Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

EURAMET Supplementary Comparison
Measurement of groove depth standards
in the range 1 µm up to 1 mm
EURAMET.L-S26
EURAMET project 1407
Final Report

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1 Document control

Version Draft A.2	Issued on 4th September 2019
Version Draft B	Issued on 27th February 2020
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2 Abstract

A comparison measurement between 10 national metrology institutes on two types of depth setting standards was conducted using mostly tactile but also two optical instruments for measurement. Three etched silicon standards with depths of 5, 20 and 50 µm and one diamond turned nickel coated copper standard with depths of 200, 600 and 900 µm were measured. The cross section of the grooves was trapezoidal. Most of the participants confirmed their CMC entries. Since many measurements had to be made, contamination of the standards and heavy wear on the standards were also observed after the comparison was completed. The wear consists of indentation marks from stylus instruments on both types of standards and as many as 70 scratch marks on the nickel coated copper artefact used. This indicates that the contact pressure of the tactile measuring devices used by some partners was too high. This can be caused by a too high probing force or a too small probing tip radius. Thus, for future comparisons the actual probing force and actual tip radius need to be measured during the comparison by the participants to assure that the recommended values (2 µm tip radius and 0.7 mN probing force) are not exceeded. The recently published German standard DIN 32567-3 "Determination of the influence of materials on the optical and tactile dimensional metrology – Part 3: Derivation of correction values for tactile measuring devices" [1–3] describes methods to do both.

3 Introduction

The metrological equivalence of national measurement standards and of calibration certificates issued by national metrology institutes is established by a set of key and supplementary comparisons chosen and organized by the Consultative Committees of the CIPM or by the regional metrology organizations in collaboration with the Consultative Committees.

At its meeting in July 2016, the EURAMET Technical Committee for Length, TC-L, decided upon a supplementary comparison of groove depth standards in the range 1 µm up to 1 mm, named EURAMET.L-S26, with PTB as the pilot laboratory. The comparison was registered in July 2016, artefact circulation started in September 2016 and was completed in October 2018.

4 Organization

4.1 Participants

Table 1. List of participant laboratories and their contacts.

Laboratory Code	Contact person, Laboratory	Phone, Fax, email
PTB	Uwe Brand PTB Bundesallee 100, 38116 Braunschweig (Germany)	Tel. +49 531 592 5111 Fax +49 531 592 69 5111 e-mail: Uwe.Brand@ptb.de
BEV	Michael Matus Bundesamt für Eich- und Vermessungswesen (BEV), Arltgasse 35, 1160 Wien (Austria)	Tel. +43 1 21 110 826540 Fax +43 1 21 110 826000 e-mail: michael.matus@bev.gv.at
CEM	Laura Carcedo Surface Quality Laboratory. Length Area CENTRO ESPAÑOL DE METROLOGÍA Alfar, 2 - Tres Cantos 28760 Madrid (Spain)	Tel. +34 918 074 716 Fax +34 918 074 807 e-mail: lcarcedo@cem.minetur.es
GUM	Lukasz Slusarski and Dariusz Czułek GUM Samodzielne Laboratorium Długości (Length Laboratory), ul. Elektoralna 2, 00-139 Warszawa (POLAND)	Tel. +48 22 581 93 18 e-mail: l.slusarski@gum.gov.pl
INRIM	Gian Bartolo Picotto Istituto Nazionale di Ricerca Metrologica (INRIM) Strada delle Cacce 91, 10135 Torino (Italy)	Tel. +39 011 39 19 969 e-mail: g.picotto@inrim.it
VTT	Antti Lassila and Ville Heikkinen MIKES Metrology VTT Technical Research Centre of Finland Ltd Tekniikantie 1, FI-02150 Espoo (Finland)	Tel. +358 40 514 8658 Fax +358 20 722 7001 e-mail: antti.lassila@vtt.fi
NMISA	Faith Hungwe NMISA, CSIR Campus, Meiring Naude road 0001 Pretoria (South Africa)	Tel. +27 82 78 72 452 Fax +27 82 78 72 452 e-mail: fhungwe@nmisa.org
RISE	Sten Bergstrand and Olena Flys RISE Research Institutes of Sweden AB P.O. Box 857,50115 Borås (Sweden)	Tel. +46 10 516 57 73 Fax +46 10 516 54 92 e-mail: olena.flys@ri.se sten.bergstrand@ri.se
UME	Murat Aksulu TUBİTAK UME, Boyutsal Laboratuvarı Sorumlusu TUBİTAK Gebze Yerleşkesi Barış Mah. Dr.Zeki Acar Cad. No:1 41470 Gebze / KOCAELİ (Turkey)	Tel. +90 262 679 50 00 ext. 5303/5310/5308 Fax +90 262 679 50 01 murat.aksulu@tubitak.gov.tr
VNIIMS	Vladimir Kosteev and Elena Milovanova VNIIMS Russian Research Institute for Metrological Service 46, Ozernaya st., Moscow 119361 (Russia)	Tel. +7 495 781 4506 e-mail: vkosteev@vniims.ru

4.2 Schedule

The participating laboratories were asked to specify a preferred timetable slot for their own measurements of the depth setting standards. The timetable given in table 2 has been drawn up taking these preferences into account. Each laboratory had six weeks that include customs clearance, calibration and transportation to the following participant. With its confirmation to participate, each laboratory was obliged to perform the measurements in the allocated period and to allow enough time in advance for transportation so that the following participant receives them in time. If a laboratory had technical problems to perform the measurements or customs clearance took too long, the laboratory had to contact the pilot laboratory as soon as possible and, according to whatever it decides, it could eventually be obliged to send the standards directly to the next participant before completing the measurements or even without doing any measurements.

Table 2. Schedule of the comparison.

RMO	Laboratory	No.	Original schedule	Date of measurement	Results received
EURAMET	PTB	1	2016-09-01 – 2016-10-01	September 2016	-
COOMET	VNIIMS	2	2016-10-01 – 2016-12-01	October 2016	2017-04-10
AFRIMETS	NMISA	3	2016-12-01 – 2017-02-01	December 2016	2017-02-02
EURAMET	UME	4	2017-02-01 – 2017-04-01	April 2016	2017-06-23
Pilot	PTB		2017-04-01 – 2017-06-01	-	-
EURAMET	VTT	5	2017-06-01 2017-07-15	June 2017	2017-08-24
EURAMET	BEV	6	2017-07-15 – 2017-09-01	July 2017	2017-07-26
EURAMET	INRIM	7	2017-09-01 – 2017-10-15	September 2017	2018-02-28
EURAMET	GUM	8	2017-10-15 – 2017-12-01	November 2017	2018-01-12
EURAMET	CEM	9	2017-12-01 – 2018-02-01	January 2018	2018-04-27
Pilot	PTB		2018-02-01 – 2018-02-15	-	-
EURAMET	RISE	10	2018-02-15 – 2018-04-01	March 2018	2018-05-09
EURAMET	BEV	11	2018-04-01 – 2018-05-15	- [1]	-
EURAMET	VTT	12	2018-05-15 – 2018-07-01	2018-08-03 [2]	2018-08-08
Pilot	PTB	13	2018-07-01	2018-10-22	2018-10-29

[1] Cleaning of EN19_7 [2] Second measurement

5 Artefacts

5.1 Description of artefacts

Four artefacts were used, three SiMetrics (SN 497, SN 499 and SN 502) and one PTB depth setting standard (EN19_7). The depth setting standards contain v-shaped grooves of type A1 according to the standard ISO 5436-1:2000.

The coefficients of thermal expansion given in the following table are obtained by the manufacturers and should be used as such.

Table 3. List of artefacts.

Identification	Nominal depth	Expansion coefficient /10^{-6} K^{-1}	Manufacturer
EN 19_7	200 µm, 600 µm, 900 µm	16.6 ± 0.5 [4]	PTB
SN 497	5 µm	2.56 ± 0.5 [5]	SiMetrics
SN 499	20 µm	2.56 ± 0.5 [5]	SiMetrics
SN 502	50 µm	2.56 ± 0.5 [5]	SiMetrics

5.2 Gradient of groove depth

Three profile sections (a, b and c) at distances of 0.5 mm for the standards SN 497, SN 499 and SN502 and at distances of 1 mm on the standard EN19_7 had to be measured three times (see 6.1). From these measurements an average groove depth was calculated. To estimate the constancy of the groove depth at different positions, the groove depths measured by PTB were plotted in Fig. 1-6 and the spread of the groove depths at different positions was determined. The spread of the averaged groove depths varies between 12 nm (20 µm and 200 µm groove) and 22 nm (600 µm groove) and only for the 50 µm groove a clear gradient of the groove depth of 66 nm/mm could be observed.

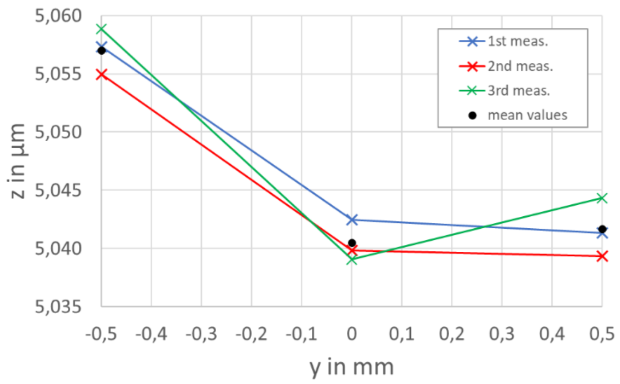

Figure 1 Measured groove depths at different measurement positions (section a: y = -0.5 mm, section b: y = 0 and section c: y = 0.5 mm) on the standard SN 497.

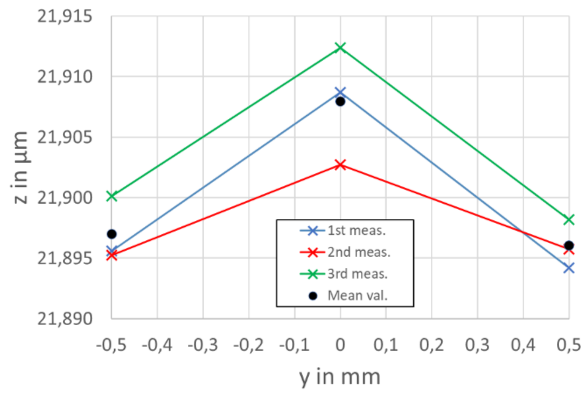

Figure 2 Measured groove depths at different measurement positions (section a: y = -0.5 mm, section b: y = 0 and section c: y = 0.5 mm) on the standard SN 499.

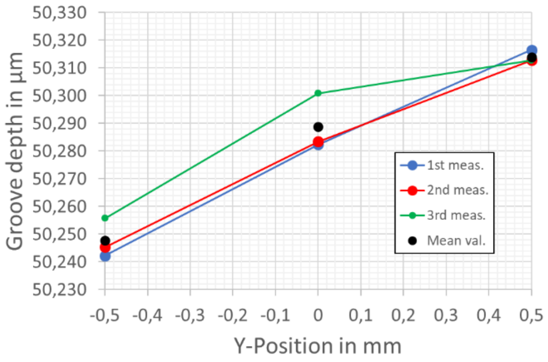

Figure 3 Measured groove depths at different measurement positions (section a: y = -0.5 mm, section b: y = 0 and section c: y = 0.5 mm) on the standard SN 502.

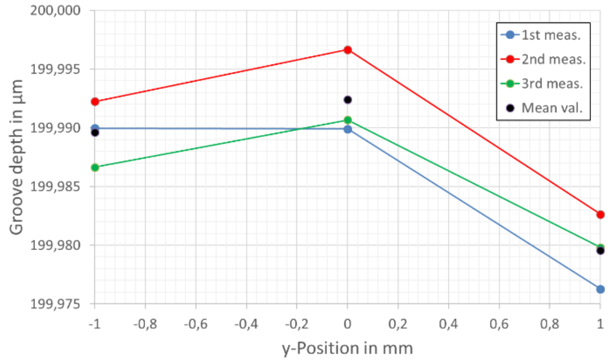

Figure 4 Measured groove depths at different measurement positions (section a: y = -1 mm, section b: y = 0 and section c: y = 1 mm) for the 200 µm groove on the standard EN19_7.

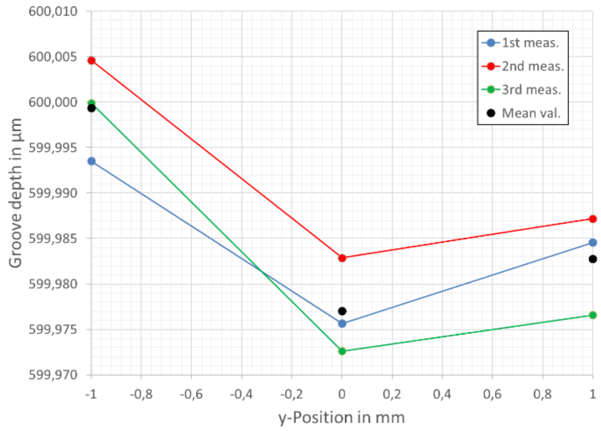

Figure 5 Measured groove depths at different measurement positions (section a: y = -1 mm, section b: y = 0 and section c: y = 1 mm) for the 600 µm groove on the standard EN19_7.

