrument*; and flatness deviation, defined as *flatness of the areal reference*.

The data set from an areal surface topography measuring instrument can be affected by various sources of noise such as:

- instability in the instrument electronics, which is also called the internal noise of the instrument;
- environmental noise generated by ground vibrations;
- ventilation (drafts or turbulence);
- sound;
- short and long-term temperature fluctuations;
- external electromagnetic disturbances; and
- vibrations generated by those components of the instrument that are designed to move during the measurement.

The majority of stylus instruments allow the recording of the output signal of the probe that contacts a sample without scanning in the x or y directions. This type of measurement is known as a static noise test and is generally performed in profile mode

From a calibration perspective, static noise tests are not necessary because they are performance tests designed to identify if there are any major issues with the set-up of the instrument. Static noise is part of the measurement noise (see Measurement noise section) of the instrument that should be included into the measurement uncertainty. The only reason for including the static noise test in this guide is that this test has been traditionally used to characterise stylus instruments.

Static noise

Static noise is a combination of the internal noise of the instrument and environmental noise while the lateral scanning system of the instrument is stationary.

The static noise test consists of repeated measurements of the stylus vertical position when the stylus is in contact with a surface of any stiff component and there is no relative lateral movement between the stylus and the component.

Generally, static noise measurements are performed in profile mode (but without lateral motion). One set of measurements has to be performed to test the static noise on the fast axis and one set on the slow axis where possible (the difference between the procedure for the two measurements is the different sampling frequencies used). The quantitative estimation of the noise is given by the *root mean square deviation from the assessed profile* with (Rq) and/or without filtering (Pq). If the instrument allows for static noise measurements in areal mode

the assessed parameter should be the *root mean square height of the scale limited surface* (Sq).

Examples of static noise tests

The software of the example instrument does not allow static noise tests on the slow axis (the y direction) to be performed. Only static noise measurements that correspond to profile measurements acquired at speed of measurement of 0.1 mm s^{-1} (Case 1) and 0.5 mm s^{-1} (Case 2) along the fast axis were performed.

It is good practice to test the instrument at a sampling frequency that is representative to the speed of measurement used in practice.

The profile length (1 mm) and sampling distance ($1 \mu\text{m}$) were chosen to be the same for both tests at each speed of measurement. Examples of fast axis static noise measurement that were levelled and filtered with a micro-roughness filter of $\lambda_s = 5 \mu\text{m}$ are shown in figure 6 and figure 7 (note that, although the static noise tests do not require physical movement of the probe, for visualisation purposes the unit of the horizontal axis is given in units of length instead frequency).

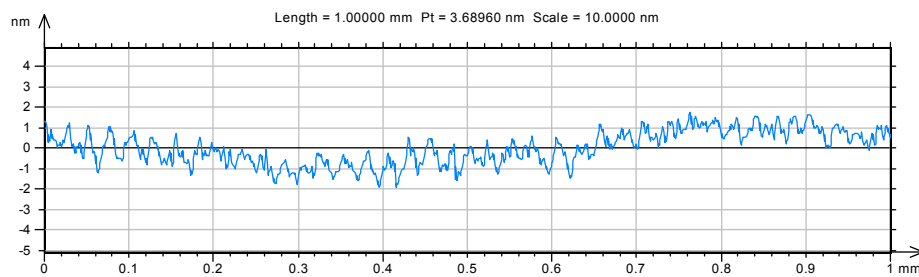


Figure 6 Measurement result for static noise in Case 1. The data is filtered using a Gaussian filter with a $5 \mu\text{m}$ cut-off

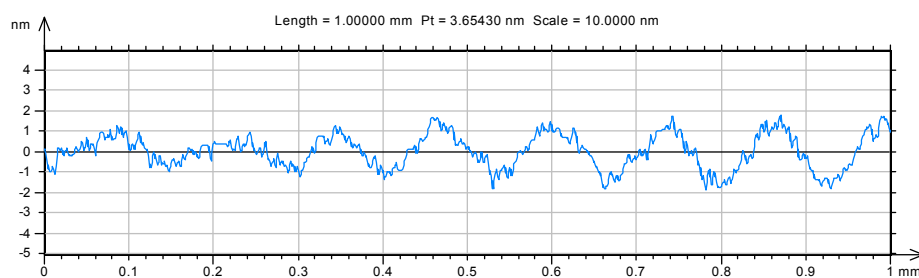


Figure 7 Measurement result for static noise in Case 2. The data is filtered using a Gaussian filter with a $5 \mu\text{m}$ cut-off

In the plots presented in figure 6 and figure 7 it can be seen that there is a dominant noise component at a temporal frequency of approximately 4 Hz. In the Fourier spectra of these two profiles, figure 8 and figure 9, the 4 Hz temporal frequency corresponds to the peak around the fifty-sixth spatial wavelength ($25 \mu\text{m}$) and in the peak around the eleventh spatial

wavelength (0.127 mm) respectively. The 4 Hz noise component is transmitted from the air conditioning system to the probing system.

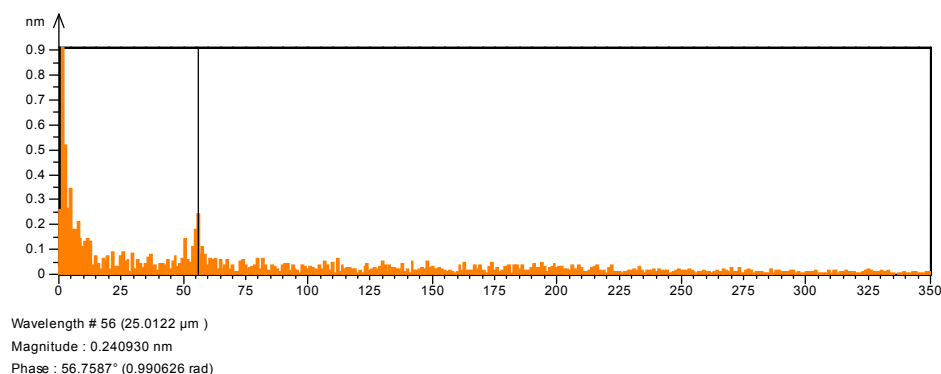


Figure 8 Fourier spectra of the static noise in Case 1 (vertical axis – amplitude, horizontal axis – spatial wavelength number)

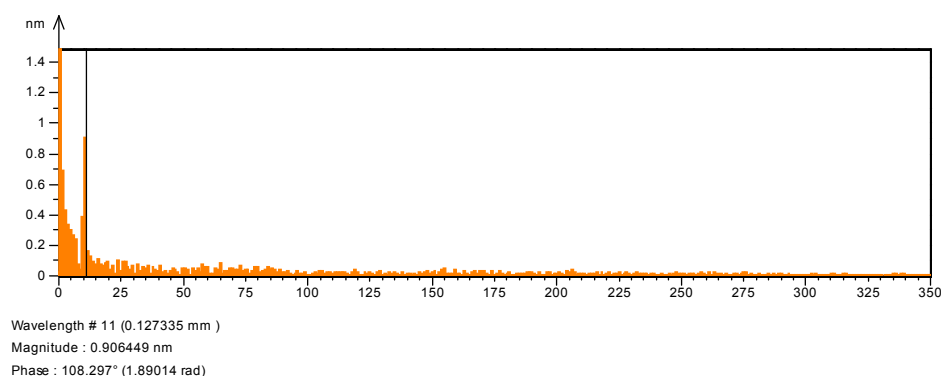


Figure 9 Fourier spectra of the static noise along the fast axes in Case 2 (vertical axis – amplitude, horizontal axis – spatial wavelength number)

After levelling the static noise profiles, the *root mean square deviation from the assessed profiles* (Pq) was calculated. The results without filtering for waviness are presented in table 5.

The difference between the static noise measurement results at 0.1 mm s^{-1} and 0.5 mm s^{-1} speed of measurement is not significant for this instrument. The value of Pq is given by the 3.6 nm amplitude of the dominant noise component of 4 Hz frequency.

Table 5 Fast axis static noise tests results without F-operator/L-filter. Pq is the root mean square deviation from the assessed profiles.

Measurement	Case 1	Case 2
-------------	--------	--------

No.	<i>Pq</i> / nm	
1	0.82	0.78
2	0.58	0.47
3	0.47	0.61
4	0.56	0.38
5	0.53	0.61
Quadratic mean	0.60	0.59

Measurement noise

The measurement noise (also called measurement repeatability or dynamic noise¹ according to ISO25178 – 601) is a combination of the internal noise of the instrument, environmental noise and the noise of the *x* and *y* drive units in the measurement along the *z* axis when scanning. Generally, the measurement noise test is performed on a flat artefact with a maximum height of the scale limited surface (*Sz*) smaller than 30 nm, without filtering the measured data.

Two techniques that do not require a calibrated flat and that are capable of isolating the measurement noise from the intrinsic roughness of the sample, and any flatness deviation of the instrument, are presented in this guide. One technique isolates the noise by subtracting two measured topographies and the other technique averages several measured topographies such that the effect of the measurement noise is reduced by the square root of the number of measurements. In both techniques the measurement noise is estimated by measuring the root mean square (RMS) value of the scale limited surface, *Sq*.

