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Geometrical product specifications (GPS) — Surface texture: Areal —

Part 700:
Calibration, adjustment and verification of areal topography measuring instruments

Spécification géométrique des produits (GPS) — État de surface: Surfacique —

Partie 700: Étalonnage, ajustage et vérification d'instruments de mesure de la topographie des surfaces

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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A list of all parts in the ISO 25178 series can be found on the ISO website.

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Introduction

This document is a geometrical product specification (GPS) standard and is to be regarded as a general GPS standard (see ISO 14638). It influences chain links E, F and G of the chains of standards on profile surface texture and areal surface texture.

The ISO/GPS matrix model given in ISO 14638 gives an overview of the ISO/GPS system, of which this document is a part. The fundamental rules of ISO/GPS given in ISO 8015 apply to this document and the default decision rules given in ISO 14253-1 apply to the specifications made in accordance with this document, unless otherwise indicated.

For more detailed information of the relation of this document to other standards and the GPS matrix model, see Annex A.

In the GPS concept, the design values of geometric parameters on workpieces and their tolerances are compared with the measurement of those parameters on the corresponding manufactured workpieces and their associated measurement uncertainties. For a reliable result it is therefore necessary to calibrate the measurement instrument involved in this process.

This document specifies default procedures for the calibration, adjustment and verification of surface topography measuring instruments, using material measures traceable to the meter through a national metrology institute or qualified laboratory, see ISO/IEC Guide 99:2007, 2.41. Default methods are recommended when no other calibration procedures have been clearly defined.

This document describes the calibration (see ISO/IEC Guide 99:2007, 2.39), adjustment (see ISO/IEC Guide 99:2007, 3.11) and verification (see ISO/IEC Guide 99:2007, 2.44) in general for topography measuring instruments.

The calibration of an instrument's metrological characteristics enables the verification of the instrument's specifications when the specifications are based on these metrological characteristics. This also enables the comparison of systems of different manufacturers that may be based on different measurement principles.

The metrological characteristics capture all of the factors that can influence a measurement result (influence quantities) and can be propagated appropriately through a specific measurement model to estimate measurement uncertainty.

Calibration is a part of the determination of the overall uncertainty of measurement. The complete evaluation of measurement uncertainty may include other factors such as operator variability, changing environmental influences, the effects of thermal and mechanical stresses on the sample part and other factors that are not accounted for in the instrument calibrations.

Alternative calibration techniques to the defaults given here are equally acceptable, depending on the capabilities of the instrumentation and provided those alternatives have clear traceability paths. Example techniques include those based on an independent realization of the meter using a natural emission wavelength, the value for which has been established with a known uncertainty.

Geometrical product specifications (GPS) — Surface texture: Areal —

Part 700: Calibration, adjustment and verification of areal topography measuring instruments

1 Scope

This document specifies generic procedures for the calibration, adjustment and verification of metrological characteristics that areal topography measuring instruments have in common, as stated in ISO 25178-600.

Because surface profiles can be extracted from surface topography images, most of the methods described in this document can be adapted to profiling instruments.

Instrument-specific issues are not covered by this document. For example, for instruments based on mechanical probing where the probe follows an additional arcuate motion, additional measures are specified in ISO 25178-701.

This document does not include procedures for area-integrating methods, although those are also stated in ISO 25178-6. For example, light scattering belongs to a class of techniques known as area-integrating methods for measuring surface topography.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 25178-600:2019, *Geometrical product specifications (GPS) — Surface texture: Areal — Part 600: Metrological characteristics for areal topography measuring methods*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
non-measured points
surface locations for which no valid measured values exist

Note 1 to entry: The handling of non-measured points is specified in 6.3.

Note 2 to entry: Non-measured points may be caused by a feature of the measuring instrument or by a defect on the surface of the measurement standard which is outside the range of the instrument.

3.2
spurious data
data that have been qualified as measurable by the measurement principle but deviate significantly from a reasonable value range, based on a priori knowledge

Note 1 to entry: Spurious data may relate to single points or a small group of points that have been classified as measurable by the measurement instrument. They are identified as spurious data by determining their values to be unlikely based on a priori knowledge about both the expected surface and the instrument, or simply by defects and contamination on the surface. Spurious data may appear as outliers or spikes.

Note 2 to entry: Spurious data can be caused by environmental conditions, such as vibration or external light sources, by interaction between the surface and instrument, or simply by defects and contamination on the surface. Spurious data may appear as outliers or spikes.

Note 3 to entry: The handling of spurious data is specified in 6.4.

3.3
measurement noise
N_M
noise added to the output signal occurring during the normal use of the instrument

[SOURCE: ISO 25178-600:2019, 3.1.15, modified — Notes to entry removed.]

3.4
instrument noise
N_I
internal noise added to the output signal caused by the instrument if ideally placed in a noise-free environment

[SOURCE: ISO 25178-600:2019, 3.1.14, modified — Notes to entry removed.]

3.5
***z*-linearity deviation**
l_z
maximum local linearity difference between the line from which the amplification coefficient is derived and the response function

[SOURCE: ISO 25178-600:2019, 3.1.11, modified — Term revised and note to entry removed.]

3.6
instrument transfer function curve
f_{ITF}
curve describing an instrument's height response as a function of the spatial frequency of the surface topography

[SOURCE: ISO 25178-600:2019, 3.1.19, modified — Term revised and notes to entry removed.]

3.7
topography fidelity
T_{FI}
closeness of agreement between a measured surface profile or measured topography and one whose uncertainties are insignificant by comparison

[SOURCE: ISO 25178-600:2019, 3.1.26, modified — Note to entry removed.]

4 Symbols and abbreviated terms

The metrological characteristics for areal topography measuring methods and associated symbols and abbreviated terms are defined in ISO 25178-600. Table 1 contains a list of these metrological characteristics.

Table 1 — List of metrological characteristics for surface texture measurement methods[a]

Metrological characteristic (and clause in this document)	Symbol	Clause and figure in ISO 25178-600:2019 containing definition	Main potential error along (ISO 25178-600:2019, 3.1.2)
Amplification coefficient (6.7)	α_x, α_y, α_z	3.1.10 (Figure 2)	*x*, *y*, *z*
Linearity deviation (6.8)	l_x, l_y, l_z	3.1.11 (Figure 2)	*x*, *y*, *z*
Flatness deviation (6.6)	z_{FLT}	3.1.12	*z*
Measurement noise (6.5)	N_M	3.1.15	*z*
Topographic spatial resolution (6.11)	W_R	3.1.20	*z*
x-*y* mapping deviations (6.9)	$\Delta_x(x,y)$, $\Delta_y(x,y)$	3.1.13	*x*, *y*
Topography fidelity (6.12)	T_{FI}	3.1.26	*x*, *y*, *z*

NOTE 1 Depending on the measurement application, other axis motion errors (see ISO 230-1, ISO 10360-7 and ISO 10360-8) can also be significant but are not listed here for surface texture measurement.

NOTE 2 The maximum measurable slope is an important limitation to be specified for a surface topography measurement instrument. However, users do not need to measure this parameter unless it is part of a measurement model.

[a] Adapted from ISO 25178-600:2019, Table 1.