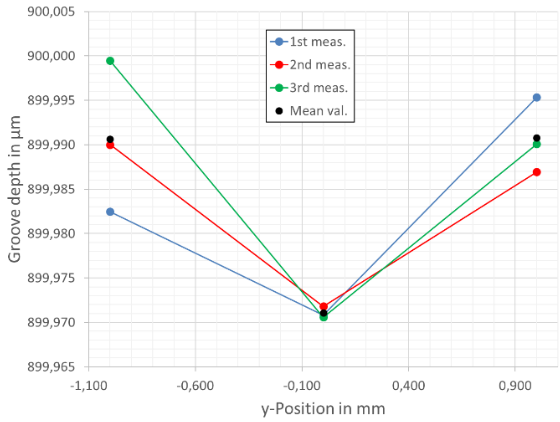

Figure 6 Measured groove depths at different measurement positions (section a: y = -1 mm, section b: y = 0 and section c: y = 1 mm) for the 900 µm groove on the standard EN19_7.

5.3 Condition of artefacts at start/end of comparison

The condition of the artefact's measurement surfaces was measured by optical microscopy before start of the comparison (see Figures 7, 9, 11, 13, 15 and 17) and after the comparison (see Figures 8,10,12,14,16 and 18). Although the participants were asked to check the condition of the artefact surfaces prior to and after measurements, only the participants who measured optically, carefully investigated the condition of the artefacts and reported contamination (see Figure 19 to Figure 22) and scratching (Figure 23) of the artefacts.

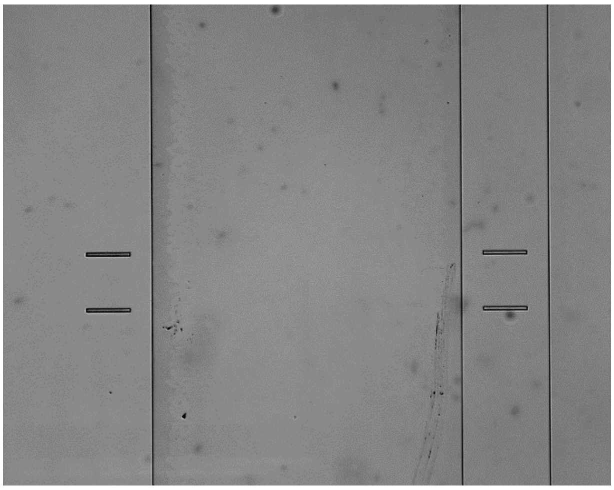

Figure 7 Microscope image of 5 µm groove before comparison measurements.

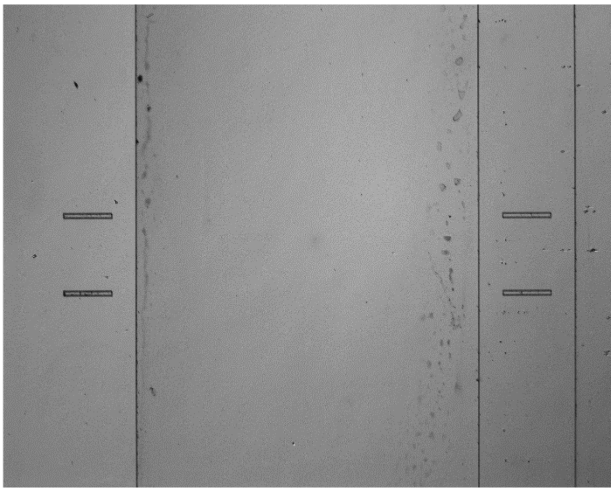

Figure 8 Microscope image of 5 µm groove after comparison measurements. The spots on the right side are marks, probably caused by diamond stylus.

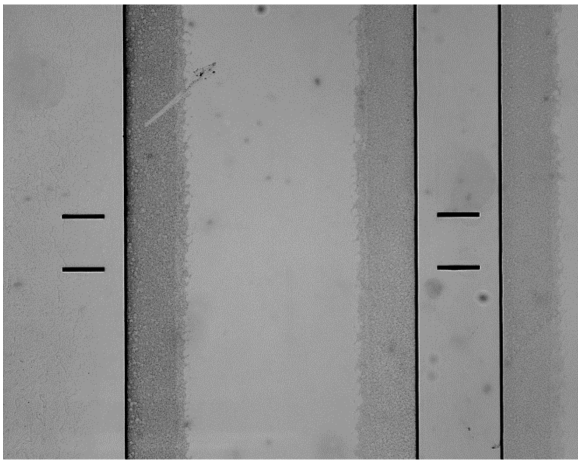

Figure 9 Microscope image of 20 µm groove before comparison measurements.

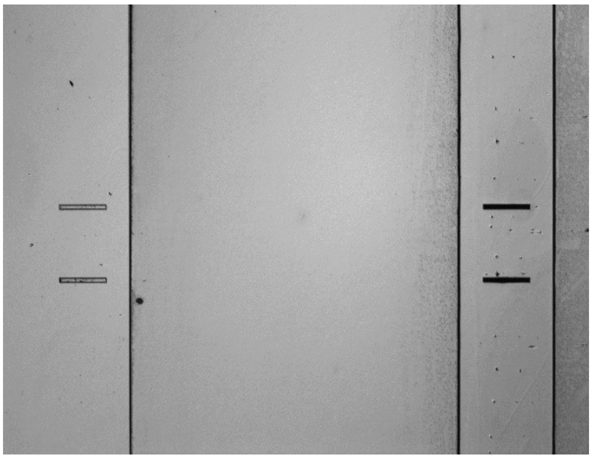

Figure 10 Microscope image of 20 µm groove after comparison measurements. The spots on the right side are marks, probably caused by diamond stylus.

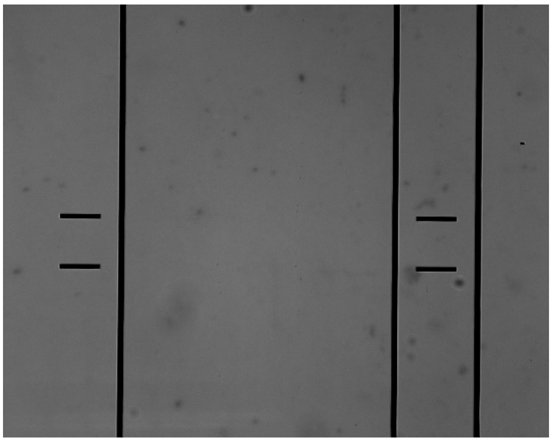

Figure 11 Microscope image of 50 µm groove before comparison measurements.

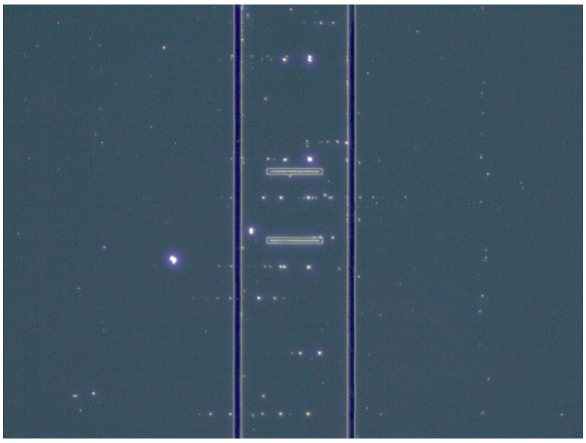

Figure 12 Microscope image of region "A" of 50 µm groove after comparison measurements. The white spots are marks, probably caused by a stylus instrument.

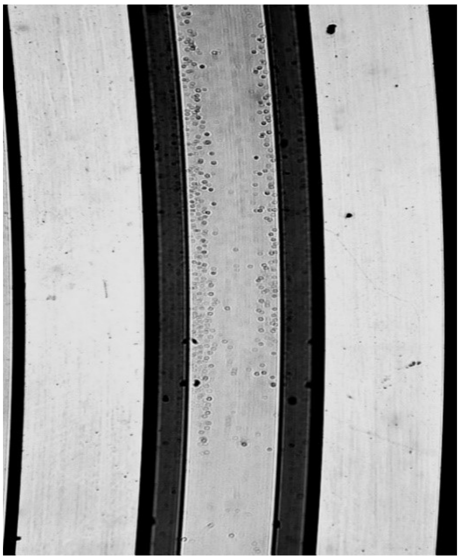

Figure 13 Microscope image of 200 µm groove before comparison measurements

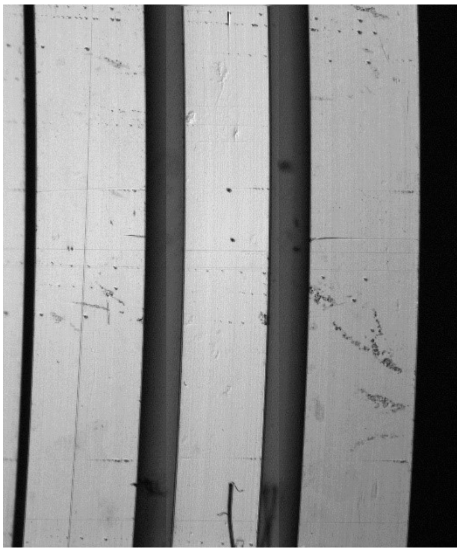

Figure 14 Microscope image of 200 µm groove after comparison measurements

Figure 15 Microscope image of 600 µm groove before comparison measurements

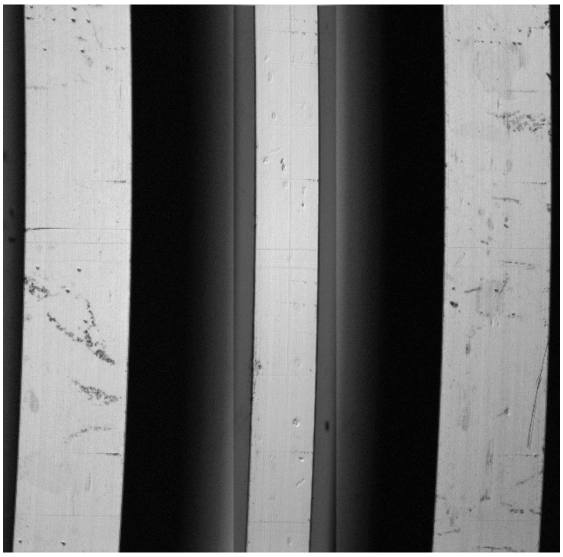

Figure 16 Microscope image of 600 µm groove after comparison measurements

Figure 17 Microscope image of 900 µm groove before comparison measurements

Figure 18 Microscope image of 900 µm groove after comparison measurements

The artefacts were not cleaned prior to the measurements. They were new and not used at the start of the comparison. No scratches and only a few contamination particles could be observed on the surfaces (see Fig. 7, 9, 11, 13, 15 and 17). During the comparison a contamination, mainly of the artefact EN19_7 containing the deeper grooves, could be observed (see Figure 19 and Figure 21)

Since the contamination of the artefact could cause considerable measurement deviations, it was decided to clean the artefact at the end of the comparison and to repeat the optical measurements. BEV cleaned the samples and most of the contamination could be removed (see Figure 22). The cleaning procedure is described in Appendix D.

Unfortunately, due to technical problems BEV was not able to measure again, but VTT measured all artefacts again. Thus, VTT's second measurement was included in the comparison. The change in VTT's measurement results is shown in Figure 20.

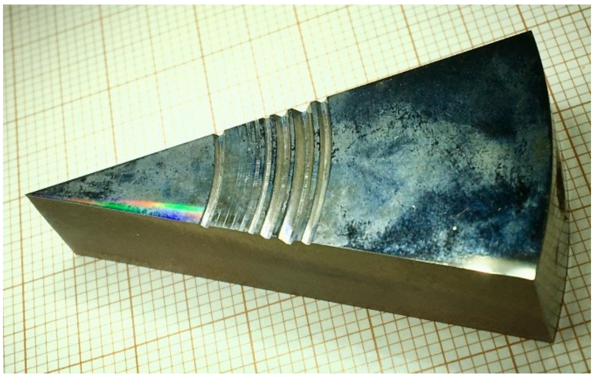

Figure 19 Contaminated artefact EN19_7 containing the three deeper grooves after all partners performed their measurements.

It can be concluded that the deviation of VTT's measurements from the reference values were significantly reduced only for the 200 µm groove. Before cleaning a deviation of 62 nm and after cleaning a deviation of only -25 nm was observed at a stated expanded uncertainty of VTT for this groove depth of 58 nm.

Thus, cleaning led to a maximum change in measured groove depth of -87 nm.