The subtraction technique requires two repeated measurements at the same position on the sample in quick succession. The measurement noise (*Sq_{noise}*) can be estimated by the *Sq* of the resulting topography divided by the square root of two

$$Sq_{noise} = \frac{Sq}{\sqrt{2}}. \quad (1)$$

When using the averaging technique, the measurement noise is given by the equation (2)

$$Sq_{noise} = \sqrt{\frac{Sq^2 - Sq_{mean}^2}{1 - \frac{1}{n}}}, \quad (2)$$

¹ Noise occurring during the motion of the drive units on the output signal

where Sq is the root mean square height of the un-averaged surface topography, Sq_{mean} is the root mean square height of the averaged surface topography, and n is the number of repeated measurements that are averaged.

It is difficult to recommend an exact number n of repeated measurements but one approach is to make sufficient repeated measurements such that the estimated measurement noise does not change appreciably with an increased number of averaged topography data.

When it is not possible to apply these methods because there is not enough time for multiple measurements (such as in the stylus case) a calibrated flat should be used. In this case the instrument noise can be determined by directly comparing the measured Sq to the certified Sq of the flat. If possible, the calibration of the flat should have been performed in similar measurement conditions to those of the operational bandwidth of the instrument to be tested. For example, an optical areal surface topography measuring instrument (a phase shifting interferometer or coherence scanning interferometer) can be used to calibrate the flat. The drawback of the measurement noise estimation from one single measurement is that the effect of flatness will contribute to the magnitude of Sq . In this situation the measurement noise cannot be solely identified.

Example of calibrated flat method

The method relies on measuring the Sq of the flat and assuming that the noise contribution of the flat is smaller than that of the instrument. This type of test does not discriminate the form errors of the instrument that are not random in nature. In this example, the measurements were performed in a set-up similar to the one presented in figure 10.

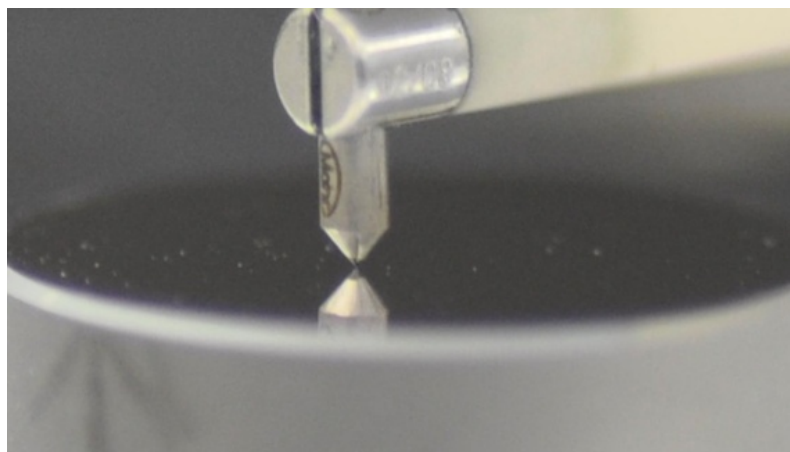


Figure 10 Measurement of a flat

Example measurement results for two measurement speeds are presented in table 6.

In this example, the flat was previously measured using a calibrated coherence scanning interferometer and the Sq value for a similar measurement spatial bandwidth did not exceed 3 nm.

Table 6 Measurement noise results using the calibrated flat method – filtered results

Measurement No.	0.1 mm s ⁻¹	0.5 mm s ⁻¹
	<i>Sq/nm</i>	
1	23	9
2	35	9
3	29	11
4	16	6
5	10	43
Root mean square	25	21

The noise measurements should be filtered before using them in measurement uncertainty calculations. According to the sampling distance, the smallest S-filter nesting index is 5 μm for the measurement that used a speed of measurement of 0.1 mm s⁻¹ and 10 μm and for the measurement that used a speed of measurement of 0.5 mm s⁻¹. The measuring window allowed for a 1 mm L-filter nesting index for both speeds of measurement.

Flatness deviation

Flatness deviation is a metrological characteristic that describes the quality of the areal reference of the instrument. The flatness errors originate from the non-ideal instrument optical components and their mounting.

Similarly to the measurement noise test, the flatness deviation test is performed on a flat artefact with a maximum height of the scale limited surface (S_z) smaller than 30 nm. In some instances this threshold value of 30 nm may not be low enough because there are instruments that are capable of measuring nanometre-scale roughness. A disadvantage of using a standard calibrated flat is the way that the flat is calibrated. Areal surface texture measuring instruments do not have similar measuring spatial bandwidths to the instruments commonly used to calibrate the flat artefact. The small wavelength filter used in the case of a calibrated flat could be as high as 0.5 mm, which is comparable in some circumstances to the size of the F-operator/L-filter nesting index. This means that the spatial bandwidth of interest is filtered out.

The flatness test uses a flat standard artefact, which is measured nominally perpendicular to the z axis of the instrument. The parameter used to quantify the quality of the areal guide is the *maximum height of the scale limited surface* (S_z). Often, the value of S_z is affected by local height variations such as scratches or dirt. The way to decrease the influence of these undesirable influence factors is to measure the topography of the flat at different locations by only moving the flat in the horizontal plane. The average surface should preserve the quality of the areal guide and diminish the influence of the contribution of the flat. The method is similar to the averaging method described in the *Measurement noise* section with the exception that, in the measurement noise test, the multiple measurements are performed at the same location of the flat.

In the case of instruments that are known to have flatness deviation larger than the S_z of the flat and its measurement noise, this averaging method does not need to be applied. In this case it is good practice to estimate the flatness deviation by measuring S_z directly without any other surface averaging on a calibrated flat.

Example of calibrated flat method

In this example the magnitude of the residual flatness of the instrument (caused mainly by the performance of the y axis stage) is larger than the S_z value reproduced by the flat standard artefact. In addition, the average method of measuring the residual flatness of the instrument is impracticable due to the non-systematic nature of the y axis stage behaviour. Thus, the direct comparison with a flat was preferred.

Experimental results are presented in table 7. The same measured data and filters used for measurement noise analysis were also used to calculate the residual flatness measurements, *i.e.* the S_z values.

Table 7 Flatness results – calibrated flat method

Measurement No.	0.1 mm s ⁻¹	0.5 mm s ⁻¹
	S_z/nm	
1	115	48
2	165	49
3	113	58
4	108	39
5	65	244
Average	113	88
Repeatability (σ_{S_z})	35	88

Amplification, linearity and perpendicularity

4

This chapter of the good practice guide aims to address the measurement challenges and provides measurement methodologies for three of the metrological characteristics: amplification coefficient, linearity error and perpendicularity of the axes. Figure 11 shows a typical example of a linear response curve. The maximum linearity error is given by the maximum deviation of the instrument response curve from the linear curve where the slope is the amplification coefficient.

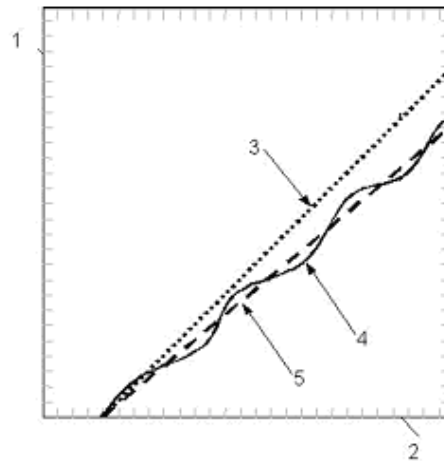


Figure 11 (ISO 25178 part 601: 2010) Example of an instrument response curve, where: 1 measured quantities, 2 input quantities, 3 ideal response curve, 4 response curve, 5 linear curve whose slope is the amplification coefficient

z axis measurement calibration

The calibration of the z amplification coefficient (α_z), linearity error (I_z) and perpendicularity consists of a series of measurements of a range of step height standard artefacts with various heights to establish the relationship between the ideal response curve and the instrument response curve. This calibration provides information about the z axis linearity errors and amplification coefficient.

The range of different step height standard artefacts should cover the entire working range in z or at very least should cover the range of interest. The linearity errors 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 constrained to pass through (0, 0) (see next example).

The amplification coefficient can be calculated using equation (3)

$$\alpha = \frac{\sum_{i=1}^n C_i I_i}{\sum_{i=1}^n C_i^2}, \quad (3)$$

where α is the amplification coefficient, C_i is the calibrated value, I_i is indicated value and n represents the number of different step height standard artefacts used.

Currently there is no standardised analysis for step height standard artefact measurement in areal mode. One method of measuring the height of the step height standard artefact that uses the areal data and standard height analysis (ISO 5436 part 1) is to calculate the height from the average of all parallel extracted profiles that run nominally perpendicular to the step direction.

Figure 12 presents a flowchart of the analysis of the measured step height standard artefact in areal mode (figure 12 top). The ISO 5436 part 1 analysis (figure 12 bottom) is performed on the central groove of the mean profile (figure 12 centre).