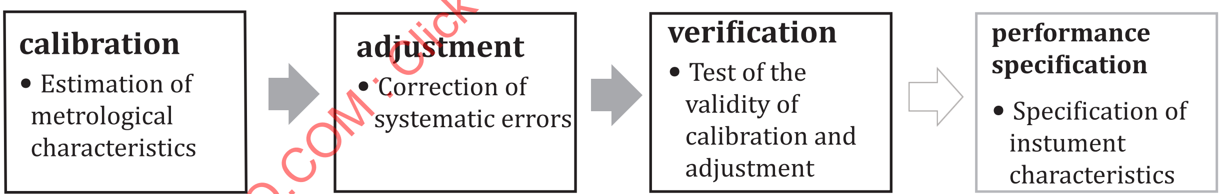
5 Calibration, adjustment and verification of an instrument

5.1 General

This document defines default methods for calibration. It also specifies the general principle for adjustment, verification and determining performance specifications, see Figure 1. Other methods used for calibration shall meet the requirements as specified here and shall be specified.

If no adjustment is necessary, the initial calibration constitutes the verification. In this case the calibration result contributes to the measurement uncertainty calculation.

If adjustment is done, verification may be done by a subsequent calibration after adjustment.



NOTE The white arrow indicates the possible subsequent comparison with specifications.

Figure 1 — Flow chart of calibration, adjustment and verification procedure

NOTE 1 Determination of the metrological characteristics is not intended to assess the errors due to the calibration and computational algorithms. These algorithms can be verified using software measurement standards, see ISO 25178-71 and ISO 25178-72.

NOTE 2 Performance specifications are typically provided by instrument manufacturers.

5.2 Methods for calibration, adjustment and verification

In this document, methods are defined for noise (6.5), flatness deviation (6.6.2), amplification (6.7.2), linearity deviation (6.8.3) and *x*-*y* mapping deviations (6.9.2). For each of these metrological characteristics a method for the determination of its value is defined. Depending on the characteristics these methods can be used both to calibrate and to verify after adjustment.

No default methods are defined for perpendicularity of the instrument *z*-axis with respect to the *x*-*y* areal reference (6.10), topographic spatial resolution (6.11) and topography fidelity (6.12).

5.3 Instrument calibration procedure

5.3.1 Calibration by measurement standards

The default procedures all include the use of material measures. Calibrated measurement standards, as defined in ISO 25178-70, shall be used during the determination of the metrological characteristics of the instruments. The deviation from the values stated in the calibration certificate shall be recorded and the uncertainty of the calibration values shall be taken into account. The measurement standards (calibrated material measures) shall be selected by taking into account the characteristics of the surface to be measured.

NOTE 1 The requirements for the material measures are described in ISO 25178-70 and for contact (stylus) instruments in ISO 25178-701:2010, 5.2.1.2.

NOTE 2 Optical flats do not need to be calibrated for the determination of noise as specified in 6.5.

5.3.2 Handling of defects on material measures

Measurement standards without defects should be selected as a first preference. In all cases, however, the possibility of surface defects (in the sense of ISO 25178-73:2019, 3.1.2) shall be addressed when a physical measurement standard is used for calibration tasks. Defects shall be identified or described in accordance with ISO 25178-73:2019, 3.2. Measurement records shall include a statement on the selected response to any encountered surface defects (ISO 25178-73:2019, 3.3), paying attention to the distinction between effective and ineffective defects. If it is not possible to plan valid measurements for a task on a defective standard, that standard shall not be used for that task.

For brevity, such defect-response statements may refer to procedures stated on the calibration certificate of the measurement standard or other suitable documentation from the supplier.

NOTE The supplier of the defective measurement standard will possibly be able to supply an alternative calibration certificate and/or associated measurement procedure that are compatible with the observed defects, allowing valid measurements to be planned without repair or replacement of the standard.

5.3.3 Measurement procedures for calibration with measurement standards

Measurement procedures specified on the calibration certificate of the measurement should be adhered to as closely as possible while using it for the determination of metrological characteristics.

5.3.4 Calibration conditions

Determination of the metrological characteristics shall be performed for each individual instrument and each instrument setup (configuration) used in practice. Environmental conditions shall be similar to working conditions for subsequent measurement activity for that instrument. The selection and configuration of evaluation software shall be the same as that used in practice.

Calibration for determining instrument specification shall be done under documented measurement conditions and these conditions shall be reported (see ISO/IEC 17025:2017, 6.3).

NOTE The instrument setup (configuration) is generally application specific.

EXAMPLE Examples of different setups (configurations):

— use of objective lenses with different magnifications;

— use of different stylus tip radii;

— use of different scanning directions;

— use of different scanning speeds;

— different environmental conditions, such as a significantly different temperature.

6 Determination of the metrological characteristics of the instrument

6.1 General

The metrological characteristics of the instrument that may influence the measurement result and the evaluated measurement uncertainty shall be determined:

— within the measurement volume defined for the intended application;

— at different positions within the measurement volume, if applicable;

— according to an agreed or accepted measurement scheme;

— for different scanning speeds or directions, if applicable.

General measurement schemes are given in the following clauses and more detailed measurement schemes may be specified for each measuring principle.

6.2 Reporting of the measurement conditions

Measurement conditions, relevant instrument settings and environmental conditions may influence the metrological characteristics and shall be reported. Potential disturbances, such as acoustic noise, vibration or lighting conditions, shall be reported but may be described qualitatively.

NOTE 1 Examples of instrument settings and environmental conditions include: temperature; humidity; internal illumination configuration; scan increment; scan speed for scanning instruments (see ISO 25178-604:2013, 2.5.12 and 2.5.13).

NOTE 2 Example phrases for qualitative reporting include "No vibrations or strong vibrations" and "no disturbance by external illumination"; see also 6.5.2.

6.3 Handling of non-measured points

By default, no interpolation and filling of non-measured points within the relevant areas is applied for the determination of the metrological characteristics. However, if interpolation and filling is applied, it shall be reported. Measurements for which a significant number of the points are non-measured should be discarded. Interpolation or other mathematical algorithms shall not change the status of non-measured points to measured points.

6.4 Handling of spurious data and outliers

Depending on a priori knowledge and later applications, spurious data within the region of interest should be removed from the measured points and should be treated in the same way as non-measured points, as specified in 6.3.

6.5 Metrological characteristic: measurement noise, N_M, and instrument noise, N_I

6.5.1 General

The instrument noise is the minimum achievable noise under the most ideal circumstances.

Evaluation of instrument noise shall be performed under the best conditions for the characterization of instrument performance, see ISO 25178-600.

For some instruments, instrument noise cannot be completely separated from other types of measurement noise because the instrument only acquires data while moving. If so, any measured noise includes a dynamic component. See also static noise (ISO 25178-600: 2019, 3.2.6) and dynamic noise (ISO 25178-600: 2019, 3.2.7).

6.5.2 Determination of measurement and instrument noise: application of filters or operators

In applications where filters or operators are used, the measurement noise determination should proceed under the same filter conditions as those used for measurements. The used filters with the applied nesting indices and the used operators shall be reported.

A quantitative statement of measurement noise shall include any filters that may influence the spatial frequencies over which the noise is determined.

An instrument noise specification shall include the relevant data acquisition time, the number of independent data points and any spatial or temporal filters that may influence the spatial frequencies over which the noise is determined (see Reference [19]).

NOTE The S-filter as a low-pass filter reduces the noise but can affect the topographic spatial resolution if this resolution is limited by the lateral sampling. When estimating the noise for the highest lateral resolution, it can be preferable to perform measurements without applying an S-filter.

EXAMPLE In a specification sheet a quantitative statement of instrument noise can be indicated as follows: full measurement area, 1 s data acquisition (at 10 averages per second) and a 3 × 3 pixel median filter.

6.5.3 Determination of measurement and instrument noise: material measures for instrument and measurement noise estimation

The default material measure for instrument noise determination should be one that:

— is compatible with the instrument measurement principle;

— has a smooth and flat surface;

— has surface properties that give an optimum signal-to-noise ratio.

