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# Calibration of the metrological characteristics of Imaging Confocal Microscopes (ICMs)

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National Measurement System

# Measurement Good Practice Guide No. 128

## Calibration of the metrological characteristics of imaging confocal microscopes (ICMs)

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**ABSTRACT**
This document is a guide to the calibration of Imaging Confocal Microscope (ICM). Methods for determining the measurement noise, flatness deviation, amplification coefficient, linearity and perpendicularity of the axes and resolution of areal surface topography measuring instruments are presented. The methods are compliant with draft international specification standards on areal surface texture.

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# Contents

# Introduction

1

The aim of this guide is to allow the user to provide surface texture measurement results with the associated uncertainties that are derived from the instrument calibration process. This good practice guide is to assist users in calibrating areal surface topography measuring instruments of type imaging confocal microscope (ICM). To make best use of this guide the users should first familiarise themselves with the content of operating manuals and application notes supplied by the instrument manufacturers.

The ICM method is defined in ISO 25178 part 6 (2010) as:

"*surface topography measurement method whereby a pinhole object illuminated by the light source is imaged by a lens onto the surface being studied and the light is reflected back through the lens to a second pinhole placed in front of a detector and acting as a spatial filter*".

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.*"

**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 magnification lens and numerical aperture. 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 an ICM 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. This guide does not cover the measurement of slopes and the effect of measuring different materials.

It is recommended that the effects of the metrological characteristics of the ICM should be studied separately from the effects of the optical 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[1].

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

**Structure of the guide**

This guide is structured in the following manner. The next chapter describes briefly the ICM configuration as in ISO/CD 25178 part 607; 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 to 5 and methods of calculating the measurement uncertainties are presented in chapter 6. The final

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

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 latest issue of the published standard.

# General

# 2

## ICM configuration

The metrology loop of an ICM consists of an active bridge and mounting table that are stably connected and on which are mounted the active optical components. A schematic setup, not including the metrological loop, is shown in figure 1.

An ICM projects structure illumination patterns onto the surface under investigation and captures the returned rays through to a pattern identical to the illumination pattern. In this way the ICM is able to discriminate for returned rays that are out of focus.

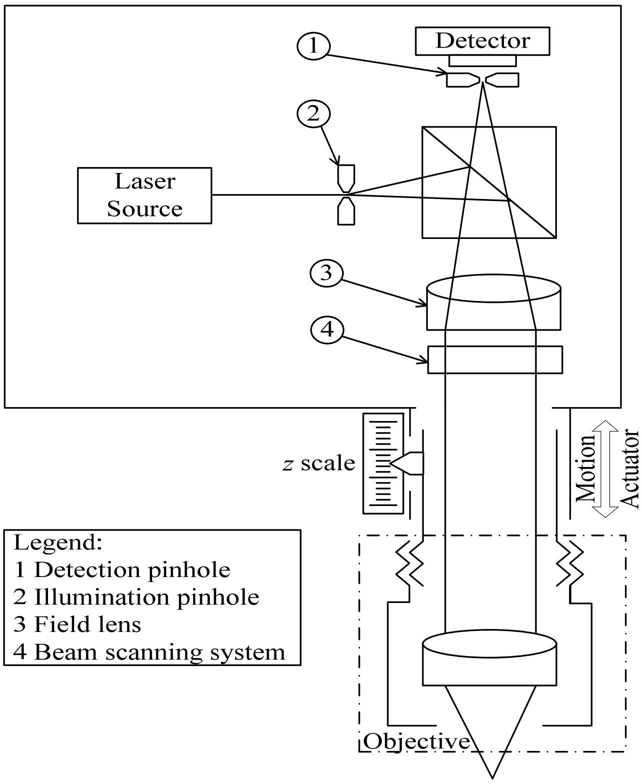


**Figure 1 ICM set-up**

Light from a laser passes an illumination pinhole and is directed towards the sample via an objective lens. On return, the light is directed towards the detection pinhole, behind which is situated a photo-detector. At the focal plane of the objective lens the illuminated spot on the surface is diffraction limited and all the rays of the returned beam pass the illumination pinhole. If the sample is moved from this position the illuminated spot increases in size and the width of the returned beam is larger than the opening of the illumination pinhole. So, whilst the sample is scanned in and out of focus of the objective lens using a linear motion actuator, the intensity of light passing the opening of the detection pinhole varies. The intensity variation with the scan position is called the axial response. Height information is attained by simply ascertaining the discreet scan position corresponding to maximum light intensity or more accurately employing fitting algorithms such as paraboloid fitting.

For areal measurements the beam is scanned over a finite area across the surface of the sample using one of the following scanning systems: galvanometric mirrors, video rate resonant scanners; disk scanning (Nipkow disk, scan disks with parallel slits or point rotating slits); and programmable array scanning.

For more details on basic operational principles and using the ICM see the operating manuals and application notes supplied by the instrument manufacturers, which gives guidance to ICM users enabling them to achieve valid surface measurements on surfaces exhibiting roughness, texture and structures.

## 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.

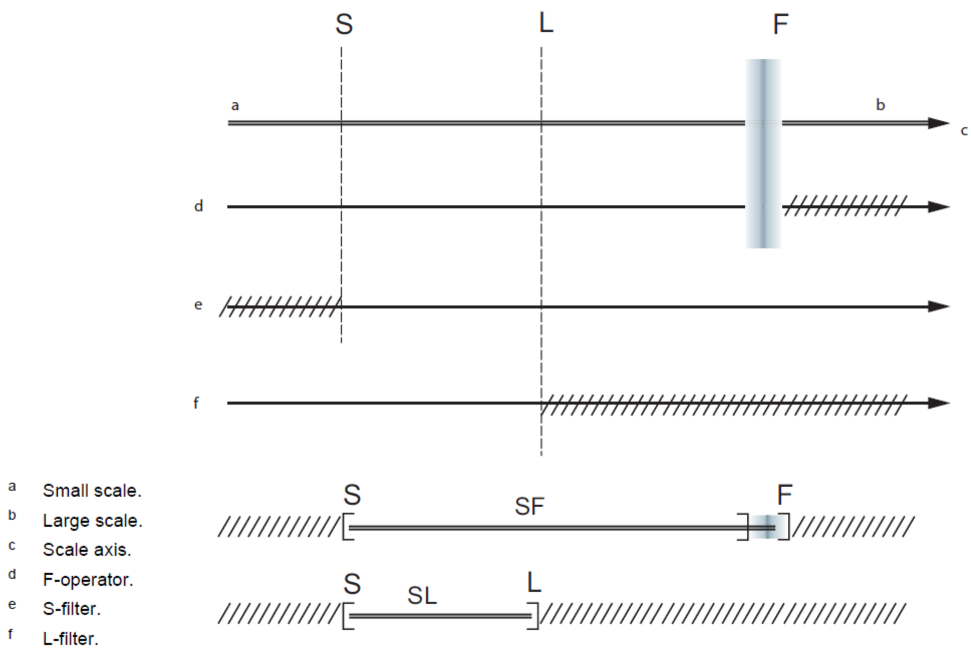


**Figure 2 (BS EN ISO 25178 – 2: 2012) – relationships between the S-filter, L-filter, F-operator and S-F and S-L surfaces**

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.

**Optical nesting index combinations**

The S-filter nesting index (equivalent to $\lambda s$ 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 $\lambda c$ 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 1 reproduces proposed recommended sets of nesting indices from ISO 25178 part 3.

**Table 1 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 /$10^n$ µm | 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 | 4001 |
| | 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 2) and nine types of areal physical measurement standards (see table 3). Optical flats are also used during the calibration process.

**Table 2 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 3 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.

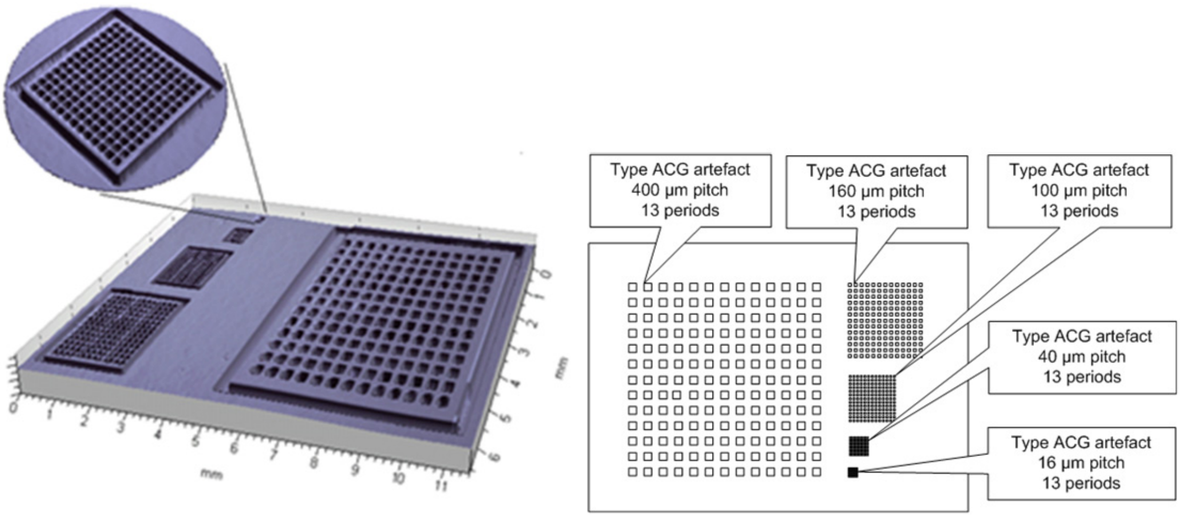


**Figure 3 NPL type ACG physical measurement standard: measured (left) and design (right)**

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).

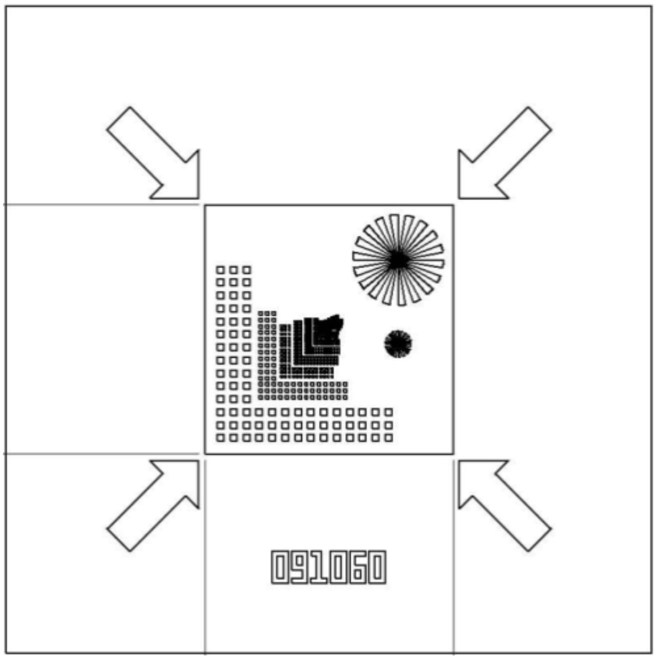


**Figure 4 NPL resolution standard artefact**

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.

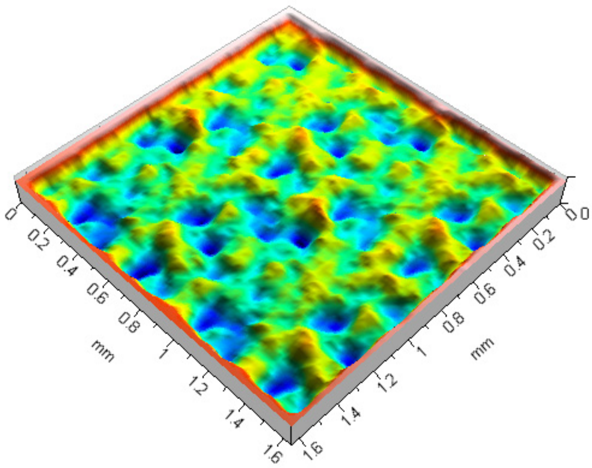


**Figure 5 NPL type AIR standard artefact - NPL Areal Instrument measurement**

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.

