Article

Effect of a Misidentified Centre of a Type ASG Material Measure on the Determined Topographic Spatial Resolution of an Optical Point Sensor

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Abstract: The article presents the determination of the topographic spatial resolution of an optical point sensor. It is quantified by the lateral period limit D_{LIM} measured on a type ASG material measure, also called (topographic) Siemens star, with a confocal sensor following both a radial measurement and evaluation, as proposed by ISO 25178-70, and the measurement and subsequent evaluation of two line scans, proposed by the NPL Good Practice Guide. As will be shown, for the latter, an only slightly misidentified target centre of the Siemens star leads to quite significant errors of the determined D_{LIM} . Remarkably, a misidentified target centre does not necessarily result in an overestimation of D_{LIM} , but lower values might also be obtained. Therefore, a modified Good Practice Guide is proposed to determine D_{LIM} more accurately, as it includes a thorough determination of the centre of the Siemens star as well. While the measurement and evaluation effort is increased slightly compared to the NPL Good Practice Guide, it is still much faster than a complete radial measurement and evaluation.

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1. Introduction and Literature Review

Surface texture determines the functional behaviour of a manufactured component and is therefore crucial in many different areas such as electronics, optics, medicine, information technology, or consumables [1–3]. As a result, surface metrology is an essential part of manufacturing metrology extensively dealt with within the ISO 25178 standards [4,5]. In the era of globalization and interchangeability, accurate and internationally comparable measurement results are indispensable [6]. Metrological comparability is ensured by the metrological traceability of the measurement result, which goes along with a statement about the measurement uncertainty [7,8]. The stylus method has been used for over 100 years in surface metrology [9], and due to the well understood interaction between the probe and the surface [10], it still serves as reference method for traceable surface measurements in different national metrology institutes [11–13]. Furthermore, atomic force microscopy (AFM, [14]) under tightly controlled environmental conditions and in ultrahigh vacuum enables a resolution down to the atomic scale [15,16], while metrological AFMs [17] ensure the traceability of the measurement results. Nevertheless, the measurement of soft surfaces by tactile methods is problematic due to the elastic or even plastic deformation of the workpiece caused by the applied probing force [18]. Not only are such issues irrelevant for optical methods, but the non-contact nature of probing also allows a measurement speed unprecedented by tactile methods [19]. Optical methods are therefore especially suited for in situ surface metrology [20]. The main benefit of in situ metrology is the more economical and also resource-efficient production due to the possibility to realize a very short quality control loop [21]. As process changes, e.g., alterations of the machine tool, influence surface

texture, the latter is an indicator of the characteristics of the manufacturing process and thus is also suited to control processes for which surface texture itself actually is not the crucial parameter [22].

Nonetheless, a main issue about optical methods is their lack of traceability, and therefore comparison measurements, including tactile methods, as well as comparisons limited to different optical instruments, frequently reveal significant deviations of the reported results [23–31]. An explanation of the deviations between the optical and the tactile methods might be that the latter probe the mechanical surface, whereas optical methods probe the electromagnetic surface [32]. However, a more important issue might be the disregard of the metrological characteristics, especially the bandwidth, of the instruments involved within the comparisons [33], since there are also examples where measurement results taken with different instruments, both tactile and optical, do not differ significantly [34,35]. Hence, the understanding of the limitations of a measuring instrument is of prime importance, and it is necessary to choose an appropriate instrument for a given surface to be measured [33]. A comprehensive review about the calibration and verification of areal surface texture measuring instruments is given in [36].

ISO 25178-600 specifies seven metrological characteristics of an instrument: amplification coefficient, linearity deviation, flatness deviation, measurement noise, topographic spatial resolution, x - y mapping deviations, and topography fidelity [37]. The scope of this paper is limited to the topographic spatial resolution W_R , which is defined as “the ability of a surface topography measuring instrument to distinguish closely spaced surface features” [37]. The standard does not specify how to quantify W_R . The most common in practice is the Rayleigh criterion [38] or the Sparrow criterion [39], which simply take the wavelength of light and the numerical aperture of the objective into account. Nevertheless, these criteria are rather the minimum values of W_R , and other influences might deteriorate W_R in practice [40]. Other approaches thus use, for instance, the instrument transfer function [41]. However, the applicability of this approach is limited [36]. An alternative possibility is the determination of the lateral period limit D_{LIM} , defined as “the spatial period of a sinusoidal profile at which the height response of an instrument falls to 50%” [37].