By default, this material measure shall be optically aligned so that a minimum measurement range of the instrument is used. Material measures with an antireflection coating for optical measurements or those causing stick-slip during mechanical measurement may not provide an optimum signal-to-noise ratio. Other types of surfaces can also be used if specified. For example, a minimum amount of roughness may be required for measurement principles such as focus variation microscopy.

The evaluation of the measurement noise is best performed on the surface to be measured on a workpiece under inspection or on a representative sample with similar surface features to the workpiece surface.

EXAMPLE Type AFL material measures as defined in ISO 25178-70 can be used for the instrument noise evaluation.

6.5.4 Determination of measurement and instrument noise: procedure for the determination of measurement noise

6.5.4.1 General

The subtraction method, 6.5.4.3, is the default method for determination of measurement noise of areal measuring instruments.

6.5.4.2 Assessed parameter

The assessed parameter is N_M according to Formula (1) or (3).

6.5.4.3 Estimation of measurement noise by the subtraction method

The default method for the determination of measurement noise is the measurement of a material measure according to 6.5.3, which shall be measured twice at the same location with the shortest possible time difference between the two sequential measurements. The two measured topographies are subtracted from each other. Ideally this makes the result independent of the exact topography of the material measure, such that no filtration nor any further form removal of the material measure is required. The vertical drift and any drift in the surface tilt can be eliminated by removing a least-squares plane from the measurements or from the measurement difference. The measurement noise N_M is the root mean square (RMS) of the remaining differences divided by $\sqrt{2}$.

The measurement noise is determined in practice by calculating the RMS height S_q (or R_q for profile measurements), as defined in ISO 25178-2, of the difference of two maps. The noise is then obtained by dividing this S_q value by $\sqrt{2}$. S_q is assessed on the S-L or S-F surface, as appropriate. The nesting indices should be as close as possible to those nesting indices used afterwards for measurements.

For scanning point sensors, the instrument noise shall be determined accordingly by profile measurements or scanning areal measurements, depending on the application.

NOTE 1 A mathematical description of the subtraction method for estimating the measurement noise is given in Formula (1).

$$N_M = \frac{1}{\sqrt{2}} S_q(z_1(x,y) - z_2(x,y)) = \frac{1}{\sqrt{2}} \sqrt{\frac{1}{A} \iint_A (z_1(x,y) - z_2(x,y))^2 \, dx \, dy} \quad (1)$$

where

N_M is the measurement noise;

S_q is the root mean square height;

A is the measured area;

z_1 is the topography result from the first measurement;

z_2 is the topography result from the second measurement.

NOTE 2 A mathematical description of the procedure for uniformly spaced discretely sampled data is given in Formula (2).

$$N_M = \frac{1}{\sqrt{2}} \sqrt{\frac{1}{N_x N_y} \sum_{j=1}^{N_x} \sum_{k=1}^{N_y} \left(z_1(x_j, y_k) - z_2(x_j, y_k)\right)^2} \quad (2)$$

where

N_M is the measurement noise obtained by the subtraction method, taking two measurements;

N_x, N_y are the number of data points in the x- and y-directions, respectively.

NOTE 3 The division by $\sqrt{2}$ accounts for the fact that each of the two measurements contributes to the noise.

NOTE 4 Although the description of instrument noise in ISO 25178-701 (there specified as dynamic noise) refers to contact (stylus) instruments, that concept is now generalized in this document as measurement noise for all scanning point sensors.

For instruments that acquire data by scanning through a range of surface heights, for example CSI and confocal microscopes, the data acquisition time may be expressed as a height-scanning rate, for example 10 µm/s.

NOTE 5 The terms “vertical resolution”, “surface height resolution” and similar are sometimes found in technical literature and in instrument brochures. “Vertical resolution” refers qualitatively to the smallest variation in surface height in a topography that can be meaningfully measured.[22]

6.5.4.4 Estimation of measurement noise by the averaging method

To obtain a stable noise estimate, and to enable an assessment of the noise stability, the object is measured several times (n, $n \geq 3$) at the same location with the shortest possible time difference between the repeated measurements. The time required to acquire the signal data for each individual measurement (defined as the 'data acquisition time') shall be reported, as well as any filtering that alters the noise value. The measured topographies are averaged, and this average is subtracted from each measurement. Ideally this makes the result independent of the exact topography of the material measure such that no filtration nor any further form removal of the material measure is required. The vertical drift and any drift in the surface tilt can be eliminated by removing a least-squares plane from the individual measurements. The RMS of the differences with the mean, corrected for the degrees of freedom, is the measurement noise obtained by averaging N_M.

NOTE 1 Mathematical description of the procedure for uniformly-spaced discretely sampled data is given in Formula (3).

$$N_\mathrm{M} = \sqrt{\frac{\sum_{i=1}^{n} \frac{1}{N_x N_y} \sum_{j=1}^{N_x} \sum_{k=1}^{N_y} \left(z_i\left(x_j, y_k\right) - z_\mathrm{m}\left(x_j, y_k\right)\right)^2}{n-1}} = \sqrt{\frac{\sum_{i=1}^{n} S_\mathrm{q}^2\left(z_i(x,y) - z_\mathrm{m}(x,y)\right)}{n-1}} \quad (3)$$

where

N_M	is the measurement noise obtained by the subtraction method, taking n measurements;
N_x, N_y	are the number of data points in the x- and y-directions, respectively;
S_q	is the root mean square height as defined in ISO 25178-2;
z_i	is the i^th topography measurement;
z_m	is the mean value of the z-coordinates of the n measurements.

NOTE 2 For $n = 2$, Formula (3) gives the same result as Formula (2), noting that for this case $z_\mathrm{m}(x,y) = ½\left(z_1(x,y) + z_2(x,y)\right)$. The derivation is given in Reference [23].

NOTE 3 If the instrument does not enable access to individual data points or the subtraction of topographies, but enables averaging of topographies, then the following Formula (4) can also be used:

$$N_\mathrm{M} = \sqrt{\frac{\sum_{i=1}^{n} S_\mathrm{q}^2\left(z_i(x,y)\right) - n \cdot S_\mathrm{q}^2\left(z_\mathrm{m}(x,y)\right)}{n-1}} \quad (4)$$

where

N_M	is the measurement noise obtained by the averaging method;
S_q	is the root mean square height as defined in ISO 25178-2;
z_i	is the i^th topography measurement;
z_m	is the mean value of the z-coordinates of the n measurements.

See 6.5.4.3.

6.5.4.5 Determination of the stabilized measurement noise by the subtraction method

If the noise is determined from pairs of measurements as in Formula (2), this noise measurement should be repeated $p \geq 3$ times; the measurement noise can be approximated by Formula (5).

$$\bar{N}_{\mathrm{M}} = \sqrt{\frac{1}{p}\sum_{i=1}^{p} N_{\mathrm{M}i}^{2}} \tag{5}$$

where

$\bar{N}_{\mathrm{M}}$ is the stabilized measurement noise obtained by the subtraction method;

$N_{\mathrm{M}i}$ is the i^{th} measurement of the measurement noise each as performed according to 6.5.4.3;

p is the number of pair combinations.

When all possible pair combinations from n (n even) measurements are taken, Formula (6) gives the same result as Formula (3).

The noise stability is given by the determination of the standard deviation of the noise values $N_{\mathrm{M}i}$.

NOTE 1 The repeated measurements only stabilize the noise value without reducing it.

NOTE 2 The recording of the noise stability can show non-periodic environmental influences or time-dependent influences.

