Report on EURAMET supplementary comparison on measurement of a 1 mm stage micrometer

Bundesamt
für Eich- und
Vermessungswesen

BEV Bundesamt für Eich- und Vermessungswesen

Report on EURAMET Supplementary Comparison Measurement of a 1 mm Stage Micrometer EURAMET project 1488 EURAMET.L-S2.3.n02 (previously EURAMET.L-S29)

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2 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 Espoo, 16-17 October 2017, the EURAMET Technical Committee for Length (TC-L) decided to carry out a supplementary comparison on stage micrometer measurements, named EURAMET.L-S29, with BEV (Bundesamt für Eich- und Vermessungswesen) as the pilot laboratory. The results of this international comparison will support the Calibration and Measurement Capabilities (CMCs) declared by the NMIs in the CIPM Mutual Recognition Arrangement (MRA). The comparison was registered in November 2019 at EURAMET and January 2020 at KCDB. Artefact circulation started in August 2020 and was completed in September 2022.

3 Organization

3.1 Participants

Table 1. List of participant laboratories and their contacts.

Laboratory, Country code RMO	**Contact person, Laboratory**	**Phone Email**
BEV (AT) EURAMET Pilot	Michael Matus Bundesamt für Eich- und Vermessungswesen Arltgasse 35, A-1160 Wien, Austria	+43 1 21110 826540 michael.matus@bev.gv.at
CEM (ES) EURAMET	Emilio Prieto*), Mª Mar Pérez Centro Español de Metrología Alfar 2, ES-28760 Tres Cantos (Madrid), Spain	+34 91 8074 716 / 801 eprieto@cem.es mmperezh@cem.es
INRIM (IT) EURAMET	Alessandro Germak Istituto Nazionale di Ricerca Metrologica Strada delle Cacce 91, 10135 Torino, Italy	+39 011 3919 924 a.germak@inrim.it
GUM (PL) EURAMET	Dariusz Czułek, Piotr Sosinowski Central Office of Measures ul. Elektoralna 2, 00-139 Warszawa, Poland	+48 22 581 95 43/07 dariusz.czulek@gum.gov.pl piotr.sosinowski@gum.gov.pl
INM (RO) EURAMET	Alexandru Duță*), Elena Dugheanu National Institute of Metrology Sos. Vitan-Bârzesti 11, 042122 Bucuresti, Romania	+40 21 334 5060 alexandru.duta@inm.ro elena.dugheanu@inm.ro
DMDM (RS) EURAMET	Slobodan Zelenika Directorate of Measures and Precious Metals Mike Alasa 14, YU - 11 000 Belgrad, Serbia	+381 11 20 24 421 zelenika@dmdm.rs
RISE (SE) EURAMET	Marianne Äremann RISE Research Institutes of Sweden AB 50115 Borås, Sweden	+46 10 516 5492 or 5481 +46 70 280 54 92 marianne.aremann@ri.se

UME (TR) EURAMET	Bulent Ozgur, Muharrem Asar Ulusal Metroloji Enstitüsü Barış Mah. Dr. Zeki Acar Cad. No:1 41470 Gebze, Kocaeli, Türkiye	+90 262 679 50 00 ext. 5300 bulent.ozgur@tubitak.gov.tr muharrem.asar@tubitak.gov.tr
NMISA (ZA) AFRIMETS	Pieter Greeff*), Kenneth Manana National Metrology Institute of South Africa Building 5 CSIR Campus, Brummeria, Pretoria 0184, South Africa	+27 12 841 4936 pgreeff@nmisa.org kmanana@nmisa.org
NIM (CN) APMP	Shuanghua Sun National Institute of Metrology No. 18, Bei San Huan Dong Rd. 100029 Beijing, China	+86 10 64524911 sunshh@nim.ac.cn
NIMT (TH) APMP	Jariya Buajarern National Institute of Metrology Thailand 3/4-5 Moo 3, Klong 5, Klong Luan 12120 Pathumthani, Thailand	+66 2 5775100 1216 jariya@nimt.or.th
INMETRO (BR) SIM	Davi Anders Brasil INMETRO Av. N. S. das Graças, 50 – Vila Operária - Xerém Duque de Caxias – RJ, Brazil	+55 21 2145 3289 dabrasil@inmetro.gov.br
INTI (AR) SIM	Bruno Gastaldi Instituto Nacional de Tecnología Industrial Av. Vélez Sarsfield 1561, Córdoba X5000JKC, Argentina	+54 0351 4684835 gastaldi@inti.gob.ar

*) Contacts retired or are on leave in the course of the project.

3.2 Schedule

The comparison was carried out in the form of a circulation. After the first three participants the original artefact suffered from a massive contamination and detoriation of the scale marks. Finally, a new artefact had to be acquired and characterized. This caused a significant delay in the circulation as shown in Table 2. It was decided to withdraw the results from participant starting from CEM on who first reported the contamination. CEM, RISE and INRIM were scheduled to calibrate the second artefact (Table 2) in loop 2.

Table 2. Schedule of the comparison. First artefact (loop 1)

RMO	**Laboratory**	**Original schedule**	**Date of measurement**	**Results received**
EURAMET	BEV	August 2020	August 2020	August 2020
EURAMET	GUM	September 2020	September 2020	December 2020
EURAMET	INM	October 2020	October 2020	November 2020
EURAMET	CEM	November 2020	November 2020	— (discarded)
EURAMET	RISE	December 2020	December 2020	— (discarded)
EURAMET	INRIM	January 2021	—	—
Pilot Lab	BEV	—	January 2021	—

Table 3 Schedule of the comparison. Second artefact (loop 2)

RMO	**Laboratory**	**Original schedule**	**Date of measurement**	**Results received**
EURAMET	BEV	—	February 2021	February 2021
EURAMET	DMDM		March 2021	May 2021
APMP	NIM		April 2021	June 2021
APMP	NIMT		June 2021	August 2021

SIM	INMETRO		July 2021	October 2021
SIM	INTI		August 2021	November 2021
Pilot Lab	BEV	—	January 2022	—
EURAMET	CEM		February 2022	May 2022
EURAMET	INRIM		March 2022	June 2022
EURAMET	RISE		April 2022	May 2022
Pilot Lab	BEV	—	May 2022	—
EURAMET	UME		June 2022	November 2022
AFRIMETS	NMISA		September 2022	November 2022
Pilot Lab	BEV	—	September 2022	—

For both loops BEV contributed with the respective first measurement only.

4 Artefacts

4.1 Description of artefacts

Both artefacts are typical stage micrometers with fairly well-defined graduation lines (Figure 1). Both are of equal type and of the same manufacturer. The scale length is 1 mm divided in 100 parts. The graduation lines have a width of approximately 3 µm and are of unequal length. 11 lines are numerical labelled in multiples of 0.1 mm (Figure 2). No cover glass is applied to the scale.

Substrate dimensions: 75.7 mm × 25.8 mm × 2.2 mm
Substrate material: Nextrema® 724-3[1]
Linear thermal expansion coefficient: $(-0.1 \pm 0.7) \cdot 10^{-6}\ K^{-1}$
Lines: vacuum deposited chromium

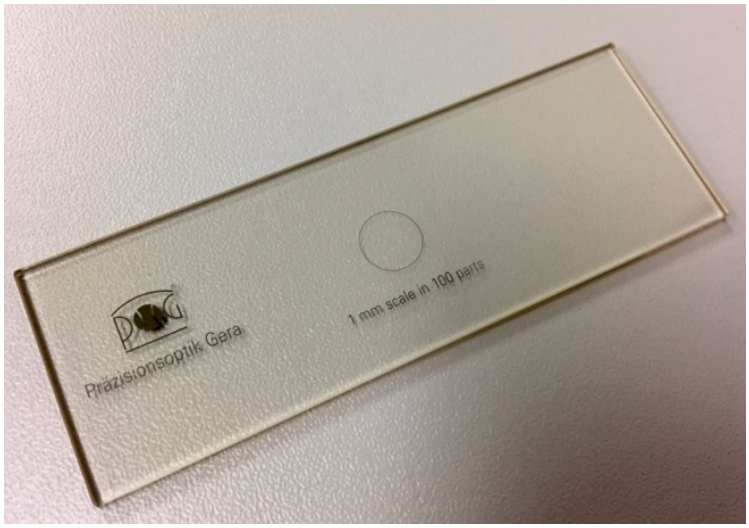


Figure 1 Stage micrometer

[1] Information by manufacturer https://www.schott.com/nextrema

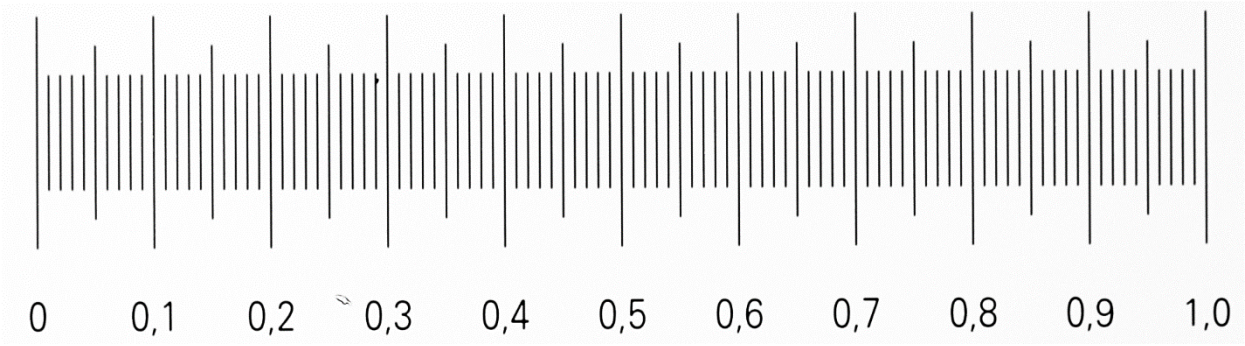


Figure 2 Microphotography of the scale

Figure 3 shows the special plastic case designed for the artefact. When properly closed with the yellow clip, the stage micrometer is securely fixed between two rubber membranes. Both membranes have a circular hole in the center. The stage micrometer can be placed in a way so that the scale is not touched by the membranes or by any other object.

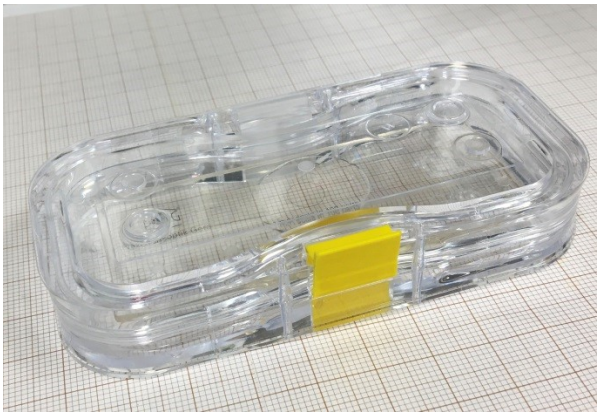


Figure 3 Transporting case. Properly closed

Figure 4 Transporting case. Placement of the artefact

4.2 Stability of artefacts

A total of four stability measurements during the course of the comparison were scheduled by the pilot laboratory. However, the original artefact was damaged after the first three participants. Only the stability of the second artefact could thus be characterized. Since both artefacts are of same make and kind, it is very likely that both are of similar stability.

Artefact 2 was measured by the pilot at the start and at the end of the circulation. Additionally, two more measurements could be performed in between (Figure 5). The total time span was 19 months. The maximum total span over all measurements and all 100 distances was 8 nm (Figure 6). This is considerable smaller than the pilot´s standard uncertainty of 24 nm. The artefact can be regarded as stable within the 95 % confidence level; hence no uncertainty has to be added to the SCRV.

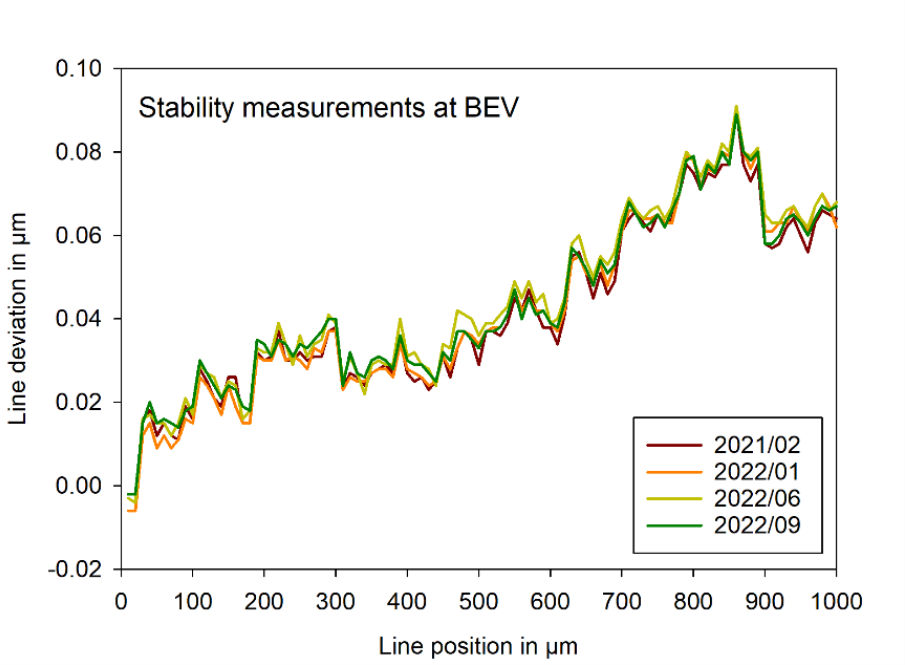


Figure 5 Stability of artefact 2 used in loop 2. Four measurements of the pilot laboratory superimposed. The standard uncertainty of each measurement is 0.024 µm.

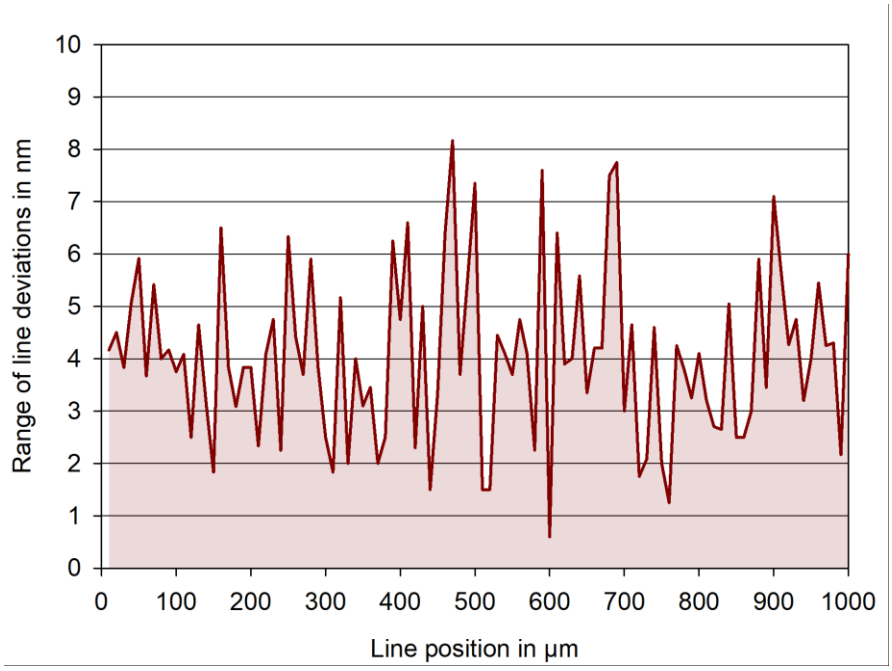


Figure 6 Stability of artefact 2 used in loop 2. Total range of the four measurements plotted in Figure 5 for each individual line.

4.3 Condition of artefacts at start/end of comparison

4.3.1 Artefact 1

As described earlier, artefact 1 (used for loop 1) was massively contaminated after three participants. CEM was the first participant who documented the bad condition of the artefact. After return to the pilot

not only a contamination but a deformation of the chromium pattern was noticed. This is already visible in Figure 7, taken prior to any cleaning attempts.

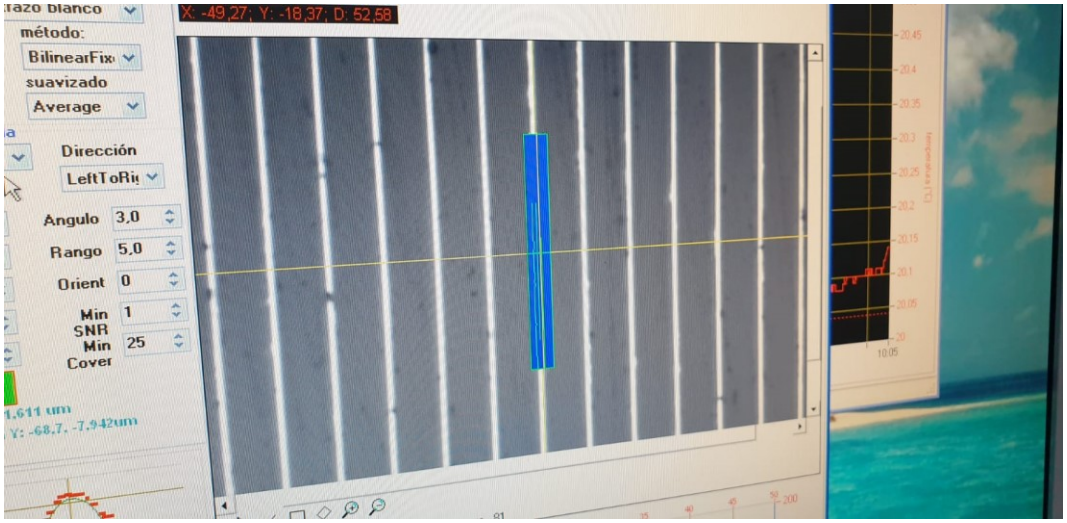


Figure 7 Image of artefact 1 in the measurement system of CEM. Picture taken before the cleaning process in November 2020.

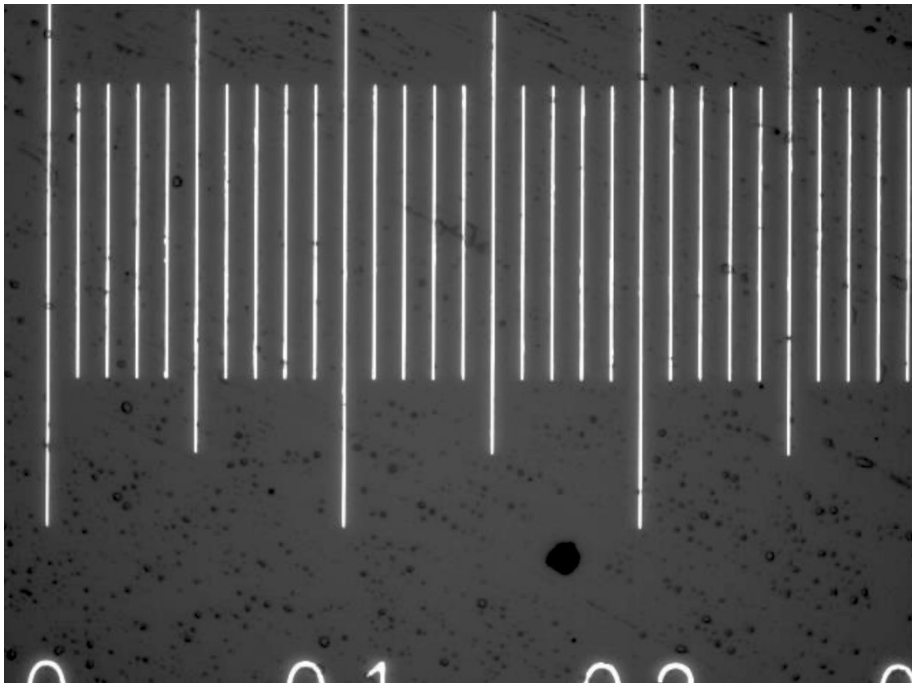


Figure 8 Microphotograph of artefact 1 taken by RISE in December 2020.

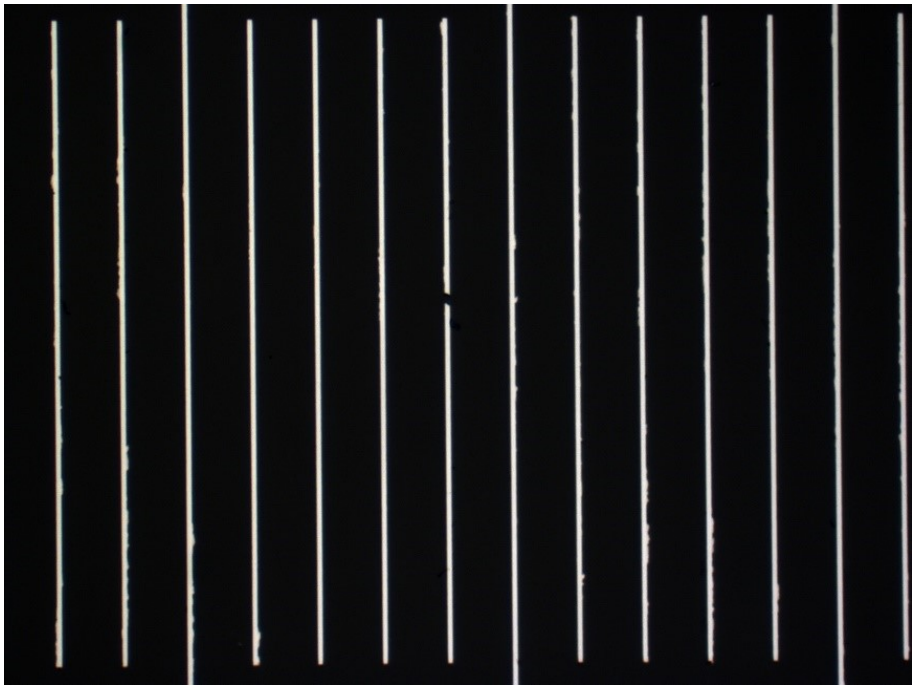


Figure 9 Artefact 1. Line at 360 µm with a gap in the region to be measured. Other lines show asymmetric chromium spreading. This influences the line center position significantly. Microphotograph taken by BEV after return of the sample in January 2021.

4.3.2 Artefact 2

For artefact 2 used for loop 2 the microscopic investigation does not show any significant change of the condition. Some dust particles accumulated during the circulation, most of them outside the measurement area.

In June 2021 NIM was the first participant who has sent reports of these contaminations as shown in Figure 10. It was possible to blow away the particles by clean and dry air.

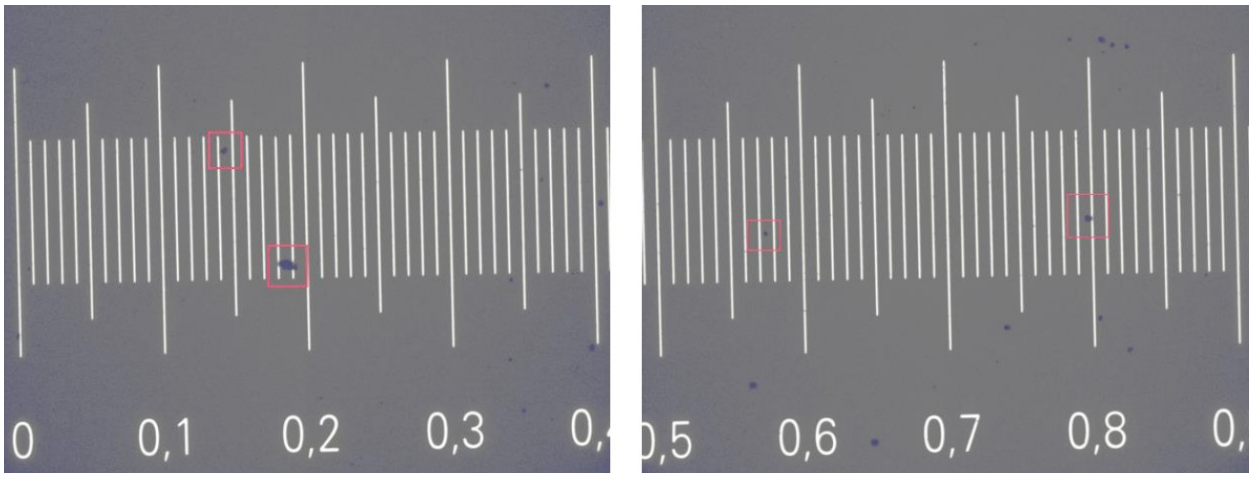


Figure 10 NIM reported two significant faults on line 19 and line 80 in June 2021

A probably non-contamination caused fault was documented by INMETRO in August 2021 in the central part of line 60. This is shown in Figure 11.

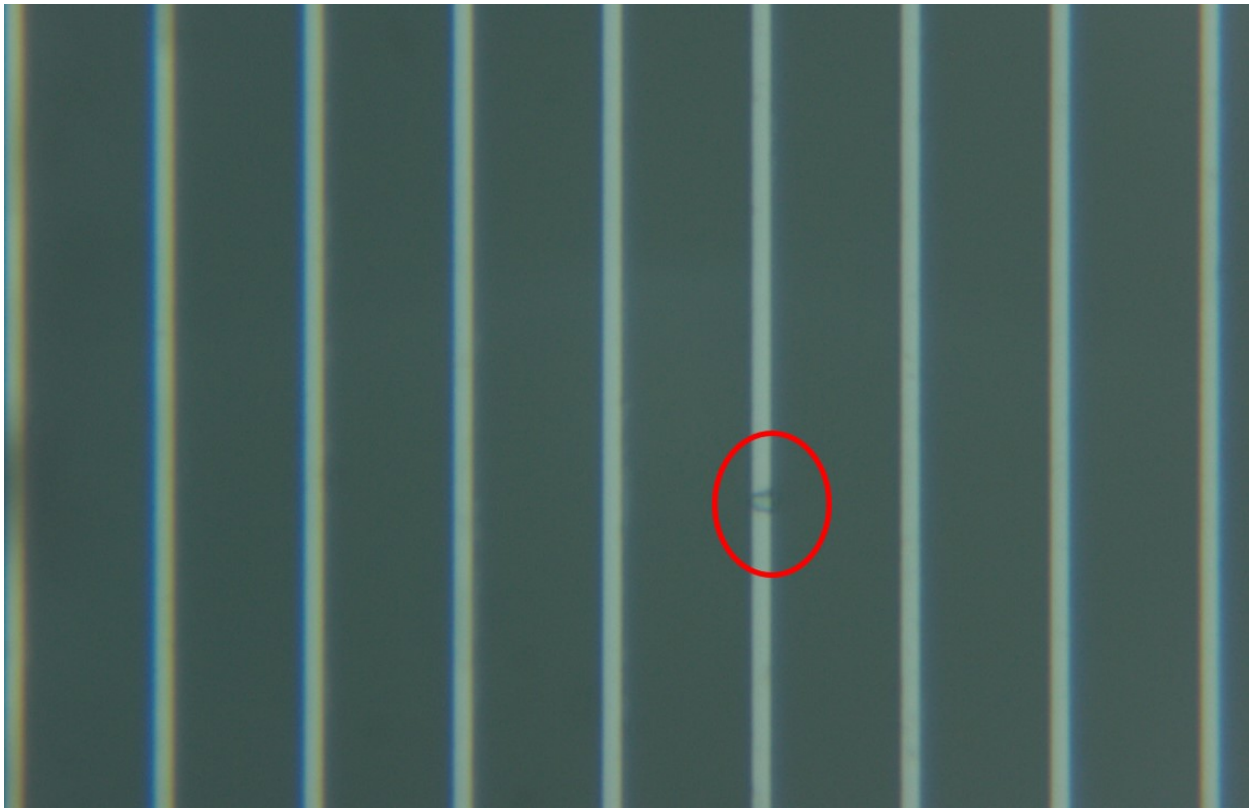


Figure 11 Change on line 60 as documented by INMETRO in August 2021

Overall the participants results did not show a noticeable drift. The stability measurements as outlined in section 4.2 support this finding.