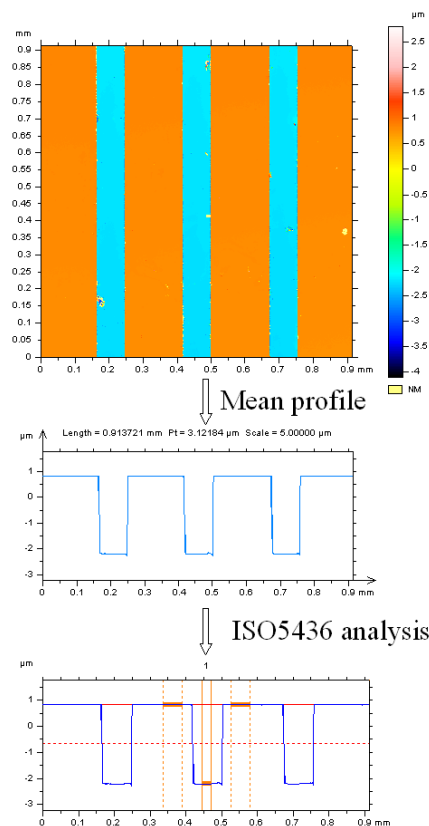


Figure 12 Flow chart of step height standard artefact analysis

An advantage of the calibration with multiple step height standard artefacts is that it accounts for x - z and y - z perpendicularity errors. The cosine error that is introduced by the z axis squareness behaves as an amplification error.

Example of calibration of α_z and l_z

When calibrating α_z and l_z of the instruments that use an xy raster scanning system the user should have the fast axis oriented nominally perpendicular to the groove length of the step

height standard artefact (see figure 13). In this orientation of the step height standard artefact relative to the fast axis of the instrument, the effects of flatness errors of the slow axis, that are generally larger than the flatness error of the fast axis, of the instrument will be minimised.

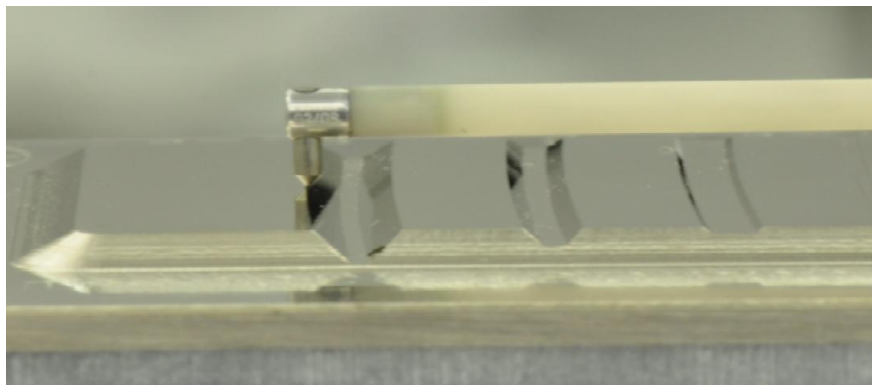


Figure 13 Measurement of a PGR type of material measurement standard

Four different step height standard artefacts (initially calibrated using the NPL Areal Instrument – a traceable stylus instrument) are measured only in the centre of the z working range. The step height standard artefacts were measured five times, which allowed a calculation of the repeatability of the measurements, Type A uncertainty (see NPL GPG 11⁴ for definition of repeatability). A summary of the results is presented in table 8: the measurement error (δ_{err}) is calculated as the difference between the measured value and the calibrated value; the repeatability (δ_{repeat}) of the step height standard artefact measurements was taken to be the standard deviation of the mean value; and the standard uncertainty of the step height standard artefacts calibrated with the NPL Areal Instrument is taken to be the traceability contribution (0.9 nm in this case).

Table 8 Summary of αz and l_z calibration results

Nominal height	18 nm	350 nm	3 μm	17 μm
$\delta_{\text{err}} / \text{nm}$	1.5	11.6	99.7	547.2
$\delta_{\text{repeat}} / \text{nm}$	0.5	0.1	0.7	2.1

The calibration of αz and l_z of the stylus instrument (see figure 14) shows an amplification coefficient significantly different from one. The standard error bars are a combination of the measurement repeatability and the calibration standard uncertainty of the step height standard artefacts.

⁴ Bell S 1999 A beginner's guide to uncertainty of measurement *Good Practice Guide No. 11* (National Physical Laboratory)

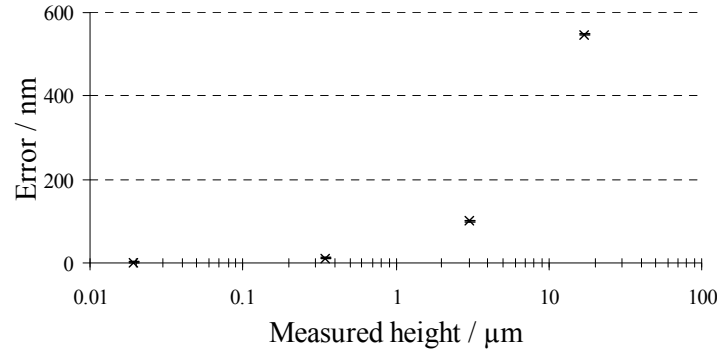


Figure 14 Calibration of α_z and l_z – error plot

Using equation (3), α_z is calculated and is found to be 1.032 18. The slope correction does leave an absolute residual error, which is a measure of l_z , of about 2 nm (see figure 15).

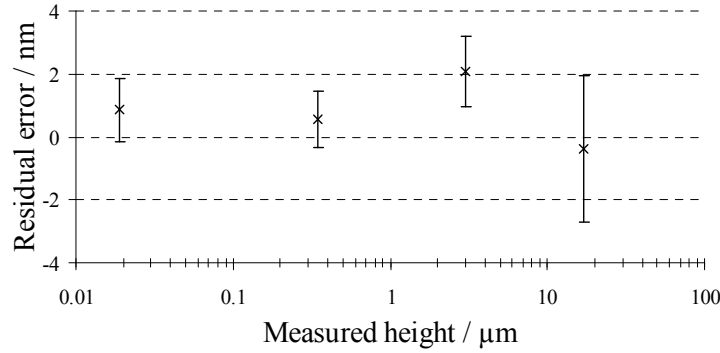


Figure 15 Calibration of α_z and l_z – residual error plot

x and y axis measurement calibration

In a similar manner to the z measurement calibration, but with a different standard artefact, the x and y measurement can be calibrated. The x and y amplification coefficients (α_x and α_y), linearity errors (l_x and l_y) and the perpendicularity (Δ_{PER}) can be measured using a calibrated cross grating standard artefact (type ACG) (see figure 16). For the measurement of amplification and linearity of the lateral axes the centre of gravity of the squares of the cross grating can be used. The perpendicularity deviation of the x and y axes can be determined by measuring the angle between two nominally orthogonal rows of square holes. The orientation of each row of square holes can be calculated by fitting a line through the centre of gravity of the corresponding squares. The measured topography should be levelled. A feature identification algorithm should be used to isolate the square holes. The position of the centre of gravity in the x and y direction can be determined using the centre of gravity of the square hole.

$$x_i = \frac{\sum x_{ij} z_{ij}}{\sum z_{ij}} \quad (4)$$

Free software that calculates the centre of gravity is available for download (see NPL Report ENG 45⁵).

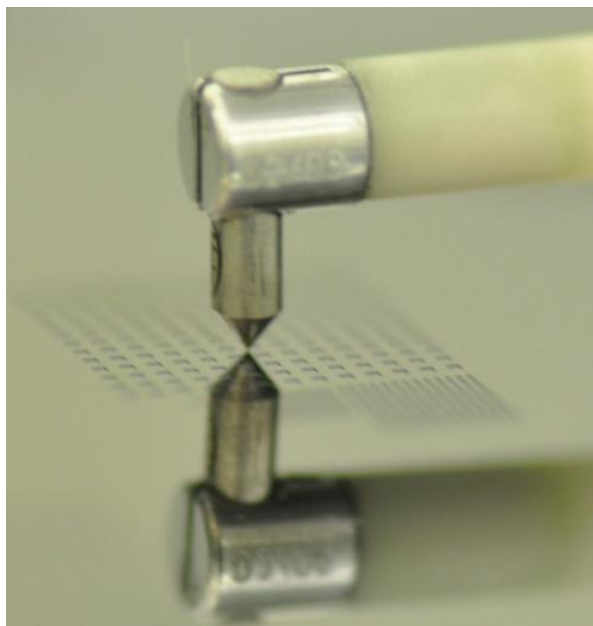


Figure 16 Measurement of a type ACG of material measurement standard

Example of calibration of α_x , α_y , l_x and l_y

To illustrate the process of calibration, a 100 μm pitch cross-grating (initially traceably calibrated using the NPL Areal Instrument) can be used to calibrate a typical instrument (see figure 17).