Following this definition, artefacts with sinusoidal structures and discrete spatial wavelengths, called chirp calibration standards, with a uniform amplitude [42] or a varying amplitude [43] might be used to determine D_{LIM} . For an aperiodic spatial frequency standard, the discrete spatial wavelengths are superimposed, and the data evaluation contains a Fourier transformation to separate the discrete spatial wavelengths and the corresponding transferred amplitude of the measuring instrument [44,45]. Also known is the application of a one-dimensional rectangular grating with varying pitches [46]. Nevertheless, all the standards mentioned so far only provide a finite number of spatial wavelengths and therefore may be unsuitable to characterize a particular optical system [47].

As an alternative, a star-like arrangement of grooves (type ASG according to ISO 25178-70 [48]), also called (topographic) Siemens star, which provides a continuous spectrum of spatial wavelengths, might be used to determine D_{LIM} of an optical system [49]. The standard proposes a radial measurement and evaluation of the star’s height to determine D_{LIM} . Nevertheless, this procedure necessitates the measurement of the complete star, which is quite time consuming when a point sensor is applied. Furthermore, the accurate determination of the centre of the Siemens star is not a trivial task since it is actually defined by the edges of the grooves that are not measurable with most optical systems because of the limited angle of acceptance of the microscope objective. In [50], the centre is determined automatically by the application of a Radon transformation. In [51], a feature-recognition method and a variance-judgment method were shown to determine the star’s centre. Instead of measuring the complete star, in [52], a faster measurement method especially suited for point sensors is demonstrated. It only measures and evaluates two lines taken at a groove and the adjacent top level, hereafter called the procedure following the NPL Good

Practice Guide [53]. Of course, the evaluation method of this procedure is still applicable if the complete star has been measured.

In [54], the significant influence of a misidentified centre on the determined D_{LIM} following the radial measurement and evaluation was proved. However, there is also a significant impact of the profile extraction on the determined D_{LIM} when following the NPL Good Practice Guide [55]. In this paper, the effect of a misidentified centre on the determined D_{LIM} of a confocal microscope is evaluated when following the NPL Good Practice Guide in Section 5.3. Based on this, in Section 5.4, a modified Good Practice Guide is proposed to determine D_{LIM} more accurately. In Section 4, D_{LIM} is determined following the radial approach. The paper starts with an introduction of the setup of the sensor system in Section 2 and the determination of the workpiece coordinate system (WCS) in Section 3.

2. Setup

The confocal microscope, patented by Minsky in 1957 [56], offers a resolution superior to conventional microscopy, which was first shown theoretically [57] and shortly thereafter empirically [58]. Particularly impressive is the comparison of confocal and conventional microscopy on biological specimens [59], but the confocal microscope soon became also a tool of dimensional metrology [60] and is nowadays described in ISO 25178-607 [61]. Nevertheless, as is usual for optical instruments, the improvement of the resolution came along with a reduction in the field of view [62], which becomes one single point of diffraction-limited size in the case of confocal microscopy. To measure a topography, it is therefore necessary to move the specimen relative to the sensor both axially and laterally. For each lateral position, the surface height is determined by finding the maximum signal of the axial response [63]. Although there are beam scanning methods that omit the necessity to mechanically move the specimen laterally, e.g., by the application of a Nipkow disk [64] or movable mirrors [65,66], for the investigations presented within this paper, we applied a setup operated in stage-scanning mode to demonstrate the determination of D_{LIM} of an optical point sensor with a Siemens star.

The setup consisted of a fibre-coupled confocal sensor firstly described in [67] and in its latest design, as it was applied for the investigations shown within this paper, in [68]. A thorough description of the sensor, including the theory of the signal formation based on general works on fibre-coupled confocal sensors of Gu et al. [69], may be found in [70]. Thus, the setup will only be briefly summarized here.

The main parts of the confocal sensor, which is shown schematically in Figure 1, were a helium–neon laser (1) with a wavelength of about 633 nm and a pin-photodetector (2), which were coupled to a narrowband single-mode fibre coupler with an integrated beam splitter with a splitting ratio of 50:50 (6) by a focusing lens (4) and a collimation lens (5). An optical isolator (3) prevents light reflected by the surface from disturbing the laser and therefore causing increased variations in the laser output power. A fibreport with an aspheric lens (7) collimated the laser light, and an infinity-corrected 100× microscope objective with an extended long working distance of 4.5 mm and a numerical aperture of 0.8 (8) focused the beam on the measuring object (9). The setup was supplemented with an illumination and camera system for the visual location and observation of the measuring object (not shown in the figure).