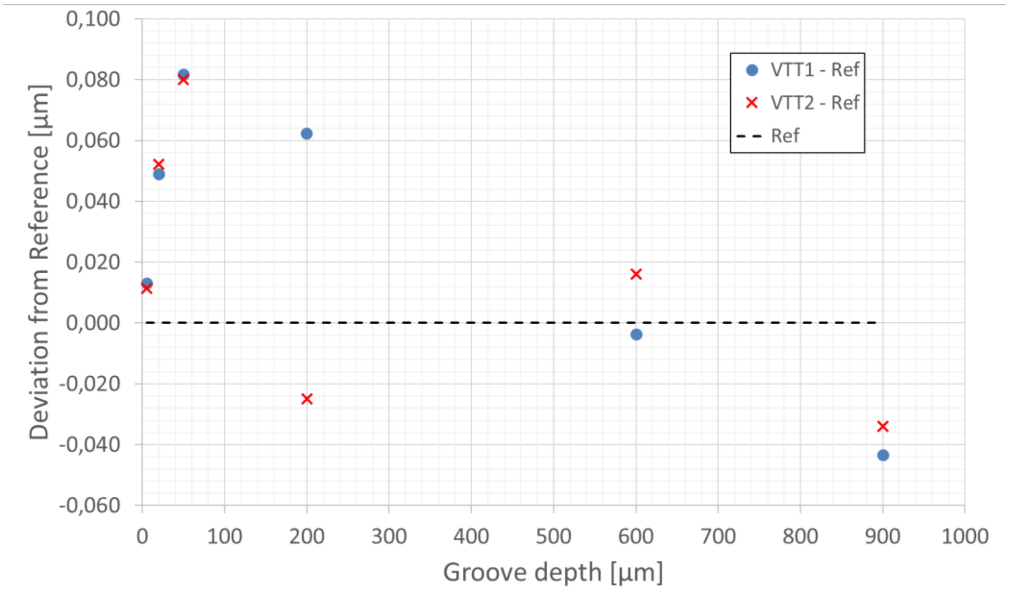

Figure 20 Deviation of VTT's first measurement (blue) and second measurement (red) after cleaning of the artefact EN19_7 with the three deepest grooves.

As expected, the three smaller grooves depths stay constant in depth, while the three deeper groove depths changed after cleaning (see Figure 20). The deviation from the reference value decreased for the 200 µm and 900 µm grooves, while the deviation of the 600 µm groove slightly increased.

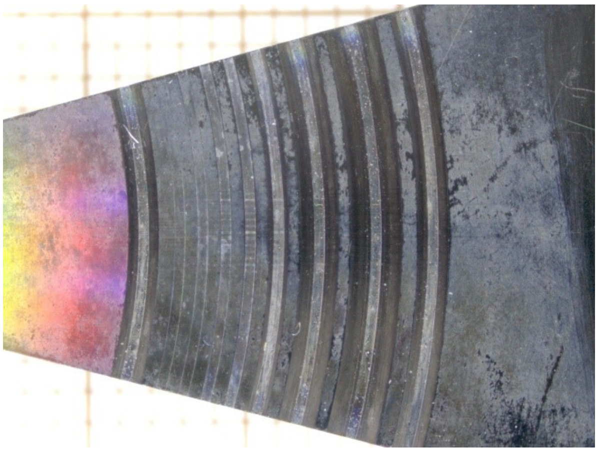

Figure 21 Contamination of artefact EN19_7 containing the three deeper grooves.

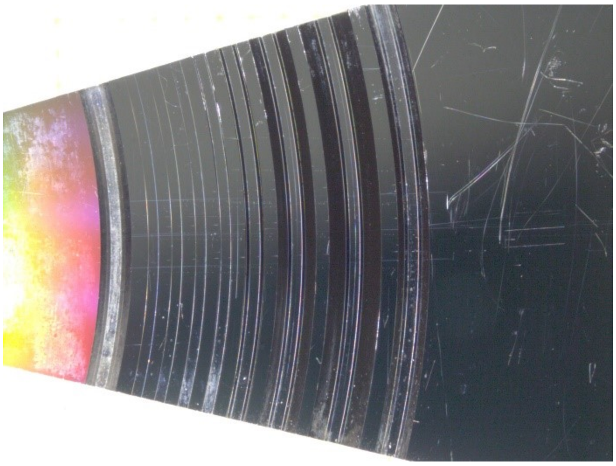

Figure 22 Condition of artefact EN19_7 after cleaning.

Beyond contamination of the artefacts, scratching seems to be a major problem for most of the tactile instruments. Figure 23 shows a microscope image of artefact EN19_7 after all partners had taken their measurements. As many as 70 scratching marks can be counted in Figure 23.

Figure 23 Microscope DIC image of artefact EN19_7 showing the huge number of scratches produced by tactile measurements.

Thus, most of the participants who measured with a stylus instrument used too high probing forces which led to a scratching of the Nickel surface of artefact EN19_7. The surface of the Silicon artefacts was also investigated for scratching tracks, but on these much harder surfaces the tracks look different. There are no continuous scratch marks to be seen, but individual holes to be recognized (see Figure 24 - **Figure 27**).

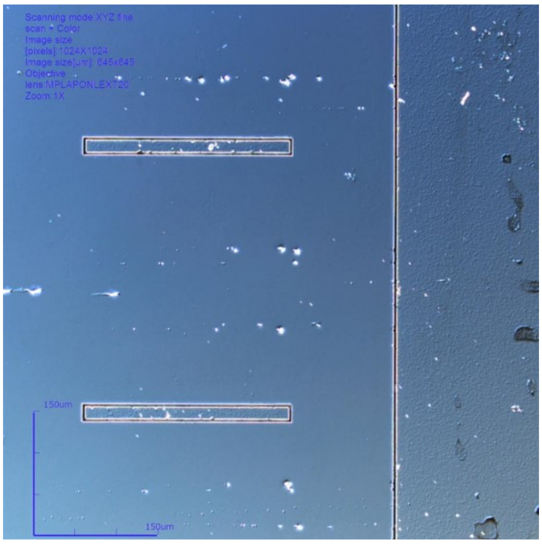

Figure 24 Microscope DIC image of artefact SN497 in the range of the left markers showing several defects on the surface resulting from tactile measurements.

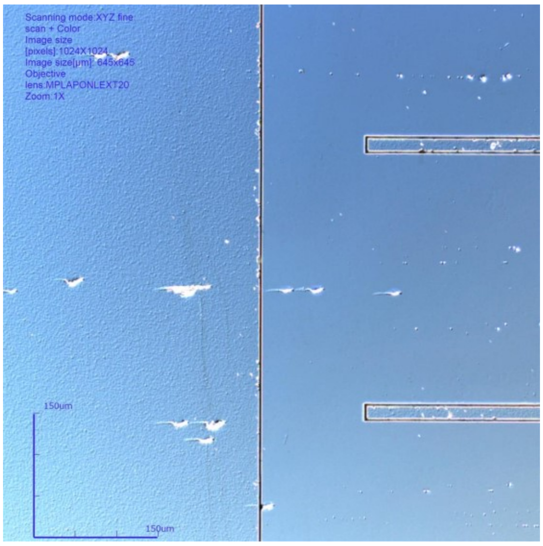

Figure 25 Microscope DIC image of artefact SN497 in the range of the right markers showing several defects on the surface resulting from tactile measurements.

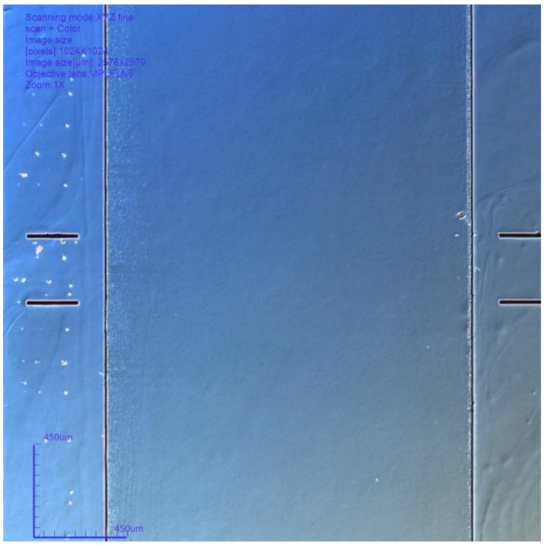

Figure 26 Microscope DIC image of artefact SN499 showing several defects on the surface resulting from tactile measurements.

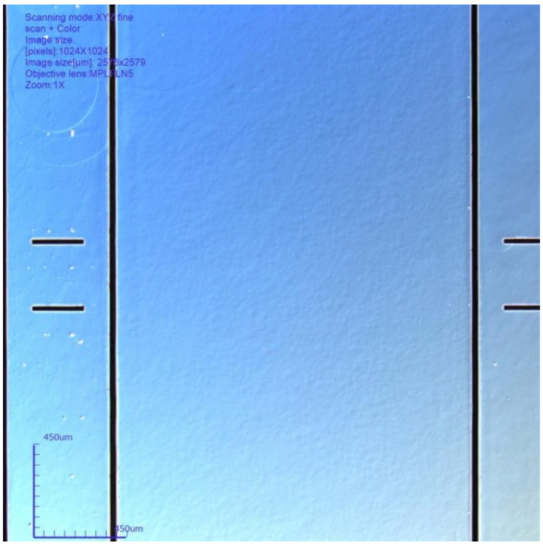

Figure 27 Microscope DIC image of artefact SN502 showing several defects on the surface resulting from tactile measurements.

6 Measuring instructions

6.1 Measurands

The depth setting standards were measured based on the standard procedure that the laboratory regularly uses for this calibration service for its customers.

6.1.1 PTB depth setting standard EN19_7

The PTB 900 µm depth setting standard contains seven grooves and two alignment grooves with a depth of 450 µm (see Figure 28 and Figure 29). For instruments with a z-measurement range of only 1 mm the alignment grooves allow to align the zero value in z-direction by probing in one of the two alignment grooves.

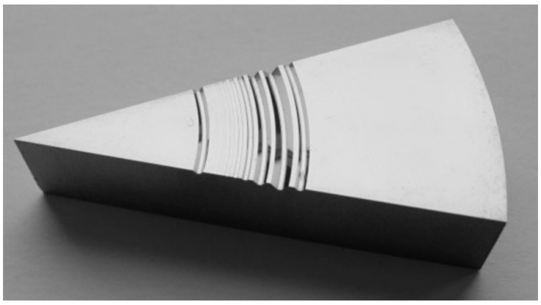

Figure 28 Photo of the 900 µm PTB depth setting standard EN19_7

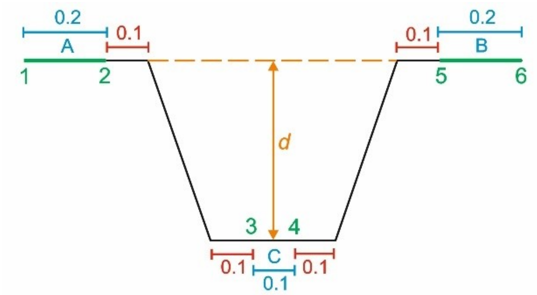

Figure 29 Evaluation of the groove depth *d* according to ISO 5436-1 (dimensions in mm)

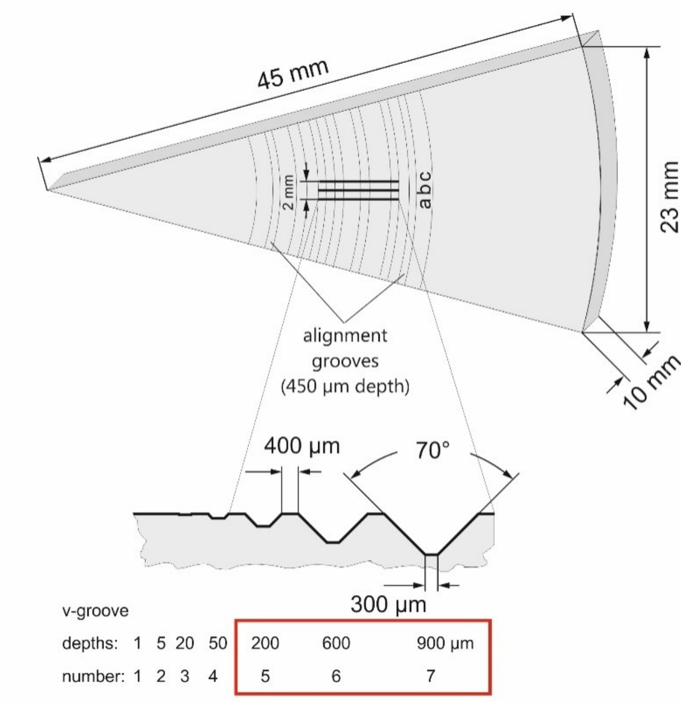

Figure 30 Depiction of the three profiles (a, b, c) to be measured on the 900 µm PTB standard and the location of the grooves on the standard

Only the depths of the three grooves with the nominal depths of 200 µm, 600 µm and 900 µm had to be measured.
Three parallel profiles ("a, b, c" see Figure 30) in the middle of the standard separated by a distance of 1 mm were measured. This procedure had to be repeated two times in order to obtain nine profiles. The measurand was the groove depth d which had to be determined for each profile according to ISO 5436-1 [6] (see Figure 30) but with a fixed groove width of 300 µm. Thus, for tilt correction the two profile sections between the marks 1 and 2 ("A") and between the marks 5 and 6 ("B") should have a distance from the upper groove edges of 0.1 mm. After tilt correction the groove depth *d* has to be determined as the mean value of the profile section "C" between the marks 3 and 4. This profile section should have a length of 0.1 mm.
The arithmetic mean of all nine groove depths was the measurand to be reported.

The ASCII data of the nine profiles measured for each groove had to be attached to the final report and the file names had to be listed in the report form.

6.1.2 SiMetrics depth setting standards

The SiMetrics depth setting standards consist of a 50 mm x 50 mm glass plate on which the depth setting standard silicon chips are bonded (see Figure 31).

Three parallel profiles ("a, b, c" see Figure 33) separated by a distance of 0.5 mm were measured. This procedure had to be repeated two times in order to obtain nine profiles. The measurand is the groove depth d which has to be determined for each profile according to ISO 5436-1 [6] (see Figure 32). For tilt correction the two profile sections between the marks 1 and 2 ("A") and between the marks 5 and 6 ("B") should have a distance from the upper groove edges of 0.1 mm. After tilt correction the groove depth d has to be determined as the mean value of the profile section between the marks 3 and 4. This profile section "C" has a width of one third of the groove width w. The following groove widths w should be used:

Table 4. List of groove widths for the evaluation of the groove depth.