6.5.4.6 Determination of the stabilized measurement noise by the averaging method

For recording the stability of the noise estimation, the measurement should be repeated at least three times ($n \geq 3$), and the measurement noise as a function of the measurement number i is determined by Formula (6).

$$N_{\mathrm{M}i} = \frac{S_{\mathrm{q}}\left(z_i(x,y) - z_{\mathrm{m}}(x,y)\right)}{\sqrt{1-n^{-1}}} \tag{6}$$

where

$N_{\mathrm{M}i}$ is the i^{th} measurement of the measurement noise;

S_{q} is the root mean square height as defined in ISO 25178-2;

z_i is the i^{th} measurement;

z_{m} is the mean value of the z-coordinates of the n measurements.

NOTE 1 The repeated measurements only stabilize the noise value without reducing it.

NOTE 2 The recording of the noise stability can show non-periodic environmental influences or time-dependent influences.

If the instrument does not enable access to individual data points and/or does not enable the subtraction of topographies, but enables averaging of topographies, and $S_{\mathrm{q}}(z_i(x,y)) > S_{\mathrm{q}}(z_{\mathrm{m}}(x,y))$ for every $i = 1 .. n$, then Formula (7) may also be used.

$$N_{\mathrm{M}i} = \sqrt{\frac{S_{\mathrm{q}}{}^{2}\left(z_i(x,y)\right) - S_{\mathrm{q}}{}^{2}\left(z_{\mathrm{m}}(x,y)\right)}{1-n^{-1}}} \tag{7}$$

where

N_{Mi} is the i^{th} measurement of the measurement noise each as performed according to 6.5.4.4;

S_q is the root mean square height as defined in ISO 25178-2;

z_i is the i^{th} topography measurement;

z_m is the mean value of the z-coordinates of the n measurements.

NOTE 3 Formula (7) is also an approximation and can slightly vary from the absolute values of Formula (6), but the stability is monitored just as effectively.

6.6 Determination of flatness deviation

6.6.1 General

The flatness deviation z_{FLT} is defined in ISO 25178-600 as the deviation of the measured topography of an ideally flat object from a plane.

A flatness specification shall include any spatial filters that may influence the spatial frequencies over which the flatness is determined (see Reference [19]).

6.6.2 Material measure for determination of flatness deviation

A flat measurement standard, preferably optically smooth, shall be used for the determination of the flatness deviation.

The measurement standard does not need to be optically smooth if the measurement principle requires a certain texture to yield results.

EXAMPLE Type AFL defined in ISO 25178-70.

6.6.3 Procedure for determination of flatness deviation

Before measurement acquisition, the measurement standard shall be mechanically levelled with respect to the coordinate system of the instrument (see 6.7.2.2). The assessed parameter for flatness deviation z_{FLT} is S_z, as defined in ISO 25178-2, where normally the S-L or the S-F surface is taken, with the least-squares surface as default reference. The S_z parameter is equivalent to the parameter *FLTt(LSPL)* as defined in ISO 12781-1.

6.6.4 Improvement of flatness deviation estimation

For the improvement of flatness deviation estimation, the measurement standard should be measured at several lateral locations on the specimen. Systems with limited positioning capabilities may use a shift in only one direction. An average topography image is obtained by averaging each point (e.g. a pixel in imaging systems) in the image.

The flatness deviation estimation can be further improved by rotating the measurement standard between the measurements at several locations.

The default method for averaging is to calculate the mean. The S_z parameter (as defined in ISO 25178-2) of the resulting averaged topography is the improved flatness deviation z_{FLT}. The number of measurements used for improvement shall be reported.

For example, in practice the lateral shift can be 1/10 of the field of view or scanning range.

For *x*-*y* scanning point principles, a typical value for the lateral shift is more than 100 sampling points.

NOTE 1 The lateral shift is used to reduce the influence of small deviations of the material measures from the ideal shape. The averaging, for example, reduces the influence of possible flatness deviations of the material measure and also reduces the influence of measurement noise. Such flatness deviations are defects that have been ignored (ISO 25178-73:2019, 3.3.6).

NOTE 2 This method does not reduce the influence from sphericity of the material measure nor, when the measurement standard is not rotated between measurements, does it reduce the influence from cylindricity and twist of the material measure.[20]

6.6.5 Application of filters and operators

In applications where filters or operators are used, the flatness determination according to 6.6.3 and 6.6.4 can proceed under the same filter conditions as those used for measurements. The used filter and its nesting index and the used operators shall be reported.

EXAMPLE The nesting index of the S-filter can be chosen according to ISO 25178-3:2012, Table 3 for a given application, if not otherwise specified in calibration clauses of the specific measurement.

In many cases, only the global form is considered for flat surfaces where smaller structures are not of interest. This is normally accomplished by applying an S-filter with a large nesting index. A polynomial fit may be used instead of the S-filter to approximate the large-scale flatness deviation.[21]

6.6.6 Calibration of flatness deviation

The procedure described in 6.6.3 and 6.6.4 is the default method for the calibration of the flatness deviation. The assessed parameter z_{FLT} (peak to pit) shall be reported or the upper limit (uncertainty) of this parameter after adjustment for the flatness deviation. The calibration shall be done in consideration of 5.3.2 and 5.3.4. The area (length and width) over which the flatness deviation is calibrated shall be reported.

6.7 Determination of the amplification coefficient α_z for the *z*-axis

6.7.1 General

The determination of the amplification coefficient α_z for the *z*-axis is based on the use of a Cartesian measuring coordinate system with three independent coordinate axes.

Some instruments include more than one translation stage with different *z*-scan ranges. The determination of the amplification coefficient of the instrument *z*-axis can be determined for both stages independently. If both stages are used for a single measurement using stitching in the *z*-direction, the determination shall be done for the combined scan.

EXAMPLE Example of an instrument with two translation stages: Piezo-driven stage for scan ranges in the micrometre scale and a motor-driven stage for scan ranges in the millimetre scale.

6.7.2 Determination of the amplification coefficient α_z for the *z*-axis: material measures

6.7.2.1 General

For the default procedure a material measure with calibrated depth as defined in ISO 25178-70 should be used. The parameter to be assessed for the amplification coefficient α_z is the depth *d*. Measurements shall be performed on the calibrated areas of the material measure as they are indicated by the supplier (see 5.3.1 and 5.3.2).

For the calibration of the instrument, the same method as used for the calibration of the material measure should be applied. Normally this method is provided on the certificate of the material measure. Differences in methods, such as an optical measurement over an area as opposed to a profile measurement using a stylus instrument, should be accounted for in the uncertainty evaluation.

6.7.2.2 Material measures: requirements of geometry and material

The material measure shall be selected such that its structure does not influence the step depth or step height determination. For example, parameters to be considered are the aspect ratio (height to width), flatness, roughness and material characteristics (see ISO 25178-70).

The structure of the material measure can influence the result, if the size of the structure is small enough that the results are influenced by the topographical spatial resolution of the measuring instrument (see 6.11.4 and ISO 25178-600:2019, 3.1.20).

NOTE If the width and aspect ratio requirements cannot be fulfilled, the procedure listed in Reference [24] can be followed.

6.7.2.3 Material measures: alignment of material measure

The evaluation region of the material measure should be adjusted to be perpendicular to the instrument *z*-axis.

If an instrument provides an automatic alignment, that alignment shall be checked before proceeding.

6.7.3 Procedure for determination of amplification coefficient α_z for the instrument *z*-axis

Measurement of step depths or step heights d is the default method for determination of the amplification coefficient α_z or correction factor. This is done by comparing the measured depth with the calibrated depth of the material measure. The coefficient is determined from the quotient of the measured depth parameter d_{cal} (numerator) and the measured depth value d (denominator), i.e. d_{cal} / d .

