APMP Key Comparison

APMP.L-K5.n01

Calibration of Step Gauge

Final Report

National Institute of Metrology, China

Beijing

May, 2025

Hengzheng Wei

Contents

1 Document control

Draft A 1 December 2022 Initial draft of report
Draft B 3 September 2023 First public draft
Final 30 May 2025 Final approved report

2 Introduction

The metrological equivalence of national measurement standards will be determined by a set of key comparisons chosen and organised by the Consultative Committees of the CIPM working closely with the Regional Metrology Organizations (RMOs). Calibration and Measurement Capabilities (CMCs), which are traceable to national measurement standards, are supported by evidence primarily coming from the results of key and supplementary comparisons, together with the operation of approved and mutually accepted quality systems.

In 2003, the APMP Technical Committee Length (TCL) decided that a new key comparison on step gauge measurements would be carried out and the resulting comparison, APMP.L-K5.2006 was undertaken, involving 13 NMIs; however several laboratories had anomalous results in that comparison. So at the 2013 APMP meeting, the APMP TCL decided to organize a follow-up comparison as a corrective action for NMIs reporting anomalous results in the 2006 comparison. This follow-up comparison is APMP.L-K5.2014. But this comparison was declared as abandoned on 13 December 2018.

APMP TC-L decided to organize the next K5 comparison in 2021. NIM is the pilot laboratory. Seven NMIs participated in this comparison. Six NMIs are from APMP and one from EURAMET.

3 Preparation of the comparison documents

The protocol document for this comparison was prepared by the pilot. This final report of the comparison was prepared according to the following guidance documents:
1. Publication of a Final Report in Metrologia’s Technical Supplement
2. CCL-WG/-MRA-GD-3 Guide to preparation of Key Comparison Reports in Dimensional Metrology
3. CCL-WG/-MRA-GD-3.2 Report template

4 Organization

4.1 Participants

Table 1: List of participant laboratories and their contacts

Laboratory Code	Contact Person	Phone, Fax, Email
NIM (Pilot)	Hengzheng Wei National Institute of Metrology,China NO.18 Bei San Huan Dong Lu Chaoyang District Beijing 100029 China	Tel: +86 10 64524931 Email: weihz@nim.ac.cn
KRISS	Jong-Ahn Kim Korea Research Institute of Standards and Science 267 Gajeong-ro Yuseong-gu Daejeon 34113 Republic of Korea	Tel: +82 42 868 5683 Email: jakim@kriss.re.kr

NIMT	Wiroj SUDATHAM National Institute of Metrology (Thailand) 3/4-5 Moo 3 Klong 5 Klong Luang Pathumthani 12120 Thailand	Tel: +66 2 577 5100 Ext. 1109 Email: wiroj@nimt.or.th
NMIA	Peter Cox National Measurement Institute, Australia 1/153 Bertie Street Port Melbourne Victoria 3207 Australia	Tel: +61 3 9644 4906 Email: Peter.Cox@measurement.gov.au
MSL	Eleanor Howick Measurement Standards Laboratory of New Zealand 69 Gracefield Road Lower Hutt New Zealand	Tel: +64 27 381 5594 Email: Eleanor.howick@measurement.govt.nz
NMIJ-AIST	Osamu Sato Research Institute of Engineering Measurement Dimensional Standards Group AIST Central 3, 1-1-1, Umezono, Tsukuba, Ibaraki 305-8563 Japan	Phone: +81-29-861-4041 Fax: +81-29-861-4080 Email: osm-satou@aist.go.jp
TUBITAK-UME	Muharrem Aşa TUBİTAK Gebze Yerleşkesi Barış Mah. Dr.Zeki Acar Cad. No:1 41470 Gebze / KOCAELİ Turkey	Tel: +90 262 679 5000 / Ext: 5305 Email: ilker.meral@tubitak.gov.tr

4.2 Schedule

The participating laboratories were asked to specify a preferred timetable slot for their own measurements of step gauge – the actual timetable is given in table 2. NMC, A*STAR withdrew from the comparison because the new lab is not ready on schedule.

Each laboratory has seven weeks that include customs clearance, calibration and transportation to the following participant. With its confirmation to participate, each laboratory is obliged to perform the measurements in the allocated period and to allow enough time in advance for transportation so that the following participant receives them in time. All participants finished the comparison on time.

Table 2. Actual Schedule of the comparison

RMO	Laboratory	Gauge Received	Gauge Despatched
APMP	NIM	---	19/07/2021
APMP	KRISS	28/07/2021	25/08/2021
APMP	NIMT	07/09/2021	21/10/2021
APMP	NMIA	29/10/2021	10/12/2021
EURAMET	TUBITAK-UME	28/12/2021	24/01/2022
APMP	MSL	28/02/2022	11/04/2022
APMP	NMIJ	28/04/2022	15/06/2022
APMP	NIM	11/07/2022	---

5 Artefact

Artefact is a 700 mm nominal length step gauge produced by ITS GmbH. The artefact is shown in Fig. 1.

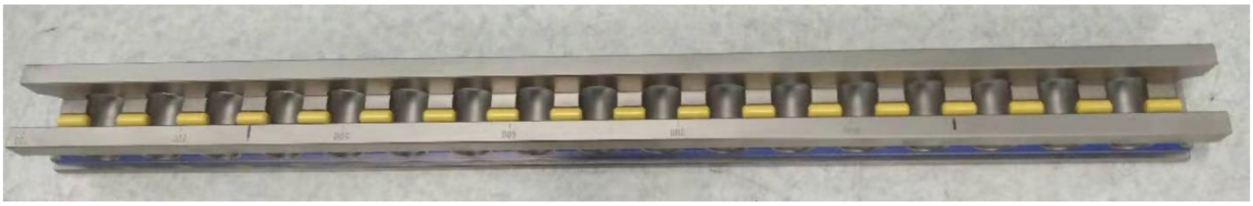

Fig. 1 Step gauge

Table 3. Details of the artefact

Manufacturer	ITS GmbH
Model	700mm
Serial Number	SE0700284
Material	Steel frame, Ceramic gauge
Weight	9.25 kg
Thermal expansion coefficient	11.5×10^{-6} K^{-1}

The main gauge represents a total length of 700 mm with 20 mm steps and consists of 36 measurement faces.
Dimensions of the artefact and reference for measurement are presented in figure 2. Note that on this gauge only the external faces may be used as alignment features. The top surface is used for Z axis alignment. The side surface is used for the X axis alignment. The target points for alignment on top and side surface are near the bessel point of step gauge.

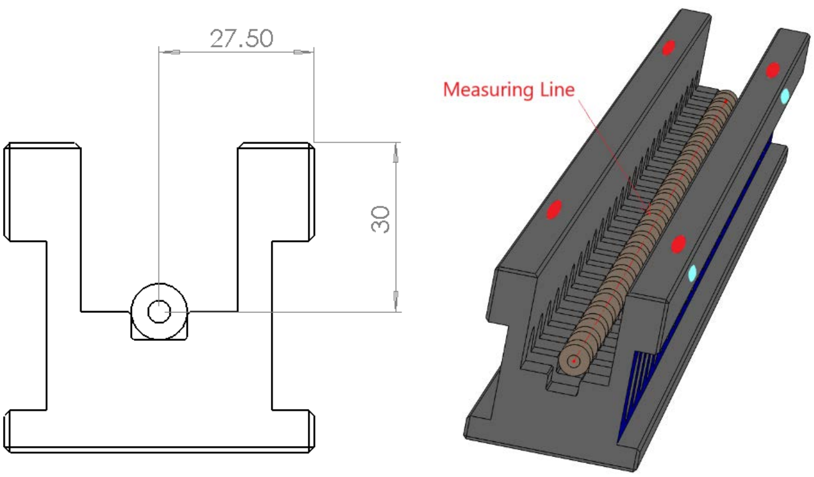

Fig. 2 Dimensions and reference position for measurement of the artefact

6 Analysis of results

6.1 Calculation of the KCRV and En

The KCRV for each measured interval is the weighted mean of the largest consistent subset of participants. The criteria for consistency was that the Birge ratio should be satisfied.

The reference value x_{ref} is calculated as weighted mean

$$x_{ref} = \frac{\sum_{i=1}^{m} x_i / u^2(x_i)}{\sum_{i=1}^{m} 1/u^2(x_i)} \quad (1)$$

Where x_i is the measurement result of different laboratories and $u(x_i)$ is the corresponding standard uncertainty value, m is number of evaluated laboratories.

The standard uncertainty of the reference value $u(x_{ref})$ is given by

$$\frac{1}{u(x_{ref})^2} = \sum_{i=1}^{m} \frac{1}{u^2(x_i)} \quad (2)$$

The chi-squared test for consistency check is performed. At first the chi-squared value χ^2_{obs} is calculated by

$$\chi^2_{obs} = \sum_{i=1}^{m} \left(\frac{x_i - x_{ref}}{u(x_i)} \right)^2 \quad (3)$$

If $\chi^2_{obs} > \chi^2_{0.05,m-1}$, the consistency check will fail. The laboratory with the highest value of $\left(\frac{x_i - x_{ref}}{u(x_i)} \right)^2$ will be excluded for the next round of evaluation. The new standard uncertainty $u(x_{ref})$, reference value x_{ref} and the chi-squared value χ^2_{obs} will be calculated again without the value of excluded laboratory. The consistency check will be calculated again, too. This procedure will be repeated till the consistency check satisfies with $\chi^2_{obs} < \chi^2_{0.05,\mathrm{m}-1}$.

For those laboratories whose measurements are not used to calculate the reference value the uncertainty is uncorrelated and given by

$$U(x_i - x_{ref}) = 2\sqrt{u^2_{x_i} + u^2_{x_{ref}}} \quad (4)$$

If a participant has contributed to the reference value for a given interval, then the uncertainty is calculated as

$$U(x_i - x_{ref}) = 2\sqrt{u^2_{x_i} - u^2_{x_{ref}}} \quad (5)$$

The En value is defined as

$$E_n = \left| \frac{(x_i - x_{ref})}{U(x_i - x_{ref})} \right| \quad (6)$$

6.2 Artefact stability

The pilot laboratory made two measurements of the artefact during the comparison. The first prior to circulation, the second after the completion of circulation. The operator of these measurements did not have sight of other participant’s data while circulation was in progress, to ensure fairness.

Pilot measurements were stable throughout the comparison period. No significant change was observed. The deviations between the two measurements are shown in Figure 3. The uncertainty bounds shown are the uncertainty of the difference between two sets of measurements defined as

$$U_{(1\text{-}2)} = \sqrt{U_1^2 + U_2^2}$$

Where $U_1 = U_2 = (0.2 + L/2000)\mu\text{m}$, k=2.

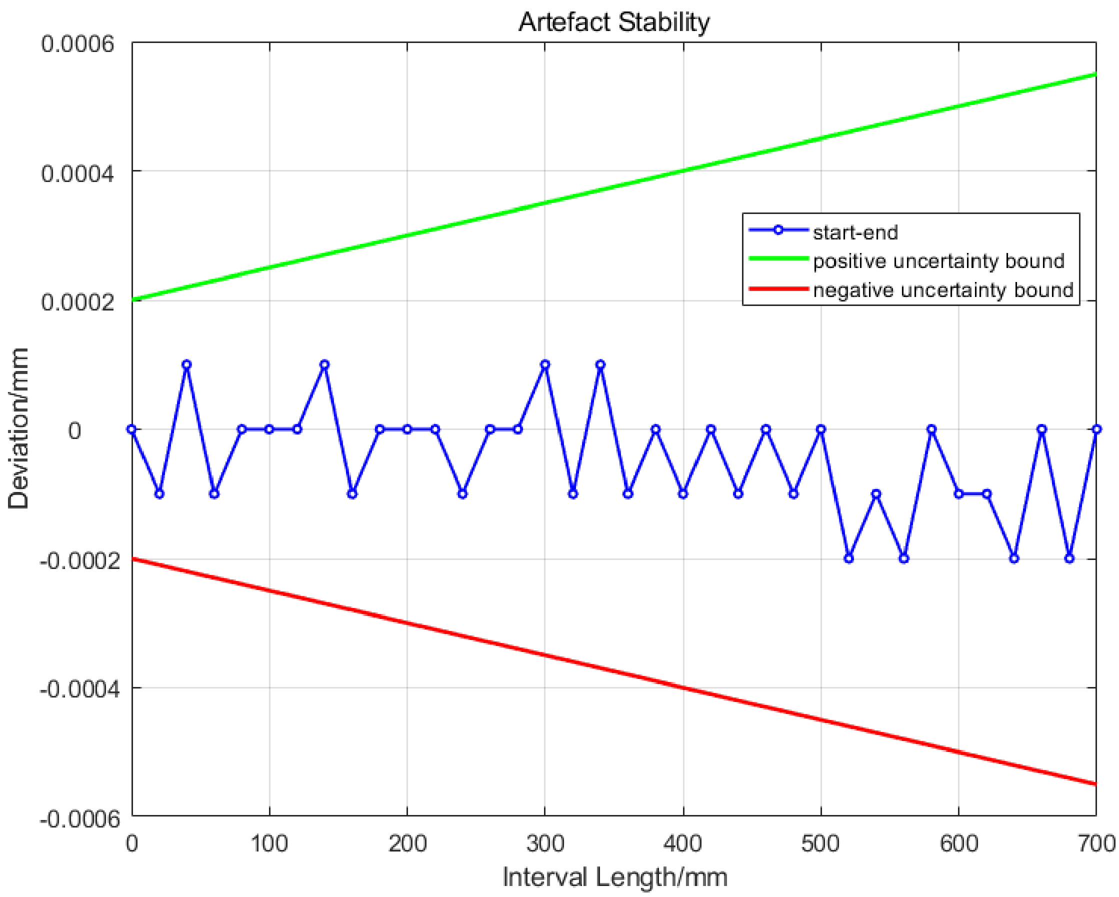

Fig. 3 Deviation between pilot measurements

6.3 Participant measurement results

The reported measurement results for each participant are shown in Table 4. The NIM values used were the measurement results taken prior to circulation.

