EURAMET Key Comparison

EURAMET.L-K5.2016

Calibration of 1-D CMM artefacts: Step Gauges (EURAMET project 1365)

Final Report

National Physical Laboratory
UK

Teddington
June 2020

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Contents

1 Document control

Draft A2	16 September 2019	Initial draft of the final report text
Draft A3	28 October 2019	Inclusion of 610 mm analysis plus revisions
Draft A4	19 December 2019	Added participant responses and minor corrections
Draft A5	10 January 2020	Amended 1020 mm KCRV and add tables of results
Draft B	30 January 2020	First public draft
Draft B2	25 February 2020	Corrected calculation of 1020 mm *E*n values
Draft B3	24 March 2020	Added final participant responses
Draft B4	19 May 2020	Reviewer corrections and added conclusion section
Final	19 June 2020	Final approved report

2 Introduction

The metrological equivalence of national measurement standards are 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.

To date, several key comparisons on 1D CMM calibration artefacts have been performed:

EUROMET.L-K5.PREV	: 1996 to 1998	: Spain, Italy, Switzerland, Netherlands, UK, Germany, Sweden
CCL-K5	: 1999 to 2002	: Spain, Mexico, South Africa, Italy, S. Korea, Switzerland, China, USA, Australia, Japan, Canada, Germany, Russian Federation
EUROMET.L-K5.2004	: 2004 to 2007	: Austria, Spain, Mexico, Czech Republic, Denmark, Poland, Romania, Brazil, Italy, France, Finland, Hungary, Australia, UK, Canada, Ireland, Sweden, Russian Federation, Netherlands
APMP.L-K5.2006	: 2005 to 2007	: Chinese Taipei, Brazil, S. Korea, Switzerland, New Zealand, China, Thailand, USA, Australia, Japan, India, Indonesia, Hong Kong)
APMP.L-K5.2006.1	: 2012 to 2013	: Japan, India

In 2003 the CCL instigated the process of inter-RMO participation in RMO key comparisons. This is designed to reduce the workload of CCL member laboratories in comparison subjects where there are too few participants to warrant the use of the classical style of comparison (CCL comparison followed by an RMO comparison in each of the regions) in which CCL member laboratories have to participate twice.

At its meeting 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. A step gauge manufactured by Mitutoyo was chosen as the artefact for this comparison because most NMIs in the APMP region are familiar with Mitutoyo step gauges. APMP.L-K5 2014 was duly commenced. However, at the 2018 APMP TC-L meeting the decision was taken to abandon the comparison due to artefact instability, after the pilot observed changes in the gauge greater than their measurement uncertainty during circulation.

EURAMET TC-L made a similar determination that a new comparison was needed in 2013, considering that it was almost 10 years since the previous European K5 comparison and planning was commenced for a circulation to begin in 2016. At the CCL meeting in 2013 it was agreed that the EURAMET comparison would be operated as an inter-RMO comparison with NPL as the pilot laboratory. Participants were invited from SIM, AFRIMETS and linking laboratories were selected from APMP. During circulation a participant from GULFMET requested inclusion and was added with the agreement of all participants.

3 Preparation of the comparison documents

The protocol document for this comparison was prepared by the pilot, Tim Coveney, from the pilot laboratory NPL (UK).

This final report of the comparison was prepared according to the following guidance documents:

Publication of a Final Report in Metrologia's Technical Supplement[1]

CCL-WG/-MRA-GD-3[2] Guide to preparation of Key Comparison Reports in Dimensional Metrology

CCL-WG/-MRA-GD-3.2[3] Report template

[1] http://www.bipm.org/utils/common/documents/CIPM-MRA/MET-Technical-Supplement.docx
[2] http://www.bipm.org/wg/CCL/CCL-WG/Allowed/General_CCL-WG_docs/CCL-WG-MRA-GD-3-v1.3.doc
[3] http://www.bipm.org/wg/CCL/CCL-WG/Allowed/General_CCL-WG_docs/CCL-WG-MRA-GD-3.2-KC-report-template.doc

4 Organization

4.1 Participants

Where provided, details of the instruments used for this comparison are found in Appendix A.