## Measurement noise

The measurement noise (also called measurement repeatability) 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

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

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

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

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, 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 using similar measurement conditions to those of the operational bandwidth of the instrument to be tested.

**Examples of subtraction and averaging method for an ICM**

In this example, the measurements were performed in a set-up similar to the one presented in figure 6.

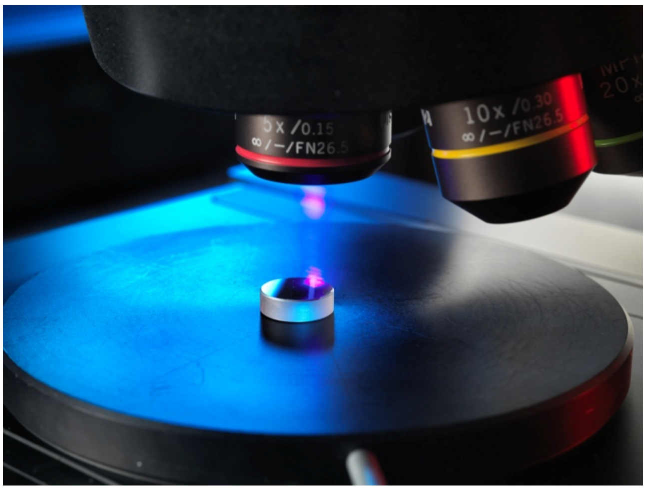


**Figure 6 Measurement of a flat**

The averaging method was tested using five repeated measurements. Example profiles extracted at the same position in the field of view of the 50×magnification lens after averaging two, three, four and five measurements are presented in see figure 7.

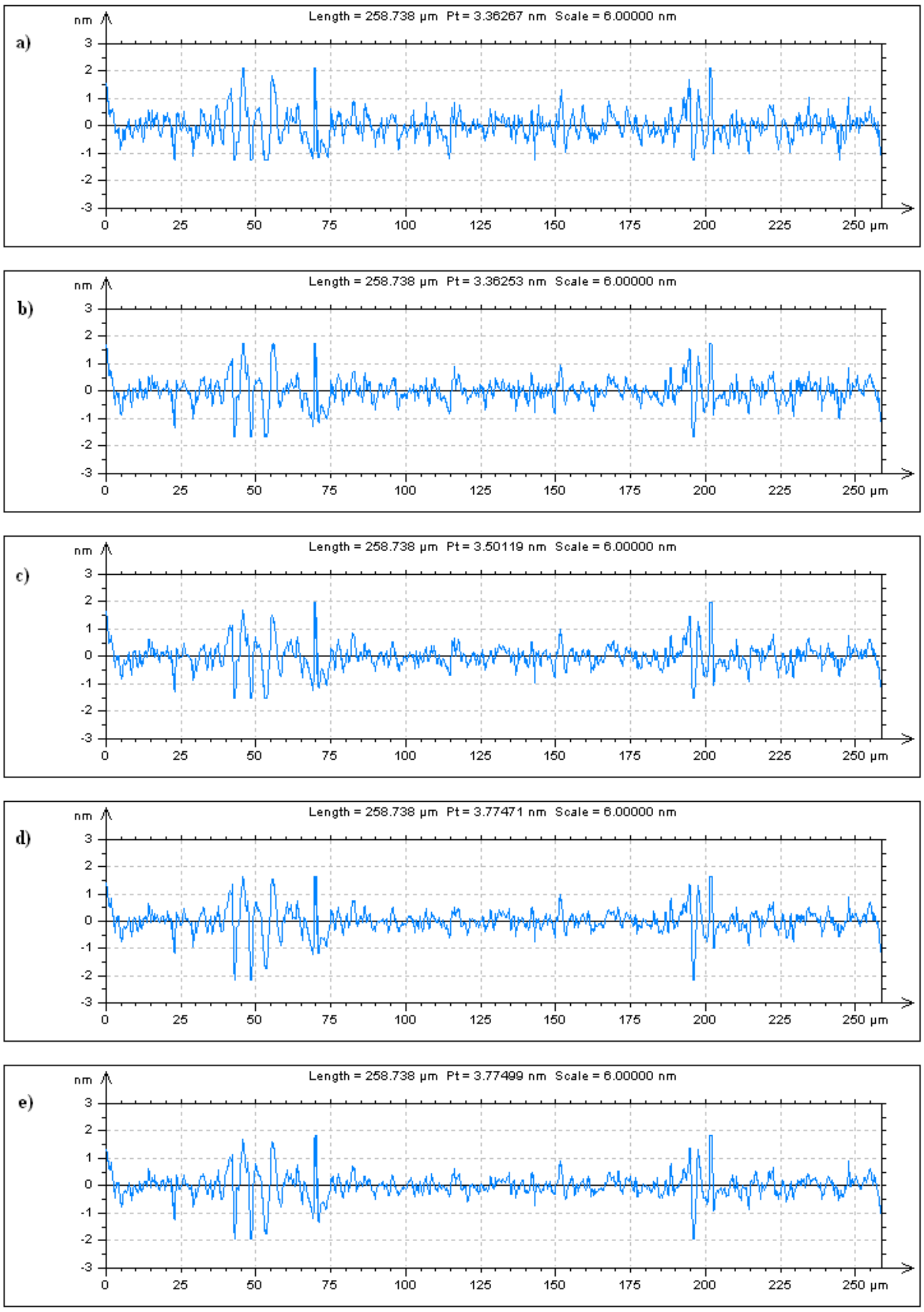


**Figure 7 50× magnification lens - example profiles extracted after: a) no averaging; b) averages of two; c) averages of three; d) averages of four; e) averages of five**

The *Sq* value was calculated for each averaged topography. The unfiltered results of the measurement noise test of the ICM show that with the increased number of averaged measurements, the $Sq_{noise}$ value decreases, so the averaging method is likely to isolate the noise from the form errors only when using a large number of measurements (see table 4).

**Table 4 Unfiltered measurement noise on a transparent glass flat – averaging method results**

| Number of averaged measurements | $Sq_{\mathrm{noise}}$ / nm | |
|---|---|---|
| | 20× | 50× |
| 2 | 9.2 | 1.9 |
| 4 | 7.1 | 2.2 |
| 8 | 6.5 | 1.7 |
| 16 | 5.4 | 1.4 |

The five repeated measurements were used to calculate the measurement noise using the subtraction method (see figure 8). The first measurement was subtracted from the second one, the second from third and so on until four new measurement noise topographies were obtained.

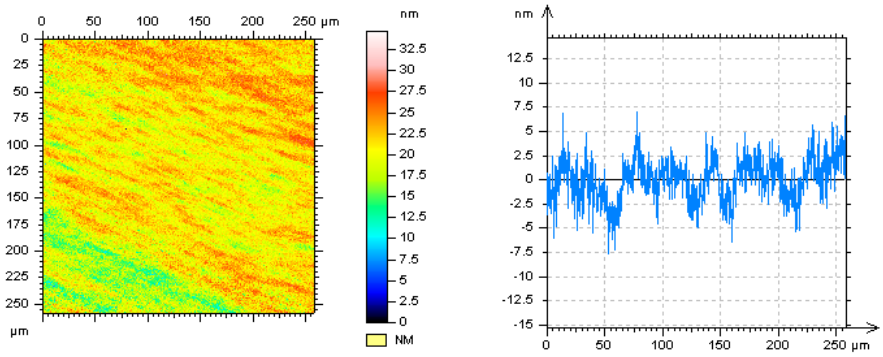


**Figure 8 50× magnification lens - subtraction measurement result: left areal, right extracted profile**

The subtraction method average result is $Sq_{noise}$ = 1.56 nm with an associated standard deviation of the mean of 0.22 nm for the case of the 50× magnification objective lens and $Sq_{noise}$ = 5.0 nm with an associated standard deviation of the mean of 1.2 nm for the case of the 20× magnification objective lens (see table 5). The difference between the two methods is not appreciable (less than 10 %).

**Table 5 Unfiltered measurement noise on a transparent glass flat – subtraction method results**

| Subtractions | $Sq_{noise}$ / nm | |
|---|---|---|
| | 20× | 50× |
| 1 | 6.7 | 1.4 |
| 2 | 4.7 | 1.5 |
| 3 | 4.3 | 1.9 |
| 4 | 4.1 | 1.5 |

## 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 (*Sz*) 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 described in this guide uses a flat standard artefact, which is measured nominally perpendicular to the optical axis of the instrument. The parameter used to quantify the quality of the areal guide is the *maximum height of the scale limited surface* (*Sz*). The value of *Sz* 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.

It is difficult to recommend the exact number of repeated measurements because the number of repeats depend on how quickly the value of *Sz* stabilises. As a guide, the measurements should be repeated until the value of *Sz* does not changing by more than 5 %.

Flatness measurements can be affected by spurious measurement data from unwanted features present on the surface of the flat, therefore, it is good practice to eliminate their effect on the measurement of the flatness deviation of the instrument. One method to eliminate these features is, for example, the use of a twelfth order polynomial to remove the form and to threshold the peaks and valleys of the residual surface that are larger than three times the *Sq* value calculated on the residual surface. As a result, the *Sp* (maximum peak height) and *Sv* (maximum pit depth) values will be three times *Sq*. The form topography and the threshold residual surface are summed to obtain the threshold surface topography (see figure 9 for the process flow).

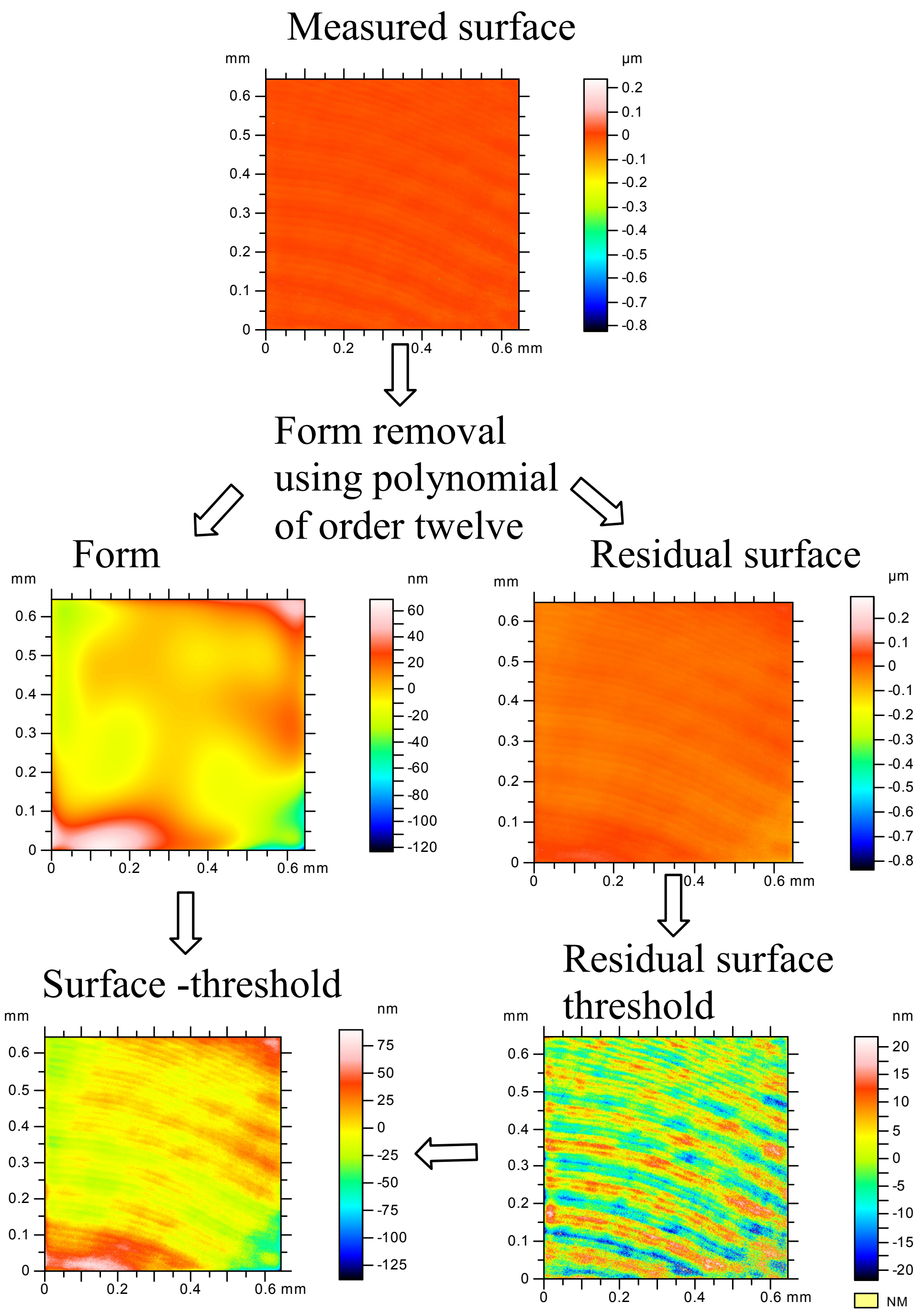


**Figure 9 Flow chart of threshold method**

In the case of instruments that are known to have flatness deviation larger than the *Sz* of the flat and its measurement noise, this averaging method does not need to be applied. The flatness can be estimated by measuring *Sz* directly without any other surface averaging on a calibrated flat.

