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# Roughness Metrology: Conversion of profiles from measurements with reference plane profilometers into skidded probe profiles

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**Deutscher Kalibrierdienst (DKD) – German Calibration Service**

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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**

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DKD expert reports are intended to present significant aspects from the field of calibration. Through publication by the DKD they are made available to the large community of calibration laboratories, both nationally and internationally.

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# 1 Introduction

Tactile methods, in particular stylus instruments, are still used for quality inspection of industrially manufactured surfaces. The comparability of these instruments is ensured by means of reference surface textures representing selected roughness parameters for the respective application. Calibration of reference surface textures enables them to serve as a material measure and turns the reference surface into a material roughness standard. Laboratories accordingly accredited by the German Accreditation Body (DAkkS), the national accreditation body of the Federal Republic of Germany, carry out the calibrations.

In the field of roughness metrology, different tactile methods are used depending on the size and characteristics of the workpieces to be tested. Components that are measured onsite as part of the manufacturing process and for which the requirements in terms of measurement accuracy are not too high are measured using hand-held devices. In case of more demanding requirements, larger profilometers with a stable workpiece holding fixture are used, connecting the measurement object with the sensors via a vertical column, a traverse unit, and a lever arm as stiff kinematic chain. The traverse unit moves the lever arm with the stylus and its probe tip relative to a reference plane inside the device. In the case of flexible devices which are held directly on very large workpieces, such as large metal sheets, there are stylus instruments with a specific design. Here, the movement of the stylus with its tip is not measured relative to the reference plane, but relative to a skid or two skids in form of a torus [1]. With this type of probe, the metrological chain is limited to the few millimetres between the stylus tip and the skids. These tori look somewhat like cylinders but have a slightly curved cylinder axis, i.e. they are realised as tori. They are usually referred to as skids. Devices with two skids operate with significantly better reproducibility than those with only one skid. For better comparability, the iron and steel industry, which is the main user of these double-skid probes, has defined a design with the standard DIN EN 10049 [2].

A variety of roughness standards are available on the market to suit a wide range of applications. These standards must be calibrated according to the measuring method used, taking into account whether the measurement is carried out with skidless probes using a reference plane or skidded probes. Up to now, the usual procedure of DAkkS-accredited laboratories consists in exchanging the probes according to the measurement order. A measurement job takes about three hours, or longer if complications arise. An exchange of the probe (lever arm with stylus) takes about half an hour. To reduce the time needed for changing the probe, orders for the same type of probe are bundled. Orders requiring the use of double-skid probes are much less frequent than those requiring reference plane probes. This means that customers might have to accept waiting times of up to three weeks when orders are bundled.

In the field of DAkkS accreditation of roughness parameters, measurements using skidded probes are an absolute exception, since usually only measurements with reference plane probes are permitted. By using probes with two skids, the surface profile is also mechanically filtered by the skids as well as by the tip shape of the stylus. The filter properties depend on the tip and skid geometry used. The form and position tolerances of the probe thus influence the measurement accuracy. This results in an expanded measurement uncertainty $U$ that is 3 to 5 percentage points greater for measurements with a double-skid probe compared to measurements with a reference plane probe [3].

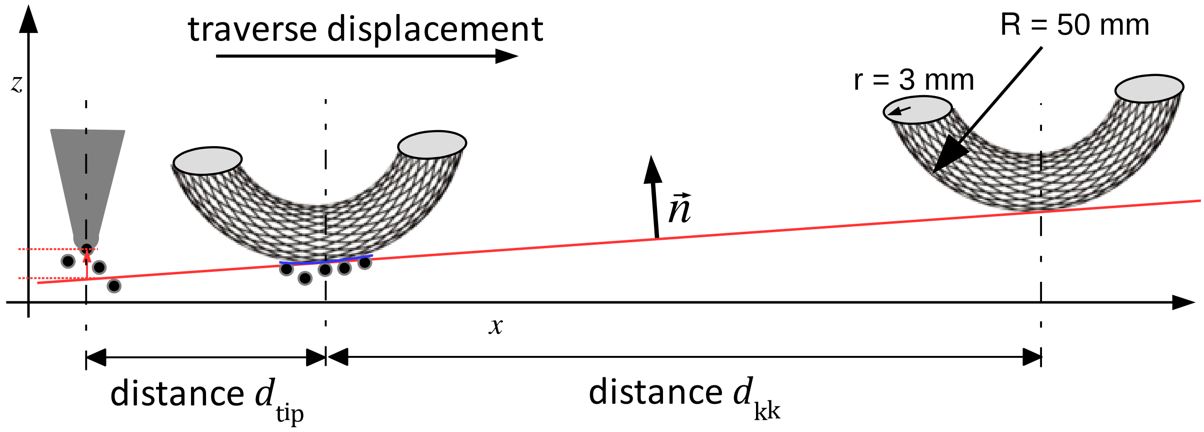


**Figure 1** Double-skid probe geometry according to EN 10049, with a distance between stylus tip and front skid of $d_{tip}$ = 4,5 mm and a distance between both skids of $d_{kk}$ = 13 mm, the radii of the skid tori are $R$ = 50 mm and $r$ = 3 mm

A procedure has been developed that aims at facilitating to completely dispense double-skid probe measurements in calibration: All standards are measured by means of a reference plane probe.

In order for profiles measured with reference plane probes to be converted to profiles that correspond to the double-skid probe measurements, these profiles must be much longer than the standardised measuring section. The total profile length to be measured must be at least as long as the measurement section specified in the standards plus the distance covered by the skids. The skid movement is calculated from a profile measured with a reference plane probe and then subtracted from that profile.

## 2 Double-skid probes according to EN 10049: Modelling

### *2.1 Modelling of the skid movement - overview*

The standard EN 10049 specifies the geometry of double-skid probes. The skids - realised as torus segments - form a line with the stylus tip, as illustrated in Fig. 1. The curvature of the respective torus is exaggerated in Fig. 1; similarly, all other dimensions are not shown to scale. For the model used to convert profiles from reference surface probe measurements into skid probe profiles, the feed axis, that is to say the profile abscissa, is referred to as the x-direction, and the direction of the topography heights, the profile ordinate, as the z-axis. The texture of the surface outside the plane spanned by the direction of feed and the direction of stylus deflection is not measured, so that the calculation of the skid movement is based on the x-z plane, which is containing the profile. With this approximation, the influence of contact between the topography and the skids outside the two-dimensional intersection plane is neglected and the information about the radius of curvature $r$ = 3 mm of the cylindrical tori remains unused.

For each probing point the skid-profile contact points lying in the x-z intersection plane are determined. Each of the two skids touches the topography at the point with the smallest distance from the skid. The straight line connecting the two skid-profile contact points and the projection of the stylus tip position onto the straight line are calculated. If $l_{\mathrm{m}}$ is the length of the measuring section according to international standards and if $d_{\mathrm{tot}}$ is the distance between the stylus tip and the x-position of the point of contact of the rear skid furthest from the tip, then the length of the profile measured by the reference plane profiler must be at least $l_{\mathrm{m}} + d_{\mathrm{tot}}$. For the standardised measuring section, a pair of contact points, their connecting line and the projection points of the probe tip position are determined for each measuring point. The projection points form the profile of the skid movement.