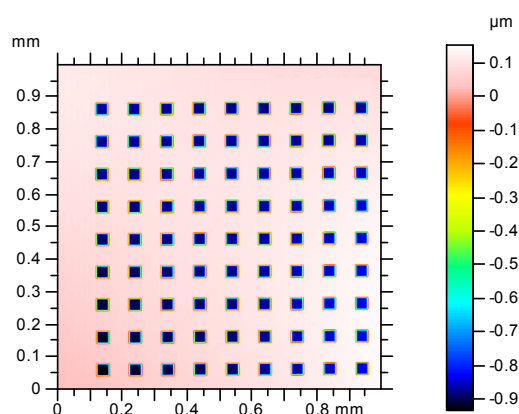


Figure 17 100 μm pitch cross grating measured by the NPL Areal Instrument

⁵ Smith I M and Giusca C L 2013 Areal Lateral Calibration Software: User Manual *Report ENG 45* (National Physical Laboratory)

The cross-grating is measured five times in the same position in the x and y working range. In order to minimise the effect of the cross-talk, the cross gratings are oriented such that the rows of squares are as parallel as possible to the x and y axes of operation of the test instrument. A maximum of 5° misalignment of the cross grating axis to the x and y axes of the instrument under test will have an insignificant effect in terms of measurement uncertainty contribution of one axis of the instrument to another, if the measurement uncertainties associated with the measurements along the x and y axes of the instrument are comparable. That is not to say that the contribution of one axis, say the y axis, has to be excluded completely from the measurement of the cross grating along of the other axis, say the x axis, and *vice versa*. The length along one of the axes has to be calculated using both x and y axis measurements.

It is good practice to filter the measured topographies using a Gaussian S-filter equal to a tenth of the nominal pitch reproduced by the cross grating. In this way the effect of noise and spurious data is minimised.

Example calibration results αx , αy , $l x$ and $l y$ are presented table 9: the measurement error (δ_{err}) is calculated as the difference between the measured value and the calibrated value; the repeatability (δ_{repeat}) is expressed as the standard deviation of the mean value of five measurements.

Table 9 Summary of αx , αy , $l x$ and $l y$ calibration results

Nominal value	x axis		y axis		
	δ_{err}	δ_{repeat}	δ_{err}	Residuals	δ_{repeat}
/ μm					
100	0.14	0.32	13.4	0.7	0.9
200	0.05	0.18	25.8	0.5	1.4
300	-0.04	0.30	35.1	-2.5	1.0
400	-0.08	0.20	46.0	-4.0	1.2
500	-0.12	0.25	61.1	-1.8	1.0
600	-0.21	0.30	77.1	1.3	0.9
700	-0.05	0.24	92.0	3.3	1.1
800	0.00	0.23	-	-	-

The calibration results αx , αy , $l x$ and $l y$ are also presented in figure 18, figure 19 and figure 20. The standard error bars are a combination of the measurement repeatability and the calibration standard uncertainty of the ACG artefacts.

The measurement errors along the x axis are within the repeatability limits (see figure 18) but the measurement along the y axis shows an amplification coefficient of 1.126 1 (see figure 19). $l y$ does not exceed $4 \mu\text{m}$ (see figure 20).

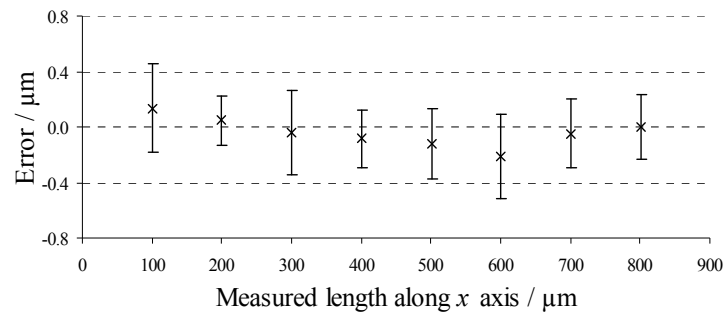


Figure 18 Calibration of αx and l_x – error plot

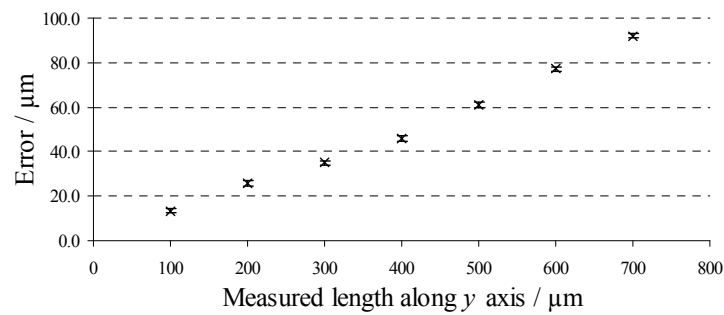


Figure 19 Calibration of αy and l_y – error plot

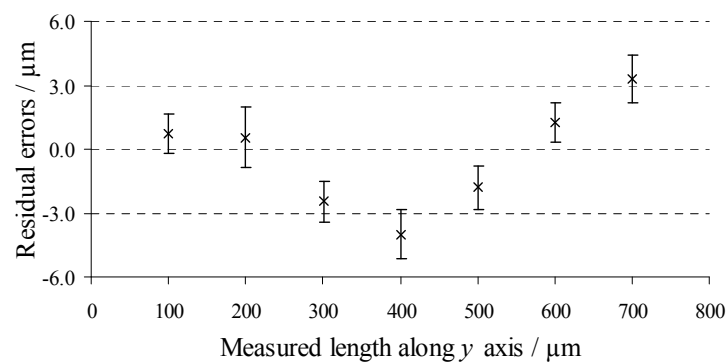


Figure 20 Calibration of αy and l_y – residuals plot

Using the same measurement results, the absolute squareness error between the x and y axes was found to be 1.1° with an associated standard deviation of the mean of 0.05° . The maximum effect of the squareness error is in this case approximately 0.02 % of the measured length. For the maximum possible measured length of 1.4 mm (diagonal measurement in the $1\text{ mm} \times 1\text{ mm}$ area) the cosine error translates to an absolute length error of $0.25\text{ }\mu\text{m}$, which is far smaller than the l_y residual errors.

Measurement uncertainty

5

This chapter presents methods for calculating the contribution of the calibration of the metrological characteristics to the uncertainty associated with the co-ordinate measurements of areal surface topography measuring instruments. The uncertainty is calculated according to the guidelines given in the *Guide to the Expression of Uncertainty in Measurement (GUM)*. See also NPL GPG 11.

The standard uncertainty associated with a measurement result can be written as the square of a quadratic sum of two components the Type A and Type B measurement uncertainty,

$$u = \sqrt{u_A^2 + u_B^2} \quad (5)$$

where u is the combined standard uncertainty, u_A is the Type A standard uncertainty and u_B is the Type B standard uncertainty. The Type A evaluation of standard uncertainty is determined statistically. According to the *GUM* the components of the Type B measurement uncertainty are taken from: *experience with or general knowledge of the behaviour and properties of relevant materials and instrument; manufacturer's specification; data provided in calibration and other certificates and uncertainties assigned to reference data taken from handbooks.*

The difference between Type A and type B evaluation of standard uncertainties is that the former is based on a frequency distribution (taken from repeated measurements) and the latter is based on an *a priori* distribution (known information that can also be given by a standard deviation).

If its components are uncorrelated, the Type B evaluation of standard uncertainty can be calculated using

$$u_B^2 = \sum_{i=1}^n C_i^2 u^2(x_i) \quad (6)$$

where C_i is the i^{th} sensitivity coefficient (see *GUM*) and the $u(x_i)$ is the uncertainty associated with the i^{th} component.

The contribution of the calibration of the metrological characteristics is part of the Type B evaluation of standard uncertainty (although measurement noise is often a random effect, the model of calibration that uses the metrological characteristics treats it as a type B component). That is to say that each of the metrological characteristics of the instrument represents a separate component of the Type B standard uncertainty.

Measurement noise and flatness deviation contribution

The results of the tests for the measurement noise and flatness deviation should be filtered before considering them in the uncertainty calculation. Table 10 presents the minimum S- and the maximum L-filter that are specific for each measurement condition (the values of the S-filter given in table 10 are based on the sampling spacing).

Table 10 S-filter is based on the maximum sampling spacing

ISO25178 part 3 filters	0.1 mm s⁻¹	0.5 mm s⁻¹
S-filter / μm	5	10
L-filter / mm	1	1

a) Un-calibrated flat method

If the measurement noise can be estimated separately from the flatness deviation, the measurement noise contribution to the overall measurement uncertainty is propagated in the form of a normal distribution that has an expectation equal to zero and a variance equal to the square of the value of the measurement noise. The residual flatness contribution to the measurement uncertainty is propagated in the form of a rectangular distribution that has a variance equal to the $Sz_{flatness}^2/12$. The combined effect of the measurement noise and residual flatness on the z axis measurement standard uncertainty u_{NF} is given by

$$u_{NF} = \sqrt{Sq_{noise}^2 + \frac{Sz_{flatness}^2}{12}} \quad (7)$$

b) Un-calibrated flat method

Using the calibrated flat method as presented in section 3 the measurement noise and the flatness deviation are superimposed such that their combined contribution is propagated in the form of a rectangular distribution with inexactly prescribed limits that has a variance equal to the $Sz_{flatness}^2/12 + \sigma_{Sz}^2/9$. The calibration of the flat should be included as the third term. The reason for not combining the flat calibration contribution with the standard deviation of Sz is that, in this example, the σ_{Sz} is very large compared to the flat calibration (3 nm).

