Physikalisch-Technische Bundesanstalt

DKD

**Guideline
DKD-R 4-2
Sheet 4**

Calibration of measuring instruments and standards for roughness metrology – Calibration of the horizontal measuring system of stylus instruments

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Deutscher Kalibrierdienst (DKD)

Since its foundation in 1977, the German Calibration Service has brought together calibration laboratories of industrial enterprises, research institutes, technical authorities, inspection and testing institutes. On 3rd May 2011, the German Calibration Service was reestablished as a *technical body* of PTB and accredited laboratories.

This body is known as *Deutscher Kalibrierdienst* (DKD for short) and is under the direction of PTB. The guidelines and guides developed by DKD represent the state of the art in the respective areas of technical expertise and can be used by the *Deutsche Akkreditierungsstelle GmbH* (the German accreditation body – DAkkS) for the accreditation of calibration laboratories.

The accredited calibration laboratories are now accredited and supervised by DAkkS as legal successor to the DKD. They carry out calibrations of measuring instruments and measuring standards for the measurands and measuring ranges defined during accreditation. The calibration certificates issued by these laboratories prove the traceability to national standards as required by the family of standards DIN EN ISO 9000 and DIN EN ISO/IEC 17025.

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Foreword

DKD guidelines are application documents that meet the requirements of DIN EN ISO/IEC 17025. The guidelines contain a description of technical, process-related, and organizational procedures used by accredited calibration laboratories as a model for defining internal processes and regulations. DKD guidelines may become an essential component of the quality management manuals of calibration laboratories. The implementation of the guidelines promotes equal treatment of the equipment to be calibrated in the various calibration laboratories and improves the continuity and verifiability of the work of the calibration laboratories. In addition, the implementation of the guidelines allows the state of the art in the respective field to be incorporated into laboratory practice.

The DKD guidelines should not impede the further development of calibration procedures and processes. Deviations from guidelines as well as new procedures are permitted in agreement with the accreditation body if there are technical reasons to support this action.

Calibrations by accredited laboratories provide the user with the security of reliable measuring results, increase the confidence of customers, enhance competitiveness in the national and international markets, and serve as metrological basis for the inspection of measuring and test equipment within the framework of quality assurance measures.

The present guideline has been drawn up by the DKD Technical Committee *Length* and approved by the Board of the DKD.

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1   Scope of application

This guideline describes how to establish traceability for the scaling of the horizontal axis of stylus instruments to the national length standard in accordance with ISO 3274. The traceability is based on the determination of the value of a horizontal surface parameter (characteristic quantity) such as RSm on a calibrated reference standard.
As Figure 1 shows, the unit of length is passed on by alternately using a standard for calibrating a device, and a calibrated device for calibrating a standard. The scope of this guideline applies to the second and to the fourth step in the dissemination chain (described in Appendix A and Appendix B, respectively).

"National standard"
Traceability to unit of length by laser interferometer

Step 1:
Calibration of the primary standard

Primary standard:
e.g. Si lateral standard

Step 2:
Calibration reference stylus instrument with primary standard

DKD-R 4-2 Sheet 4, Appendix A

Reference stylus instrument, e.g. at PTB

DKD-R 4-2 Sheet 3

Step 3: Calibration of the "geometry standard"

Secondary standard: "geometry standard"

Step 4:
Calibration stylus instrument with "geometry standard"

DKD-R 4-2 Sheet 4, Appendix B

Connected devices at DKD, in industry, etc.

Figure 1: Dissemination of the unit of length in horizontal direction in roughness measurement with stylus instruments

2 Terms and definitions

2.1 Terms from various standards

Terms for the characterisation of surface measuring devices are taken from DIN EN ISO 3274 and DIN EN ISO 25178-601, definitions of surface parameters from DIN EN ISO 4287, and measurement conditions are specified in accordance with DIN EN ISO 4288. Specifications for the calibration of stylus instruments are given in accordance with DIN EN ISO 12179.

2.2 Terms and abbreviations used herein

U_n	Expanded uncertainty of the reference standard
R_{z0}	Background noise of the device
L	Length of the lever arm on which the stylus tip is located
H	Height of the stylus
$P_{Sm,Normal}$	P_{Sm} of the reference standard used for establishing traceability (taken from its calibration certificate)
$P_{Sm,M,Normal}$	Currently measured parameter on the reference standard
$P_{Sm,Objekt}$	parameter to be measured on the object to be calibrated
D_x	Measuring point distance in feed direction
l	Profile length: part of the measuring section that has been included in the evaluation of P_{Sm}
n	Number of profile elements included in the evaluation of P_{Sm}
σ	Slope of the profile at zero crossing
p	Length of the profile elements

3 Measuring device

The measuring device to be used for the implementation of this guideline is a stylus instrument according to DIN EN ISO 25178-601. It must be possible to align the surface of the standard parallel to the feed direction. The coordinate system is shown in Figure 2.

The radius of the stylus tip must be 2 µm to 5 µm, the measuring point distance must be ≤ 0.5 µm. The feed rate must be ≤ 0.5 mm/s.

4 Ambient conditions

The temperature change during measurement must be less than ± 0.5 K.
The absolute temperature must be between 18 °C and 25 °C.
Temperature gradients, for example those caused by direct sunlight, must be avoided.

5 Calibration procedure

To determine the horizontal scaling, standards of type PPS and PPT (DIN EN ISO 25178-70) are measured. The scanned profile consists of regularly arranged profile elements with clearly distinguishable peaks and valleys. The value of the average distance between the profile elements is determined by calculating the parameter P_{Sm}. This procedure achieves an averaged scaling of the part of the horizontal axis used for the current measurement. For evaluations using R_{Sm}, the calibration must be carried out individually for each wave filter used and the corresponding scanning distance; it only applies to this combination.