## 2.2 *Description of the algorithm*

Below, the algorithm for possible implementations is described in detail. For each contact point $x_i$ of the front profile section, two contact points with the skids are identified, i.e. one point per skid on which it rests. The length of the skids and thus the width of the intervals below a skid is estimated as $w_{\mathrm{K}} = 6\,\mathrm{mm}$. For each probing point, the two contact points are determined iteratively.

**Step 1:** *Determination of the index sets of the points under the skids:* the index set $\{i_1, \dots, n_1\}$ of the points of the profile measured with the skidless profiler $z_{\mathrm{B}}$ which would lie under the front skid (the skid closer to the stylus tip) and the index set $\{i_2, \dots, n_2\}$ of the measuring points under the rear skid. The following applies to the profile points under the front skid:

$$x_i + d_{\mathrm{tip}} - \frac{1}{2} w_{\mathrm{K}} \leq x_{j_1} \leq x_i + d_{\mathrm{tip}} + \frac{1}{2} w_{\mathrm{K}} \quad \text{with} \quad j_1 \in \{i_1, \dots, n_1\}. \tag{1}$$

The following applies to the profile points under the rear skid

$$x_i + d_{\mathrm{tip}} + d_{\mathrm{kk}} - \frac{1}{2} w_{\mathrm{K}} \leq x_{j_2} \leq x_i + d_{\mathrm{tip}} + d_{\mathrm{kk}} + \frac{1}{2} w_{\mathrm{K}} \quad \text{with} \quad j_2 \in \{i_2, \dots, n_2\}. \tag{2}$$

**Step 2:** *Determination of the initial values for the two contact points, assuming that the skids are not toroidal but cylindrical, both of which lie horizontally at the same height above the profile.* This means that for each skid, $\nu = 1, 2$. the highest point in its area, i.e. the maximum of the ordinate values of the respective profile section, is determined as follows:

$$z_{k_\nu} = \max_{j_\nu \in \{i_\nu, \dots, n_\nu\}} \{z_{\mathrm{R}, j_\nu}\}. \tag{3}$$

The straight line defined by the two points $(x_{k_1}, z_{k_1})$ and $(x_{k_2}, z_{k_2})$ can be inclined in such a way that mountain peaks from the neighbourhood lie above it. Taking into account the curvature of the tori, it is tested whether there exist any profile points above the skid contour, i.e. inside the skid. To do this, the unit vector $\vec{u}$ of the direction of the straight line connecting the points $(x_{k_1}, z_{k_1})$ and $(x_{k_2}, z_{k_2})$ is calculated. The direction vector $\vec{u}$ points from the point of contact of the front skid $\vec{r}_{k_1} = \binom{x_{k_1}}{z_{k_1}}$ to the point of contact of the rear skid $\vec{r}_{k_2} = \binom{x_{k_2}}{z_{k_2}}$. The arrangement of the device is chosen so that $x_{k_1} < x_{k_2}$ applies. The normal vector $\vec{n}$ to the straight line is perpendicular to $\vec{u}$, i.e.

$$\vec{u} = \binom{u_x}{u_z} = \frac{\vec{r}_{k_2} - \vec{r}_{k_1}}{|\vec{r}_{k_2} - \vec{r}_{k_1}|} \quad \hookrightarrow \quad \vec{n} = \binom{-u_z}{u_x}. \tag{4}$$

The initial vectors are denoted $\vec{n}_0$ and $\vec{r}_{k_1,0}$.

**Step 3:** *Iterative determination of the skid contact, with κ being used as the iteration index*. Instead of calculating the distances to the circle segments of the torus contours, the distances to the straight line connecting the contact points are calculated. The circular shape of the tori is taken into account by subtracting it from each scanning point within the relevant profile areas.

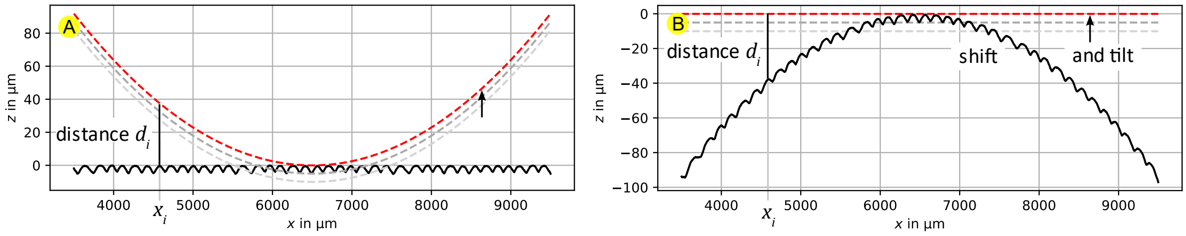


**Figure 2** Illustration of how to determine the distances between the skid and the profile: the curvature of the skid torus is converted into the profile in order to be able to easily calculate the distances to a straight line.

Fig. 2 illustrates this procedure. The distance of a point from a straight line with normal vector $\vec{n}$ is

$$d_{j_\nu} = \left(\vec{r}_{j_\nu} - \vec{r}_{k_1,\kappa}\right) \cdot \vec{n}_\kappa \,. \tag{5}$$

The distance is defined in such a way that the numerical value of the distance of the points above the skid contour is positive. Points with a positive distance value lie inside the skids and are therefore to be interpreted as non-physical. The two indices $k_1$ and $k_2$ for the maxima

$$d_{k_\nu} = \max_{j_\nu \in \{i_\nu, \dots, n_\nu\}} \{d_{j_\nu}\} \quad \text{with} \quad \nu = 1, 2 \tag{6}$$

are determined. For the new index $k_1$, the contact point $\vec{r}_{k_1}$ is used as starting point $\vec{r}_{k_1,\kappa+1}$ of the next iteration step. From this, the normal vector $\vec{n}_{\kappa+1}$ is calculated together with point $\vec{r}_{k_2,\kappa+1}$.

**Step 4:** *The iteration terminates if no remaining positive distances $d_{j_\nu}$ exist.*

**Step 5:** *Determination of the skid line*. At the lateral position $x_i$ of the stylus tip, the z-value $z_{\mathrm{skid},i}$ on the straight line, which is defined by the two contact points, is calculated as follows:

$$z_{\mathrm{skid},i} = \vec{r}_{k_1,\kappa+1} + \frac{x_i - x_{k_1,\kappa+1}}{n_{z,\kappa+1}} \vec{u}_{\kappa+1} \tag{7}$$

This is the projection of the stylus tip location vector onto the straight line.