The combined effect of the measurement noise and flatness deviation on the z measurement standard uncertainty is presented in table 11 for the two scannig speeds used as examples.

Table 11 Measurement noise and residual flatness contribution to the uncertainty associated with the measurements along the z axis

Scanning speed / mm s ⁻¹	0.1	0.5
Uncertainty (u_{NF}) / nm	35	39

Amplification, linearity and perpendicularity

In practice the calculated amplification coefficients (αx , αy and αz) are either used to adjust the instrument or the instrument is used without correction. The adjustment process also implies that the amplification and linearity tests have to be repeated. This means that the contribution of the amplification coefficient and linearity errors to the measurement uncertainty can be calculated as a combination of the measurement errors, traceability, reproducibility and repeatability.

The contribution of the linearity errors to the measurement uncertainty (u_{error}) is propagated in the form of a rectangular distribution that has a variance equal to the square of the value of the error divided by three ($\delta^2_{\text{error}}/3$). The repeatability contribution to the overall measurement uncertainty (u_{repeat}) is propagated in the form of a normal distribution that has an expectation equal to zero and a variance equal to the square of the value of the repeatability (δ^2_{repeat}). The combined effect of the measurement errors, traceability ($u_{\text{traceability}}$), repeatability and/or reproducibility on the co-ordinate measurement standard uncertainty u_{T-x} , u_{T-y} and u_{T-z} is given by

$$u_{T-i} = \sqrt{u_{\text{traceability}}^2 + u_{\text{repeat}}^2 + u_{\text{error}}^2} \quad (8)$$

where $i = \{x, y, z\}$.

The cosine errors of the z axis relative to the areal reference guide are included into the measurement errors along the z axis. The perpendicularity between the x and y axis contribution to the measurement uncertainty is propagated in the form of a rectangular distribution that has a variance equal to the square of the value of the maximum possible length error produced by the cosine error divided by three.

Another term to be added into equation (8) is the measurement reproducibility. The reproducibility should be included if the instrument is used at different positions in the working range. For example, the instrument can be used to measure height differences at different positions in z range not only at 50 %. The metrological characteristics should be tested at different positions in the working range of the instrument (x , y and z) such that the reproducibility can be calculated.

Example of uncertainty associated with z measurement

An example of the standard measurement uncertainties associated with the calibration of the z scale is presented in table 12. The instrument has small linearity errors that allow the

combined contribution of the amplification coefficient and linearity errors to the z standard measurement uncertainty to be below 3 nm of the measured height, throughout the calibrated range, when the instrument is adjusted.

Table 12 Amplification and linearity contribution to the z measurement uncertainty

Nominal height	δ_{error}	adjusted δ_{error}	δ_{repeat}	$u_{\text{traceability}}$	u_{T-z}	adjusted u_{T-z}
	/nm					
18 nm	1.5	0.9	0.5	0.9	1.3	1.1
350 nm	11.6	0.6	0.1	0.9	6.8	1.0
3 μm	99.7	2.1	0.7	0.9	58	1.6
17 μm	547.2	-0.4	2.1	0.9	316	2.3

Example of uncertainty associated with x measurement

An example of the standard measurement uncertainties associated with the x measurement is presented in table 13. The adjustment in this case was not necessary as the repeatability value is larger than the maximum absolute value of the error.

Table 13 Amplification and linearity contribution to the x measurement uncertainty

Nominal height μm^{-1}	δ_{error}	δ_{repeat}	$u_{\text{traceability}}$	u_{T-x}
	/ μm			
100	0.14	0.32	0.017	0.33
200	0.05	0.18	0.021	0.18
300	-0.04	0.30	0.022	0.31
400	-0.08	0.20	0.033	0.21
500	-0.12	0.25	0.024	0.26
600	-0.21	0.30	0.045	0.32
700	-0.05	0.24	0.037	0.24
800	0.00	0.23	0.049	0.23

Example of uncertainty associated with y measurement

An example of the standard measurement uncertainties associated with the y measurement is presented in table 14. If the y measurements are adjusted the measurement uncertainty drops significantly and the repeatability value becomes comparable to the maximum absolute value of the error.

Table 14 Amplification and linearity contribution to the y measurement uncertainty

Nominal height μm^{-1}	δ_{error}	adjusted δ_{error}	δ_{repeat}	$u_{\text{traceability}}$	u_{T-y}	adjusted u_{T-y}
	/ μm					
100	13.4	0.7	0.9	0.016	7.8	1.0
200	25.8	0.5	1.4	0.019	15	1.5
300	35.1	-2.5	1.0	0.021	20	1.7
400	46.0	-4.0	1.2	0.013	27	2.6
500	61.1	-1.8	1.0	0.016	35	1.5
600	77.1	1.3	0.9	0.013	45	1.2
700	92.0	3.3	1.1	0.014	53	2.2

Example of uncertainty associated with x and y perpendicularity

The perpendicularity contribution to the measurement uncertainty ($u_{\text{squareness}}$) is $0.14 \mu\text{m}$, based on the error of $0.25 \mu\text{m}$ estimated for the maximum possible measured length of 1.4 mm (diagonal measurement in the $1 \text{ mm} \times 1 \text{ mm}$ area).

Combined uncertainty

The combined contribution of the metrological characteristics calibration can be calculated using equation (6), where the sensitivity coefficients (C_i) are all equal to one and $u(x_i)$ is the contribution of each of the metrological characteristics to the measurement uncertainty. The models for calculating the contribution of the calibration of the x , y and z scales are given below

$$\begin{cases} u_x = u_{T-x} \\ u_y = u_{T-y} \\ u_z = \sqrt{u_{NF}^2 + u_{T-z}^2} \end{cases} \quad (9)$$

There are different ways of presenting the measurement uncertainty associated with the calibration of the metrological characteristics of the instrument. One way is presented in Table 12 to Table 14, but also the uncertainty can be presented as a sum of length proportional terms and a fixed term, or only as a fixed term. The uncertainty expressed as a combination of length proportional terms and a fixed term is useful to use for the case in which the amplification coefficient is considerably larger than the linearity errors and is not corrected or adjusted. The fixed term representation is used when an overall value of the measurement uncertainty associated with the coordinate measurements is required.

The uncertainties associated with the z measurements after instrument adjustment are dominated by the residual flatness and measurement noise contribution, which makes the standard uncertainty associated with the z measurement as large as 40 nm.

The measurement uncertainties associated with the y measurements after instrument adjustment are dominated by the linearity errors and measurement repeatability, such that the standard measurement uncertainty is in excess of 2.6 μm .

Summary of calibration results

The calibration results can be summarised using the template presented in table 15.

Table 15 Template for summary of calibration results

Metrological characteristic (Unit)	Comments	Value /Unit	Uncertainty contribution /Unit
x y measurements			
amplification and linearity (.....)	<i>Physical measurement standard SNo / Type:</i> Nominal pitch:.....mm <i>Calibrated range:</i> x range:.....mm y range:.....mm z range:.....mm	<i>Tested measurement range:</i> x range: from.....% to% y range: from.....% to% z range: from.....% to%	
x and y perpendicularity (.....)	<i>Physical measurement standard SNo / Type:</i> <i>Method used:</i>	<i>Tested measurement range:</i> x range: from.....% to% y range: from.....% to%	
resolution (.....)	<i>Physical measurement standard (s) SNo / Type:</i> <i>Method used:</i>	<i>Tested measurement range:</i> x range: from.....% to% y range: from.....% to%	
x y standard uncertainty (.....)			
z measurements			
Measurement noise (.....)	Filters nesting index: S-filter:.....µm L-filter:.....mm Method used: Subtraction Addition Calibrated flat	Physical measurement standard S/No:..... Calibrated: Yes/No <i>Tested measurement range:</i> x range: from.....% to% y range: from.....% to% z range: from.....% to%	
Residual flatness (.....)	Filters nesting index: S-filter:.....µm L-filter:.....mm Method used: Average Calibrated flat	Physical measurement standard S/No:..... Calibrated: Yes/No <i>Tested measurement range:</i> x range: from.....% to% y range: from.....% to% z range: from.....% to%	
amplification, linearity (.....)	<i>Physical measurement standard (s) SNo / Type:</i> Nominal value(s):.....mm <i>Calibrated range:</i> z range:.....mm	<i>Tested measurement range:</i> x range: from.....% to% y range: from.....% to% z range: from.....% to%	
z standard uncertainty (.....)			

Measurement Examples

6

This chapter provides a number of examples in which the results of the calibration tests are used to calculate the measurement uncertainty associated with the measurement and calculation of the height on a type PGR of material measurement standard, and of Sq on a type AIR of material measurement standard.

The contribution of the metrological characteristics to the uncertainty associated with the calculation of a parameter from an areal measurement has to be considered on a case by case basis. For example, the calculation of the height of a type PGR material measurement standard requires averaging the measured profiles along the y axis, which has a different effect on the flatness deviation contribution from the effect of the L-filter that is used in the calculation of areal parameters. Following this, it is useful to fill in the summary table (see table 15) of the calibration results for each measurement case.