The sensor was integrated into a nano measuring machine (NMM-1) [71,72] with a range of motion of 25 mm × 25 mm × 5 mm, operated within a thermostating housing with a long-term temperature stability of 17 mK [73]. The NMM-1 fulfils the Abbe comparator principle [74] in all three coordinate axes by keeping the measuring system (three perpendicular homodyne Michelson interferometers fed by stabilized helium–neon lasers with a resolution of less than 0.1 nm each) fixed and moving the measuring object. The measuring object was placed on a corner mirror, which defines the coordinate system and provides the three orthogonal measuring mirrors for the interferometers of the NMM-1. The focal point of the confocal sensor was approximately located at the intersection of the interferometer beams and kept at this position permanently. Furthermore, the additional angle sensors

and the angle control of the corner mirror about the x - and y -axes of the NMM-1 reduce the angular deviations during movement and thus any first-order deviations that arise. The measuring object was a type ASG material measure with a radius r of $70\text{ }\mu\text{m}$ and a nominal step height of 200 nm and 18 grooves of the NPL Bento Box [75]. The control of the NMM-1 and the evaluation of the data were conducted with MATLAB.

Figure 1. Schematic of the sensor: 1, laser; 2, pin photodetector; 3, optical isolator; 4, focusing lens; 5, collimation lens; 6, fibre coupler; 7, collimation lens; 8, microscope objective; 9, measuring object.

3. Determination of the Workpiece Coordinate System

Aided by the camera system, 18 points just outside the grooves of the Siemens star and its centre were roughly located manually (cf. Figure 2, red circles). At each point, an axial probing was conducted by sampling the values of the NMM-1 interferometers and the signal of the photodetector V_{in} . Although the axial response of a confocal sensor on a plane surface is a sinc^2 -function [76], it is common to fit a Gaussian curve to the full axial response to determine the surface height with a high accuracy [63]. Thus, the surface height z_M was determined by Gaussian curve fitting to the full axial response. To these 18 surface points a plane has been fitted following the least squares method. This plane defines the xy -plane of the WCS. Furthermore, from each surface point, a probing was conducted in the direction of the roughly determined centre of the Siemens Star. The edge of the Siemens star was determined, searching the location of the minimum value of V_{in} , as

is shown in Figure 3. As it is problematic to measure high slopes with optical systems [77] and the measurement of edges might lead to great errors, such as batwing-effects [78], it is beneficial to use the unprocessed signal V_{in} instead of z_M to determine an edge's position. To all determined positions of the edges, or rather their orthographic projection on the xy -plane of the WCS, a circle was fitted to determine the centre of the Siemens star, which is the origin of the WCS as well. The determined positions of the edges are also shown as red crosses in Figure 2.

For the subsequent areal measurements of the Siemens star, lateral scans were conducted at different heights. Only in postprocessing was the axial response at each lateral point retrieved to determine z_M by Gaussian curve fitting. It is well known that a decreased amplitude of the axial response may lead to less reliable data points [79]. Thus, all measured points were rejected for which the amplitude of the fitted Gaussian curve was below a certain threshold. The threshold was 50% of the amplitude of the fitted Gaussian curve of the axial response on a plane area near the Siemens star. This filter already blocks edge effects, similar to batwings in coherence scanning interferometry [78] to some extent [80]. An axial range of $4\text{ }\mu\text{m}$ was covered by the lateral scans with a step between two adjacent heights of 50 nm . The lateral scans were centred around $z_{WCS} = 0$.

Figure 2. Whole Siemens star and the cut through $r = 60\text{ }\mu\text{m}$ (left) and its centre in more detail with the cut through $r = 9\text{ }\mu\text{m}$ (right). The cuts are shown in Figure 4. Shown also are the manually located positions just outside the grooves (red circles) and the determined edges (red crosses).

Figure 3. Lateral probing from just outside the Siemens star in the direction of its centre. Marked as a red cross is the determined location of the edge of the Siemens star.

Figure 4. Radial cuts at $r = 60\text{ }\mu\text{m}$ (left) and $r = 9\text{ }\mu\text{m}$ (right).