5.1 Calibration capability of the device

Before calibrating the device, it must be checked according to its operating instructions, using the settings under which it is to be used later on. These settings relate to the selection of λ_c and λ_s filters, measuring section and position of the tracks in relation to the feed unit.

The device is suitable for calibration under laboratory conditions if the following limit values are not exceeded. For on-site calibrations in industrial environments, higher limit values may be defined and agreed due to harsher conditions.

5.1.1 Testing the background noise

The value of Rz_0 is determined on a plane face glass across the measuring section and the part of the feed unit that is to be used later on. The background noise must be less than 30 nm.

5.1.2 Testing the vertical calibration

The z-axis of the device is checked in accordance with DKD-R 4-2 Sheet 1 by measuring a depth setting standard with a known depth and shape. The value of Pt (for nominal depths from 1 to 10 µm) must be measured with a deviation of less than 1 % from the nominal value. If calibrated measured height values (Ra, Rz) are available for testing a geometry standard in accordance with section 5.1.3, then it is also possible to check the vertical calibration capability by measuring these values. The deviation of the measured values from the calibrated values must be smaller than the expanded measurement uncertainty of the standard.

5.1.3 Testing of the lateral axis

A geometry standard is used to check the axis parallel to the feed direction. The deviation of the measured value from P_{Sm} must be smaller than the expanded measurement uncertainty of this standard.

6 Measurement uncertainty in general

6.1 Model

The standard uncertainties of the influence quantities influencing the uncertainty of the parameter P_{Sm} are added up quadratically, and the sum is then multiplied by the coverage factor k which ensures a coverage probability of 95 %.

In accordance with the definition in DIN EN ISO 4287 (ISO 21920-2 is new but not yet binding):

$$P_{Sm} = \frac{1}{n} \cdot \sum_{i=1}^{n} Xs_i \ ,$$

with i being the number of the i-th profile element of the length Xs_i. As the profile elements are seamlessly connected to each other, the sum of the P_{Sm} is the profile length l. The profile length l is the distance between the starting point x_a and the end point x_e of the analysed profile of the measuring length l_n.

The following model is used for the profile length l:

$$l = n \cdot P_{Sm} + \delta x_a + \ \delta x_e$$

with the approach for the influence quantities $\delta x_a = \delta x_e = \delta x$ of the horizontal deviation of the individual measurement of the profile end.

x_a and x_e are so far apart that they are not correlated by the λ_s filter. Due to the waviness filter, the uncertainty of the points of the R profile is practically equal to the uncertainty of the points of the unfiltered P profile (reference: [15]). Therefore, these considerations apply to both R_{Sm} and P_{Sm}.

For the uncertainty of P_{Sm} it follows that

$$u^2(P_{\text{Sm}}) = \frac{1}{n^2} \cdot \left(2 \cdot u^2(\delta x) + u^2(l) \right) \tag{1}$$

with $u(\delta x)$ being the uncertainty of profile end position and $u(l)$ the uncertainty of the profile length l.

Note

The measurement uncertainty according to the new definition of P_{Sm} (2019) can result in a smaller value compared to the old P_{Sm} definition (DIN EN ISO 4287: 1989). This is due to the fact that when counting the profile elements in the measuring section, fewer profile parts are omitted and therefore there are more profile elements than previously when counting the individual measuring sections.

6.2 Influence quantities

The following model applies to the positional deviations of the profile element end point:

$$\delta x = \delta x_0 + \delta x_{\text{w}} + \delta x_{\text{b}} + \delta x_{\text{dig}}.$$

The influence quantities in detail:

δx_0 Noise in the x position due to noise of the contacting system in the vertical direction.

δx_{w} Position deviation due to the waviness Wt_0 of the standard; in the previous version of the DKD guideline, this was found to be negligible.

δx_{b} Deviation due to arcuate movement, negligible as a higher-order error if correction of the stylus tip geometry is taken into account.

δx_{dig} Deviation in the definition of a profile element due to the measuring point distance D_x.

The following model applies to the profile length l:

$$l = l_r + l_{\text{th}} + l_{\text{g}}$$

with l_{r} being the profile length on the reference standard, l_{g} the deviation due to the unknown measurement position in the profile, and l_{th} the thermally induced change in length of the reference standard.

6.3 Uncertainty components (independent of the standard)

The sources of uncertainty mentioned in this section apply to stylus instruments in general, regardless of the characteristic features of the standard. To determine the total uncertainty of the horizontal calibration, the uncertainty components arising during the calibration process due to the different interaction between the lateral standard (see Appendix A) or the groove spacing standard (see Appendix B) with their characteristic features and the device are added.

6.3.1 Measuring point distance

The zero crossing of the signal for localising a profile element can only be determined with a maximum deviation of $\pm D_x/2$ when carrying out the evaluation in real space (D_x: horizontal sampling interval). The resulting uncertainty $u(\delta x)$ due to the digitisation has a uniform distribution with D_x being the span.

$$u^2(\delta x_{\text{dig}}) = \frac{D_x^2}{12}$$

If the evaluation is carried out in the frequency domain, this contribution may be smaller.

7 Traceability

The uncertainty due to the traceability process contains:

The uncertainty of the horizontal scaling factor which is determined during calibration of the device by determining P_{Sm} via the profile length $(n \cdot P_{\text{Sm,Normal}})$ on a reference standard. In addition to the unit of length, the uncertainty of the reference standard $u(P_{\text{Sm,Normal}})$, which is shown in its calibration certificate, is also passed on.