Depth setting standard	nominal groove depth µm	groove width w / mm	*length of "C"* $w/3$ mm
SN 497	5	1.772	0.591
SN 499	20	1.749	0.583
SN 502	50	1.708	0.569
EN19_7	200, 600, 900	0.300	0.100

The arithmetic mean of the three groove depths for each section ("a, b, c") is the measurand to be reported.
The ASCII data of the nine profiles measured for each groove had to be attached to the final report and the file names had to be listed in the report form.

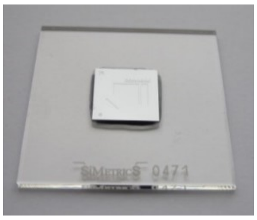

Figure 31 The SiMetrics depth setting standards consist of a glass plate with the bonded silicon chip on it and an engraved serial number

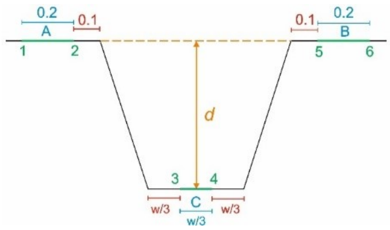

Figure 32 Evaluation of the groove depth *d* for the SiMetrics grooves according to ISO 5436-1 (dimensions in mm)

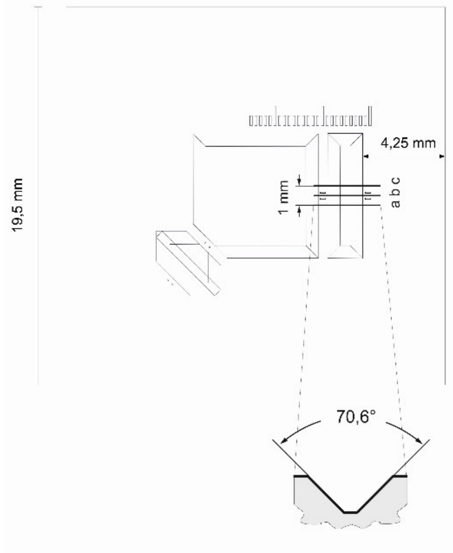

Figure 33 Depiction of the SiMetrics depth setting standards and the location of three profiles (a, b, c) to be measured

7 Results

7.1 Measurement uncertainties

The uncertainty of measurement should be estimated according to the ISO *Guide to the Expression of Uncertainty in Measurement*. The participating laboratories are encouraged to use all known influence parameters for the method applied by them. The groove depth *d* of the standards is expressed as a function of the input quantities x_i

$$d = f(x_i) \quad (1)$$

The combined standard uncertainty $u_c(d)$ is the square sum of the standard uncertainties of the input quantities $u(x_i)$, each weighted by a sensitivity coefficient c_i

$$u_c^2(h) = \sum_i c_i^2 u^2(x_i) \text{ with } c_i = \frac{\partial h}{\partial x_i} \quad (2)$$

Since the MRA requires that participants submit results supported by a full uncertainty calculation, the participants were requested to report their measurement uncertainty budget in a table (see appendix C) whose format corresponds with the scheme below:

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(h)$	Degrees of freedom v_i

For the type of probability distribution please use: N = normal; R = rectangular; T = triangular; U = U-shaped.

Alternatively, participants were asked to simply submit an overall uncertainty value. Ideally, for range-based CMCs, the participant could submit both an uncertainty expression plus a value for each measurand.

As well as stating a measurement uncertainty for each measurand, the participant should also state the calculated or assumed degrees of freedom.

7.2 Changes to results after Draft A.1

VNIIMS uncertainty data had to be changed. In the sensor nonlinearity instead of “mm” the unit “µm” was used leading to too large uncertainty contributions. This was changed in the version Draft A.2.

GUM had reported expanded uncertainties instead of standard uncertainties. This led to only small changes of the reference value. This was changed in the version Draft B.

8 Analysis

8.1 Calculation of the KCRV

The weighted mean was the KCRV for each measurand. Before the weights could be assigned and the mean taken, it was necessary to exclude any clear outliers from the analysis. The analysis for each measurand proceeds as follows:

We assume the total number of participants submitting a result is I.

Each laboratory reports a measured value, x_i, and its associated standard uncertainty $u(x_i)$.

<ITERATION START> Compute the normalised weight, w_i, for the result x_i is given by:

$$w_i = C \cdot \frac{1}{[u(x_i)]^2} \tag{1}$$

where the normalising factor, C, is given by:

$$C = \frac{1}{\sum_{i=1}^{I}\left(\frac{1}{u(x_i)}\right)^2} \tag{2}$$

Then calculate the weighted mean, $\bar{x}_w$, which is given by:

$$\bar{x}_w = \sum_{i=1}^{I} w_i \cdot x_i \tag{3}$$

The uncertainty of the weighted mean is calculated by:

$$u(\bar{x}_w) = \sqrt{\frac{1}{\sum_{i=1}^{I}\left(\frac{1}{u(x_i)}\right)^2}} = \sqrt{C} \tag{4}$$

After deriving the weighted mean and its associated standard uncertainty, the deviation of each laboratory’s result from the weighted mean is determined simply as $x_i - \bar{x}_w$. The uncertainty of this deviation is calculated as a combination of the uncertainties of the result, $u(x_i)$, and the uncertainty of the weighted mean $u(\bar{x}_w)$. The uncertainty of the deviation from the weighted mean is given by equation (5), which includes a minus sign to take into account the correlation between the two uncertainties (it would be a plus sign if dealing with uncorrelated uncertainties, such as when comparing data from two separate laboratories).

$$u(x_i - \bar{x}_w) = \sqrt{[u(x_i)]^2 - [u(\bar{x}_w)]^2} \quad (5)$$

For the determination of the key comparison reference value KCRV, statistical consistency of the results contributing to the KCRV is required. A check for statistical consistency of the results with their associated uncertainties can be made by calculating the E_n value for each laboratory's result, where E_n is defined as the ratio of the deviation from the weighted mean, divided by the expanded uncertainty of this deviation:

$$E_n = \frac{x_i - \bar{x}_w}{2\sqrt{[u(x_i)]^2 - [u(\bar{x}_w)]^2}} \quad (6)$$

The results are examined and any result for which $|E_n| > 1$ is considered as an inconsistent result. Identify the result with the largest $|E_n|$, go back to <ITERATION START> and repeat the analysis, but excluding this result from contributing to the weighted mean – *i.e.* they have a weighting of zero. Because inconsistent results are no longer correlated with the weighted mean, when calculating their deviation from the weighted mean, and when calculating their E_n value, a positive sign is used in equation (5) and consequently in the denominator of equation (6).

This process is iterated until there are no inconsistent results contributing to the weighted mean. After reaching consistency, the calculated weighted mean is the KCRV (see Table 5 -Table 10).

Figure 34 - Figure 39 show the measured depth values and expanded uncertainties in comparison to the weighted mean (red lines) and their uncertainties (red dotted lines).

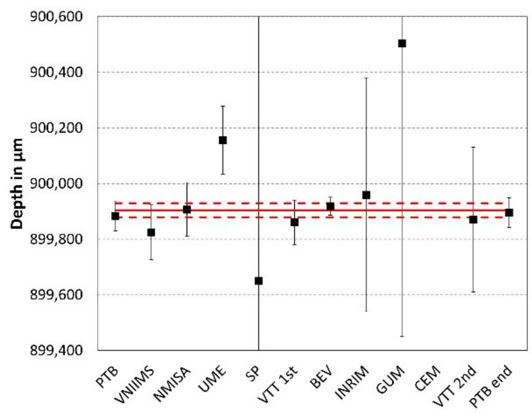

Figure 34 Measured depth values of the participants for the 900 µm groove (red line: KCRV, dotted red lines: expanded uncertainty of KCRV).

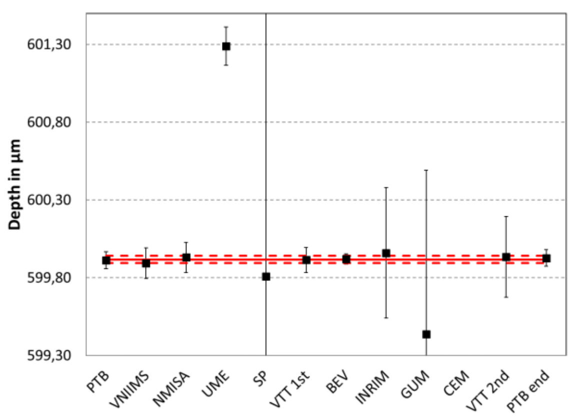

Figure 35 Measured depth values of the participants for the 600 µm groove (red line: KCRV, dotted red lines: expanded uncertainty of KCRV).

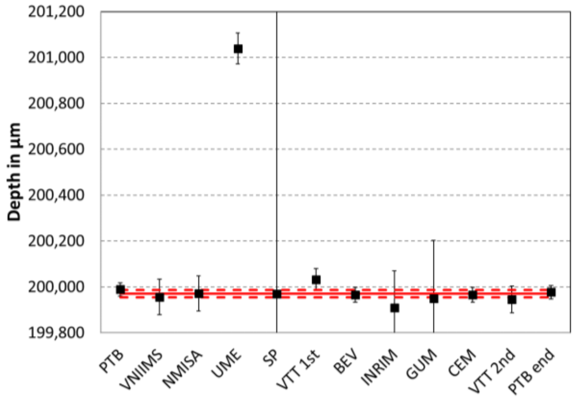

Figure 36 Measured depth values of the participants for the 200 µm groove (red line: KCRV, dotted red lines: expanded uncertainty of KCRV).

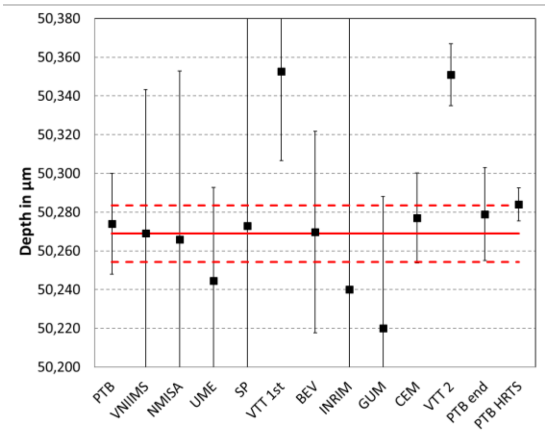

Figure 37 Measured depth values of the participants for the 50 µm groove (red line: KCRV, dotted red lines: expanded uncertainty of KCRV).

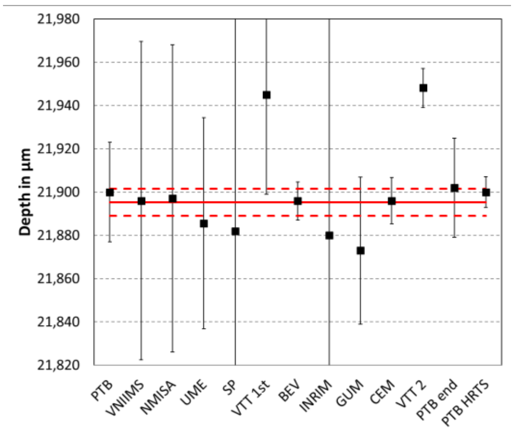

Figure 38 Measured depth values of the participants for the 20 µm groove (red line: KCRV, dotted red lines: expanded uncertainty of KCRV).

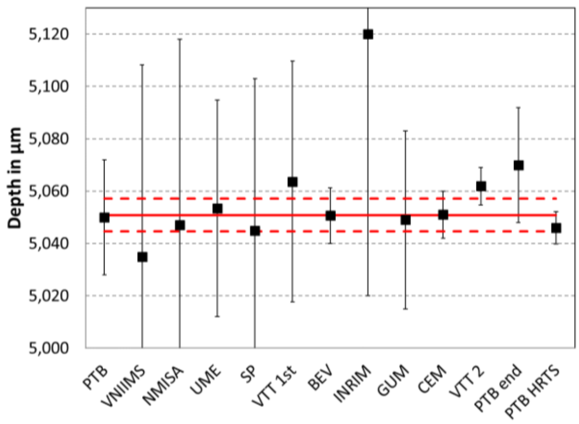

Figure 39 Measured depth values of the participants for the 5 µm groove (red line: KCRV, dotted red lines: expanded uncertainty of KCRV).

8.2 Calculation of Degrees of Equivalence

The Degree of Equivalence, DoE, for a laboratory result x_i is calculated simply as $x_i - \bar{x}_w$. The uncertainty of the DoE is calculated using either

$u(x_i - \bar{x}_w) = \sqrt{[u(x_i)]^2 - [u(\bar{x}_w)]^2}$ for results which contributed to the weighted mean

or $u(x_i - \bar{x}_w) = \sqrt{[u(x_i)]^2 + [u(\bar{x}_w)]^2}$ for results which made no contribution. The tables 5-10 show the measurement values, standard and expanded uncertainties, E_n values, degrees of equivalence $x_i - \bar{x}_w$, associated expanded uncertainties $U(x_i - \bar{x}_w)$ and the contribution to the mean value and to the weighted mean for all six groove depths.