Table 4. participant reported results

Nominal Length /mm	NIM /mm	KRISS /mm	NIMT /mm	NMIA /mm	MSL /mm	TUBITAK-UME /mm	NMIJ /mm
20	20.00445	20.00449	20.00441	20.00458	20.00454	20.00430	20.00444
40	39.90760	39.90757	39.90757	39.90685	39.90770	39.90780	39.90754
60	59.91182	59.91186	59.91180	59.91206	59.91198	59.91190	59.91180
80	79.90050	79.90033	79.90043	79.90001	79.90053	79.90070	79.90041

100	99.90443	99.90447	99.90446	99.90473	99.90443	99.90480	99.90447
120	119.94077	119.94064	119.94072	119.94035	119.94068	119.94070	119.94065
140	139.94653	139.94670	139.94667	139.94721	139.94651	139.94700	139.94665
160	159.94034	159.94016	159.94028	159.93993	159.94020	159.94040	159.94019
180	179.94627	179.94634	179.94636	179.94674	179.94626	179.94670	179.94632
200	199.96189	199.96171	199.96191	199.96156	199.96174	199.96220	199.96179
220	219.96726	219.96731	219.96736	219.96772	219.96713	219.96740	219.96729
240	239.93433	239.93409	239.93428	239.93407	239.93400	239.93480	239.93415
260	259.93850	259.93857	259.93866	259.93912	259.93839	259.93900	259.93859
280	279.93466	279.93444	279.93464	279.93436	279.93442	279.93520	279.93450
300	299.93873	299.93878	299.93888	299.93924	299.93861	299.93920	299.93879
320	319.90942	319.90917	319.90941	319.90918	319.90917	319.90980	319.90924
340	339.91312	339.91316	339.91331	339.91393	339.91301	339.91360	339.91319
360	359.88753	359.88736	359.88764	359.88753	359.88728	359.88810	359.88744
380	379.89347	379.89356	379.89370	379.89430	379.89330	379.89410	379.89354
400	399.88098	399.88065	399.88104	399.88083	399.88063	399.88120	399.88084
420	419.88361	419.88358	419.88385	419.88467	419.88342	419.88410	419.88371
440	439.86027	439.85998	439.86044	439.86057	439.86004	439.86070	439.86023
460	459.86231	459.86226	459.86260	459.86339	459.86218	459.86320	459.86245
480	479.85843	479.85824	479.85864	479.85876	479.85815	479.85880	479.85839
500	499.86453	499.86461	499.86487	499.86562	499.86432	499.86540	499.86467
520	519.85272	519.85251	519.85294	519.85296	519.85236	519.85360	519.85270
540	539.85878	539.85883	539.85915	539.86012	539.85855	539.85940	539.85894
560	559.92236	559.92211	559.92257	559.92286	559.92196	559.92280	559.92229
580	579.92775	579.92772	579.92807	579.92901	579.92737	579.92800	579.92784
600	599.90289	599.90257	599.90310	599.90338	599.90234	599.90330	599.90281
620	619.90478	619.90479	619.90517	619.90617	619.90426	619.90530	619.90492
640	639.88208	639.88182	639.88239	639.88253	639.88150	639.88270	639.88210
660	659.88811	659.88808	659.88853	659.88933	659.88760	659.88870	659.88827
680	679.87550	679.87519	679.87578	679.87577	679.87491	679.87610	679.87548
700	699.87813	699.87810	699.87855	699.87905	699.87776	699.87880	699.87829

6.4 Participant measurement uncertainty

The technical protocol specified that the uncertainty of measurement should be estimated according to the ISO Guide to the Expression of Uncertainty in Measurement. Typical standard uncertainties (k = 1) communicated by the participants are shown in Table 5. Some equations reported have the standard form $u=\sqrt{A^2+(BL)^2}=\mathrm{Q}[A, B*L]$, where A is the fixed term and B is the constant of proportionality for the length dependent term of the uncertainty. The measured length L is expressed in m and the standard uncertainty u is expressed in µm.

Table 6 shows the reported standard uncertainties supplied by each participant for the measured intervals.

Table 5. participant measurement uncertainty

Participant	Measurement uncertainty	Participant	Measurement uncertainty
NIM	Q[0.10μm, 0.32L]	TUBITAK-UME	Q[0.325μm, 0.8696L]
KRISS	Q[0.28μm, 0.17L]	MSL	0.098μm+0.27L
NIMT	Q[0.106μm, 0.289L]	NMIJ	Q[0.086μm, 0.24L]
NMIA	No formula reported	/	/

Table 6. participant reported standard uncertainties

Nominal Length /mm	**NIM /μm**	**KRISS /μm**	**NIMT /μm**	**NMIA /μm**	**MSL /μm**	**TUBITAK-UME /μm**	**NMIJ /μm**
20	0.10	0.06	0.11	0.36	0.08	0.33	0.09
40	0.10	0.12	0.11	0.36	0.09	0.33	0.09
60	0.10	0.11	0.11	0.36	0.10	0.33	0.09
80	0.10	0.18	0.11	0.36	0.08	0.33	0.09
100	0.10	0.20	0.11	0.37	0.10	0.34	0.09
120	0.11	0.12	0.11	0.37	0.12	0.35	0.10
140	0.11	0.10	0.11	0.37	0.13	0.35	0.10
160	0.11	0.10	0.12	0.38	0.13	0.36	0.10
180	0.12	0.13	0.12	0.38	0.11	0.37	0.10
200	0.12	0.18	0.12	0.39	0.12	0.38	0.10
220	0.12	0.16	0.12	0.39	0.15	0.39	0.11
240	0.13	0.25	0.13	0.40	0.16	0.40	0.11
260	0.13	0.25	0.13	0.40	0.16	0.42	0.11
280	0.13	0.23	0.13	0.41	0.13	0.43	0.11
300	0.14	0.23	0.14	0.42	0.14	0.44	0.12
320	0.14	0.15	0.14	0.42	0.16	0.46	0.12
340	0.15	0.15	0.14	0.43	0.14	0.47	0.12
360	0.15	0.19	0.15	0.44	0.16	0.49	0.13
380	0.16	0.20	0.15	0.45	0.16	0.50	0.13
400	0.16	0.30	0.16	0.46	0.16	0.52	0.13
420	0.17	0.26	0.16	0.46	0.19	0.53	0.14
440	0.17	0.21	0.17	0.47	0.21	0.55	0.14
460	0.18	0.21	0.17	0.48	0.20	0.56	0.14
480	0.18	0.18	0.17	0.49	0.19	0.58	0.15
500	0.19	0.18	0.18	0.50	0.19	0.60	0.15
520	0.19	0.20	0.18	0.51	0.21	0.61	0.16
540	0.20	0.19	0.19	0.52	0.23	0.63	0.16
560	0.21	0.16	0.19	0.53	0.24	0.65	0.16

580	0.21	0.15	0.20	0.54	0.23	0.66	0.17
600	0.22	0.22	0.20	0.55	0.23	0.68	0.17
620	0.22	0.20	0.21	0.56	0.24	0.70	0.18
640	0.23	0.22	0.21	0.57	0.26	0.72	0.18
660	0.23	0.21	0.22	0.59	0.26	0.74	0.19
680	0.24	0.21	0.22	0.60	0.27	0.75	0.19
700	0.25	0.21	0.23	0.61	0.25	0.77	0.19

6.5 KCRV

The KCRV for each interval value and the associated uncertainty are shown in Table 7. The reference value for each face is the weighted mean of the largest consistent subset of participants. The calculation method is describe in section 6.1.

Table 7. KCRV values

Interval	KCRV /mm	KCRV Uncertainty /µm	Interval	KCRV /mm	KCRV Uncertainty /µm
0 mm - 20 mm	20.00448	0.04	**0 mm - 380 mm**	379.89355	0.07
0 mm - 40 mm	39.90759	0.04	**0 mm - 400 mm**	399.88086	0.07
0 mm - 60 mm	59.91185	0.04	**0 mm - 420 mm**	419.88370	0.08
0 mm - 80 mm	79.90046	0.04	**0 mm - 440 mm**	439.86024	0.08
0 mm - 100 mm	99.90446	0.05	**0 mm - 460 mm**	459.86243	0.08
0 mm - 120 mm	119.94069	0.05	**0 mm - 480 mm**	479.85840	0.08
0 mm - 140 mm	139.94664	0.05	**0 mm - 500 mm**	499.86465	0.08
0 mm - 160 mm	159.94023	0.05	**0 mm - 520 mm**	519.85269	0.08
0 mm - 180 mm	179.94632	0.05	**0mm - 540mm**	539.85892	0.08
0 mm - 200 mm	199.96182	0.05	**0mm - 560mm**	559.92229	0.08
0 mm - 220 mm	219.96729	0.06	**0mm - 580mm**	579.92780	0.08
0 mm - 240 mm	239.93421	0.06	**0mm - 600mm**	599.90279	0.09
0 mm - 260 mm	259.93858	0.06	**0mm - 620mm**	619.90496	0.10
0 mm - 280 mm	279.93455	0.06	**0mm - 640mm**	639.88205	0.09
0 mm - 300 mm	299.93878	0.06	**0mm - 660mm**	659.88820	0.10
0 mm - 320 mm	319.90929	0.06	**0mm - 680mm**	679.87542	0.10
0 mm - 340 mm	339.91318	0.06	**0mm - 700mm**	699.87822	0.10
0 mm - 360 mm	359.88747	0.07	/	/	/

6.6 Participant results by face

The deviation of each participant's result from the reference value is determined simply as $x_i - x_{ref}$. The expand uncertainty of this deviation is calculated with formula (4) and (5).

The following plots, Figures 4 through 38, show the deviation from the reference value of each participant for each interval measured and corresponding expand uncertainty with k=2.

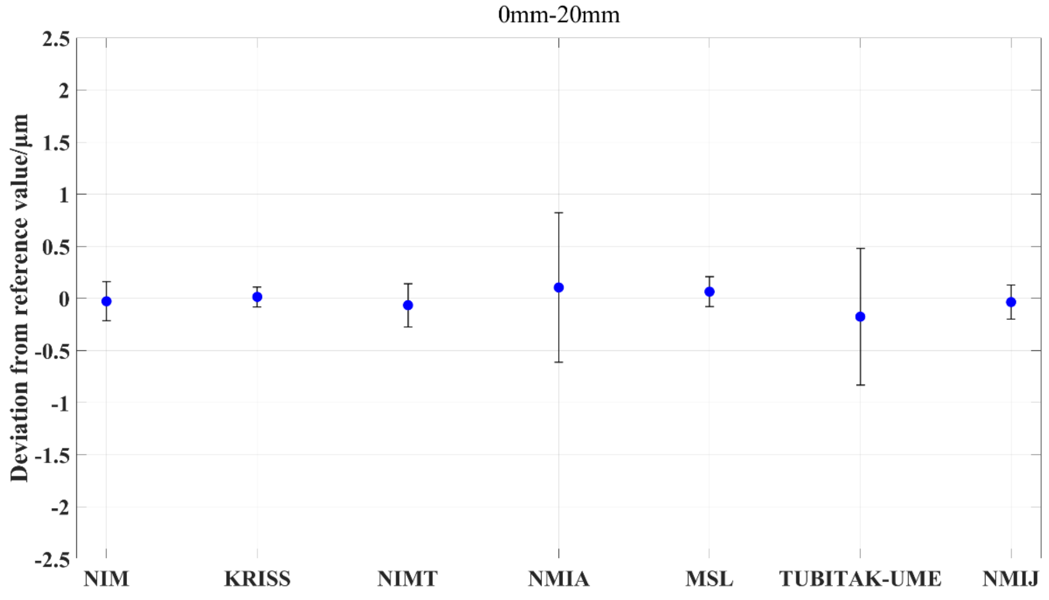

Fig. 4 participant deviations from KCRV for this interval (k = 2)

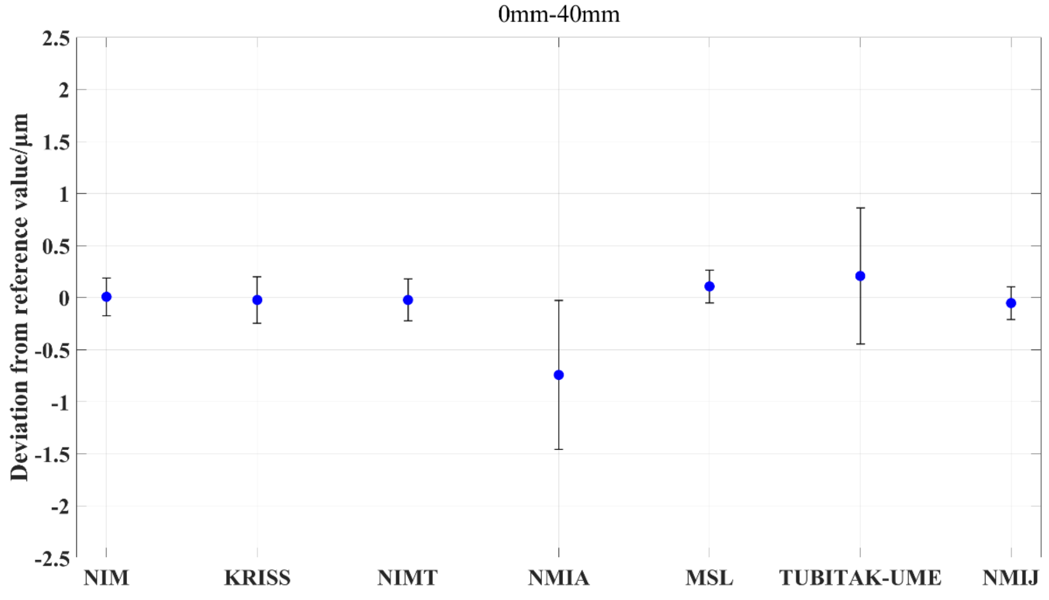

Fig. 5 participant deviations from KCRV for this interval (k = 2)

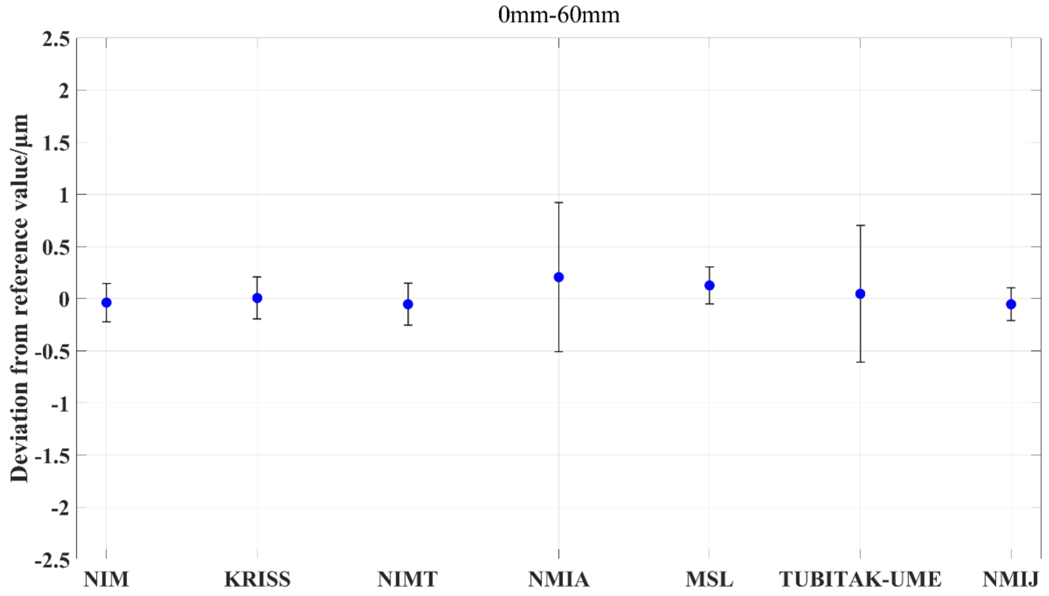

Fig. 6 participant deviations from KCRV for this interval (k = 2)

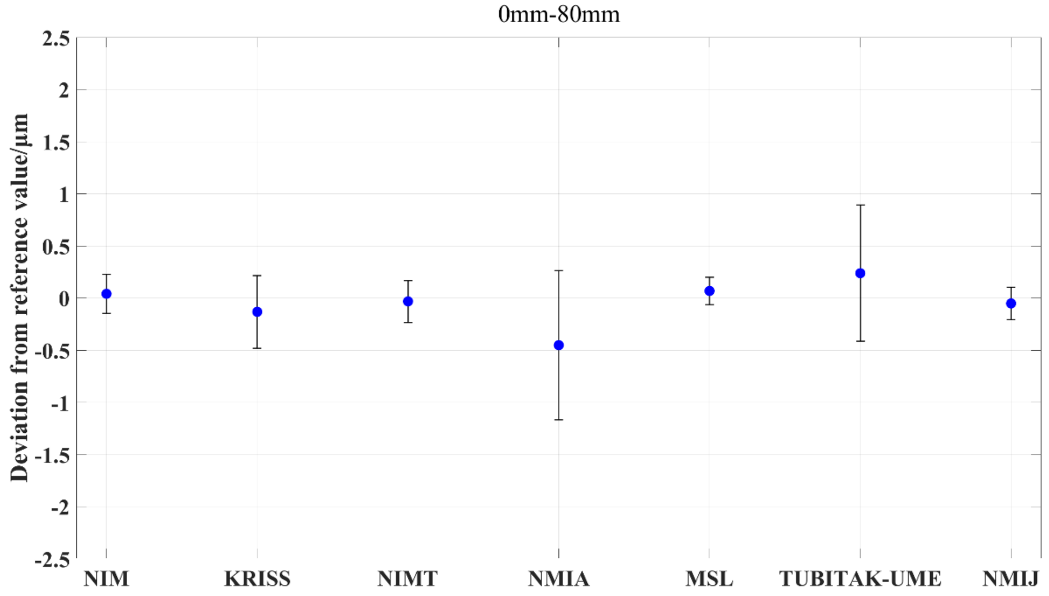

Fig. 7 participant deviations from KCRV for this interval (k = 2)