In addition, the summary table can be amended with new cells to allow the input of other influence factors that contribute to the measurement uncertainty associated with the parameter calculation, such as Type A uncertainty (repeatability) or the contribution of the software that is used to calculate areal surface texture parameters.

Example 1 - Step height (type PGR) measurements

The step height physical measurement standard measured in this example is similar to the 350 nm step height physical measurement standard used to calibrate the z scale of the instrument (see table 18). The central groove is the measurement groove. The other two grooves are for position identification only.

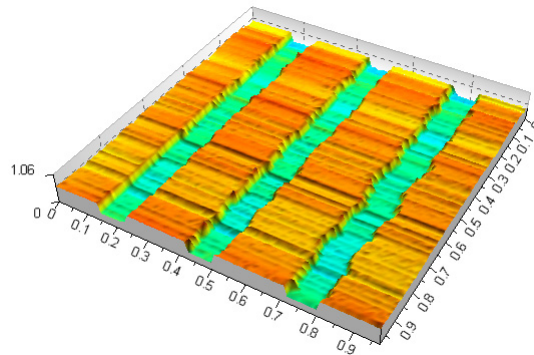


Figure 21 Measurement result of a 350 nm step height physical measurement standard

According to equation (5) the standard measurement uncertainty associated with the step height measurement is a combination of Type A and Type B measurement uncertainties. The Type A measurement uncertainty is given by the standard deviation of the mean value of the minimum of three repeated measurements. The Type B measurement uncertainty will include the measurement noise, the flatness deviation contribution and a linearity and amplification contribution, and it is given by

$$u_B^2 = C_{NF}^2 u_{NF}^2 + C_{T-z}^2 u_{T-z}^2 \quad (9)$$

Measurement noise and flatness deviation contribution

Since the step height analysis in areal mode calculates the mean profiles along the x axis of the instrument (see figure 22) some of the effects of the y axis flatness deviation on the measurement uncertainty associated with the step height calculation are diminished.

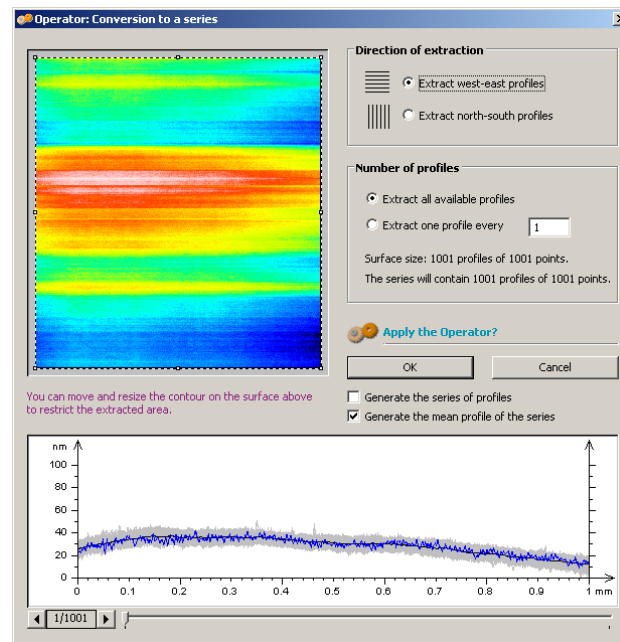


Figure 22 Extraction of mean profile along the x axis

As the step height calculation uses a limited area of the measured topography, only 0.3 mm in the 350 nm physical measurement standard case, the contribution of the measurement noise and flatness deviation has to be calculated on a reduced length of the mean profile (see figure 23).

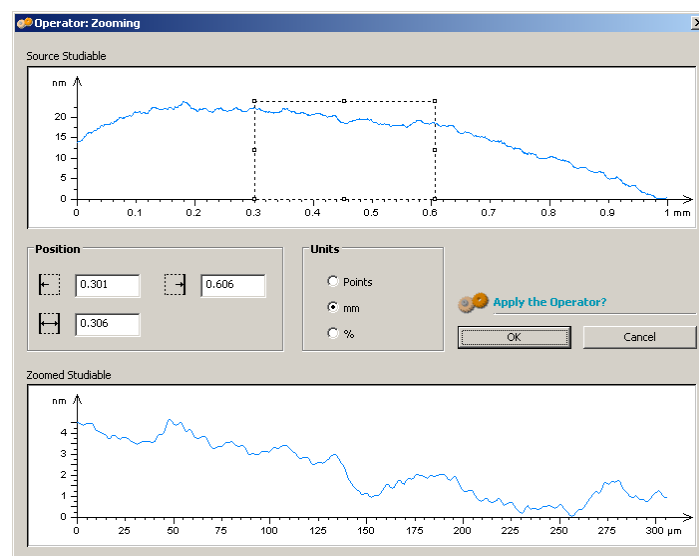


Figure 23 Zoom operation of the mean profile

The u_{NF} for a step height measurement can be estimated by measuring Pt , directly without any surface averaging, on a flat (note that Pt was used instead Sz as the analysis is performed on a profile). The measurement noise and the flatness deviation are superimposed such that their combined contribution is propagated in the form of a rectangular distribution with inexactly prescribed limits that has a variance equal to $Pt_{flatness}^2/12 + \sigma_{PT}^2/9$, where σ_{PT} is the standard deviation. It follows that the u_{NF} for the 350 nm step height measurement for 0.5 mm s^{-1} speed of scanning is 0.66 nm (see table 16).

Table 16 Example of u_{NF} values for 0.5 mm s^{-1} speed of scanning

Measurement No.	Pt /nm
1	2.64
2	2.15
3	2.50
4	1.89
5	2.26
Average	2.29
Repeatability (σ_{Sz})	0.13
u_{NF}	0.66

The step height analysis algorithm calculates the distance between two parallel lines that are fitted through a restricted number of the topography data points (see figure 24). In this situation, the sensitivity coefficients that are used to propagate the measurement noise and flatness deviation component are given by equation (10)

$$C_{NF}^2 = \frac{3d}{W} + \frac{3d}{4W} = 3.75 \frac{d}{W}, \quad (10)$$

where C_{NF} is the sensitivity coefficient, d is the sampling interval and W is the width of the groove. For a Type PGR step height physical measurement standard similar to the one presented in figure 24, the width of the groove is approximately 0.09 mm. If the sampling interval is $1 \text{ } \mu\text{m}$ the C_{NF} is approximately $0.042^{1/2}$.

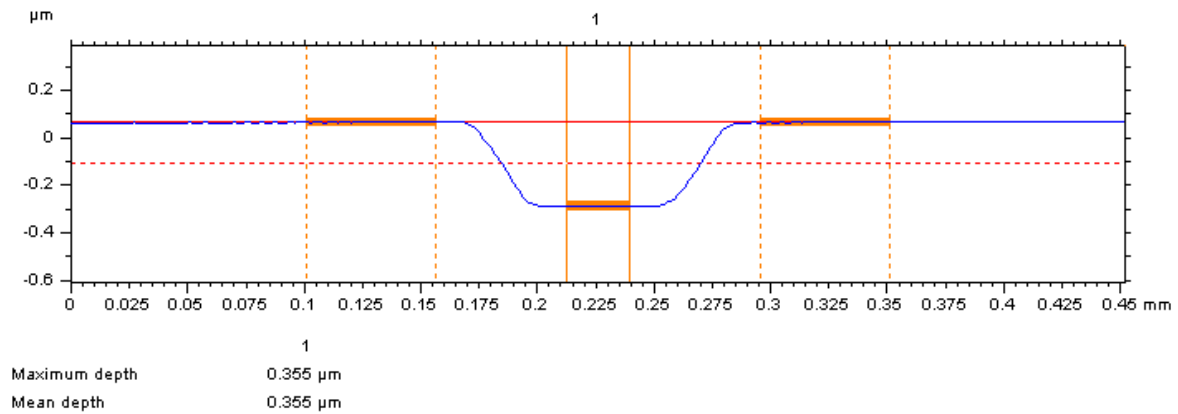


Figure 24 Example of step height analysis in profile mode

Amplification and linearity contribution

The contribution of amplification and linearity remains unchanged such that in the u_{T-z} will not exceed 2.3 nm (see table 10) and the sensitivity coefficient will be equal to one.

Type A evaluation of standard uncertainty

The Type A standard uncertainty is calculated as the standard deviation of the mean of three repeated measurements (see table 17 for example). If the non-uniformity of the physical measurement standard is not known, the three repeated measurements can be performed at slightly different positions along the length of the groove such that the Type A standard uncertainty will account for non-uniformity of the physical measurement standard.