**Step 6:** *The profile relative to the skid line* is then calculated from the difference between the profile measured with the reference surface probe and the skid line:

$$z_{\mathrm{S},i} = z_{\mathrm{R},i} - z_{\mathrm{skid},i} \tag{8}$$

## 3 Adjustment of the stylus tip

The common calibration orders for measurements using reference surface profilers require the use of a stylus tip with a radius of 2 µm, while skid probe measurements use tips with a radius of 5 µm. Yet the time required to change a stylus tip should also be avoided. The material measurement standards used as reference surface textures for sheet metal in iron and steel metallurgy have structures that are designed in such a way that the radii of curvature of the valley bottoms are generally greater than 5 µm. The change in the tip curvature therefore mainly affects the gradient of the side walls, so that it has more of an effect on parameters such as $R_\mathrm{a}$, which average over all profile points, and hardly any effect on extreme parameters such as $R_\mathrm{z}$, $R_\mathrm{max}$ or $R_\mathrm{zx}$.

One method of adapting the profiles is to use algorithms in order to apply morphological operations to the profiles. The morphological operation of erosion with a structuring element that is constructed of a circle segment and two straight lines is applied to the profile of the skidless probe. For a tip with a cone angle $\theta$ and a radius $R_\mathrm{tip}$, the structuring element is designed in such a way that the straight lines of the 2D section of the cone connect tangentially to the circle segment. The circle segment lies in the interval

$$x \in \left[-R_\mathrm{tip}\cos\frac{\theta}{2}, R_\mathrm{tip}\cos\frac{\theta}{2}\right]. \tag{9}$$

If the centre of the circle segment at point $x = 0$ has the height value $z = 0$ and the circle segment with cone is opened upwards, then the height values $z_\mathrm{tr}$ at the two interval limits, which represent the transition points from the circle segment to the straight lines, are as follows:

$$z_\mathrm{tr} = R_\mathrm{tip}\left(1 - \sin\frac{\theta}{2}\right). \tag{10}$$

The structuring element is calculated as follows:

$$z = \begin{cases} R_\mathrm{tip} - \sqrt{R_\mathrm{tip}^2 - x^2} & \text{if} \quad -R_\mathrm{tip}\cos\frac{\theta}{2} < x < R_\mathrm{tip}\cos\frac{\theta}{2} \\ z_\mathrm{tr} + \left(x - R_\mathrm{tip}\cos\frac{\theta}{2}\right)/\tan\frac{\theta}{2} & \text{else} \end{cases}. \tag{11}$$

A possible algorithm for the morphological operations is described by Villarrubia 1997 [4] with a source code. This algorithm applies to probing in the vertical direction.

The profile $z_\mathrm{e,R}$ eroded by a tip radius $R_\mathrm{tip} = 2$ µm is then used to determine the skid line and the profile $z_\mathrm{S}$ which runs relative to the skid line, i.e. the height values $z_{\mathrm{S},i} = z_{\mathrm{e,R},i} - z_{\mathrm{skid},i}$, are calculated. Finally, the morphological operation of dilation with a structuring element consisting of a straight line and a circle segment with radius $R_{\mathrm{tip}} = 5$ µm is applied to the profile.

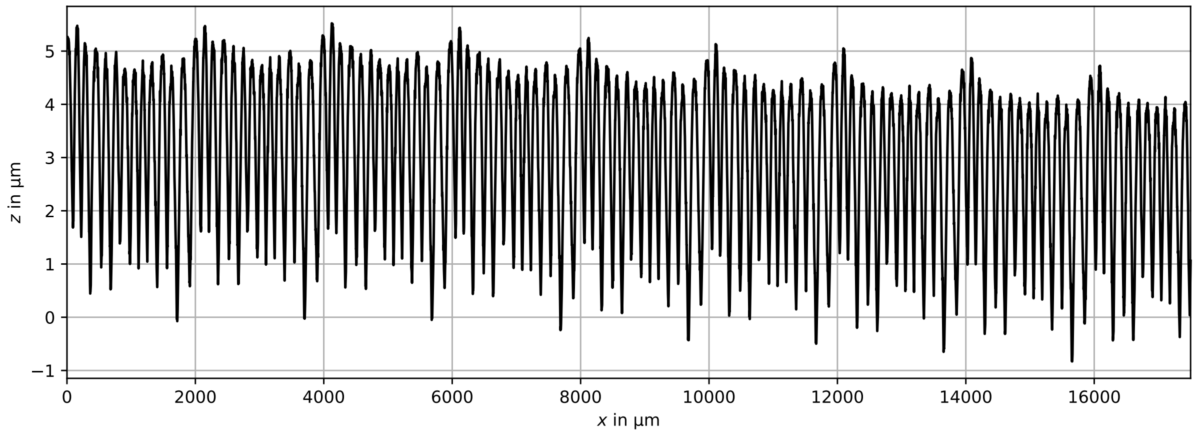


**Figure 3** Profile measured on a roughness standard for sheet metal with a double-skid system

## 4 Study using a roughness standard for sheet metal surfaces

The calibration of roughness standards for the visualisation of sheet metal surfaces is a typical calibration task for which double-skid probes are used. Fig. 3 shows the typical characteristics of a profile scan on a roughness standard for thin sheet metal surfaces, measured with a skid probe and a stylus tip radius of 5 µm. In general, the roughness standards are manufactured in such a way that the essential topographical features repeat themselves. The length of a period should be an integer divisor of the section length and shall not exceed the total evaluation length. This is important in order to obtain the same roughness parameter values for different measuring positions. The influence of filtration on the roughness parameters, including the filtering effect of skid movement and tip size, depends on the microgeometry of the surface texture features. After all, the representation of the microstructures is deformed by filtration.

The size of the probing tip determines the change in the gradients and curvatures of the measured profile, depending on the gradients and curvatures of the surface texture. Fig. 4 shows detailed views of the texture features of the roughness standard for thin sheet surfaces: The solid black curve shows the measured profile section. The red dashed curve shows the profile section after performing the operation of erosion with the structuring element representing a tip with a radius of 2 µm. Concave features of the surface texture that are smaller than the structuring element, in this case the tip calculated using a circle segment, cannot be reconstructed.

To obtain a profile that would be expected from a measurement with a larger probe tip, the profile resulting from a smaller tip after being eroded is then delated. The green dash-dotted curve depicted in the diagrams of Fig. 4 is the result of the dilation with a radius of 5 µm applied to the red dashed curve.