4. Radial Measurement and Evaluation of D_{LIM}

To begin with, D_{LIM} is determined following an radial measurement and evaluation of the amplitude. The amplitude a of each radial cut is determined by

$$a = \sqrt{X^2 + Y^2}, \quad (1)$$

where X and Y are determined by a Fourier series approximation with

$$X = \frac{1}{n} \cdot \sum_{i=1}^n z_{\text{WCS},i} \cdot \sin\left(2\pi \cdot \frac{18 \cdot i}{n}\right) \quad \text{and} \quad (2)$$

$$Y = \frac{1}{n} \cdot \sum_{i=1}^n z_{\text{WCS},i} \cdot \cos\left(2\pi \cdot \frac{18 \cdot i}{n}\right), \quad (3)$$

with n denoting the number of data points of a cut and $i = 1, \dots, n$. Furthermore, the phase angle ϕ is determined by

$$\phi = \text{atan2}(Y/X). \quad (4)$$

Figure 4 shows the radial cuts at $r = 60 \mu\text{m}$ and $r = 9 \mu\text{m}$. The sine fit is calculated by

$$z_i = a \cdot \sin\left(2\pi \cdot \frac{18 \cdot i}{n} + \phi\right). \quad (5)$$

In Figure 5, a and ϕ of each radial cut are shown over r . The amplitude, unaffected by the lateral resolution of the optical system, a_0 , is calculated as mean of the amplitudes for the three highest radii (dashed red line). The radius for which a falls to 50% of a_0 (dashed green line) is r_{LIM} . To determine r_{LIM} , the function $r(a)$ is calculated as linear polynomial with the data points, for which a is below 50% of a_0 for the first time (for a decreasing r) and its eight neighbour data points. The calculated function $r(a)$ is shown as dashed magenta line and is used to calculate r_{LIM} by

$$r_{\text{LIM}} = r(0.5 \cdot a_0), \quad (6)$$

which is $6.753 \mu\text{m}$, and thus $D_{\text{LIM}} = 2.36 \mu\text{m}$, calculated by

$$D_{\text{LIM}} = \frac{2\pi \cdot r_{\text{LIM}}}{18}. \quad (7)$$

Note the peak of a for $r \approx 2 \mu\text{m}$. According to [54], this might be an artefact of a misidentified target centre.

This procedure is used to determine r_{LIM} and D_{LIM} throughout the remainder of the paper. Nevertheless, it should be noted that this is already an alteration of the NPL Good Practice Guide, because the latter calculates a_0 just as the maximum value of a [53]. Nevertheless, as especially confocal systems tend to show an increased a just before the drop [53] (p. 42), we rather propose calculating a_0 for a r that is unaffected by the limited lateral resolution of the sensor.

Figure 5. a and ϕ over r . The dashed red line indicates the a unaffected by the lateral resolution of the optical system, a_0 , calculated as mean of the amplitudes for the three highest radii (red crosses), and the green dashed line is 50% of a_0 . The polynomial $r(a)$ is shown as magenta dashed line and r_{LIM} as dashed black line.

5. Measurement and Evaluation of D_{LIM} according to the NPL Good Practice Guide

In this section, D_{LIM} is evaluated according to the NPL Good Practice Guide. In the first part of this section, the evaluation is conducted with the areal measurement data of the complete star. In comparison, in the second part of this section, not only the evaluation but also the measurement is conducted according to the NPL Good Practice Guide. Thus, only two line scans are conducted instead of a complete radial measurement of the Siemens star.

5.1. Evaluation of the Areal Measurement according to the NPL Good Practice Guide

Following the NPL Good Practice Guide, two lines are taken from the radially measured data: one line through the middle of a groove, $z_{WCS,l}$, and one through the middle of the adjacent top level, $z_{WCS,h}$, as depicted in Figure 6. The phase angle to go through the middle was $(\phi + 90^\circ) / 18$, with the ϕ of the radial cut at $r = 60 \mu\text{m}$ calculated according to Equation (4). As shown in Figure 5, right, ϕ is very stable for the radii or rather the wavelengths $\lambda = 2\pi \cdot r / 18$ that are well over D_{LIM} , and therefore a different r might also have been chosen.

The evaluation of D_{LIM} is conducted with the difference of $z_{WCS,l}$ and $z_{WCS,h}$, Δz , as is depicted in Figure 7. a_0 is calculated as mean of Δz of the utmost radii, and the cut-off at each side is calculated with a polynomial regression (similar to the procedure described in Section 4). The distance between both cut-offs, $2r_{LIM}$, is $14.688 \mu\text{m}$, and therefore $D_{LIM} = 14.688 \mu\text{m} \cdot \pi / 18 = 2.56 \mu\text{m}$.