5 Measuring instructions

5.1 Handling the artefact

The technical protocol gives instructions on the handling of the artefact:

“The stage micrometer shall only be handled by authorized persons wearing appropriate gloves. It should be stored in such a way as to prevent damage. The side bearing the graduation should not came in contact with other objects; the transportation box (Figure 4) is constructed in a way to avoid any contact with its walls.

Before making the measurements, the stage micrometer needs to be checked to verify that the measuring surface is not damaged. Micrographic images are the most appropriate way for this check. The condition of the graduation should be documented in the form provided in Appendix B of the technical protocol.

No other measurements are to be attempted by the participants and the stage micrometer should not be used for any purpose other than described in this document. The stage micrometer may not be given to any party other than the participants in the comparison. When not in use, place the scale back into its container to avoid dust or dirt deposits.

The stage micrometer should be examined before despatch and any change in condition during the measurement at each laboratory should be communicated to the pilot laboratory. Ensure that the content of the package is complete before shipment. Always use the original packaging.”

5.2 Cleaning

The technical protocol gives instructions on the cleaning of the artefact:

"The principle rule is not to clean the artefact at all! No cleaning of the scale should be tried besides blowing away dust particles using dry, clean air or other clean gases. Especially, rubbing the surface with soft tissues or any other firm physical contact will possibly damage the line structures of the standards. Application of solvents such as acetone or alcohol is strictly forbidden. If it is necessary to clean the scale before the measurement, please get in contact with the pilot."

During the course of the comparison CEM noticed an extreme contamination of the artefact. It is speculated that a carrier opened the package in an improper way. CEM got in contact with the pilot and it was tried to clean the stage micrometer using a technique commonly applied for laser resonator mirrors. However, this was unsuccessful and the artefact had to be substituted (see section 4.3).

5.3 Traceability

Length measurements should be traceable to the latest realisation of the metre as set out in the current "*Mise en Pratique*". Temperature measurements should be made using the International Temperature Scale of 1990 (ITS-90).

5.4 Measurands

The stage micrometer shall be measured based on the standard procedure that the laboratory regularly uses for this calibration service for its customers.

The measurand e_i is the deviation of the distance[2] l_i between the reference line to the considered line from the nominal distance L_i:

$$e_i = l_i - L_i$$

The distance l_i has to be determined between the center line position of the reference line (zero line, labelled "0") and the center line position of the measured line. All measurements should be performed over the section of 50 µm width. That is, it should be tried to apply an effective slit height or CCD image window height of 50 µm for the analysis of measurements (Figure 12). This 50 µm window should be positioned symmetrical with respect to the graduation. Since the artefact does not have any guiding structures, there is some arbitrariness in the alignment. This fact and any deviation from the given measurand definition should be recognized by appropriate uncertainty contributions. This decision must be made by the participant (not the pilot).

The measurement results shall be corrected for the reference conditions as stated in section 5.6.

All 100 values e_1 to e_{100} as defined above have to be measured and reported by each participant.

[2] In the technical protocol this quantity was denoted as d_i. To avoid confusion with the deviation from the SCRV, it has been renamed to l_i in this document.

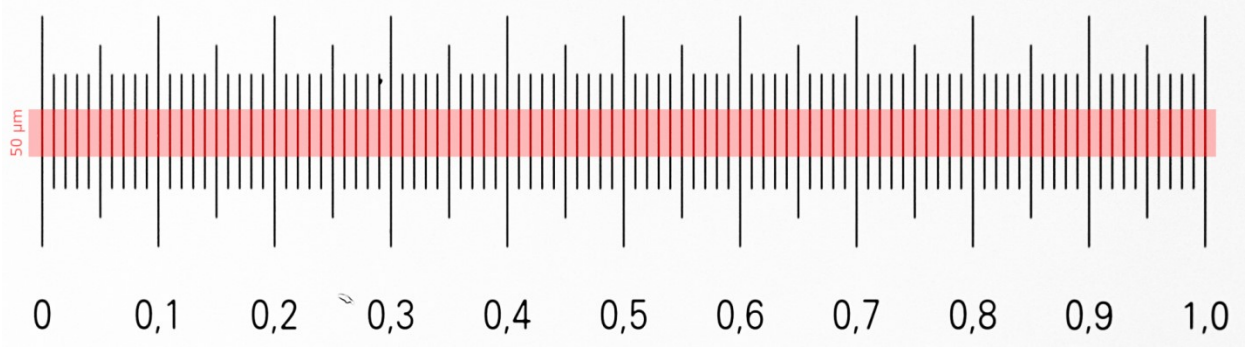


Figure 12 The 50 µm region (in pink) over which the line centers are to be evaluated.

5.5 Measurement uncertainty

The uncertainty of measurement shall be estimated according to the ISO Guide to the Expression of Uncertainty in Measurement. The participating laboratories are encouraged to use their usual model for the uncertainty calculation.

The participants are asked to report the standard uncertainty $u(e_i)$ (or u_i for short) for each of the 100 individual measurement values in the report file. Moreover, the expanded measurement uncertainty U has to be expressed in the usual length-dependent form:

$$U = Q[a, b \cdot L] \equiv \sqrt{a^2 + (b \cdot L)^2}$$

using a coverage factor of $k = 2$.

5.6 Reference condition

Measurement results should be reported for the reference temperature of 20 °C. For corrections, the linear thermal expansion coefficient indicated in section 4.1 should be used. The reference orientation is horizontal with the graduation facing upwards.

6 Results

6.1 Results and standard uncertainties as reported by participants

In the first loop only three NMIs could take part before the respective artefact was destroyed irrecoverably. Table 4 summarizes the results (values and associated standard uncertainties) for each of the participants. As a guide for the eye a plot of the results is presented in Figure 13. Only the values (without uncertainties) are plotted.

In loop 2 the remaining NMIs (11 including BEV) took part calibrating the second artefact. Table 5 summarizes the results (values and associated standard uncertainties) for each of the participants. As a guide for the eye plots of the results are presented in Figure 14 and Figure 15, respectively.

Table 4. Deviation from nominal length (Line deviation, in µm) of the individual scale marks and their standard uncertainties, as reported by the laboratories of loop 1. The order of participants presented in the table heading does not correspond to the chronological order. For chronological order see Table 2.

Line	INM		BEV.1		GUM	
	e_i	u_i	e_i	u_i	e_i	u_i
	µm	µm	µm	µm	µm	µm
1	-0,240	0,500	-0,001	0,024	0,017	0,045
2	0,100	0,500	-0,005	0,024	0,013	0,045
3	0,210	0,500	0,015	0,024	0,046	0,045
4	0,050	0,500	0,014	0,024	0,034	0,045
5	-0,230	0,500	0,012	0,024	0,044	0,045
6	-0,090	0,500	0,011	0,024	0,035	0,045
7	-0,140	0,500	0,011	0,024	0,045	0,045
8	-0,110	0,500	0,011	0,024	0,046	0,045
9	-0,140	0,500	0,009	0,024	0,045	0,045
10	-0,110	0,500	0,012	0,024	0,033	0,045
11	-0,030	0,500	0,025	0,024	0,059	0,045
12	-0,120	0,500	0,024	0,024	0,055	0,045
13	-0,150	0,500	0,020	0,024	0,054	0,045
14	-0,260	0,500	0,019	0,024	0,046	0,045
15	-0,220	0,510	0,015	0,024	0,048	0,045
16	-0,080	0,510	0,014	0,024	0,041	0,045
17	-0,220	0,510	0,014	0,024	0,046	0,045
18	-0,300	0,510	0,014	0,024	0,043	0,045
19	0,820	0,510	0,023	0,024	0,057	0,045
20	-0,020	0,510	0,022	0,024	0,045	0,045
21	-0,320	0,510	0,023	0,024	0,062	0,045
22	-0,240	0,510	0,026	0,024	0,049	0,045
23	-0,340	0,510	0,023	0,024	0,055	0,045
24	-0,420	0,510	0,026	0,024	0,051	0,045
25	-0,500	0,520	0,023	0,024	0,057	0,045
26	-0,350	0,520	0,023	0,024	0,047	0,045
27	-0,300	0,520	0,027	0,024	0,054	0,045
28	-0,170	0,520	0,029	0,024	0,046	0,045
29	-0,230	0,520	0,027	0,024	0,058	0,045
30	-0,150	0,520	0,028	0,024	0,044	0,045
31	-0,250	0,520	0,012	0,024	0,044	0,045
32	-0,170	0,520	0,010	0,024	0,036	0,045
33	-0,110	0,530	0,011	0,024	0,049	0,045
34	-0,220	0,530	0,012	0,024	0,039	0,045
35	-0,340	0,530	0,012	0,024	0,046	0,045
36	-0,300	0,530	0,014	0,024	0,050	0,045
37	-0,220	0,530	0,013	0,024	0,048	0,045
38	-0,070	0,530	0,010	0,024	0,036	0,045
39	-0,110	0,540	0,013	0,024	0,039	0,045
40	-0,110	0,540	0,013	0,024	0,042	0,045
41	-0,220	0,540	0,014	0,024	0,039	0,045
42	-0,130	0,540	0,014	0,024	0,042	0,045
43	-0,210	0,540	0,012	0,024	0,040	0,045
44	-0,090	0,550	0,012	0,024	0,040	0,045
45	-0,250	0,550	0,011	0,024	0,037	0,045
46	-0,230	0,550	0,012	0,024	0,023	0,045
47	-0,300	0,550	0,017	0,024	0,041	0,045
48	-0,480	0,550	0,018	0,024	0,042	0,045
49	-0,320	0,560	0,017	0,024	0,041	0,045
50	-0,330	0,560	0,013	0,024	0,031	0,045
51	-0,190	0,560	0,019	0,024	0,037	0,045
52	-0,260	0,560	0,017	0,024	0,028	0,045
53	-0,170	0,570	0,015	0,024	0,029	0,045
54	-0,130	0,570	0,018	0,024	0,031	0,045
55	-0,120	0,570	0,023	0,024	0,029	0,045
56	-0,260	0,570	0,022	0,024	0,031	0,045
57	-0,220	0,580	0,019	0,024	0,025	0,045
58	-0,150	0,580	0,016	0,024	0,027	0,045
59	0,000	0,580	0,018	0,024	0,013	0,045
60	-0,110	0,580	0,016	0,024	0,014	0,045
61	-0,270	0,590	0,016	0,024	0,013	0,045
62	-0,230	0,590	0,019	0,024	0,024	0,045
63	-0,200	0,590	0,027	0,024	0,015	0,045
64	-0,230	0,590	0,026	0,024	0,033	0,045
65	-0,260	0,600	0,024	0,024	0,018	0,045
66	-0,200	0,600	0,025	0,024	0,011	0,045
67	-0,160	0,600	0,026	0,024	0,016	0,045
68	-0,240	0,600	0,025	0,024	0,021	0,045
69	-0,030	0,610	0,025	0,024	0,013	0,045
70	-0,280	0,610	0,028	0,024	0,019	0,045
71	-0,310	0,610	0,038	0,024	0,029	0,045
72	-0,320	0,620	0,037	0,024	0,034	0,045
73	-0,110	0,620	0,034	0,024	0,018	0,045
74	-0,180	0,620	0,031	0,024	0,016	0,045
75	-0,030	0,620	0,028	0,024	0,008	0,045
76	-0,190	0,630	0,030	0,024	0,017	0,045
77	-0,020	0,630	0,026	0,024	0,003	0,045
78	-0,430	0,630	0,033	0,024	0,018	0,045
79	-0,100	0,640	0,038	0,024	0,011	0,045
80	-0,180	0,640	0,037	0,024	0,026	0,045
81	-0,160	0,640	0,037	0,024	0,016	0,045
82	-0,070	0,650	0,044	0,024	0,021	0,045
83	-0,040	0,650	0,042	0,024	0,011	0,045
84	-0,040	0,650	0,040	0,024	0,019	0,045
85	-0,050	0,660	0,041	0,024	0,005	0,045
86	-0,050	0,660	0,041	0,024	0,026	0,045
87	0,020	0,660	0,039	0,024	0,015	0,045
88	-0,020	0,670	0,041	0,024	0,017	0,045
89	0,050	0,670	0,039	0,024	0,004	0,045
90	0,000	0,670	0,023	0,024	-0,011	0,045
91	-0,020	0,680	0,021	0,024	-0,022	0,045
92	0,040	0,680	0,021	0,024	-0,014	0,045
93	-0,140	0,680	0,019	0,024	-0,014	0,045
94	-0,050	0,690	0,023	0,024	-0,014	0,045
95	0,020	0,690	0,022	0,024	-0,016	0,045
96	0,170	0,690	0,023	0,024	-0,015	0,045
97	0,150	0,700	0,023	0,024	-0,015	0,045
98	0,010	0,700	0,025	0,024	-0,005	0,045
99	0,110	0,700	0,024	0,024	-0,018	0,045
100	0,030	0,710	0,024	0,024	-0,012	0,045

In Tables 4 to 8, the comma is used as the decimal separator instead of the period. This is a consequence of the software used to create them. There should not be any misunderstandings in this context.

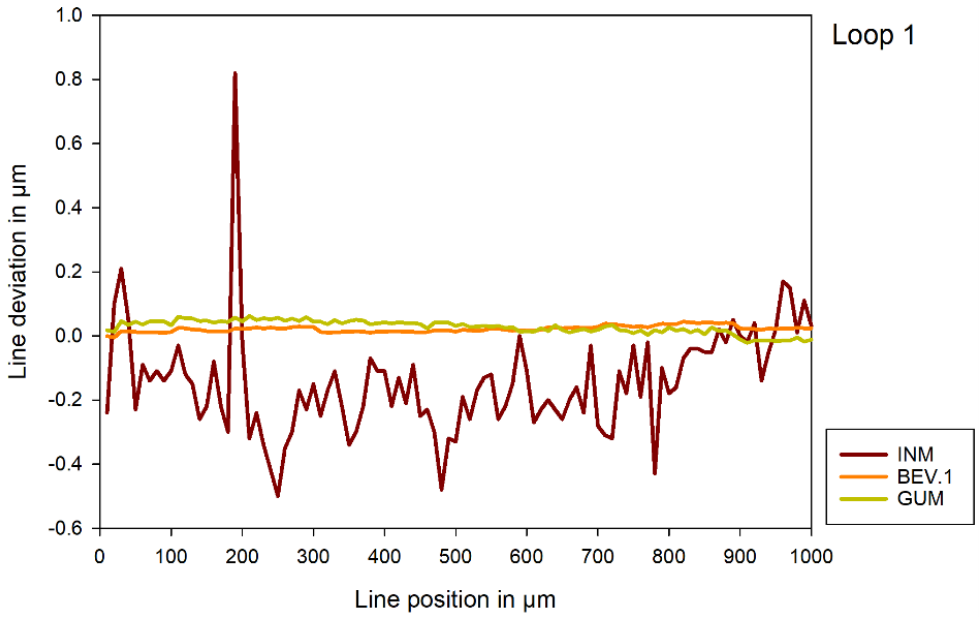


Figure 13 Plot of the results of participants for loop 1. Note the different ordinate scaling as compared to Figure 14 and Figure 15. This is necessary because of the very large deviations of INM as compared to the other participants. The INM results are still in accordance with the SCRV due to the high expanded measurement uncertainty (up to 1.42 µm).

Table 5. Deviation from nominal length (Line deviation, in µm) of the individual scale marks and their standard uncertainties, as reported by the laboratories of loop 2. The order of participants presented in the table heading does not correspond to the chronological order. For chronological order see Table 3.

Line	NIMT		INMETRO		NIM		BEV.2		DMDM		INTI		RISE		CEM		NMISA		INRIM		UME	
	e_i	u_i	e_i	u_i	e_i	u_i	e_i	u_i	e_i	u_i	e_i	u_i	e_i	u_i	e_i	u_i	e_i	u_i	e_i	u_i	e_i	u_i
	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm
1	0,018	0,144	-0,006	0,020	-0,004	0,014	-0,003	0,024	-0,001	0,034	-0,005	0,035	-0,010	0,120	-0,003	0,025	-0,015	0,033	-0,014	0,090	0,000	0,100
2	0,033	0,144	-0,009	0,020	-0,006	0,014	-0,004	0,024	-0,011	0,034	-0,001	0,035	-0,010	0,120	-0,004	0,025	-0,014	0,033	-0,022	0,090	0,000	0,100
3	0,024	0,144	0,013	0,020	0,014	0,014	0,016	0,024	-0,004	0,034	0,016	0,035	0,010	0,120	0,016	0,025	0,000	0,033	0,000	0,090	0,000	0,100
4	0,029	0,144	0,008	0,020	0,012	0,014	0,018	0,024	-0,002	0,034	0,014	0,035	0,000	0,120	0,013	0,025	0,016	0,033	0,022	0,090	0,000	0,100
5	0,043	0,144	0,008	0,020	0,010	0,014	0,012	0,024	0,001	0,034	0,014	0,035	0,000	0,120	0,012	0,025	0,010	0,033	0,010	0,090	0,000	0,100
6	0,028	0,144	0,007	0,020	0,009	0,014	0,015	0,024	-0,001	0,034	0,012	0,035	0,000	0,120	0,016	0,025	0,013	0,033	0,014	0,090	-0,010	0,100
7	0,054	0,144	0,009	0,020	0,007	0,014	0,012	0,024	-0,003	0,034	0,018	0,035	-0,010	0,120	0,009	0,025	0,011	0,033	0,036	0,090	0,000	0,100
8	0,041	0,144	0,005	0,020	0,010	0,014	0,011	0,024	0,002	0,034	0,014	0,035	-0,020	0,120	0,012	0,025	0,010	0,033	-0,010	0,090	0,000	0,100
9	0,049	0,144	0,009	0,020	0,010	0,014	0,019	0,024	-0,008	0,034	0,019	0,035	0,020	0,120	0,020	0,025	0,024	0,033	0,006	0,090	-0,010	0,100
10	0,039	0,144	0,014	0,020	0,012	0,014	0,016	0,024	-0,005	0,034	0,023	0,035	0,000	0,120	0,017	0,025	0,012	0,033	0,007	0,090	0,000	0,100
11	0,035	0,144	0,017	0,020	0,021	0,014	0,028	0,024	0,010	0,034	0,028	0,035	0,000	0,120	0,028	0,025	0,025	0,033	0,027	0,090	0,000	0,100
12	0,036	0,144	0,016	0,020	0,018	0,014	0,025	0,024	0,010	0,034	0,029	0,035	0,000	0,120	0,023	0,025	0,016	0,033	0,015	0,090	0,000	0,100
13	0,046	0,144	0,011	0,020	0,020	0,014	0,021	0,024	0,002	0,034	0,026	0,035	0,010	0,120	0,023	0,025	0,020	0,033	0,040	0,090	0,010	0,100
14	0,049	0,144	0,015	0,020	0,019	0,014	0,019	0,024	0,005	0,034	0,022	0,035	0,010	0,120	0,015	0,025	0,017	0,033	-0,003	0,090	0,000	0,100
15	0,038	0,144	0,010	0,020	0,019	0,014	0,026	0,024	0,005	0,034	0,024	0,035	0,000	0,120	0,024	0,025	0,018	0,033	0,022	0,090	0,000	0,100
16	0,031	0,144	0,007	0,020	0,015	0,014	0,026	0,040	0,001	0,034	0,021	0,035	0,020	0,120	0,021	0,025	0,026	0,033	0,027	0,090	0,000	0,100
17	0,048	0,144	0,009	0,020	0,011	0,014	0,015	0,024	-0,004	0,034	0,023	0,035	-0,010	0,120	0,012	0,025	0,006	0,033	0,035	0,090	0,000	0,100
18	0,047	0,144	0,003	0,020	0,014	0,014	0,015	0,024	0,002	0,034	0,020	0,035	-0,010	0,120	0,013	0,025	0,005	0,033	-0,005	0,090	0,000	0,100
19	0,058	0,144	0,016	0,020	0,025	0,014	0,032	0,024	0,013	0,034	0,036	0,035	0,050	0,120	0,029	0,025	0,037	0,033	0,032	0,090	0,000	0,100
20	0,076	0,144	0,016	0,020	0,025	0,014	0,030	0,024	0,004	0,034	0,036	0,035	0,000	0,120	0,030	0,025	0,026	0,033	0,022	0,090	0,000	0,100
21	0,047	0,144	0,024	0,020	0,024	0,014	0,031	0,024	0,007	0,034	0,037	0,035	0,000	0,120	0,028	0,025	0,028	0,033	0,026	0,090	0,000	0,100
22	0,063	0,144	0,022	0,020	0,024	0,014	0,037	0,040	0,006	0,034	0,037	0,035	0,030	0,120	0,034	0,025	0,046	0,033	0,022	0,090	0,000	0,100
23	0,056	0,144	0,022	0,020	0,029	0,014	0,030	0,024	0,014	0,034	0,038	0,035	0,020	0,120	0,028	0,025	0,041	0,033	0,034	0,090	0,000	0,100
24	0,063	0,144	0,023	0,020	0,029	0,014	0,030	0,024	-0,002	0,034	0,031	0,035	0,000	0,120	0,027	0,025	0,026	0,033	0,048	0,090	0,000	0,100
25	0,045	0,144	0,024	0,020	0,027	0,014	0,032	0,024	0,012	0,034	0,038	0,035	0,010	0,120	0,024	0,025	0,027	0,033	-0,004	0,090	0,010	0,100
26	0,072	0,144	0,021	0,020	0,025	0,014	0,030	0,024	0,010	0,034	0,034	0,035	0,000	0,120	0,022	0,025	0,028	0,033	-0,002	0,090	0,000	0,100
27	0,069	0,144	0,030	0,020	0,027	0,014	0,031	0,024	0,012	0,034	0,046	0,035	0,010	0,120	0,025	0,025	0,030	0,033	0,018	0,090	0,000	0,100
28	0,103	0,144	0,029	0,020	0,032	0,014	0,031	0,024	0,008	0,034	0,040	0,035	0,020	0,120	0,029	0,025	0,030	0,033	0,026	0,090	0,000	0,100
29	0,086	0,144	0,032	0,020	0,031	0,014	0,037	0,024	0,006	0,034	0,045	0,035	0,030	0,120	0,031	0,025	0,036	0,033	0,014	0,090	0,010	0,100
30	0,078	0,144	0,033	0,020	0,031	0,014	0,038	0,024	0,012	0,034	0,049	0,035	0,020	0,120	0,033	0,025	0,031	0,033	0,017	0,091	0,010	0,100
31	0,067	0,144	0,004	0,020	0,014	0,014	0,023	0,024	0,005	0,034	0,025	0,035	0,030	0,120	0,019	0,025	0,019	0,033	0,009	0,091	0,000	0,100
32	0,065	0,144	0,003	0,020	0,011	0,014	0,027	0,024	0,002	0,034	0,034	0,035	0,030	0,120	0,023	0,025	0,031	0,033	0,007	0,091	0,000	0,100
33	0,047	0,144	0,000	0,020	0,019	0,014	0,026	0,024	0,007	0,034	0,031	0,035	0,010	0,120	0,021	0,025	0,027	0,033	0,022	0,091	0,000	0,100
34	0,053	0,144	-0,007	0,020	0,017	0,014	0,024	0,024	0,000	0,034	0,031	0,035	0,000	0,120	0,020	0,025	0,023	0,033	0,027	0,091	0,000	0,100
35	0,073	0,144	0,002	0,020	0,019	0,014	0,027	0,024	0,002	0,034	0,032	0,035	-0,020	0,120	0,027	0,025	0,021	0,033	0,007	0,091	0,000	0,100
36	0,082	0,144	0,003	0,020	0,017	0,014	0,028	0,024	-0,009	0,034	0,030	0,035	0,010	0,120	0,027	0,025	0,031	0,033	0,034	0,091	0,000	0,100
37	0,063	0,144	-0,001	0,020	0,016	0,014	0,029	0,024	-0,001	0,034	0,036	0,035	0,020	0,120	0,025	0,025	0,030	0,033	0,027	0,091	0,000	0,100
38	0,077	0,144	-0,005	0,020	0,020	0,014	0,027	0,024	0,008	0,034	0,033	0,035	0,020	0,120	0,027	0,025	0,026	0,033	0,029	0,091	0,000	0,100
39	0,070	0,144	0,000	0,020	0,024	0,014	0,035	0,040	0,015	0,034	0,038	0,035	0,040	0,120	0,034	0,025	0,034	0,033	0,027	0,091	0,010	0,100
40	0,064	0,144	0,000	0,020	0,021	0,014	0,027	0,024	-0,002	0,034	0,041	0,035	0,010	0,120	0,025	0,025	0,013	0,033	0,034	0,091	0,010	0,100
41	0,070	0,144	0,012	0,020	0,021	0,014	0,025	0,024	0,003	0,034	0,039	0,035	0,010	0,120	0,023	0,025	0,014	0,033	-0,012	0,091	0,000	0,100
42	0,070	0,144	0,012	0,020	0,023	0,014	0,026	0,024	0,001	0,034	0,040	0,035	0,000	0,120	0,023	0,025	0,018	0,033	0,004	0,091	0,000	0,100
43	0,093	0,144	0,000	0,020	0,024	0,014	0,023	0,024	-0,001	0,034	0,038	0,035	-0,010	0,120	0,019	0,025	0,025	0,033	0,008	0,091	0,000	0,100
44	0,088	0,144	-0,003	0,020	0,024	0,014	0,025	0,024	0,001	0,034	0,032	0,035	-0,010	0,120	0,022	0,025	0,024	0,033	0,022	0,091	0,000	0,100
45	0,082	0,144	-0,004	0,020	0,021	0,014	0,031	0,024	0,005	0,034	0,040	0,035	0,020	0,120	0,028	0,025	0,045	0,033	-0,022	0,091	0,010	0,100
46	0,074	0,144	0,001	0,020	0,020	0,014	0,026	0,024	0,002	0,034	0,033	0,035	-0,010	0,120	0,023	0,025	0,041	0,033	-0,038	0,091	0,000	0,100
47	0,092	0,144	0,006	0,020	0,025	0,014	0,033	0,024	0,010	0,034	0,047	0,035	0,020	0,120	0,030	0,025	0,047	0,033	0,016	0,091	0,010	0,100
48	0,090	0,144	0,008	0,020	0,033	0,014	0,037	0,024	0,010	0,034	0,045	0,035	0,020	0,120	0,034	0,025	0,053	0,033	0,020	0,091	0,010	0,100
49	0,089	0,144	0,004	0,020	0,028	0,014	0,035	0,024	0,009	0,034	0,045	0,035	0,010	0,120	0,030	0,025	0,054	0,033	-0,006	0,091	0,010	0,100
50	0,077	0,144	-0,004	0,020	0,027	0,014	0,029	0,024	0,006	0,034	0,044	0,035	-0,010	0,120	0,027	0,025	0,060	0,033	0,014	0,091	0,010	0,100
51	0,098	0,144	0,019	0,020	0,031	0,014	0,037	0,024	0,016	0,034	0,054	0,035	-0,010	0,120	0,032	0,025	0,038	0,033	-0,008	0,091	0,010	0,100
52	0,081	0,144	0,017	0,020	0,030	0,014	0,037	0,024	0,002	0,034	0,057	0,035	-0,010	0,120	0,029	0,025	0,038	0,033	0,002	0,091	0,010	0,100
53	0,097	0,144	0,010	0,020	0,036	0,014	0,036	0,024	0,005	0,034	0,051	0,035	0,000	0,120	0,035	0,025	0,045	0,033	-0,012	0,091	0,010	0,100
54	0,099	0,144	0,011	0,020	0,037	0,014	0,039	0,024	0,003	0,034	0,052	0,035	-0,010	0,120	0,038	0,025	0,039	0,033	-0,006	0,091	0,010	0,100
55	0,108	0,144	0,016	0,020	0,041	0,014	0,045	0,024	0,009	0,034	0,055	0,035	0,020	0,120	0,046	0,025	0,043	0,033	-0,002	0,091	0,010	0,100
56	0,089	0,144	0,017	0,020	0,036	0,014	0,042	0,024	-0,006	0,034	0,054	0,035	-0,010	0,120	0,037	0,025	0,027	0,033	0,012	0,091	0,000	0,100
57	0,079	0,144	0,010	0,020	0,033	0,014	0,047	0,024	-0,003	0,034	0,056	0,035	0,000	0,120	0,040	0,025	0,043	0,033	0,006	0,091	0,010	0,100
58	0,094	0,144	0,009	0,020	0,037	0,014	0,042	0,024	-0,003	0,034	0,050	0,035	-0,030	0,120	0,040	0,025	0,043	0,033	0,006	0,091	0,010	0,100
59	0,116	0,144	0,006	0,020	0,031	0,014	0,038	0,024	0,001	0,034	0,052	0,035	0,000	0,120	0,044	0,025	0,042	0,033	0,000	0,091	0,010	0,100
60	0,091	0,144	0,002	0,020	0,037	0,014	0,038	0,024	-0,010	0,034	0,056	0,035	-0,050	0,120	0,035	0,025	0,033	0,033	0,034	0,091	0,000	0,100
61	0,075	0,144	0,006	0,020	0,032	0,014	0,034	0,024	-0,003	0,034	0,053	0,035	-0,040	0,120	0,034	0,025	0,036	0,033	0,046	0,091	0,020	0,100
62	0,095	0,144	0,010	0,020	0,036	0,014	0,041	0,024	0,001	0,034	0,060	0,035	-0,040	0,120	0,033	0,025	0,038	0,033	0,024	0,091	0,020	0,100
63	0,097	0,144	0,018	0,020	0,052	0,014	0,055	0,024	0,007	0,034	0,069	0,035	-0,010	0,120	0,050	0,025	0,059	0,033	0,030	0,091	0,010	0,100
64	0,124	0,144	0,016	0,020	0,049	0,014	0,056	0,024	0,003	0,034	0,064	0,035	0,030	0,120	0,054	0,025	0,065	0,033	0,080	0,091	0,010	0,100
65	0,094	0,144	0,015	0,020	0,047	0,014	0,051	0,024	-0,001	0,034	0,064	0,035	-0,020	0,120	0,049	0,025	0,054	0,033	0,048	0,091	0,020	0,100
66	0,103	0,144	0,017	0,020	0,046	0,014	0,045	0,024	-0,001	0,034	0,058	0,035	-0,030	0,120	0,044	0,025	0,044	0,033	0,042	0,091	0,010	0,100
67	0,096	0,144	0,027	0,020	0,046	0,014	0,051	0,024	0,004	0,034	0,068	0,035	-0,020	0,120	0,047	0,025	0,057	0,033	0,044	0,091	0,020	0,100
68	0,106	0,144	0,024	0,020	0,049	0,014	0,046	0,024	-0,004	0,034	0,063	0,035	-0,030	0,120	0,043	0,025	0,046	0,033	0,065	0,091	0,010	0,100
69	0,090	0,144	0,024	0,020	0,047	0,014	0,049	0,024	0,006	0,034	0,064	0,035	-0,020	0,120	0,046	0,025	0,057	0,033	0,059	0,091	0,020	0,100
70	0,113	0,144	0,019	0,020	0,055	0,014	0,061	0,024	0,007	0,034	0,075	0,035	-0,010	0,120	0,053	0,025	0,065	0,033	0,023	0,091	0,020	0,100
71	0,116	0,144	0,027	0,020	0,061	0,014	0,064	0,024	0,015	0,034	0,083	0,035	-0,020	0,120	0,059	0,025	0,064	0,033	0,035	0,091	0,020	0,100
72	0,121	0,144	0,024	0,020	0,060	0,014	0,066	0,024	0,009	0,034	0,087	0,035	-0,020	0,120	0,057	0,025	0,064	0,033	0,013	0,091	0,020	0,100
73	0,098	0,144	0,021	0,020	0,062	0,014	0,063	0,024	0,002	0,034	0,079	0,035	-0,010	0,120	0,055	0,025	0,063	0,033	0,019	0,091	0,020	0,100
74	0,112	0,144	0,018	0,020	0,057	0,014	0,061	0,024	0,011	0,034	0,077	0,035	0,000	0,120	0,060	0,025	0,064	0,033	0,069	0,091	0,020	0,100
75	0,099	0,144	0,019	0,020	0,060	0,014	0,065	0,024	0,004	0,034	0,076	0,035	-0,010	0,120	0,056	0,025	0,076	0,033	0,037	0,091	0,020	0,100
76	0,106	0,144	0,025	0,020	0,056	0,014	0,063	0,024	0,006	0,034	0,075	0,035	-0,030	0,120	0,058	0,025	0,053	0,033	0,031	0,091	0,020	0,100
77	0,111	0,144	0,027	0,020	0,052	0,014	0,064	0,024	0,006	0,034	0,078	0,035	0,000	0,120	0,056	0,025	0,055	0,033	0,033	0,091	0,020	0,100
78	0,107	0,144	0,031	0,020	0,062	0,014	0,070	0,024	0,019	0,034	0,078	0,035	0,010	0,120	0,066	0,025	0,064	0,033	0,055	0,091	0,020	0,101
79	0,114	0,144	0,043	0,020	0,068	0,014	0,077	0,040	0,021	0,034	0,082	0,035	0,000	0,120	0,072	0,025	0,076	0,033	0,049	0,091	0,030	0,101
80	0,127	0,144	0,037	0,020	0,068	0,014	0,075	0,024	0,010	0,034	0,090	0,035	-0,010	0,120	0,071	0,025	0,075	0,033	0,021	0,091	0,030	0,101
81	0,081	0,144	0,038	0,020	0,066	0,014	0,071	0,024	0,002	0,034	0,092	0,035	-0,020	0,120	0,068	0,025	0,066	0,033	0,023	0,091	0,020	0,101
82	0,105	0,144	0,035	0,020	0,064	0,014	0,075	0,024	0,016	0,034	0,093	0,035	0,010	0,120	0,069	0,025	0,077	0,033	0,023	0,091	0,040	0,101
83	0,115	0,144	0,036	0,020	0,073	0,014	0,074	0,024	0,003	0,034	0,093	0,035	-0,020	0,120	0,070	0,025	0,073	0,033	0,055	0,091	0,040	0,101
84	0,116	0,144	0,031	0,020	0,068	0,014	0,077	0,024	0,011	0,034	0,088	0,035	0,000	0,120	0,080	0,025	0,094	0,033	0,025	0,091	0,050	0,101
85	0,124	0,144	0,040	0,020	0,072	0,014	0,077	0,024	0,005	0,034	0,097	0,035	-0,010	0,120	0,074	0,025	0,084	0,033	0,037	0,091	0,060	0,101
86	0,110	0,144	0,046	0,020	0,074	0,014	0,090	0,040	0,011	0,034	0,095	0,035	0,010	0,120	0,087	0,025	0,114	0,033	-0,011	0,091	0,040	0,101
87	0,091	0,144	0,049	0,020	0,069	0,014	0,077	0,024	0,000	0,034	0,096	0,035	0,020	0,120	0,074	0,025	0,087	0,033	0,049	0,091	0,040	0,101
88	0,126	0,144	0,048	0,020	0,073	0,014	0,073	0,024	0,000	0,034	0,090	0,035	0,000	0,120	0,068	0,025	0,083	0,033	0,065	0,091	0,040	0,101
89	0,120	0,144	0,054	0,020	0,071	0,014	0,077	0,024	0,002	0,034	0,091	0,035	0,010	0,120	0,073	0,025	0,092	0,033	0,055	0,091	0,060	0,101
90	0,110	0,144	0,032	0,020	0,052	0,014	0,058	0,024	-0,004	0,034	0,072	0,035	-0,020	0,120	0,056	0,025	0,072	0,033	0,030	0,092	0,050	0,101
91	0,105	0,144	0,022	0,020	0,050	0,014	0,057	0,024	-0,002	0,034	0,080	0,035	-0,030	0,120	0,054	0,025	0,064	0,033	-0,002	0,092	0,030	0,101
92	0,113	0,144	0,025	0,020	0,051	0,014	0,058	0,024	-0,005	0,034	0,085	0,035	-0,020	0,120	0,055	0,025	0,063	0,033	0,016	0,092	0,030	0,101
93	0,113	0,144	0,023	0,020	0,058	0,014	0,062	0,024	-0,003	0,034	0,078	0,035	-0,030	0,120	0,052	0,025	0,067	0,033	-0,006	0,092	0,030	0,101
94	0,097	0,144	0,023	0,020	0,060	0,014	0,064	0,024	0,000	0,034	0,083	0,035	-0,010	0,120	0,060	0,025	0,069	0,033	0,046	0,092	0,040	0,101
95	0,101	0,144	0,030	0,020	0,059	0,014	0,060	0,024	0,002	0,034	0,080	0,035	-0,020	0,120	0,053	0,025	0,056	0,033	0,028	0,092	0,030	0,101
96	0,109	0,144	0,037	0,020	0,055	0,014	0,056	0,024	-0,009	0,034	0,076	0,035	-0,020	0,120	0,055	0,025	0,051	0,033	0,060	0,092	0,030	0,101
97	0,104	0,144	0,036	0,020	0,055	0,014	0,063	0,024	0,000	0,034	0,079	0,035	-0,030	0,120	0,064	0,025	0,061	0,033	0,042	0,092	0,040	0,101
98	0,105	0,144	0,039	0,020	0,061	0,014	0,066	0,024	0,007	0,034	0,078	0,035	0,000	0,120	0,065	0,025	0,063	0,033	0,032	0,092	0,030	0,101
99	0,154	0,144	0,042	0,020	0,058	0,014	0,065	0,024	0,002	0,034	0,079	0,035	-0,020	0,120	0,058	0,025	0,059	0,033	0,020	0,092	0,040	0,101
100	0,102	0,144	0,039	0,020	0,058	0,014	0,064	0,024	0,003	0,034	0,083	0,035	-0,020	0,120	0,060	0,025	0,055	0,033	0,025	0,092	0,040	0,101