It must be taken into account that the measuring position on the reference standard during calibration of the instrument may differ from the measuring position during the calibration of the reference standard. An estimated value for the uncertainty is determined from the standard deviation $s(P_{\text{Sm,M,Normal}})$ which results from the own measurement of P_{Sm} on the reference standard over the profile length l (with n profile elements) at the m_{t} positions at which the reference standard was calibrated according to the calibration certificate. Thus,

$$u^2(l_{\text{r}}) = n^2 \cdot u^2(P_{\text{Sm,Normal}}) + \frac{n^2}{m_{\text{t}}} \cdot s^2(P_{\text{Sm,M,Normal}}).$$

Both quantities have a Gaussian probability distribution.

7.1.1 Temperature influence

The temperature difference between calibration and use of the reference standard creates a systematic deviation. The coefficient of thermal expansion α_{th} of the carrier material must be taken into account in order to correct a changed length $l_{\text{th}} = \Delta T \cdot \alpha_{\text{th}} \cdot l$.

When calculating the uncertainty of the thermal length change $u(l_{\text{th}})$, assuming realistic conditions ($\Delta T = 2$ K, $u(\Delta T) = 0.2$ K, $u_{\text{rel}}(\alpha_{\text{th}}) = 1 \cdot 10^{-2}$, $u_{\text{rel}}(l) = 10^{-4}$), both the influence of the temperature difference $u(\Delta T)$ and that of the thermal expansion coefficient $u(\alpha_{\text{th}})$ must be considered individually as a source of uncertainty.

With a rectangular probability distribution, the following results for $u^2(l_{\text{th}})$:

$$u^2(l_{\text{th}}) = \frac{1}{12} \cdot [(u(\Delta T) \cdot \alpha_{\text{th}} \cdot l)^2 + (\Delta T \cdot u(\alpha_{\text{th}}) \cdot l)^2].$$

7.1.2 Influence of materials

If standards are made of a composite of different materials (for example, Si lateral standards with a mix of silicon ($\alpha_{\text{th}} = 2.5 \cdot 10^{-6} \text{K}^{-1}$) and glass ($\alpha_{\text{th}} = 8.5 \cdot 10^{-6} \text{K}^{-1}$) , then these values are to be considered as span for $u(\alpha_{\text{th}})$, and a rectangular distribution is to be assumed for $u(\alpha_{\text{th}})$.

7.1.3 Stability over time

Depending on the manufacturing process (e.g. moulding technique) and the history of the standards (e.g. recrystallisation, temperature cycles), a change in their dimensions over time is to be expected. To account for this, the recalibration interval must be adapted to experience.

7.2 Arc motion

In many stylus instruments, the transmission mechanism from the stylus tip movement to the displacement transducer is the angular movement of a lever (length L). The vertical movement enforced by the surface contact causes the stylus tip to move in an arcuate manner; this arc-shaped movement depends on the height dz (see Figure 2).
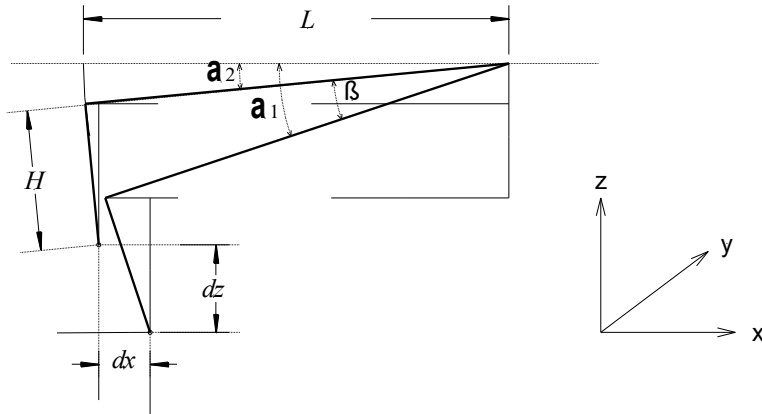
Figure 2: Influence of the arcuate movement

The movement of the stylus tip, which is deflected by the height dz, is the combination of the rotation of the end of the lever arm (length L) from angle α_1 to angle α_2 on a circular arc around the angle $\beta = \frac{\alpha_1 + \alpha_2}{2}$ and a tilting of the stylus tip axis (length H). The resulting horizontal component of the stylus tip movement is

$$dx = [\frac{H}{L} + \tan(\frac{\alpha_1 + \alpha_2}{2})] \cdot dz \qquad (2)$$

In case of an ideal standard, this deviation is the same for each profile element and would therefore have no effect on a horizontal distance parameter such as P_{Sm} as a difference parameter.

Moreover, dz is the height difference between the starting points of neighbouring profile elements, caused by the waviness of the standard and the straightness deviations of the stylus guidance. Over a distance of common P_{Sm} values, these deviations are in the range of a few nm, so that dx is negligibly small according to equation 2.

8   Calibration certificate

The calibration certificate must contain the following information:
- calibration item or characteristics of the stylus instrument to be calibrated
- reference standard used for calibration (type, its calibration date, institution having carried out the calibration)
- measurement conditions (filter, velocity, stylus tip, contact force)
- measuring point plan or reference to corresponding literature
- description of the evaluation or reference to corresponding literature
- measurement results of the characteristic quantity P_{Sm}, its standard deviation, measurement uncertainty with coverage factor k and the deviation of the measured characteristic quantity from the reference value
- place of calibration

9 Repeating the calibration, intermediate test

This complete calibration must be carried out and documented on a regular basis. The recalibration period depends on

- the stability of the ambient conditions,
- the change of components of the device,
- the frequency of use,
- the stability of the standard over time,
- the requirements regarding the uncertainty.

As an intermediate test, which must be carried out at least once a week or before use, it is sufficient to measure a traverse length on a calibrated roughness standard with a regular profile and to document the deviation of the indicated values.