Figure 6. One line through the middle of a groove (black) and one through the middle of the adjacent top level (red).

Figure 7. Δz over r and the calculation of $2r_{LIM}$.

5.2. Measurement and Evaluation according to the NPL Good Practice Guide

The main intention of the NPL Good Practice Guide is to achieve a far shorter measurement time when only two line scans are conducted compared to the complete measurement of the Siemens star. Therefore, a line scan has been conducted through the middle of a groove and through the middle of the adjacent top level with a scanning length of 50 μm and a point distance of 5 nm each and the angle again determined using ϕ of the Fourier series of the radial measurement at $r = 60 \mu\text{m}$. Furthermore, to evaluate the effect of a misidentified target centre, several parallel line scans were conducted with a distance of 50 nm (in sum, 31 line scans both on the groove and on the adjacent top level). In Figure 8, the line scans on the top adjacent to the groove are shown. Also shown is the line scan going through the previously determined centre of the Siemens star (dashed black line). As is perceptible, this line scan does not go through the actual centre of the Siemens star. To determine the line scan going the closest through the actual centre, for each scan line, D_{LIM} is calculated using V_{in} instead of z_{WCS} , as V_{in} is not deteriorated by edge effects. The line scan with the smallest D_{LIM} is the one going the closest through the actual centre (dashed red line). The distance between the dashed red line and the dashed black line is 250 nm.

The novel centre point of the Siemens star, C_n , is determined as intersection point of the line scan with the smallest D_{LIM} in the groove and the line scan with the smallest D_{LIM} on the adjacent top level. For each line scan, r is calculated as signed distance to C_n and Δz is calculated with the nearest-neighbour point. As the point distance is by far smaller than D_{LIM} , the slight mismatch of a few nm is negligible. The determination of D_{LIM} necessitates the evaluation of the topographic data z_{WCS} ; therefore, in Figure 9, left, Δz over r is shown. It can be seen that there is noise on the data. In contrast, the Fourier series approximation for the radial evaluation (cf. Section 4) already incorporates a low-pass filter to remove the noise. Measurement noise is a separate characteristic of an optical instrument according to ISO 25178-600 [37]. Thus, it is removed with a mean value filter of length 100 ($\cong 500 \text{ nm}$) for the line scans. Although the effect of this filter on the determined D_{LIM} is rather small, as there are many data points contributing to the calculation of a_0 and the polynomial, it certainly facilitates choosing the right data points to calculate the polynomial. It is noteworthy that filtering is also applied for the evaluation of chirp measurement standards [81]. On the right side of the figure, the filtered data and the evaluation of $2r_{LIM}$, which is 12.698 μm , are shown. Therefore, $D_{LIM} = 2.22 \mu\text{m}$.

Figure 8. V_{in} and z_{WCS} for the line scans on the top adjacent to the groove. Shown in black is the line scan going through the previously determined centre of the Siemens star, and shown in red is the line scan going through C_n .

Figure 9. (Left): Δz calculated with the line scans going through C_n over r . (Right): Δz filtered and calculation of $2r_{LIM}$.

5.3. Effect of a Misidentified Target Centre

To quantify the effect of a misidentified target centre, D_{LIM} was calculated also with the adjacent lines of the ones going the closest through C_n . The results are shown in Table 1. In Table 2, the corresponding distance of the intersection point of the two scan lines to C_n is shown. Due to the sharp angle between the two scan lines (10°), a slight offset of one scan line results in a mismatch of the centre amplified by the factor of $1/\sin(10^\circ) \approx 5.76$. Therefore, although the offsets are only in a range of ± 100 nm, the distance between the intersection point of the two lines and C_n reaches more than one μm for a disadvantageous combination of the offsets, and the difference between the maximum ($2.64 \mu\text{m}$) and minimum ($1.94 \mu\text{m}$) value of D_{LIM} is therefore already $0.70 \mu\text{m}$. Taking the $2.22 \mu\text{m}$ as reference, the deviations are 19 % (maximum value) and 13 % (minimum value). Remarkably, a misidentified target centre does not necessarily result in an overestimation of D_{LIM} , but lower values might also be obtained. This is probably a result of the well-known edge effects observable with many optical systems. These findings strongly underline the necessity to modify the NPL Good Practice Guide to include a thorough determination of the Siemens star's centre before the actual determination of D_{LIM} .