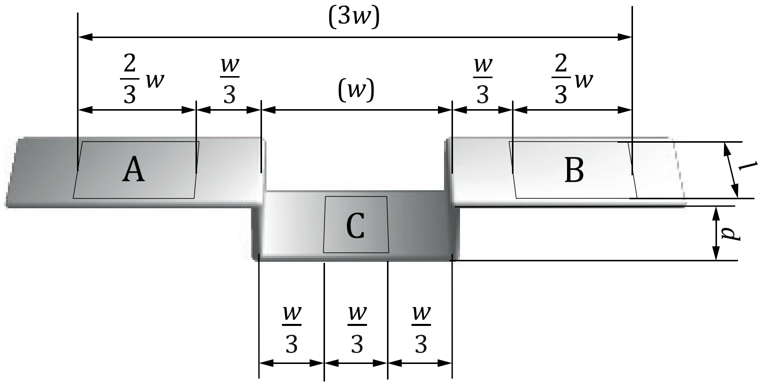
A single-step material measure can be sufficient for some given applications.[25] Alternatively, the use of several step heights or a multi-step material measure is preferred if the instrument is used for the determination of texture parameters involving different *z*-scales. In this case the amplification coefficient is determined by fitting a line to the determined step depths or step heights using the least-squares method (see Figure 4).

6.7.4 Type PGR (profile-groove-rectangular): groove, straight (rectangular or trapezoidal) measurement areas

6.7.4.1 General

The default measurement areas for a rectangular type PGR material measure consistent with ISO 25178-70 and ASME B46.1-2009[26] are shown in Figure 2. The default areas for a trapezoidal material measure are shown in Figure 3.

Other measurement areas may be used consistent with the design of the material measure and the measurement principle, if documented.



Key

A, B reference areas for levelling

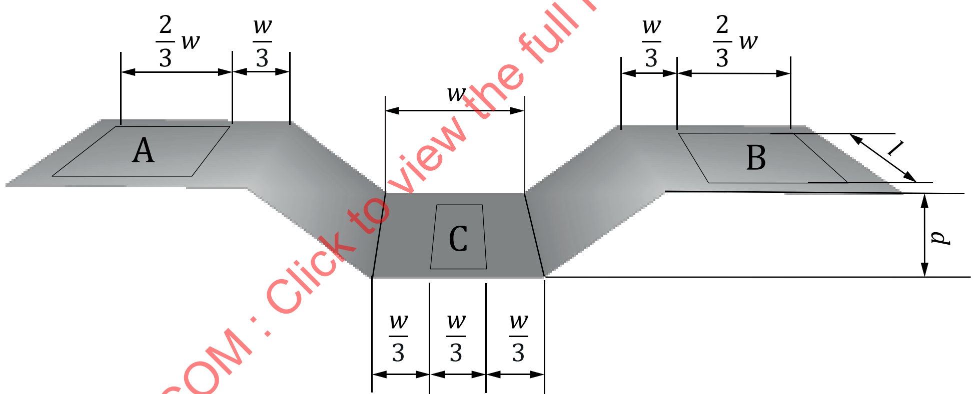
C groove (plateau) area

w groove (plateau) width

l length of measurement areas

d depth

Figure 2 — Default measurement areas for a type PGR material measure having a central groove



Key

A, B reference areas for levelling

C groove (plateau) area

w groove (plateau) width

l length of measurement areas

d depth

Figure 3 — Measurement areas for a type PGR material measure for a trapezoidal material measure

6.7.4.2 Type PGR: groove, straight (rectangular or trapezoidal) analysis methods: areal method

Least-square parallel planes should be fitted to the data points of areas A, B and C.

Alternatively, a least-square plane shall be fitted to areas A and B and subsequently subtracted from the entire topography (i.e. a levelling or tilt correction operation). The data points of region C define the groove depth (or step height) *d*.

The height or depth *d* shall be determined by calculating the distance of the centroid (centre of gravity point) of the region C to the plane levelled to the reference areas A and B.

6.7.4.3 Type PGR: groove, straight (rectangular or trapezoidal) analysis methods: profile method

The areal method is the preferred method, except for instruments generating topography images from line profiles, where the profile method is preferred.

Least-squares lines shall be fitted to areas A and B and subsequently a levelling by rotation (tilt correction) shall be carried out. The mean depth of the data points of region C (or height, for a positive feature) shall then be calculated. For areal data, a levelling of regions A and B shall be performed before extracting the profiles.

A set of at least nine parallel profiles shall be extracted and the depth (or height) *d* independently evaluated for each profile. The average depth (or height) of the data points of region C shall be reported as the depth (or height) *d*.

The distance between the profiles shall be chosen so as to maximize coverage of the area specified by the manufacturer of the material measure, subject to the avoidance of relevant surface defects.

For a groove or plateau standard that exhibits significant linearity deviations over its length, the evaluation of *d* by profile measurements is the default method for this type of calibration.

NOTE 1 A trapezoidal material measure as specified in Reference [27] is a possible alternative for instruments with a large measuring volume. The measuring volume is defined in ISO 25178-600:2019, 3.1.8.

NOTE 2 Different filters are used for line profiles and areal measurements; see the ISO 16610 series.

EXAMPLE Instruments generating topography images from line profiles are contact (stylus) instruments (see ISO 25178-601) or non-contact (confocal chromatic probe) instruments (see ISO 25178-602).

6.7.5 Other material measures for the instrument *z*-axis calibration

A variety of material measures may be employed for *z*-axis calibration in place of type PGR material measures. Calibration techniques for areal topography measuring instruments should be consistent with the calibration procedure, which is described in the certificate of the material measure.

Non-exhaustive examples provided in ISO 25178-70 include the following:

— type PDG: double groove;

— type AGP: grooves, perpendicular;

— type ACG: cross grid.

Single-sided steps have also been used as height calibration material measures.[28] They are particularly useful where double-sided steps may be difficult to fabricate and unavailable. Staircases composed of single-sided steps are also useful for simultaneous measurement of *z*-amplification and linearity deviation.[28] To avoid bias due to surface curvature, straight lines are fitted to profile data, preferably equally displaced from the step transition, subject to the avoidance of relevant surface defects. Steps based on atomic lattice properties with nanometre[29] and subnanometre[30] heights are particularly useful where double-sided steps may be difficult to fabricate and unavailable.

NOTE Best results are obtained when the user employs the same definition for the step height or groove depth (including the width *w*) as employed by the laboratory where the material measure was calibrated. If the same definition is not used, the resulting measurement uncertainty can potentially increase.

6.7.6 Procedure for determination of amplification coefficient α_z for the instrument *z*-axis: range and distance of measurement positions for the calibration of the *z*-scale of the instrument

For instruments with a scan range that is larger than the groove depths of the material measure, the procedure is done at different heights within the scan range (see for example References [31] and [32]).

The complete intended *z*-range for the instrument's application should be used for the determination of the amplification coefficient of the instrument *z*-axis. The distance of the positions within the *z*-scale should be selected to cover the complete intended *z*-range.

Material measures with more than one step height can be used.

NOTE 1 Deviation from a linear amplification curve results from linearity deviations along the *z*-axis. Thus, the calibration of the *z*-scale at different positions within the *z*-range can be used for the calibration of linearity deviation.

NOTE 2 Material measures with much smaller step heights than the scan range of the instrument are often used for the calibration of the instruments, which are intended for determination of texture parameters.