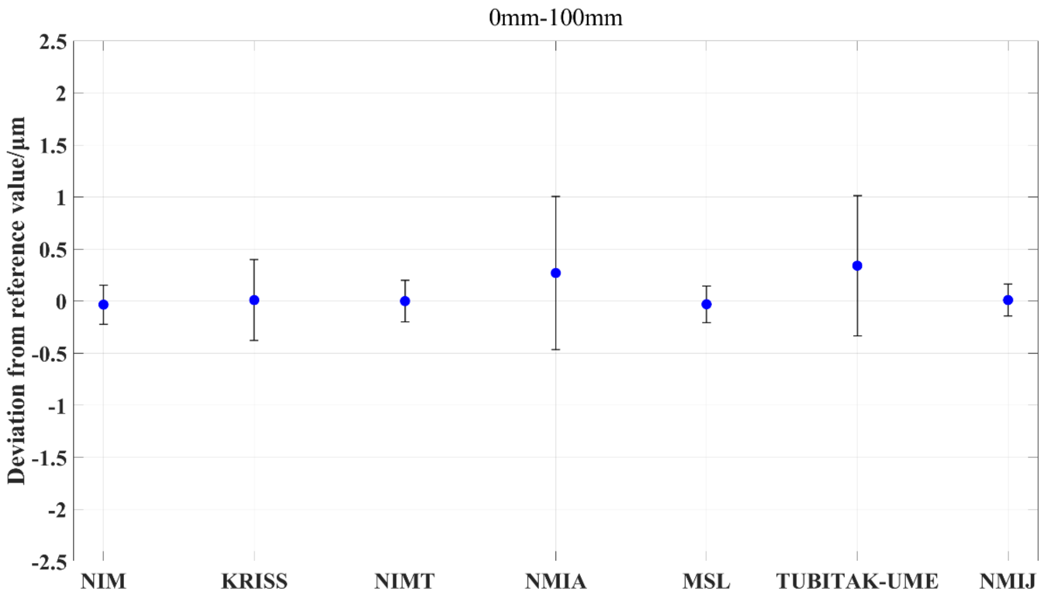

Fig. 8 participant deviations from KCRV for this interval (k = 2)

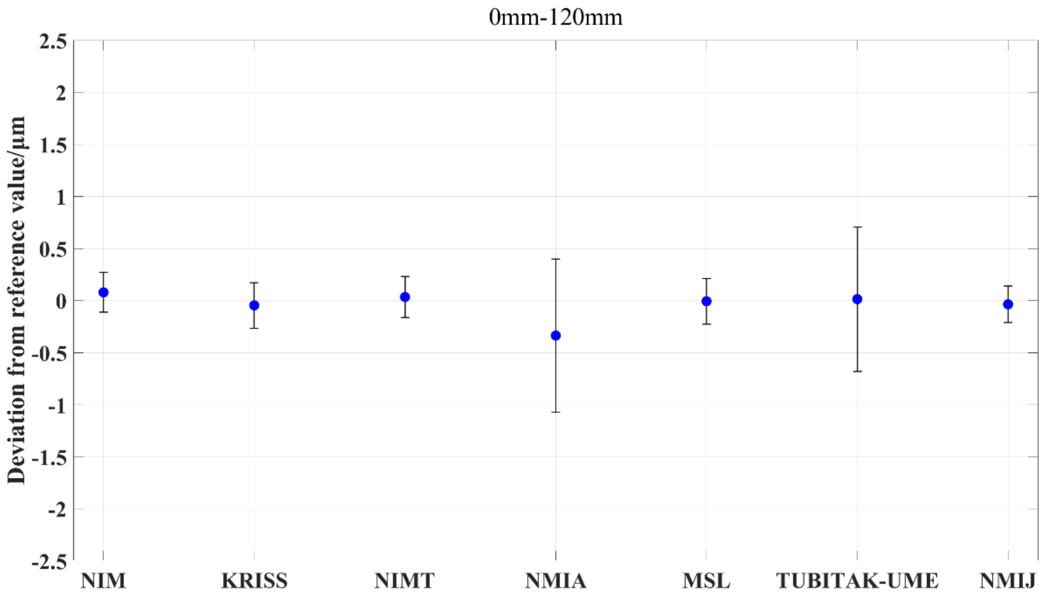

Fig. 9 participant deviations from KCRV for this interval (k = 2)

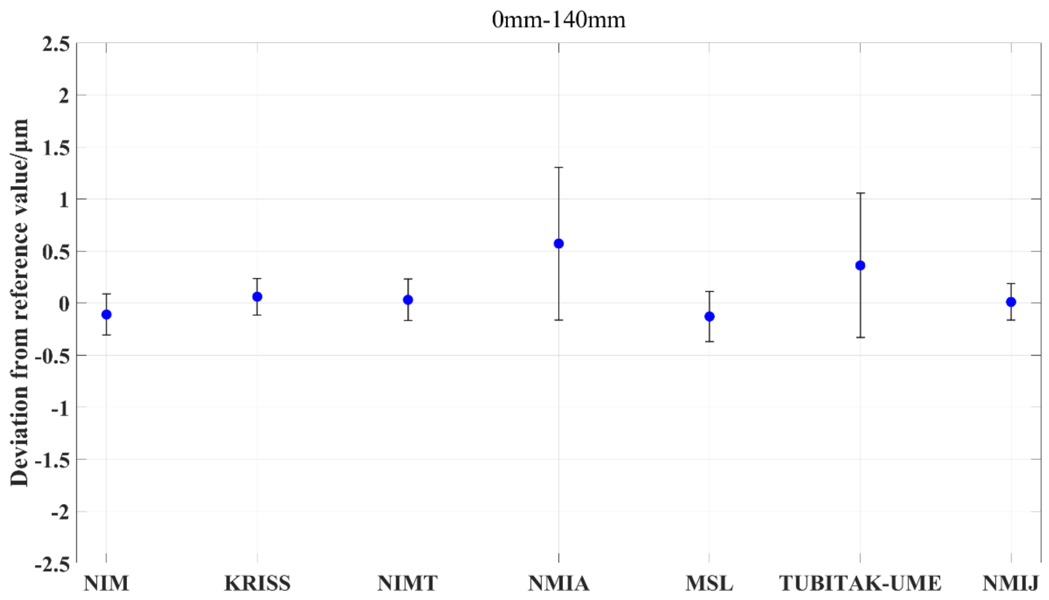

Fig. 10 participant deviations from KCRV for this interval (k = 2)

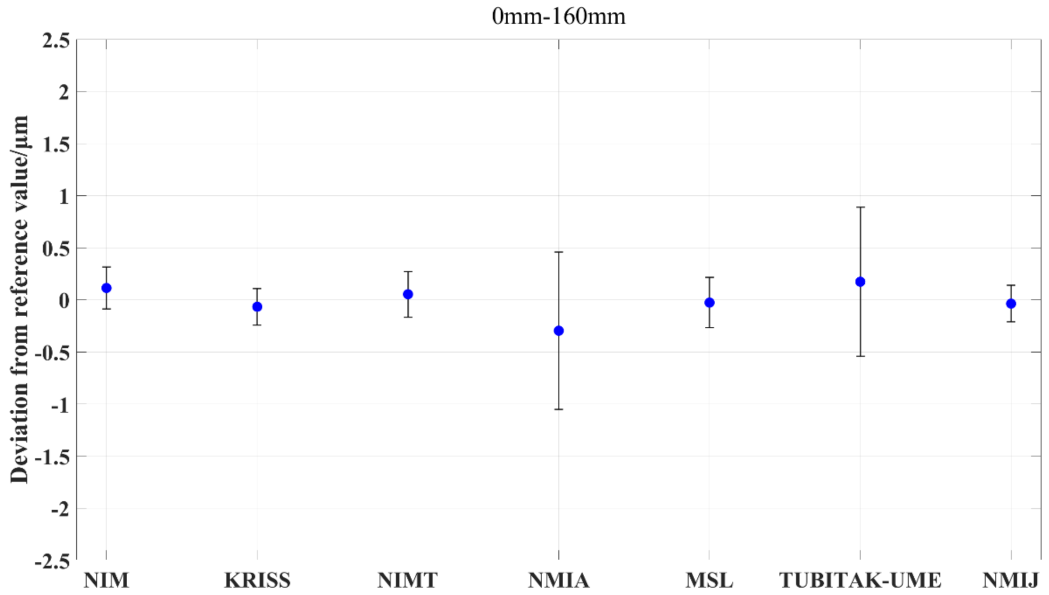

Fig. 11 participant deviations from KCRV for this interval (k = 2)

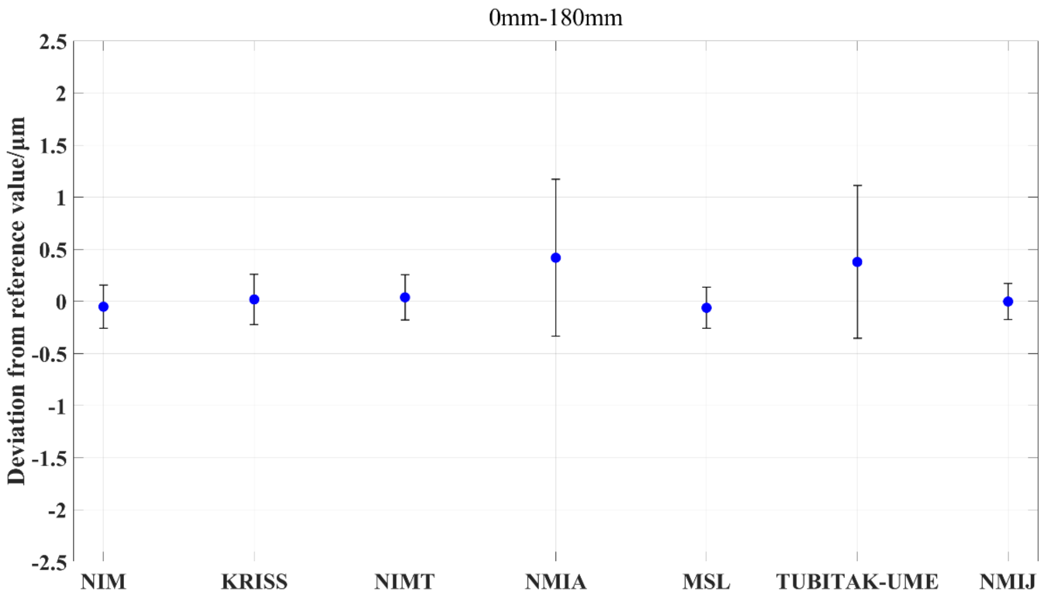

Fig. 12 participant deviations from KCRV for this interval (k = 2)

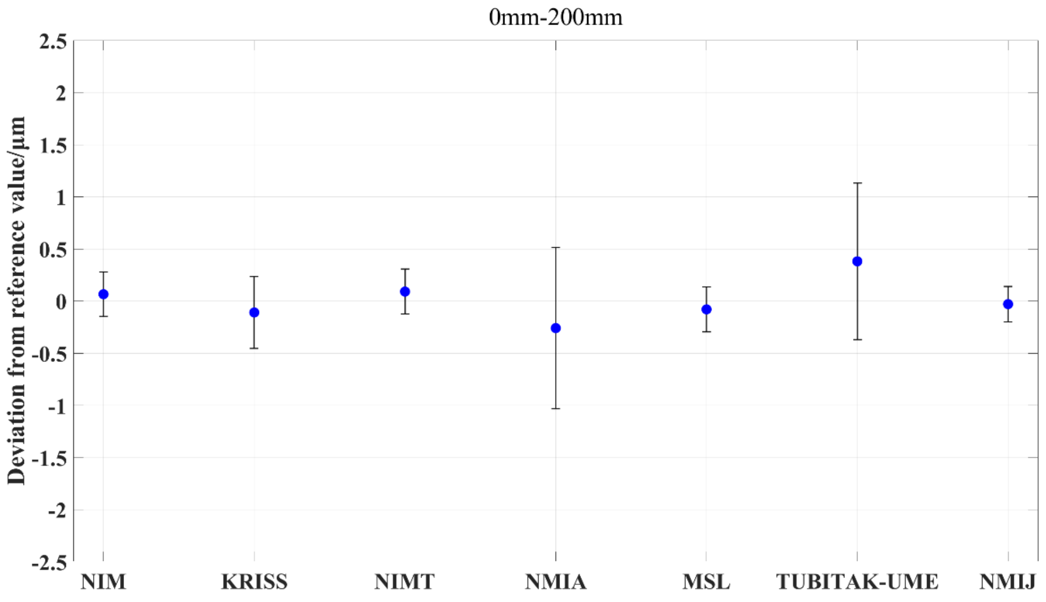

Fig. 13 participant deviations from KCRV for this interval (k = 2)

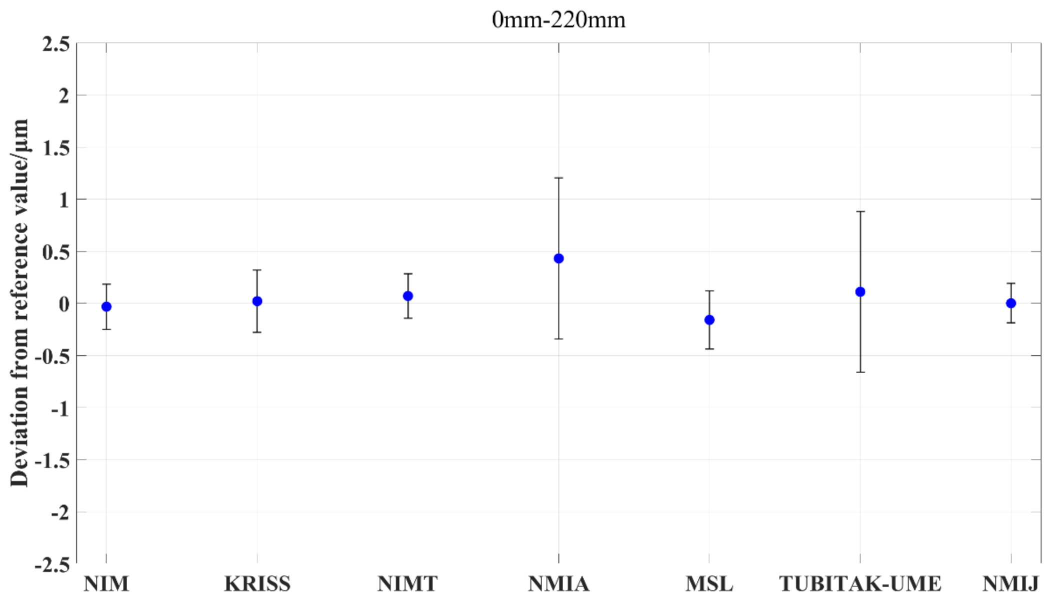

Fig. 14 participant deviations from KCRV for this interval (*k* = 2)