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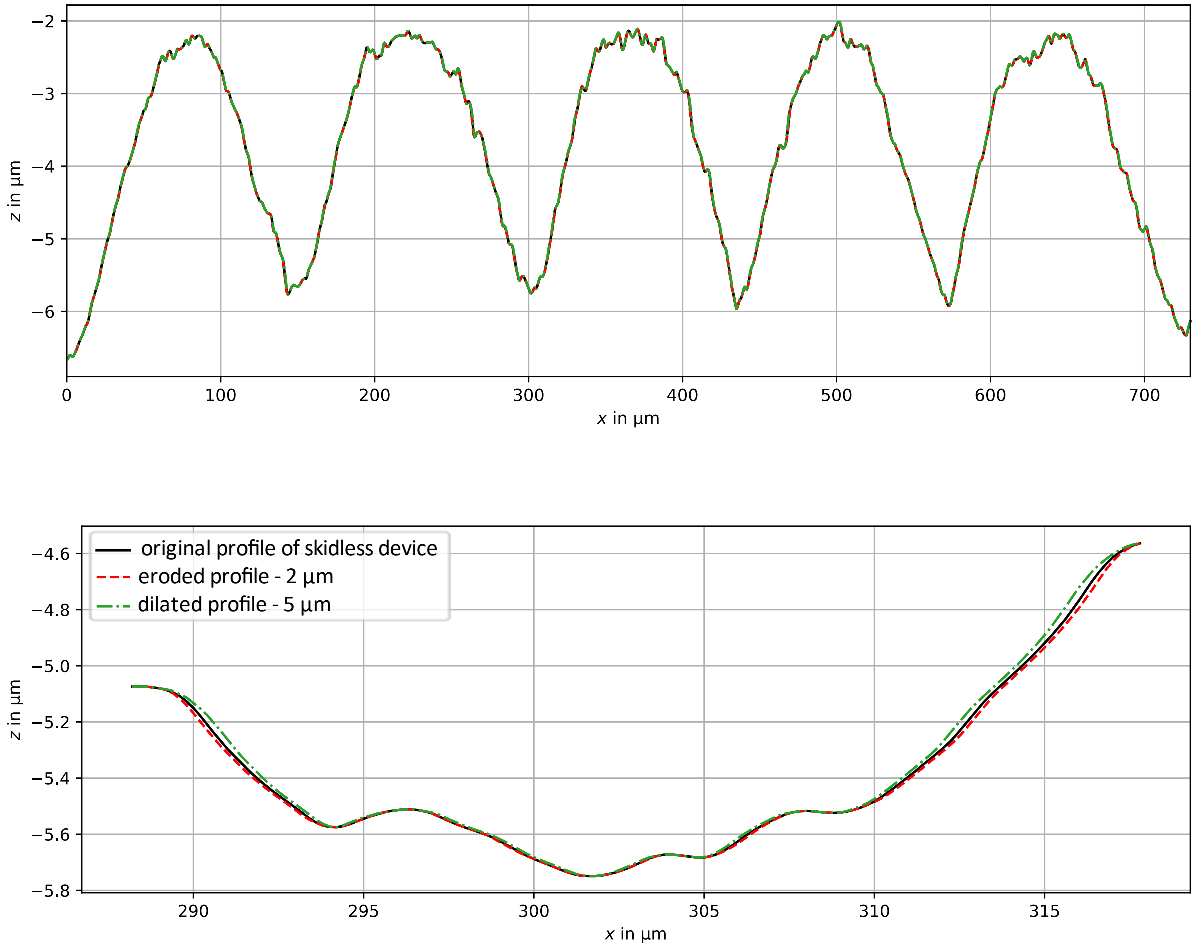


**Figure 4** Profile sections to visualise the influence of the stylus tip size

With this type of surface texture, the radii of curvature in the valleys and on the peaks are greater than 5 µm and it can be seen that the transformation due to the probe tips has an effect on the shape of the flanks. This means that a morphological tip size transformation on this type of profiles has an effect on $R_a$, but no noticeable effect on $R_z$, $R_{zmax}$ ($R_{max}$) or $R_{zx}$.

Table 1 shows the results of the transformation of a reference plane probe measurement into a skid probe measurement. The values in the line "2 µm" show the result without any conversions of the tip radius. The line with "5 µm" shows the result from the profile dilated with a circular segment having a radius of 5 µm. The dilation was applied to the profile obtained from the profile of the reference plane probe after having been eroded by 2 µm, and from which the skid line was determined and then subtracted from the eroded profile. The dispersion shown in the table results from the determination of the parameters from exactly one profile, but from 6 different positions of evaluation intervals that were shifted with respect to each other in steps of 1 mm. The indicated numerical values represent one standard deviation. The evaluation length for calculating the roughness parameters is 12,5 mm, the cut-off wavelength for decomposing roughness and waviness is $\lambda_c = 2{,}5$ mm. Furthermore, 17,5 mm is used for the length of the primary profile.

If no noise filter is used, the difference between the analysis with or without tip size transformation lies in the sub-nanometre range for the extreme parameters, i.e. for the parameters quantifying the maximum profile heights, $R_z, R_{zmax}$ $(R_{max})$ and $R_{zx}$ . If the filter is applied with $\lambda_s = 8{,}3333$ µm, it is around 3 nm. With a roughness parameter value of 5,5 µm, the changes due to a different choice of the tip radius are therefore less than one per mil. The dispersion of the values, $R_z, R_{zmax}$ and $R_{zx}$ due to the dependence on the position of the evaluation region is estimated to be approximately 8 nm to 11 nm. This uncertainty is related to the inhomogeneity of the surface texture. The arithmetic average roughness (arithmetic mean height) $R_a$

Without noise filter

| $R_{tip}$ | $R_a$/µm | $R_z$/µm | $R_{zmax}$/µm | $R_{zx}$/µm |
|---|---|---|---|---|
| 2 µm | 1,2266 ± 0,0025 | 5,5216 ± 0,0115 | 5,5783 ± 0,0083 | 5,5977 ± 0,0075 |
| 5 µm | 1,2236 ± 0,0025 | 5,5214 ± 0,0115 | 5,5781 ± 0,0083 | 5,5973 ± 0,0076 |
| Diff./µm | 0,0030 | 0,0002 | 0,0002 | 0,0004 |

With noise filter $\lambda_s = 8{,}3333$ µm

| $R_{tip}$ | $R_a$/µm | $R_z$/µm | $R_{zmax}$/µm | $R_{zx}$/µm |
|---|---|---|---|---|
| 2 µm | 1,2235 ± 0,0025 | 5,4498 ± 0,0085 | 5,5123 ± 0,0102 | 5,5410 ± 0,0103 |
| 5 µm | 1,2205 ± 0,0025 | 5,4466 ± 0,0086 | 5,5076 ± 0,0092 | 5,5377 ± 0,0107 |
| Diff./µm | 0,0030 | 0,0032 | 0,0047 | 0,0033 |

**Table 1** Influence of the tip conversion for a roughness standard for sheet metal; the indicated scatter is a standard deviation

is $R_a = 1{,}22$ µm. For this parameter, both the dispersion due to the position of the evaluation interval and the change due to the different choice of tip radii are around 3 nm, which is just under 0,3 per cent.

In this study, a profile measured without skids and a profile measured with the double-skid probe were matched as closely as possible in order to minimise the influence of the inhomogeneity of the topography. Nevertheless, the height parameters $R_z$, $R_{zmax}$ and $R_{zx}$ deviate by 0,10 µm between the profile measured with a real skid probe and the profile obtained by transformation. The difference between these parameters, as obtained from the evaluation of the skid probe profiles and the evaluation of the original skidless probe profiles, is 0,55 µm.