6.7.7 Range and distance of measurement position for the calibration of a reduced *z*-scale of the instrument

If the instrument is only used in a certain *z*-range, the calibration can be done within the reduced *z*-range. Thus, if a region of preferable performance can be located, it may be used with its local correction coefficient. The reduced *z*-range and the position within the complete *z*-range shall be reported.

For verification, the evaluation of a single step standard can be sufficient to confirm proper adjustment and operation of the instrument within the expected bounds of uncertainty of the measurement.[33]

NOTE The calibration can lead to smaller measurement uncertainties within a reduced *z*-scale.

6.8 Determination of *z*-linearity deviation l_z

6.8.1 General

The linearity deviation is defined in ISO 25178-600:2019, 3.1.11. Ideally, all measured amplification coefficients for different step heights and at different positions within the *z*-scan range have the same value, see 6.7.3. However, hysteresis effects or nonlinearities of the translation stage can lead to deviations.

6.8.2 Determination of the complete and local *z*-linearity deviation l_z: *z*-scan range

By default, the linearity deviation of the complete *z*-range is determined. If a local linearity deviation is determined only for a shorter range instead of the complete range, the position of that shorter range within the complete *z*-range shall be reported.

6.8.3 Determination of *z*-linearity deviation l_z

First, the amplification coefficient shall be determined according to 6.7. For the detection of linearity deviations, measurement at a number of positions and step heights is required.

The assessed parameter is the maximum deviation of measured depths to the calibrated depth d_{cal} after adjustment of the amplification coefficient α_z. This is the value of l_z that shall be reported (see Figure 4, key item 5, and ISO 25178-600:2019, 3.1.11).

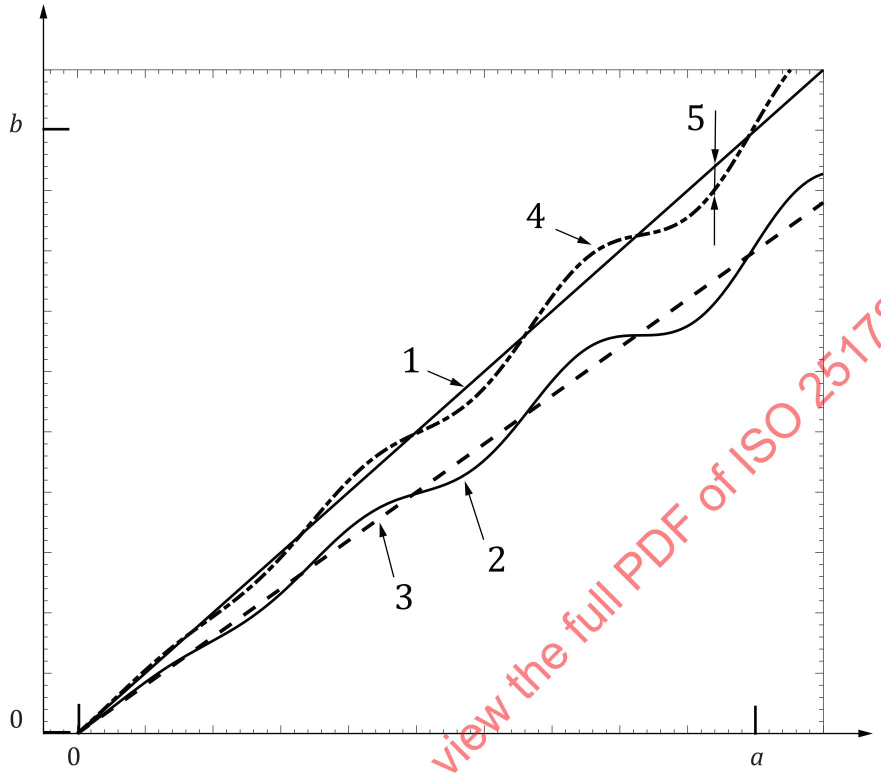
Material measures with more than one step height can be used.

The maximum linearity deviation over the complete *z*-measurement range shall be reported.

Both amplification and linearity may be determined from the results of the same type of measurements.

For instruments with multiple *z*-scan axes, each axis may be specified separately.

NOTE The maximum value for the linearity deviations of the *z*-scan unit can be a measured value above or below the ideal reference curve, see Figure 4.



Key

a calibrated value of height *z*

b measured value of height *z*

1 ideal response curve

2 actual response curve of the instrument with long and short wavelength deviations

3 best-fit line from which the amplification coefficient α_z (slope) is derived (before adjustment)

4 actual response curve of the instrument after adjustment of amplification α_z

5 local linearity deviation l_z (after adjustment)

Figure 4 — Schematic representation of *z*-axis linearity deviation

6.8.4 Determination of *z*-linearity deviation l_z: sizes of step heights to be measured

The step heights to be measured within the *z*-range of the measurement application shall be small enough to detect all small-scale linearity deviations that can have a significant impact on the measurement uncertainty.

EXAMPLE A spindle-driven axis typically has a short wavelength nonlinearity corresponding to its pitch and a long wavelength nonlinearity over the whole length of the spindle.

NOTE For linearity deviations that appear within a small range in a periodic way, such as in PSI instruments (ISO 25178-603), the use of a tilted optical flat can be more appropriate (see 6.8.6).

6.8.5 Determination of *z*-linearity deviation l_z: positions within the instrument *z*-range

The measurement should be done at five or more positions within the *z*-range. Any critical *z*-positions where the linearity deviation is comparatively high shall be identified. If required, additional measurements should be performed to better characterize the linearity deviation around these critical positions.

Both amplification and linearity deviation can be determined from the results of the same type of measurements.

For instruments with multiple *z*-scan axes, each axis can be specified separately.

A combination of more than one measurement standard can be used.

6.8.6 Determination of *z*-linearity deviation l_z: Non-default methods

The use of other calibration methods for calibrating the *z*-axis linearity deviation shall be reported.

The linearity deviations of the *z*-scan unit may be measured with an external position measurement device, such as a laser interferometer or a capacitive sensor.

A tilted reference specimen, for example an optical flat, compared with topography measured in levelled state, can give an indication of the nonlinearity of the *z*-axis.[34]

6.9 Determination of the amplification coefficients α_x and α_y in *x*- and *y*-direction and mapping deviation Δ_x (x,y) and Δ_y (x,y)

6.9.1 General

The mapping deviations, Δ_x (x,y) and Δ_y (x,y), of the instrument's *x*- and *y*-axes are defined in ISO 25178-600:2019, 3.1.13 as a gridded image of *x*- and *y*-deviations of actual coordinate positions on a surface from their nominal positions.