Table 1: List of participant laboratories and their contacts

Laboratory Code	Contact person, Laboratory	Laboratory Code	Contact person, Laboratory
BEV	Michael Matus BEV Arltgasse 35 1160 Wien Austria	INRIM	G. Picotto & A. Balsamo Istituto Nazionale di Ricerca Metrologica Str. delle cacce, 91 10135 Torino Italy
VTT MIKES	Antti Lassila MIKES Metrology, VTT Technical Research Centre of Finland Ltd Tekniikantie 1 FIN-02151 Espoo Finland	VSL	Richard Koops Thijsseweg 11 2629 JA Delft The Netherlands
SP	Agneta Jakobsson SP Technical Research Institute of Sweden Measurement Technology Box 857 SE-501 15 Borås Sweden	MKEH (Now BFKH)	Krisztián Gáborfi 1124 Budapest Németvölgyi út 37-39 Budapest Hungary
CENAM	Edgar Arizmendi Reyes Centro Nacional de Metrologia CENAM KM 4.5, Carretera a los Cués El Marqués Querétaro 76246 Mexico	CMI	Vit Zeleny Czech Metrology Institute - Laboratories of Fundamental Metrology V botanice 4 150 72 Praha 5 Czech Republic
CEM	Joaquin Rodriguez Centro Español de Metrología CEM Calle del Alfar, 2 28760 Tres Cantos Madrid Spain	GUM	Zbigniew Ramotowski Główny Urząd Miar Central Office of Measures (GUM) Dyrektor Zakładu Długości i Kąta Director of Length & Angle Department ul. Elektoralna 2 00-139 Warsaw Poland

<table>
<tr><th>Laboratory Code</th><th>Contact person, Laboratory</th><th>Laboratory Code</th><th>Contact person, Laboratory</th></tr>
<tr><td>NIST</td><td>John R. Stoup
NIST
Bldg 220, Rm A109
Gaithersburg, MD 20899
USA</td><td>INM</td><td>Alexandru DUTA & Elena DUGHEANU
Romanian Bureau of Legal Metrology- National Institute of Metrology Bucharest (BRML-INM),
11 Vitan-Barzesti
Sector 4
Bucharest
Romania</td></tr>
<tr><td>INMETRO

(See note 1)</td><td>João Alves
INMETRO - National Institute of Metrology, Quality and Technology
Mechanical Division - Dimensional Metrology Laboratory
Av. N. Sra. das Graças, 50 - Prédio 3
25250-020 Vila Operária
Xerém - Duque de Caxias
Rio de Janeiro
Brazil</td><td>NMISA

(see note 2)</td><td>Oelof Kruger
NMISA
Meiring Naudé Road
Brummeria
Pretoria, 0040
South Africa</td></tr>
<tr><td>TUBITAK-UME</td><td>Okhan Ganioglu & Ilker Meral
TÜBİTAK Gebze Yerleşkesi
P.K. 54 41470 Gebze/KOCAELİ
Turkey</td><td>NIM</td><td>Weinong Wang
National Institute of Metrology
No. 18, Bei San Huan Dong Lu
Beijing 100029
China</td></tr>
<tr><td>METAS</td><td>Rudolf Thalmann
Federal Institute of Metrology METAS
Sector Length, Optics and Time
Lindenweg 50
3003 Bern-Wabern
Switzerland</td><td>NRC</td><td>Greg Reain
National Research Council Canada
1200 Montreal Road, Building M-36
Ottawa, Ontario
K1A 0R6
Canada</td></tr>
</table>