Table 17 Measurements of a 350 nm step height physical measurement standard

Measurement No.	Height /nm
1	348.83
2	348.68
3	348.97
Average	348.83
u_A	0.08

Combined standard uncertainty

According to equation (5) the combined standard uncertainty associated with the step height standard artefact measurement is:

$$u^2 = u_A^2 + u_B^2 = (0.08^2 + 0.042^2 \times 0.66^2 + 2.3^2) \text{ nm}^2 \cong 2.4^2 \text{ nm}^2 \quad (11)$$

Expanded uncertainty

The calculation of the expanded uncertainty requires the value of the coverage factor (k) for a 95 % confidence level. Assuming that the type B components are exactly known, the value of the coverage factor is based on the number of effective degrees of freedom (ν) that can be calculated with

$$\nu = (n-1) \times \frac{u^4}{u_A^4} \quad (12)$$

Values for k can be obtained from table G2 on page 78 of *JCGM 100:2008 Evaluation of measurement data — Guide to the expression of uncertainty in measurement* (http://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf).

For this example the coverage factor is equal to two because

$$\nu = 2 \times \frac{2.3^4}{0.08^4} \cong \infty \quad (13)$$

It follows that the measurement result can be expressed as:

$$h = (348.8 \pm 4.6) \text{ nm}, (k = 2) \quad (14)$$

A summary of the calibration results can be presented in a table similar to table 18.

Table 18 Main uncertainty components affecting the depth calculation of step height standard artefact of 350 nm

Uncertainty component (Unit)	Comments	Value /Unit	Sensitivity coefficient /Unit	Uncertainty contribution/ Unit
Measurement noise and flatness deviation (nm)	Filters nesting index: S-filter: N/A μm L-filter: N/A mm	0.66	0.042	0.028
	Method used: Flat measurement			
Amplification and linearity of the z scale (nm)	Physical measurement standard S/No: Platen B Calibrated: Yes/No	2.3	1	2.3
	Tested measurement range: x range: (0 to 1.4) mm y range: 50 % ± 1 mm z range: 50 %			
Type A (nm)	Physical measurement standard type/SNo: PGR/16237			0.08
Depth standard uncertainty				2.3

Example 2 –Type AIR test

In this example an type AIR of physical measurement standard was measured (see figure 25) and only the Sq parameter was compared with the calibrated value. The measurement area of the physical measurement standard is a square with a nominal side of 1.5 mm.

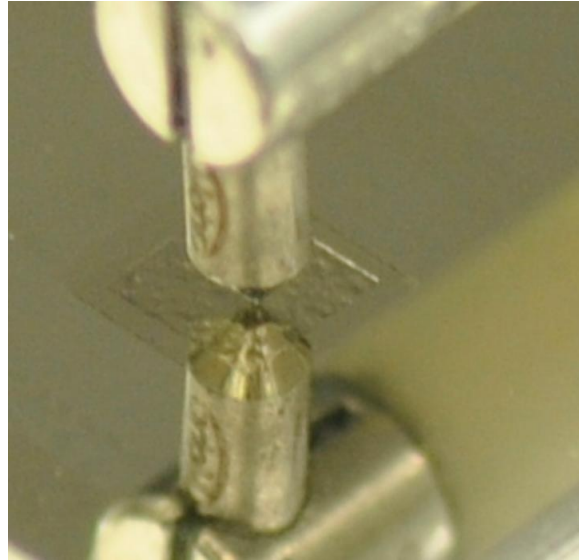


Figure 25 Measurement of an type AIR physical measurement standard

Three measurements are performed at a speed of scanning along the x axis of 0.5 mm s^{-1} (see figure 26) with a $2 \mu\text{m}$ sampling distance in both x and y directions. The Sq value was calculated in a central region of 1 mm by 1 mm of the physical measurement standard.

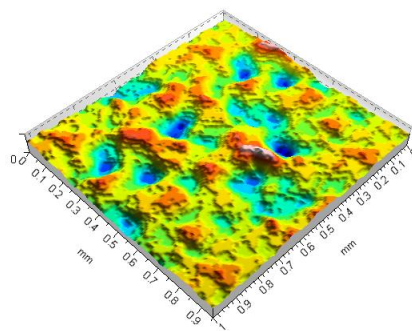


Figure 26 Measurement result of the central area of the type AIR physical measurement standard

The standard uncertainty associated with the type AIR physical measurement standard measurement is a combination of type A and type B measurement uncertainties. The type A measurement uncertainty is given by the standard deviation of the mean value of a minimum of three repeated measurements. The type B measurement uncertainty will include the

measurement noise – the flatness deviation contribution and a linearity and amplification contribution, and it is given by equation (9), where the sensitivity coefficients have to be recalculated to suit the conditions of the current measurement example.

Measurement noise and flatness deviation contribution

The value of the measurement noise and flatness deviation uncertainty component that affects the z axis measurements is directly taken from table 9, and is in this case is 39 nm.

The value of Sq is calculated using the model given in equation (15)

$$Sq = \sqrt{\frac{\sum_{NM} (z_{ij} - \bar{z})^2}{NM}}, \quad (15)$$

where N is number of points measured along the x axis, M is number of points measured along the y axis, the z_{ij} is a height measurement corresponding to an arbitrary position inside the NM grid of points and $\bar{z}$ is

$$\bar{z} = \frac{\sum_{NM} z_{ij}}{NM} \quad (16)$$

C_{ij} is the sensitivity coefficient corresponding to z_{ij} and is calculated using

$$C_{ij} = \frac{\partial Sq}{\partial z_{ij}} \cong \frac{1}{Sq} \frac{|z_{ij} - \bar{z}|}{NM} \quad (17)$$

Considering that the contribution of the NM height measurements to the Sq measurement uncertainty has a correlated effect, the residual flatness and measurement noise contribution to the Sq measurement uncertainty can be calculated as follows

$$u(NF) = \sum_{NM} C_{ij} u_{NF} = \frac{Sq}{Sq} u_{NF} \quad (18)$$

Amplification and linearity contribution

The calculation of the amplification and linearity of the contribution to the Sq measurement uncertainty can be performed in the same manner as in the $u(NF)$ case

$$u(T - z) = \sum_{NM} C_{ij} u_{T-z} = \frac{Sa}{Sq} u_{T-z} \quad (19)$$

It follows that

$$u_B = \frac{Sa}{Sq} \sqrt{u_{NF}^2 + u_{T-z}^2} \quad (20)$$

Type A evaluation of standard uncertainty

Type A uncertainty is calculated as the standard deviation of the mean of three repeated measurements (see table 19).

Table 19 Measurements of type AIR standard artefact

Measurement No.	<i>Sq</i> /nm
1	943
2	942
3	920
Average	935
u_A	7

Combined standard uncertainty

The uncertainty associated with the measurement of the type AIR physical measurement standard is given by equation (21)

$$u^2 = u_A^2 + u_B^2 = \left[7^2 + \frac{723^2}{935^2} (39^2 + 2.3^2) \right] \text{nm}^2 \cong 31^2 \text{nm}^2 \quad (21)$$

Expanded uncertainty

Using equation (12) to calculate the number of effective degrees of freedom, the coverage factor was found to be $k = 2$. It follows that the measurement result can be expressed as

$$Sq = (0.94 \pm 0.06) \mu\text{m}, (k = 2). \quad (22)$$

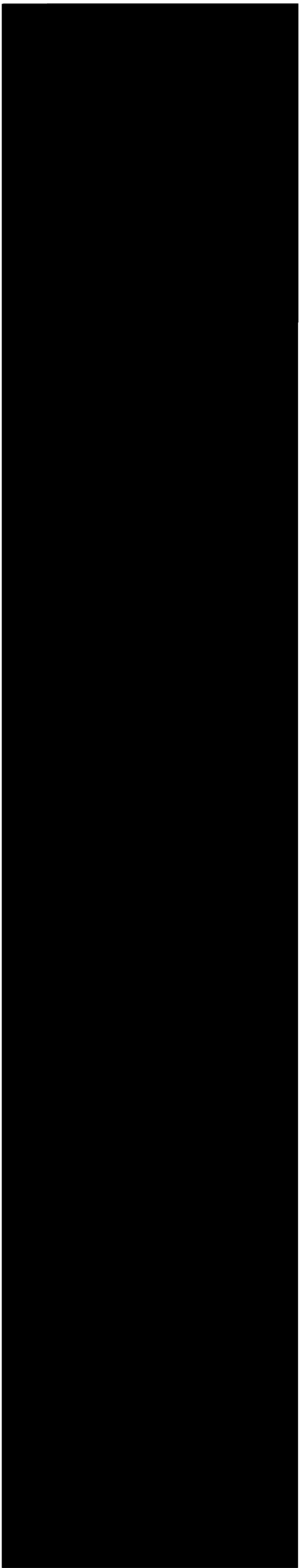
The calibrated value of Sq at the same position was $(918 \pm 5) \text{ nm}$ ($k = 2$), which gives a measurement error of 17 nm, well within the standard uncertainty associated with the measurement of Sq by this stylus instrument.

A summary of the calibration results can be presented in a table similar to table 20.