Fig. 5 shows the comparison for the arithmetic average roughness (arithmetic mean height) and for the three maximum height parameters. The parameters being compared are those calculated from the profiles measured with a reference plane probe and with a skidded probe. In the

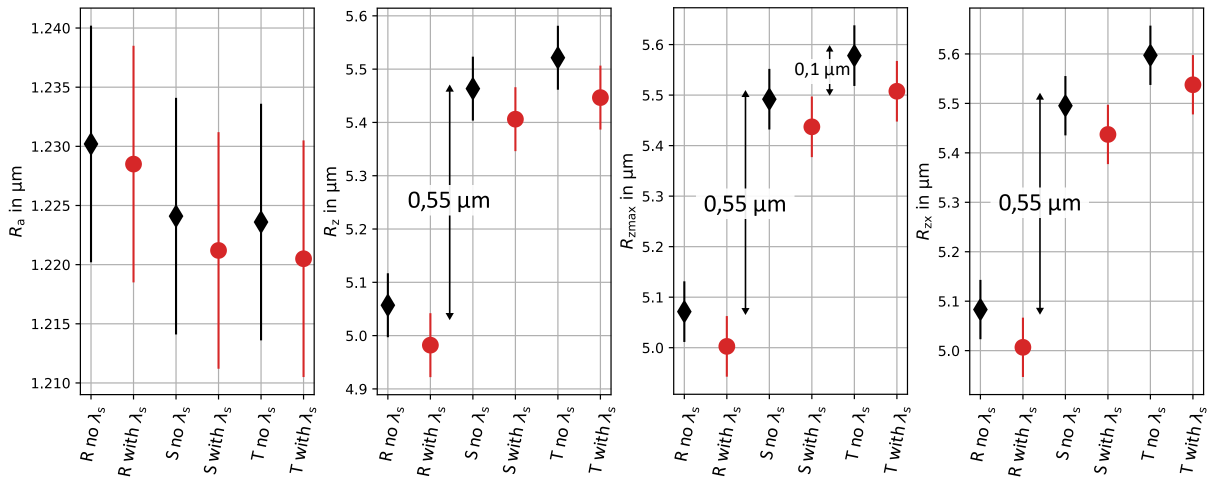


**Figure 5** Comparison of the parameters, each calculated from profiles measured with a reference plane probe (R) and with a skid probe (S), as well as from profiles of the reference plane probe that were transformed according to the procedure described in Section 3 (T). The black diamonds represent the results without noise filtering and the red circles with filtering ($\lambda_s = 8{,}3333$ µm). The uncertainties are twice the standard deviations from the scattering of the different measuring points which are given in calibration certificates

axis labelling, these are labelled R for **r**eference plane probe and S for **s**kid probe. The entries labelled T for transformation were determined from profiles of the reference plane probe, which were converted according to the procedure described in section 3. In this first study, the difference of 100 nm could neither be attributed to a possible uncertainty in the scaling of the axes nor to any signs of wear on the skids. These two effects were investigated. The scaling problem was analysed by measuring one profile period each from the skid probe and from the reference plane probe, assigning them to each other and transforming them to the same scale, which shows a change in the roughness parameters of just below 3 nm. The contours of the two skids were measured to analyse the influence of the skid geometry. The skid contour measurement data was processed so that it could be incorporated into the model. The profile being measured on the skid contour had to be resampled to match with the profiles of the reference plane probe measurements by interpolation using cubic splines. Incorporating the microgeometry of the skids resulted in only a slight change in the height parameters in the order of 3 nm to 4 nm.

In the calibration certificates, the expanded total uncertainties for the arithmetic mean height value are given as $U(R_a) = 40$ nm and for the maximum height (roughness depth mean value from all section lengths) as $U(R_z) = 300$ nm, so that a deviation of 100 nm in the height parameters, $R_z, R_{zmax}$ ($R_{max}$ ) and $R_{zx}$ is acceptable. The change in the parameter $R_a$ is within the range of scattering due to the inhomogeneity of the surface texture.

As to the lateral parameters, there is no significant difference whether the profiler method uses skids or not. The peak count $R_{Pc}$ defined in DIN EN 10049 [2] provides the values $R_{Pc} = 64{,}8\ \frac{1}{\text{cm}}$ and $65{,}6\ \frac{1}{\text{cm}}$ for the sheet metal roughness standard used in this study, depending on the position of the measuring point. In calibration certificates, the total uncertainty for this parameter is given as $U(R_{\mathrm{Pc}}) = 2\,\frac{1}{\mathrm{cm}}$ . The standard DIN EN 10049 defines the parameter $R_{\mathrm{Pc}}$ as the number of peaks over the entire evaluation length and specifies that $R_{\mathrm{Pc}}$ is given as an absolute number per cm. Due to the integer value for the number of peaks per evaluation length, there are discrete steps. If a change by one profile peak occurs for different measurement positions over an evaluation distance of 12,5 mm resp. 1,25 cm, then this amounts to a discrete change of $\frac{1}{1{,}25\mathrm{cm}} = 0{,}8\,\frac{1}{\mathrm{cm}}$. Therefore, in the example examined here, we have the two values 64,8 $\mathrm{cm}^{-1}$ and (64,8+0,8) $\mathrm{cm}^{-1}$ = (65,6) $\mathrm{cm}^{-1}$. A similar parameter is defined in DIN EN 21920-2 resp. ISO 21920-2 [5], which is also a measure of the number of peaks per centimetre, but it is determined from the mean wavelength $R_{\mathrm{sm}}$ by taking its inverse quantity $R_{\mathrm{pc}} = {}^{1}/_{R_{\mathrm{sm}}}$. Changes due to the filter effect of the skid movement are not visible here, only a scattering of the values due to the inhomogeneity of the surface. The average wavelength of the converted profiles was $R_{\mathrm{sm}} = (153{,}1 \pm 0{,}5)$ µm regardless of whether the noise filter was switched on, that of the real skid sensor $R_{\mathrm{sm}} = (153{,}5 \pm 0{,}5)$ µm, and the average wavelength of the profiles of the reference plane probe measurement $R_{\mathrm{sm}} = (153{,}8 \pm 0{,}5)$ µm. The resulting peak number is $R_{\mathrm{pc}} = (65{,}13\ \pm 0{,}18)\ \frac{1}{\mathrm{cm}}$.

## 5 Validation of the algorithms against long-term measurements on a working standard

The methods described in sections 3 and 4 use the algorithms listed in Annexes A and B.

The validation of these algorithms was carried out in the DAkkS-accredited calibration laboratory of HOMMEL ETAMIC JENOPTIK Industrial Metrology Germany GmbH in Villingen-Schwenningen against long-term measured values from double-skid probe measurements (SN 85064) on a working standard for thin sheet surfaces (SN 8044, surface profile as in Fig. 3).

This working standard has been used regularly since the beginning of 2018 to check the calibration measuring system for roughness standards there, so that an extensive database is available.

Fig. 6 compares the values of a long-term series of double-skid probe measurements (S) for the parameters $R_{\mathrm{max}}$ (according to DIN 4768:1985 [6]), $R_z$ and $R_a$ (each according to DIN EN ISO 4287:1998 [7]) with the results from a measurement with a reference plane probe (R) and the transformation method (T) using the reference plane probe measurement. The measured values for $R_{\mathrm{Pc}}$ (according to DIN EN 10049) are not compared in accordance with the reasons described in Section 4.