10 Bibliography

[1]   DIN 1319-3 Grundbegriffe der Meßtechnik; Begriffe für die Meßunsicherheit und für die Beurteilung von Messgeräten und Messeinrichtungen

[2]   DIN 1319-4 Grundbegriffe der Meßtechnik; Behandlung von Unsicherheiten bei der Auswertung von Messungen

[3]   DIN V 32950:1997-04 (ISO/TR 14638) Geometrische Produktspezifikation (GPS) Übersicht

[4]   DIN EN ISO 3274:1998-04 Oberflächenbeschaffenheit: Tastschnittverfahren Nenneigenschaften von Tastschnittgeräten

[5]   DIN EN ISO 4287:1998-10 Oberflächenbeschaffenheit: Tastschnittverfahren Benennungen, Definitionen und Kenngrößen der Oberflächenbeschaffenheit

[6]   DIN EN ISO 4288:1998-04 Oberflächenbeschaffenheit: Tastschnittverfahren Regeln und Verfahren für die Beurteilung der Oberflächenbeschaffenheit

[7]   DIN EN ISO 5436-1 (Entwurf 1998-07) Oberflächenbeschaffenheit: Normale Teil 1 Maßverkörperungen

[8]   DIN EN ISO 16610-21:2012 Geometrische Produktspezifikation (GPS) - Filterung - Teil 21: Lineare Profilfilter: Gauß-Filter (ISO 16610-21:2011)

[9]   DIN EN ISO 12179 Oberflächenbeschaffenheit: Tastschnittverfahren Kalibrierung von Tastschnittgeräten

[10] EA-4/02 M:2022 Evaluation of the Uncertainty of Measurement in Calibration, 4th April 2022, https://european-accreditation.org/publications/ea-4-02-m/

[11] DKD-R 4-2 Blatt 1 Kalibrieren von Messgeräten und Normalen für die Rauheitsmesstechnik - Blatt 1: Kalibrieren von Normalen für die Rauheitsmesstechnik

[12] DKD-R 4-2 Blatt 2 Kalibrieren von Messgeräten und Normalen für die Rauheitsmesstechnik - Blatt 2: Kalibrieren des vertikalen Messsystems von Tastschnittgeräten

[13] DKD-R 4-2 Sheet 3 Calibration of instruments and standards for roughness metrology - Sheet 3: Calibration of standards with periodic profiles in horizontal direction by means of stylus instruments

[14] WECC Doc. 19 Guidelines for the Expression of the Uncertainty of Measurement in Calibrations

[15] M. Krystek: Einfluss des Wellenfilters auf die Unsicherheit eines Messergebnisses bei Rauheitsmessungen. Tagungsband der DIN-Tagung „GPS 99", 5.-6.-Mai 1999, Mainz, S. 4-1 – 4-11. Beuth-Verlag, ISBN 3-410-14534-6

[16] ISO 25178-601:2010 Geometrical product specifications (GPS) - Surface texture: Areal - Part 601: Nominal characteristics of contact (stylus) instruments

[17] ISO 25178-70:2014 Geometrical product specification (GPS) - Surface texture: Areal - Part 70: Material measures

## A   Appendix: Calibration with Si lateral standard

A.1   Carrying out the measurement

12 scanning sections are to be distributed on the standard in accordance with an agreed measuring point plan (see chapter A1.4).

The noise during the probing process is measured by measuring R_{z0} on a flat section of the standard. The measurement conditions that are used during the calibration process with the lateral standard apply. An average of 3 measurements gives a sufficiently stable value.

A.1.1 Description of the standard

The standard for calibrating the horizontal axis of stylus instruments is a line measure according to Figure A1, which consists of regularly arranged lines etched in silicon.
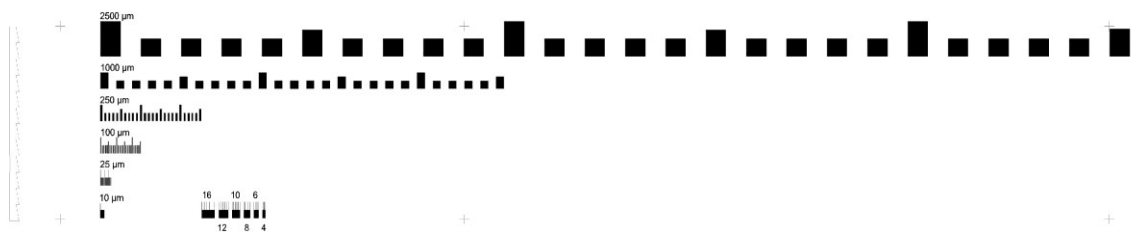
Figure A1: Lateral standard, overview

The line elements on it have a depth of approx. 5 µm. This value is neither tolerated nor calibrated. The depth and the flank angle (54.7°) resulting from the etching process guarantee:

- stable probing conditions with a good signal-to-noise ratio for the stylus instrument
- a well-defined signal in the case of optical edge detection
- non-critical production

The overall lengths and divisions of the scaling are selected to fit into the passband of the roughness band-passes that apply to the various wave filters in ISO 4288. Nominal values for the standard are given in Table A1.

Division No.	Division spacing / µm	Line width / µm	Evaluation length / mm	cut-off λ_c / mm	Velocity / mm/s
1	2500	1250	40	8	0.5
2	1000	500	12.5	2.5	0.1
3	250	125	4	0.8	0.1
4	100	50	1.25	0.25	0.1
5	25	12.5	0.4	0.08	0.05
6	10	5	0.125	0.025	0.01

Table A1: Summary of nominal properties of the lateral standard and measurement conditions

A.1.2 Preparatory measures

The lateral standard is examined for scratches by visual inspection with the naked eye. If scratches are detected, a magnifying glass (10x magnification) must be used to look for shell-shaped chips at the edges. In case of existing chips, it is necessary to look for a flawless track. If this is not possible, the standard must be discarded. If there is a history of use of the standard, the number of uses must be noted.