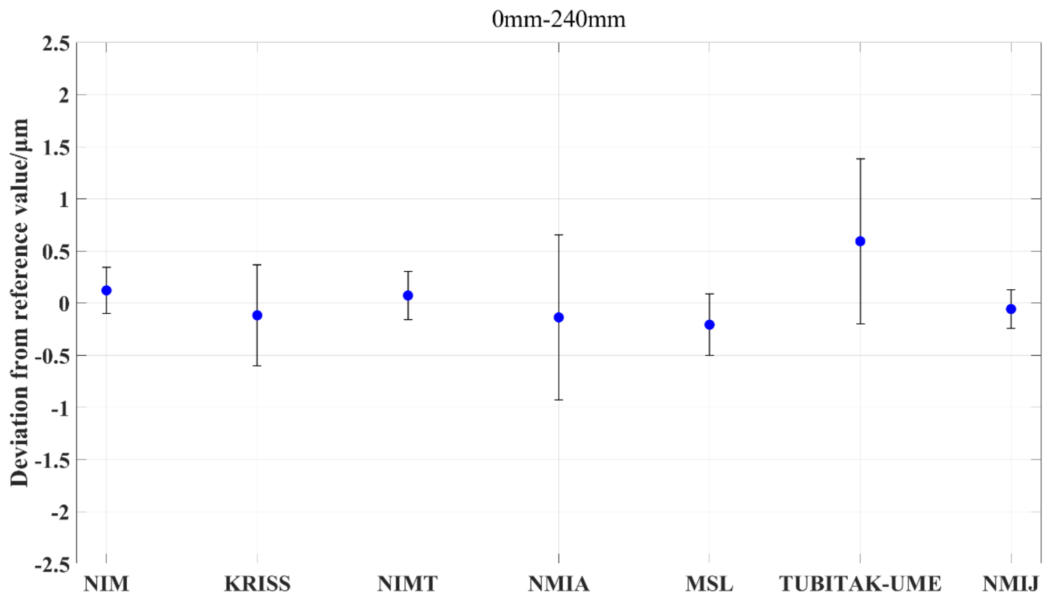

Fig. 15 participant deviations from KCRV for this interval (*k* = 2)

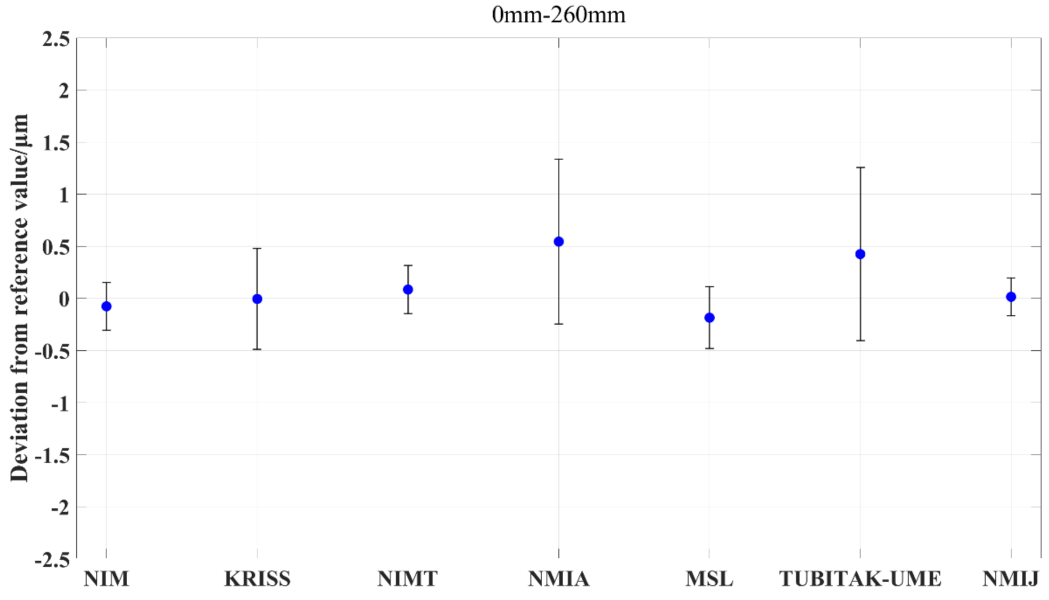

Fig. 16 participant deviations from KCRV for this interval (k = 2)

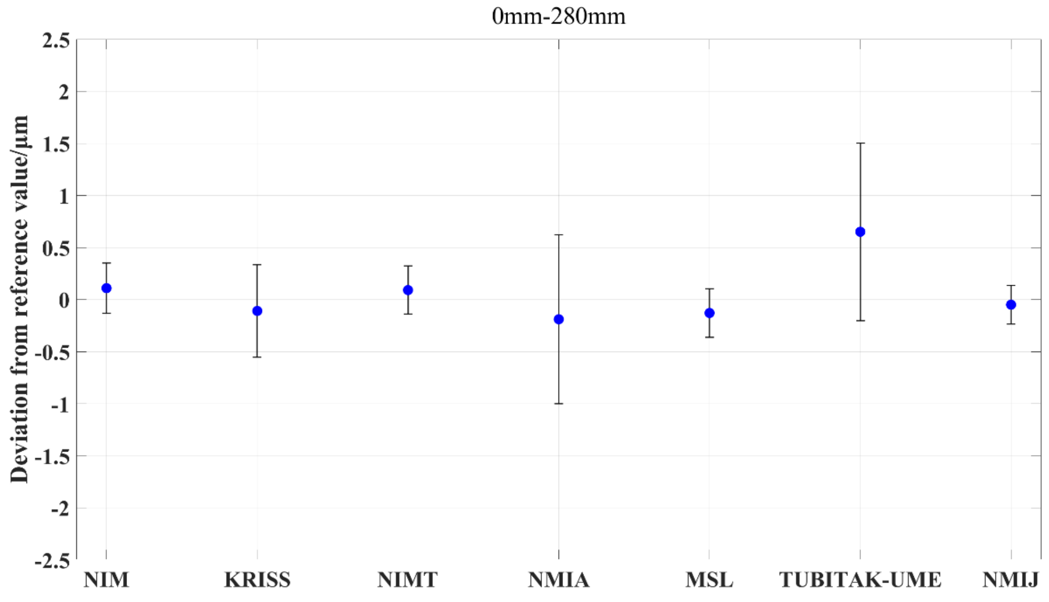

Fig. 17 participant deviations from KCRV for this interval (k = 2)

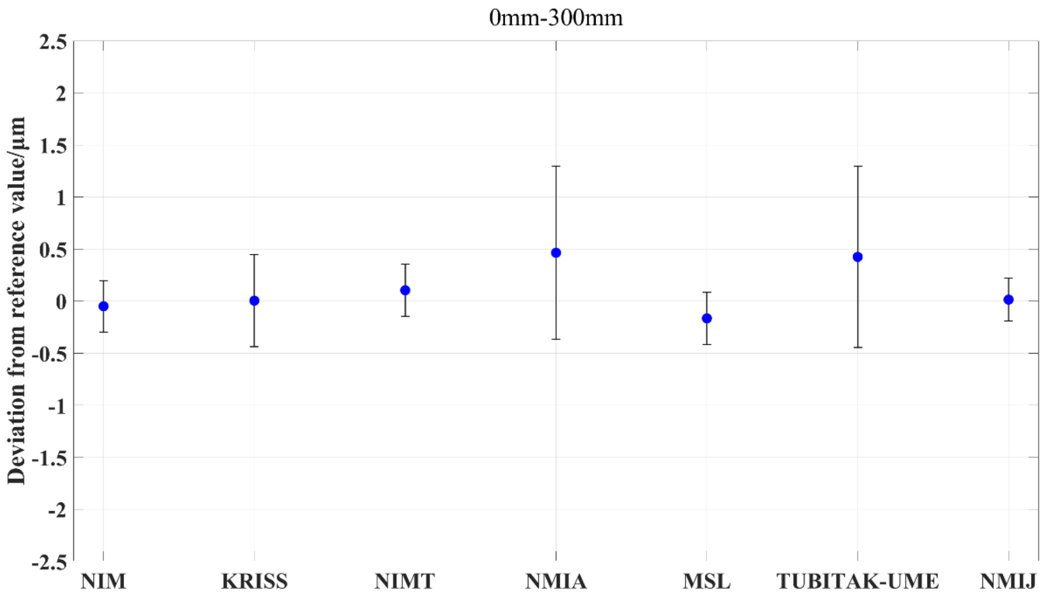

Fig. 18 participant deviations from KCRV for this interval (k = 2)

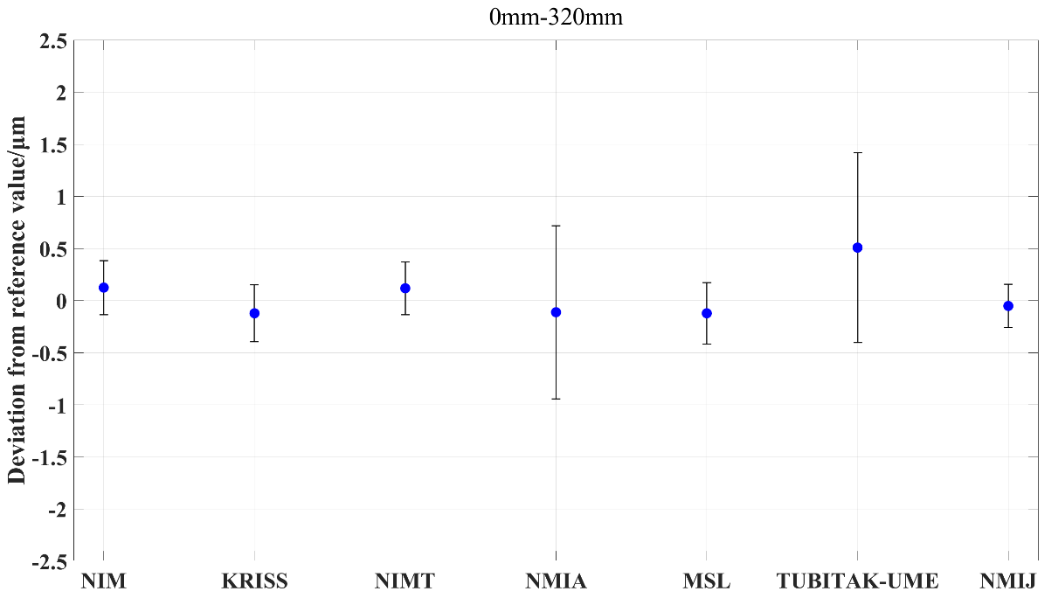

Fig. 19 participant deviations from KCRV for this interval (k = 2)

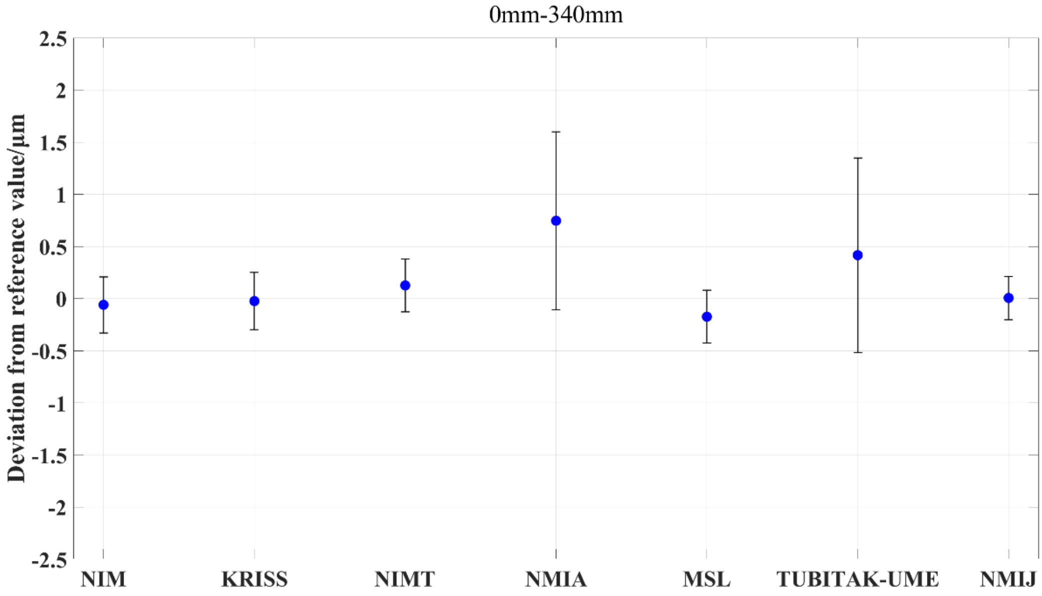

Fig. 20 participant deviations from KCRV for this interval (k = 2)

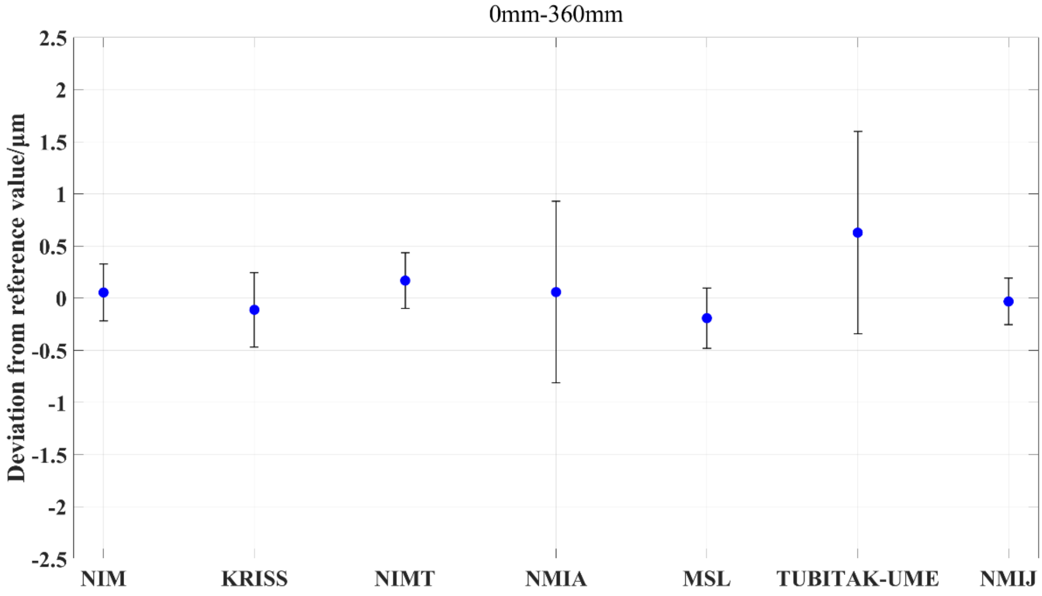

Fig. 21 participant deviations from KCRV for this interval (k = 2)