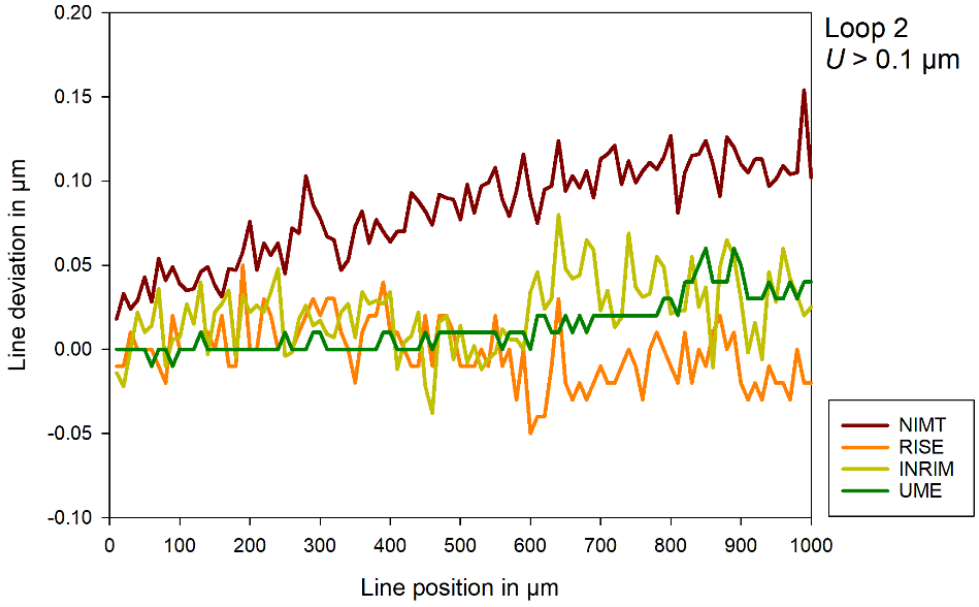


Figure 14 Plot of the results of participants for loop 2. Institutes claiming an expanded uncertainty larger than 0.1 µm (0.18 µm to 0.29 µm).

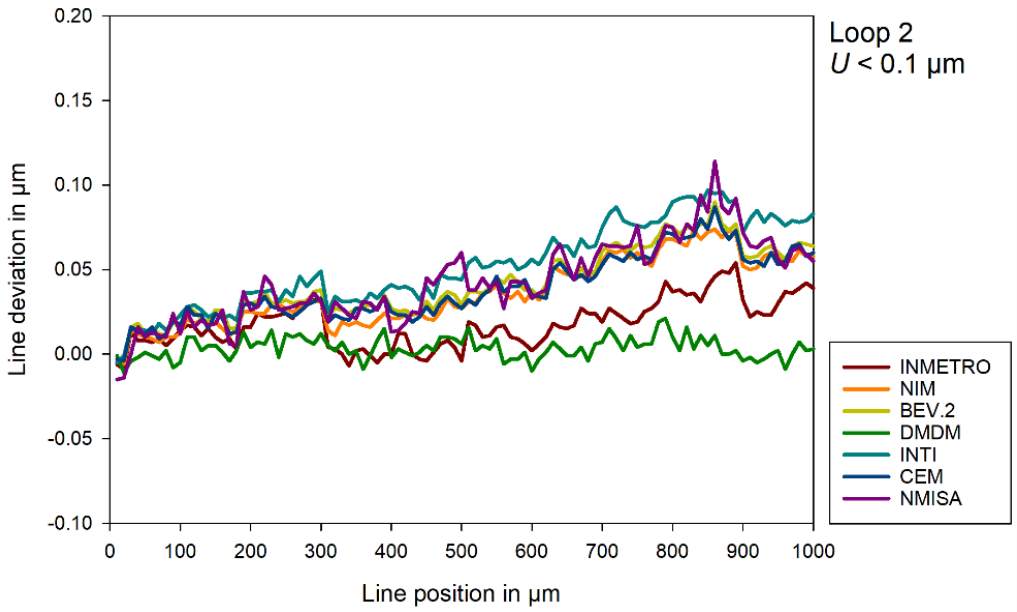


Figure 15 Plot of the results of participants for loop 2. Institutes claiming an expanded uncertainty smaller than 0.1 µm (0.028 µm to 0.070 µm).

6.2 Measurement uncertainties

The participants were asked to submit an overall standard uncertainty value for each of the measurands e_i separately. Moreover, they were asked to submit an uncertainty expression to be comparable to the respective range-based CMC. It was asked for a rounding to the nearest nanometer. It was not required to state the calculated or assumed degrees of freedom.

6.3 Changes to results after Draft A.1

INRIM had reported expanded uncertainties instead of standard uncertainties. By comparison to the published CMC entries this error is plausible.

INMETRO realized a problem with their setup and increased their uncertainty values marginally.

Obviously, these changes caused a slight modification of the reference values, but the overall findings were not affected. No participant showed E_n values large than 1, irrespective of the requested changes.

6.4 Calculation of the SCRV

The technical protocol of this comparison is very specific on the calculation of the reference values and how to treat outliers or other suspicious results. Luckily none of the different measures had to be applied. All results were consistent and no participant stated extremely small or implausible uncertainties. This is quite remarkable since a total of 1400 individual values were subject to the calculation.

The SCRV for each individual line could thus be calculated as the weighted mean of all participants. The procedure was applied for both artefacts separately. A total of 200 SCRV were so obtained, 100 for each artefact.

The total number of participants submitting results is denoted by N (3 for loop 1 and 11 for loop 2). For simplicity no index for the two loops is introduced in the following.

Each laboratory (indexed by j) reports a set of 100 measured values (indexed by i), $e_{i,j}$ and their associated standard uncertainties $u(e_{i,j}) \equiv u_{i,j}$.

The normalised weights, $w_{i,j}$, for the results $e_{i,j}$, are given by:

$$w_{i,j} = \frac{C_i}{u_{i,j}^2}$$

Where the normalising factors, C_i, are given by:

$$C_i = \sum_{j=1}^{N} \frac{1}{u_{i,j}^2}$$

Using the normalized weights the reference values for each line are the weighted means, $e_{i,\mathrm{ref}}$, which are given by:

$$e_{i,\mathrm{ref}} = \sum_{j=1}^{N} w_{i,j} \cdot e_{i,j}$$

The associated standard uncertainties of the reference values are calculated by:

$$u_{i,\mathrm{ref}} = \sqrt{C_i}$$

The reference values and their associated standard uncertainties for both loops are compiled in Table 6 and Figure 16, respectively.

Table 6 Supplementary comparison reference values (SCRV) for both artefacts and for each line

Line	SCRV loop 1	
	$e_{l,ref}$	$u_{l,ref}$
	µm	µm
1	0,002	0,021
2	-0,001	0,021
3	0,022	0,021
4	0,019	0,021
5	0,019	0,021
6	0,016	0,021
7	0,018	0,021
8	0,019	0,021
9	0,017	0,021
10	0,016	0,021
11	0,032	0,021
12	0,031	0,021
13	0,027	0,021
14	0,024	0,021
15	0,022	0,021
16	0,020	0,021
17	0,021	0,021
18	0,020	0,021
19	0,032	0,021
20	0,027	0,021
21	0,031	0,021
22	0,031	0,021
23	0,029	0,021
24	0,031	0,021
25	0,030	0,021
26	0,027	0,021
27	0,032	0,021
28	0,032	0,021
29	0,033	0,021
30	0,031	0,021
31	0,019	0,021
32	0,016	0,021
33	0,019	0,021
34	0,018	0,021
35	0,019	0,021
36	0,021	0,021
37	0,020	0,021
38	0,016	0,021
39	0,019	0,021
40	0,019	0,021
41	0,019	0,021
42	0,020	0,021
43	0,018	0,021
44	0,018	0,021
45	0,017	0,021
46	0,014	0,021
47	0,022	0,021
48	0,022	0,021
49	0,022	0,021
50	0,016	0,021
51	0,023	0,021
52	0,019	0,021
53	0,018	0,021
54	0,021	0,021
55	0,024	0,021
56	0,024	0,021
57	0,020	0,021
58	0,018	0,021
59	0,017	0,021
60	0,016	0,021
61	0,015	0,021
62	0,020	0,021
63	0,024	0,021
64	0,027	0,021
65	0,022	0,021
66	0,021	0,021
67	0,023	0,021
68	0,024	0,021
69	0,022	0,021
70	0,025	0,021
71	0,036	0,021
72	0,036	0,021
73	0,030	0,021
74	0,027	0,021
75	0,024	0,021
76	0,027	0,021
77	0,021	0,021
78	0,029	0,021
79	0,032	0,021
80	0,034	0,021
81	0,032	0,021
82	0,039	0,021
83	0,035	0,021
84	0,035	0,021
85	0,033	0,021
86	0,038	0,021
87	0,033	0,021
88	0,036	0,021
89	0,031	0,021
90	0,015	0,021
91	0,011	0,021
92	0,014	0,021
93	0,012	0,021
94	0,014	0,021
95	0,014	0,021
96	0,014	0,021
97	0,015	0,021
98	0,018	0,021
99	0,015	0,021
100	0,016	0,021

Line	SCRV loop 2	
	$e_{l,ref}$	$u_{l,ref}$
	µm	µm
1	-0,005	0,008
2	-0,007	0,008
3	0,012	0,008
4	0,012	0,008
5	0,010	0,008
6	0,010	0,008
7	0,009	0,008
8	0,009	0,008
9	0,012	0,008
10	0,013	0,008
11	0,022	0,008
12	0,019	0,008
13	0,018	0,008
14	0,017	0,008
15	0,018	0,008
16	0,015	0,009
17	0,011	0,008
18	0,011	0,008
19	0,026	0,008
20	0,024	0,008
21	0,025	0,008
22	0,027	0,009
23	0,028	0,008
24	0,026	0,008
25	0,026	0,008
26	0,024	0,008
27	0,028	0,008
28	0,030	0,008
29	0,031	0,008
30	0,032	0,008
31	0,015	0,008
32	0,015	0,008
33	0,017	0,008
34	0,014	0,008
35	0,018	0,008
36	0,017	0,008
37	0,017	0,008
38	0,018	0,008
39	0,022	0,009
40	0,018	0,008
41	0,019	0,008
42	0,020	0,008
43	0,018	0,008
44	0,018	0,008
45	0,020	0,008
46	0,018	0,008
47	0,025	0,008
48	0,029	0,008
49	0,026	0,008
50	0,023	0,008
51	0,030	0,008
52	0,029	0,008
53	0,030	0,008
54	0,031	0,008
55	0,036	0,008
56	0,031	0,008
57	0,031	0,008
58	0,031	0,008
59	0,029	0,008
60	0,028	0,008
61	0,027	0,008
62	0,031	0,008
63	0,044	0,008
64	0,044	0,008
65	0,040	0,008
66	0,038	0,008
67	0,042	0,008
68	0,040	0,008
69	0,042	0,008
70	0,047	0,008
71	0,053	0,008
72	0,052	0,008
73	0,050	0,008
74	0,049	0,008
75	0,051	0,008
76	0,049	0,008
77	0,048	0,008
78	0,056	0,008
79	0,062	0,009
80	0,061	0,008
81	0,058	0,008
82	0,060	0,008
83	0,062	0,008
84	0,063	0,008
85	0,065	0,008
86	0,070	0,009
87	0,065	0,008
88	0,065	0,008
89	0,067	0,008
90	0,048	0,008
91	0,045	0,008
92	0,046	0,008
93	0,048	0,008
94	0,052	0,008
95	0,050	0,008
96	0,049	0,008
97	0,051	0,008
98	0,055	0,008
99	0,053	0,008
100	0,053	0,008

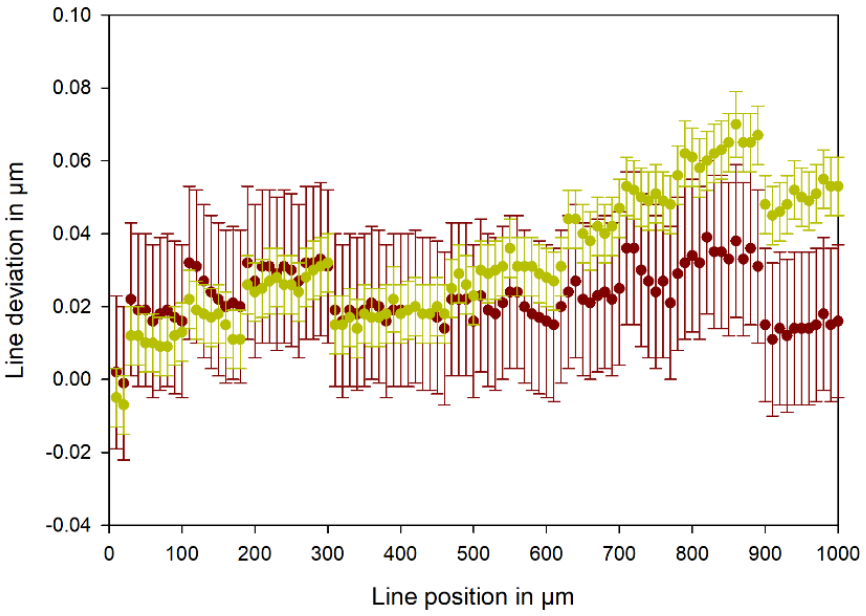


Figure 16 Reference values (SCRV) for the two artefacts used in the two loops. Red symbols for loop 1, green symbols for loop 2. Error bars denote the standard uncertainties of the reference values.

6.5 Calculation of Degrees of Equivalence

The Degree of Equivalence, DoE, for a laboratory result is simply the difference of each laboratory's result from the reference values. For each laboratory there exist 100 DoE. They are denoted by $d_{i,j}$:

$$d_{i,j} = e_{i,j} - e_{i,\mathrm{ref}}$$

Since all results contributed to the weighted mean, their associated standard uncertainty is given by:

$$u(d_{i,j}) = \sqrt{u_{i,j}^2 - u_{i,\mathrm{ref}}^2}$$

The minus sign reflects the impact of correlation between the individual deviations and the reference deviation, calculated from all individual deviations for each line position.

Finally, the deviations normalized to their expanded uncertainties (E_n, assuming $k = 2$) are determined for each laboratory j and each line i by:

$$E_{\mathrm{n}\,i,j} = \frac{d_{i,j}}{2\,u(d_{i,j})}$$

The calculated results (DoE) for the participants are presented in Table 7 (for loop 1) and Table 8 (for loop 2), respectively. Table 9 summarized the absolute E_n values for all participants.

6.5.1 Tabular representation of DoE results

Table 7 Degree of equivalence (DoE) with standard uncertainties for the participants of loop 1. The order of participants presented in the table heading does not correspond to the chronological order. For chronological order see Table 2.

Line	INM		BEV.1		GUM	
	d_i	$u(d_i)$	d_i	$u(d_i)$	d_i	$u(d_i)$
	µm	µm	µm	µm	µm	µm
1	-0,242	0,500	-0,004	0,011	0,015	0,040
2	0,101	0,500	-0,004	0,011	0,014	0,040
3	0,188	0,500	-0,007	0,011	0,024	0,040
4	0,031	0,500	-0,004	0,011	0,015	0,040
5	-0,249	0,500	-0,007	0,011	0,025	0,040
6	-0,106	0,500	-0,005	0,011	0,019	0,040
7	-0,158	0,500	-0,007	0,011	0,027	0,040
8	-0,129	0,500	-0,008	0,011	0,027	0,040
9	-0,157	0,500	-0,008	0,011	0,028	0,040
10	-0,126	0,500	-0,004	0,011	0,017	0,040
11	-0,062	0,500	-0,007	0,011	0,027	0,040
12	-0,151	0,500	-0,007	0,011	0,024	0,040
13	-0,177	0,500	-0,007	0,011	0,027	0,040
14	-0,284	0,500	-0,005	0,011	0,022	0,040
15	-0,242	0,510	-0,007	0,011	0,026	0,040
16	-0,100	0,510	-0,006	0,011	0,021	0,040
17	-0,241	0,510	-0,007	0,011	0,025	0,040
18	-0,320	0,510	-0,006	0,011	0,023	0,040
19	0,788	0,510	-0,009	0,011	0,025	0,040
20	-0,047	0,510	-0,005	0,011	0,018	0,040
21	-0,351	0,510	-0,008	0,011	0,031	0,040
22	-0,271	0,510	-0,005	0,011	0,018	0,040
23	-0,369	0,510	-0,007	0,011	0,026	0,040
24	-0,451	0,510	-0,005	0,011	0,020	0,040
25	-0,530	0,520	-0,007	0,011	0,027	0,040
26	-0,377	0,520	-0,005	0,011	0,020	0,040
27	-0,332	0,520	-0,005	0,011	0,022	0,040
28	-0,202	0,520	-0,003	0,011	0,014	0,040
29	-0,263	0,520	-0,006	0,011	0,025	0,040
30	-0,181	0,520	-0,003	0,011	0,013	0,040
31	-0,269	0,520	-0,007	0,011	0,025	0,040
32	-0,186	0,520	-0,005	0,011	0,020	0,040
33	-0,129	0,530	-0,008	0,011	0,030	0,040
34	-0,238	0,530	-0,006	0,011	0,021	0,040
35	-0,359	0,530	-0,007	0,011	0,027	0,040
36	-0,321	0,530	-0,007	0,011	0,029	0,040
37	-0,240	0,530	-0,007	0,011	0,028	0,040
38	-0,086	0,530	-0,006	0,011	0,020	0,040
39	-0,129	0,540	-0,005	0,011	0,020	0,040
40	-0,129	0,540	-0,006	0,011	0,023	0,040
41	-0,239	0,540	-0,005	0,011	0,020	0,040
42	-0,150	0,540	-0,006	0,011	0,022	0,040
43	-0,228	0,540	-0,006	0,011	0,022	0,040
44	-0,108	0,550	-0,006	0,011	0,022	0,040
45	-0,267	0,550	-0,005	0,011	0,020	0,040
46	-0,244	0,550	-0,002	0,011	0,009	0,040
47	-0,322	0,550	-0,005	0,011	0,019	0,040
48	-0,502	0,550	-0,005	0,011	0,020	0,040
49	-0,342	0,560	-0,005	0,011	0,019	0,040
50	-0,346	0,560	-0,004	0,011	0,015	0,040
51	-0,213	0,560	-0,004	0,011	0,014	0,040
52	-0,279	0,560	-0,002	0,011	0,009	0,040
53	-0,188	0,570	-0,003	0,011	0,011	0,040
54	-0,151	0,570	-0,003	0,011	0,010	0,040
55	-0,144	0,570	-0,001	0,011	0,005	0,040
56	-0,284	0,570	-0,002	0,011	0,007	0,040
57	-0,240	0,580	-0,001	0,011	0,005	0,040
58	-0,168	0,580	-0,002	0,011	0,009	0,040
59	-0,017	0,580	0,001	0,011	-0,004	0,040
60	-0,126	0,580	0,001	0,011	-0,002	0,040
61	-0,285	0,590	0,001	0,011	-0,002	0,040
62	-0,250	0,590	-0,001	0,011	0,004	0,040
63	-0,224	0,590	0,003	0,011	-0,009	0,040
64	-0,257	0,590	-0,001	0,011	0,006	0,040
65	-0,282	0,600	0,002	0,011	-0,004	0,040
66	-0,221	0,600	0,003	0,011	-0,010	0,040
67	-0,183	0,600	0,002	0,011	-0,007	0,040
68	-0,264	0,600	0,001	0,011	-0,003	0,040
69	-0,052	0,610	0,003	0,011	-0,009	0,040
70	-0,305	0,610	0,002	0,011	-0,006	0,040
71	-0,346	0,610	0,003	0,011	-0,007	0,040
72	-0,356	0,620	0,001	0,011	-0,002	0,040
73	-0,140	0,620	0,004	0,011	-0,012	0,040
74	-0,207	0,620	0,004	0,011	-0,011	0,040
75	-0,054	0,620	0,005	0,011	-0,016	0,040
76	-0,217	0,630	0,003	0,011	-0,010	0,040
77	-0,041	0,630	0,005	0,011	-0,018	0,040
78	-0,459	0,630	0,004	0,011	-0,011	0,040
79	-0,132	0,640	0,006	0,011	-0,021	0,040
80	-0,214	0,640	0,003	0,011	-0,008	0,040
81	-0,192	0,640	0,005	0,011	-0,016	0,040
82	-0,109	0,650	0,005	0,011	-0,018	0,040
83	-0,075	0,650	0,007	0,011	-0,024	0,040
84	-0,075	0,650	0,005	0,011	-0,016	0,040
85	-0,083	0,660	0,008	0,011	-0,028	0,040
86	-0,088	0,660	0,003	0,011	-0,012	0,040
87	-0,013	0,660	0,005	0,011	-0,018	0,040
88	-0,056	0,670	0,005	0,011	-0,019	0,040
89	0,019	0,670	0,008	0,011	-0,027	0,040
90	-0,015	0,670	0,008	0,011	-0,026	0,040
91	-0,031	0,680	0,009	0,011	-0,033	0,040
92	0,026	0,680	0,008	0,011	-0,028	0,040
93	-0,152	0,680	0,007	0,011	-0,026	0,040
94	-0,064	0,690	0,008	0,011	-0,028	0,040
95	0,006	0,690	0,009	0,011	-0,030	0,040
96	0,156	0,690	0,008	0,011	-0,029	0,040
97	0,135	0,700	0,008	0,011	-0,030	0,040
98	-0,008	0,700	0,007	0,011	-0,023	0,040
99	0,095	0,700	0,009	0,011	-0,033	0,040
100	0,014	0,710	0,008	0,011	-0,028	0,040

Table 8 Degree of equivalence (DoE) with standard uncertainties for the participants of loop 2. The order of participants presented in the table heading does not correspond to the chronological order. For chronological order see Table 3.