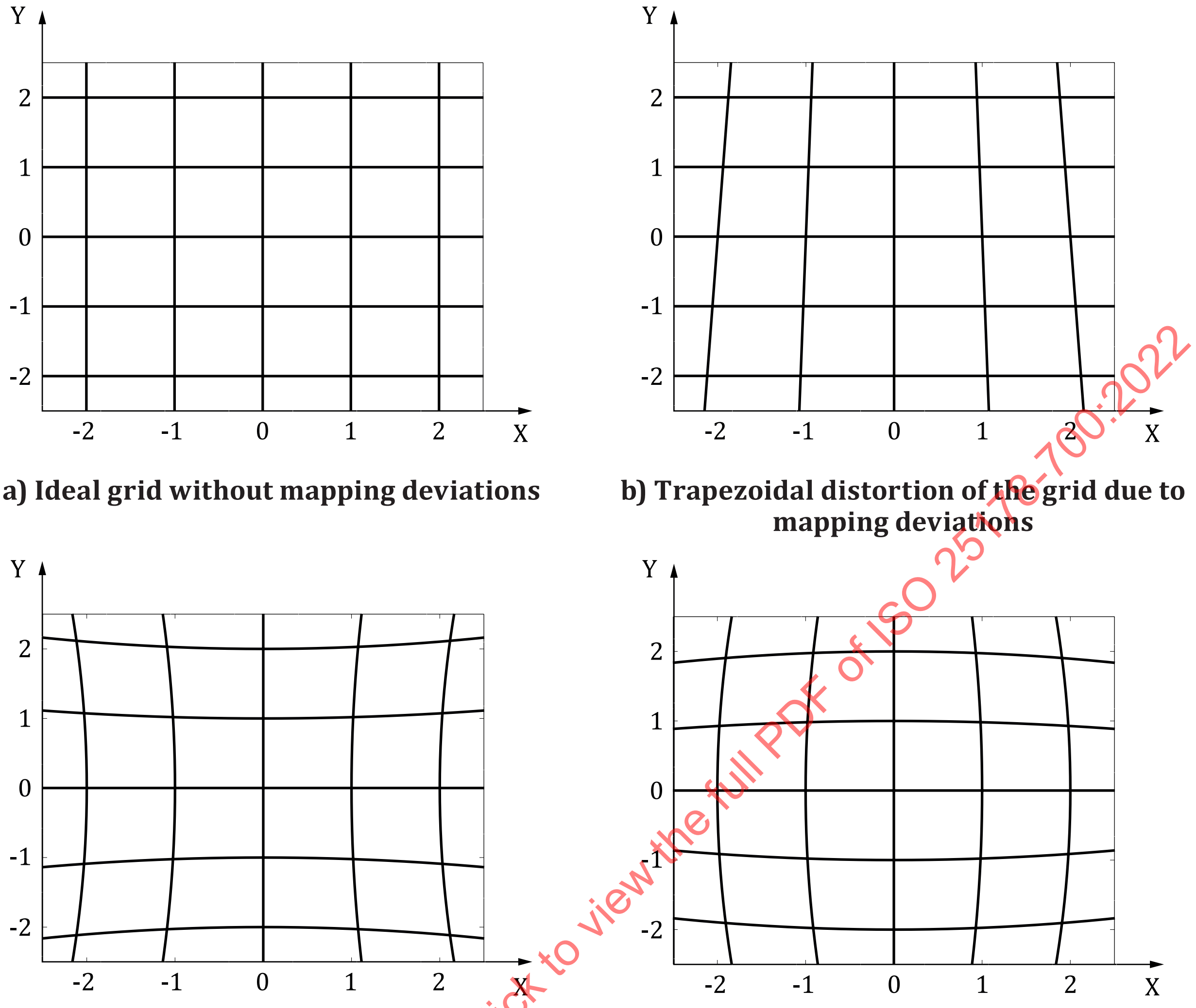
In this subclause, a procedure to characterize the mapping deviations is outlined. These mapping deviations are used to derive the amplification coefficients and linearity deviations in the *x*- and *y*-directions.

NOTE 1 For optical instruments, the mapping deviation can be caused by the aberrations in the optical elements.

NOTE 2 For contact (stylus) instruments and optical point sensors with a moving stage, the mapping deviations of the *x*- and *y*-axes are caused by their individual straightness and linearity deviation. This is the case also for scanning probe systems.

NOTE 3 The contribution of the mapping deviations to the overall measurement uncertainty can be negligible depending on the parameter considered (e.g. a step height or the S_a parameter).

NOTE 4 Examples of mapping deviations are given in Figure 5.



a) Ideal grid without mapping deviations

b) Trapezoidal distortion of the grid due to mapping deviations

c) Cushion-shaped distortion

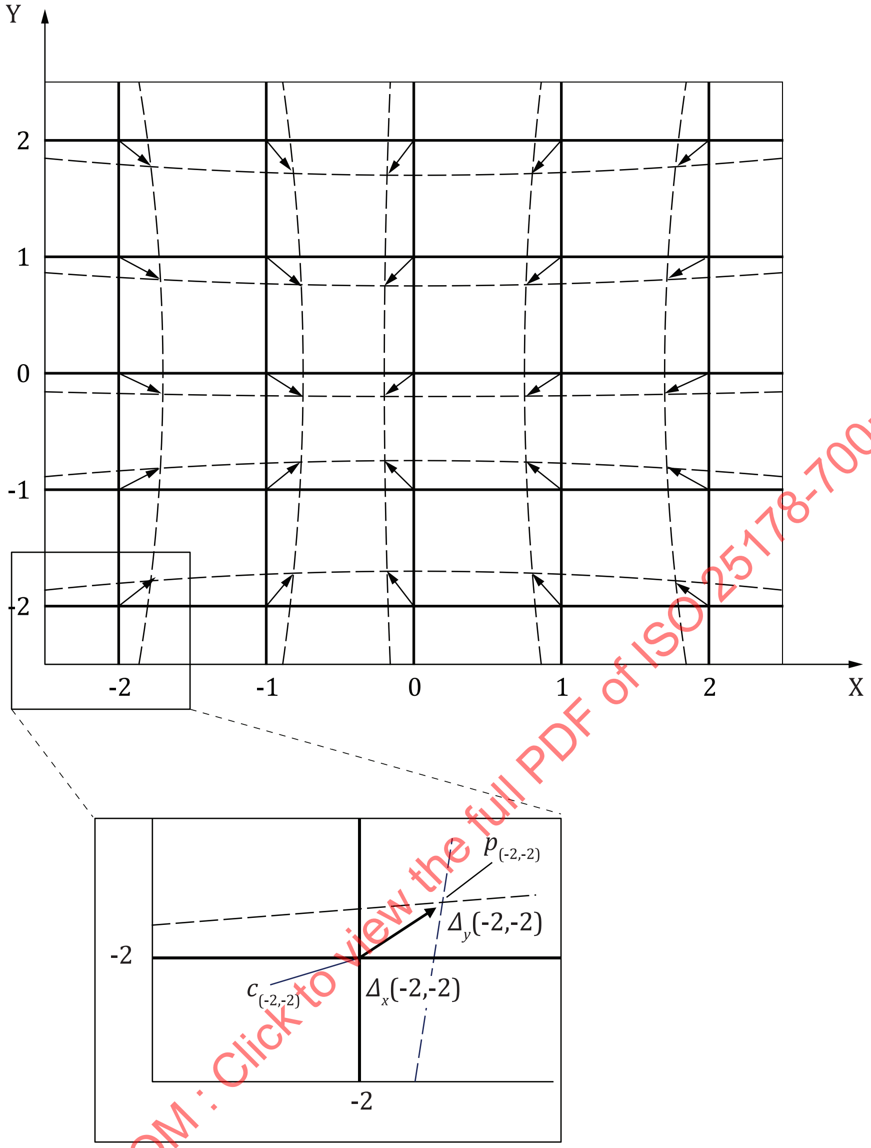
d) Barrel-shaped distortion due to mapping deviations possibly caused by aberration

Figure 5 — Examples of *x*-*y* grid positions illustrating mapping deviations

6.9.2 Determination of the amplification coefficient α_x and α_y in *x*- and *y*-direction and mapping deviation Δ_x (x,y) and Δ_y (x,y): material measures

The default method for the determination of the amplification factors and mapping deviations of the *x*- and *y*-axes is with material measures with calibrated distances in the *x*-*y* plane (i.e. type ACG). The *x*- and *y*-axes of the material measures shall be aligned parallel to the instrument axes to avoid possible cosine error or corrections. The calibrated positions of the grid intersection points are expressed by c (x,y) for the grid intersection points with the indices (x, y). The determined positions of the grid intersection points are expressed by p (x,y). The assessed parameters for each grid intersection point are the coordinate differences Δ_x (x,y) and Δ_y (x,y) of the calibrated positions with respect to the determined position.