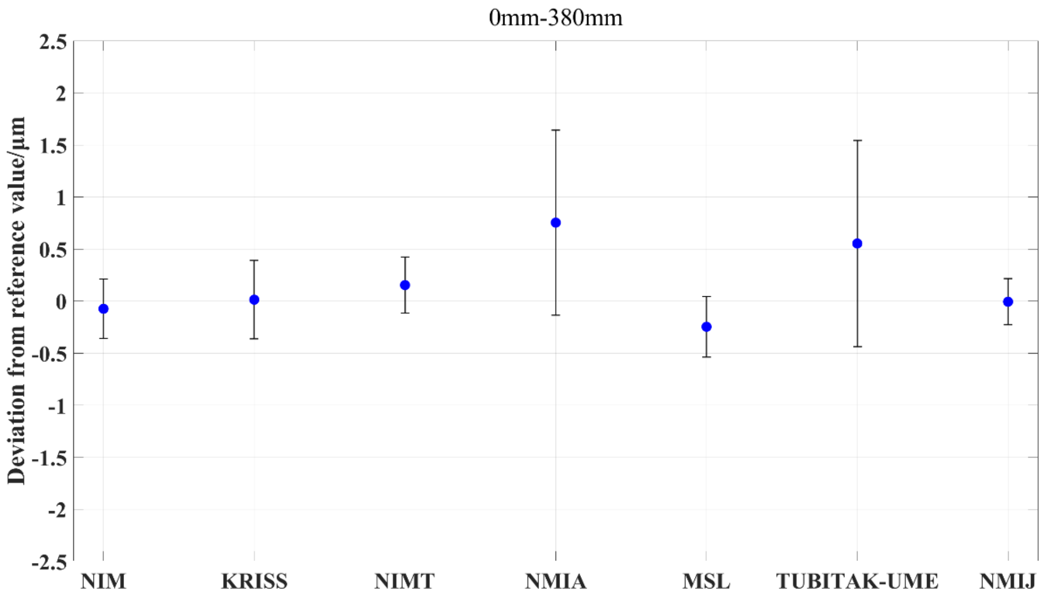

Fig. 22 participant deviations from KCRV for this interval (k = 2)

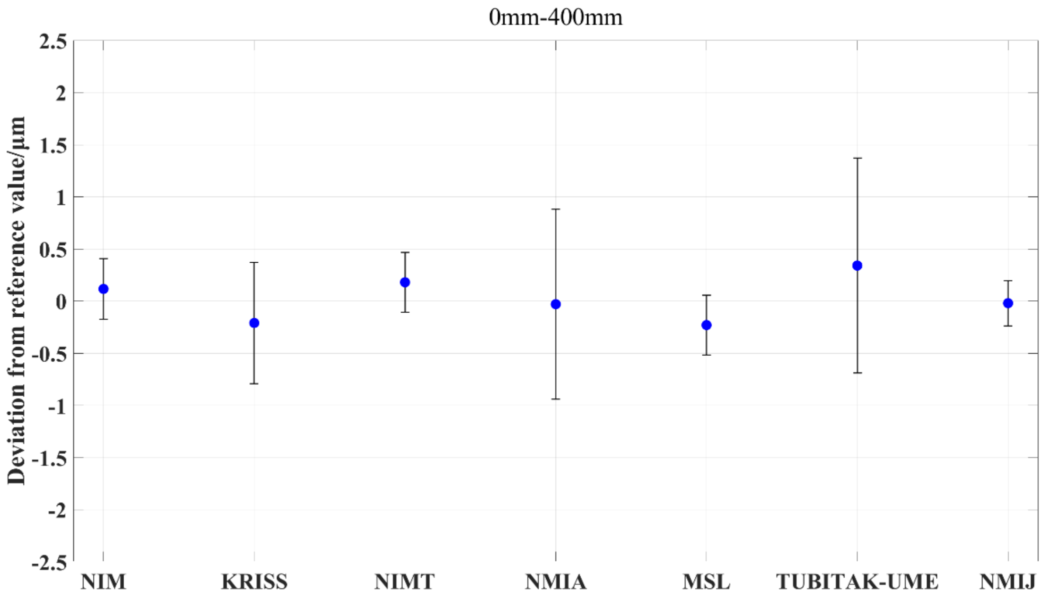

Fig. 23 participant deviations from KCRV for this interval (k = 2)

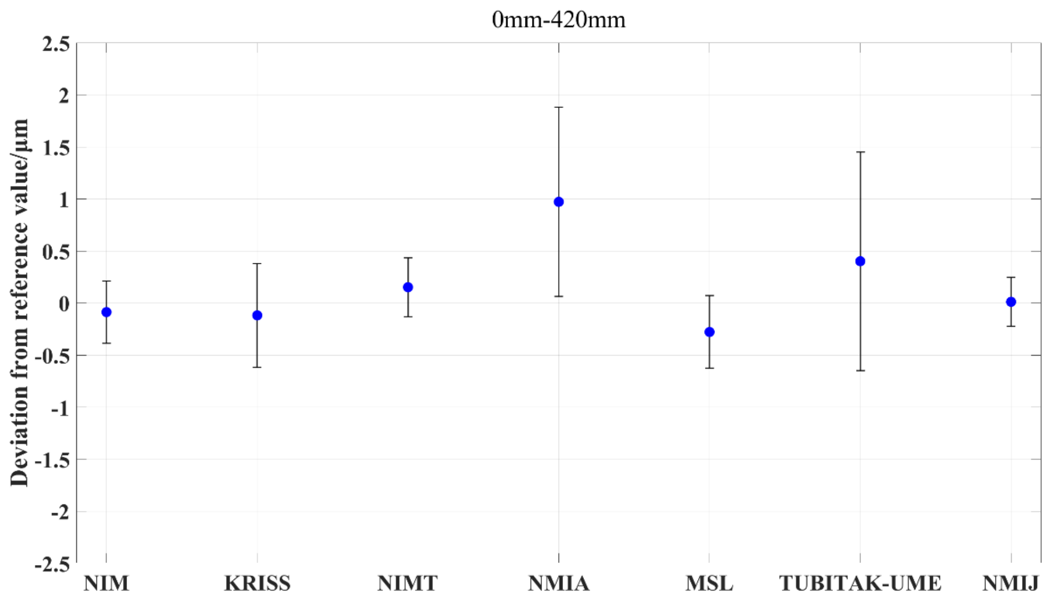

Fig. 24 participant deviations from KCRV for this interval (k = 2)

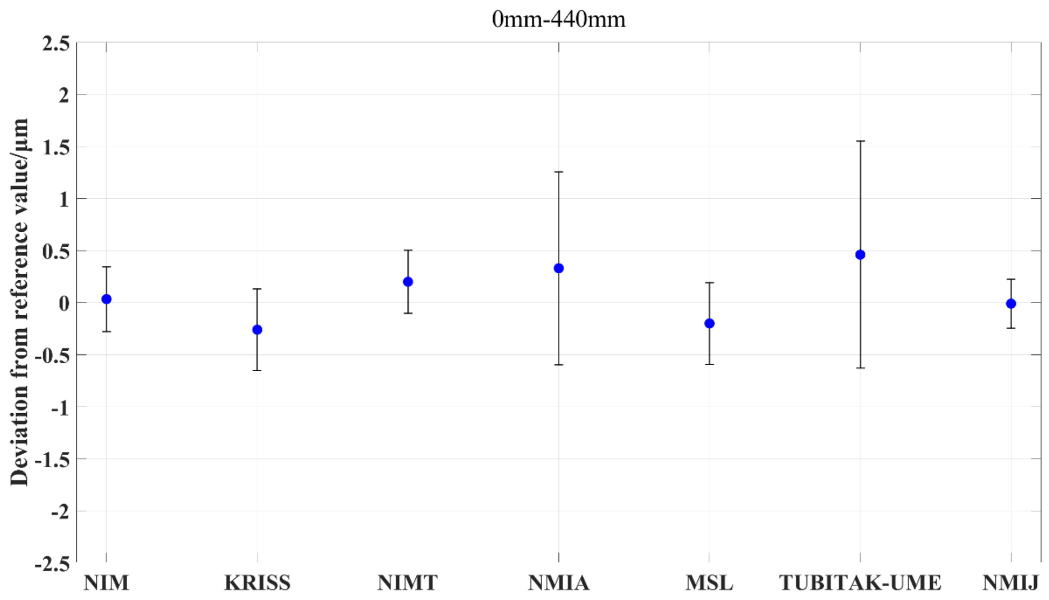

Fig. 25 participant deviations from KCRV for this interval (k = 2)

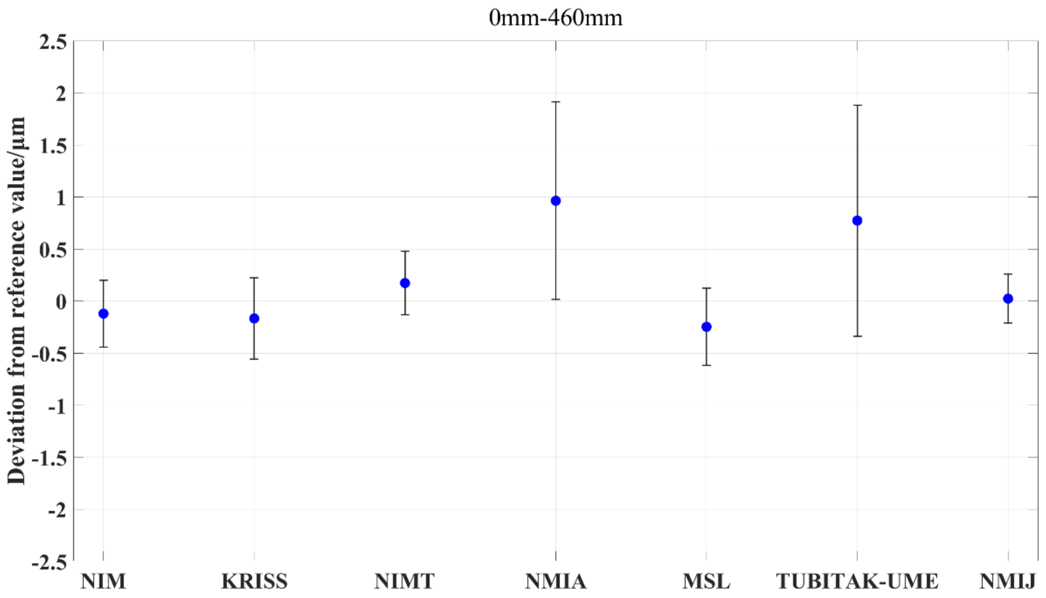

Fig. 26 participant deviations from KCRV for this interval (*k* = 2)

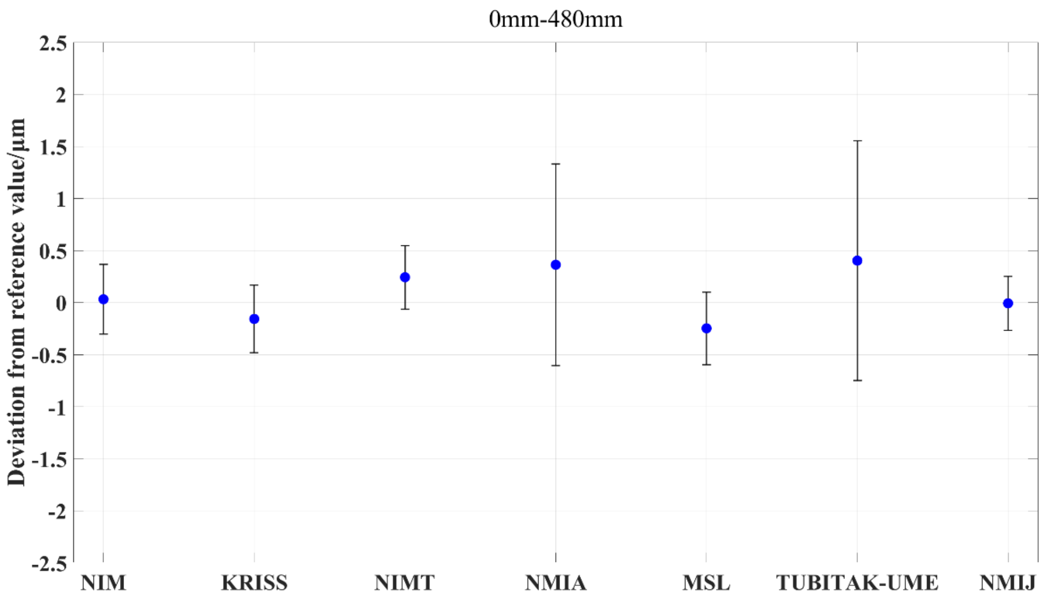

Fig. 27 participant deviations from KCRV for this interval (*k* = 2)

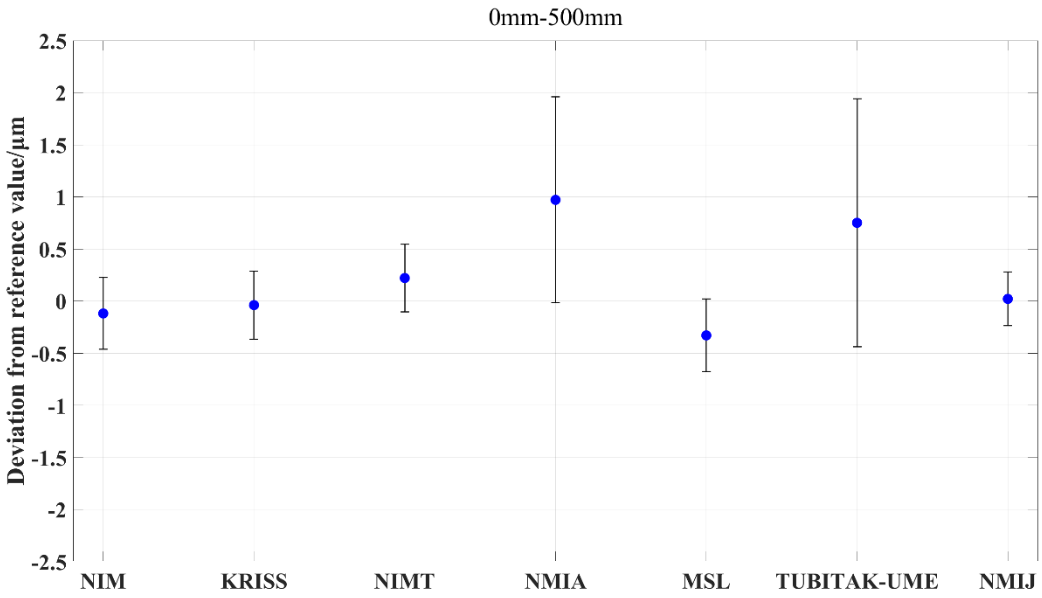

Fig. 28 participant deviations from KCRV for this interval (k = 2)

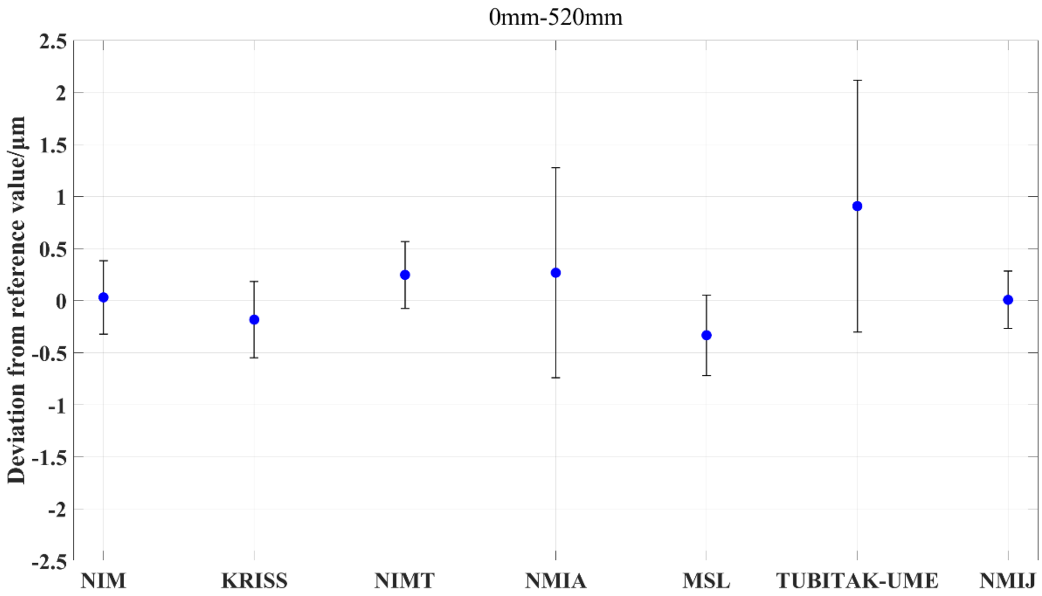

Fig. 29 participant deviations from KCRV for this interval (k = 2)