Table 5. 900 µm groove: Measurement values, standard and expanded uncertainties, E_n values, degrees of equivalence $\boldsymbol{x_i - \bar{x}_w}$, associated expanded uncertainties $\boldsymbol{U(x_i - \bar{x}_w)}$ and contribution to the weighted mean (*: no measurement available).

900 µm	x_i µm	$u(x_i)$ µm	$U(x_i)$ µm	E_n	$(x_i - \bar{x}_w)$ µm	$U(x_i - \bar{x}_w)$U(xi-x̄w) µm	Contribution to ref. val.
PTB	899.884	0.027	0.054	0.42	-0.020	0.048	Y
VNIIMS	899.825	0.049	0.098	0.84	-0.079	0.095	Y
NMISA	899.907	0.049	0.097	0.03	0.003	0.094	Y
UME	900.156	0.061	0.123	2.01	0.252	0.125	N
RISE	899.650	4.160	8.320	0.03	-0.254	8.320	Y
BEV	899.919	0.016	0.032	0.76	0.015	0.019	Y
INRIM	899.960	0.210	0.420	0.13	0.056	0.419	Y
GUM	900.504	0.527	1.054	0.57	0.600	1.054	Y
CEM	*	*	*	*	*	*	*
VTT 2nd	899.870	0.130	0.260	0.13	-0.034	0.259	Y
Mean value	899.940						
Stand. dev.	0.231						
Ref. value	**899.904**						
Uncertainty	**0.025**						

Table 6. 600 µm groove: Measurement values, standard and expanded uncertainties, E_n values, degrees of equivalence $\boldsymbol{x_i - \bar{x}_w}$, associated expanded uncertainties $\boldsymbol{U(x_i - \bar{x}_w)}$ and contribution to the weighted mean (*: no measurement available).

600 µm	x_i µm	$u(x_i)$ µm	$U(x_i)$ µm	E_n	$(x_i - \bar{x}_w)$ µm	$U(x_i - \bar{x}_w)$U(xi-x̄w) µm	Contribution to ref. val.
PTB	599.913	0.022	0.044	0.12	-0.004	0.037	Y
VNIIMS	599.893	0.045	0.090	0.28	-0.024	0.087	Y
NMISA	599.931	0.044	0.088	0.16	0.014	0.085	Y
UME	601.287	0.052	0.104	12.82	1.370	0.107	N
RISE	599.810	2.770	5.540	0.02	-0.107	5.540	Y
BEV	599.921	0.016	0.032	0.17	0.004	0.022	Y
INRIM	599.960	0.160	0.320	0.13	0.043	0.319	Y
GUM	599.437	0.351	0.702	0.68	-0.480	0.702	Y
CEM	*	*	*	*	*	*	*
VTT 2nd	599.934	0.087	0.174	0.10	0.017	0.172	Y
Mean value	599.850						
Stand. dev.	0.162						
Ref. value	**599.917**						
Uncertainty	**0.024**						

Table 7. 200 µm groove: Measurement values, standard and expanded uncertainties, E_n values, degrees of equivalence $\boldsymbol{x_i - \bar{x}_w}$, associated expanded uncertainties $\boldsymbol{U(x_i - \bar{x}_w)}$ and contribution to the weighted mean.

200 µm	x_i µm	$u(x_i)$ µm	$U(x_i)$ µm	E_n	$(x_i - \bar{x}_w)$ µm	$U(x_i - \bar{x}_w)$U(x_i-$\bar{x}_w$) µm	Contribu-tion to ref. val.
PTB	199.989	0.015	0.029	0.78	0.019	0.024	Y
VNIIMS	199.956	0.039	0.078	0.19	-0.014	0.076	Y
NMISA	199.971	0.038	0.076	0.01	0.001	0.074	Y
UME	201.039	0.034	0.067	15.50	1.069	0.069	N
RISE	199.970	0.920	1.840	0.00	0.000	1.840	Y
BEV	199.965	0.016	0.032	0.18	-0.005	0.028	Y
INRIM	199.910	0.080	0.160	0.38	-0.060	0.159	Y
GUM	199.949	0.127	0.254	0.08	-0.021	0.253	Y
CEM	199.965	0.016	0.032	0.19	-0.005	0.028	Y
VTT 2nd	199.945	0.029	0.058	0.45	-0.025	0.056	Y
Mean value	199.958						
Stand. dev.	0.021						
Ref. value	**199.970**						
Uncertainty	**0.016**						

Table 8. 50 µm groove: Measurement values, standard and expanded uncertainties, E_n values, degrees of equivalence $\boldsymbol{x_i - \bar{x}_w}$, associated expanded uncertainties $\boldsymbol{U(x_i - \bar{x}_w)}$ and contribution to the weighted mean.

50 µm	x_i µm	$u(x_i)$ µm	$U(x_i)$ µm	E_n	$(x_i - \bar{x}_w)$ µm	$U(x_i - \bar{x}_w)$U(x_i-$\bar{x}_w$) µm	Contribu-tion to mean
PTB	50.274	0.013	0.026	0.24	0.005	0.022	Y
VNIIMS	50.269	0.037	0.074	0.00	0.000	0.073	Y
NMISA	50.266	0.044	0.087	0.03	-0.003	0.086	Y
UME	50.245	0.024	0.048	0.53	-0.024	0.046	Y
RISE	50.273	0.233	0.466	0.01	0.004	0.466	Y
BEV	50.270	0.026	0.052	0.02	0.001	0.050	Y
INRIM	50.240	0.070	0.140	0.21	-0.029	0.139	Y
GUM	50.220	0.034	0.068	0.74	-0.049	0.066	Y
CEM	50.277	0.012	0.023	0.45	0.008	0.018	Y
VTT 2nd	50.351	0.008	0.016	3.81	0.082	0.022	N
Mean value	50.259						
Stand. dev.	0.019						
Ref. value	**50.269**						
Uncertainty	**0.015**						

Table 9. 20 µm groove: Measurement values, standard and expanded uncertainties, E_n values, degrees of equivalence $\boldsymbol{x_i - \bar{x}_w}$, associated expanded uncertainties $\boldsymbol{U(x_i - \bar{x}_w)}$ and contribution to the weighted mean.

20 µm	x_i µm	$u(x_i)$ µm	$U(x_i)$ µm	E_n	$(x_i - \bar{x}_w)$ µm	$U(x_i - \bar{x}_w)$ U(xi-x̄w) µm	Contribution to mean
PTB	21.900	0.012	0.023	0.21	0.005	0.022	Y
VNIIMS	21.896	0.037	0.074	0.01	0.001	0.073	Y
NMISA	21.897	0.036	0.071	0.02	0.002	0.071	Y
UME	21.886	0.024	0.049	0.20	-0.010	0.048	Y
RISE	21.882	0.103	0.206	0.06	-0.013	0.206	Y
BEV	21.896	0.004	0.009	0.11	0.001	0.006	Y
INRIM	21.880	0.070	0.140	0.11	-0.015	0.140	Y
GUM	21.873	0.017	0.034	0.67	-0.022	0.033	Y
CEM	21.896	0.005	0.011	0.09	0.001	0.009	Y
VTT 2nd	21.948	0.005	0.009	4.82	0.053	0.011	N
Mean value	21.890						
Stand. dev.	0.009						
Ref. value	**21.895**						
Uncertainty	**0.006**						

Table 10. 5 µm groove: Measurement values, standard and expanded uncertainties, E_n values, degrees of equivalence $\boldsymbol{x_i - \bar{x}_w}$, associated expanded uncertainties $\boldsymbol{U(x_i - \bar{x}_w)}$ and contribution to the weighted mean.

5 µm	x_i µm	$u(x_i)$ µm	$U(x_i)$ µm	E_n	$(x_i - \bar{x}_w)$ µm	$U(x_i - \bar{x}_w)$ U(xi-x̄w) µm	Contribution to mean
PTB	5.050	0.011	0.022	0.04	-0.001	0.021	Y
VNIIMS	5.035	0.037	0.073	0.22	-0.016	0.073	Y
NMISA	5.047	0.036	0.071	0.05	-0.004	0.071	Y
UME	5.054	0.021	0.041	0.06	0.003	0.041	Y
RISE	5.045	0.029	0.058	0.10	-0.006	0.058	Y
BEV	5.051	0.005	0.011	0.02	0.000	0.009	Y
INRIM	5.120	0.050	0.100	0.69	0.069	0.100	Y
GUM	5.049	0.017	0.034	0.06	-0.002	0.033	Y
CEM	5.051	0.005	0.009	0.02	0.000	0.007	Y
VTT 2	5.062	0.004	0.007	1.16	0.011	0.010	N
Mean value	5.056						
Stand. dev.	0.023						
Ref. value	**5.051**						
Uncertainty	**0.006**						

8.3 Discussion of results

Outliers that had to be excluded from contributing to the KCRV (weighted mean) are:

- from UME for the groove depths 900/600/200 µm,

- from VTT for the groove depths 50/20/5 µm.

UME used a smaller uncertainty in the comparison than the one stated in their existing CMC entry. This led to the systematic outliers for the three deeper grooves (200/600/900 µm). Nevertheless, the existing CMC entry stating higher uncertainties (Q[33,13*d*] (*d* in µm)) is confirmed by UME's measurements in this comparison.

UME used their new roughness measurement device MarSurf XCR-20 for the first time in this intercomparison. The uncertainty *U* = Q[33; 13*d*] nm (with *d* in µm) in UMEs CMC entry belongs to their old roughness measurement device Mahr Perthometer Concept (produced in 1995). UME thought to achieve more precise results in the comparison using their new device. Indeed, good results were obtained in the 0 - 50 µm range, but since they didn't have groove depth standards beyond 50 µm, they were not able to obtain precise measurements in the 50 - 1000 µm range. A PTB calibrated groove depth standard with 8 grooves whose depths are varying from 1 µm to 900 µm was used as a reference depth standard for all measurements in the comparison. The cross sections of the grooves are trapezoid. The grooves whose nominal depths are 5 µm, 20 µm, 50 µm, 200 µm, 600 µm and 900 µm were used to calculate calibration factors on this reference standard. In the comparison, for the grooves with depths 5 µm, 20 µm, 50 µm the calibration procedure works quite well, as can be seen by the En values which are < 0.1 (see Table 8, Table 9 and Table 10). UME currently has not yet understood the cause of the deviations for the 900/600/200 µm grooves. The problem may be caused by the long probe arm which is used for the measurement of the 900/600/200 µm grooves. Or it may be caused by not calibrating the device at the same day as the intercomparison measurements.

In future UME intends to decrease their CMC uncertainty in the 0.01 - 50 µm range to *U* = Q[38, 3*d*] nm (with *d* in µm) which is larger than both the UME deviation from the weighted average and the UME uncertainty given in the intercomparison. For the range 51 - 900 µm, UME intends not to apply for a CMC entry under the current condition of their stylus instrument, until they resolve the issue about their measurement system and procedure.

VTT measured optically using a Bruker GT-K optical 3D profiler (coherence scanning interferometer) with a 2.5x magnification objective, a 0.55x secondary lens and a pixel size of 7.1 µm. For this instrument no CMC entry exists. The stated expanded uncertainty for these measurements was Q[23.4, 35.6*d*] with *d* in µm. The three outliers could be explained by a contamination of the silicon artefacts, since only the artefact EN19_7 (900/600/200 µm) but not the silicon artefacts were cleaned before VTT measured again (VTT 2nd). Another reason for the observed deviations is that VTT did not have good calibration samples for heights between 1 µm and 500 µm at the time of the comparison. The optical instrument used, currently has no CMC entry, but the entry was requested. This service will be greyed out when it is published until all corrective actions are performed.

After the comparison only a few marks were found on the surfaces of the three silicon artefacts, but as many as 70 scratch marks on the nickel coated copper artefact EN19_7. This indicates that the contact pressure used for the measurements was too high for many participants. This can be caused by a too high probing force or a too small probing tip radius. Thus, for future comparisons the actual probing force and actual tip radius need to be measured during the comparison by the participants to assure that the values recommend (2 µm tip radius and 0.7 mN probing force [4]) are not exceeded. The recently published German standard DIN 32567-3 "Production equipment for microsystems – Determination of the influence of materials on the optical and tactile dimensional metrology – Part 3: Derivation of correction values for tactile measuring devices" describes methods to do both.

8.4 Linking of result to other comparisons

There is no need in linking Supplementary Comparisons.

This was the first EURAMET comparison on depth setting standards up to 1 mm depth. Previous comparisons on smaller depth setting standards are:

- EUROMET.L-S3 (Depth Setting Standards) up to depths of 3.2 µm, published in 1997 [7]

- EUROMET.L-S11 (Surface Texture) up to depths of 8 µm, published in 2004 [8]

- EUROMET.L-S15 (Step Height Standards) up to depths of 2 µm, published in 2006 [9]

- EUROMET.L-S15.a (Step Height Standards and 1D Gratings) up to depths of 2 µm, published in 2009 [8]

- APMP.L-K8 2008-2010 with groove depth sizes of 0.4 µm to 10 µm [9]

- EURAMET.L-K8.2013 (Surface Roughness Standards) where an A2-standard with depths down to 9 µm was one of the artefacts [10].