**Example flatness deviation test**

An example of flatness deviation measurement results is presented in table 6.

**Table 6 Unfiltered measured flatness of the ICM**

| Number of repeated measurements | $Sz_{flatness}$ / nm | |
|---|---|---|
| | 20× | 50× |
| 2 | 210 | 34 |
| 3 | 207 | 35 |
| 4 | 202 | 32 |
| 5 | 203 | 38 |
| 6 | 203 | 31 |
| 7 | 199 | 30 |
| 8 | 195 | 29 |
| 9 | 197 | 29 |
| 10 | 193 | 28 |

After averaging ten measurements *Sz* is found to be 193 nm for the 20× magnification objective lens and 28 nm for the 50× magnification objective lens(see figure 10 and table 6). Before the data threshold the maximum *Sz* value of the repeated measurements was in excess of 1 µm for 20× magnification objective lens and 300 nm for 50× magnification objective lens. In the ICM case the flatness deviation is more likely to be inherited from the *xy* scanning system.

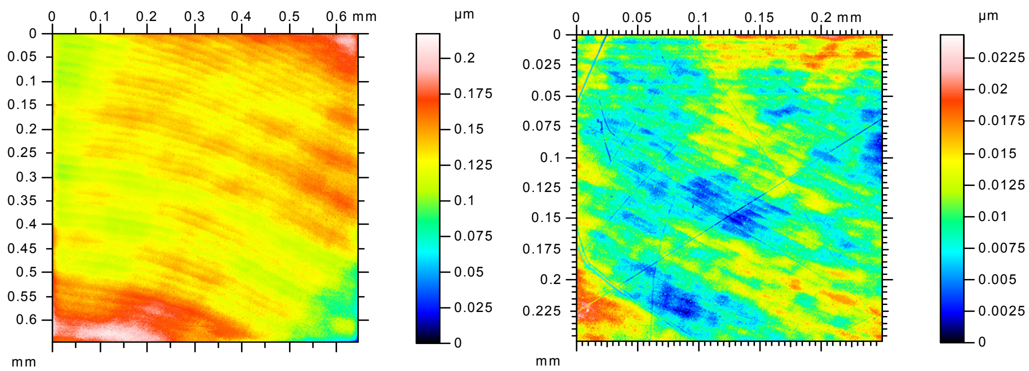


**Figure 10 Flatness results after thresholding and without averaging : 20× magnification objective lens (left) and 50× magnification objective lens (right)**

# 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.

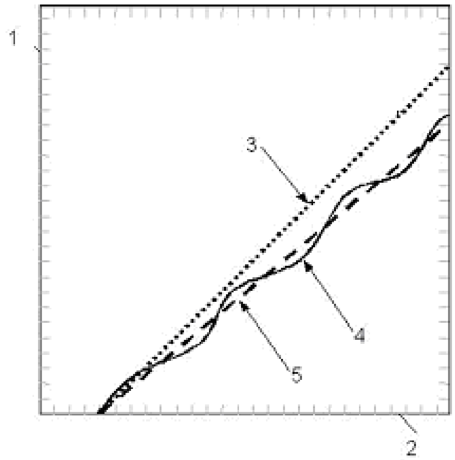


**Figure 11 (ISO 25178 part 601: 2010) Example of an instrument response curve, where: 1 measured quantities, 2 input quantities, 3 ideal response curve, 4 response curve, 5 linear curve whose slope is the amplification coefficient**

## *z* axis measurement calibration

The calibration of the *z* amplification coefficient (*αz*), linearity error (*lz*) 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)

$$\alpha = \frac{\sum_i^n C_i I_i}{\sum_i^n C_i^2}, \tag{3}$$

where $\alpha$ 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).

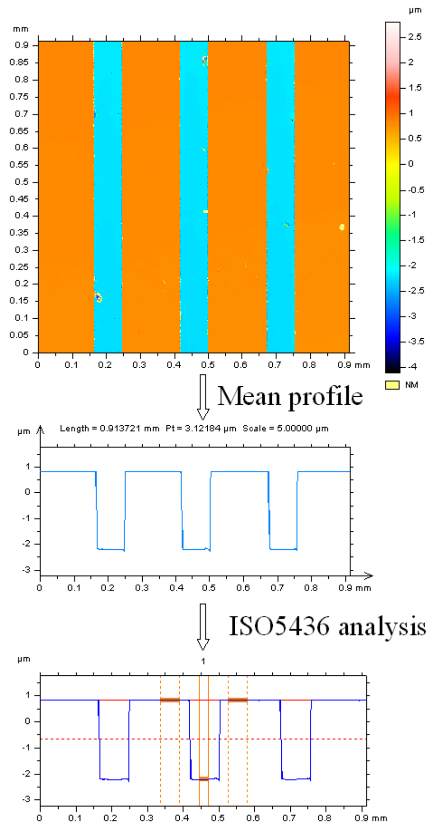


**Figure 12 Flow chart of step height standard artefact analysis**

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 $\alpha z$ and $lz$**

Four different step height standard artefacts (initially calibrated using the NPL Areal Instrument – a traceable stylus instrument) are measured in five positions within the range of the instrument (at 10 %, 30 %, 50 %, 70 % and 90 % of the instrument working range) allowing a determination of the reproducibility of the measurements within the instrument range (see NPL GPG 11[3] for definition of repeatability and reproducibility). At each of the five positions, the step height standard artefacts were measured five times, which allowed a calculation of the repeatability of the measurements (Type A uncertainty). Example of the results is presented in table 7: the measurement error ($\delta_{\mathrm{err}}$) is calculated as the difference between the measured value and the calibrated value; the repeatability ($\delta_{\mathrm{repeat}}$) of the step height standard artefact measurements was taken to be the maximum standard deviation of the mean value calculated at each of the five positions inside the instrument range; the reproducibility ($\delta_{\mathrm{reprod}}$) was calculated as the standard deviation of the average values of the step height standard artefacts measured in each of the five positions; and the calibration standard uncertainty of the step height standard artefacts with the NPL Areal Instrument is taken to be the traceability contribution (0.9 nm in this case).

**Table 7 Summary of $\alpha z$ and $lz$ calibration results**

| Nominal height | 19 nm | | 350 nm | | 3 µm | | 17 µm | |
|---|---|---|---|---|---|---|---|---|
| Magnification objective | 20× | 50× | 20× | 50× | 20× | 50× | 20× | 50× |
| $\delta_{\mathrm{err}}$ (at 50 %)/nm | -3.3 | 1.1 | -14.4 | -5.7 | -13.5 | 5.3 | -16.2 | 6.0 |
| $\delta_{\mathrm{repeat}}$/nm | 0.4 | 0.3 | 2.3 | 1.0 | 3.3 | 3.8 | 7.6 | 10.4 |
| $\delta_{\mathrm{reprod}}$/nm | 4.6 | 6.4 | 8.7 | 9.0 | 17.4 | 10.8 | 13.7 | 14.3 |

Example of $\alpha z$ and $lz$ of the 20× and 50× magnification lenses are presented in figure 13 and figure 14, respectively. The standard uncertainty bars are calculated as the quadrature sum of the repeatability, reproducibility and traceability values. The choice of magnification lens affects the results of the calibration of the $z$ axis scale of the instrument therefore, the calibration of the $z$ axis should be performed for all lens configurations.

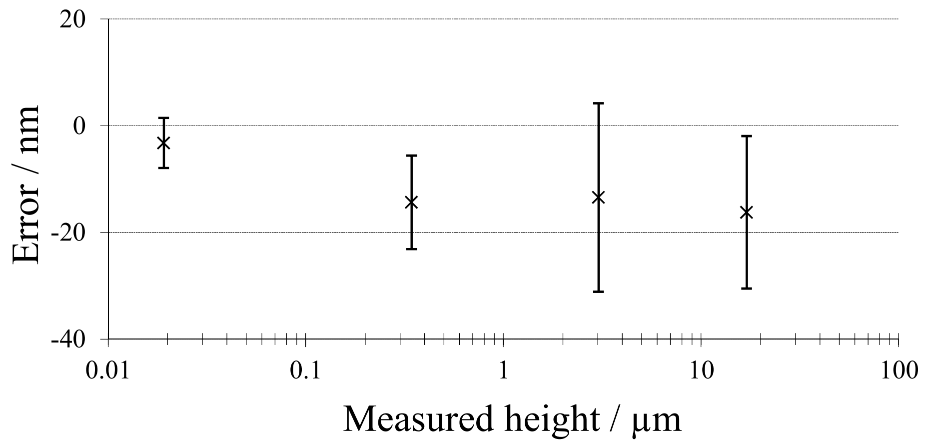


**Figure 13 Calibration of the $z$ axis of an instrument equipped with 20× magnification lenses – measurement error plot**

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

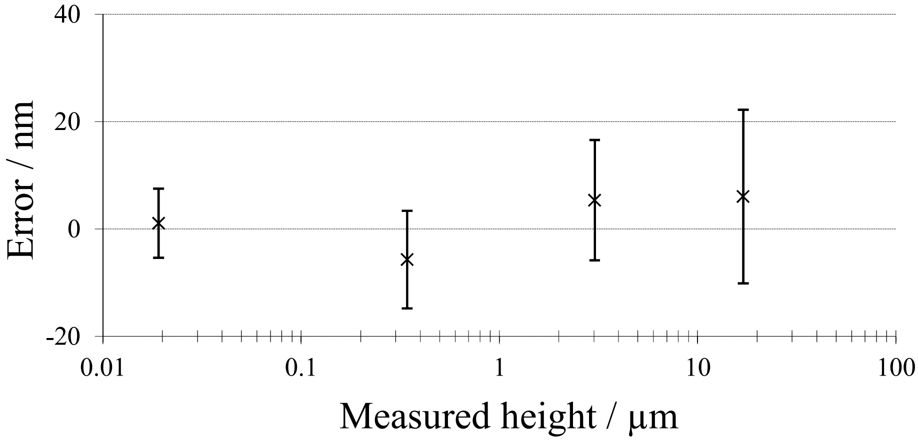


**Figure 14 Calibration of the *z* axis of an instrument equipped with 50× magnification lenses – measurement error plot**

In this example the 18 nm artefact could not be measured in the 20× magnification lens configuration at 90 % of the instrument working range, due to a large flatness deviation. In order to estimate the quality of the *z* axis scale without the flatness deviation effect, a reference flat was measured at each of the five locations in the instrument range that were used to measure the step height standard artefacts, and then subtracted from the corresponding measured topography of the step height standard artefacts. The flatness deviation corrected results presented in table 8 (measurement error plots presented in figure 15 and figure 16) are valid for the whole working range of the instrument. Only improvements in the measurement of the 18 nm step height artefact for both magnification lenses and of the 350 nm artefact for 20× magnification lens are recorded.