The direction of the profile sections must be parallel to the axis of the grid. The alignment is sufficient (cosine error of the length measurement < 10^{-4}) if a stylus section on division 2 intersects the short lines at the beginning **and** end.

A.1.3 Measurement conditions

Divisions 1 to 5 are to be measured, with or without λs, using a stylus tip radius of 5 µm or 2 µm over an evaluation distance according to ISO 4288. The recommended feed rate must be selected in accordance with Table A1. The smallest possible vertical measuring range must be selected.

Note on Table A1: The measurement conditions for track 6 are outside the standard conditions. Track 6 can only be measured without λs because otherwise a nonsensical bandwidth would result.

A.1.4 Measuring point plan
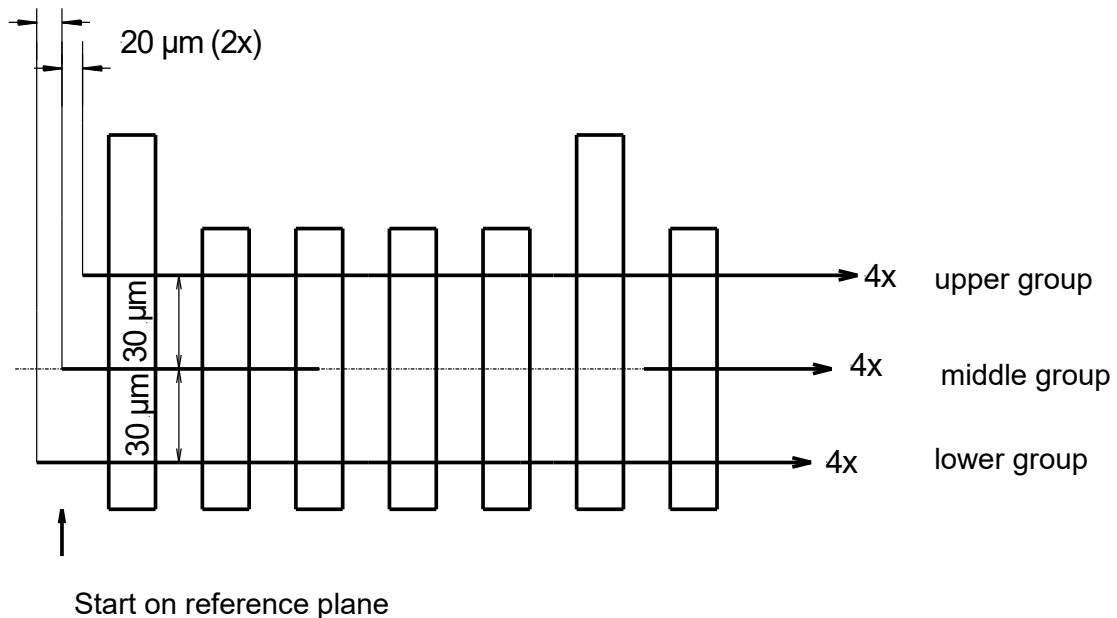
Figure A2: Measuring point plan, not-to-scale

The measuring point plan in Figure A2 with 12 scanning sections in 3 groups, each with 4 nominally identical probing contacts, considers the following aspects:
- different locations and probing conditions during calibration and transfer,
- repeatability of the instrument to be calibrated,
- deviation of the lines from the ideal form
- influence of different profile elements at the ends of the profile to create different evaluation conditions according to ISO 12179.

A.1.5 Evaluation

Determination of P_{Sm}, its deviation from the calibration value $P_{\mathrm{Sm,Normal}}$, R_{z0} and the standard deviation of the estimated values of P_{Sm} in groups that are defined as follows:

$s^2\big(P_{\mathrm{Sm,(1-12)}}\big)$, $s^2\big(P_{\mathrm{Sm,(1-4)}}\big)$, $s^2\big(P_{\mathrm{Sm,(5-8)}}\big)$, $s^2\big(P_{\mathrm{Sm,(9-12)}}\big)$
all tracks   upper group   middle group   lower group

The mean value of P_{Sm}, its standard deviation, its measurement uncertainty, and its deviations from the calibration value form part of the calibration certificate for instrument calibration.

A.2 Measurement uncertainty with Si lateral standard

The uncertainty components arising from the standard-dependent interaction with the stylus instrument are listed here in addition to those mentioned in chapter 6.3.

A.2.1 Noise from the device

Due to the edge angle specified by the etching technique, vertical noise also has an effect in the horizontal direction according to the model described below (see Figure A3).
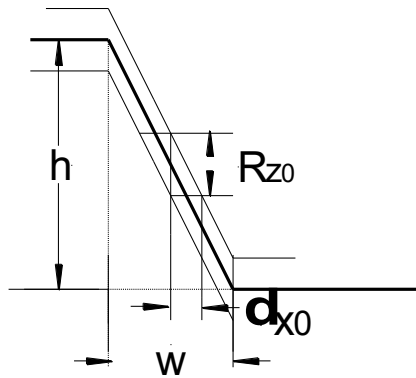
Figure A3: Influence of Rz_0 on the edge detection

$$\delta x_0 = \frac{h}{w} \cdot R_{z0}.$$

In the scanned profile, the measured edge angle depends on the relationship between the edge angle of the standard and the cone angle of the probe tip.