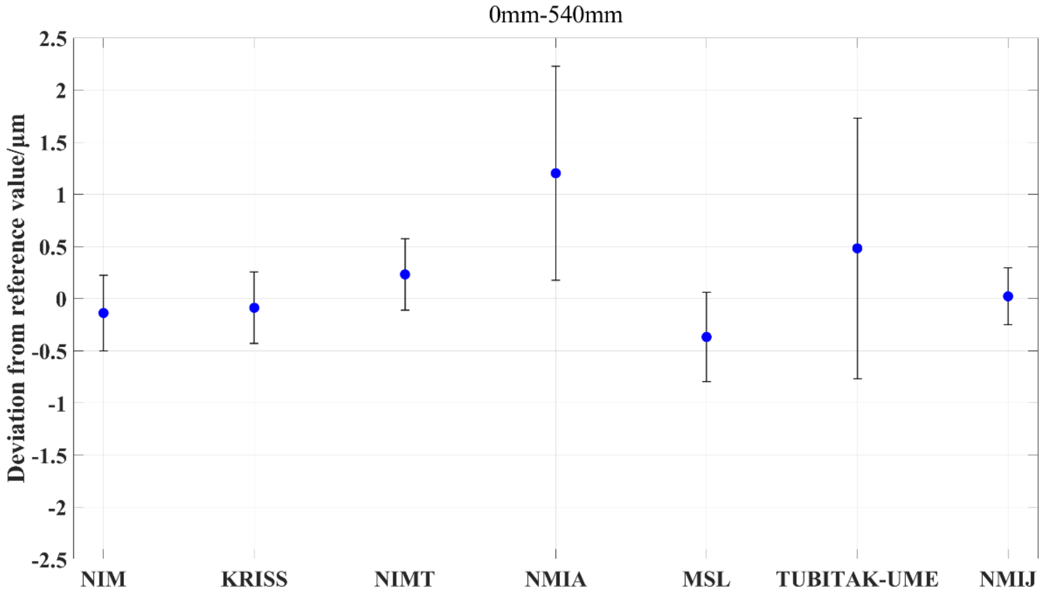

Fig. 30 participant deviations from KCRV for this interval (k = 2)

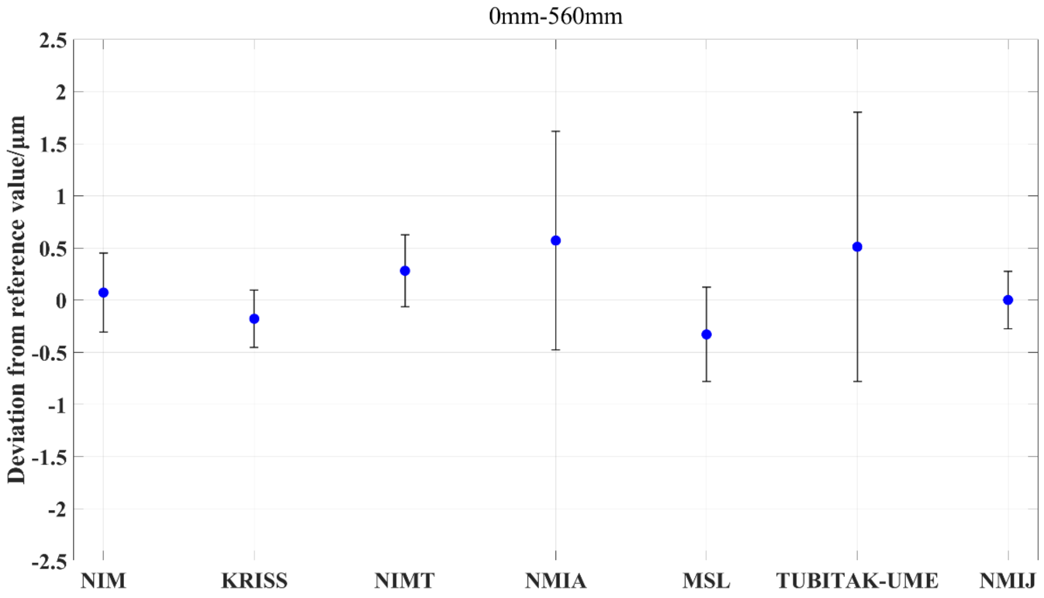

Fig. 31 participant deviations from KCRV for this interval (k = 2)

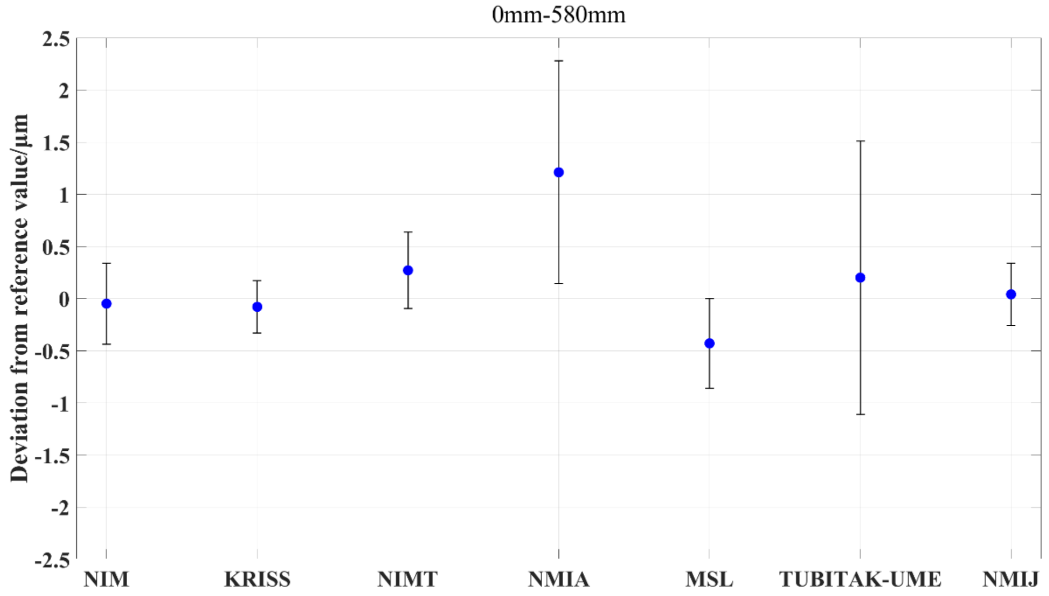

Fig. 32 participant deviations from KCRV for this interval (k = 2)

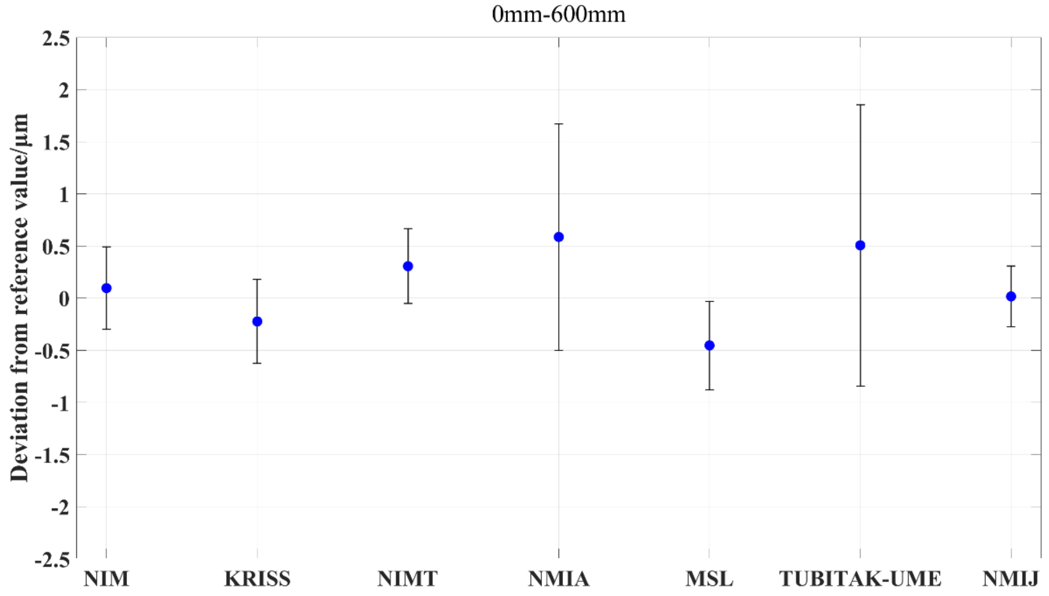

Fig. 33 participant deviations from KCRV for this interval (k = 2)

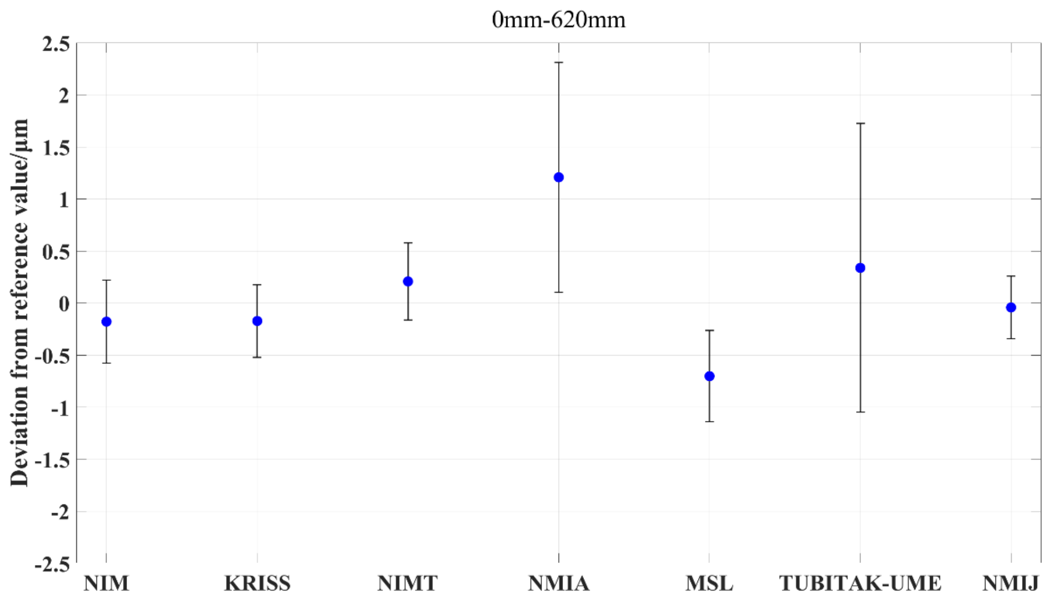

Fig. 34 participant deviations from KCRV for this interval (k = 2)

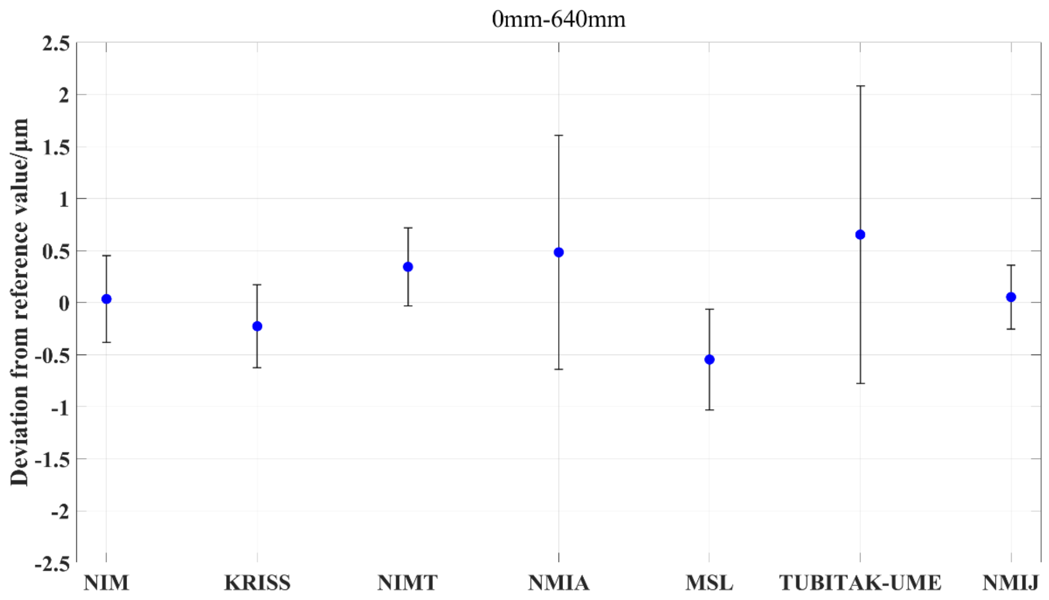

Fig. 35 participant deviations from KCRV for this interval (k = 2)

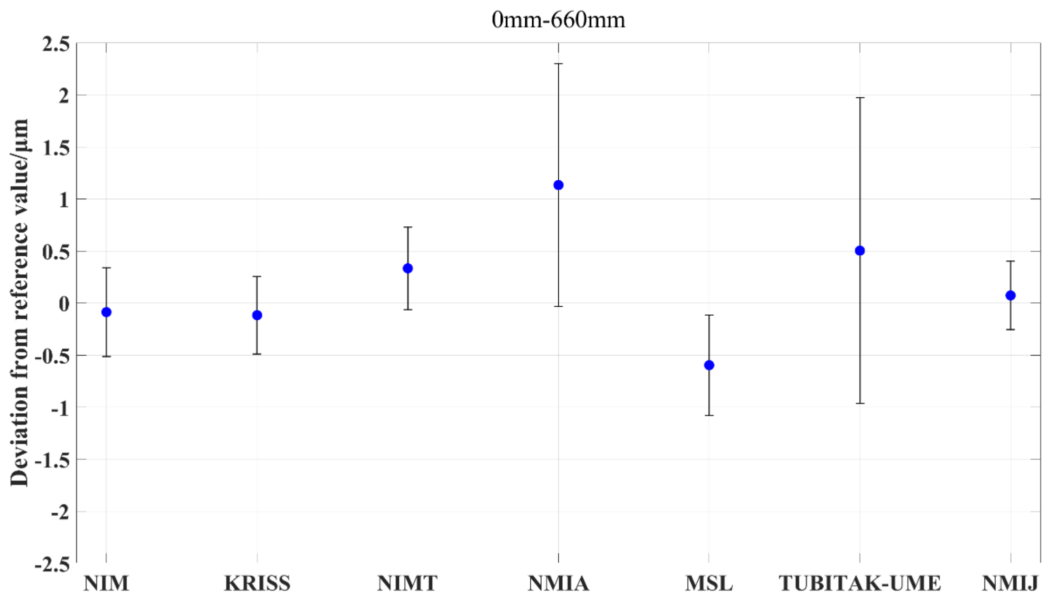

Fig. 36 participant deviations from KCRV for this interval (k = 2)