**Table 8 *z* axis scale calibration results**

| Nominal height | 19 nm | | 350 nm | | 3 µm | | 17 µm | |
|---|---|---|---|---|---|---|---|---|
| **Magnification objective** | **20×** | **50×** | **20×** | **50×** | **20×** | **50×** | **20×** | **50×** |
| $\delta_{err}$ (at 50 %)/nm | 0.1 | 0.4 | -11.3 | -5.7 | -10.1 | 5.3 | -16.2 | 6.0 |
| $\delta_{repeat}$/nm | 0.6 | 0.2 | 2.3 | 1.0 | 3.3 | 3.8 | 7.6 | 10.4 |
| $\delta_{reprod}$/nm | 1.8 | 1.0 | 6.6 | 9.0 | 17.3 | 10.8 | 13.7 | 14.3 |
| Traceability/nm | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 |

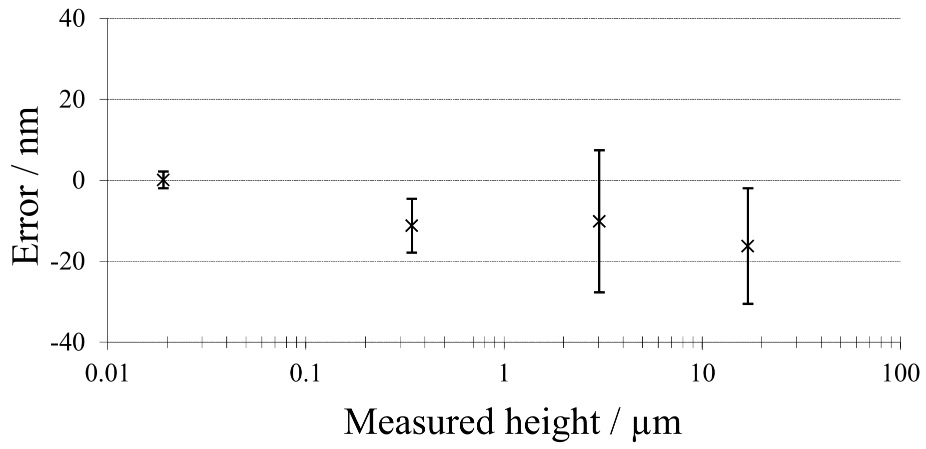


**Figure 15 Calibration of the *z* axis of an instrument equipped with 20× magnification lenses – measurement error plot after flat correction**

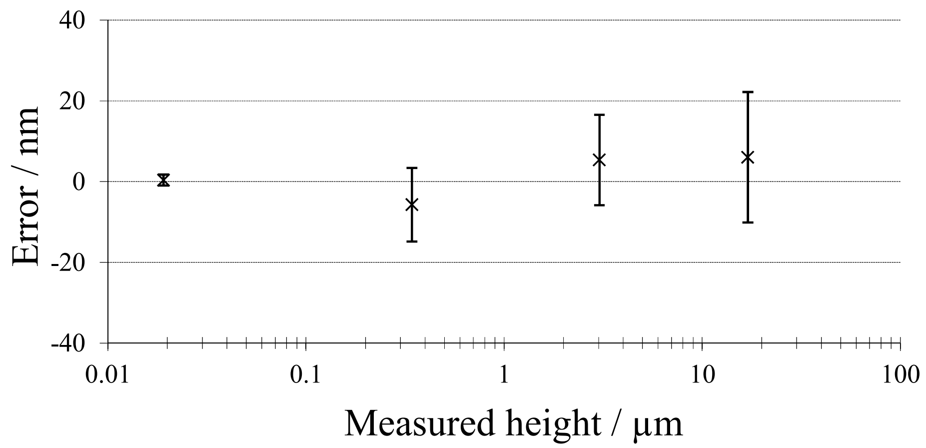


**Figure 16 Calibration of the *z* axis of an instrument equipped with 50× magnification lenses – measurement error plot after flat correction**

## *x* and *y* scale - calibration measurements

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 ($\alpha x$ and $\alpha y$), linearity errors (*lx* and *ly*) and the perpendicularity ($\Delta_{PER}$) can be measured using a calibrated cross grating standard artefact (ACG type) (see figure 17). 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 though 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.

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

Free software that calculates the centre of gravity is available for download (see NPL Report ENG 45[4]).

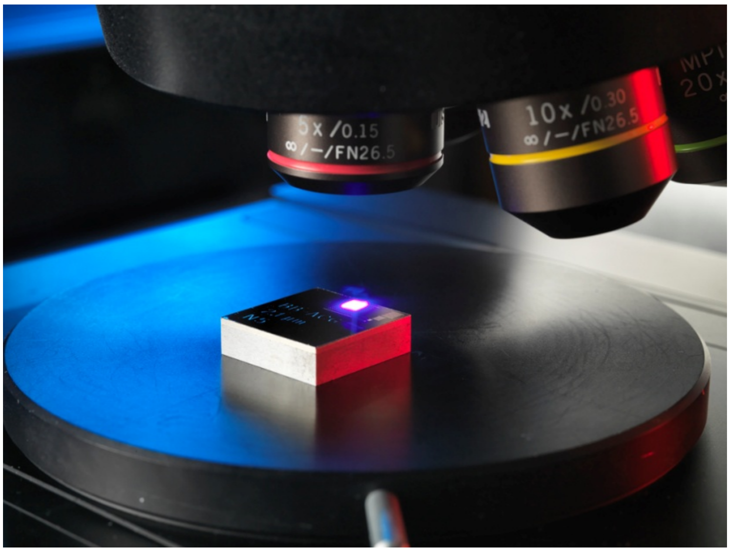


**Figure 17 Measurement of an ACG type of material measurement standard**

**Example of calibration of *αx, αy*, *lx* and *ly***

To illustrate the process of calibration, a 100 µm and a 30 µm pitch cross-grating (initially traceably calibrated using the NPL Areal Instrument) can be used to calibrate a typical instrument (see figure 18).

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.

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

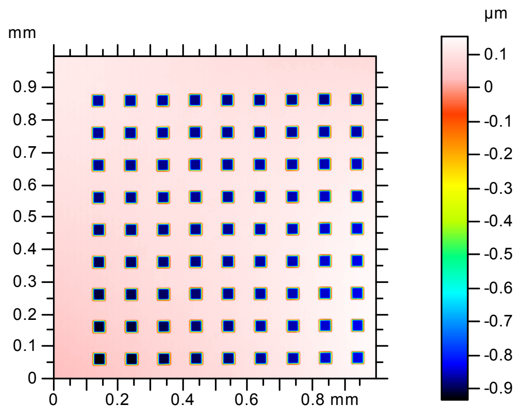


**Figure 18 100 µm pitch cross grating measured by the NPL Areal Instrument**

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.

In this example the measurement results at 10 %, 30 %, 50 %, 70 % and 90 % of the instrument vertical working range were compared to the values reproduced by the calibrated cross grating artefacts. At each of the five positions the cross grating artefacts were measured only once.

Example calibration results *αx, αy*, *lx* and *ly* for a 20× magnification lens are presented in figure 19 for a 50× magnification lens are presented in figure 20. The standard error bars are a combination of the measurement reproducibility and the calibration standard uncertainty of the ACG artefacts.

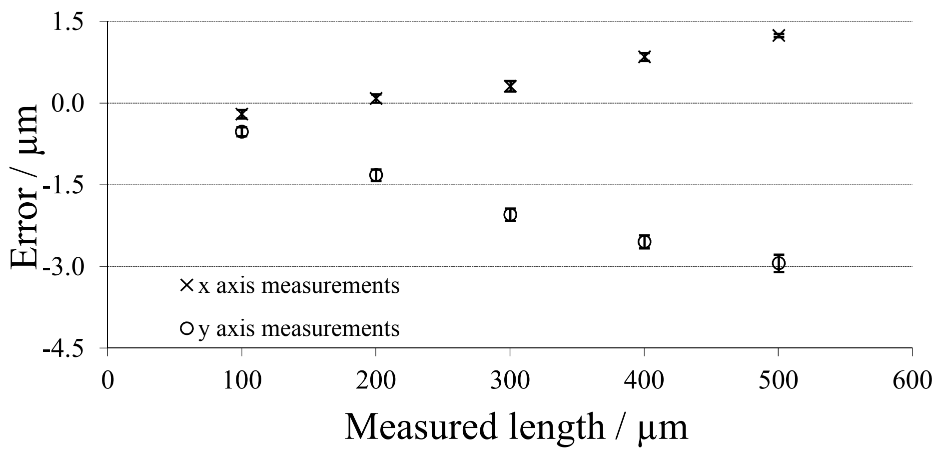


**Figure 19 Example *αx, αy, ly* and *lx* calibration results of an instrument equipped with 20× magnification lenses – standard measurement error plot**

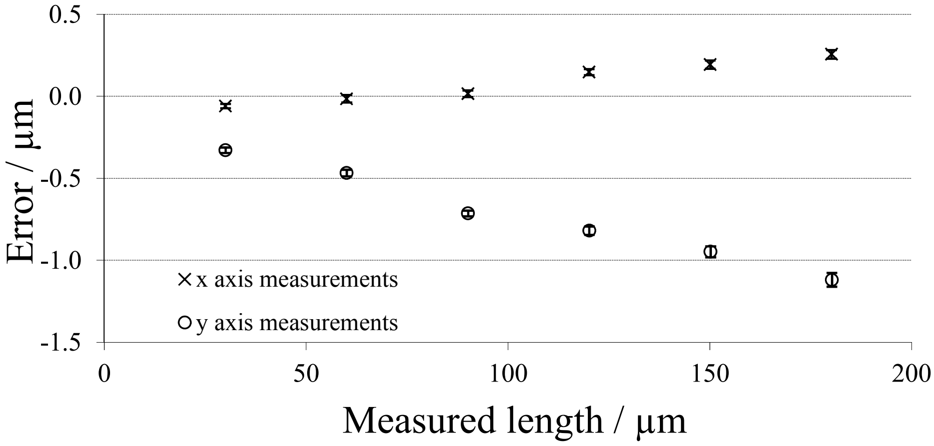


**Figure 20 Example *αx, αy, ly* and *lx* calibration results of an instrument equipped with 20× magnification lenses – standard measurement error plot**

A common amplification coefficient for each axis (1.0019 for *αx* and 0.993 57 for *αy*) can be used to improve the lateral measurements of the instrument in both magnification lens configurations. The correction will generate a linearity error in excess of 500 nm with the 20× lens (see figure 21 and figure 22) and 140 nm with the 50× lens (see figure 23 and figure 24).