Cone angle	w/h
90° (wider than etch angle)	1 (arctan of the cone angle
60° (steeper than etch angle)	0.7 (arctan of the etch angle)

Table A2: Dependence of w w/h due to flank angle of the standard and flank angle of the stylus tip

Assuming a rectangular distribution, the uncertainty of this component is as follows:

$$u^2(\delta x_0) = \frac{1}{12} \cdot \left(\frac{h}{w} \cdot R_{z0} \right)^2.$$

A.2.2 Combined measurement uncertainty

The combined uncertainty of the horizontal scaling of the instrument is:

$$u^2(P_{Sm}) = \frac{1}{n^2} [2 \cdot u^2(\delta x_{dig}) + u^2(\delta x_0) + u^2(l_r) + u^2(l_{th}) + u^2(l_g)].$$

If the uncertainty components from chapters 6.3 and A.2.1 are used here, then

$$u^2(P_{\text{Sm}}) = u^2\big(P_{\text{Sm,Normal}}\big) + \frac{1}{m_{\text{t}}} \cdot s^2\big(P_{\text{Sm,M,Normal}}\big) + \frac{1}{12 \cdot n^2} \cdot (u(\Delta T) \cdot \alpha_{\text{th}} \cdot l)^2 + \frac{1}{12 \cdot n^2}(\Delta T \cdot u(\alpha_{\text{th}}) \cdot l)^2 + \frac{D_x^2}{6 \cdot n^2} + \frac{1}{6 \cdot n^2} \cdot \left(\frac{h}{w} \cdot Rz_0\right)^2$$

(3)

For illustration purposes in the following order: reference standard uncertainty, statistics on the standard, temperature, coefficient of thermal expansion, digitisation, noise.

The uncertainty component $\frac{1}{m_{\text{t}}} \cdot s^2\big(P_{\text{Sm,M,Normal}}\big)$ from the traceability process with the lateral standard is made up of the results of all profile sections and the grouped measurements:

$$\frac{1}{m_{\text{t}}} \cdot s^2\big(P_{\text{Sm,M,Normal}}\big) = \frac{1}{12} \cdot s^2\big(P_{\text{Sm,(1-12)}}\big)$$
$$+ \frac{1}{3} \cdot \left[\frac{1}{12} \cdot s^2\big(P_{\text{Sm,(1-4)}}\big) + \frac{1}{12} \cdot s^2\big(P_{\text{Sm,(5-8)}}\big) + \frac{1}{12} \cdot s^2\big(P_{\text{Sm,(9-12)}}\big)\right]$$

Table A3 shows example values for a nominal grating period of RSm = 250 µm.

Chap.	Short term	Determined by	Input quantity	Method, distribution	u^2/ nm^2
6.3.2	Reference standard	$u^2(P_{\mathrm{Sm,Normal}})$	$U(P_{\mathrm{Sm},n})$= 4 nm k = 2	B Gaussian	4
6.3.2	Measuring position (traceability)	$\frac{1}{12} \cdot s^2(P_{\mathrm{Sm},1-12})+$ $\frac{1}{3} \cdot \{ \frac{1}{12} \cdot s^2(P_{\mathrm{Sm},1-4})+$ $\frac{1}{12} \cdot s^2(P_{\mathrm{Sm},5-8})+$ $+ \frac{1}{12} \cdot s^2(P_{\mathrm{Sm},9-12})\}$	$s(P_{\mathrm{Sm},1\text{-}12})$ = 90 nm $s(P_{\mathrm{Sm},1\text{-}4})$ = 40 nm $s(P_{\mathrm{Sm},5\text{-}8})$ = 50 nm $s(P_{\mathrm{Sm},9\text{-}12})$ = 30 nm	A Gaussian	814
6.3.3	Temperature difference	$\frac{1}{12 \cdot n^2} \cdot (u(\Delta T) \cdot \alpha_{\mathrm{th}} \cdot l)^2$	n = 16, $u(\Delta T)$ = 0.2 K l= 4 mm, $\alpha_{\mathrm{th}} = 2.5 \cdot 10^{-6}\mathrm{K}^{-1}$	A rectangular	0.002
6.3.3	Expansion coefficient	$\frac{1}{12 \cdot n^2} \cdot (\Delta T \cdot u(\alpha_{\mathrm{th}}) \cdot l)^2$	ΔT = 2 K $u(\alpha_{\mathrm{th}}) = 5 \cdot 10^{-6}\mathrm{K}^{-1}$	A rectangular	0.52
6.3.1	Measuring point distance	$\frac{D_x^2}{6 \cdot n^2}$	$D_x = 0.5$ µm	B rectangular	163
A2.1	Noise	$\frac{1}{6 \cdot n^2} \cdot \left(\frac{h}{w} \cdot Rz_0\right)^2$	Rz_0 = 0.010 µm w/h = 1	A rectangular	0.07
A2.4	$u^2(P_{\mathrm{Sm}})$	Sum of the uncertainties			982
5.1	$u(P_{\mathrm{Sm}})$	$\sqrt{u^2(P_{\mathrm{Sm}})}$	rounded up		32 nm
	$U(P_{\mathrm{Sm}})$	$k \cdot u(P_{\mathrm{Sm}})$	k = 2		64 nm
	$U_{\mathrm{rel}}(P_{\mathrm{Sm}})$	$\dfrac{u(P_{\mathrm{Sm}})}{P_{\mathrm{Sm}}}$			$3 \cdot 10^{-4}$

Table A3: Summary of the measurement uncertainty during calibration with Si lateral standard with example values

Simplifications
As the example shows, some contributions are negligibly small compared to others (proportion < 10 %). If they are omitted to simplify the calculation, the value of the remaining measurement uncertainty must be rounded up by at least 10 %.

B Appendix: Calibration with geometrical standard

B.1 Carrying out the measurement

At least 12 scanning sections must be distributed on the standard (see chapter B1.4). The noise during the probing process is measured by measuring R_{z0} on a flat piece of the geometry standard. The measurement conditions that are used for the calibration process with the geometry standard apply. An average of 3 measurements gives a sufficiently stable value.