For comparison, Fig. 6 also shows the reference results from two calibrations performed by PTB in 2018 (C.C. 57317 PTB 18) and in 2023 (C.C. 57029 PTB 23), which were performed with a

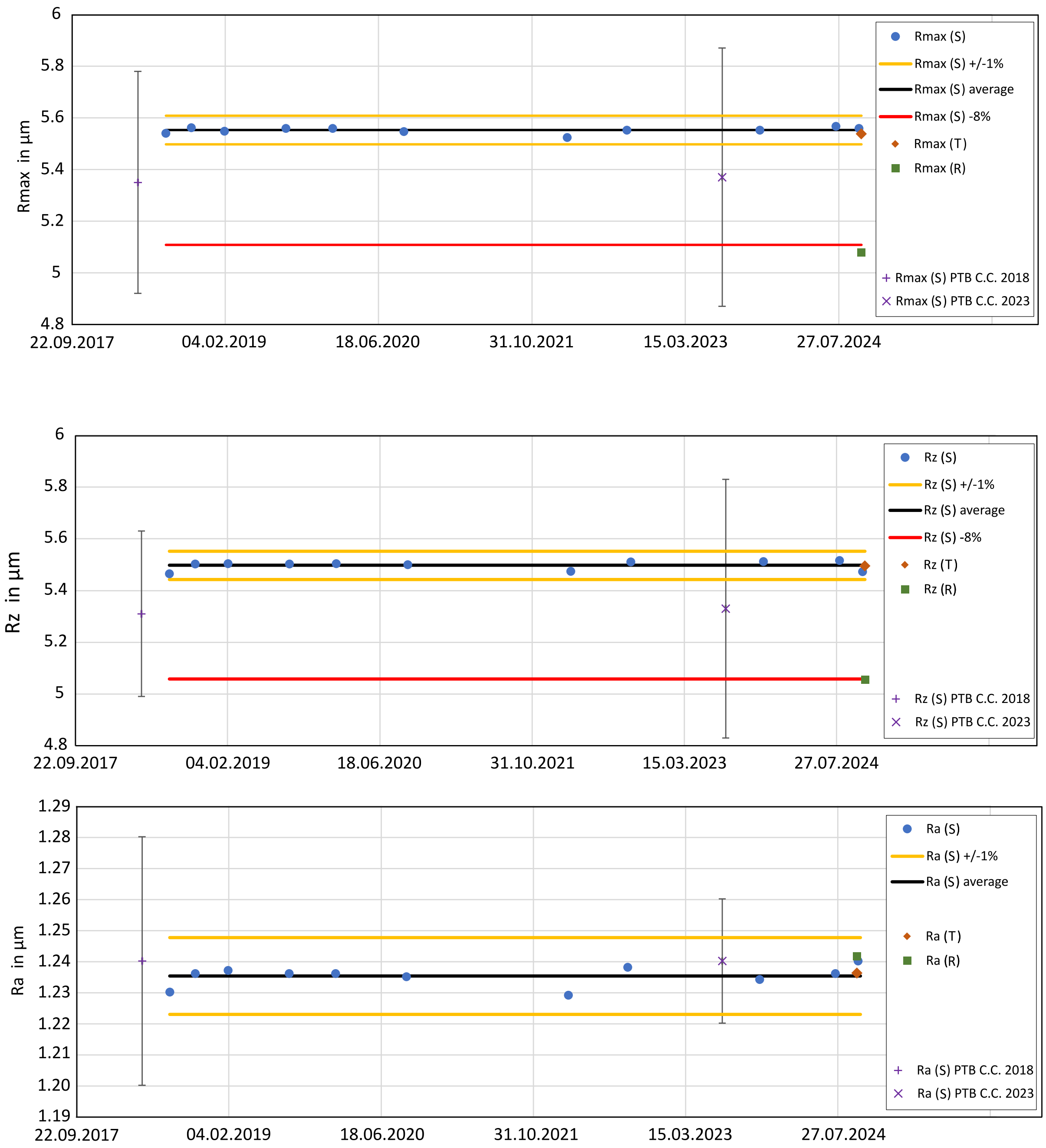


**Figure 6** Comparison of the long-term measured values of the parameters $R_{max}$ according to DIN 4768:1985 (*above*), $R_z$ according to DIN EN ISO 4287:1998 (centre) and $R_a$ according to DIN EN ISO 4287:1998 (*below*) from the measurements carried out with double-skid probes (S) with results from a measurement with e reference plane probe (R) as well as the skid transformation method (T) and two PTB reference calibrations dating from 2018 and 2023. Filtering was carried out with $\lambda_s$ = 8,3333 µm for the data by HOMMEL ETAMIC and $\lambda_s$ = 8,0 µm for the data in the calibration certificates.

double-skid probe (SN 099824) of the same type. The uncertainty bars represent the expanded measurement uncertainties specified in the calibration certificates (C.C.).

- The values of the long-term study from double-skid probe measurements (S) vary only minimally around a common mean value and always deviate from this by less than ±1 %.
- The PTB reference values for $R_{max}$ and $R_z$ deviate by more than 1 % from the mean value of the long-term series. The real geometric deviations of PTB's double-skid probe from the ideal geometry are assumed to be the cause. This fact is taken into account in the measurement uncertainty budget. As a result, the expanded measurement uncertainties of the PTB reference values cover the range of values of the long-term series measured at HOMMEL ETAMIC very well.
- The measured values from the reference plane profilometry (R) are approx. 8 % smaller for $R_{max}$ and $R_z$, and approx. 0,5 % larger for $R_a$ compared to the measured values from the double-skid probe measurements (S).
- The measured values from the skidless to skidded transformation method (T) using the profile measured by the reference plane profiler (R) lie almost perfectly within the interval depicted in Fig. 6 by the yellow lines, which represent the long-term measured values from the double-skid probe measurements (S).

The results of this comparison validate the skidless to skidded transformation method in an exceptional way. Due to the small deviations from the values being obtained measuring on the working standard over a long period of time, a reduction of the expanded measurement uncertainties is recommended when using the transformation method.

## 6 Summary

This expert report presents a procedure for the calibration of roughness standards used to represent the surface quality of sheet metal, which makes it possible to dispense with the use of double-skid probes during calibration.

When using this procedure, profiles acquired with reference plane profilers are converted into skid probe profiles. This is relevant for the maximum height parameters, $R_z$, $R_{zmax}$ and $R_{zx}$. For thin sheets with typical $R_z$ values in the range of 5 µm to 5,5 µm, the results of skid and reference plane profilers differ by approximately 0,6 µm. The uncertainty of the skidless to skidded transformation procedure is approximately 0,1 µm. There is no significant change in the values when determining the arithmetic mean height $R_a$ and the peak value $R_{Pc}$ or $R_{pc}$, so there is no need to convert those values.

The skidless to skidded transformation method helps to reduce time needed for modification and adjustment of the measuring set-up, and it eliminates uncertainty components due to form and position tolerances of the double-skid probes. Reduction of the smallest accredited measurement uncertainties is therefore recommended.