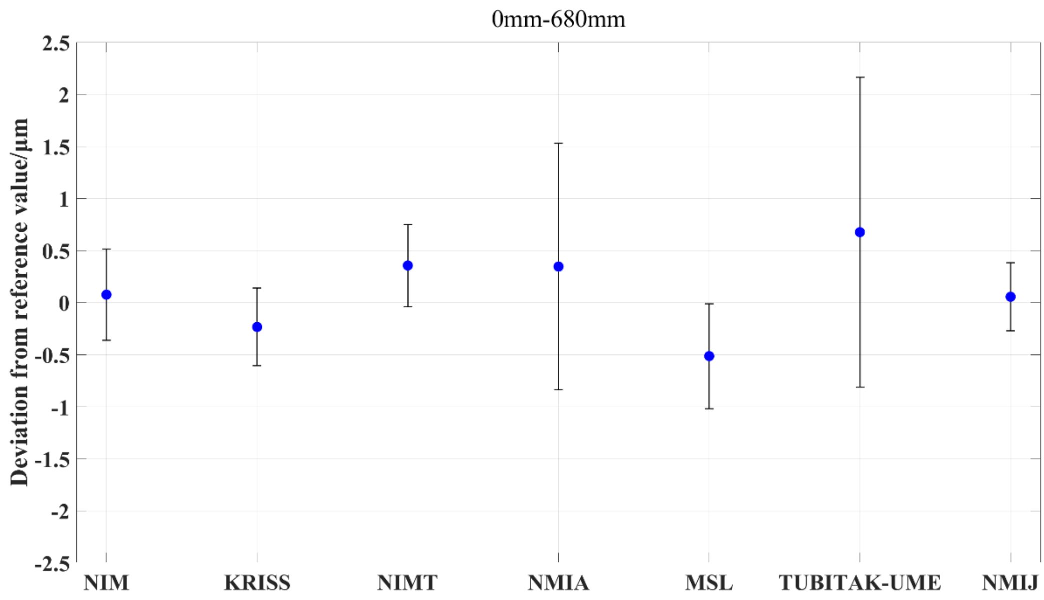

Fig. 37 participant deviations from KCRV for this interval (k = 2)

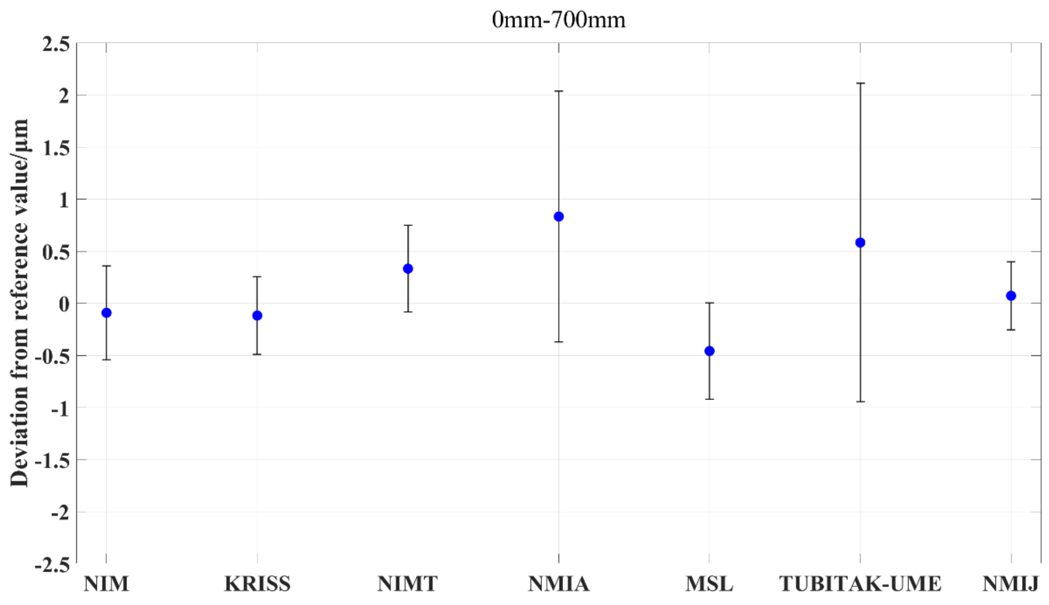

Fig. 38 participant deviations from KCRV for this interval (k = 2)