Table 20 Main uncertainty components affecting the Sq calculation of $0.9 \mu\text{m}$

Uncertainty component (Unit)	Comments	Value /Unit	Sensitivity coefficient /Unit	Uncertainty contribution/ Unit
Measurement noise and flatness deviation (nm)	Filters nesting index: S-filter: 10 μm L-filter: 1 mm Method used: Flat measurement Physical measurement standard S/No: Platen B Calibrated: Yes/No Tested measurement range: x range: (0 to 1.4) mm y range: 50 % ± 1 mm z range: 50 %	39	0.77	30
Amplification and linearity of the z scale (nm)	Calibrated z range: (0.018 to 17) μm Tested measurement range: x range: (0 to 1.4) mm y range: 50 % ± 1 mm z range: 50 %	2.3	0.77	1.8
Type A (nm)	Artefact type/SNo: ADT/123			7
Sq standard uncertainty				31

Appendices



Links to other useful sources of information

National and international organizations

National Physical Laboratory

The National Physical Laboratory (NPL) is the UK's National Measurement Institute and is a world-leading centre of excellence in developing and applying accurate measurement standards, science and technology. For more than a century NPL has developed and maintained the nation's primary measurement standards. These standards underpin an infrastructure of traceability throughout the UK and the world that ensures accuracy and consistency of measurement.

NPL ensures that cutting edge measurement science and technology have a positive impact in the real world. NPL delivers world-leading measurement solutions that are critical to commercial research and development, and support business success across the UK and the globe.

Good measurement improves productivity and quality; it underpins consumer confidence and trade and is vital to innovation. NPL undertakes research and shares its expertise with government, business and society to help enhance economic performance and the quality of life.

NPL's measurements help to save lives, protect the environment, enable citizens to feel safe and secure, as well as supporting international trade and companies to innovation. Support in areas such as the development of advanced medical treatments and environmental monitoring helps secure a better quality of life for all. NPL is a world-leading centre in the development and application of highly accurate measurement techniques. As the UK's national standards laboratory, NPL underpins the National Measurement System (NMS), ensuring consistency and traceability of measurements throughout the UK. NPL offers a unique range of measurement services, contract research, consultancy and training services. Other areas of expertise include the design and characterisation of engineering materials, and mathematical software, especially its application to measurement and instrumentation.

For more information on the wide range of metrology services, facilities and research work carried out at NPL either visit the NPL web site at www.npl.co.uk or contact the NPL via e-mail: enquiry@npl.co.uk.

National Institute of Standards and Technology (NIST)

NIST is the equivalent of NPL in the United States of America. The NIST web site is www.nist.gov and often contains documents relevant to this guide in .pdf format.

EURAMET - European Association of National Metrology Institutes

The European Association of National Metrology Institutes (EURAMET) is the Regional Metrology Organisation (RMO) of Europe. On 1st July 2007 EURAMET e.V. became the successor to EUROMET – the previous RMO which had coordinated European metrology needs for over 20 years. EURAMET coordinates the cooperation of National Metrology

Institutes (NMIs) of Europe in fields like research in metrology, traceability of measurements to the SI units, international recognition of national measurement standards and of the Calibration and Measurement Capabilities (CMC) of its members.

EURAMET currently over 30 members (including NPL) and associate members, and operates several Technical Committees, one for each physical metrology subject field, plus committees dealing with interdisciplinary metrology and quality matters. More details and information about the many cooperative projects run by EURAMET and its members can be found on the EURAMET web site: www.euramet.org.

Networks

To support businesses to interact with NPL and facilitate the connection with measurement experts, NPL has set up a national network on measurement for UK businesses with the support of National Measurement Office (NMO). The network brings sector and technology based communities closer to the measurement expertise through a number of community engagement mechanisms which include events, workshops, webinars, joint publications etc. In addition to supporting businesses to access measurement resources and capabilities, the network also provide insights on measurement innovations through measurement news, broker relationships with technology experts and provides a forum to engage in discussions and virtual networking with the measurement community through _connect and LinkedIn. A number of free resources including over 100 different good practice guides from ‘beginner’s guides’ to measurement and uncertainty to more specialised guides for measurement professionals and practicing scientists are free to download from the NPL website. To join the growing number of over 3000 businesses in the Measurement Network and learn what measurement can do for your business visit www.npl.co.uk/measurement-network.

Training courses

NPL training teaches the underpinning measurement principles and methods across a range of science and technology subjects from foundation through to expert level. The training is aimed at developing metrology skills and an awareness of why measurement best practice is vital to increase corporate productivity and competitiveness; and to satisfy regulatory requirements. A selection of NPL courses lead to an ‘Award in Metrology’ under the National Qualifications and Credits Framework for work placed learning.

Courses are available in, but not limited to, the following topics: Introduction to measurement, Understanding and evaluating measurement uncertainty, Dimensional measurement, Laser safety, Instrumentation and sensors, Temperature, Electrical, Radiation Dosimetry, Geometrical Tolerancing and Portable, coordinate measurement systems. Further information is available at: www.npl.co.uk/training.

International standards

International Organization for Standardization (ISO)

The International Organization for Standardization (ISO) is a worldwide federation on national standards bodies from some 140 countries.

The mission of ISO is to promote the development of standardisation and related activities in the world with a view to facilitating the international exchange of goods and services, and to develop cooperation in the sphere of intellectual, scientific, technological and economic activity.

ISO's work results in international agreements that are published as International Standards.

Further information of ISO can be found at www.iso.ch.

ISO surface texture standards

Profile standards

The following ISO specification standards relate to the measurement of profile using stylus instruments and are included in this guide for completeness.

ISO 3274 (1996) Geometrical product specifications (GPS) – Surface texture: Profile method – Nominal characteristics of contact (stylus) instruments

ISO 4287 (1997) Geometrical product specifications (GPS) – Surface texture: Profile method – Terms, definitions and surface texture parameters

ISO 4288 (1996) Geometrical product specifications (GPS) – Surface texture: Profile method – Rules and procedures for the assessment of surface texture

ISO 5436 (2000) Geometrical product specifications (GPS) – Surface texture: Profile method – Measurement standards – Part 1 Material measures

ISO 16610 part 21 (2011) Geometrical product specifications (GPS) – Filtration – Part 21: Linear profile filters: Gaussian filters

ISO 13565 (1996) Geometrical product specifications (GPS) – Surface texture: Profile method; Surface having stratified functional properties – Part 1: Filtering and general measurement conditions

ISO 13565 (1996) Geometrical product specifications (GPS) – Surface texture: Profile method; Surface having stratified functional properties – Part 2: Height characterization using the linear material ratio curve

ISO 13565 (2000) Geometrical product specifications (GPS) – Surface texture: Profile method; surfaces having stratified functional properties – Part 3: Height characterization using the material probability curve

ISO 12085 (1996) ISO 13565 (1996) Geometrical product specifications (GPS) – Surface texture: Profile method – Motif parameters

Areal standards

The following ISO specification standards relate to the measurement of areal surface texture using stylus and optical instruments.

ISO 25178 part 2 (2012) Geometrical product specification (GPS) – Surface texture: Areal – Part 2: Terms, definitions and surface texture parameters. International Organization for Standardization

ISO 25178 part 3 (2012) Geometrical product specification (GPS) – Surface texture: Areal – Part 3: Specification operators. International Organization for Standardization

ISO 25178 part 6 (2010) Geometrical product specification (GPS) – Surface texture: Areal – Part 6: Classification of methods for measuring surface texture. International Organization for Standardization

ISO 25178 part 601 (2010) Geometrical product specification (GPS) – Surface texture: Areal – Part 601: Nominal characteristics of contact (stylus) instruments. International Organization for Standardization

ISO 25178 part 602 (2010) Geometrical product specification (GPS) – Surface texture: Areal – Part 602: Nominal characteristics of non-contact (confocal chromatic probe) instruments. International Organization for Standardization

ISO 25178 part 701 (2010) Geometrical product specification (GPS) – Surface texture: Areal – Part 701: Calibration and measurement standards for contact (stylus) instruments. International Organization for Standardization

Literature

Surface texture books

Blunt L, Jiang X 2003 Advanced techniques for assessment surface topography (Kogan Page Science)

Leach R K 2001 The measurement of surface texture using stylus instruments NPL Good Practice Guide No. 37 (available from www.npl.co.uk)

Petzing J, Coupland J M, Leach R K 2012 The measurement of rough surface topography using coherence scanning interferometry NPL Good Practice Guide No. 116 (available from www.npl.co.uk)

Leach R K 2009 Fundamental principles of engineering nanometrology (Elsevier)

Leach R K 2011 Optical measurement of surface topography (Springer)

Mainsah E, Greenwood J A, Chewynd D G 2001 Metrology and properties of engineering surfaces (Kluwer Academic Publishers)

Smith G T 2001 Industrial metrology: surface and roundness (Springer-Verlag)

Stout K J, Blunt L 2000 Three dimensional surface topography (Prenton Press)

Thomas T R 1999 Rough surface 2nd edition (Imperial College Press)

Whitehouse D J 2011 Handbook of surface and nanometrology 2nd edition (CRC Press)

General measurement and instrumentation guides

Bell S 2001 A beginner's guide to uncertainty of measurement NPL Good Practice Guide No. 11 (available from www.npl.co.uk)

Birch K 2001 Estimating uncertainties in testing NPL Good Practice Guide No. 36 (available from www.npl.co.uk)

Flack D R, Hannaford J 2005 Fundamental good practice in dimensional metrology NPL Good Practice Guide No. 80 (available from www.npl.co.uk)