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## Annex A Source code of the transformation algorithm: skid probe

Profiles measured with a reference plane profiler can be approximately converted into profiles that correspond to the profiles measured by skidded probes using the method described in Section 2.2. The algorithm `skidline` calculates the skid line $z_{\mathrm{skid}}$, Eq. (7).

The algorithm `skidline` is called as follows:

```
x_skid, z_skid, sin_skid = skid_model.skidline(x_B, ze_B, dtip, dkk, w_k, Rkufe)
#
# if a measurement of the topography of the skids is existing:
#   csp_le, csp_ri are the pointers to the structs, containing the
#   cubic splines: from scipy.interpolate import CubicSpline
#   csp_le = scipy.interpolate.CubicSpline(x_Kufetopo_le, z_Kufetopo_le)
# where le denotes left, the skid closer to the tip
#       ri denotes right, the rear skid
#
x_skid, z_skid, sin_skid = skid_model.skidline(x_B, ze_B, dtip, dkk, w_k, Rkufe, [1],\
                                                                   csp_le, csp_ri)
#
#
# Evaluation of the transformed profile
#   ze_B: profile of the skidless profiler (with reference plane), after erosion of tip
#   iB_1: initial index for the beginning of the profile, if there are points to
#         be omitted, for instance those that do not belong to the roughness
#         structure, but to some localization structure
#
z_fake = ze_B[iB_1:iB_1+len(z_skid)] - z_skid[iB_1:len(z_skid)]
```

The following functions belong to the module `skid_model`

```
def skidline(x, z, dtip, dkk, w_k, radius_k, *xtz):
    # if a model exists describing a straightness deviation
    # as a cosine: a * cos(2 pi  (x - x_0)  / wl)
    # then xtz is filled
    # xtz[0][0]: amplitude, xtz[0][1]: wl, xtz[0][2] x_0 of skid 1 (close to tip)
    # xtz[1][0]: amplitude, xtz[1][1]: wl, xtz[1][2] x_0 of skid 2 (other side to tip)

    x_k1_left = dtip - 0.5 * w_k
    x_k1_right = dtip + 0.5 * w_k
    x_k2_left = x_k1_left + dkk
    x_k2_right = x_k1_right + dkk
    dx = x[1] - x[0]
    n_dist_from_end = int(np.ceil(x_k2_right/dx))
    n_data = len(x)

    n_use = n_data - n_dist_from_end

    x_skid = np.zeros(n_use)
    z_skid = np.zeros(n_use)
    sin_skid = np.zeros(n_use)
```

```
    for i_d in range(0, n_use):
#
# Step 1: set of indices of the points below the skids
#
        i_k1 = np.where(((x[i_d]+x_k1_left) < x) & (x < (x[i_d]+x_k1_right)))[0]
        i_k2 = np.where(((x[i_d]+x_k2_left) < x) & (x < (x[i_d]+x_k2_right)))[0]
#
# Step 2: initial values of the touching/contact points
#
        r_A, nvec = get_touchpoints_initial(x[i_k1], z[i_k1], x[i_k2], z[i_k2])
        readyflag = 0
        iter = 0
#
# Step 3: iterative determination of the skid-profile contact
#
        while (readyflag == 0) and (iter < 5):
            z_skidcurv1 = skid_curvature(x[i_k1], radius_k, nvec)
            z_skidcurv2 = skid_curvature(x[i_k2], radius_k, nvec)

            if len(xtz) > 0:
                if len(xtz[0]) == 3:
                    z_skidcurv1 += skid_formdeviation_cos(x[i_k1]-np.mean(x[i_k1]),\)
                                                  xtz[0][0], xtz[0][1], xtz[0][2])
                    z_skidcurv2 += skid_formdeviation_cos(x[i_k2]-np.mean(x[i_k2]),\
                                                  xtz[1][0], xtz[1][1], xtz[1][2])
                elif len(xtz[0]) == 1:
                    skid1_formdev = xtz[1](x[i_k1]-np.mean(x[i_k1]))
                    z_skidcurv1 += skid1_formdev
                    z_skidcurv2 += xtz[2](x[i_k2]-np.mean(x[i_k2]))
            readyflag, r_A, nvec = get_touchpoint_iterate(r_A, nvec, x[i_k1], \
                                   z[i_k1]+z_skidcurv1, x[i_k2], z[i_k2]+z_skidcurv2)
            iter += 1

#
# Step 5: Determination of the skid line Eq. (7)
#
        r_tip = get_skidreference_pt(r_A, nvec, x[i_d])
        x_skid[i_d] = r_tip[0]
        z_skid[i_d] = r_tip[1]
        sin_skid[i_d] = nvec[0]
    return x_skid, z_skid, sin_skid
```

The function `skid_formdeviation_cos` represents an initial, preliminary model equation used purely for test purposes the results of which are not discussed further here. The results reported in this article refer to the cubic splines in `skid1_formdev`.

The functions called in the function `skidline` are

- `get_touchpoints_initial`
- `skid_curvature`
- `get_touchpoint_iterate`

The initial values for the contact points where the skids touch the profile are determined from the distance to the approximation line, which lies horizontally. The normal vector to the straight line connecting the two "touchpoints" is calculated using equation (3).

```
def get_touchpoints_initial(x_k1, z_k1, x_k2, z_k2):
#
# within Step 2: evaluation of the normal vector according to Eq.(3)
#
    i_k1 = np.argmax(z_k1)
    i_k2 = np.argmax(z_k2)
    r_A = np.array([x_k1[i_k1], z_k1[i_k1]])
    r_k2 = np.array([x_k2[i_k2], z_k2[i_k2]])
    nvec = get_normalvec(r_A, r_k2)
    return r_A, nvec
```

The sub-function for calculating the normal vector is shown here:

```
def get_normalvec(rk1, rk2):
#
# vector that is normal to the straight line, which
#   is connecting the two skid contact points rk1 and rk2
#   Eq.(4)
#
    u = rk2 - rk1
    mue = np.sqrt(u[0]**2 + u[1]**2)
    u /= mue
    n = np.array([-u[1], u[0]])
    return n
```

Within the iteration loop, the circular contour of the skids is subtracted from the profile so that the Hessian normal form can simply be used to calculate the distances, Eq. (5). The circular segments are aligned with respect to the direction of the straight line from the previous iteration step.

```
def skid_curvature(x_skid, R_skid, nvec):
#
# within Step 3:
#   opens downwards, the pole is set to zero, all other values are negative
#   to be subtracted from the profile of the skidless instrument
#
    x_skid -= (np.mean(x_skid) - R_skid*nvec[0])
    z_skid = np.sqrt(R_skid**2 - x_skid**2) - R_skid + x_skid * nvec[0]
    z_max = np.max(z_skid)
    z_skid -= z_max
    return z_skid
```