9 Appendix A Equipment and measuring uncertainties of the participants

A wide range of equipment has been used. Therefore, this appendix describes the equipment

Table 11 Equipment and measuring uncertainties of the participants

Partici-pant	Instruments used	Probing force (µN)	Tip radius/ lateral resolution (µm)	Cone angle of tip (°)	Traverse speed (µm/s)	Traceability of z-axis	CMC entry for depths from d_{min} to d_{max} d_{min} … d_{max}	Expanded uncertainty U (nm)
PTB	Stylus instrument Mahr Surf LD120	500	2	60	100	Depth setting standards traceable to laser inter-ferometry	0.1 µm … 5 mm	Q[22,36*d*] (*d* in mm)
BEV	Nano measuring machine SIOS NMM-1-0016 with laser focus sensor	0	-	-	20/50	Laser interfero-meter	0.01 µm … 10 µm	Q[5,10*d*] (*d* in µm) (**) Published CMC uncertainty for a different instrument
CEM	KLA Tencor P-6 Stylus Profiler	20	2	60	50, 100	Depth setting standards traceable to laser interferometry (SIOS NMM)	0.01 µm … 15 µm	Q[2,20*d*] (*d* in µm)

GUM	Form Talysurf i-Series contact profilometer	1000	2		500	Depth setting standard calibrated by PTB	0.1 µm… 100 µm	Q[30,0.5*d*] (*d* in µm)
INRIM	Talysurf II stylus profilometer with interferometric head	1000	2.5	90	500	Reference sphere, gauge block step heights	0.01 µm … 15 µm	Q[1,4.7*d*], (*d* in µm) (**) Published CMC uncertainty for a different instrument
NMISA	Form Talysurf PGI 840	1000	2		250	Diameter standard	0.01 … 3000 µm	(4 + 20*d*) (*d* in µm)
RISE	Form Talysurf 120 with inductive pick-up	< 0.7 mN	2	90	500	Gauge blocks	0.05 µm … 1000 µm	Q[5,20*d*] (*d* in µm)
UME	Mahr Surf XCR 20 (pick up MFW-250 B)	700	2	60	100	Depth setting standard calibrated by PTB	0.01 µm … 50 µm	No CMC entry available for this instrument. Requested uncertainty: Q[38,3*d*] (*d* in µm) (*) Available CMC entry: Q[33,13*d*] (*d* in µm)
VNIIMS	Form Talysurf PGI 420	70	2		250	reference sphere	1 µm … 3 µm	Q[1.6,0.007*d*] (*d* in nm)

VTT	Bruker GT-K optical 3D profiler (coherence scanning interferometer)	objective 2.5 x and 0.55x secondary lens	pixel size 7.5 µm			Gauge blocks		No CMC entry available for this instrument. Requested uncertainty: Q[23.4, 35.6*d*] (*d* in µm) (*)

Q[a,b] is the quadrature sum of a & b, and *d* is the groove depth.

(*) CMCs that are not official at the present moment because they are still in process

(**) CMCs that correspond to a different declared technique

10 Appendix B All measurements performed

The pilot laboratory carried out the first and last measurement of the standards and at the end of the comparison measurements also carried out a control measurement with its traceable reference stylus instrument HRTS [11] which has a vertical measurement range of 450 µm. Thus, the two deepest grooves could not be measured.

The list of measured values also contains the first measurement of the VTT (VTT 1st) before cleaning the standard EN19_7.

Table 12. 900 µm groove: Measurement values, standard and expanded uncertainties, E_n values, degrees of equivalence $\boldsymbol{x_i - \bar{x}_w}$, associated expanded uncertainties $\boldsymbol{U(x_i - \bar{x}_w)}$ and contribution to the weighted mean.

900 µm	x_i µm	$u(x_i)$ µm	$U(x_i)$ µm	E_n	$(x_i - \bar{x}_w)$ µm	$U(x_i - \bar{x}_w)$ µm	Contribu-tion to ref. val.
PTB	899.884	0.027	0.054	0.42	-0.020	0.048	Y
VNIIMS	899.825	0.049	0.098	0.84	-0.079	0.095	Y
NMISA	899.907	0.049	0.097	0.03	0.003	0.094	Y
UME	900.156	0.061	0.123	2.01	0.252	0.125	N
RISE	899.650	4.160	8.320	0.03	-0.254	8.320	Y
VTT 1st	899.861	0.040	0.080	0.52	-0.043	0.084	N
BEV	899.919	0.016	0.032	0.76	0.015	0.019	Y
INRIM	899.960	0.210	0.420	0.13	0.056	0.419	Y
GUM	900.504	0.527	1.054	0.57	0.600	1.054	Y
CEM	*	*	*	*	*	*	*
VTT 2nd	899.870	0.130	0.260	0.13	-0.034	0.259	Y
PTB end	899.896	0.027	0.054	0.14	-0.008	0.060	N
Mean value	899.940						
Stand. dev.	0.231						
Ref. value	**899.904**						
Uncertainty	**0.025**						

Table 13. 600 µm groove: Measurement values, standard and expanded uncertainties, E_n values, degrees of equivalence $\boldsymbol{x_i - \bar{x}_w}$, associated expanded uncertainties $\boldsymbol{U(x_i - \bar{x}_w)}$ and contribution to the weighted mean.

600 µm	x_i µm	$u(x_i)$ µm	$U(x_i)$ µm	E_n	$(x_i - \bar{x}_w)$ µm	$U(x_i - \bar{x}_w)$ µm	Contribution to ref. val.
PTB	599.913	0.022	0.044	0.12	-0.004	0.037	Y
VNIIMS	599.893	0.045	0.090	0.28	-0.024	0.087	Y
NMISA	599.931	0.044	0.088	0.16	0.014	0.085	Y
UME	601.287	0.052	0.104	12.82	1.370	0.107	N
RISE	599.810	2.770	5.540	0.02	-0.107	5.540	Y
VTT 1st	599.914	0.032	0.064	0.05	-0.003	0.068	N
BEV	599.921	0.016	0.032	0.17	0.004	0.022	Y
INRIM	599.960	0.160	0.320	0.13	0.043	0.319	Y
GUM	599.437	0.351	0.702	0.68	-0.480	0.702	Y
CEM	*	*	*	*	*	*	*
VTT 2nd	599.934	0.087	0.174	0.10	0.017	0.172	Y
PTB end	599.927	0.023	0.045	0.19	0.01	0.051	N
Mean value	599.850						
Stand. dev.	0.162						
Ref. value	**599.917**						
Uncertainty	**0.024**						

Table 14. 200 µm groove: Measurement values, standard and expanded uncertainties, E_n values, degrees of equivalence $\boldsymbol{x_i - \bar{x}_w}$, associated expanded uncertainties $\boldsymbol{U(x_i - \bar{x}_w)}$ and contribution to the weighted mean.

200 µm	x_i µm	$u(x_i)$ µm	$U(x_i)$ µm	E_n	$(x_i - \bar{x}_w)$ µm	$U(x_i - \bar{x}_w)$ µm	Contribution to ref. val.
PTB	199.989	0.015	0.029	0.78	0.019	0.024	Y
VNIIMS	199.956	0.039	0.078	0.19	-0.014	0.076	Y
NMISA	199.971	0.038	0.076	0.01	0.001	0.074	Y
UME	201.039	0.034	0.067	15.50	1.069	0.069	N
RISE	199.970	0.920	1.840	0.00	0.000	1.840	Y
VTT 1st	200.032	0.024	0.048	1.23	0.062	0.051	N
BEV	199.965	0.016	0.032	0.18	-0.005	0.028	Y
INRIM	199.910	0.080	0.160	0.38	-0.060	0.159	Y
GUM	199.949	0.127	0.254	0.08	-0.021	0.253	Y
CEM	199.965	0.016	0.032	0.19	-0.005	0.028	Y
VTT 2nd	199.945	0.029	0.058	0.45	-0.025	0.056	Y
PTB end	199.977	0.015	0.029	0.20	0.007	0.033	N
PTB HRTS	199.947	0.008	0.016	0.83	-0.023	0.028	N
Mean value	199.958						
Stand. dev.	0.021						
Ref. value	**199.970**						
Uncertainty	**0.016**						

Table 15. 50 µm groove: Measurement values, standard and expanded uncertainties, E_n values, degrees of equivalence $\boldsymbol{x_i - \bar{x}_w}$, associated expanded uncertainties $\boldsymbol{U(x_i - \bar{x}_w)}$ and contribution to the weighted mean.

50 µm	x_i µm	$u(x_i)$ µm	$U(x_i)$ µm	E_n	$(x_i - \bar{x}_w)$ µm	$U(x_i - \bar{x}_w)$ µm	Contribu-tion to mean
PTB	50.274	0.013	0.026	0.24	0.005	0.022	Y
VNIIMS	50.269	0.037	0.074	0.00	0.000	0.073	Y
NMISA	50.266	0.044	0.087	0.03	-0.003	0.086	Y
UME	50.245	0.024	0.048	0.53	-0.024	0.046	Y
RISE	50.273	0.233	0.466	0.01	0.004	0.466	Y
VTT 1st	50.353	0.023	0.046	1.74	0.084	0.048	N
BEV	50.270	0.026	0.052	0.02	0.001	0.050	Y
INRIM	50.240	0.070	0.140	0.21	-0.029	0.139	Y
GUM	50.220	0.034	0.068	0.74	-0.049	0.066	Y
CEM	50.277	0.012	0.023	0.45	0.008	0.018	Y
VTT 2nd	50.351	0.008	0.016	3.81	0.082	0.022	N
PTB end	50.279	0.012	0.024	0.36	0.010	0.028	N
PTB HRTS	50.284	0.004	0.009	0.89	0.015	0.017	N
Mean value	50.259						
Stand. dev.	0.019						
Ref. value	**50.269**						
Uncertainty	**0.015**						

Table 16. 20 µm groove: Measurement values, standard and expanded uncertainties, E_n values, degrees of equivalence $\boldsymbol{x_i - \bar{x}_w}$, associated expanded uncertainties $\boldsymbol{U(x_i - \bar{x}_w)}$ and contribution to the weighted mean.

20 µm	x_i µm	$u(x_i)$ µm	$U(x_i)$ µm	E_n	$(x_i - \bar{x}_w)$ µm	$U(x_i - \bar{x}_w)$ µm	x_i
PTB	21.900	0.012	0.023	0.21	0.005	0.022	Y
VNIIMS	21.896	0.037	0.074	0.01	0.001	0.073	Y
NMISA	21.897	0.036	0.071	0.02	0.002	0.071	Y
UME	21.886	0.024	0.049	0.20	-0.010	0.048	Y
RISE	21.882	0.103	0.206	0.06	-0.013	0.206	Y
VTT 1st	21.945	0.023	0.046	1.07	0.050	0.046	N
BEV	21.896	0.004	0.009	0.11	0.001	0.006	Y
INRIM	21.880	0.070	0.140	0.11	-0.015	0.140	Y
GUM	21.873	0.017	0.034	0.67	-0.022	0.033	Y
CEM	21.896	0.005	0.011	0.09	0.001	0.009	Y
VTT 2nd	21.948	0.005	0.009	4.82	0.053	0.011	N
PTB end	21.902	0.012	0.023	0.28	0.007	0.024	N
PTB HRTS	21.900	0.004	0.007	0.50	0.005	0.009	N
Mean value	21.890						
Stand. dev.	0.009						
Ref. value	**21.895**						
Uncertainty	**0.006**						

Table 17. 5 µm groove: Measurement values, standard and expanded uncertainties, E_n values, degrees of equivalence $\boldsymbol{x_i - \bar{x}_w}$, associated expanded uncertainties $\boldsymbol{U(x_i - \bar{x}_w)}$ and contribution to the weighted mean.

5 µm	x_i µm	$u(x_i)$ µm	$U(x_i)$ µm	E_n	$(x_i - \bar{x}_w)$ µm	$U(x_i - \bar{x}_w)$ µm	Contribu-tion to mean
PTB	5.050	0.011	0.022	0.04	-0.001	0.021	Y
VNIIMS	5.035	0.037	0.073	0.22	-0.016	0.073	Y
NMISA	5.047	0.036	0.071	0.05	-0.004	0.071	Y
UME	5.054	0.021	0.041	0.06	0.003	0.041	Y
RISE	5.045	0.029	0.058	0.10	-0.006	0.058	Y
VTT 1st	5.064	0.023	0.046	0.28	0.013	0.046	N
BEV	5.051	0.005	0.011	0.02	0.000	0.009	Y
INRIM	5.120	0.050	0.100	0.69	0.069	0.100	Y
GUM	5.049	0.017	0.034	0.06	-0.002	0.033	Y
CEM	5.051	0.005	0.009	0.02	0.000	0.007	Y
VTT 2	5.062	0.004	0.007	1.16	0.011	0.010	N
PTB end	5.070	0.011	0.022	0.84	0.019	0.023	N
PTB HRTS	5.046	0.003	0.006	0.55	-0.005	0.009	N
Mean value	5.056						
Stand. dev.	0.023						
Ref. value	**5.051**						
Uncertainty	**0.006**						

11 Appendix C Measuring uncertainties of the participants

Most of the participants submitted results supported by a full uncertainty calculation. Some partners submitted two uncertainty budgets, one for the three silicon standards (50/20/5 µm) and a separate one for the three deeper grooves (900/600/200 µm). The following abbreviations are used for the different uncertainty distributions:

N = normal; R = rectangular; T = triangular; U = U-shaped.