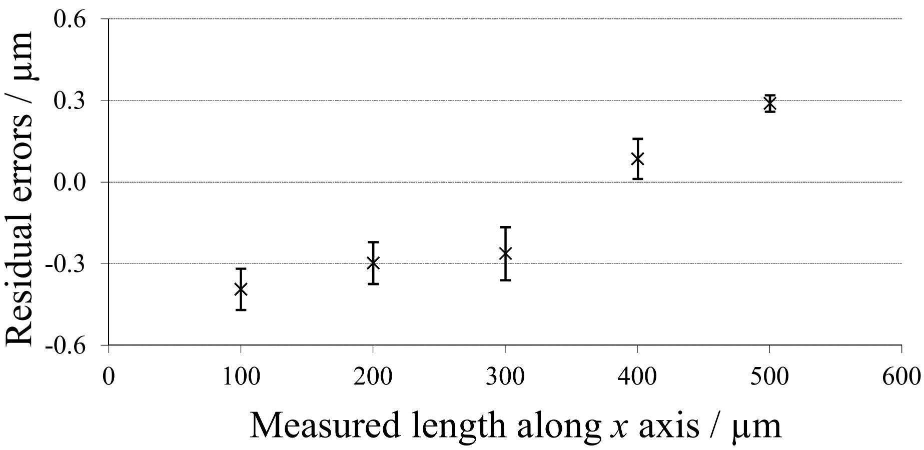


**Figure 21 Example *αx* and *lx* calibration results of an instrument equipped with 20× magnification lenses – residual errors after correcting the results using the 1.001 9 amplification factor**

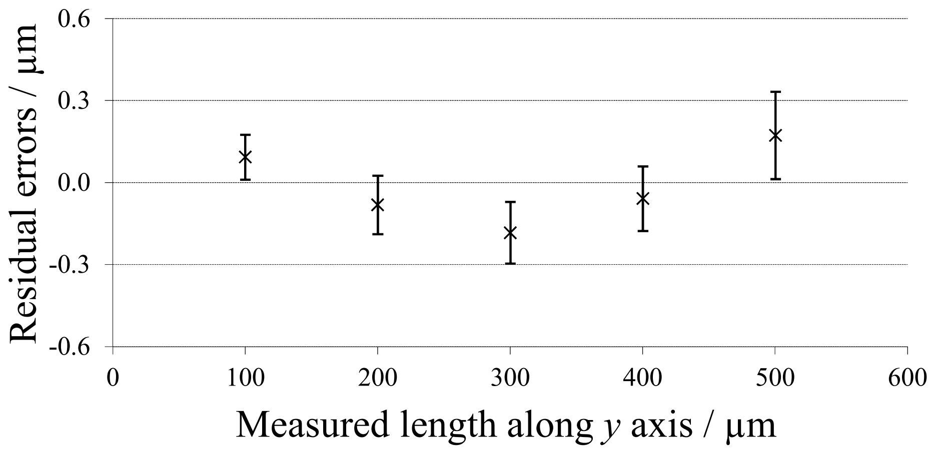


**Figure 22 Example *αy* and *ly* calibration results of an instrument equipped with 20× magnification lenses – residual errors after correcting the results using the 0.993 57 amplification factor**

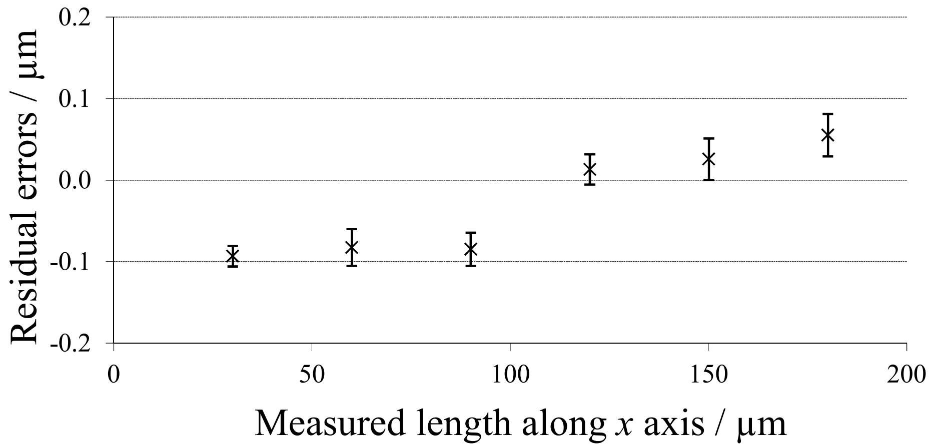


**Figure 23 Example *αx* and *lx* calibration results of an instrument equipped with 50× magnification lenses – residual errors after correcting the results using the 1.001 9 amplification factor**

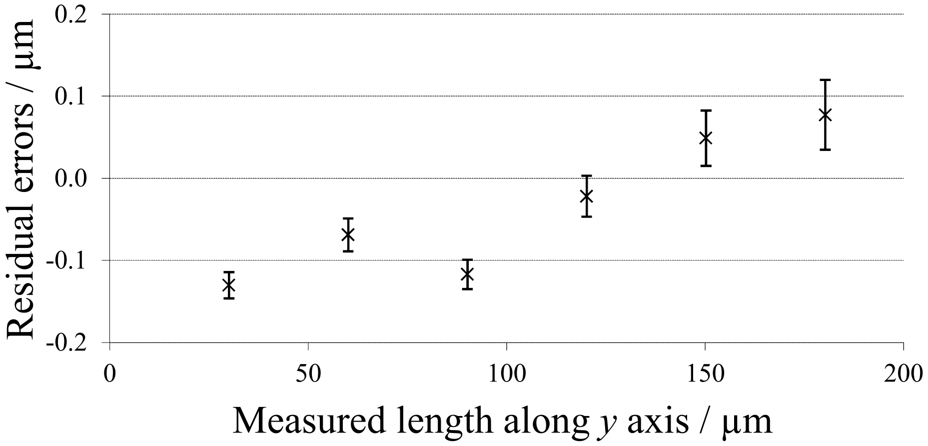


**Figure 24 Example *αy* and *ly* calibration results of an instrument equipped with 50× magnification lenses – residual errors after correcting the results using the 0.993 57 amplification factor**

The linearity and amplification errors after adjustment are smaller than, or at least comparable, to the pixel size or to the optical resolution of the instrument.

Using the same measurement results, the absolute squareness error between the $x$ and $y$ axes was found to be 0.3º with an associated standard deviation of the mean of 0.1º. The maximum effect of the squareness error is in this case approximately 0.0014 % of the measured length. For the maximum possible measured length of 1.4 mm (diagonal measurement in the 1 mm × 1 mm area) the cosine error translates to an absolute length error of 0.2 nm, which is far smaller than the *ly* residual errors.

# Resolution

5

The measurement of the resolution of the *z* axis should be performed on a structure such as a groove several times wider than the lateral resolution of the instrument, decoupling in this way the influence of the lateral resolution from the measurement of the depth of the groove.

Conversely, the measurement tests can be designed in such a way that the instrument can measure accurately the pitch of a periodic structure that is close to the lateral resolution of the instrument. In this case, 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 height difference. The lateral period limit has therefore been defined (ISO 25178 part 3 2013) to overcome the problem with the lateral resolution definition. Theoretically, the value of the lateral period limit is at least twice the value of the optical lateral resolution determined using the Rayleigh criterion.

Note that the lateral resolution of some instruments can be limited by the instrument sampling distances along the *x* and *y* axis, especially of those instruments fitted with a CCD camera.

Type ASG of physical measurement standards can be used to measure the resolution of areal instruments in a way compliant with the lateral period limit definition ("*spatial period of a sinusoidal profile at which the optical response falls to 50 %*"). Note that the lateral period limit definition calls for a sinusoidal type of physical measurement standard, whereas the material measure used in this chapter has a rectangular profile. However, the analysis method presented in this chapter can be used to measure the lateral period limit on a type ASP that has a sinusoidal profile. At the time of writing of this guide, low amplitude sinusoidal profiles with varying pitch have not yet been produced.

The advantage of using a type ASG of standard instead of a traditional grid is that the ASG provides a continuous range of varying pitch. Often the star patterns are assessed using circular profiles of different diameters centred into the apex of the star (see figure 25). Circular profiles have no advantage over grid measurements because the technique is limited to a discrete series of pitch values.

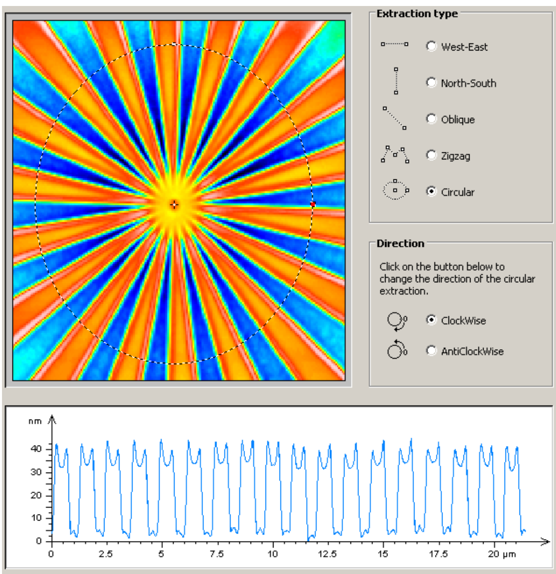


**Figure 25 Example of circular profile extraction on a ASG type of standard**

One way of fully exploiting the advantage of ASG standards is to assess the star pattern with profiles that are extracted along the radius of the star. To find the 50 % cut-off, two profiles are required. One extracted through the middle of two diametrically opposed upper petals (see figure 26 left) and one running through the middle of two diametrically opposed lower petals (see figure 26 right). The two profiles should be extracted from adjoining upper and lower petals. The measured data should be used without applying any filtering.

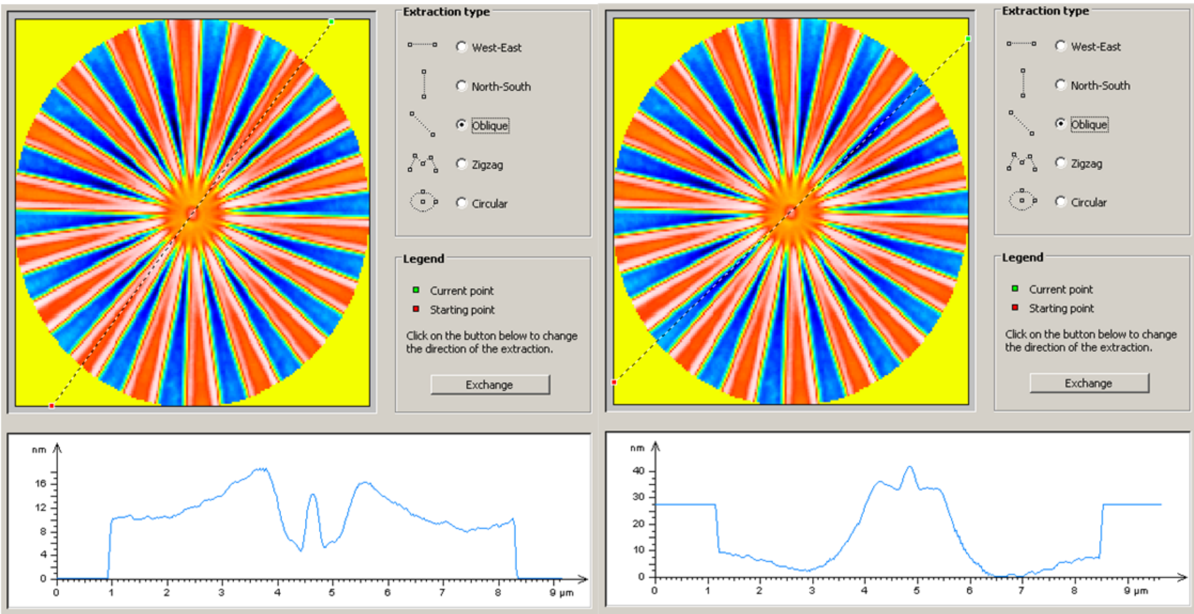


**Figure 26 Example of linear profile extraction: left - profile extracted through the middle of two diametrically opposed upper petals; right - profile extracted through the middle of two diametrically opposed lower petals**

The profile resulting from subtracting these two profiles from each other (see figure 27) allows the measurement of the resolution of the instrument.

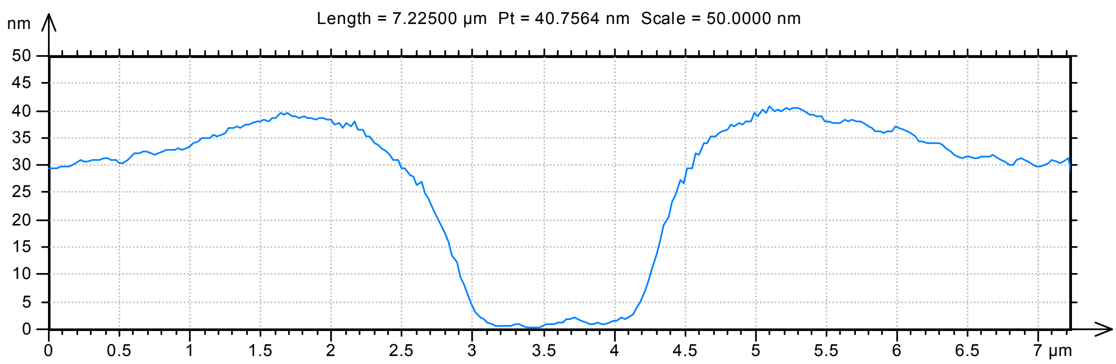


**Figure 27 Height difference between the upper petals and lower petals**

Figure 27 shows the height difference between the upper petals and lower petals. As the profiles cross the apex of the ASG standard the height difference drops, highlighting the loss of lateral resolution. To find out what the resolution of the instrument is, based on 50 % cut-off rule, the vertical scale of the profile is normalised to the maximum height value and the lateral scale is divided by $\pi n$ (see figure 28), where $n$ is the number of upper or lower petals (18 in this case).