7 Participant deviations by length

7.1 NIM

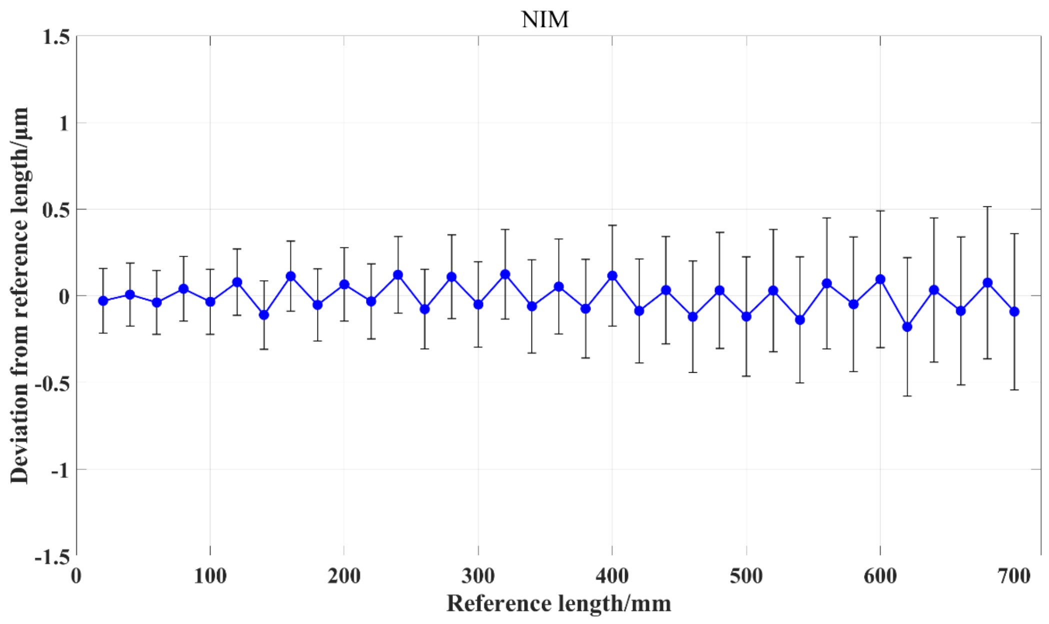

Fig. 39 NIM Deviation from Reference Value

7.2 KRISS

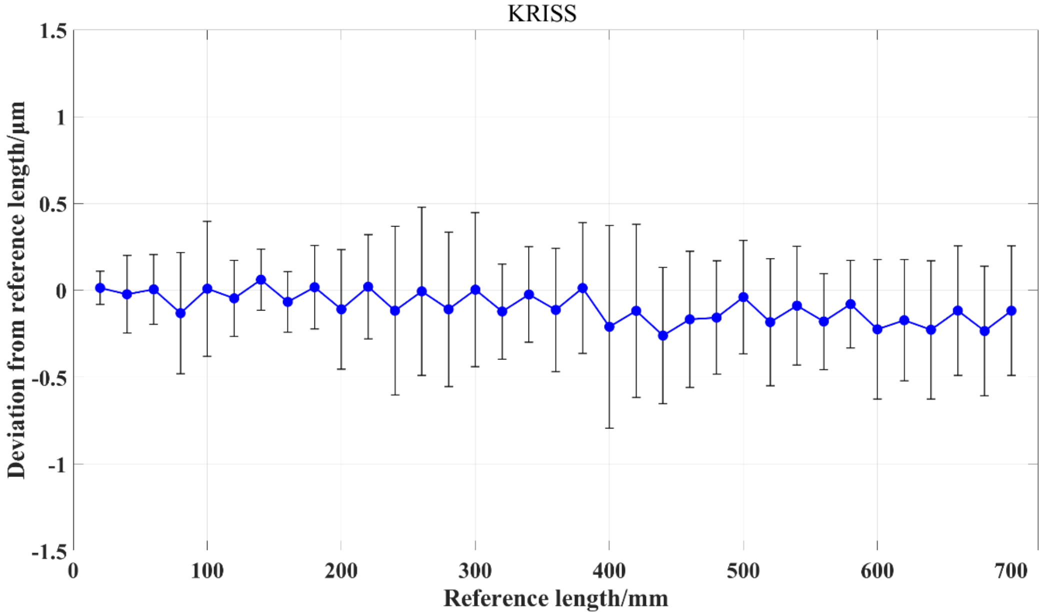

Fig. 40 KRISS Deviation from Reference Value

7.3 NIMT

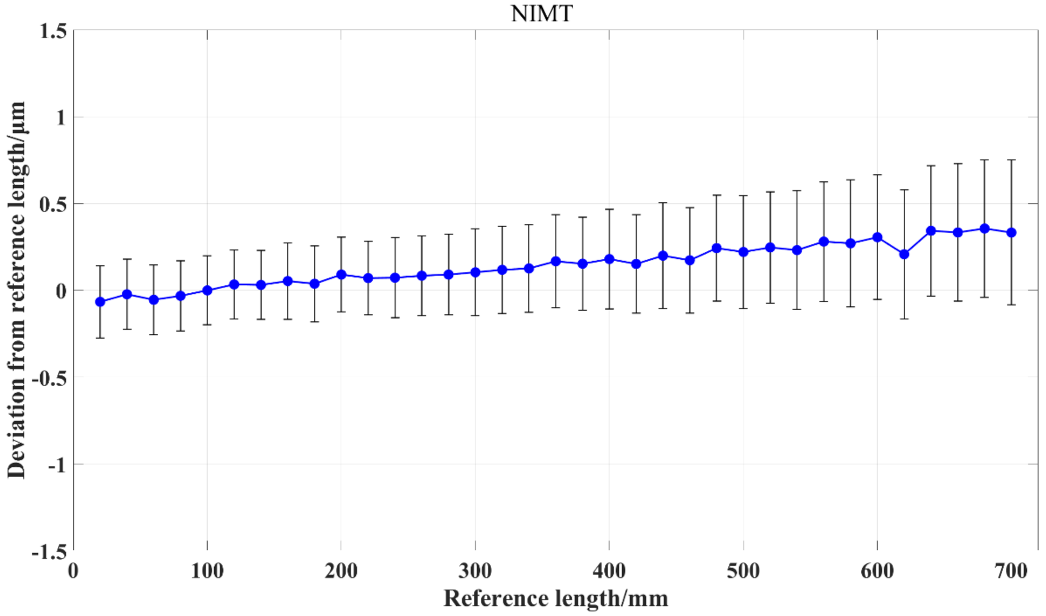

Fig. 41 NIMT Deviation from Reference Value

7.4 NMIA

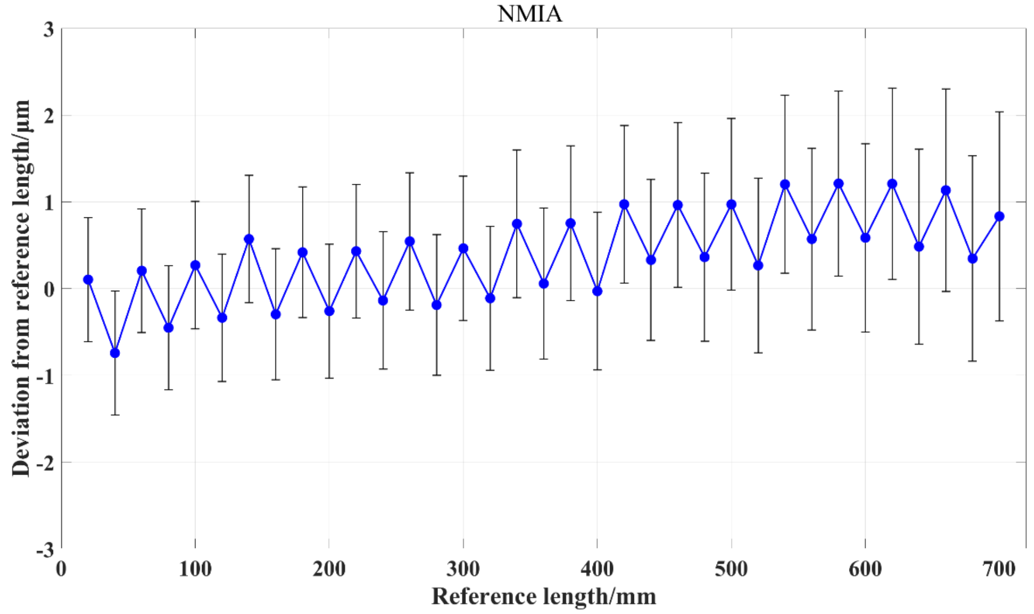

Fig. 42 NMIA Deviation from Reference Value

7.5 MSL

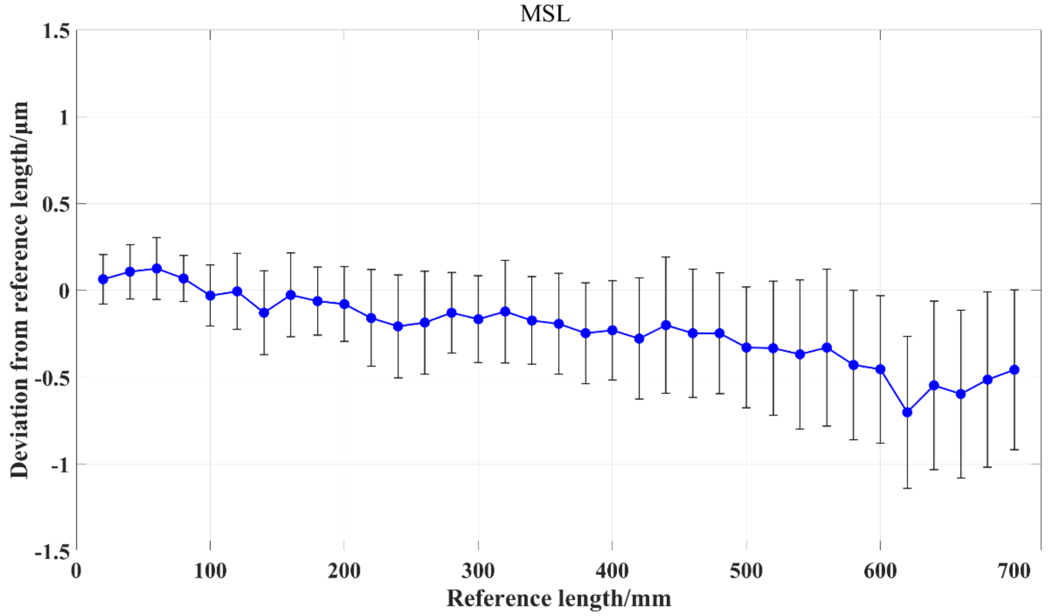

Fig. 43 MSL Deviation from Reference Value

7.6 TUBITAK-UME

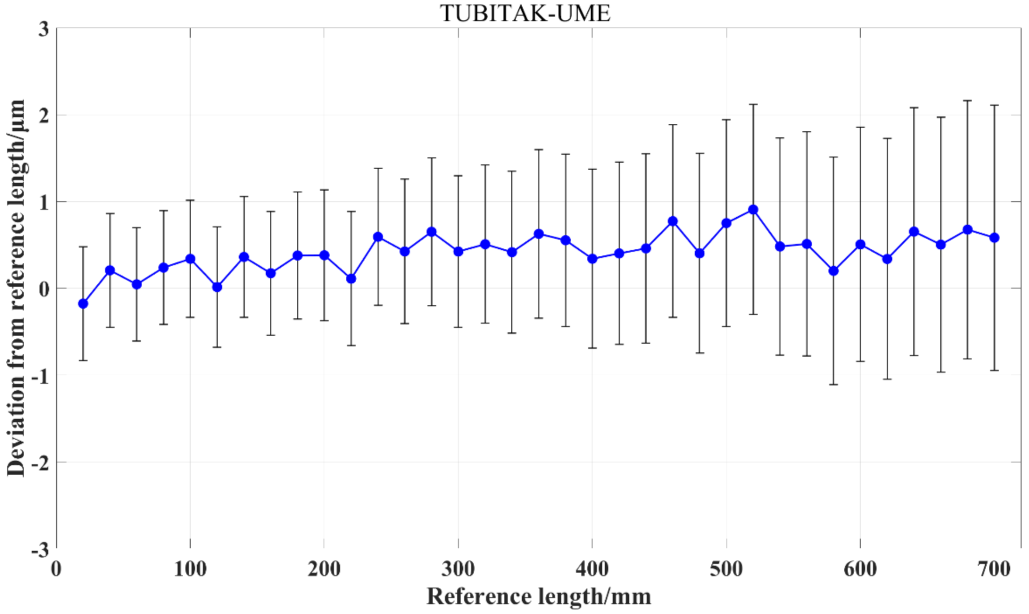

Fig. 44 TUBITAK-UME Deviation from Reference Value

7.7 NMIJ

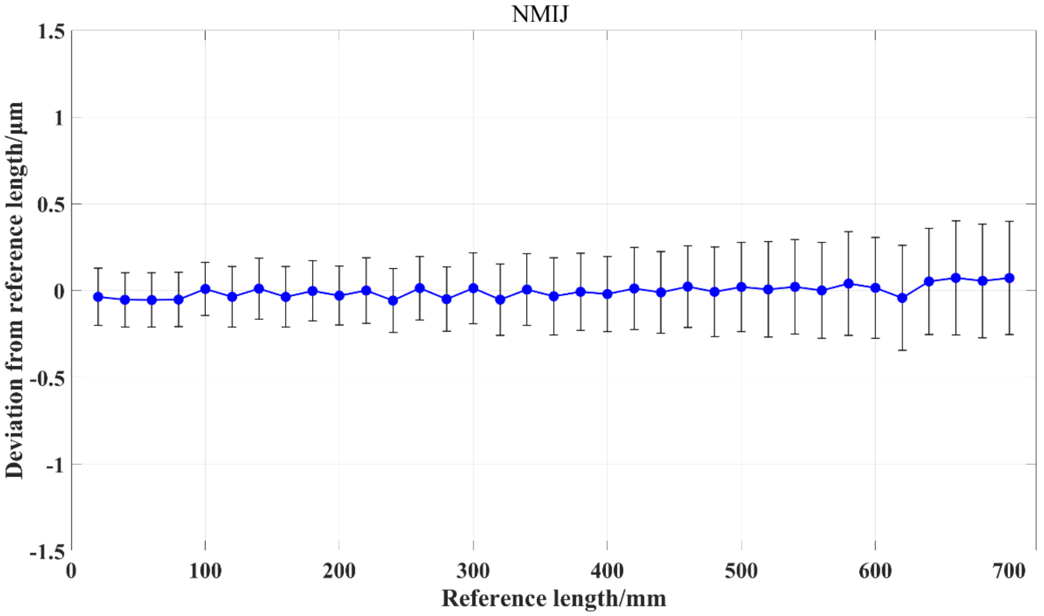

Fig. 45 NMIJ Deviation from Reference Value

8 Participant En values

The En values for each participant's measurement of each interval relative to the reference value are shown in Table 8. En values are calculated with formula (6). If En > 1 values in the case are shown in red font.

Table 8. En values for participants

Nominal Length /mm	NIM /µm	KRISS /µm	NIMT /µm	NMIA /µm	MSL /µm	TUBITAK-UME /µm	NMIJ /µm
20	0.15	0.14	0.32	0.14	0.45	0.27	0.22
40	0.04	0.10	0.11	1.04	0.68	0.32	0.34
60	0.21	0.03	0.27	0.29	0.70	0.07	0.35
80	0.22	0.38	0.16	0.63	0.51	0.36	0.33
100	0.18	0.02	0.00	0.37	0.18	0.50	0.06
120	0.41	0.21	0.17	0.46	0.03	0.02	0.21
140	0.56	0.35	0.16	0.78	0.53	0.52	0.06
160	0.56	0.38	0.24	0.39	0.11	0.24	0.21
180	0.25	0.07	0.17	0.55	0.32	0.52	0.01
200	0.31	0.32	0.42	0.34	0.37	0.51	0.17
220	0.15	0.07	0.33	0.56	0.57	0.14	0.00
240	0.55	0.24	0.31	0.17	0.70	0.75	0.31
260	0.34	0.01	0.37	0.69	0.63	0.51	0.08
280	0.45	0.25	0.39	0.23	0.56	0.76	0.27
300	0.20	0.01	0.41	0.56	0.67	0.49	0.07
320	0.48	0.45	0.47	0.14	0.41	0.56	0.25
340	0.22	0.09	0.50	0.88	0.69	0.45	0.03
360	0.19	0.32	0.62	0.07	0.66	0.65	0.15
380	0.26	0.03	0.57	0.85	0.85	0.56	0.03
400	0.40	0.36	0.63	0.03	0.80	0.33	0.09
420	0.29	0.24	0.54	1.07	0.80	0.38	0.05
440	0.11	0.67	0.66	0.35	0.51	0.42	0.05
460	0.38	0.43	0.57	1.02	0.67	0.70	0.10
480	0.09	0.48	0.80	0.37	0.71	0.35	0.03
500	0.35	0.12	0.68	0.98	0.95	0.63	0.08
520	0.09	0.50	0.77	0.26	0.86	0.75	0.02
540	0.38	0.26	0.68	1.17	0.86	0.39	0.08
560	0.19	0.65	0.82	0.54	0.73	0.40	0.00
580	0.12	0.32	0.74	1.13	0.99	0.15	0.13
600	0.24	0.56	0.85	0.54	1.07	0.37	0.05
620	0.45	0.49	0.56	1.10	1.35	0.24	0.14
640	0.08	0.57	0.91	0.43	1.13	0.46	0.17
660	0.20	0.31	0.84	0.97	1.24	0.34	0.22
680	0.17	0.63	0.90	0.29	1.02	0.45	0.17
700	0.20	0.32	0.80	0.69	0.99	0.38	0.22

A summary of the number of measurements for each institution that did not demonstrate equivalence to the comparison reference value is shown in Table 9. Given that the expanded uncertainty provides an approximately 95% probability of a measured value being within the uncertainty range of the reference value it is correct to conclude that, for a large sample of measurements, up to 5 % of measurements may fail to demonstrate equivalence without invalidating the claimed uncertainty. Any participant which has less than 5 % of measured intervals at En > 1 is considered to have demonstrated the validity of their submitted uncertainty.

Table 9. Summary of participant En values

Participant	Number of intervals where En>1	Percentage of intervals where En>1	Uncertainty validity demonstrated?
NIM	0	0	YES
KRISS	0	0	YES
NIMT	0	0	YES
NMIA	6	17	NO
MSL	5	14	NO
TUBITAK-UME	0	0	YES
NMIJ	0	0	YES

9 References

[1] Cox M.G., Evaluation of key comparison data, Metrologia, 2002, 39, 589-595

[2] T. Coveney, Final Report of EUROMET .L-K5.2016, 2020

[3] T. Valenta, Final Report of EURAMET Project No. 1396, 20

10 Appendix A: Measurement Methods and Instruments used by the participants

The Measurement Methods and Instruments used by the participants are shown below. Not all the participants supplied a statement.

10.1 NIM

The instrument used for step gauge calibration consists of three-axis laser interferometer and a coordinate measuring machine. The Step Gauge is aligned and positioned with Leitz PMM-C 12107 high accuracy Coordinate Measuring Machine (CMM). The measurement data is recorded by three-axis laser interferometer. With the three laser interferometer measurement data the data in the step gauge measurement line is calculated. A circuit device is manufactured to synchronized CMM probing signal. The refractive index of air for wavelength and the thermal compensations are automatically compensated.

10.2 KRISS

The KRISS linear measuring system consists of a multi-axis stage, a three-axis laser interferometer, a controller, and environmental monitoring sensors. A vacuum pre-loaded air bearing stage translates a probing part coarsely over 2000 mm range using a friction wheel driven by a geared dc motor. The probing part includes the probe and two plane mirrors for the three-axis interferometer. A multi-axis fine stage constructed using PZT actuators and monolithic flexure guides controls linear position of the probing part and reduces angular motion error of the coarse stage. Using outputs of the three-axis laser interferometer and the probe, the positions of gauge faces of end standards are measured. For end standard measurements, a linear variable differential transformer (LVDT) probe is employed to detect the positions of gauge surfaces, and tip size of the contact probe is calibrated using a 5 mm reference gauge block. The probing point is determined to minimize Abbe offset, and the fine stage actively compensates the angular motion error within ±0.2″ using the angular displacement measured by the interferometer. Main part of a controller for the measuring system was configured using an industrial PC and a PXI controller. A field-programmable gate array (FPGA) I/O board installed in the PXI controller interfaces the displacement sensor signals and applies output signals to the actuators. Time critical tasks such as the position feedback control and the angular motion error compensation are implemented on the PXI controller, and other tasks such as interfacing with environmental monitoring and sample temperature sensors, are executed on the industrial PC.

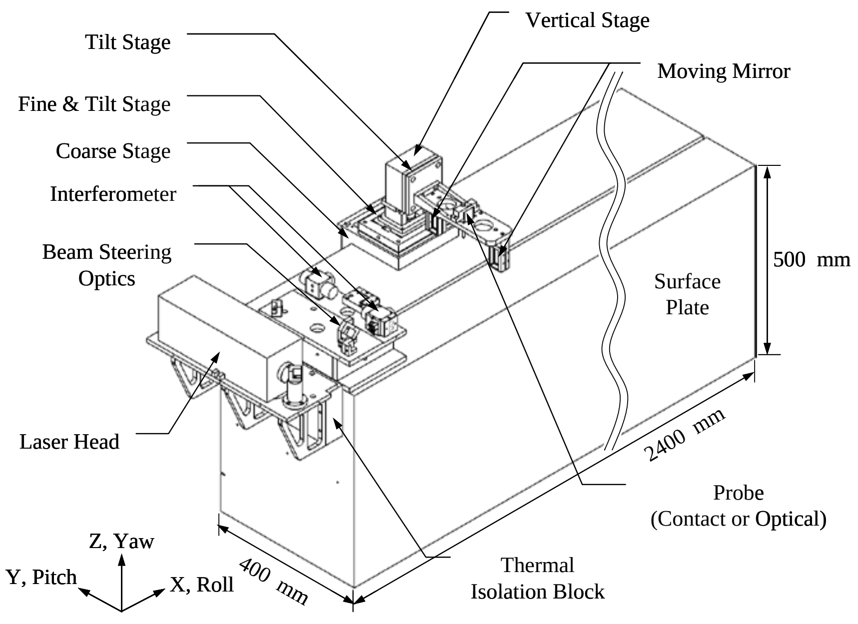

Figure 2. Configuration of the interferometric linear measuring system.

10.3 NIMT

Figure 3.Photo shows an overview of the step gauge measurement.

The step gauge was measured by integration of Coordinate Measuring Machine, CMM and Laser Interferometers as shown in above photo. Step gauge was supported at the Bessel points on a flat iron table and aligned according to this protocol with parallel to both CMM and laser axes. By synchronized probing signal, the central lengths of a step gauge are acquired by plane-mirror interferometers. The refractive index of air for wavelength and the thermal compensations are real time automatically compensated by the measuring software.

10.4 NMIA

Brown & Sharpe Global Performance CMM fitted with a Renishaw SM25-1 probe and running PCDMIS 2017 R2 software. For the step gauge measurements a set of reference length bars spanning the range 20 mm to 700 mm and a CTR2000 digital thermometer system were used. Measurements were performed by a substitution method whereby the reference length bars were measured shortly after the step gauge in approximately the same spatial location and orientation to correct for CMM scale errors.

10.5 MSL

The step gauge was measured by comparison with calibrated gauge blocks on a Mitutoyo Legex 574 Coordinate Measuring Machine. Five calibrated gauge blocks ranging from 100 mm to 500 mm (in 100 mm steps) were measured parallel to a chosen measurement line in two opposite orientations. The step gauge was measured along this line in the two orientations and in a third position displaced 20 mm from the first position. A third repeat set of gauge block measurements were made in the first position. A least squares technique was used to remove the systematic machine errors from the measurements and produce results traceable to the gauge block calibration. This process was repeated with the measurement line along two diagonals of the CMM bed.

10.6 TUBITAK-UME

Zeiss Prismo7 S-ACC Coordinate Measuring Machine (CMM) has been used for calibration of the step gauge using 5 mm diameter ruby probe. CMM is located inside a conserved laboratory that has a temperature control system. CMM has its own 2 temperature sensors (PT-100). Temperature measurements are made by 2 CMM sensors and also using 4 extra sensors (Pt100) with the help of a Multimeter.

Table 1. Technical data for CMM

Zeiss Prismo7 S-ACC	Gold VAST Head
Max Length Measuring Capability	(1200x900x700) mm
Resolution	0.1 μm
Guides	Aerostatic

The scales of CMM are periodically verified utilising HP5529A laser interferometer and calibrated by gauge blocks and step gauges to ensure the manufacturer specification. It is found that the deviation was less then manufacturer specifications, It was about 0.25μm.

Distance measurements: CMM is used as a comparator. Therefore, gauge substitution method is used during the measurement process. A calibrated step gauge and gauge blocks are measured with CMM. CMM deviation from reference step gauge and gauge blocks certificate value is also taken into consideration. CMM is set using reference gauge blocks which are traceable to UME and step gauge which is traceable to NPL for calibration of test step gauge. References (Gauges and step) and Test step are clamped side by side on Y-axis of the CMM. All measurements are made using automatic software which was developed using PCM language in CALYPSO environment. Temperature of the environment is about (20± 0.3)℃.

Setting standards: Step Gauge and a set of gauge blocks which have dimensions starting from 50 mm up to 1000 mm long are used to compare the results. Gauge blocks are just used for the verification of the results that are taken from the step gauge using substitution method. UME results given in the comparison are taken from the step gauge substitution.

Temperature measurements: Temperature in the laboratory is registered to be in (20± 0.3) ℃ and better than (20± 0.1) ℃ in working volume.The temperature is kept within (20± 0.1) ℃ during the measurement. 6 Pt100 sensors are located in different places in measuring volume near to the test and the reference devices. Previous tests showed that the temperature difference between step gauges and scale is less than 0.1 °C after stabilisation. Temperature correction is made for the results.

Measurement probes and measurement force: The probe is ruby with diameter 5 mm. 0.2 N measuring forces are applied during the measurement.

10.7 NMIJ

The step gauge was measured using the 4-pass laser interferometer which sampled synchronously with the coordinate measuring machine (CMM).

The diameter of the probe stylus tip of the CMM used in the measurement of the step gauge was calibrated through the measurement of a gauge block with the same system.