B.1.1 Description of the standard

The reference standard of type PPS as described in ISO 25178-70 contains almost sinusoidal periodic grooves with a spacing between 50 µm and 200 µm. The number of periods is so large that the measuring distances can be set on the standard in accordance with the filter conditions in ISO 4288. The standards are usually made of glass or produced by moulding in nickel. Additional layers can be applied for hardening or to reduce friction.

B.1.2 Preparatory measures

The reference standard is checked for scratches by visual inspection with the naked eye. The standard must not be used for calibration in areas with scratches.

The direction of the profile sections must be perpendicular to the lines of the grid. The alignment is sufficient (cosine error of the length measurement $<10^{-4}$) if the stylus tip moves parallel to the edge of the measuring field over a scanning distance of 12.5 mm by eye. This can also be observed when the stylus tip is slightly raised.

The standard can be cleaned with a soft microfibre cloth moistened with isopropanol. The wiping direction must be parallel to the grooves.

B.1.3 Measurement conditions

The stylus tip radius must be 2 µm to 5 µm depending on the measuring conditions. The feed rate must be $\leq$ 0.5 mm/s. The measurement can be carried out with or without λ_s.

The geometry standards used must be calibrated for the measurement conditions of λ_c = 0.25 mm, λ_c = 0.8mm and λ_c = 2.5 mm.

B.1.4 Measuring point plan

According to Figure B1, the measuring point plan contains 12 scanning sections. Their distribution is chosen to cover the range of the standard over which it was calibrated according to the information given in the calibration certificate. The arrangement of the scanning sections considers the following aspects:

- repeatability of the device,
- deviations of the profile elements from the ideal form
- uncertainty in the positioning of the measuring points with regard to the subsequent use of the device.
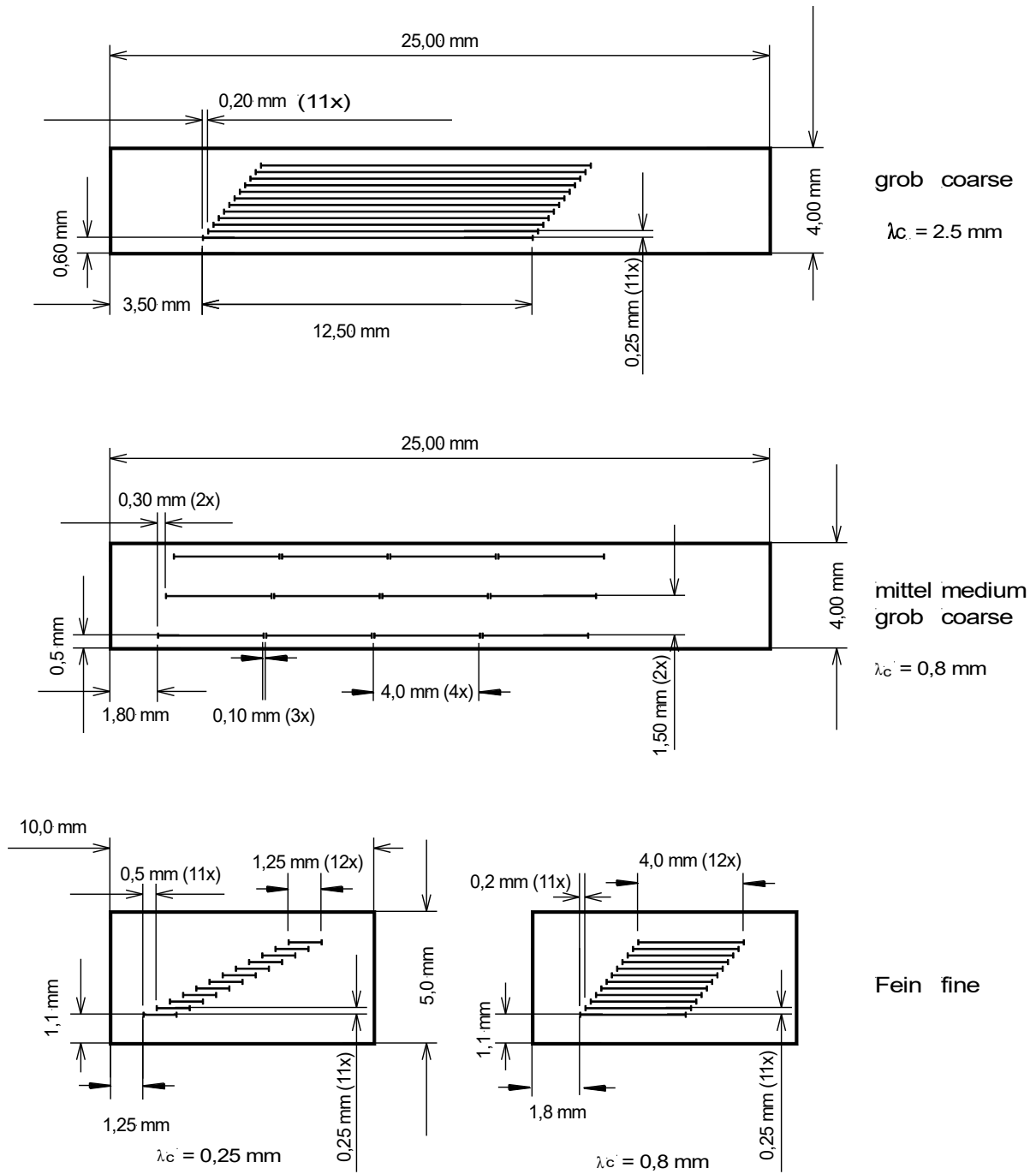
Figure B1: Examples of measuring point plans commonly used in the calibration of standards

B.1.5 Evaluation

The profile must be aligned in such a way that both ends lie on the same profile feature. This means, for example, that the profile must be trimmed such that both ends lie on a zero crossing

with the same sign. This prevents systematic misalignment due to an unequal number of peaks and valleys.