Table 1. D_{LIM} in μm calculated with the lines having an offset to the ones going the closest through C_n .

		offset 1 in μm				
		−0.100	−0.050	0.000	0.050	0.100
offset 2 in μm	−0.100	2.18	2.20	2.24	2.39	2.63
	−0.050	2.15	2.18	2.31	2.39	2.64
	0.000	2.15	2.18	2.22	2.38	2.62
	0.050	2.03	2.13	2.18	2.20	2.57
	0.100	1.94	2.00	2.14	2.16	2.37

Table 2. Distance to C_n in μm .

		offset 1 in μm				
		−0.100	−0.050	0.000	0.050	0.100
offset 2 in μm	−0.100	0.101	0.293	0.569	0.851	1.135
	−0.050	0.294	0.050	0.285	0.567	0.851
	0.000	0.570	0.285	0	0.285	0.570
	0.050	0.852	0.567	0.285	0.05	0.294
	0.100	1.135	0.851	0.569	0.293	0.101

5.4. Modified Good Practice Guide

Based on the presented findings, we propose the following summarized procedure to determine the D_{LIM} of an optical point sensor using a Siemens star:

1. Roughly determine the centre of the Siemens star.
2. Conduct a radial measurement on a radius where the structures are well resolvable.
3. Calculate the phase of the structures by a Fourier series approximation of this radial measurement.

4. Conduct several parallel line scans with a small offset in the direction of the phase of the structures in a groove and on an adjacent top level.
5. Determine the line scans going through the centre of the Siemens star by finding, for the scans both in a groove and on an adjacent top level, the one with the smallest D_{LIM} when evaluating the unprocessed raw signal, for instance, of the photodetector, not the topographic data.
6. Calculate D_{LIM} with the topographic data of the two line scans that go through the centre of the Siemens star. An appropriate low-pass filter should be applied to reduce the noise level of the data.

6. Summary

In this article, the determination of D_{LIM} of an optical point sensor, or a confocal sensor to be more specific, with a type ASG material measure, also called a (topographic) Siemens star, has been shown. It has been determined following the radial approach, as proposed by ISO 25178-70 [48] and following the NPL Good Practice Guide [53]. For the latter, only two lines taken at a groove and the adjacent top level are measured and evaluated, leading to a much faster evaluation of D_{LIM} . Nonetheless, as has been shown, only slight lateral errors of the scan lines lead to significant errors of the intersection point of the scan lines and the actual centre of the Siemens star and therefore of the determined D_{LIM} . Errors of up to 19 % of the determined D_{LIM} have been shown for lateral errors of the scan lines of ± 100 nm. Remarkably, a misidentified target centre does not necessarily result in an overestimation of D_{LIM} , but lower values might also be obtained. Therefore, a modified Good Practice Guide has been proposed to determine D_{LIM} more accurately. It includes a thorough determination of the centre of the Siemens star. While the measurement and evaluation effort is increased slightly compared to the NPL Good Practice Guide, it is still much faster than a complete radial measurement and evaluation.

7. Conclusions

The application of the presented procedure necessitates access to the raw data of the measuring instrument to accurately determine the centre of the Siemens star. These data are seldom accessible in practice, but there are still some general conclusions that might be drawn from the presented findings. The determination of the seven metrological characteristics of ISO 25178-600, including D_{LIM} , might be used to estimate the measurement uncertainty for a surface topography measurement in a simple manner following the metrological characteristics framework [36]. This framework assumes to always overestimate the measurement uncertainty by deliberately counting some influence quantities more than once. Nevertheless, as has been shown within this publication, an inaccurate positioner might lead to a significant underestimation of D_{LIM} , which in turn might lead to an underestimation of the uncertainty estimated following the metrological characteristics framework. Thus, an accurate lateral positioner is a prerequisite for the determination of D_{LIM} with a Siemens star and a point sensor. If the lateral positioner has larger errors, it is preferable to determine D_{LIM} with other measures such as chirped calibration standards or rectangular gratings. On the downside, it might also be possible to increase the angle between both scan lines and therefore to not measure the adjacent but a slightly further top level. This reduces the effect an inaccurate line scan has on the discrepancy of the intersection point between both scan lines and the actual centre point of the Siemens star.

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