In the next iteration step, the "touchpoints" and the normal vector of the line connecting the two points are determined again for the thus curved profile sections. The corresponding function is as follows:

```
def get_touchpoint_iterate(r_A, nvec, x_k1, z_k1, x_k2, z_k2):
#
# within step 3: evaluation of Eq.(4)
#
    tiny = 1e-7
    d_A = nvec[0]*r_A[0] + nvec[1]*r_A[1]
    d_k1 = nvec[0]*x_k1 + nvec[1]*z_k1 - d_A
    d_k2 = nvec[0]*x_k2 + nvec[1]*z_k2 - d_A
    i_k1 = np.argmax(d_k1)
    i_k2 = np.argmax(d_k2)
    r_A = np.array([x_k1[i_k1], z_k1[i_k1]])
    r_k2 = np.array([x_k2[i_k2], z_k2[i_k2]])
    nvec = get_normalvec(r_A, r_k2)
    if (d_k1[i_k1] > tiny) or (d_k2[i_k2] > tiny):
        readyflag = 0
    else:
#
# within step 4: terminate, if no more positive distances exist
#
        readyflag = 1
    return readyflag, r_A, nvec
```

The array labelled `ze_B` in the calling environment contains either the profile heights after erosion or the raw data, depending on whether a tip correction is performed. If the array `ze_B` represents the eroded profile, the array `z_fake`, which represents the profile transformed to a fictitious skid probe measurement, is dilated. The algorithms for eroding and dilating are shown in Annex B.

## Annex B Conversion of tip geometries of a probe

The conversion of the tip radii, if required, is carried out by applying the morphological operations erosion and dilation. A possible implementation for measurements with probing direction vertical to the surface was published by John Villarrubia in 1997 with source code in programming language C [4]. For the investigations described here it was ported to Python.

The erosion is realised with the following function:

```
def erodewithapex_profile(x_raw, z_raw, circ_radius, halfconeangle, x_hwidth):
    n_tip_r, z0_tip = make_conetip(circ_radius, halfconeangle, x_hwidth, \
                                                            x_raw[1]-x_raw[0])
    z_erode = np.copy(z_raw)
    for k in range(0, n_tip_r):
        z_tip = z_raw[k] + z0_tip[n_tip_r-k:]
        i_tip = np.arange(0,len(z0_tip[n_tip_r-k:]), dtype=int)
        iabove = np.where(z_erode[i_tip] > z_tip)[0]
        if (len(iabove) > 0):
            z_erode[i_tip[iabove]] = z_tip[iabove]
    for k in range(n_tip_r, len(z_erode)-n_tip_r):
        z_tip = z_raw[k] + z0_tip
        i_tip = np.arange(k-n_tip_r,k+n_tip_r+1, dtype=int)
        iabove = np.where(z_erode[i_tip] > z_tip)[0]
        if (len(iabove) > 0):
            z_erode[i_tip[iabove]] = z_tip[iabove]
    for k in range(len(z_erode)-n_tip_r, len(z_erode)):
        j = len(z_erode) - k
        z_tip = z_raw[k] + z0_tip[0:n_tip_r+j]
        i_tip = np.arange(k-n_tip_r,k-n_tip_r+len(z_tip), dtype=int)
        iabove = np.where(z_erode[i_tip] > z_tip)[0]
        if (len(iabove) > 0):
            z_erode[i_tip[iabove]] = z_tip[iabove]
    return z_erode
```

The `make_conetip` sub-function called at the beginning of the `erodewithapex_profile` function represents the structuring element for the erosion and dilation operations.

```
def make_conetip(circ_radius, halfconeangle, hwidth, dx):
    x_transi = circ_radius * np.cos(halfconeangle)
    z_transi = circ_radius * (1.0 - np.sin(halfconeangle))
    x_tip_r = np.arange(0, hwidth, dx)
    n_tip_r = len(x_tip_r)
    i_circ = np.where(x_tip_r <= x_transi)[0]
    z_tip_r = np.zeros(n_tip_r)
    z_tip_r[i_circ] = circ_radius - np.sqrt(circ_radius**2 - x_tip_r[i_circ]**2)
    z_tip_r[max(i_circ)+1:] = z_transi + \
                (x_tip_r[max(i_circ)+1:] - x_transi) / np.tan(halfconeangle)
    z_tip = np.append(np.flip(z_tip_r), z_tip_r[1:])
    return n_tip_r-1, z_tip
```

The structuring element `make_conetip` represents the section through a conical, spherically rounded tip because the morphological operations are applied to profiles in the x-z plane. It is a segment of a circle flanked by two straight line segments as explained in Section 3 Eq. (11). The dilation is also performed with `make_conetip`.

```
def dilatewithapex_profile(x_raw, z_raw, circ_radius, halfconeangle, x_hwidth):
    n_tip_r, z0_tip = make_conetip(circ_radius, halfconeangle, x_hwidth, \
                                                            x_raw[1]-x_raw[0])
    z_dilate = np.copy(z_raw)
    for k in range(0, n_tip_r):
        z_tip = z_raw[k] - z0_tip[n_tip_r-k:]
        i_tip = np.arange(0,len(z0_tip[n_tip_r-k:]), dtype=int)
        ibelow = np.where(z_dilate[i_tip] < z_tip)[0]
        if (len(ibelow) > 0):
            z_dilate[i_tip[ibelow]] = z_tip[ibelow]
    for k in range(n_tip_r, len(z_dilate)-n_tip_r):
        z_tip = z_raw[k] - z0_tip
        i_tip = np.arange(k-n_tip_r,k+n_tip_r+1, dtype=int)
        ibelow = np.where(z_dilate[i_tip] < z_tip)[0]
        if (len(ibelow) > 0):
            z_dilate[i_tip[ibelow]] = z_tip[ibelow]
    for k in range(len(z_dilate)-n_tip_r, len(z_dilate)):
        j = len(z_dilate) - k
        z_tip = z_raw[k] - z0_tip[0:n_tip_r+j]
        i_tip = np.arange(k-n_tip_r,k-n_tip_r+len(z_tip), dtype=int)
        ibelow = np.where(z_dilate[i_tip] < z_tip)[0]
        if (len(ibelow) > 0):
            z_dilate[i_tip[ibelow]] = z_tip[ibelow]
    return z_dilate
```

The trick with the rotation of the structuring element for the dilation is explained in detail by Villarrubia in his open access article [3]. The functions are called with

```
rtip_B    = 2.0
rtip_K    = 5.0
halfcone  = np.pi*45.0/180.0
halfwidth = 8.0
#
# profile that has been measured with skidless intrument
#   x_B: abscissa values (knot points along traverse axis)
#   z_B_raw: ordinate values (height values)
# erosion as tip correction
ze_B = mathutils.erodewithapex_profile(x_B, z_B_raw, rtip_B, halfcone, halfwidth)
#
# algorithm to transform the profile into a profile as of a skidded instrument
...
z_fake = ze_B[iB_1:iB_1+len(z_skid)-iB_2] - z_skid[iB_1:len(z_skid)]
#
# dilation to account for the tip of the skidded profilometer
#
zd_fake = mathutils.dilatewithapex_profile(x_skid[iB_1:len(z_skid)], z_fake, rtip_K,\
                                                                  halfcone, halfwidth)
```

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