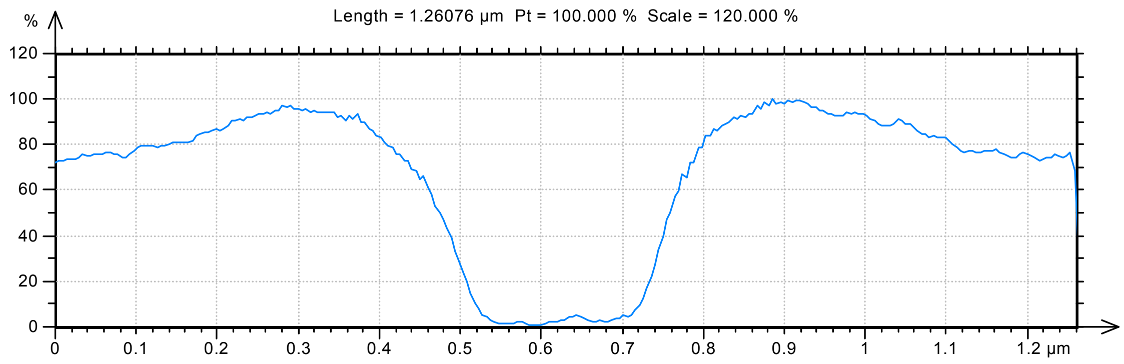


**Figure 28 Normalised profile**

The resolution of the instrument is given by the width of the central depression at 50 % (see figure 29).

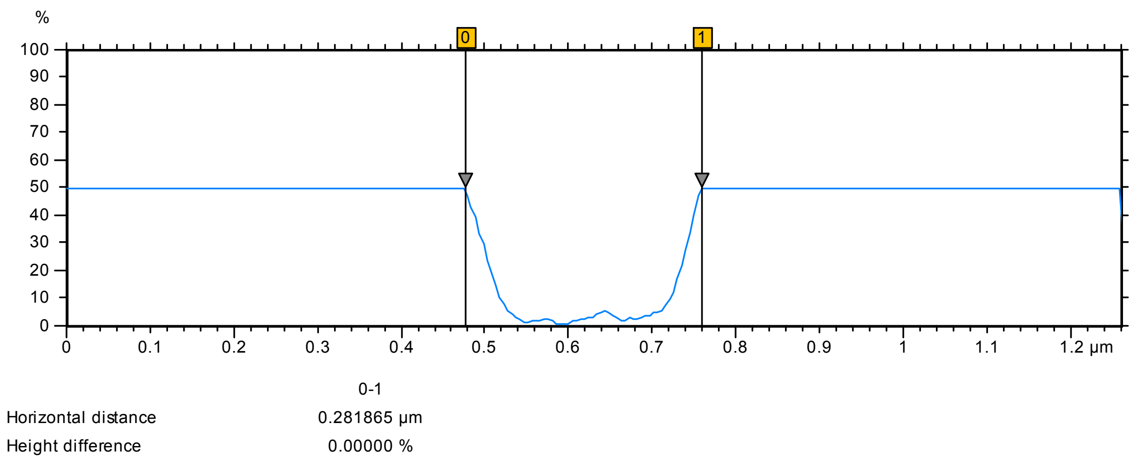


**Figure 29 Example of measurement of the resolution at 50 % cut-off**

The data used to produce figure 25 to figure 29 are measured using an atomic force microscope. The atomic force microscope was used to qualify the ASG type standard. Figure 29 suggests that the sample can be used to measure lateral resolution larger than 0.28 µm. The summits flanking the depression are from the manufacturing process and they are not caused by a measurement error.

**Example of resolution test**

The measured topography of the ASG type standard with 20× magnification lens is shown in figure 30 - left and with 50× magnification lens presented in figure 30 - right.

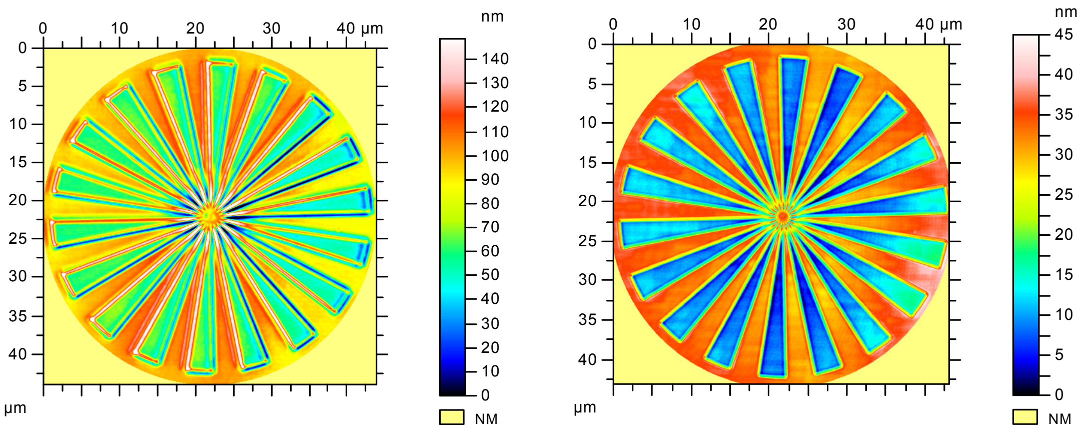


**Figure 30 ASG measurement: left - 20× magnification lens results; right - 50× magnification lens results**

According to the instrument specification, the resolution of the 20× magnification lens, theoretically, is limited by the optical resolution, which is 400 nm (based on the Rayleigh criterion), as well for the resolution of the 50× magnification theoretical limit, which is 250 nm.

The lateral period limit, based on the 50 % optical cut off definition, is 2.3 µm and 0.9 µm for the 20× and 50× magnification lenses, respectively (see figure 31 and figure 32).

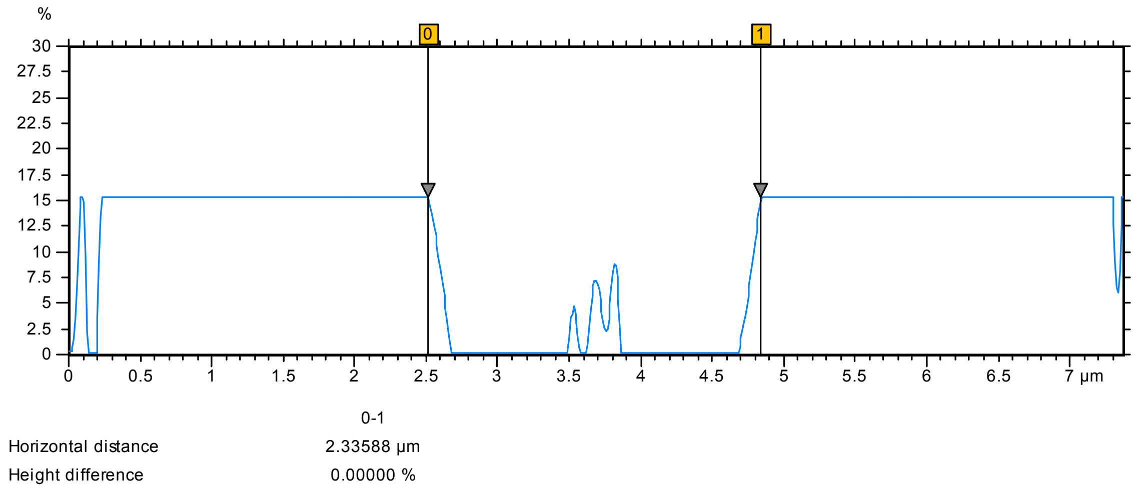


**Figure 31 Measurement of the resolution at 50 % cut-off width 20× magnification lens**

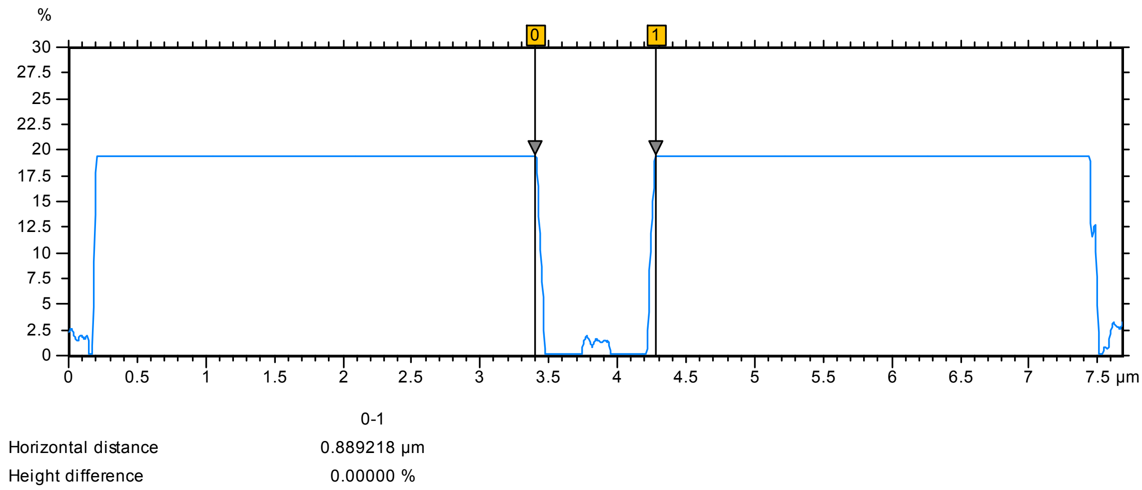


**Figure 32 Measurement of the resolution at 50 % cut-off width 50× magnification lens**

For the data in figure 31 and figure 32 the drop off was assessed on the descending slopes. The structure in the middle is attributed to some defocusing problems. Note also the 15 % and 20 % cut-off instead of 50 %. The reason is that the amplitude of the profile increases just before dropping off, which is a common confocal effect (see top circled area in figure 33) and the height inversion (see bottom circled area in figure 33).

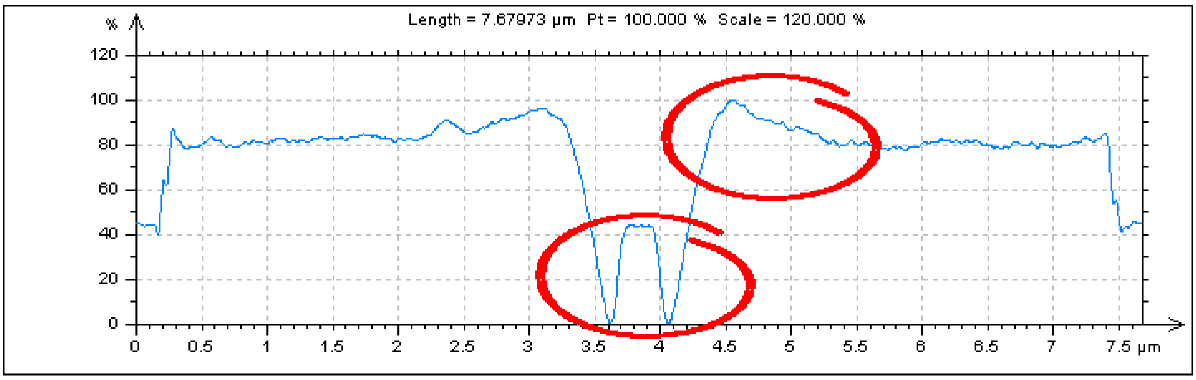


**Figure 33 Normalised height difference between the raised petals and dropped ones (50× magnification lens)**

# 6

# Measurement uncertainty

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,

$$u = \sqrt{u_A^2 + u_B^2}, \tag{5}$$

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

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

where $C_i$ is the $i^{\text{th}}$ sensitivity coefficient (see GUM) and the $u(x_i)$ is the uncertainty associated with the $i^{\text{th}}$ 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 8 presents the minimum S- and the maximum L-filter that are specific for each magnification lens (the values of the S-filter given in table 8 are based on the sampling spacing).