Line	NIMT		INMETRO		NIM		BEV.2		DMDM		INTI		RISE		CEM		NMISA		INRIM		UME	
	d_i	$u(d_i)$	d_i	$u(d_i)$	d_i	$u(d_i)$	d_i	$u(d_i)$	d_i	$u(d_i)$	d_i	$u(d_i)$	d_i	$u(d_i)$	d_i	$u(d_i)$	d_i	$u(d_i)$	d_i	$u(d_i)$	d_i	$u(d_i)$
	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm
1	0,022	0,144	-0,001	0,018	0,001	0,011	0,002	0,022	0,003	0,033	0,000	0,034	-0,005	0,120	0,002	0,024	-0,011	0,031	-0,009	0,090	0,005	0,100
2	0,040	0,144	-0,002	0,018	0,001	0,011	0,002	0,022	-0,004	0,033	0,006	0,034	-0,003	0,120	0,003	0,024	-0,007	0,031	-0,015	0,090	0,007	0,100
3	0,011	0,144	0,001	0,018	0,002	0,011	0,003	0,022	-0,016	0,033	0,004	0,034	-0,002	0,120	0,004	0,024	-0,013	0,031	-0,012	0,090	-0,012	0,100
4	0,018	0,144	-0,004	0,018	0,000	0,011	0,006	0,022	-0,013	0,033	0,002	0,034	-0,012	0,120	0,001	0,024	0,005	0,031	0,010	0,090	-0,012	0,100
5	0,033	0,144	-0,002	0,018	0,000	0,011	0,002	0,022	-0,009	0,033	0,004	0,034	-0,010	0,120	0,002	0,024	0,000	0,031	0,000	0,090	-0,010	0,100
6	0,018	0,144	-0,003	0,018	-0,001	0,011	0,005	0,022	-0,011	0,033	0,002	0,034	-0,010	0,120	0,006	0,024	0,003	0,031	0,004	0,090	-0,020	0,100
7	0,045	0,144	0,001	0,018	-0,002	0,011	0,003	0,022	-0,011	0,033	0,009	0,034	-0,019	0,120	0,000	0,024	0,002	0,031	0,027	0,090	-0,009	0,100
8	0,032	0,144	-0,004	0,018	0,001	0,011	0,002	0,022	-0,007	0,033	0,005	0,034	-0,029	0,120	0,003	0,024	0,001	0,031	-0,019	0,090	-0,009	0,100
9	0,037	0,144	-0,004	0,018	-0,002	0,011	0,007	0,022	-0,020	0,033	0,007	0,034	0,008	0,120	0,008	0,024	0,011	0,031	-0,006	0,090	-0,022	0,100
10	0,026	0,144	0,001	0,018	-0,001	0,011	0,003	0,022	-0,018	0,033	0,010	0,034	-0,013	0,120	0,004	0,024	-0,001	0,031	-0,006	0,090	-0,013	0,100
11	0,013	0,144	-0,005	0,018	-0,001	0,011	0,006	0,022	-0,011	0,033	0,006	0,034	-0,022	0,120	0,006	0,024	0,003	0,031	0,005	0,090	-0,022	0,100
12	0,017	0,144	-0,003	0,018	-0,001	0,011	0,006	0,022	-0,009	0,033	0,010	0,034	-0,019	0,120	0,004	0,024	-0,003	0,031	-0,004	0,090	-0,019	0,100
13	0,028	0,144	-0,007	0,018	0,002	0,011	0,003	0,022	-0,017	0,033	0,008	0,034	-0,008	0,120	0,005	0,024	0,002	0,031	0,022	0,090	-0,008	0,100
14	0,032	0,144	-0,002	0,018	0,002	0,011	0,002	0,022	-0,011	0,033	0,005	0,034	-0,007	0,120	-0,002	0,024	0,001	0,031	-0,020	0,090	-0,017	0,100
15	0,020	0,144	-0,008	0,018	0,001	0,011	0,008	0,022	-0,013	0,033	0,006	0,034	-0,018	0,120	0,006	0,024	0,000	0,031	0,004	0,090	-0,018	0,100
16	0,016	0,144	-0,008	0,018	0,000	0,011	0,010	0,039	-0,014	0,033	0,006	0,034	0,005	0,120	0,006	0,023	0,011	0,031	0,012	0,090	-0,015	0,100
17	0,037	0,144	-0,002	0,018	0,000	0,011	0,004	0,022	-0,015	0,033	0,012	0,034	-0,021	0,120	0,001	0,024	-0,005	0,031	0,024	0,090	-0,011	0,100
18	0,036	0,144	-0,008	0,018	0,003	0,011	0,005	0,022	-0,008	0,033	0,009	0,034	-0,021	0,120	0,002	0,024	-0,006	0,031	-0,016	0,090	-0,011	0,100
19	0,033	0,144	-0,010	0,018	-0,001	0,011	0,007	0,022	-0,013	0,033	0,010	0,034	0,024	0,120	0,003	0,024	0,011	0,031	0,006	0,090	-0,026	0,100
20	0,052	0,144	-0,008	0,018	0,001	0,011	0,006	0,022	-0,020	0,033	0,012	0,034	-0,024	0,120	0,006	0,024	0,002	0,031	-0,002	0,090	-0,024	0,100
21	0,021	0,144	-0,001	0,018	-0,001	0,011	0,006	0,022	-0,018	0,033	0,012	0,034	-0,025	0,120	0,003	0,024	0,003	0,031	0,001	0,090	-0,025	0,100
22	0,036	0,144	-0,005	0,018	-0,003	0,011	0,010	0,039	-0,021	0,033	0,010	0,034	0,003	0,120	0,007	0,023	0,020	0,031	-0,005	0,090	-0,027	0,100
23	0,028	0,144	-0,006	0,018	0,001	0,011	0,001	0,022	-0,014	0,033	0,010	0,034	-0,008	0,120	0,000	0,024	0,013	0,031	0,006	0,090	-0,028	0,100
24	0,037	0,144	-0,003	0,018	0,003	0,011	0,004	0,022	-0,028	0,033	0,005	0,034	-0,026	0,120	0,001	0,024	0,000	0,031	0,022	0,090	-0,026	0,100
25	0,019	0,144	-0,002	0,018	0,001	0,011	0,005	0,022	-0,014	0,033	0,012	0,034	-0,016	0,120	-0,002	0,024	0,001	0,031	-0,030	0,090	-0,016	0,100
26	0,048	0,144	-0,003	0,018	0,001	0,011	0,006	0,022	-0,014	0,033	0,010	0,034	-0,024	0,120	-0,002	0,024	0,004	0,031	-0,026	0,090	-0,024	0,100
27	0,041	0,144	0,002	0,018	-0,001	0,011	0,003	0,022	-0,016	0,033	0,018	0,034	-0,018	0,120	-0,003	0,024	0,002	0,031	-0,010	0,090	-0,028	0,100
28	0,074	0,144	-0,001	0,018	0,002	0,011	0,001	0,022	-0,022	0,033	0,010	0,034	-0,010	0,120	-0,001	0,024	0,000	0,031	-0,004	0,090	-0,030	0,100
29	0,054	0,144	0,001	0,018	0,000	0,011	0,005	0,022	-0,026	0,033	0,014	0,034	-0,001	0,120	0,000	0,024	0,005	0,031	-0,017	0,090	-0,021	0,100
30	0,046	0,144	0,001	0,018	-0,001	0,011	0,006	0,022	-0,020	0,033	0,017	0,034	-0,012	0,120	0,001	0,024	-0,001	0,031	-0,015	0,091	-0,022	0,100
31	0,052	0,144	-0,010	0,018	-0,001	0,011	0,009	0,022	-0,009	0,033	0,010	0,034	0,015	0,120	0,004	0,024	0,005	0,031	-0,006	0,091	-0,015	0,100
32	0,050	0,144	-0,013	0,018	-0,004	0,011	0,012	0,022	-0,013	0,033	0,019	0,034	0,015	0,120	0,008	0,024	0,016	0,031	-0,008	0,091	-0,015	0,100
33	0,030	0,144	-0,017	0,018	0,002	0,011	0,009	0,022	-0,010	0,033	0,014	0,034	-0,007	0,120	0,004	0,024	0,009	0,031	0,005	0,091	-0,017	0,100
34	0,039	0,144	-0,021	0,018	0,003	0,011	0,010	0,022	-0,014	0,033	0,017	0,034	-0,014	0,120	0,006	0,024	0,008	0,031	0,013	0,091	-0,014	0,100
35	0,055	0,144	-0,015	0,018	0,001	0,011	0,009	0,022	-0,015	0,033	0,014	0,034	-0,038	0,120	0,009	0,024	0,004	0,031	-0,011	0,091	-0,018	0,100
36	0,064	0,144	-0,014	0,018	0,000	0,011	0,010	0,022	-0,026	0,033	0,013	0,034	-0,007	0,120	0,010	0,024	0,014	0,031	0,017	0,091	-0,017	0,100
37	0,046	0,144	-0,018	0,018	-0,001	0,011	0,012	0,022	-0,017	0,033	0,019	0,034	0,003	0,120	0,008	0,024	0,013	0,031	0,010	0,091	-0,017	0,100
38	0,059	0,144	-0,023	0,018	0,002	0,011	0,009	0,022	-0,010	0,033	0,015	0,034	0,002	0,120	0,009	0,024	0,008	0,031	0,011	0,091	-0,018	0,100
39	0,048	0,144	-0,022	0,018	0,002	0,011	0,013	0,039	-0,008	0,033	0,016	0,034	0,018	0,120	0,012	0,023	0,012	0,031	0,005	0,091	-0,012	0,100
40	0,046	0,144	-0,018	0,018	0,003	0,011	0,009	0,022	-0,019	0,033	0,023	0,034	-0,008	0,120	0,007	0,024	-0,005	0,031	0,016	0,091	-0,008	0,100
41	0,050	0,144	-0,008	0,018	0,002	0,011	0,006	0,022	-0,016	0,033	0,020	0,034	-0,009	0,120	0,004	0,024	-0,006	0,031	-0,031	0,091	-0,019	0,100
42	0,050	0,144	-0,009	0,018	0,003	0,011	0,006	0,022	-0,019	0,033	0,020	0,034	-0,020	0,120	0,003	0,024	-0,003	0,031	-0,016	0,091	-0,020	0,100
43	0,075	0,144	-0,018	0,018	0,006	0,011	0,005	0,022	-0,019	0,033	0,020	0,034	-0,028	0,120	0,001	0,024	0,007	0,031	-0,010	0,091	-0,018	0,100
44	0,070	0,144	-0,021	0,018	0,006	0,011	0,007	0,022	-0,017	0,033	0,014	0,034	-0,028	0,120	0,004	0,024	0,006	0,031	0,004	0,091	-0,018	0,100
45	0,061	0,144	-0,024	0,018	0,001	0,011	0,011	0,022	-0,015	0,033	0,020	0,034	0,000	0,120	0,008	0,024	0,025	0,031	-0,042	0,091	-0,010	0,100
46	0,056	0,144	-0,017	0,018	0,002	0,011	0,008	0,022	-0,016	0,033	0,015	0,034	-0,028	0,120	0,005	0,024	0,023	0,031	-0,056	0,091	-0,018	0,100
47	0,066	0,144	-0,019	0,018	0,000	0,011	0,008	0,022	-0,016	0,033	0,022	0,034	-0,005	0,120	0,005	0,024	0,022	0,031	-0,009	0,091	-0,015	0,100
48	0,061	0,144	-0,022	0,018	0,004	0,011	0,007	0,022	-0,020	0,033	0,016	0,034	-0,009	0,120	0,005	0,024	0,023	0,031	-0,009	0,091	-0,019	0,100
49	0,063	0,144	-0,022	0,018	0,002	0,011	0,009	0,022	-0,017	0,033	0,019	0,034	-0,016	0,120	0,004	0,024	0,028	0,031	-0,032	0,091	-0,016	0,100
50	0,053	0,144	-0,027	0,018	0,004	0,011	0,006	0,022	-0,018	0,033	0,021	0,034	-0,033	0,120	0,004	0,024	0,036	0,031	-0,009	0,091	-0,013	0,100
51	0,067	0,144	-0,011	0,018	0,001	0,011	0,007	0,022	-0,014	0,033	0,024	0,034	-0,040	0,120	0,002	0,024	0,007	0,031	-0,038	0,091	-0,020	0,100
52	0,053	0,144	-0,011	0,018	0,001	0,011	0,008	0,022	-0,026	0,033	0,028	0,034	-0,039	0,120	0,000	0,024	0,010	0,031	-0,027	0,091	-0,019	0,100
53	0,067	0,144	-0,020	0,018	0,006	0,011	0,006	0,022	-0,025	0,033	0,021	0,034	-0,030	0,120	0,005	0,024	0,014	0,031	-0,042	0,091	-0,020	0,100
54	0,068	0,144	-0,020	0,018	0,006	0,011	0,008	0,022	-0,028	0,033	0,021	0,034	-0,041	0,120	0,007	0,024	0,008	0,031	-0,037	0,091	-0,021	0,100
55	0,071	0,144	-0,020	0,018	0,005	0,011	0,009	0,022	-0,027	0,033	0,019	0,034	-0,016	0,120	0,010	0,024	0,006	0,031	-0,038	0,091	-0,026	0,100
56	0,058	0,144	-0,014	0,018	0,005	0,011	0,011	0,022	-0,037	0,033	0,023	0,034	-0,041	0,120	0,006	0,024	-0,004	0,031	-0,019	0,091	-0,031	0,100
57	0,048	0,144	-0,021	0,018	0,002	0,011	0,016	0,022	-0,034	0,033	0,025	0,034	-0,031	0,120	0,009	0,024	0,013	0,031	-0,025	0,091	-0,021	0,100
58	0,063	0,144	-0,022	0,018	0,006	0,011	0,010	0,022	-0,034	0,033	0,019	0,034	-0,061	0,120	0,009	0,024	0,012	0,031	-0,025	0,091	-0,021	0,100
59	0,087	0,144	-0,023	0,018	0,002	0,011	0,009	0,022	-0,028	0,033	0,023	0,034	-0,029	0,120	0,015	0,024	0,014	0,031	-0,029	0,091	-0,019	0,100
60	0,063	0,144	-0,026	0,018	0,009	0,011	0,010	0,022	-0,038	0,033	0,028	0,034	-0,078	0,120	0,007	0,024	0,005	0,031	0,006	0,091	-0,028	0,100
61	0,048	0,144	-0,021	0,018	0,005	0,011	0,007	0,022	-0,030	0,033	0,026	0,034	-0,067	0,120	0,007	0,024	0,009	0,031	0,019	0,091	-0,007	0,100
62	0,064	0,144	-0,020	0,018	0,005	0,011	0,010	0,022	-0,029	0,033	0,029	0,034	-0,071	0,120	0,002	0,024	0,008	0,031	-0,007	0,091	-0,011	0,100
63	0,053	0,144	-0,026	0,018	0,008	0,011	0,011	0,022	-0,037	0,033	0,025	0,034	-0,054	0,120	0,006	0,024	0,015	0,031	-0,014	0,091	-0,034	0,100
64	0,080	0,144	-0,028	0,018	0,005	0,011	0,012	0,022	-0,041	0,033	0,020	0,034	-0,014	0,120	0,010	0,024	0,022	0,031	0,036	0,091	-0,034	0,100
65	0,054	0,144	-0,025	0,018	0,007	0,011	0,011	0,022	-0,041	0,033	0,024	0,034	-0,060	0,120	0,009	0,024	0,014	0,031	0,008	0,091	-0,020	0,100
66	0,066	0,144	-0,021	0,018	0,008	0,011	0,008	0,022	-0,039	0,033	0,020	0,034	-0,068	0,120	0,006	0,024	0,007	0,031	0,004	0,091	-0,028	0,100
67	0,054	0,144	-0,015	0,018	0,004	0,011	0,008	0,022	-0,038	0,033	0,026	0,034	-0,062	0,120	0,005	0,024	0,014	0,031	0,002	0,091	-0,022	0,100
68	0,066	0,144	-0,016	0,018	0,009	0,011	0,005	0,022	-0,044	0,033	0,023	0,034	-0,070	0,120	0,003	0,024	0,005	0,031	0,025	0,091	-0,030	0,100
69	0,049	0,144	-0,018	0,018	0,005	0,011	0,007	0,022	-0,036	0,033	0,022	0,034	-0,062	0,120	0,004	0,024	0,015	0,031	0,017	0,091	-0,022	0,100
70	0,066	0,144	-0,028	0,018	0,008	0,011	0,013	0,022	-0,040	0,033	0,028	0,034	-0,057	0,120	0,006	0,024	0,017	0,031	-0,024	0,091	-0,027	0,100
71	0,063	0,144	-0,026	0,018	0,008	0,011	0,011	0,022	-0,038	0,033	0,030	0,034	-0,073	0,120	0,006	0,024	0,011	0,031	-0,018	0,091	-0,033	0,100
72	0,070	0,144	-0,028	0,018	0,008	0,011	0,014	0,022	-0,043	0,033	0,035	0,034	-0,072	0,120	0,005	0,024	0,012	0,031	-0,039	0,091	-0,032	0,100
73	0,047	0,144	-0,029	0,018	0,012	0,011	0,013	0,022	-0,048	0,033	0,029	0,034	-0,060	0,120	0,005	0,024	0,012	0,031	-0,031	0,091	-0,030	0,100
74	0,063	0,144	-0,032	0,018	0,008	0,011	0,012	0,022	-0,038	0,033	0,028	0,034	-0,049	0,120	0,011	0,024	0,014	0,031	0,020	0,091	-0,029	0,100
75	0,049	0,144	-0,031	0,018	0,009	0,011	0,014	0,022	-0,047	0,033	0,025	0,034	-0,061	0,120	0,005	0,024	0,025	0,031	-0,014	0,091	-0,031	0,100
76	0,058	0,144	-0,023	0,018	0,007	0,011	0,015	0,022	-0,043	0,033	0,026	0,034	-0,079	0,120	0,009	0,024	0,004	0,031	-0,018	0,091	-0,029	0,100
77	0,063	0,144	-0,021	0,018	0,004	0,011	0,016	0,022	-0,042	0,033	0,030	0,034	-0,048	0,120	0,008	0,024	0,007	0,031	-0,015	0,091	-0,028	0,100
78	0,051	0,144	-0,025	0,018	0,006	0,011	0,014	0,022	-0,037	0,033	0,022	0,034	-0,046	0,120	0,010	0,024	0,008	0,031	-0,001	0,091	-0,036	0,100
79	0,052	0,144	-0,019	0,018	0,006	0,011	0,015	0,039	-0,041	0,033	0,020	0,034	-0,062	0,120	0,010	0,023	0,015	0,031	-0,013	0,091	-0,032	0,100
80	0,066	0,144	-0,024	0,018	0,007	0,011	0,014	0,022	-0,051	0,033	0,029	0,034	-0,071	0,120	0,010	0,024	0,014	0,031	-0,040	0,091	-0,031	0,100
81	0,023	0,144	-0,020	0,018	0,008	0,011	0,012	0,022	-0,056	0,033	0,034	0,034	-0,078	0,120	0,010	0,024	0,008	0,031	-0,035	0,091	-0,038	0,100
82	0,045	0,144	-0,025	0,018	0,004	0,011	0,016	0,022	-0,044	0,033	0,033	0,034	-0,050	0,120	0,009	0,024	0,017	0,031	-0,037	0,091	-0,020	0,100
83	0,053	0,144	-0,026	0,018	0,011	0,011	0,011	0,022	-0,059	0,033	0,031	0,034	-0,082	0,120	0,008	0,024	0,011	0,031	-0,007	0,091	-0,022	0,100
84	0,053	0,144	-0,031	0,018	0,005	0,011	0,014	0,022	-0,052	0,033	0,025	0,034	-0,063	0,120	0,017	0,024	0,032	0,031	-0,038	0,091	-0,013	0,100
85	0,059	0,144	-0,025	0,018	0,007	0,011	0,013	0,022	-0,059	0,033	0,032	0,034	-0,075	0,120	0,009	0,024	0,019	0,031	-0,028	0,091	-0,005	0,100
86	0,040	0,144	-0,024	0,018	0,004	0,011	0,020	0,039	-0,058	0,033	0,025	0,034	-0,060	0,120	0,017	0,023	0,045	0,031	-0,081	0,091	-0,030	0,100
87	0,026	0,144	-0,016	0,018	0,004	0,011	0,012	0,022	-0,065	0,033	0,031	0,034	-0,045	0,120	0,009	0,024	0,022	0,031	-0,016	0,091	-0,025	0,100
88	0,061	0,144	-0,016	0,018	0,008	0,011	0,008	0,022	-0,065	0,033	0,025	0,034	-0,065	0,120	0,003	0,024	0,018	0,031	0,000	0,091	-0,025	0,100
89	0,053	0,144	-0,013	0,018	0,004	0,011	0,010	0,022	-0,065	0,033	0,024	0,034	-0,057	0,120	0,006	0,024	0,025	0,031	-0,012	0,091	-0,007	0,100
90	0,062	0,144	-0,016	0,018	0,004	0,011	0,010	0,022	-0,053	0,033	0,024	0,034	-0,068	0,120	0,008	0,024	0,024	0,031	-0,018	0,092	0,002	0,100
91	0,060	0,144	-0,023	0,018	0,005	0,011	0,012	0,022	-0,047	0,033	0,035	0,034	-0,075	0,120	0,009	0,024	0,019	0,031	-0,047	0,092	-0,015	0,100
92	0,066	0,144	-0,022	0,018	0,005	0,011	0,012	0,022	-0,051	0,033	0,039	0,034	-0,066	0,120	0,009	0,024	0,017	0,031	-0,030	0,092	-0,016	0,100
93	0,065	0,144	-0,026	0,018	0,010	0,011	0,013	0,022	-0,051	0,033	0,030	0,034	-0,078	0,120	0,004	0,024	0,019	0,031	-0,054	0,092	-0,018	0,100
94	0,046	0,144	-0,028	0,018	0,008	0,011	0,012	0,022	-0,052	0,033	0,031	0,034	-0,062	0,120	0,008	0,024	0,017	0,031	-0,006	0,092	-0,012	0,100
95	0,051	0,144	-0,020	0,018	0,009	0,011	0,010	0,022	-0,048	0,033	0,030	0,034	-0,070	0,120	0,003	0,024	0,006	0,031	-0,022	0,092	-0,020	0,100
96	0,061	0,144	-0,011	0,018	0,006	0,011	0,008	0,022	-0,057	0,033	0,027	0,034	-0,069	0,120	0,006	0,024	0,002	0,031	0,011	0,092	-0,019	0,100
97	0,053	0,144	-0,016	0,018	0,004	0,011	0,012	0,022	-0,052	0,033	0,028	0,034	-0,081	0,120	0,013	0,024	0,009	0,031	-0,009	0,092	-0,011	0,100
98	0,050	0,144	-0,017	0,018	0,006	0,011	0,011	0,022	-0,048	0,033	0,023	0,034	-0,055	0,120	0,010	0,024	0,008	0,031	-0,023	0,092	-0,025	0,100
99	0,101	0,144	-0,011	0,018	0,005	0,011	0,011	0,022	-0,051	0,033	0,026	0,034	-0,073	0,120	0,005	0,024	0,005	0,031	-0,033	0,092	-0,013	0,100
100	0,049	0,144	-0,014	0,018	0,005	0,011	0,011	0,022	-0,050	0,033	0,030	0,034	-0,073	0,120	0,007	0,024	0,003	0,031	-0,028	0,092	-0,013	0,100

6.5.2 Graphical representation of DoE results for selected line marks

Only ten line marks are selected for a general visual impression of the scatter of participants results. The complete numerical results are presented in Table 7 and Table 8, respectively.