11.1 PTB

Table 18 Exemplary standard uncertainty budget for PTB measurements

Quantity X_i	Estimate x_i	Uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(d)$	Degrees of freedom ν_i
Scattering	0	10.9 nm	N	1	3.6 nm	8
Flatness feed unit, drift	0	10.5 nm	R	1	6.1 nm	∞
Form deviation	0	10 nm	R	1	5.8 nm	∞

Reproducibility calibration Instrument	899.884	4.2E-6	N	1	3.8 nm	5
Reference standard	0	10 nm	N	1	10 nm	∞
Gradient groove depth in y-direction	0	± 0.2 mm	R	10 nm/mm	2.0 nm	∞
Noise	0	2.0 nm	R	1	1.2 nm	∞
Thermal expansion	0	1.73	R	1	1.0 nm	∞
					27 nm	1925

11.2 BEV

Table 19 BEV standard uncertainty budget for the groove depths 900/600/200 µm

Quantity X_i	estimate x_i	uncertainty $u(x_i)$	probability distribution	sensitivity coefficient c_i	uncertainty contribution $u_i(d)$	degrees of freedom v_i
N_1	0	1 nm	N	1	0.0010 µm	∞
N_2	0	0.1 nm	R	1	0.0001 µm	∞
N_3	0	0.2 nm	R	1	0.0001 µm	∞
N_4	0	4 nm	R	1	0.0023 µm	∞
P_1	0	±5 µm per edge	R	0.00004	0.0002 µm	∞
P_2	0	±100 µm	R	2 nm/mm	0.0002 µm	∞
P_3	0	15 nm	N	1	0.0150 µm	∞
P_4	0	10 % of correction	N	1	0.0007 µm 0.0019 µm 0.0033 µm	∞
S_1	0	0.0008 µm 0.0027 µm 0.0035 µm	X	1	0.0008 µm 0.0027 µm 0.0035 µm	∞

N_1: z-laser interferometer, traceability
N_2: z-laser interferometer, influence of interpolation error on fit value
N_3: z-laser interferometer, influence of resolution on fit value
N_4: z-reference mirror form deviations, influence on fit value
P_1: Contribution due to feature edge localization in scan direction taking into account sample form deviation
P_2: Contribution due to profile localization normal to scan direction taking into account sample form deviation
P_3: Inequality of optical surface properties between groove and top (contamination, etc.)
P_4: Thermal expansion effects
S_1: "Scatter" σ_{n-1} as defined in protocol

Table 20 BEV standard uncertainty budget for the groove depths 50/20/5 µm

Quantity X_i	estimate x_i	uncertainty $u(x_i)$	probability distribution	sensitivity coefficient c_i	uncertainty contribution $u_i(d)$	degrees of freedom v_i
N_1	0	0.1 nm	N	1	0.0001 µm	∞
N_2	0	0.1 nm	R	1	0.0001 µm	∞

N_3	0	0.2 nm	R	1	0.0001 µm	∞
N_4	0	4 nm	R	1	0.0023 µm	∞
P_1	0	±5 µm per edge	R	-	0.0002 µm	∞
P_2	0	±5 µm	R	58 nm/mm	0.0002 µm	∞
P_3	0	3 nm	N	1	0.0003 µm	∞
P_4	0	10 % of correction	N	1	0.0005 µm	∞
S_1	0	0.0047 µm 0.0037 µm 0.0260 µm	X	1	0.0047 µm 0.0037 µm 0.0260 µm	∞

11.3 CEM

Table 21 CEM standard uncertainty budget for the groove depths 900/600/200 µm

Quantity X_i	estimate x_i	Uncertainty $u(x_i)$	probability distribution	sensitivity coefficient c_i	uncertainty contribution $u_i(d)$	degrees of freedom v_i
d_{ref20}	199971.3 nm	9	N	0.99997	8.999734	60
d_{refm20}	199341.365 nm	2.681 nm	N	1.00313	2.689839	109
inhomogenity		2.676 nm		0.999973		109
σ (dpm) max-min(Avi) resolution	2.889 nm 4.537 nm 1.000 nm	0.463 nm 2.619 nm 0.289 nm	N R R			38 100 100
Expans. coeff. α	16.6E-6 K^{-1}	0.5E-6 K^{-1}	R	318937.767		60
T thermometer		0.024 K		3.308979		118
calibration drift resolution ΔT	0.005 K 0.01 K 0.01 K 0.08 K	0.003 K 0.006 K 0.003 K 0.023 K	N R R R			60 100 100 100
C1(noise)	0 nm	0.82272 nm	R	1	0.82272	100
C2(T)	0 nm	0.32472 nm	R	1	0.32472	100
d_{20}	199335.482nm	12.6921nm	N	1.003160	12.73357	112
inhomogenity		12.69205 nm		0.999970		113
σ (dpm) max-min(Avi) resolution small sample	8.031 nm 3.591 1.000 nm 21.181 nm	2.677 nm 2.073 nm 0.289 nm 12.229 nm	N R R R			8 100 100 100
Expans. coeff.	16.6E-6 K^{-1}	0.5E-6 K^{-1}	R	354806.675		60
T thermometer		0.035 K		3.308969		108
calibration drift resolution ΔT	0.005 K 0.01 K 0.01 K 0.12 K	0.003 K 0.006 K 0.003 K 0.035 K	N R R R			60 100 100 100
rounded	0.399 nm					

d = 199965,399 nm uc (*d*) = 16.2 nm v_{eff} = 202

Table 22 CEM standard uncertainty budget for the groove depths 50/20/5 µm

Quantity X_i	estimate x_i	Uncertainty $u(x_i)$	probability distribution	sensitivity coefficient c_i	uncertainty contribution $u_i(d)$	degrees of freedom v_i
d_{ref20}	5052 nm	3	N	0.999 715	2.999 14	60
d_{refm20}	5051.079 nm	0.427 26 nm	N	0.999 897	0.427 21	233
inhomogenity		0.427 236 nm		0.999 995		234
σ (d_{refm20}) max-min(Av_i) resolution	1.159 nm 0.441 nm 1.000 nm	0.186 nm 0.254 nm 0.289 nm	N R R			38 100 100
Expans. coeff.	2.56E-6 K^{-1}	0.5E-6 K^{-1}	R	9091.8994		60
T thermometer		0.024 K		0.012 931		118
calibration drift resolution ΔT	0.005 K 0.01 K 0.01 K 0.08 K	0.003 K 0.006 K 0.003 K 0.023 K	N R R R			60 100 100 100
C1(noise)	0 nm	0.9295 nm	R	1	0.929 534	100
C2(T)	0 nm	0.001 115 nm	R	1	0.001 115	100
d_{20}	5049.636 nm	2.5585 nm	N	1,000 182	2.558 997	71
inhomogenity		2.558 53 nm		0.999 995		72
σ (dpm) max-min(Avi) resolution small sample	4.158 nm 1.750 nm 1.000 nm 3.250 nm	1.386 nm 1.010 nm 0.289 nm 1.876 nm	N R R R			8 100 100 100
Expans. coeff.	2.56E-6 K^{-1}	0.5E-6 K^{-1}	R	10 099.221		60
T thermometer		0.019 K		0.012 927		133
calibration drift resolution ΔT	0.005 K 0.01 K 0.01 K 0.06 K	0.003 K 0.006 K 0.003 K 0.017 K	N R R R			60 100 100 100
rounded	0.442 nm					
		d = 5050,6 nm		uc (*d*) = 4.5 nm		ν_{eff} = 212

11.4 GUM

Table 23 GUM standard uncertainty budget for the groove depths 900/600/200 µm

Quantity X_i	Estimate x_i	Uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(d)$	Degrees of freedom v_i
D_n	75,308 µm	12.5 nm	N	1	12.5 nm	100
ΔPt	0 nm	0.33 nm	R	1	0.33 nm	8
b	0 nm	$s_r(Pt_m)$	N	1	$s_r(Pt_m)$	100
z_t	0 nm	$s_t(Pt_m)$	N	1	$s_t(Pt_m)$	100
z_{ref}	0 nm	4.18 nm	R	1	4.18 nm	8
z_0	0 nm	10.45 nm	R	1	10.45 nm	8
A	0 nm	1.44 nm	R	1	1.44 nm	8

Table 24 GUM standard uncertainty budget for the groove depths 50/20/5 µm

Quantity X_i	estimate x_i	uncertainty $u(x_i)$	probability distribution	sensitivity coefficient c_i	uncertainty contribution $u_i(d)$	degrees of freedom ν_i
D_n	24.003 µm	11.5 nm	N	1	11.5	100
ΔPt	0 nm	0.33 nm	R	1	0.33 nm	8
b	0 nm	$s_r(Pt_m)$	N	1	$s_r(Pt_m)$	100
z_t	0 nm	$s_t(Pt_m)$	N	1	$s_t(Pt_m)$	100
z_{ref}	0 nm	4.18 nm	R	1	4.18 nm	8
z_0	0 nm	10.45 nm	R	1	10.45 nm	8
A	0 nm	1.44 nm	R	1	1.44 nm	8

Used symbols:
D_n - Reference standard depth
ΔPt - Transfer of Pt from reference standard
b - repeatability of reference standard measurement
z_t - heterogenity of measured standard
z_{ref} - nonlinearity of measuring station
z_0 - noise of measuring station
A - tilt of measured standard

11.5 INRIM

Table 25 INRIM standard uncertainty budget for the groove depth 900 µm

EN19_7 nominal groove depth 900 µm							
Quantity (x_i)	$u(x_i)$	*unit*	$u(x_i)/x_i$	*distrib.*	ν_i	$c_i = \delta f/\delta x_i$	$u_i(y)$/nm
Repeatability	2,9	nm		*N*	8	1	3
z-axis calibration			2,2E-04	*N*	10	900060	198
Probe readings							
digital resolution 16 bit ADC	10	nm		*R*	100	0,58	6
profile noise	50	nm		*R*	50	0,58	29
straightness (x-axis)	50	nm		*R*	50	0,58	29
levelling			5E-05	*N*	50	900060	45
Thermal effects	1,7E-05	K^{-1}		*N*	50	450030	7
CTE $16{,}6 \cdot 10^{-6}$/°C							

Combined standard uncertainty	**208**	**nm**
ν_{eff}	**12**	
k	**2,18**	
Expanded uncertainty	**452**	**nm**

Table 26 INRIM standard uncertainty budget for the groove depth 5 µm

SN 497 nominal groove depth 5 µm							
Quantity (x_i)	$u(x_i)$	*unit*	$u(x_i)/x_i$	*distrib.*	ν_i	$c_i = \delta f/\delta x_i$	$u_i(y)$ /nm
Repeatability	4,5	nm		*N*	8	1	4
z-axis calibration			5E-03	*N*	10	5121	26
Probe readings							
digital resolution 16 bit ADC	10	nm		*R*	100	0,58	6
profile noise	50	nm		*R*	50	0,58	29
straightness (x-axis)	50	nm		*R*	50	0,58	29
levelling			1E-04	*N*	50	5121	1

combined standard uncertainty	**49**	**nm**
ν_{eff}	**80**	
k	**2**	
Expanded uncertainty	**98**	**nm**

11.6 NMISA

Standard uncertainty budget for all grove depths

Table 27 NMISA standard uncertainty budget for all groove depths

Quantity X_i	Estimate x_i	Uncertainty $u(x_i)$ nm	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(d)$	Degrees of freedom ν_i
Machine specification	0	(70 + 30 *d*[mm])	N	1		∞
Repeatability	0	$\sigma_r = \sqrt{\frac{\sum_{i=1}^{n}(x - \bar{x})}{n}}$	N	1		8
Total standard uncertainty (all groove depths)	$\sqrt{((70+30d)^2 + {\sigma_r}^2)}$					

The machine specifications take into account:

- temperature of the machine
- linearity of the probe
- resolution
- software fitting errors

11.7 RISE

Table 28 RISE standard uncertainty budget for the groove depths 900/600/200 µm

Quantity X_i	estimate x_i (nm)	uncertainty $u(x_i)$ (nm)	probability distribution	sensitivity coefficient c_i	uncertainty contribution $u_i(d)$ (nm)	degrees of freedom v_i
Amplification (±0.8%)	0.8	0.462	R	d	0.462*d*	100
Surface variation (topography)	32.0	20.2	N	0.632	20.2	26
Guideway profile (Wt)	14.0	8.1	R	1	8.1	1000
Noise	3.0	3.0	N	1	3.0	50
Contact deformation	2.0	2.0	R	1	2.0	1000
Resolution	15.9	4.6	R	1	4.6	1E+08
Assessment error	15.0	15.0	R	1	15.0	1000
Tip radius	0.0	0.0	R	1	0	1000
Repeatability	2.0	0.9	N	1	0.9	4
Temperature contribution	1.7	1.7	R	1	1.7	100

Table 29 RISE standard uncertainty budget for the groove depths 50/20/5 µm

quantity X_i	estimate x_i (nm)	uncertainty $u(x_i)$ (nm)	probability distribution	sensitivity coefficient c_i	uncertainty contribution $u_i(d)$ (nm)	degrees of freedom v_i
Amplification (±0.8%)	0.8	0.462	R	d	0.462d	100
Surface variation (topography)	15.0	9.49	N	0.632	9.5	26
Guideway profile (Wt)	14.0	8.1	R	1	8.1	1000
Noise	3.0	3.0	N	1	3.0	50
Contact deformation	2.0	2.0	R	1	2.0	1000
Resolution	0.6	0.2	R	1	0.2	1E+08
Assessment error	10.0	10.0	R	1	10.0	1000
Tip radius	0	0	R	1	0	1000
Repeatability	8.0	3.6	N	1	3.6	4