**Table 8 S-filter is based on the maximum sampling spacing**

| ISO25178-3 filters | 20× | 50× |
|---|---|---|
| S-filter / µm | 2.5 | 0.8 |
| L-filter / mm | 0.5 | 0.25 |

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 $Sz^2_{flatness}/12$. The combined effect of the measurement noise and residual flatness on the $z$ axis measurement standard uncertainty $u_{NF}$ is given by

$$u_{NF} = \sqrt{Sq^2_{noise} + \frac{Sz^2_{flatness}}{12}} \quad (7)$$

The combined effects of the measurement noise and residual flatness on the $z$ axis measurement standard uncertainty are presented in table 9.

**Table 9 Measurement noise and residual flatness contribution to the measurement uncertainty associated with the *z* axis measurements using the data from table 5 and table 4**

| Uncertainty contribution | 20× | 50× |
|---|---|---|
| $Sq_{\text{noise}}$ / nm | 4.1 | 1.4 |
| $Sz_{\text{flatness}}$ / nm | 162 | 27 |
| **$u_{NF}$ / nm** | **47** | **8** |

## Amplification, linearity and perpendiculaity

In practice the calculated amplification coefficients ($\alpha x$, $\alpha y$ and $\alpha z$) 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 measurement errors to the measurement uncertainty ($u_{\mathrm{error}}$) 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 ($\delta^2_{\mathrm{error}}/3$). The repeatability and reproducibility contribution to the overall measurement uncertainty ($u_{\mathrm{repeat}}$ and $u_{\mathrm{reprod}}$) 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 or reproducibility ($\delta^2_{\mathrm{repeat}}$ or $\delta^2_{\mathrm{reprod}}$). The combined effect of the measurement errors, traceability ($u_{\mathrm{traceabilty}}$), repeatability and/or reproducibility on the co-ordinate measurement standard uncertainty $u_{T\text{-}x}$, $u_{T\text{-}y}$ and $u_{T\text{-}z}$ is given by

$$u_{T-i} = \sqrt{u^2_{\mathrm{traceability}} + u^2_{\mathrm{repeat}} + u^2_{\mathrm{reprod}} + u^2_{\mathrm{error}}}, \tag{8}$$

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.

**Example of uncertainty associated with *z* measurement**

Example of the standard measurement uncertainties associated with the calibration of the $z$ scale for a typical ICM is presented in table 10. The data indicates that small step heights (around 18 nm) can be measured with standard uncertainties smaller than 2.1 nm, close to the standard measurement uncertainties achievable by primary instruments.

**Table 10 Amplification and linearity of the z scale contribution to the measurement uncertainty**

| Nominal height | $u_{error}$ | | $u_{repeat}$ | | $u_{reprod}$ | | $u_{traceability}$ | | $u_{T\text{-}z}$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 20× | 50× | 20× | 50× | 20× | 50× | 20× | 50× | 20× | 50× |
| /nm | | | | | | | | | | |
| 18 | 0.1 | 0.22 | 0.56 | 0.20 | 1.8 | 1.0 | 0.90 | 0.90 | 2.1 | 1.4 |
| 350 | 6.5 | 3.3 | 2.3 | 1.0 | 6.6 | 9.0 | 0.90 | 0.90 | 8.0 | 9.3 |
| 3 000 | 5.9 | 3.1 | 3.3 | 3.8 | 17 | 11 | 0.91 | 0.91 | 18 | 12 |
| 17 000 | 9.4 | 3.5 | 7.6 | 10 | 14 | 14 | 0.95 | 0.95 | 17 | 18 |

**Example of uncertainty associated with *x* and *y* measurement**

Example of the standard measurement uncertainties, without adjustment, associated with the *x* and *y* measurements are presented in in table 11 and corresponding to 50× and 20× magnification lens, respectively. In the 50× magnification lens configuration the maximum $u_{T\text{-}x}$ and $u_{T\text{-}y}$ (648 nm) is larger than the theoretical lateral resolution of the instrument (ca. 250 nm). In the 20× magnification lens configuration the maximum $u_{T\text{-}x}$ and $u_{T\text{-}y}$ (1.7 µm) is three times larger than the theoretical lateral resolution of the instrument (ca. 600 nm).

**Table 11 Amplification and linearity of the lateral scales contribution to the measurement uncertainty for the 50× magnification lens – no adjustment**

| Nominal length | $u_{error}$ | | $u_{reprod}$ | | $u_{traceability}$ | | $u_{T\text{-}x}$ | $u_{T\text{-}y}$ |
|---|---|---|---|---|---|---|---|---|
| | *x* | *y* | *x* | *y* | *x* | *y* | | |
| /µm | | | | | | | | |
| 30 | 0.035 | 0.190 | 0.007 | 0.008 | 0.010 | 0.014 | 0.037 | 0.191 |
| 60 | 0.009 | 0.270 | 0.018 | 0.014 | 0.013 | 0.014 | 0.024 | 0.271 |
| 90 | 0.009 | 0.413 | 0.014 | 0.011 | 0.015 | 0.014 | 0.022 | 0.413 |
| 120 | 0.085 | 0.473 | 0.014 | 0.017 | 0.012 | 0.019 | 0.087 | 0.474 |
| 150 | 0.111 | 0.548 | 0.017 | 0.023 | 0.019 | 0.024 | 0.114 | 0.549 |
| 180 | 0.148 | 0.647 | 0.020 | 0.024 | 0.016 | 0.035 | 0.150 | 0.648 |

**Table 12 Amplification and linearity of the lateral scales contribution to the measurement uncertainty for the 20× magnification lens - no adjustment**

| Nominal length | $u_{error}$ | | $u_{reprod}$ | | $u_{traceability}$ | | $u_{T\text{-}x}$ | $u_{T\text{-}y}$ |
|---|---|---|---|---|---|---|---|---|
| | $x$ | $y$ | $x$ | $y$ | $x$ | $y$ | | |
| /µm | | | | | | | | |
| 100 | 0.118 | 0.306 | 0.074 | 0.080 | 0.014 | 0.017 | 0.140 | 0.317 |
| 200 | 0.047 | 0.766 | 0.073 | 0.106 | 0.025 | 0.014 | 0.090 | 0.773 |
| 300 | 0.177 | 1.184 | 0.095 | 0.111 | 0.021 | 0.020 | 0.202 | 1.190 |
| 400 | 0.488 | 1.472 | 0.066 | 0.117 | 0.032 | 0.011 | 0.493 | 1.477 |
| 500 | 0.715 | 1.699 | 0.020 | 0.159 | 0.023 | 0.010 | 0.716 | 1.706 |

Using the correction factor αx of 1.0019 to adjust the amplification of the x scale and αy of 0.9936 to adjust the amplification of the y scale for both of the 20× and 50× magnification lens configuration, the maximum measurement uncertainty decreases from 650 nm to less than 100 nm for the 50× magnification lens configuration and from 1.7 µm to less than 250 nm for the 20× magnification lens configuration (table 13 and table 14).

**Table 13 Amplification and linearity of the lateral scales contribution to the measurement uncertainty for the 50× magnification lens –adjusted**

| Nominal length | $u_{error}$ | | $u_{reprod}$ | | $u_{traceability}$ | | $u_{T\text{-}x}$ | $u_{T\text{-}y}$ |
|---|---|---|---|---|---|---|---|---|
| | $x$ | $y$ | $x$ | $y$ | $x$ | $y$ | | |
| /µm | | | | | | | | |
| 30 | 0.054 | 0.075 | 0.007 | 0.008 | 0.010 | 0.014 | 0.055 | 0.077 |
| 60 | 0.048 | 0.040 | 0.018 | 0.014 | 0.013 | 0.014 | 0.053 | 0.045 |
| 90 | 0.049 | 0.068 | 0.014 | 0.011 | 0.015 | 0.014 | 0.053 | 0.070 |
| 120 | 0.008 | 0.013 | 0.014 | 0.017 | 0.012 | 0.019 | 0.020 | 0.028 |
| 150 | 0.015 | 0.028 | 0.017 | 0.023 | 0.019 | 0.024 | 0.030 | 0.044 |
| 180 | 0.032 | 0.045 | 0.020 | 0.024 | 0.016 | 0.035 | 0.041 | 0.062 |

**Table 14 Amplification and linearity of the lateral scales contribution to the measurement uncertainty for the 20× magnification lens - adjusted**

| Nominal length | $u_{error}$ | | $u_{reprod}$ | | $u_{traceability}$ | | $u_{T\text{-}x}$ | $u_{T\text{-}y}$ |
|---|---|---|---|---|---|---|---|---|
| | *x* | *y* | *x* | *y* | *x* | *y* | | |
| /µm | | | | | | | | |
| 100 | 0.228 | 0.054 | 0.074 | 0.080 | 0.014 | 0.017 | 0.240 | 0.098 |
| 200 | 0.172 | 0.047 | 0.073 | 0.106 | 0.025 | 0.014 | 0.188 | 0.117 |
| 300 | 0.152 | 0.106 | 0.095 | 0.111 | 0.021 | 0.020 | 0.181 | 0.155 |
| 400 | 0.049 | 0.034 | 0.066 | 0.117 | 0.032 | 0.011 | 0.088 | 0.123 |
| 500 | 0.166 | 0.099 | 0.020 | 0.159 | 0.023 | 0.010 | 0.169 | 0.188 |

**Example of uncertainty associated with *x* and *y* perpendicularity**

The perpendicularity contribution to the measurement uncertainty ($u_{PER}$) is 12 nm, based on the error of 20 nm estimated for the maximum possible measured length of 1.4 mm (diagonal measurement in the 1 mm × 1 mm area).

## Lateral resolution

The lateral resolution contribution to the measurement uncertainty, $u_{Res}$, is propagated in the form of a rectangular distribution that has a variance equal to the $Res^2/3$, where *Res* is the lateral topographical resolution. The lateral resolution contribution to the measurement uncertainty is equal to 1.3 µm and 0.5 µm with the 20× and 50× magnification lens, respectively.

## 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

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

There are different ways of presenting the measurement uncertainty associated with the calibration of the metrological characteristics of the instrument. One way is presented table 10 and table 11, 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.

In the 20× magnification lens case the measurement uncertainties associated with calibration of the *z* scale are dominated by the residual flatness and measurement noise contribution, which makes the maximum standard uncertainty associated with the *z* scale calibration as large as 52 nm. In the 50× magnification lens case the maximum combined measurement uncertainty is 20 nm. However, it is still possible to measure surface topography much smaller than this value. The main contributor to this combined uncertainty is due to the traceability – the primary calibration has a relatively large uncertainty. However, when calculating surface texture parameters, it is still possible to have values which are smaller than the combined uncertainty – this is due to the averaging effect of the parameter calculation and the fact that all the values are referenced to a mean line (see Example 2 in the Measurement Examples chapter).

The uncertainties associated with the lateral measurements are dominated by resolution, such that the standard measurement uncertainty is in excess of 0.4 µm in the in the 20× magnification lens configuration and 0.13 µm in the 50× magnification lens configuration.

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

# Measurement Examples

7

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 an 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 14) 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 figure 34). The central groove is the measurement grove. The other two grooves are for position identification only.

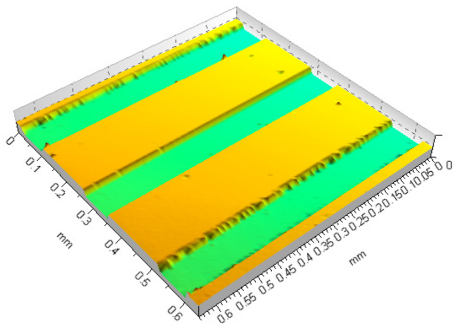

**Figure 34 Measurement result of a 350 nm step height physical measurement standard using the 20× magnification lens**

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

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

### Measurement noise and residual flatness contribution

Since the step height analysis in areal mode calculates the mean profiles along the *x* axis of the instrument (see figure 35) some of the effects of the *y* axis flatness deviation on the measurement uncertainty associated with the step height calculation are diminished.