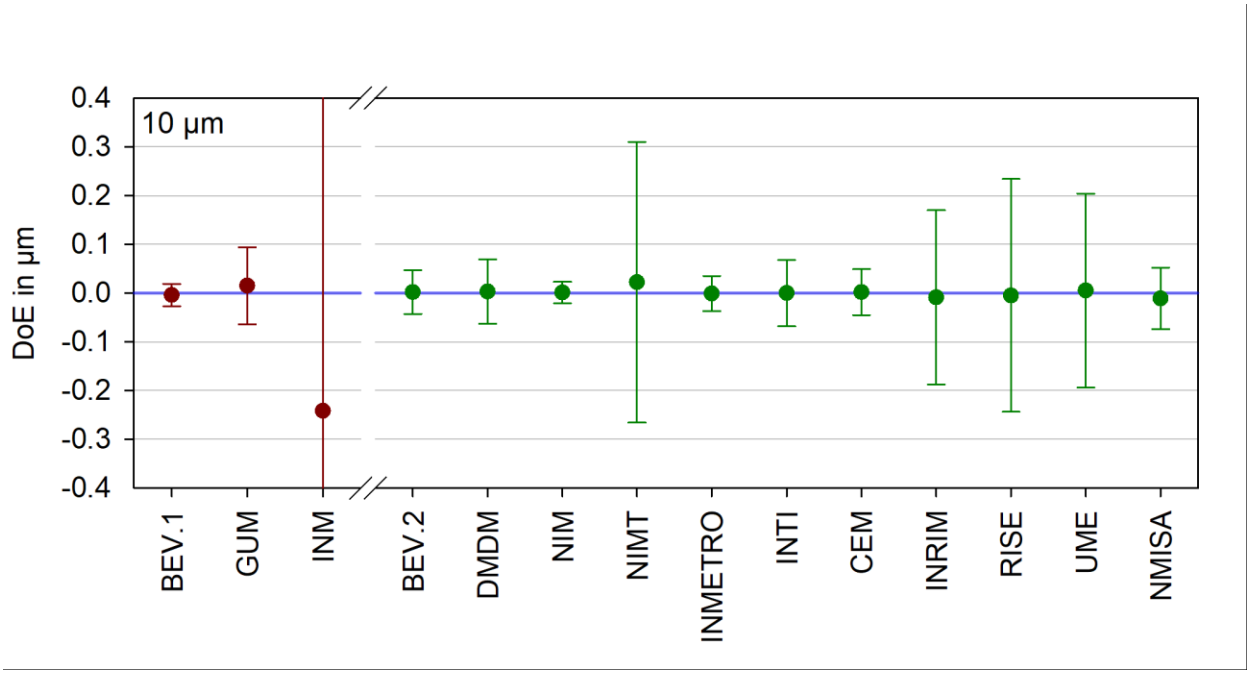


Figure 17 Degree of equivalence (d_1) of all participants for the line mark 10 µm. The error bars denote the expanded measurement uncertainty $U(d_1)$ for k = 2. Red symbols (left to axis break) for results of participants of loop 1, green symbols (right to axis break) for results of participants of loop 2. Error bars for INM are too large for the chosen scale.

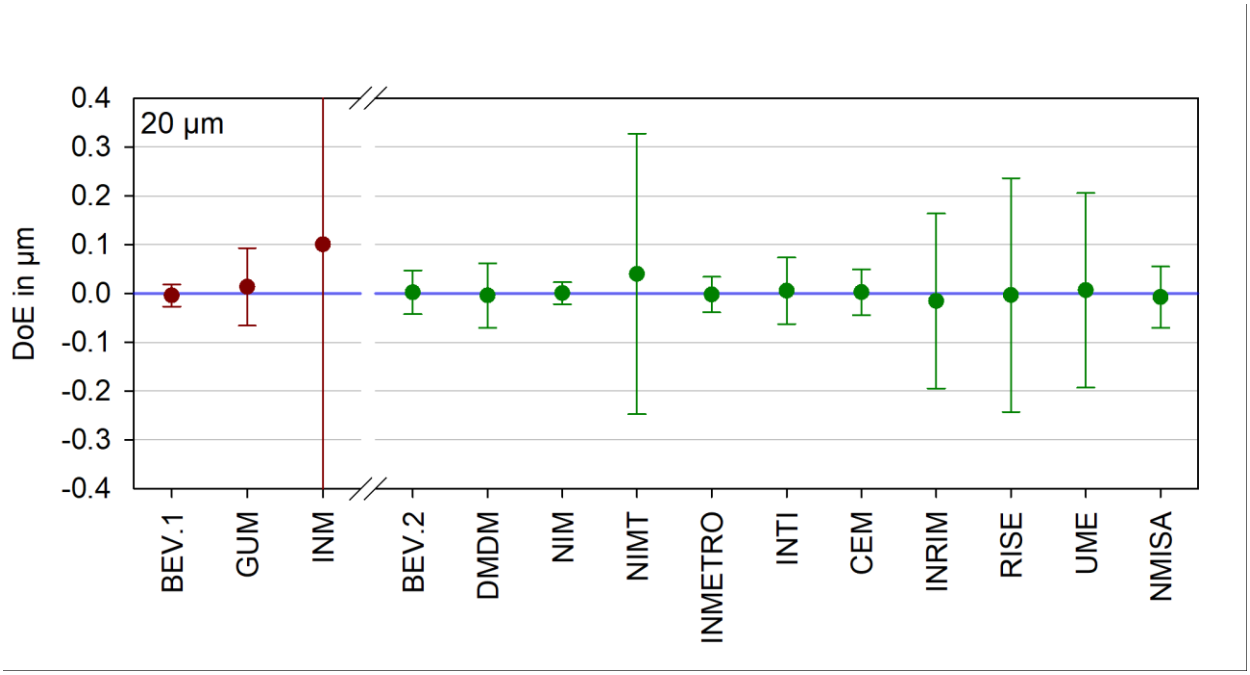


Figure 18 Degree of equivalence (d_2) of all participants for the line mark 20 µm. The error bars denote the expanded measurement uncertainty $U(d_2)$ for k = 2. Red symbols (left to axis break) for results of participants of loop 1, green symbols (right to axis break) for results of participants of loop 2. Error bars for INM are too large for the chosen scale.

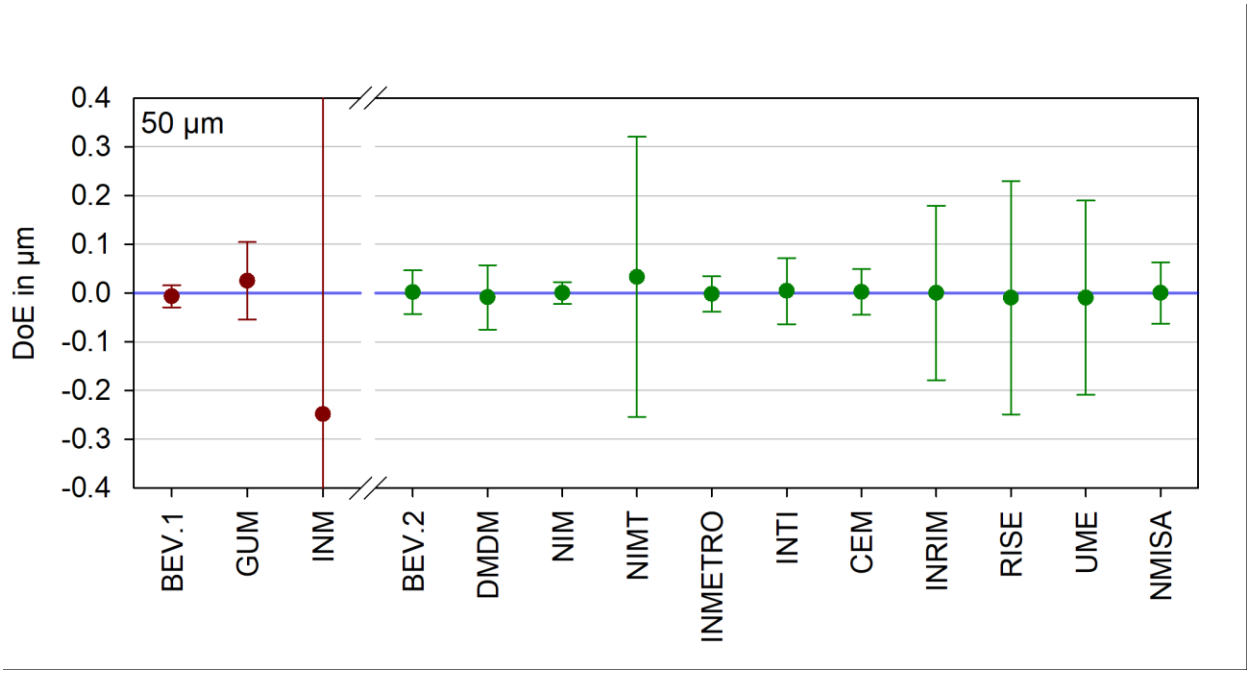


Figure 19 Degree of equivalence (d_5) of all participants for the line mark 50 µm. The error bars denote the expanded measurement uncertainty $U(d_5)$ for k = 2. Red symbols (left to axis break) for results of participants of loop 1, green symbols (right to axis break) for results of participants of loop 2. Error bars for INM are too large for the chosen scale.

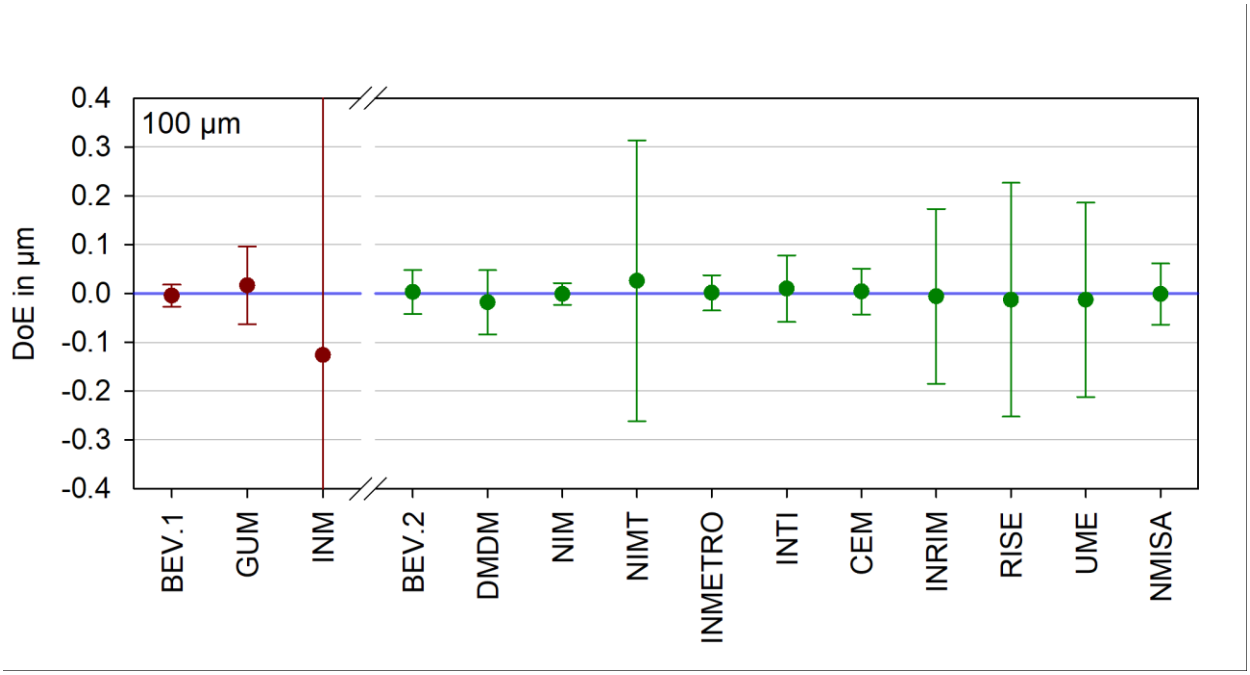


Figure 20 Degree of equivalence (d_{10}) of all participants for the line mark 100 µm. The error bars denote the expanded measurement uncertainty $U(d_{10})$ for k = 2. Red symbols (left to axis break) for results of participants of loop 1, green symbols (right to axis break) for results of participants of loop 2. Error bars for INM are too large for the chosen scale.

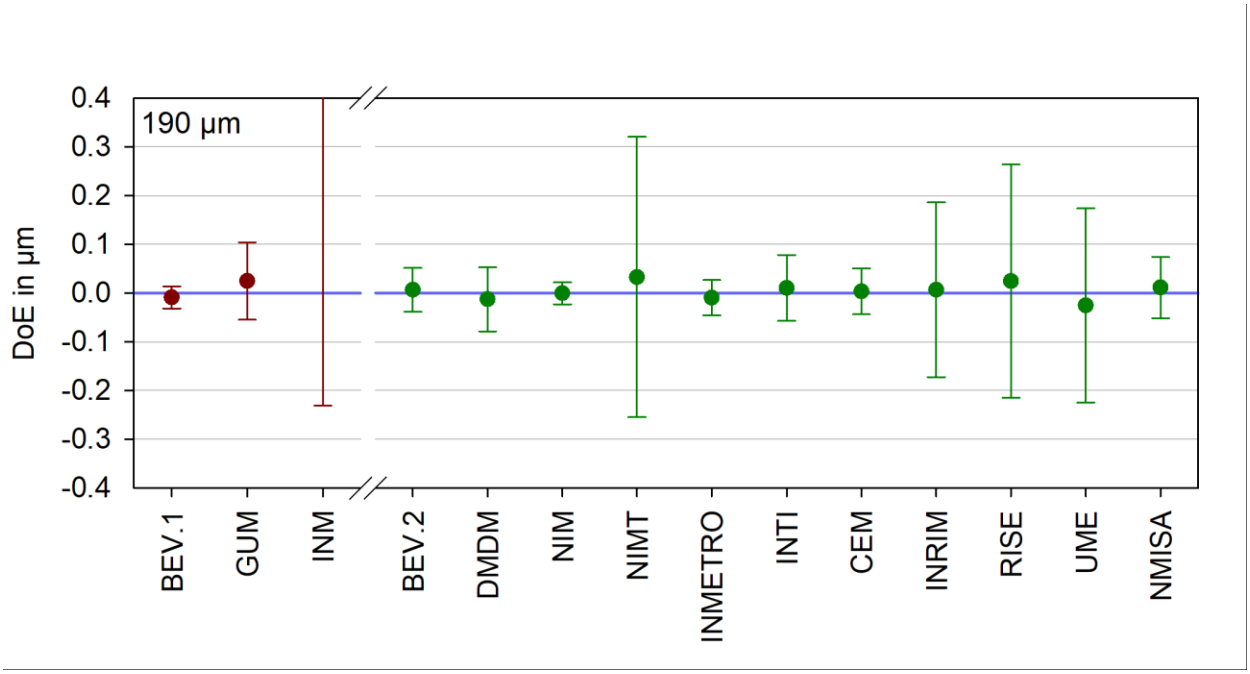


Figure 21 Degree of equivalence (d_{19}) of all participants for the line mark 190 µm. The error bars denote the expanded measurement uncertainty $U(d_{19})$ for k = 2. Red symbols (left to axis break) for results of participants of loop 1, green symbols (right to axis break) for results of participants of loop 2. Error bars for INM are too large for the chosen scale.

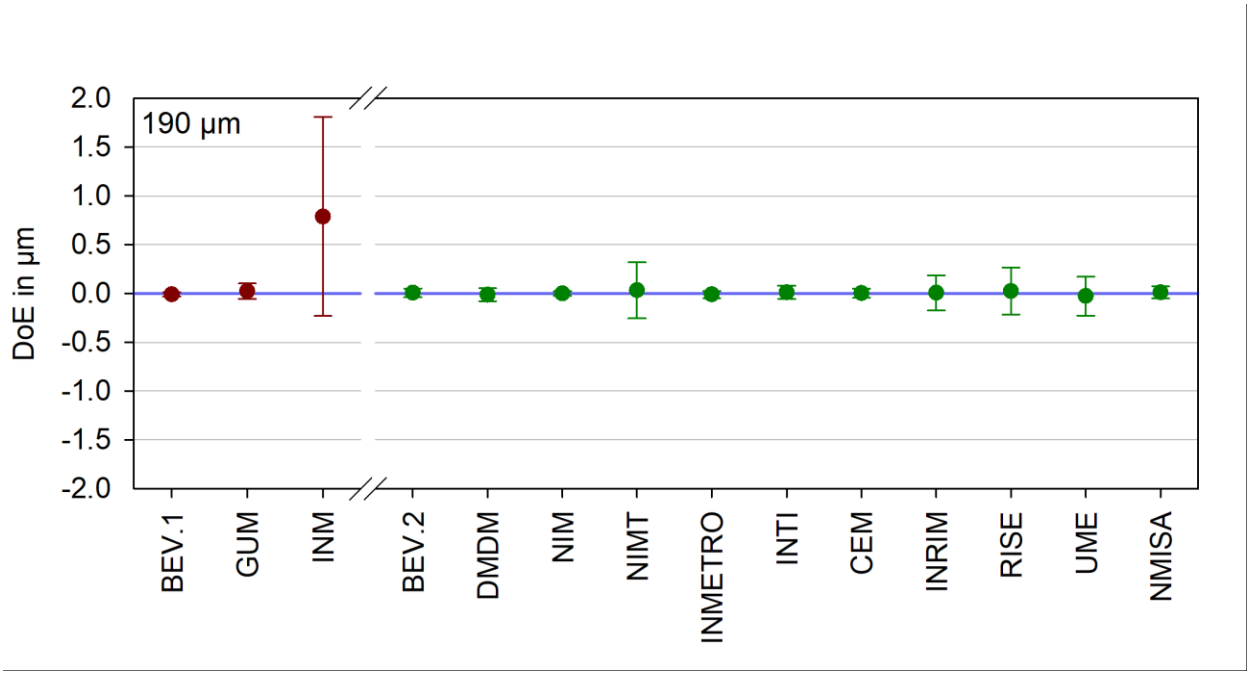


Figure 22 Degree of equivalence (d_{19}) of all participants for the line mark 190 µm. Same data as of Figure 21 with expanded ordinate scale to visualize INM value.

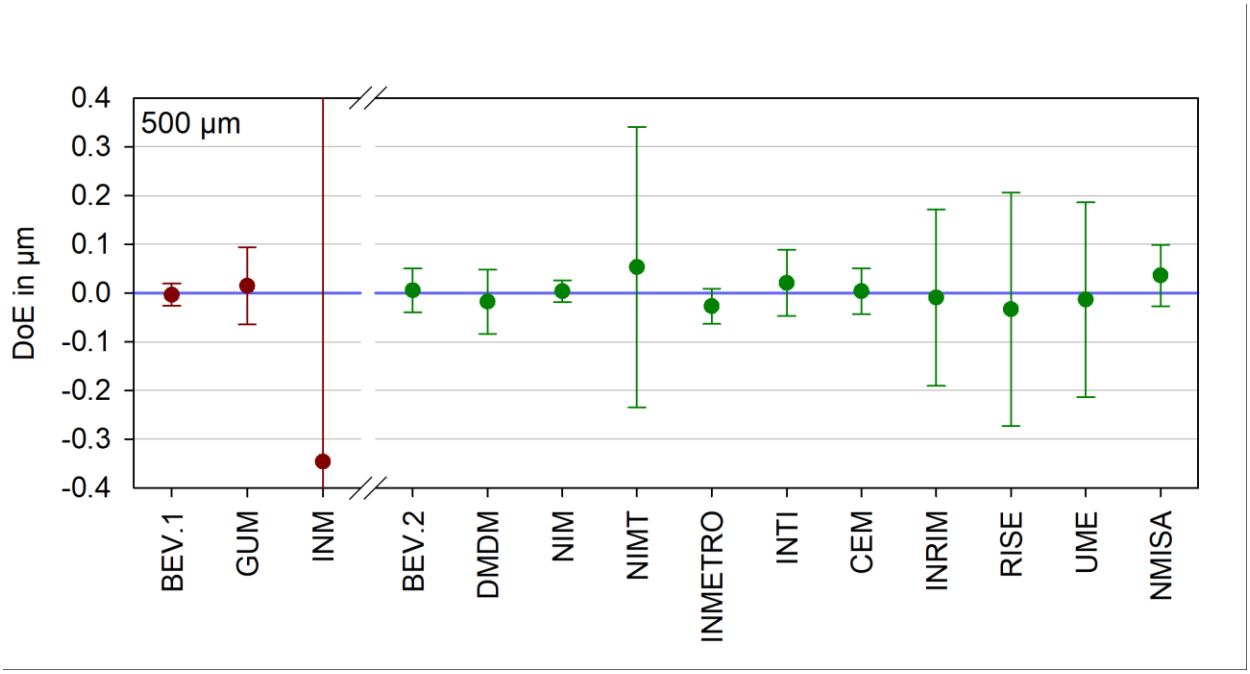


Figure 23 Degree of equivalence (d_{50}) of all participants for the line mark 500 µm. The error bars denote the expanded measurement uncertainty $U(d_{50})$ for k = 2. Red symbols (left to axis break) for results of participants of loop 1, green symbols (right to axis break) for results of participants of loop 2. Error bars for INM are too large for the chosen scale.

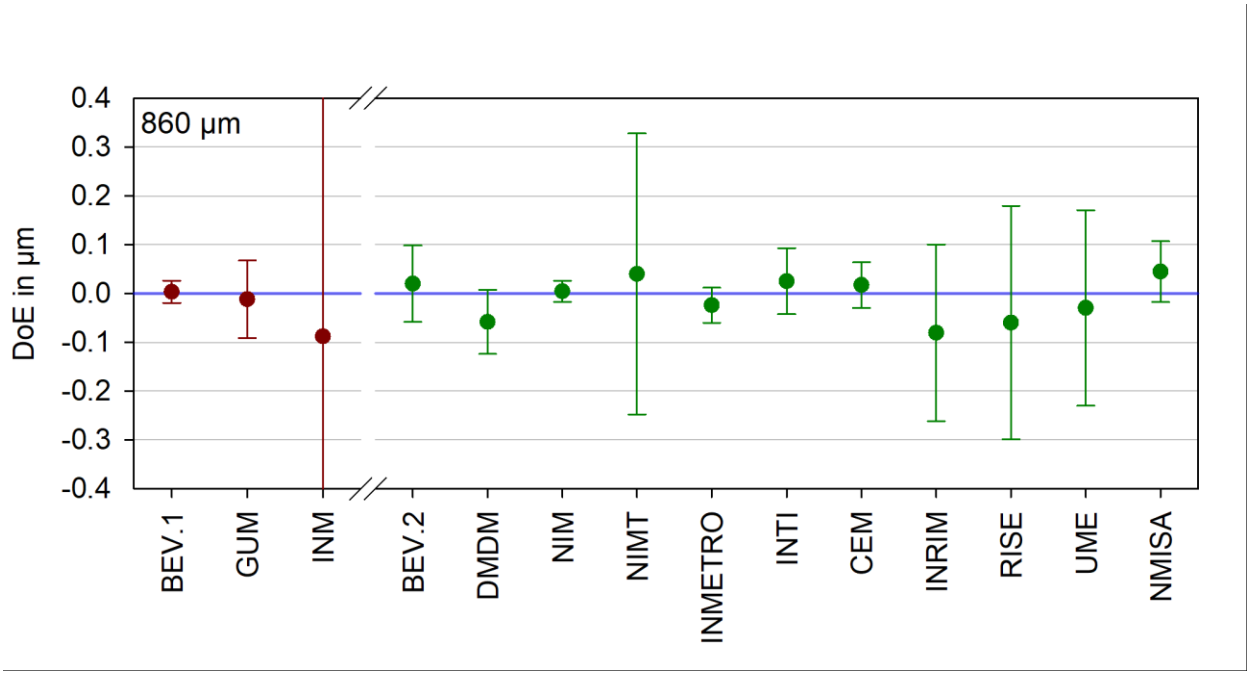


Figure 24 Degree of equivalence (d_{86}) of all participants for the line mark 860 µm. The error bars denote the expanded measurement uncertainty $U(d_{86})$ for k = 2. Red symbols (left to axis break) for results of participants of loop 1, green symbols (right to axis break) for results of participants of loop 2. Error bars for INM are too large for the chosen scale. For loop 2 some participants reported a worse line quality at 860 µm. The results also show considerably higher scatter.

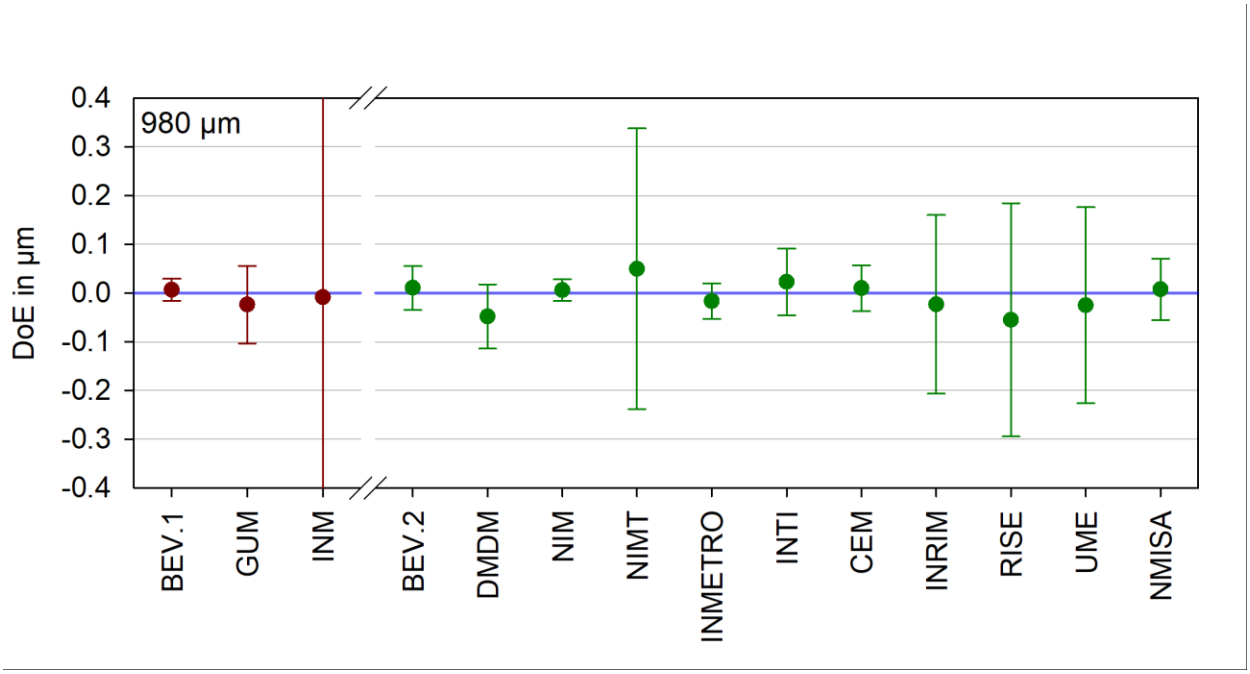


Figure 25 Degree of equivalence (d_{98}) of all participants for the line mark 980 µm. The error bars denote the expanded measurement uncertainty $U(d_{98})$ for k = 2. Red symbols (left to axis break) for results of participants of loop 1, green symbols (right to axis break) for results of participants of loop 2. Error bars for INM are too large for the chosen scale.

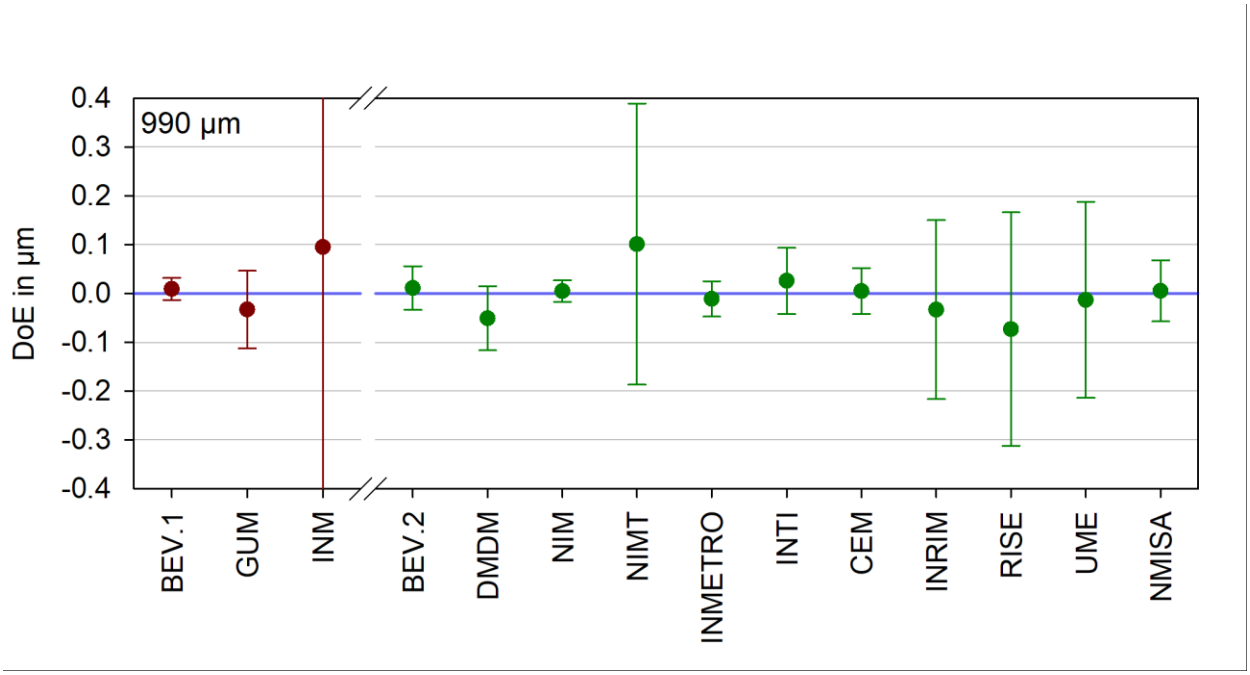


Figure 26 Degree of equivalence (d_{99}) of all participants for the line mark 990 µm. The error bars denote the expanded measurement uncertainty $U(d_{99})$ for k = 2. Red symbols (left to axis break) for results of participants of loop 1, green symbols (right to axis break) for results of participants of loop 2. Error bars for INM are too large for the chosen scale.