The number of intersection points should be at least 25 (5 × 5) distributed evenly over the measurement area, as illustrated in Figure 6.



Key

Solid lines	calibrated material measure grid
Dotted lines	measured grid test specimen
Arrow	difference vector between grid intersection coordinates $c(-2,-2)$ and measured grid intersection coordinates $p(-2,-2)$

Figure 6 — Difference vectors between calibrated material measure grid intersection coordinates $c_{x,y}$ and measured grid intersection coordinates $p_{x,y}$

6.9.3 Determination of the amplification coefficient α_x and α_y in *x*- and *y*-direction and mapping deviation Δ_x (x,y) and Δ_y (x,y): assessed measurement volume

Measurements shall be done on the calibrated area of the material measures, paying attention to the presence of surface defects within that area (see 5.3.2). The measurements shall span at least 95 % of the *x*- and *y*-axes lengths of the measurement area of the instruments and at least three *z*-positions inside the instrument *xyz* working range. If a smaller fraction of the measurement area of the instrument is used, it shall be reported. Spurious points should be eliminated.

NOTE For some types of instruments, the *x*- and *y*-amplification coefficients and mapping deviation will possibly be judged to be independent of the *z*-position. For such instruments, measurement at only one *z*-position is sufficient.

6.9.4 Procedure for the determination of the amplification coefficient α_x and α_y and mapping deviation $\Delta_x\,(x,y)$ and $\Delta_y\,(x,y)$ of the *x*- and *y*-axes

The following default procedure is used to determine the amplification coefficient and linearity deviation of the *x*- and *y*-axes:

a) The material measure shall be levelled to the *x*-*y* plane.

b) For each grid intersection point (knot) the position $p_{x,y}$ shall be determined.

c) The amplification coefficients, α_x and α_y, in the *x*- and *y*-directions are determined by scaling, rotation and translation of the measured grid positions $p_{x,y}$ in a way that the transformed positions $p'_{u,v}$ show a minimum value for the mean square sum of the mapping deviation lengths $[\Delta_x\,(x,y)^2 + \Delta_y\,(x,y)^2]$ from the calibrated positions $c_{x,y}$ using the least-squares method. For example, the rotation is needed if the *x*-axis and *y*-axis of the material measure are different from those of the instrument.

d) The linearity deviations, l_x and l_y, are defined as the largest values of $\Delta_x\,(x,y)$ and $\Delta_y\,(x,y)$, respectively.

This method is valid for instruments such as microscopes that acquire topography from an extended or finite field of view without *x*-*y* translation. Point or line (point array) sensors with *x* and *y* translation stages and lateral position sensors can use different methods.

For the precise determination of the grid intersection positions various software algorithms from image processing may be used. An example is the *PSm*-method given in the VDI guideline 2655-1.3;[35] other examples are given in the NPL good practice guide 127[36].

6.10 Perpendicularity of the instrument *z*-axis with respect to the *x*-*y* areal reference

A deviation of the perpendicularity of the instrument *z*-axis (orthogonality) (see ISO 25178-600:2019, 3.1.2) would lead to shape distortions of the measured topography. It is important to differentiate between the mechanical and optical instrument axis on one hand and the coordinate system axis of the component being measured on the other hand.

No default methods are defined for determining the perpendicularity of the instrument *z*-axis with respect to the *x*-*y* areal reference due to the small influence of the perpendicularity deviations under typical measurement conditions and the lack of applicable material measures.

6.11 Topographic spatial resolution W_R

6.11.1 General

The topographic spatial resolution shall be characterized by any of several parameters listed in ISO 25178-600:2019, 3.1.20. A default method for calibration is not defined here.

The VDI guideline 2655-1.3[35] and Reference [34] provide descriptions about the calibration of the topographical spatial resolution, the material measures and the calculation of the related parameters. In addition, there are several published papers on available calibration methods.[36–39]

6.11.2 Material measures for topographic spatial resolution

Material measures for calibration of the topographic spatial resolution include structures with variable width, grating constants or spatial wavelengths, including parallel lines, chirped material measures[38] or star-shaped groove types (type ASG). A procedure using the ASG type is specified in the NPL good practice guides 127 (CSI)[36] or 128 (confocal instruments)[37]. In some cases, a sharp edge or step feature in the surface topography provides the equivalent of the line spread function, which can be analysed to determine the spatial frequency response of the instrument.[39]

6.11.3 Instrument transfer function (ITF) curve f_{ITF}

There is no default method for calibration of the ITF curve.

A requirement for the use of the f_{ITF} curve for calibration is that the instrument response is linear over the full spatial frequency range of the evaluation, such that the response to each spatial frequency component is independent of all other spatial frequency components. This imposes limits on the maximum surface slope, the surface topography or the range of surface heights that can usefully be measured. More detailed descriptions of the use, calibration and limitations of the ITF curve are given in Reference [39].

6.11.4 Lateral period limit D_{LIM}

The lateral period limit D_{LIM} can be established consistent with ISO 25178-600:2019, 3.1.21 using the 50 % transmission point on the ITF curve (6.11.3). Limitations in the use of the ITF curve apply to the use of the lateral period limit when applying this method of calibration for the topographic spatial resolution.

6.11.5 Use of optical lateral resolution parameters

For surface topography instruments that rely on optical imaging systems, the optical lateral resolution as defined in ISO 25178-600:2019, 3.3.7, can be used to determine the topographic spatial resolution W_R, if it can be demonstrated by instrument modelling and/or experiment that the optical lateral resolution applies for a specific topography measurement method and range of surface structures. Defined parameters for optical lateral resolution include the Rayleigh criterion (ISO 25178-600:2019, 3.3.8), the Sparrow criterion (ISO 25178-600:2019, 3.3.9) and the Abbe resolution limit (ISO 25178-600: 2019, 3.3.10). When specifying the topographic spatial resolution W_R as an optical lateral resolution parameter, the criterion that was used and the method by which it was determined shall be specified. Details regarding the limits of applicability of optical lateral resolution parameters for topographic spatial resolution can be found in Reference [39].

6.12 Topography fidelity T_{FI}

6.12.1 General

The measured profile or topography is assumed to have been acquired after calibration, adjustment and verification of the other six metrological characteristics in Table 1. In this case the topography fidelity accounts for all remaining effects where the other six metrological characteristics have been evaluated and accounted for. The topography fidelity depends on influence quantities that can include surface slopes and discontinuous features (sharp edges) as well as the specimen properties, such as refractive index, reflectivity and the presence of transparent thin films, the elastic modulus or hardness.

There are no default methods for determination of the topography fidelity. Acceptable methods include comparison with reference metrology, the use of reproducibility tests with variations in part orientation between measurements, experimental methods to determine sensitivities of the measured results to changes in the instrument configuration and the use of virtual instruments.[40,41]

6.12.2 Determination of the topography fidelity T_{FI} using reference metrology

A structured material measure with known and/or calibrated shapes having known uncertainty may be used for the determination of the topography fidelity. The shape of the material measure should be close to the shape of the surface to be evaluated. To quantify the topography fidelity, the topography of the material measure as measured should be compared with the reference topography as obtained by an independent calibration or as known or estimated by other means. This comparison will normally consist of the evaluation of the topography difference after optimum alignment of both topographies. For the quantification, the surface texture parameters as defined in ISO 25178-2, applied to the difference topography, can be used. An example parameter is the RMS difference as defined by the S_q parameter which makes it similar to the noise estimator specified in Formula (1). Examples are given