11.8 UME

Table 30 UME standard uncertainty budget for the groove depths 900 µm

Uncertainty Sources				Input Data					Sensitivity Coefficients				Variances				
Explanations	Symbol	Estimated Value	Unit	Symbol	Value	Unit	Prob.Dist	Multiplier	Symbol	Value		Unit	Value		Unit	u_i	v_i
Groove depth (U_n: Uncertainty of Ref. Groove depth standard)	D_n	900016	nm	u_{Dn}	114	nm	Normal	0,5	C_{Dn}	0,000001	z_u	1,000156	4,0E-09	z_u^2	nm²	57,0	100
Inaccuracy of measurement location on a groove of the Ref. Groove depth standard	P_{tmy}	900016	nm	u_{Ptmy}	1	nm	Uniform	0,5774	C_{Ptmy}	0,000001	z_u	1,000156	4,1E-13	z_u^2	nm²	0,6	100
Reproducebility on the groove of the Ref. Groove depth standard (mt = 15)	b	78	nm	u_b	78	nm	Normal	0,26	C_b	0,000001	z_u	1,000156	5,0E-10	z_u^2	nm²	20,1	14
D_n	D_n	900016	nm	u_{Dn}	114	nm	Normal	0,5	C_{Dn}	0,00000000001	z_u	1,16E-05	5,4E-19	z_u^2	nm²	0,0	100
Linear thermal expansion coefficient of the Ref. Groove depth standard	α_{ref}	16,6E-6	1/K	u_α	5E-07	1/K	Uniform	0,5774	C_α	1	z_u	630109,2	4,1E-14	z_u^2	nm²	0,2	100
ΔT: (Ref. Groove depth standard's temperature - 20) °C	ΔT	0,7	°C	$u_{\Delta T}$	0,3	°C	Normal	0,5	$C_{\Delta T}$	0,00002	z_u	14,90658	6,2E-12	z_u^2	nm²	2,2	100
Topography of test standard for 3 different measurement positions (m_t = 9)	D_m	900156	nm	u_{Dm}	23	nm	Normal	0,33	C_{Dm}	1,00000			58,8		nm²	7,7	8
Straightness deviation of the datum of the device (Wt measured on an optical flat)	z_{ref}	20	nm	u_{Zref}	10	nm	Uniform	0,5774	C_{Zref}	1,00000			33		nm²	5,8	100
Background noise (Rzo measured on an optical flat without λs filter for Δx = 0,0001 mm, measurement speed V = 0,1 mm/s)	z_0	18	nm	u_{Zo}	9	nm	Uniform	0,5774	C_{Zo}	0,035355			0,034		nm²	0,2	100
Uncertainty caused by inexact knowledge of plastic deformation (for metallic standards)	z_{pl}	5	nm	u_{pl}	5	nm	Uniform	0,5774	C_{pl}	1,00000			8,3		nm²	2,9	100
Alignment error of the curve fitting (A)	P_{tr}	20	nm	u_{Ptr}	5,0	nm	Uniform	0,5774	C_{Ptr}	1,00000			8		nm²	2,9	100
D_m	D_m	900156	nm	u_{Dm}	23	nm	Normal	0,5	C_{Dm}	0,000012			1,8E-08		nm²	0,0	100
Linear thermal expansion coefficient of the groove depth standard	α_{test}	16,6E-6	1/K	u_α	5E-07	1/K	Uniform	0,5774	C_α	630109,2			0,0		nm²	0,2	100
ΔT: (Test groove depth standard's temperature - 20) °C	ΔT	0,7	°C	$u_{\Delta T}$	0,3	°C	Normal	0,5	$C_{\Delta T}$	14,94259			5,0		nm²	2,2	100
Number of profile points at the top profile sections	n_h	4000														Total	
Number of profile points at the bottom profile section	n_l	1000													ν_{eff}	121	

TOTAL VARIANCE	u^2 =	113,9	+	4,5E-09 D^2	nm²
Standard Uncertainty	u =	61,4			nm

Table 31 UME standard uncertainty budget for the groove depth 50 µm

Uncertainty Sources				Input Data					Sensitivity Coefficients				Variances				
Explanations	Symbol	Estimated Value	Unit	Symbol	Value	Unit	Prob.Dist	Multiplier	Symbol	Value		Unit	Value		Unit	u_i	v_i
Groove depth (U_n: Uncertainty of Ref. Groove depth standard)	D_n	50009	nm	u_{Dn}	43	nm	Normal	0,5	C_{Dn}	0,000020	z_u	1,004711	1,8E-07	z_u^2	nm²	21,6013	100
Inaccuracy of measurement location on a groove of the Ref. Groove depth standard	P_{tmy}	50009	nm	u_{Ptmy}	1	nm	Uniform	0,5774	C_{Ptmy}	0,000020	z_u	1,004711	1,3E-10	z_u^2	nm²	0,5801	100
Reproducebility on the groove of the Ref. Groove depth standard (mt = 15)	b	14	nm	u_b	14	nm	Normal	0,26	C_b	0,000020	z_u	1,004711	5,2E-09	z_u^2	nm²	3,6318	14
D_n	D_n	50009	nm	u_{Dn}	43	nm	Normal	0,5	C_{Dn}	0,00000000023	z_u	1,16E-05	2,5E-17	z_u^2	nm²	0,0003	100
Linear thermal expansion coefficient of the Ref. Groove depth standard	α_{ref}	16,6E-6	1/K	u_α	5E-07	1/K	Uniform	0,5774	C_α	1	z_u	35171,22	4,1E-14	z_u^2	nm²	0,0102	100
ΔT: (Ref. Groove depth standard's temperature - 20) °C	ΔT	0,7	°C	$u_{\Delta T}$	0,3	°C	Normal	0,5	$C_{\Delta T}$	0,00002	z_u	0,832051	6,2E-12	z_u^2	nm²	0,1248	100
Topography of test standard for 3 different measurement positions (m_t = 9)	D_m	50244,6	nm	u_{Dm}	24,5	nm	Normal	0,33	C_{Dm}	1,00000			66,7		nm²	8,1667	8
Straightness deviation of the datum of the device (Wt measured on an optical flat)	z_{ref}	20	nm	u_{Zref}	10	nm	Uniform	0,5774	C_{Zref}	1,00000			33		nm²	5,7735	100
Background noise (Rzo measured on an optical flat without λs filter for Δx = 0,0001 mm, measurement speed V = 0,1 mm/s)	z_0	18	nm	u_{Zo}	9	nm	Uniform	0,5774	C_{Zo}	0,020634			0,011		nm²	0,1072	100
Uncertainty caused by inexact knowledge of plastic deformation (for metallic standards)	z_{pl}	0	nm	u_{pl}	0	nm	Uniform	0,5774	C_{pl}	1,00000			0,0		nm²	0,0000	100
Alignment error of the curve fitting (A)	P_{tr}	10	nm	u_{Ptr}	2,5	nm	Uniform	0,5774	C_{Ptr}	1,00000			2		nm²	1,4434	100
D_m	D_m	50244,6	nm	u_{Dm}	25	nm	Normal	0,5	C_{Dm}	0,000012			2,0E-08		nm²	0,0001	100
Linear thermal expansion coefficient of the groove depth standard	α_{test}	16,6E-6	1/K	u_α	5E-07	1/K	Uniform	0,5774	C_α	35171,22			0,0		nm²	0,0102	100
ΔT: (Test groove depth standard's temperature - 20) °C	ΔT	0,7	°C	$u_{\Delta T}$	0,3	°C	Normal	0,5	$C_{\Delta T}$	0,834060			0,0		nm²	0,1251	100
Number of profile points at the top profile sections	n_h	4000														Total	
Number of profile points at the bottom profile section	n_l	5690													ν_{eff}	123	

TOTAL VARIANCE	u^2 =	102,1	+	1,9E-07 D^2	nm²
Standard Uncertainty	u =	24,1			nm

D_n : Groove depth (Un: Uncertainty of Ref. groove depth standard)
P_{tmy} : Inaccuracy of measurement location on a groove of the Ref. groove depth standard. It is given as $G*a_y$. G = 20 nm/mm and a_y = 0.05 mm. So $G*a_y$ = 1 nm
b : Reproducibility on the groove of the Ref. groove depth standard. 5 different measurement locations, 3 repetitions at each position (m_t = 15)
α_r : Linear thermal expansion coefficient of the Ref. groove depth standard
ΔT_r : (Ref. Groove depth standard's temperature - 20) °C
D_m : Topography of test standard for 3 different measurement positions (m_t = 9)

z_{ref} : Straightness deviation of the datum of the device (Wt measured on an optical flat)
z_0 : Background noise (Rzo measured on an optical flat without ls filter for Dx = 0.0001 mm, measurement speed V = 0.1 mm/s)
z_{pl} : Uncertainty caused by inexact knowledge of plastic deformation (for metallic standards)
A : Alignment error of the curve fitting (Residual roughness P_{tr})
α_t : Linear thermal expansion coefficient of the test groove depth standard
ΔT_t : (Test groove depth standard's temperature - 20) °C
n_h : Number of profile points at the top profile sections
n_l : Number of profile points at the bottom profile section

11.9 VNIIMS

Table 32 VNIIMS standard uncertainty budget for all grooves

quantity X_i	estimate x_i, µm	uncertainty $u(x_i)$, µm	probability distribution	sensitivity coefficient c_i	uncertainty contribution $u_i(d)$, µm	degrees of freedom v_i
Uncertainty of calibration standard	0	0.003	N	1	0.0015	∞
Self-noise	0	0.0042	R	1	0.00243	∞
Sensor resolution	0	0.0032	R	1	0.00185	∞
Sensor nonlinearity	0	0.007+0.003*H	N	1	0.0035+0.0015*H	∞
Datum bar Straightness	0	0.02	N	1	0.01	∞

11.10 VTT

Table 33 VTT standard uncertainty budget for the three deeper grooves (900/600/200 µm)

Quantity X_i	Estimate x_i	Uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(d)$	Degrees of freedom v_i
periodic nonlinearity	0	1.0 nm	R	1	1.0 nm	20
repeatability σ_r	0	3.3 nm	N	1	3.3 nm	20
scale nonlinearity σ_{lin}	0	144×10^{-6}	R	1	$144 \times 10^{-6} \times d$	100
amplification error σ_s	0	10.6×10^{-6}	N	d	$10.6 \times 10^{-6} \times d$	20

temperature correction factor T_{corr}	*16.6* × 10^{-6}/°C	0.5 × 10^{-6}/°C	N	0.4°C × *d*	0.2 × 10^{-6} × *d*	100
temperature T-20°C	0.4°C	0.04°C	N	*16.6* × 10^{-6} /°C × *d*	0.66 × 10^{-6} × *d*	100
total standard uncertainty $\boldsymbol{u(d)}$	(EN 19_7)		$\sqrt{(3.5\ nm)^2 + (144\ \times 10^{-6} \times d)^2}$			≥101

Table 34 VTT standard uncertainty budget for the three silicon grooves (50/20/5 µm)

Quantity X_i	Estimate x_i	Uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(d)$	Degrees of freedom ν_i
periodic nonlinearity	0	1.0 nm	R	1	1.0 nm	20
repeatability σ_r	0	3.3 nm	N	1	3.3 nm	20
scale nonlinearity σ_{lin}	0	144 × 10^{-6}	R	1	144 × 10^{-6} × *d*	100
amplification error σ_s	0	10.6 × 10^{-6}	N	d	10.6 × 10^{-6} × *d*	20
temperature correction factor T_{corr}	*2.56* × 10^{-6} /°C	0.5 × 10^{-6} /°C	N	0.1°C × *d*	50 × 10^{-9} × *d*	100
temperature T-20°C	-0.1°C	0.02 C	N	*0.256* × 10^{-6} /°C × *d*	5.1 × 10^{-9} × *d*	100
total standard uncertainty $\boldsymbol{u(d)}$	(SN 497, SN 499, SN 502)	$\sqrt{(3.5\ nm)^2 + (144\ \times 10^{-6} \times d)^2}$				≥25

12 Appendix D Cleaning procedure for artefact EN19_7 at BEV

The cleaning was performed iteratively under microscopic control.
1. Cleaning sample with purified compressed gas → a few of the larger particles were removed only.
2. Soaking the sample in 2-Propanol overnight, drying with purified compressed gas → no visible change.
3. Soaking the sample in acetone overnight, drying with purified compressed gas → no visible change.
4. Ultrasonic bath for 3 minutes in 2-Propanol at 20 °C, drying with purified compressed gas → no visible change but some of the finer particles were removed.
5. Ultrasonic bath for 3 minutes in acetone at 20 °C, drying with purified compressed gas → no visible change.
6. Wiping the lands of sample with lens cleaning tissue soaked in acetone approximately 10 times. No force applied → no visible change.
5. Wiping the lands and grooves with lens cleaning tissue soaked in acetone and Q-tips applying increasing force with the wooden handle → the colored surface layer gradually disappears. After some

100 moves the appearance of grooves and lands become visually identical. The cleaning was stopped at this stage.

The stained surface layer was very difficult to remove and resemble corrosion products.

Used cleaning supplies:
- Cotton Tipped Applicators (Puritan, 15 cm, wood handle, Ref.: 806-WC)
- Lens Cleaning Tissue (ThorLabs, MC 50E)
- Airduster GDB (Electrolube, Ref.: GDP400)
- Acetone (residue analysis grade, UN1090, AppliChem)
- 2-Propanol (technical, VWR Chemicals)
- Ultrasonic Bath (EMAG, Emmi-40HC)

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