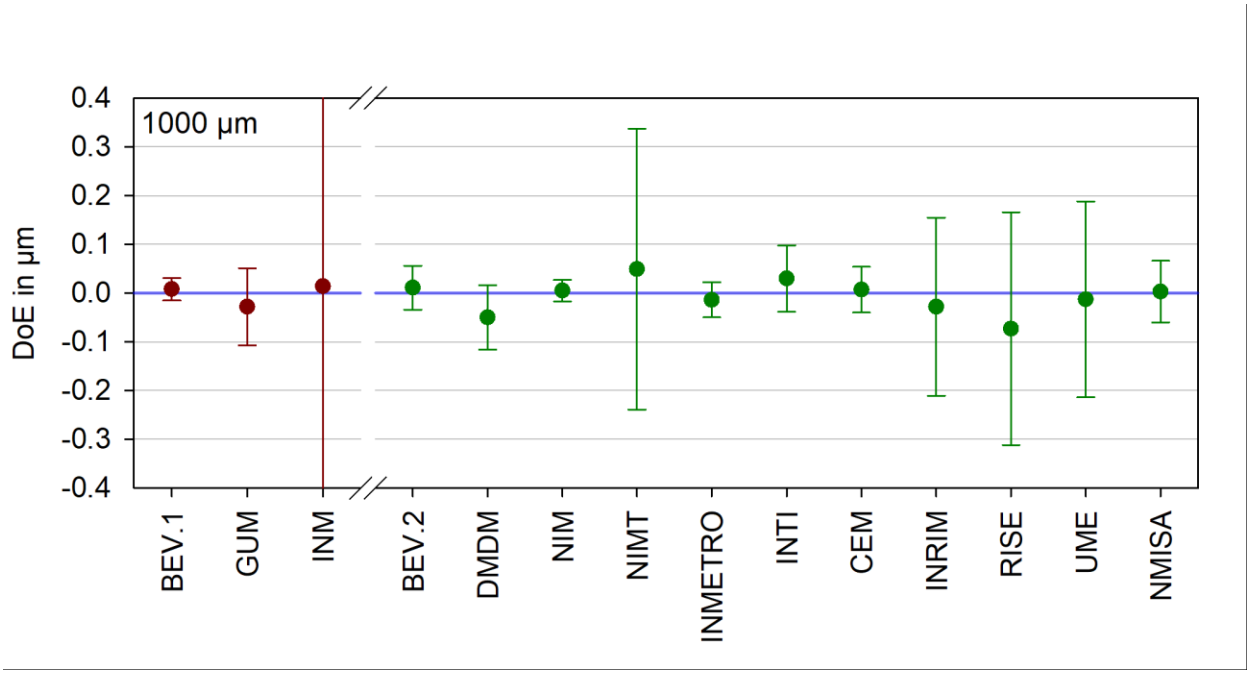


Figure 27 Degree of equivalence (d_{100}) of all participants for the line mark 1000 µm. The error bars denote the expanded measurement uncertainty $U(d_{100})$ for k = 2. Red symbols (left to axis break) for results of participants of loop 1, green symbols (right to axis break) for results of participants of loop 2. Error bars for INM are too large for the chosen scale.

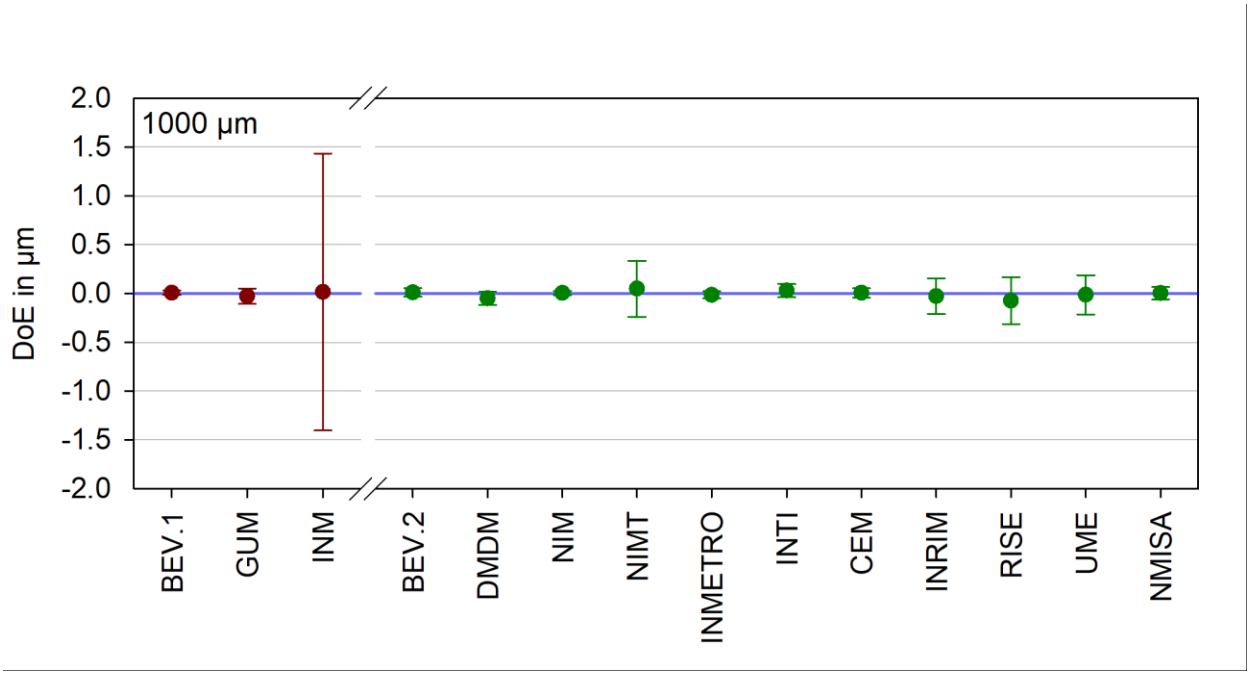


Figure 28 Degree of equivalence (d_{100}) of all participants for the line mark 1000 µm. Same data as of **Figure 27** with expanded ordinate scale to visualize INM value.

6.5.3 Tabular representation of normalized DoE results (E_n)

Table 9 summarizes the E_n values of all participants for both loops. The are rounded to two decimal figures.

Table 9 Absolute values of E_n for all participants. Left participants of loop 1, right for loop 2. The order of participants presented in the table heading does not correspond to the chronological order.

Line	INM	BEV.1	GUM
1	0,24	0,16	0,19
2	0,10	0,18	0,17
3	0,19	0,32	0,30
4	0,03	0,20	0,19
5	0,25	0,29	0,32
6	0,11	0,23	0,24
7	0,16	0,32	0,33
8	0,13	0,33	0,35
9	0,16	0,34	0,35
10	0,13	0,20	0,21
11	0,06	0,33	0,33
12	0,15	0,29	0,31
13	0,18	0,32	0,34
14	0,28	0,24	0,27
15	0,24	0,30	0,33
16	0,10	0,26	0,27
17	0,24	0,29	0,32
18	0,31	0,26	0,29
19	0,77	0,39	0,31
20	0,05	0,22	0,22
21	0,34	0,36	0,39
22	0,27	0,20	0,23
23	0,36	0,29	0,32
24	0,44	0,21	0,26
25	0,51	0,30	0,35
26	0,36	0,21	0,25
27	0,32	0,24	0,27
28	0,19	0,15	0,17
29	0,25	0,29	0,31
30	0,17	0,14	0,16
31	0,26	0,29	0,32
32	0,18	0,24	0,25
33	0,12	0,37	0,38
34	0,22	0,24	0,27
35	0,34	0,31	0,34
36	0,30	0,33	0,36
37	0,23	0,33	0,35
38	0,08	0,25	0,25
39	0,12	0,24	0,25
40	0,12	0,28	0,29
41	0,22	0,23	0,25
42	0,14	0,26	0,28
43	0,21	0,26	0,28
44	0,10	0,27	0,28
45	0,24	0,23	0,26
46	0,22	0,09	0,11
47	0,29	0,21	0,24
48	0,46	0,20	0,25
49	0,31	0,21	0,24
50	0,31	0,16	0,19
51	0,19	0,16	0,18
52	0,25	0,09	0,11
53	0,16	0,13	0,14
54	0,13	0,12	0,13
55	0,13	0,05	0,06
56	0,25	0,07	0,09
57	0,21	0,05	0,07
58	0,14	0,10	0,12
59	0,01	0,05	0,05
60	0,11	0,03	0,02
61	0,24	0,05	0,03
62	0,21	0,03	0,05
63	0,19	0,13	0,12
64	0,22	0,05	0,07
65	0,24	0,07	0,05
66	0,18	0,15	0,13
67	0,15	0,11	0,09
68	0,22	0,05	0,03
69	0,04	0,12	0,12
70	0,25	0,10	0,08
71	0,28	0,11	0,09
72	0,29	0,04	0,02
73	0,11	0,16	0,15
74	0,17	0,16	0,14
75	0,04	0,20	0,20
76	0,17	0,14	0,13
77	0,03	0,23	0,23
78	0,36	0,17	0,14
79	0,10	0,27	0,26
80	0,17	0,12	0,10
81	0,15	0,22	0,20
82	0,08	0,23	0,22
83	0,06	0,31	0,30
84	0,06	0,21	0,20
85	0,06	0,35	0,35
86	0,07	0,15	0,15
87	0,01	0,23	0,23
88	0,04	0,24	0,23
89	0,01	0,34	0,34
90	0,01	0,33	0,33
91	0,02	0,42	0,42
92	0,02	0,34	0,35
93	0,11	0,33	0,32
94	0,05	0,36	0,36
95	0,00	0,38	0,38
96	0,11	0,36	0,37
97	0,10	0,37	0,38
98	0,01	0,30	0,30
99	0,07	0,41	0,42
100	0,01	0,36	0,36

Line	NIMT	INMETRO	NIM	BEV.2	DMDM	INTI	RISE	CEM	NMISA	INRIM	UME
1	0,08	0,02	0,03	0,05	0,05	0,00	0,02	0,04	0,17	0,05	0,02
2	0,14	0,06	0,03	0,05	0,06	0,08	0,01	0,05	0,12	0,09	0,03
3	0,04	0,03	0,09	0,08	0,24	0,06	0,01	0,08	0,20	0,07	0,06
4	0,06	0,10	0,01	0,14	0,20	0,03	0,05	0,03	0,08	0,06	0,06
5	0,11	0,05	0,01	0,04	0,13	0,06	0,04	0,05	0,01	0,00	0,05
6	0,06	0,07	0,04	0,10	0,17	0,03	0,04	0,13	0,05	0,02	0,10
7	0,16	0,01	0,08	0,06	0,17	0,13	0,08	0,00	0,03	0,15	0,04
8	0,11	0,10	0,04	0,05	0,11	0,07	0,12	0,06	0,02	0,11	0,05
9	0,13	0,11	0,11	0,15	0,31	0,10	0,03	0,16	0,18	0,04	0,11
10	0,09	0,04	0,04	0,07	0,28	0,15	0,05	0,09	0,02	0,03	0,06
11	0,05	0,14	0,03	0,13	0,17	0,09	0,09	0,13	0,05	0,03	0,11
12	0,06	0,09	0,04	0,14	0,14	0,15	0,08	0,09	0,04	0,02	0,09
13	0,10	0,20	0,08	0,06	0,25	0,11	0,03	0,10	0,03	0,12	0,04
14	0,11	0,05	0,11	0,05	0,17	0,08	0,03	0,04	0,01	0,11	0,08
15	0,07	0,22	0,05	0,17	0,20	0,09	0,07	0,13	0,00	0,02	0,09
16	0,05	0,22	0,00	0,13	0,21	0,09	0,02	0,13	0,17	0,07	0,08
17	0,13	0,05	0,01	0,10	0,23	0,18	0,09	0,02	0,08	0,13	0,05
18	0,13	0,22	0,15	0,10	0,13	0,14	0,09	0,05	0,10	0,09	0,05
19	0,11	0,27	0,02	0,15	0,19	0,15	0,10	0,07	0,18	0,04	0,13
20	0,18	0,22	0,05	0,14	0,30	0,18	0,10	0,13	0,03	0,01	0,12
21	0,07	0,02	0,05	0,13	0,27	0,17	0,11	0,06	0,05	0,00	0,13
22	0,13	0,13	0,13	0,13	0,32	0,15	0,01	0,16	0,31	0,03	0,13
23	0,10	0,16	0,04	0,03	0,21	0,15	0,03	0,00	0,21	0,03	0,14
24	0,13	0,08	0,15	0,10	0,42	0,08	0,11	0,03	0,00	0,12	0,13
25	0,06	0,05	0,04	0,12	0,21	0,18	0,07	0,04	0,02	0,17	0,08
26	0,17	0,08	0,04	0,13	0,21	0,15	0,10	0,04	0,06	0,15	0,12
27	0,14	0,06	0,04	0,06	0,25	0,27	0,08	0,06	0,03	0,06	0,14
28	0,26	0,02	0,10	0,02	0,33	0,15	0,04	0,01	0,00	0,02	0,15
29	0,19	0,02	0,02	0,12	0,39	0,20	0,01	0,01	0,08	0,10	0,11
30	0,16	0,02	0,06	0,14	0,31	0,25	0,05	0,02	0,02	0,08	0,11
31	0,18	0,28	0,02	0,19	0,14	0,15	0,06	0,09	0,08	0,03	0,07
32	0,17	0,35	0,19	0,26	0,20	0,28	0,06	0,17	0,26	0,05	0,08
33	0,10	0,47	0,09	0,20	0,16	0,20	0,03	0,08	0,15	0,03	0,09
34	0,14	0,57	0,13	0,22	0,21	0,25	0,06	0,12	0,13	0,07	0,07
35	0,19	0,42	0,07	0,21	0,23	0,21	0,16	0,20	0,06	0,06	0,09
36	0,22	0,39	0,02	0,23	0,40	0,19	0,03	0,21	0,22	0,09	0,09
37	0,16	0,49	0,04	0,26	0,26	0,28	0,01	0,17	0,21	0,06	0,08
38	0,21	0,63	0,10	0,21	0,15	0,22	0,01	0,20	0,13	0,06	0,09
39	0,17	0,62	0,08	0,16	0,12	0,23	0,07	0,25	0,19	0,03	0,06
40	0,16	0,48	0,15	0,19	0,29	0,34	0,03	0,15	0,08	0,09	0,04
41	0,17	0,21	0,08	0,14	0,25	0,29	0,04	0,08	0,09	0,17	0,10
42	0,17	0,24	0,12	0,13	0,29	0,29	0,09	0,06	0,04	0,09	0,10
43	0,26	0,51	0,27	0,11	0,29	0,30	0,12	0,02	0,11	0,05	0,09
44	0,24	0,57	0,27	0,15	0,26	0,21	0,12	0,09	0,10	0,02	0,09
45	0,21	0,65	0,04	0,24	0,23	0,29	0,00	0,17	0,40	0,23	0,05
46	0,20	0,47	0,08	0,18	0,24	0,22	0,12	0,10	0,36	0,31	0,09
47	0,23	0,53	0,00	0,19	0,24	0,32	0,02	0,11	0,36	0,05	0,08
48	0,21	0,60	0,16	0,16	0,30	0,23	0,04	0,10	0,37	0,05	0,10
49	0,22	0,61	0,09	0,20	0,26	0,28	0,07	0,08	0,44	0,18	0,08
50	0,19	0,75	0,16	0,12	0,27	0,30	0,14	0,08	0,58	0,05	0,07
51	0,23	0,30	0,03	0,16	0,21	0,35	0,17	0,04	0,12	0,21	0,10
52	0,18	0,30	0,07	0,19	0,40	0,42	0,16	0,01	0,15	0,15	0,09
53	0,23	0,55	0,26	0,13	0,38	0,30	0,13	0,10	0,23	0,23	0,10
54	0,24	0,54	0,27	0,17	0,42	0,31	0,17	0,15	0,12	0,20	0,11
55	0,25	0,55	0,22	0,20	0,41	0,28	0,07	0,21	0,10	0,21	0,13
56	0,20	0,39	0,24	0,25	0,56	0,34	0,17	0,13	0,06	0,10	0,15
57	0,17	0,57	0,10	0,35	0,51	0,37	0,13	0,20	0,20	0,14	0,10
58	0,22	0,60	0,27	0,23	0,52	0,28	0,25	0,19	0,19	0,14	0,11
59	0,30	0,64	0,11	0,21	0,42	0,34	0,12	0,33	0,22	0,16	0,09
60	0,22	0,72	0,40	0,23	0,58	0,41	0,33	0,15	0,08	0,03	0,14
61	0,17	0,58	0,23	0,15	0,46	0,39	0,28	0,15	0,14	0,11	0,03
62	0,22	0,56	0,24	0,22	0,44	0,43	0,30	0,05	0,12	0,04	0,05
63	0,19	0,71	0,35	0,24	0,57	0,37	0,23	0,12	0,24	0,08	0,17
64	0,28	0,77	0,24	0,28	0,63	0,30	0,06	0,22	0,35	0,20	0,17
65	0,19	0,69	0,31	0,24	0,62	0,35	0,25	0,19	0,23	0,04	0,10
66	0,23	0,58	0,38	0,17	0,59	0,30	0,28	0,14	0,11	0,02	0,14
67	0,19	0,42	0,16	0,19	0,58	0,38	0,26	0,10	0,23	0,01	0,11
68	0,23	0,44	0,38	0,11	0,67	0,33	0,29	0,05	0,09	0,14	0,15
69	0,17	0,50	0,24	0,15	0,54	0,33	0,26	0,09	0,24	0,10	0,11
70	0,23	0,77	0,35	0,30	0,61	0,41	0,24	0,12	0,28	0,13	0,14
71	0,22	0,71	0,36	0,25	0,58	0,44	0,30	0,13	0,17	0,10	0,16
72	0,24	0,77	0,37	0,32	0,65	0,52	0,30	0,11	0,20	0,21	0,16
73	0,16	0,81	0,52	0,28	0,74	0,42	0,25	0,10	0,19	0,17	0,15
74	0,22	0,87	0,35	0,26	0,58	0,41	0,21	0,23	0,23	0,11	0,15
75	0,17	0,87	0,42	0,31	0,71	0,37	0,25	0,12	0,40	0,07	0,15
76	0,20	0,64	0,33	0,33	0,65	0,39	0,33	0,20	0,06	0,10	0,14
77	0,22	0,57	0,18	0,36	0,64	0,44	0,20	0,17	0,12	0,08	0,14
78	0,18	0,69	0,28	0,31	0,55	0,33	0,19	0,22	0,14	0,00	0,18
79	0,18	0,53	0,29	0,20	0,62	0,30	0,26	0,22	0,24	0,07	0,16
80	0,23	0,65	0,31	0,31	0,78	0,43	0,30	0,21	0,23	0,22	0,15
81	0,08	0,55	0,34	0,28	0,86	0,50	0,33	0,21	0,13	0,20	0,19
82	0,16	0,69	0,20	0,35	0,66	0,49	0,21	0,20	0,27	0,20	0,10
83	0,18	0,72	0,49	0,25	0,89	0,45	0,34	0,17	0,17	0,04	0,11
84	0,18	0,86	0,24	0,31	0,79	0,37	0,26	0,37	0,51	0,21	0,06
85	0,21	0,69	0,33	0,29	0,90	0,48	0,31	0,20	0,30	0,15	0,02
86	0,14	0,67	0,20	0,26	0,89	0,37	0,25	0,37	0,72	0,45	0,15
87	0,09	0,44	0,18	0,27	0,99	0,46	0,19	0,19	0,34	0,09	0,12
88	0,21	0,45	0,38	0,18	0,99	0,37	0,27	0,07	0,29	0,00	0,12
89	0,18	0,36	0,18	0,23	0,98	0,35	0,24	0,13	0,40	0,07	0,03
90	0,21	0,46	0,17	0,22	0,80	0,35	0,28	0,17	0,38	0,10	0,01
91	0,21	0,62	0,22	0,27	0,72	0,51	0,31	0,19	0,30	0,26	0,07
92	0,23	0,60	0,21	0,27	0,78	0,57	0,28	0,18	0,27	0,17	0,08
93	0,22	0,71	0,43	0,29	0,78	0,44	0,33	0,08	0,30	0,30	0,09
94	0,16	0,78	0,38	0,27	0,78	0,46	0,26	0,18	0,27	0,03	0,06
95	0,18	0,56	0,41	0,22	0,73	0,44	0,29	0,07	0,10	0,12	0,10
96	0,21	0,31	0,28	0,17	0,87	0,40	0,29	0,13	0,03	0,06	0,09
97	0,18	0,44	0,16	0,26	0,79	0,41	0,34	0,27	0,15	0,05	0,06
98	0,17	0,46	0,26	0,23	0,73	0,34	0,23	0,21	0,12	0,13	0,13
99	0,35	0,30	0,21	0,25	0,78	0,38	0,31	0,10	0,08	0,18	0,07
100	0,17	0,39	0,24	0,24	0,75	0,45	0,30	0,16	0,04	0,15	0,06

6.6 Discussion of results

Below is a summary of the findings and a short discussion of results for this comparison.

- Despite extensive precautions on artefact handling, the stage micrometer was effectively destroyed after three participants only. It was necessary to split the comparison in two loops with a second artefact of the same make and kind. This was not foreseen in the technical protocol and caused a serious delay.
- Beside this accident, the stability and the quality of the type of artefact was excellent.
- The result analysis included 1400 individual results, not counting the stability measurements by the pilot.

- All E_n values were smaller than 1 already from the pre-draft A state on. No separate analysis of a largest consistent subset was necessary therefore. (Table 9)
- With the exception of one participant (INM), the expanded measurement uncertainty for this service covered the range of 28 nm up to 290 nm (span of approximately 1:10). The uncertainties are plausible and adequate for this service category.
- However, one participant (INM) stated a very high expanded measurement uncertainty of up 1420 nm. This is also twice as large than their published CMC value.
- The first loop with only three participants (BEV, GUM, INM) is effectively numerically equivalent to a bilateral comparison since one participant stated very high uncertainties.
- No link between the two loops was performed. BEV is the only participant common to both loops.
- From the statistical point of view (which might not be adequate) it is tempting to assume that the participants somehow overestimate some uncertainty contributions (1400 values without a single outlier).
- All published CMCs (with the exception of INM) are confirmed or even outperformed (see section 6.6.1).

6.6.1 Reported and published measurement uncertainties

The participants were asked to state the expanded measurement uncertainties for this comparison as well as published CMCs for this service. Table 10 summarizes this data. All values have been converted to nanometres. The expanded uncertainty is parametrized by the two constants a and b as in the following equation:

$$U = Q[a, b \cdot L] \equiv \sqrt{a^2 + (b \cdot L)^2}$$

Table 10 Stated and published expanded measurement uncertainties for participants of this comparison

NMI	This comp		CMC		Comment
	a	***b***	***a***	***b***	
BEV	48 nm	0	400 nm	0	
GUM	90 nm	0	268 nm	0	
INM	1000 nm	0.0005	500 nm	0.0005	Reported uncertainty much higher than CMC. Stated uncertainty equation not compliant with reported results. See INM comment below.
DMDM	68 nm	0.38E−06	—	—	
NIM	28 nm	0.16E−06	104 nm	0.16E−06	
NIMT	288 nm	0.487E−06	—	—	
INMETRO	40 nm	0.443E−06	—	—	
INTI	70 nm	0.01	—	—	
CEM	50 nm	0.25E−06	60 nm	0.30E−06	
INRIM	90 nm	2.0E−06	90 nm	5.0E−06	
RISE	240 nm	22E−06	500 nm	0.5E−06	
UME	200 nm	2.6E−06	—	—	
NMISA	65 nm	0.001	250 nm	0.001	

INM commented its reported results after circulation of the draft A report:

“The artefact was suspected to be damaged, before we realized and we reported the found values of the measurements. The microphotography of the artefact, that clearly were presented in Figure 8, 9, 10 and 11 from Draft B.0 of the Report, are confirming our presumption.

The reported values were influenced by the asymmetric deformation of the stage micrometer lines and the resulted and calculated uncertainty had to be increased.

Next step will be to participate in bilateral comparison and reinstate, at least, the current CMC uncertainty."

6.7 Linking of result to other comparisons

The CIPM does not require to link supplementary comparisons. No link was performed therefore.

7 Equipment and measuring processes of the participants

Despite the seemingly standardized artefact, a wide range of equipment or techniques has been used. The participants have been asked to supply this information verbatim in a format ready for inclusion.

7.1 BEV

For the calibration of stage micrometers BEV uses the Nanopositioning and Nanomeasuring Machine NMM-1 (SIOS GmbH) with a laser focus sensor as the probing element. The NMM provides a measuring range of 25 mm × 25 mm × 4 mm, controlled by three orthogonally laser interferometers. The axes of three interferometers intersect virtually at the point of the probing element thus providing Abbe-free length measurements in all three coordinates. In this procedure the laser focus sensor is used to keep the surface of the stage micrometer in this point. The stage is moved in z-direction while scanning in the x- and y-directions. Beside the height information (which is not used in this application) the LFS provides also reflectivity values of the surface. The reflectivity is used for the line detection.

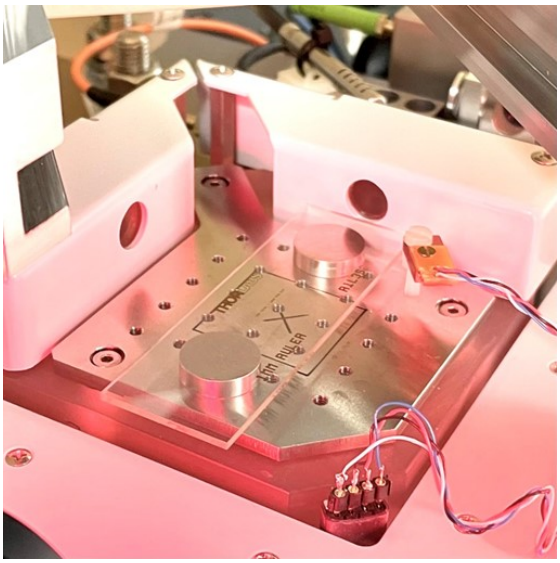
A rectangular field, which includes the ROI, of the sample is scanned and the reflectivity with its (x, y) coordinates is recorded. Usually a point spacing of 10 nm or 20 nm and a profile number of around 50 was used for the reported results. Both scan directions (regarding to the profiles) are recorded and evaluated. The duration of a typical scan is about 2 hours and produces files of up to 4 GB. The files are text files of a proprietary format.