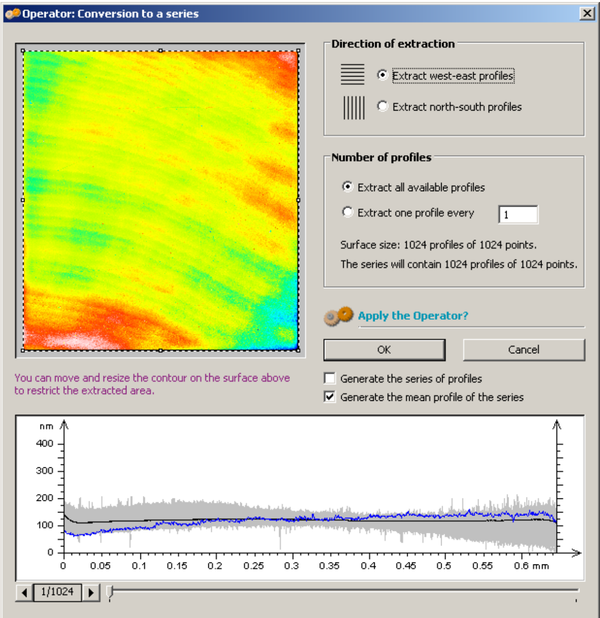


**Figure 35 Extraction of mean profile along the *x* axis**

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 36).

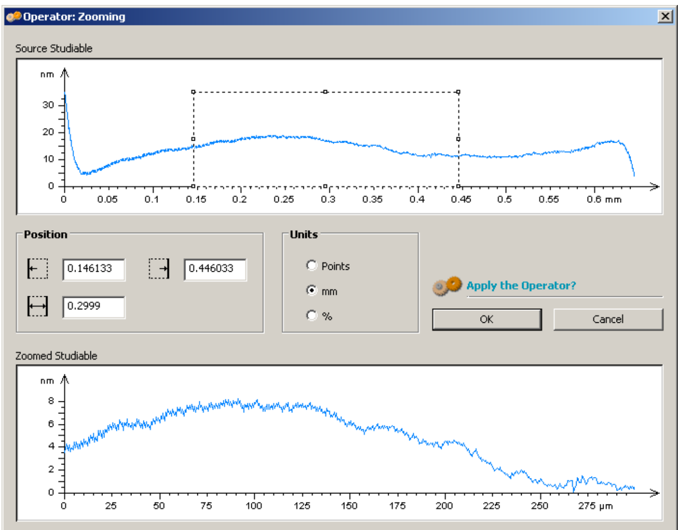


**Figure 36 Zoom operation of the mean profile**

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 $Pt^2_{flatness}/12 + \sigma^2_{PT}/9$, where $\sigma_{PT}$ is the standard deviation. It follows that the $u_{NF}$ for the 350 nm step height measurement using the 20× magnification lens is 5 nm (see table 16).

**Table 16 Example of $u_{NF}$ values for 20× magnification lens**

| **Measurement No.** | ***Pt* /nm** |
|---|---|
| 1 | 8.8 |
| 2 | 20 |
| 3 | 4.2 |
| 4 | 14 |
| 5 | 33 |
| **Average** | 16 |
| **Repeatability ($\sigma_{Pt}$)** | 5 |
| $u_{NF}$ | 5 |

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 37). In this situation, the sensitivity coefficients that are used to propagate the measurement noise and flatness deviation component are given by equation (10)

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

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 37, the width of the groove is approximately 0.09 mm. If the sampling distance is approximately 0.6 µm the $C_{NF}$ is approximately $0.025^{1/2}$.

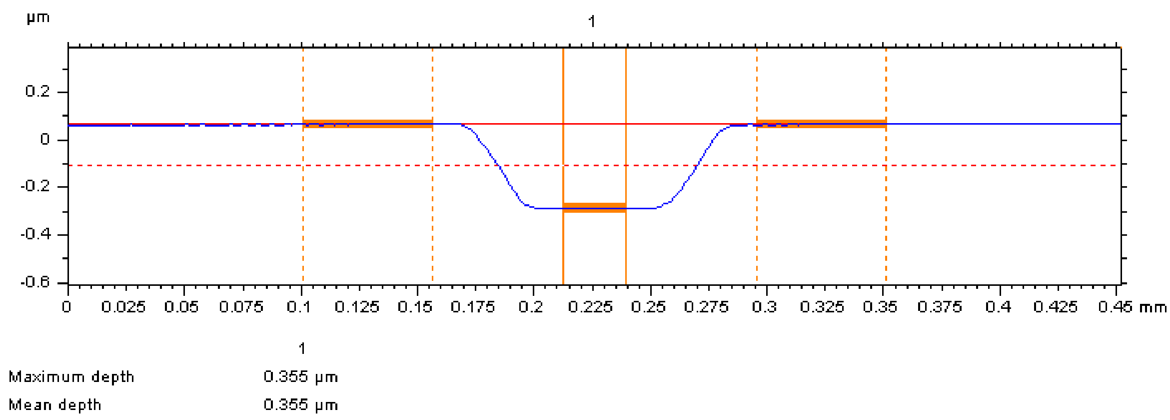


**Figure 37 Example of step height analysis in profile mode**

**Amplification and linearity contribution**

The contribution of amplification and linearity remains unchanged such that in the $u_{T\text{-}z}$ will not exceed 1.0 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 | 326.5 |
| 2 | 335.0 |
| 3 | 327.7 |
| Average | 329.7 |
| $u_A$ | 2.7 |

**Combined standard uncertainty**

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

$$u^2 = u_A^2 + u_B^2 = \left(2.7^2 + 0.025^2 \times 5^2 + 8.0^2\right)\text{nm}^2 \cong 8.4^2\ \text{nm}^2 . \tag{11}$$

**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 ($\nu$) that can be calculated with

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

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

$$\nu = 2 \times \frac{8.4^4}{2.7^4} \cong \infty . \tag{13}$$

It follows that the measurement result can be expressed as:

$$h = (330 \pm 17)\,\text{nm}, (k = 2) . \tag{14}$$

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 residual flatness (nm)** | **Filters nesting index:**<br>S-filter: N/A<br>L-filter: N/A<br>**Method used:**<br>Flat measurement | **Artefact:**<br>S/No: Platen B<br>Calibrated: ~~Yes/~~No<br>**Tested measurement range:**<br>*x* range: 0.9 mm<br>*y* range: 0.9 mm<br>*z* range: 50 % | 5.0 | 0.025 | 0.028 |
| **Amplification and linearity of the *z* scale (nm)** | **Calibrated *z* range:**<br>(0.018 to 350) µm | **Tested measurement range:**<br>*x* range: 0.9mm<br>*y* range: 0.9 mm<br>*z* range: 50 % | 8.0 | 1 | 2.3 |
| **Type A (nm)** | **Artefact type/SNo:** PGR/16234 | | | | 2.7 |
| **Depth standard uncertainty** | | | | | 8.4 |

## Example 2 – Type AIR test

In this example an type AIR of physical measurement standard was measured (see figure 38) 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.

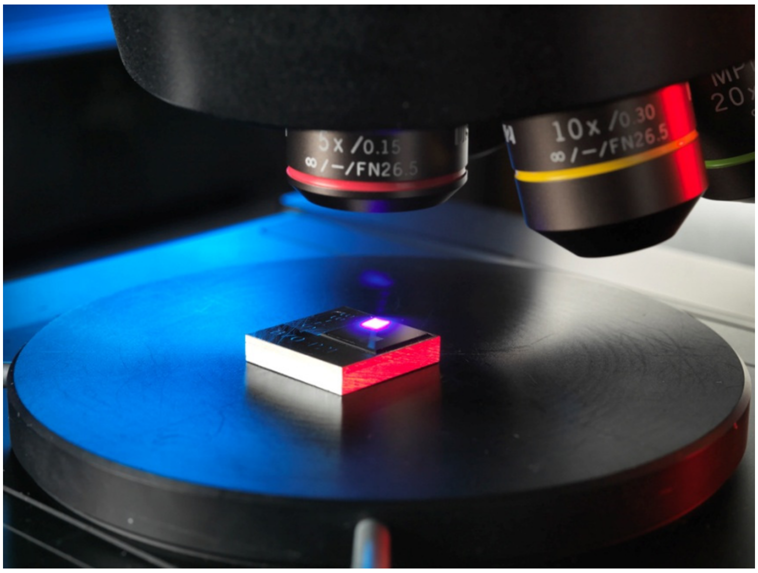


**Figure 38 Measurement of an type AIR physical measurement standard**

Three measurements were performed in the 20× magnification lens configuration (see figure 39) with a 0.6 µm sampling distance in both *x* and *y* directions. The *Sq* value was calculated in a central region of 0.6 mm by 0.6 mm of the physical measurement standard.

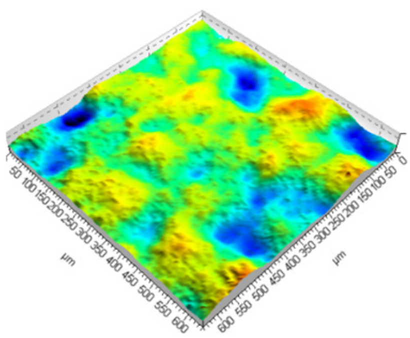


**Figure 39 Measurement result of the central area of the type AIR physical measurement standard**

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 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 residual flatness 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 47 nm.

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

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

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

$$\bar{z} = \frac{\sum_{NM} z_{ij}}{NM} \quad . \tag{16}$$

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

$$C_{ij} = \frac{\partial Sq}{\partial z_{ij}} \cong \frac{1}{Sq}\frac{\left|z_{ij} - \bar{z}\right|}{NM} . \tag{17}$$

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

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

**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

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

It follows that

$$u_B=\frac{Sa}{Sq}\sqrt{u_{NF}^2+u_{T-z}^2}\,. \tag{20}$$

**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.** | ***Sq* /nm** |
|---|---|
| 1 | 1021.70 |
| 2 | 1021.48 |
| 3 | 1020.94 |
| Average | 1021.37 |
| $u_A$ | 0.23 |

**Combined standard uncertainty**

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

$$u^2=u_A^2+u_B^2=\left[0.23^2+\frac{740^2}{1021^2}\left(47^2+17^2\right)\right]\text{nm}^2\cong 38^2\ \text{nm}^2\,. \tag{21}$$

**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

$$Sq = \left(1.02 \pm 0.08\right) \mu\text{m}, (k = 2)\,. \qquad (22)$$

The calibrated value of *Sq* at the same position was (1027 ± 10) nm ($k = 2$), which gives a measurement error of - 6 nm, well within the standard uncertainty associated with the measurement of *Sq* by the NPL Areal 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 1 µm**

| **Uncertainty component (Unit)** | **Comments** | **Value /Unit** | **Sensitivity coefficient /Unit** | **Uncertainty contribution/ Unit** |
|---|---|---|---|---|
| **Measurement noise and residual flatness (nm)** | **Filters nesting index:**<br>S-filter: 2.5 µm<br>L-filter: 0.5 mm<br>**Method used:**<br>Flat measurement<br>**Artefact:**<br>S/No: Platen B<br>Calibrated: ~~Yes/~~No<br>**Tested measurement range:**<br>*x* range: (0 to 1.4) mm<br>*y* range: 50 % ± 1 mm<br>*z* range: 50 % | 47 | 0.77 | 36 |
| **Amplification and linearity of the *z* scale (nm)** | **Calibrated *z* range:**<br>(0.018 to 17) µm<br>**Tested measurement range:**<br>*x* range: (0 to 1.4) mm<br>*y* range: 50 % ± 1 mm<br>*z* range: 50 % | 17 | 0.77 | 13 |
| **Type A (nm)** | **Artefact type/SNo:** AIR/123 | | | 0.23 |
| ***Sq* standard uncertainty** | | | | 38 |

# 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 (Kluwar 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)