The following values are determined:

The mean value of $P_{\text{Sm,Normal}}$, its standard deviation, its deviation from the calibration value and R_{z0}. The mean value of $P_{\text{Sm,M,Normal}}$, its standard deviation, its measurement uncertainty, and its deviation from the calibration value $P_{\text{Sm,Normal}}$ form part of the calibration certificate for instrument calibration.

B.2 Measurement uncertainty with geometry standard

The uncertainty components arising from the standard-dependent interaction with the stylus instrument are listed here in addition to those mentioned in chapter 6.3.

B.2.1 Noise from the device

Due to the slope of the profile when passing through the zero line, a vertical noise leads to an uncertainty in the horizontal measurement (see Figure B2). Therefore, the model outlined below applies to δx_0. If the vertical noise is characterised by R_{z0} then, according to Figure B2, $\delta x_0 = \frac{R_{z0}}{\sigma}$. Here, $\sigma = \frac{P_t}{2} \cdot \frac{2\pi}{p}$, the profile slope at the zero crossing of the sine profile and p is the length of a profile element. Assuming a rectangular probability distribution,

$$u^2(\delta x_0) = \frac{1}{12} \cdot \left(\frac{R_{z0}}{\sigma}\right)^2$$
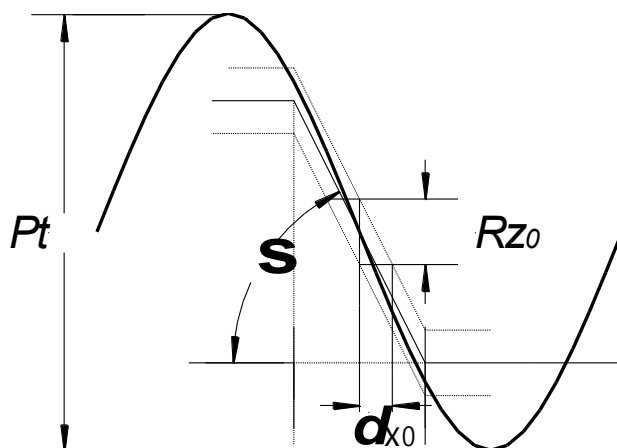
Figure B2: Influence of the background noise on the detection of the profile elements

B.2.2 Combined measurement uncertainty

The combined measurement uncertainty is made up of the components listed in chapter 6.3 and in chapter B2.1. These are in the following order: reference standard uncertainty, statistics on the standard, temperature, coefficient of thermal expansion, digitisation, noise.

$$u^2(P_{\text{Sm}}) = u^2(P_{\text{Sm},n}) + \frac{1}{m_t} \cdot s^2(P_{\text{Sm,Bezug}}) + \frac{1}{12 \cdot n^2} \cdot (u(\Delta T) \cdot \alpha_{\text{th}} \cdot l)^2 + \frac{1}{12 \cdot n^2}(\Delta T \cdot u(\alpha_{\text{th}}) \cdot l)^2 + \frac{D_x^2}{6 \cdot n^2}$$

$$+ \frac{1}{6 \cdot n^2} \cdot \left(\frac{R_{z0}}{\sigma}\right)^2 \qquad (4)$$

Table B1 shows an example for the measurement uncertainty during calibration using a reference standard with a period of P_{Sm} = 200 µm over a scanning distance of 4 mm with an amplitude of Pt = 10 µm

Chap.	Short term	Determined by	Input quantity	Method, distribution	u^2/nm^2
6.3.2	Reference standard	$u^2(P_{Sm,n})$	$U(P_{Sm,n})$ = 60 nm $k = 2$	B Gaussian	900
6.3.2	Measuring position (traceability)	$\frac{1}{m_t} \cdot s^2(P_{Sm,Bezug})$	$m_t = 12$ $s(P_{Sm,Bezug})$ $= 100$ nm	A Gaussian	833
6.3.3	Temperature difference ΔT	$\frac{1}{12 \cdot n^2} \cdot (u(\Delta T) \cdot \alpha_{th} \cdot l)^2$	$n = 20$, $u(\Delta T) = 0.1$ K l= 4 mm, $\alpha_{th} = 6 \cdot 10^{-6}$K^{-1}	A rectangular	0.0012
6.3.3	Expansion coefficient α_{th}	$\frac{1}{12 \cdot n^2} \cdot (\Delta T \cdot u(\alpha_{th}) \cdot l)^2$	$\Delta T = 2$ K, $u(\alpha_{th})$ $= 6 \cdot 10^{-6}$K^{-1}	A, rectangular	0.12
6.3.1	Measuring point distance	$\frac{D_x^2}{6 \cdot n^2}$	$D_x = 0.5$ µm	B rectangular	104
B2.1	Noise	$\frac{1}{6 \cdot n^2} \cdot \left(\frac{R_{z0}}{\sigma}\right)^2$	Rz_0 = 0.020 µm $\sigma = 1$	A rectangular	0.2
B2.4	$u^2(P_{Sm})$	Sum of the variances			1838
5.1	$u(P_{Sm})$	$\sqrt{u^2(P_{Sm})}$	rounded up		43 nm
	$U(P_{Sm})$	$k \cdot u(P_{Sm})$	$k = 2$		86 nm
	$U_{rel}(P_{Sm})$	$\frac{u(P_{Sm})}{P_{Sm}}$			$5 \cdot 10^{-4}$

Table B1: Summary of the measurement uncertainty during calibration with a geometry standard, with example values

Simplifications
As the example shows, some contributions are negligibly small compared to others (proportion <10 %). If they are omitted to simplify the calculation, the value of the remaining measurement uncertainty must be rounded up by at least 10 %.