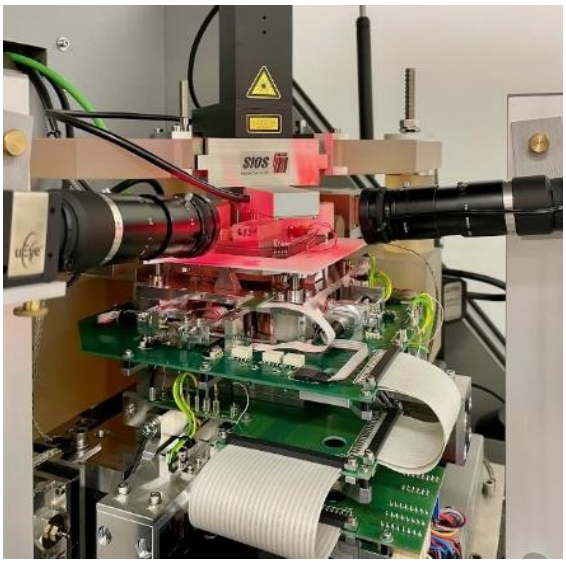
The sample temperature is measured with a Pt100 sensor near the stage micrometer. Due to the construction principle of the machine the sample temperature deviates significantly from the air temperature of the laboratory.

Traceability route
Traceability is guaranteed by the laser interferometers of the NMM. The three sources are calibrated by beat measurement with an iodine stabilized HeNe-laser. The environmental sensors are calibrated in house also.

Principle of line center detection
The scan data files are analysed using a homemade software. The evaluation is performed for each profile separately. The reflectivity data is segmented using a threshold to detect edges eventually after applying morphological filters. Line center is defined as the mid-point of two edges with opposite orientation. The evaluation procedure delivers also quality parameters like line width variation and edge roughness. The algorithm is documented in https://github.com/matusm/NmmStageMicro

Temperature range during measurements
20,9 °C to 22.8 °C (sample temperature)



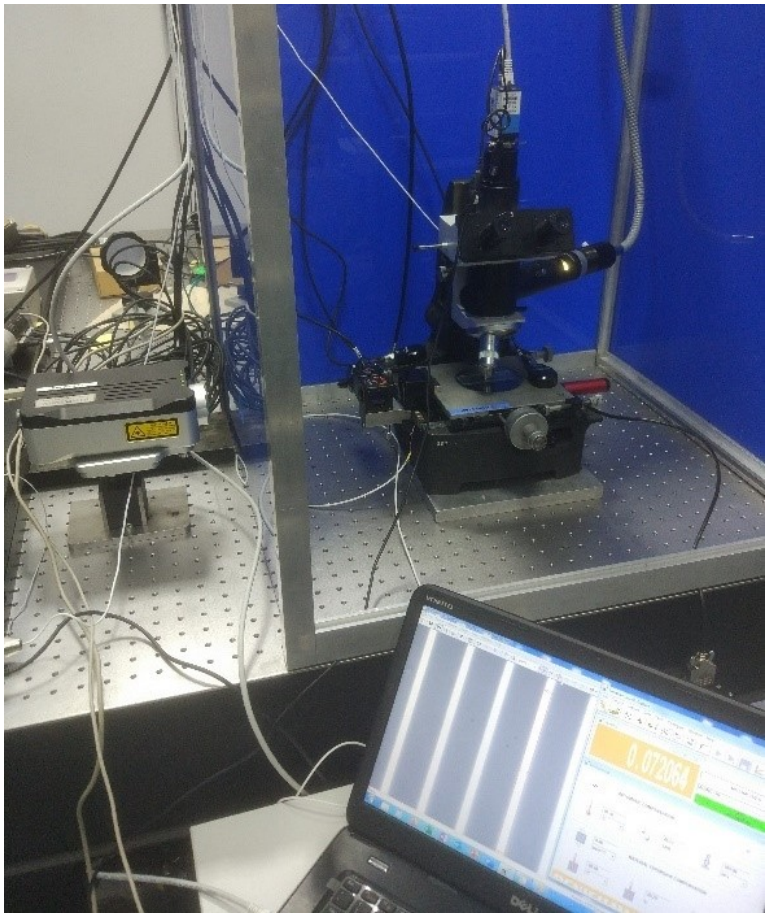


7.2 GUM

The stage micrometer was measured on the upgraded measuring microscope (Epi-illumination type in comparison) with CCD-camera.

The line spacing is measured with the laser interferometer Renishaw XL-80.

The stage is moved by piezoelectric actuators and high-resolution stepper motor, placed opposite each other.



Traceability route
Laser interferometer (Renishaw XL-80)

Principle of line center detection
The lines were positioned symmetrical in the 50 µm height ROI window and a width adjusted to the width of the graduation lines. The scale lines are aligned in ROI by eye in a symmetrical manner with precision piezo-electric actuator.

Temperature range during measurements
20,00 °C to 20.50 °C (for all measurements);
Temperature variation during a series of 3 measurements: 0,10 °C

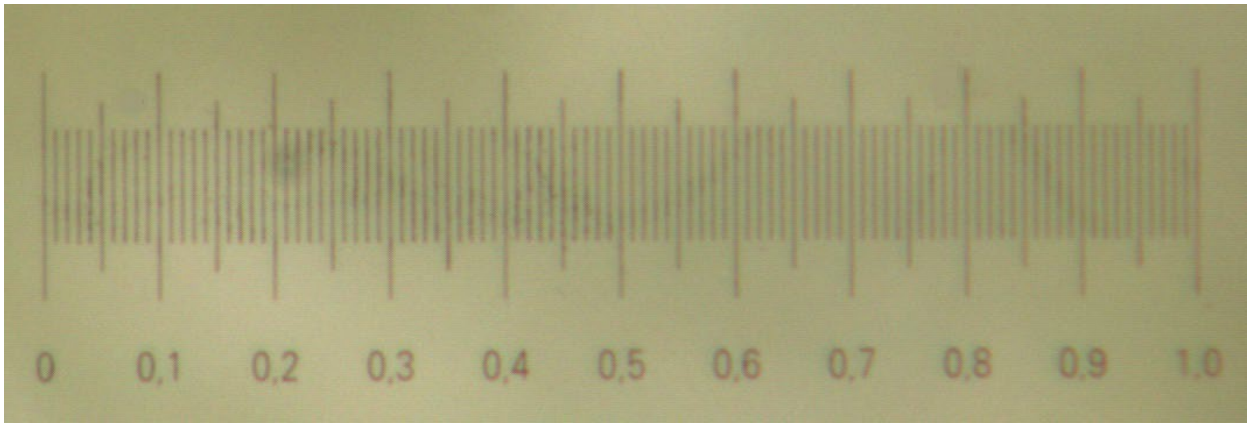
Additional remarks
24 series (3×8) of measurements were made, separately every 0.01 mm and separately every 0.02 mm. Due to small negative linear thermal expansion coefficient ($(-0.1 \pm 0.7) \cdot 10^{-6}$ K^{-1}), its value has been included only in the measurement uncertainty.

7.3 INM

Instrument: measurement length machine, equipped with an optical microscope and CCD camera.

The longitudinal comparator is based on the cinematic method, according to Abbe principle: the line scale of the stage micrometer must be aligned on the same longitudinal axis with measurement direction, in the scope to eliminate the first order errors. Because the line scale was very short, it was supported with the whole surface on the special carriage of the comparator and the scale was illuminated from bottom.

The standard used for the calibration of the length measuring machine is a laser interferometer used in current calibration services offered by INM.



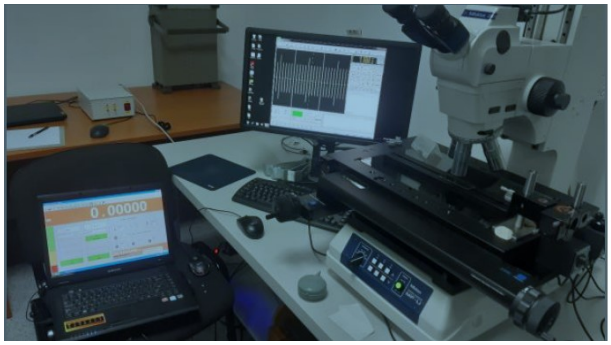
Method of measurement consists in the displacement of the scale along the measurement direction. During one measurement between the beginning and the end of the measurement, difference between the thermometer readings was equal to Δt_g = 0.01 °C

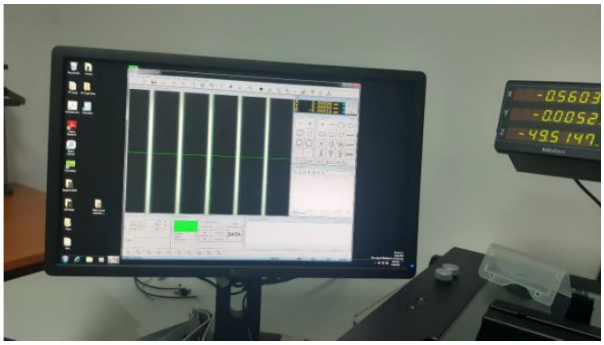
The difference between the temperature of the room and the reference temperature was 0.1 °C … 0.2 °C during all measurements.

7.4 DMDM

Positioning system: CCD measuring microscope Mitutoyo MF-UB3017C (3 axes type), glass measuring stage (300x170) mm, LED illumination, reflected light, objective Mitutoyo M Plan Apochromat 50X magnification NA 0.55, total magnification: 500X optical, 4X digital, CCD camera Mitutoyo Vision unit 3.0 MP, commercial software Mitutoyo QSPAK Vue ver.4.0

Measuring system: Laser interferometer Renishaw XL80, Renishaw measuring sensors for air and material temperature, air pressure and relative humidity, commercial Renishaw software for linear (distance) measurement.





Traceability route
Laser interferometer

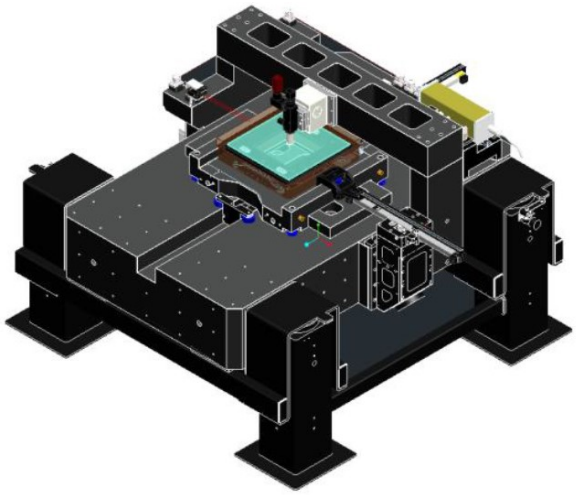
Principle of line center detection
Visually, using CCD camera, Mitutoyo software and different types of crosshairs. There is no special software dedicated for line center detection. Measuring stage with stage micrometer was moving manually and microscope objective was fixed during measurements.

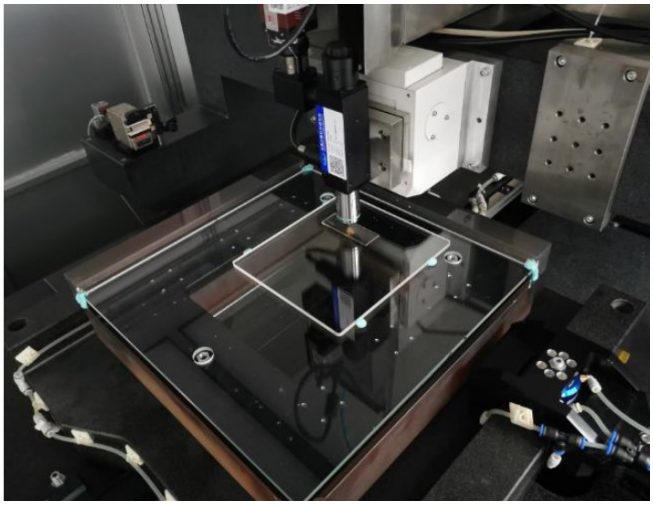
Temperature range during measurements
19.50 °C to 20.50 °C

7.5 NIM

The results of this comparison are obtained by the high precision two-dimensional measuring instrument with laser system. The two-dimensional measuring instrument with laser system was established with the techniques of laser interferometry and image aiming. It is a non-contact 2D coordinates measuring system with laser interferometer as length measuring standard, imaging with CCD and microscopy, auto measuring with computer image processing and error compensating techniques. The measuring range of the instrument is 300 mm × 300 mm, which can reach to 500 mm in a single direction by splicing measurement.

The coaxial reflected light is used for illumination in this comparison.



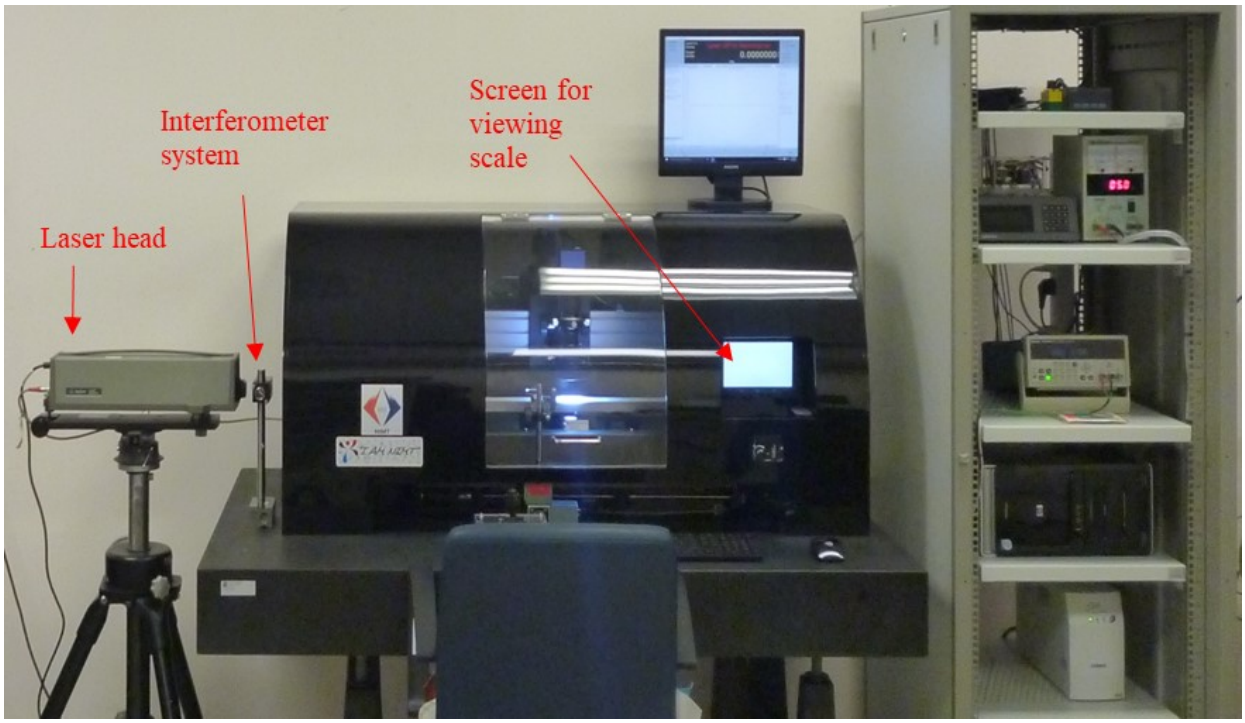


Traceability route
The laser interferometer uses a frequency-stabilized laser as the measuring light source, and the laser wavelength is traced to the national 633nm wavelength standard.

Principle of line center detection
During measurements, the optical imaging system is fixed, the micrometer moves with the working platform, and its line is aimed with the optical imaging system. The line space is the sum of the displacement of the movement platform measured by the laser interferometer and that of the line measured by the optical imaging system. The center of the line is calculated by parallel line fitting algorithm.

Temperature range during measurements
19.95 °C to 20.05 °C

7.6 NIMT



Traceability route
The wavelength of Laser Interferometer was calibrated using Iodine stabilized He-Ne laser by beat frequency method.

Principle of line center detection
We measure the left side of the line of scale and measure the right side of the line of scale to find the center line.

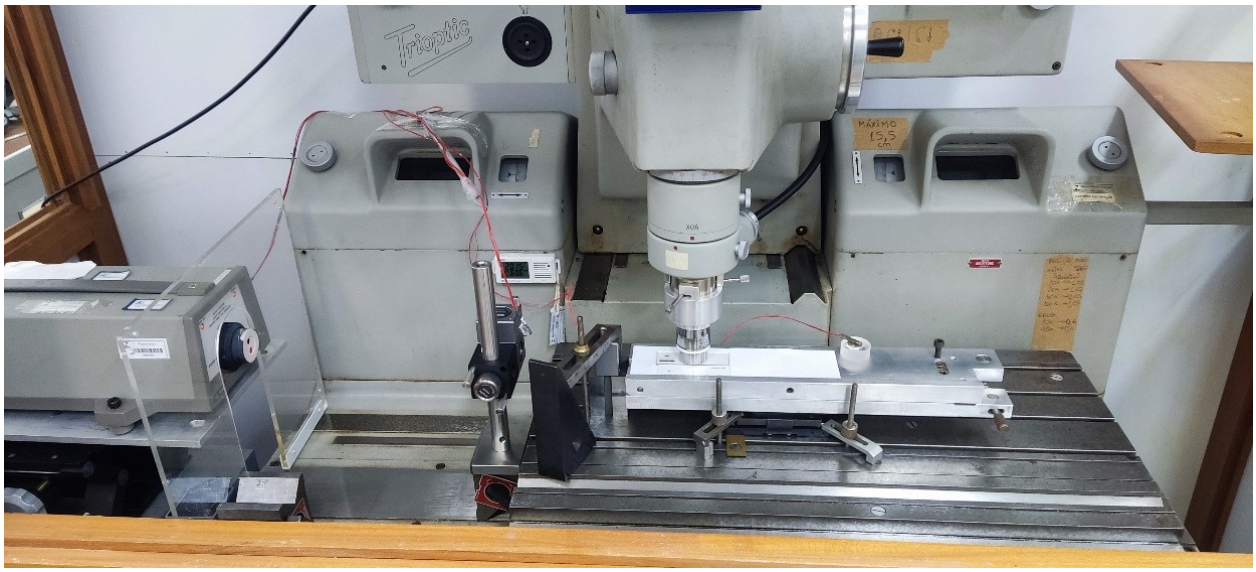
Temperature range during measurements
19.52 °C to 19.74 °C

7.7 INMETRO

Inmetro´s linescales measurement system is composed by a laser system, SIP-Trioptic measure machine, vision system and reflected illumination. A special alignment and levelling table are mounted over the machine table. The special table has screws which rotates the table in two different angles that allows the rotation of artifact in pitch and yaw. The artifact is placed on the special table and a lens set with a CCD camera acquires images of the artifact.

For levelling, the artifact is moved together with the table of measure machine in scale direction and the pitch movement is adjusted to ensure the focus in the full scale at a certain magnification. For alignment, the table is also moved in the scale direction and in this case, the bottom of the first and the last scale lines are considered to adjust scale position and make sure that it remains at same image pixel position. The yaw rotation is used for that. In some cases, that is not the present one, the artifact has alignment structures that may be used to align it.

A laser system is aligned with measure machine table movement and gives traceability to the measurement system combined with pixels counting of snapped images. The pixel calibration is made each running by two images of the same line. The center pixel position is obtained computationally in different positions and it is correlated with the laser display at that position. These values allow estimation of the real recomposed line position.



The distances are obtained by the difference between the line of interest and the reference line (zero point). The region of interest (ROI) of the images is mainly took at middle of lines. The highest magnification of the system disposes an image region around 60 µm height and a pixel size of 60 nm. The system allows measurements range up to 300 mm unidirectional standards.

It is also possible to measure bidimensional gages using this system although the limit for this other direction is about 150 mm. For that, another table is attached to the special table. The procedure for levelling is the same of the previous one but, in this case, the table stays still and the lens set moves.

An additional levelling is needed in this case to rotate the artifact in roll. On other bidirectional artifact direction.

Traceability route
The traceability is provided by a laser interferometer system. The pixels are calibrated each running by the snapping of two image and the correlated laser positions. The final center line position is composed of these laser and center pixel lines positions. Measurements are compensated using reference conditions

described below at additional remarks. For that, calibrated temperature, air pressure and humidity sensors are used to monitor these variables throughout the calibration.

Principle of line center detection
The line center detector starts with a Kirsch edge detector (a convolution matrix is applied to the image matrix using eight different directions to find the highest intensity directional edge). The found points are weighted to transform them in subpixel edges points. The first edge fit is performed at each edge. For noise attenuation, the error between edge points and first fits is used considering an interval from median point to reduce the influence of probable noise points. A second edge fits is performed and the center position of the line is calculated by average value of edges second fits middle positions.

Temperature range during measurements
Air: 19.858 °C to 20.174 °C
Standard: 19.877 °C to 20.041 °C

Additional remarks
Reference conditions for reported results:

Air temperature: 20 °C
Standard temperature: 20 °C
Air pressure: 760 mmHg
Relative humidity: 50 %
CO2 concentration: 0.04 %

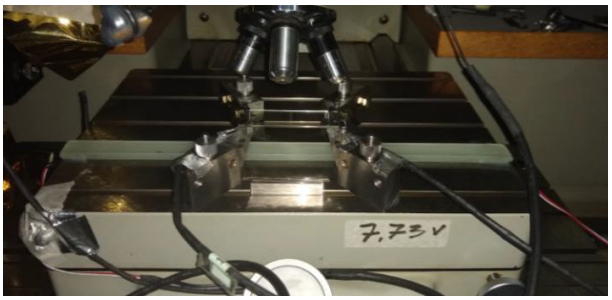
Uncertainty budget

Input Quantity x_i	Distrib.	$U(x_i)$ unit	v_i	$c_i = \partial dL/\partial x_i$	$u_i(dL)/\ nm$
Repeatibility	N	5 nm	19	1	5
Resolution	R	1 nm	100	1	0.3
Laser instability	R	3 nm	50	1	2
Laser alignment	R	6 nm	50	1	3
Deadpath	R	25 nm	50	1	14
Abbe error XZ	R	4 nm	50	1	3
Abbe error XY	R	1 nm	50	1	0.5
Pixel size	R	15 nm	100	1	9
Center deviation	R	12 nm	50	1	7
Air temperature	R	0.03 °C	50	1.63E-8 (1/°C)	0.02
Atm. Pressure	R	49 Pa	100	2.7E-9 (1/Pa)	0.08
Humidity	N	18 Pa	100	3.7E-10 (1/Pa)	0.004
Standard Temp.	N	0.01 °C	50	1E-7 (1/°C)	0.0006
Wavelength	N	3 pm	100	1.3E-5 (1/mm)	0.00002
Horizontal alignment	R	0.6 mrad	50	6E-4 (1/rad)	0.2
Vertical alignment	R	0.05 mrad	50	5E-5 (1/rad)	0.002
Expansion coef.	R	0.7E-7 (1/°C)	100	131 °C	0.005

Combined standard uncertainty: $u_i(dL) = 20\ nm;$
Effective degree of freedom: $v_{eff}(dL) = \infty;$
Expanded uncertainty: $U\_95\ (dL) = Q[40\ nm, 443E^{-9}\ L];$

7.8 INTI

CMM SIP, model 420-M.
Laser HP, model 5529A.
Fixed microscope Zeiss with Basler CCD camera
Thermometer Cole Palmer, model 08502-16.
Illumination type: LED white light




Traceability route
Laser interferometer HP, model 5529A calibrated by beat frequency with reference laser He-Ne of INTI.

Principle of line center detection
A microscope with a camera and in-house software for the line detection was used.

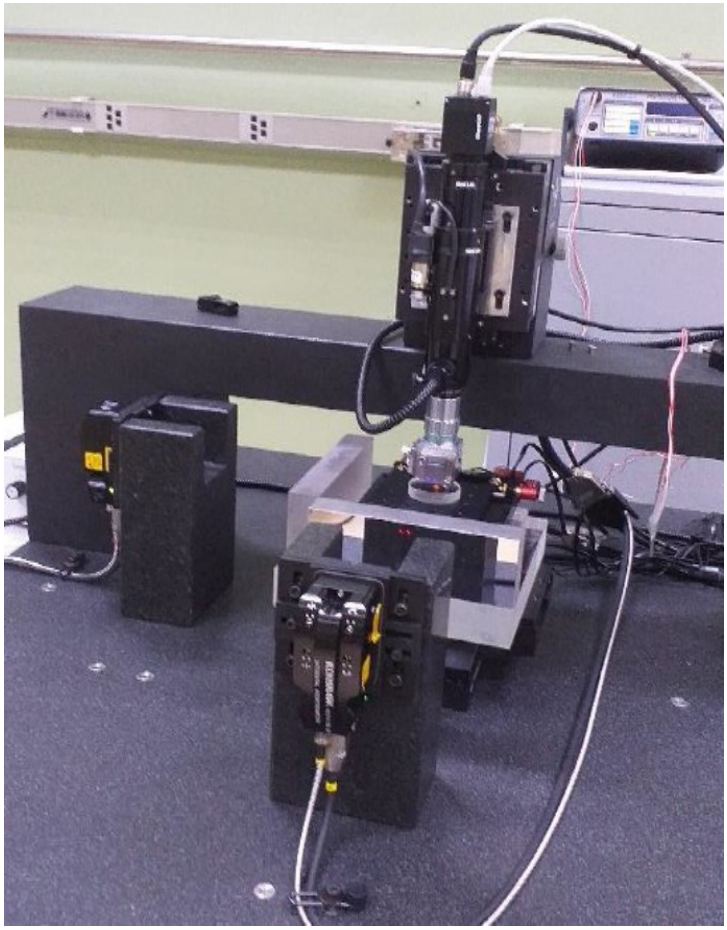
Temperature range during measurements
The temperature range of the room is (20.0 ± 0.5) °C. The change of the gauge temperature during measurement was less than 0.1 °C

7.9 CEM

The distances between graduation lines were measured with a 2D measuring system with 110 mm x 110 mm range. The system consists in a high accuracy XY stage with a Zerodur® block with two perpendicular mirrors attached. On top of the block there is a motorized six-DoF table used for fine alignment. The system is completed by an additional Z-axis that holds a high-quality optical objective, a motorized zoom and a CCD camera. Two reference mirrors are attached to the objective.

Movement of both axes is measured by a differential interferometric system made up of two stabilized Renishaw RLU20 laser encoders and two differential RLD10-DI detectors. Air temperature, pressure and humidity were measured to determine the refraction index of the air by Edlen formula.

The graduations lines are localised by means of a microscope with a CCD camera and an episcopic coaxial illumination system. In each measurement, the graduation line is aligned with the centre of the field of view of the microscope while the reading of the interferometer is captured. The relative position is determined by digital image analysis with subpixel accuracy.



Traceability route
Laser interferometer calibrated against the length national standard.

Principle of line center detection
The line scale was aligned parallel to X-axis of the 2D measuring system. Each vertical graduation line is analysed within the ROI of 50 µm width around the center line position. The center of the line profile is the average of the left and right edges. The edge locations are determined by the Best Projection method, finding the strongest projected edge location to determine the straight edge, using the vision library of National Instruments.

Temperature range during measurements

20.05 °C to 20.34 °C

Additional remarks

Uncertainty Budget

Stage micrometer

Id cal/comp :	

Description artefact:	
Description:	1 mm
Manufacturer:	Präzissionoptik Gera
Serial number:	BEV
Substrate material:	Nextrema ® 724-3A

Translation stage:	units	value
Id traslation stage:		
Yaw of y-axis:	"	12
Pitch of y-axis:	"	12
Abbe offset y:	mm	0,5
Abbe offset z:	mm	0,5

Interferometer:	units	value
Vacuum wavelenth value:	nm	632,99
Vacuum wavelenth uncertainty:	rel.	1,0E-08
Edlèn equation:	rel.	1,0E-08
Air temperature uncertainty:	°C	0,05
Air pressure uncertainty:	Pa	35
Air humidity uncertainty:	Pa	48
Drift temperature (during measurement):	°C	0,3
Drift pressure (during measurement):	Pa	10
Drift humidity (during measurement):	Pa	10
Interferometer deadpath:	mm	20
Optics nonlinearity:	nm	2,2
Optics thermal drift:	nm	4
cosine error (laser missalignment)	nm	5,00E-09

Stage properties:	units	
Stage alignement horiz.:	µm/mm	0,05
Stage alignement vert.:	µrad	100
Line definition:	nm	10
Temperature deviation between calibration:	°C	0,05
Thermal exp. coef.:	°C^{-1}	-1,0E-07
Uncertainty exp. coef.:	°C^{-1}	7,0E-07
Drift temp along measurement	°C	0,3

Image processing	units	
Microscope magnification deviation axis:	nm/pixel	70
	pixel	0,001
Influence of line edge detection algorithm	nm	14

Measurement:	units	
Repeatability:	µm	0,05
N° of measures:		30

Length:	mm	1

Input quantity x_i	Symbol	Value	Units	Probability distribution	uncertainties $u(x_i)$	uncertainties $u_R(x_i)$	degrees of freedom, υ partial	degrees of freedom, υ total	sensitivity coefficient c_i	sensitivity coefficient value	uncertainty contribution to u(L) $u_i(L)$	units	degrees of freedom υ	relative weight (in %)
Interferometer														
Vacuum wavelength	λ_0	632,990	nm	normal (k=2)		2,4E-09 λ_0		100	$\partial l/\partial\lambda_0$=m/n=L/	1	L/λ_0	1,22E-09 *L*	100	2,5E-07
Index of refraction (calculation)	n=f(t,p,hr)								$\partial l/\partial n$=m/λ_0/n^2=L/n			9,47E-08 *L*	188	1,5E-03
temperature measurement	*t*					0,09 °C		116	$\partial l/\partial\alpha$	8,56E-07				
thermometer measurement uncertainty	cal_t	0,05	°C	normal (k=2)	0,025 °C		100							
drift temperature during measurement	Δt	0,3	°C	rectang.	0,09 °C		100							
pressure measurement	*p*					17,74 Pa		105	$\partial l/\partial n$	3,00E-09				
sensor measurement uncertainty	cal_P	35	Pa	normal (k=2)	17,5 Pa		100							
drift pressure during measurement	Δp	10	Pa	rectang.	2,887 Pa		100							
humidity measurement	*hr*					24,17 Pa		102	$\partial l/\partial hr$	3,63E-10				
sensor measurement uncertainty	cal_{hr}	48	Pa	normal (k=2)	24 Pa		100							
drift humidity during measurement	Δhr	10	Pa	rectang.	2,89 Pa		100							
Edlèn equation	n_{air}	1,00E-08	(1)	normal (k=1)	1,0E-08		100		1	1				
Dead path error	c_{DP}=DP.Δn (2)	1,89	nm	rectang.	1,1 nm			100	1	1	1,1 nm		100	0,20
Optics thermal drift	c_{otd}	4,0	nm	rectang.	2,3 nm			100	1	1	2,3 nm		100	0,88
Optics nonlineality	c_{onl}	2,2	nm	rectang.	1,3 nm			100	1	1	1,3 nm		100	0,27
Cosine error (laser missalignment)	c_{cos}	5,00E-09	*L*	rectang.	2,9E-09 L	1,4E-09 *L*		100	1	1	1,44E-09 *L*		100	3,5E-07
Translation stage														
Errors due to Abbe offsets and pitch and yaw of translation stage	$\partial l_{yaw-pitch}$	41	nm	rectang.	11,9 nm			100	1		11,9 nm		100	23,37
Stage properties														
Stage alignement horiz.	∂l_{hor}	5,00E-05	rad	rectang.	1,2E-09 L			100	1	1	1,2E-09 *L*		100	2,6E-07
Stage alignement vert.	∂l_{vert}	1,00E-04	rad	rectang.	5,0E-09 L			100	1	1	5,00E-09 *L*		100	4,1E-06
Line definition	∂l_{def}	10	nm	rectang.	2,9 nm			100	1	1	2,9 nm		100	1,38
Thermal exp. coef.	α_s	-1,0E-07	°C^{-1}	rectang.	7,0E-07 °C^{-1}		100		Δt L	0,092 L	6,47E-08 *L*		100	6,9E-04
Temperature of stage	t_{st}					0,092 °C			$\Delta\alpha$ L	-1,0E-07 L	-9,24E-09 *L*		100	1,4E-05
drift along the time	$drift_T$	0,3	°C	rectang.	0,087 °C		100							
calibration sensor	t_{cal}	0,05	°C	normal (k=2)	0,025 °C		100							
temperature deviation	Δt_{stm}	0,05	°C	rectang.	0,020 °C		100							
reading	read													0,00
repeatability	s_{rep}	0,05	µm	normal	15,8 nm		9			1	15,8 nm		29	41,42
Image procesing														
microscope magnification (deviation of axis)	mag_{axis}	0,1	nm	normal	0,1 nm					1	0,1 nm		100	0,00
line edge detection algorithm	alg	14	nm	normal	14,0 nm					1	14,0 nm		100	32,48
													Σ =	100,00

(1) refs.: *Metrologia*, 1994, 31, 315-316 and *Metrologia*, 1998, 35, 133-139.

(2) Δn calculated for L=DP, taking into account ΔP, ΔT and ΔHR variations as previously considered.

u_c = Q [a ; b*L*]

U (*k*=2) = Q [60 nm ;0,3 x 10^{-6} *L*]

a = 24,566

b = 1,15E-07

$\upsilon_{(L=1\ mm)}$ = 133

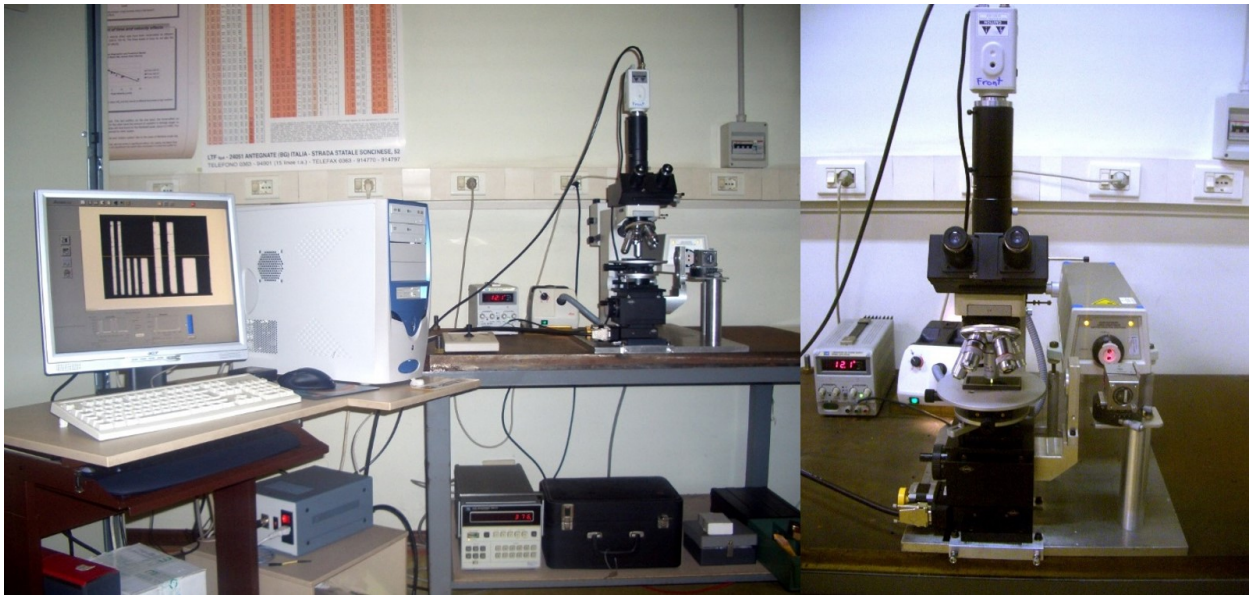
(*) = main contributions

U (*k*=2)= 2 * Q [25 nm ; 1,2E-07 *L*]

7.10 INRIM

Measurement station consists essentially of:

- a metallographic microscope, equipped with:
  - 12 V – 100 W halogen illuminator, with a fine adjustment of framed field luminous intensity;
  - 5-position objective holder including flat-achromatic objectives 2,5X, 5X, 10X, 20X, 50X.
- a solid-state high sensitivity CCD;
- a multi cross-stage sample holder, with a configuration, as follows:
  - a special stage for allowing manual movements till to 15 mm along the z axis in order to keep the plane with the examined objects on the focus plane containing the optical path of the microscope and the axis of the probe. Practically, the user makes the right focus by this stage and not by the microscope coarse focusing that is blocked.
  - A motorized x-axis driven by the software.
  - A 360° rotary table.
  - A x/y manual motion by micrometric screw in order to center the field of view manually.
  - A circular plate for support of samples to be measured.
- HP laser interferometer composed of HP5518A head and HP5508A reader (wavelength 632991378 fm ± 6 fm) perfectly aligned along motorized x-axis.
- Automatic measuring software (based on IMRiM patent).



Measurement procedure and principle of line center detection

The micrometer is positioned on a support plate adjustable transversally at 90° by means of two manual micrometric slides.

Manual slides are positioned on the upper plate of a vertical slide, which is also manual.

The support plate can rotate relative to the top plate of the vertical slide and the top plate of the slide can rotate relative to the vertical slide.

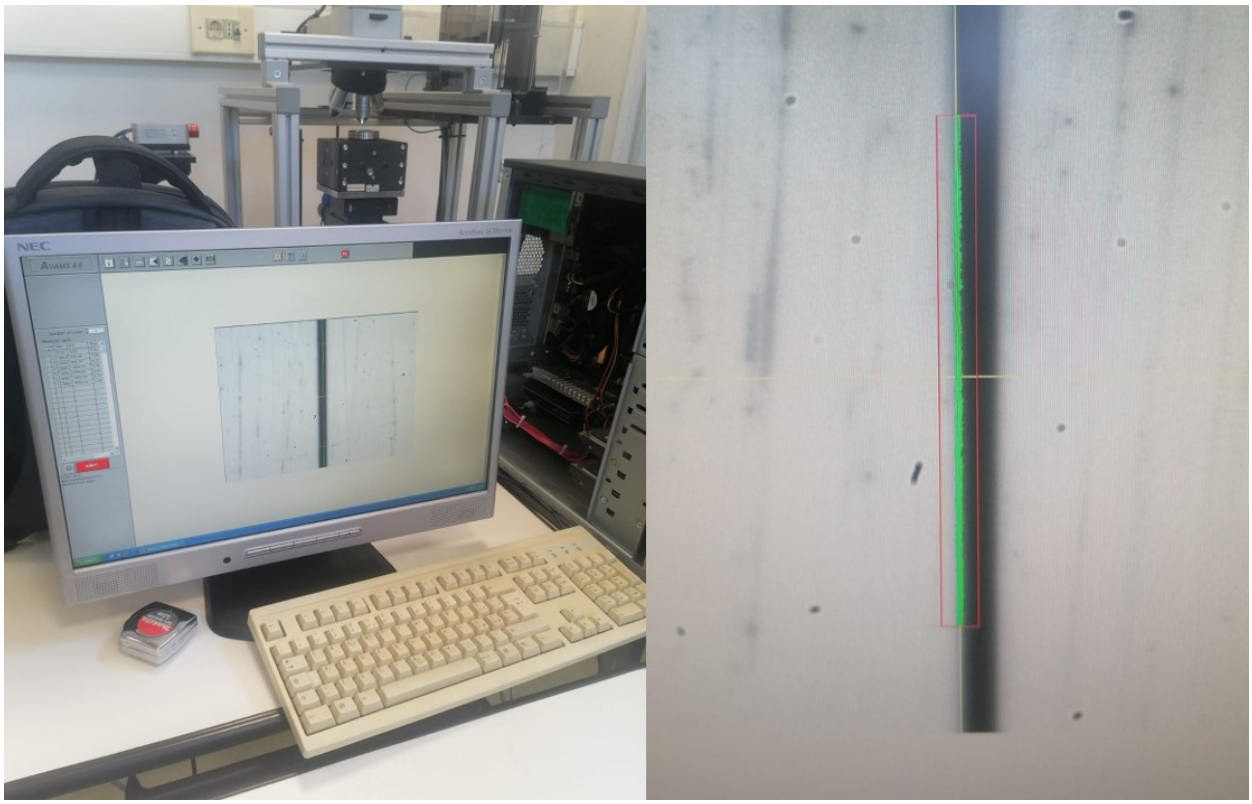
A motorized slide supports the system of manual slides and micrometer and carries out the movements.

The interferometric system, with a corner-cube integral with the mobile part of the motorized table, measures its movements by detecting the absolute position of the micrometer.

The various lines to be calibrated are brought inside the scanning window of the optical system by means of the motorized translation table.

A graphics processing program is used on the PC which, using a series of image analysis routines, reconstructs the profile of the features and determines their positioning within the scanning window.

Everything is controlled by the “Avams” software program operating on a PC.



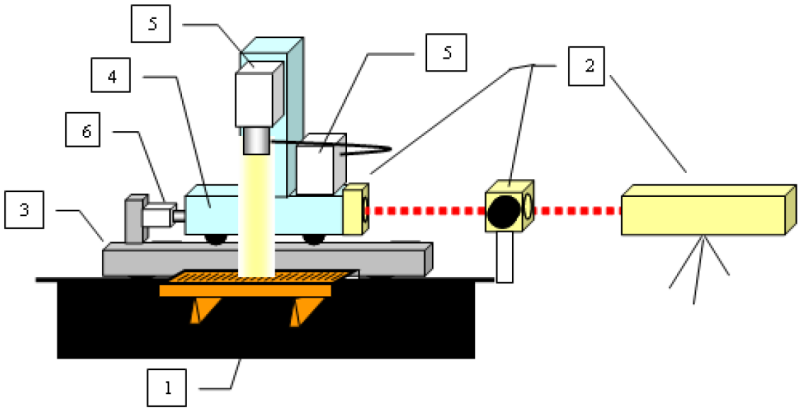
Traceability route
Laser interferometer (see above)

7.11 RISE

The system, presented in Figure 1, is in an underground laboratory with air temperature and humidity control. The temperature is 20 ± 0.2 °C and humidity 50 ± 5 % RH. All sensitive systems in the lab are standing on huge air-damped concrete blocks and the personnel has a separate floor, vibration isolated from the instrumentation, to use.

The measurement system is built up on a 1-D measuring bench (ULMM 3000) with a total measuring length of three meters. The scale is placed on mechanical supports of the bench with functionality for scale alignment. Flat support of the scale is used.

The translation stage of the bench consists of two parts. The main part is sliding (i.e. rolling) on a rail, used for manually moving it coarsely to the nominal positions of a line on a scale. The second part, mounted on the main part, is used for fine-tuning the translation. A microscope (Meiji MC-50, 20x lens) is mounted on this stage. A vision system is used in a closed loop with a piezo actuator (NPL NanoVision) for automatic fine tuning the microscope over the actual line.



1. Measuring artefact
2. Interferometer system
3. Measuring bench (ULMM 3000)
4. Fine positioning stage
5. Line detection system (including microscope, CCD camera, illumination)
6. Piezo motor

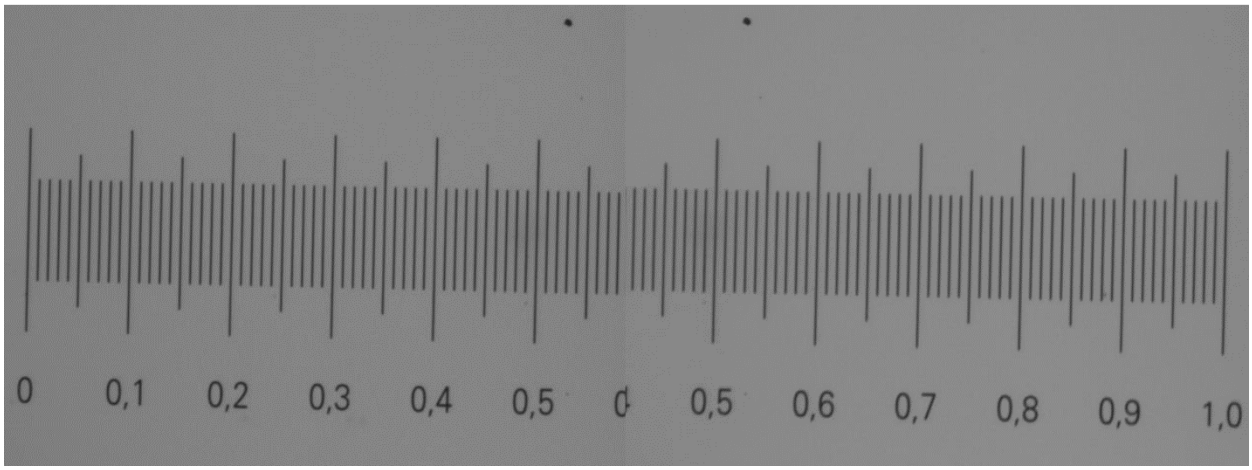
Traceability route
A laser interferometer (Agilent 5519A System) is used for detecting the position of the lines. The retroreflector is mounted close to the microscope.

Principle of line center detection
NPL NanoVision sub-pixel accuracy length measurement system was used for line center detection. NPL NanoVision utilises digital analysis techniques to extract detailed edge and feature position information from images of the measured graticules. It works in combination with a piezo-electric stage pusher for fine motion control.

Temperature range during measurements
20.01 °C to 20,07 °C
The air- and material temperature of the scale (i.e scale support) are measured with an Isotech microK-800 system during the whole calibration process.

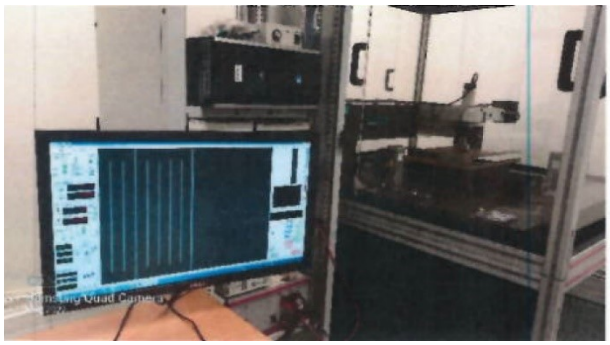
Additional remarks

Pictures after measurements, before departure, are shown below. There are dust particles on the glass around the scale, but we did not try to remove anything in case that would affect or damage the scale.



7.12 UME

The instrument used for the comparison is a 2D measuring instrument equipped with laser interferometer on its x and y axis. Air bearing x-y table moves on granite surface plate using nano-motors. Measurement is performed with front illuminated (reflected from sample) digital microscope with 50× objective with homemade software.



Traceability route
Traceability of measurement is provided with laser interferometer.

Principle of line center detection
Line center detection is done manually using home-made software.

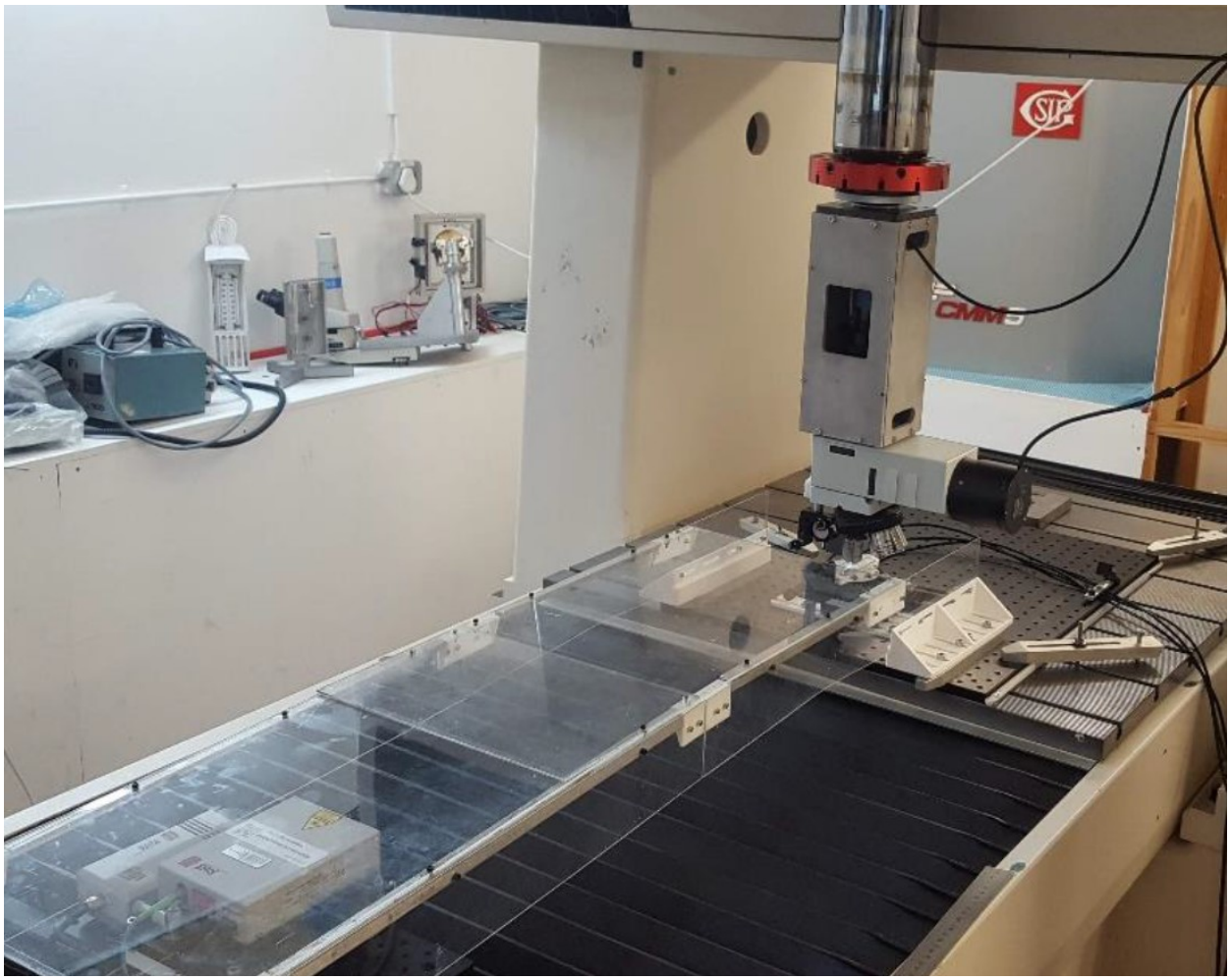
Temperature range during measurements
19.70 °C to 20,30 °C

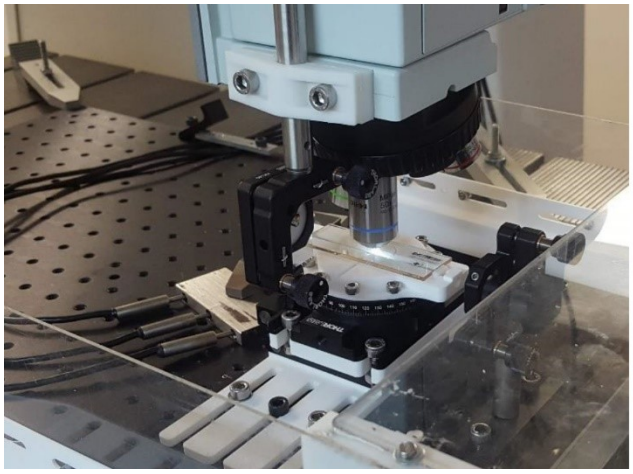
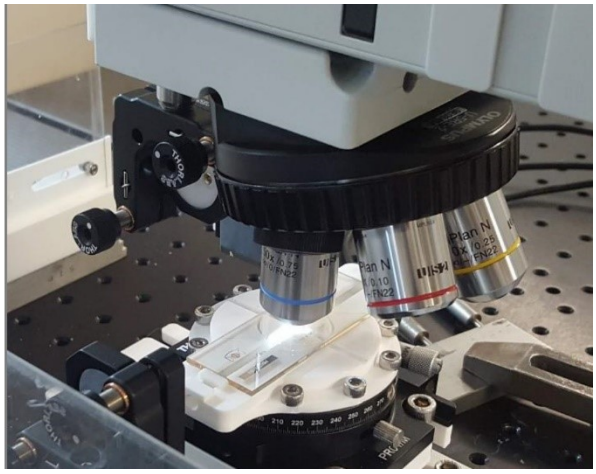
7.13 NMISA

The instrument used was a fully automated, retrofitted SIP5 CMM, using an optical microscope with co-axial illumination. A digital camera was used to capture image frames with a 50x magnification objective. Each frame was analysed to determine the current line mark centre position relative to image centre, with inhouse developed software using the Python programming language. A dual beam plane mirror interferometer is used for the measurement axis.

The SIP5 measurement table moves, while the camera remains stationary. The dual-beam plane mirror laser interferometer measures the table displacement which has movement range of 500 mm. One plane mirror attached as close as possible to the stage micrometer on the measurement table, and the second plane mirror attached the microscope. The measurement table beam axis positioned to be as close as possible to the stage micrometer axis, to reduce Abbe offsets. The face of the stationary mirror is approximately aligned to the centre of the microscope objective (looking from the side). The measurement is therefore taken as the distance between these two plane mirrors to reduce the effect of zero reference point drift. A Perspex “shield” is also placed over the beam path and next to the stage micrometer to reduce air-currents blowing over the beam and thermal gradients.

The stage micrometer is placed on a 3D-printed support, which allows for gentle clamping from the sides (in the direction of measurement). This support is bolted to a rotation stage, allowing for fine alignment of the stage micrometer scale axis to the image axis. Finally, the rotation stage is attached on top of a tilt stage to adjust the vertical alignment using the limited depth-of-field of the 50x magnification (i.e., using the out-of-focus for alignment).



Traceability route
Traceability is through the SIOS dual-beam plane-mirror laser interferometer which was calibrated against a (calibrated) stabilised He-Ne laser.

Principle of line center detection
An image frame is captured by a digital camera. A certain rectangular Region of Interest (ROI) is selected, around the image centre. If required, pre-processing filters can be applied to the ROI. Next, the ROI is divided into horizontal sections and the line centre as well as other line parameters, such as line width, are estimated for each section. The average line centre is calculated as well as the standard deviation. The other parameters can be used to estimate the line quality.

Line centre detection per segment is done by detecting the left and right edge(s) of the visible lines. An average per image column (over Y-axis, where the line scale axis is in the image X-axis) is used to find the edges. Again, certain filters can be applied to this average line, if required. Now, an edge is the interpolated sub-pixel X-axis location where column-average crosses a certain threshold. This threshold can be manually set, or determined as the mid-range value, or the middle of a three-bin histogram.

Normally, the ROI is selected in such a way that only one line mark is inside the ROI. However, the line closest to image X-axis centre is selected if more than one edge pair or line mark are found in the ROI.

Temperature range during measurements
19.50 °C to 20,00 °C

Additional remarks
A linear image calibration factor (e.g., in µm/pixel) is automatically estimated when the measurement starts. This factor relates the image pixels to metre, as measured with the laser interferometer. A correction to the measured position is then applied to subsequent measurements by multiplying the calibration factor with the distance from the linear centre to image X-axis centre. This correction is required since the positioning resolution of X-axis stage is not sufficient to position the current line centre on the image X-axis centre. The X-axis stage position also drifts (in the order of nanometres) immediately after coming to a stop, most likely due to the SIP5 hydrostatic linear bearings.

The correction value is determined for each new frame if a line is found. This value, along with the relative displacement measured by the laser interferometer, thermometer measurements and other variables are continuously logged, when a specific line is measured, and an average result determined over a set time-period. Since the system is completely automated, this can be repeated many times. Furthermore, the software architecture designed to allow for complete recalculation of the result per nominal value per set number. This means that the result and data is not hidden in a “black box” and allows for post-measurement data analysis.

For the reported results, the effect of drift over was reduced by dividing the nominal values into four sub-groups (0 – 250, 250 – 500, 500 – 750 and 750 – 1000), each using the scale zero mark as zero (i.e., 0, 750, 760, …1000). Each group was repeated 10 times and an average calculated over the 10 sets.