Laboratory Code	Contact person, Laboratory	Laboratory Code	Contact person, Laboratory
NMIJ	Toshiyuk Takatsuji Research Institute for Engineering MeasurementNational Metrology Institute of Japan (NMIJ) National Institute of Advanced Industrial Science and Technology (AIST) AIST Central 3 1-1-1 Umezono Tsukuba Ibaraki 305-8563 Japan	NPLI	Dr. Rina Sharma/Mr. Vinod Kumar, Length, Dimension and Nanometrology CSIR-National Physical Laboratory Dr. K.S. Krishnan Road New Delhi -110012 India
NMC/A*STAR	Shihua Wang Optical Metrology National Metrology Centre/A*STAR 1 Science Park Drive Singapore 118221	SASO-NMCC (See Note 3)	Faisal A. Alqahtani/ Nasser Alqahtani National Measurement and Calibration Center (Building No. 4), Saudi Standards, Metrology and Quality Org. Riyadh - Al Muhammadiyah - in front of King Saud University Saudi Arabia
LNE	José-Antonio Salgado Laboratoire national de métrologie et d'essais 1, rue Gaston Boissier 75724 Paris cedex 15 France	NPL (Pilot)	Tim Coveney NPL National Physical Laboratory Hampton Road Teddington TW11 0LW UK

Table 2: Informal NMI Participants

Laboratory Code	Contact person, Laboratory
PTB (See note 4)	Dr. Harald Bosse Physikalisch-Technische Bundesanstalt (PTB) Abteilung 5: Fertigungsmesstechnik (Division 5: Precision Engineering) Bundesallee 100 38116 Braunschweig GERMANY

Note 1 INMETRO were unable to make measurements during the comparison due to logistical difficulties

Note 2 NIMSA withdrew from the comparison after logistical issues prevented them making measurements during their allocated slot. Measurements in a later slot were not possible due to planned upgrade work on the measurement system.

Note 3 SASO-NMCC were added to the comparison during the circulation with the agreement of all other participants

Note 4 PTB were unable to make measurements during the comparison for technical reasons (their participation was on an informal basis)

4.2 Schedule

In order to support the varying CMCs of the participants, it was decided that two artefacts will be used in the comparison: a 610 mm step gauge and a 1020 mm step gauge. Each artefact will be circulated in a loop independent of the other.

Each laboratory was allocated a 4 week window in which to complete their measurements. This time included incoming customs clearance, calibration, outgoing customs formalities and transportation to the following participant. There were some breaks in the schedule due to no laboratory being available to measure at that time. Where such a break meant that an artefact was at a participant's site for longer than the 4 week window the participants were instructed that they should not use this additional time for further measurement in order to maintain the fairness of the comparison.

Key comparisons are designed to test the CMCs of participants. According to document CIPM MRA-D-04 Calibration and Measurement Capabilities in the context of the CIPM MRA:

> *"A CMC is a calibration and measurement capability available to customers under normal conditions"*
>
> *"Under a CMC, the measurement or calibration should be:*
>
> *- performed according to a documented procedure and have an established uncertainty budget under the management system of the NMI or the accredited laboratory;*
>
> *- performed on a regular basis (including on demand or scheduled for convenience at specific times in the year); and*
>
> *- available to all clients."*

Therefore, it should be possible to perform the measurements of this comparison as if they were being performed for a customer, according to a pre-agreed timetable (barring unforeseen equipment failures). The timetabling was designed to demonstrate this.

The two artefacts were circulated in two independent loops, both starting and ending at the pilot laboratory. During the two loops, there were intermediate measurements by the pilot laboratory to confirm artefact stability.

The schedule as proposed in the protocol can be seen in Table 3 and Table 4.

Table 3: Original schedule of the comparison for the 610 mm step gauge

RMO	Laboratory	Starting date
EURAMET	NPL	26/09/2016
EURAMET	INRIM	24/10/2016
EURAMET	MKEH	30/01/2017
EURAMET	CMI	27/02/2017
EURAMET	GUM	27/03/2017
EURAMET	INM	24/04/2017
EURAMET	NPL	22/05/2017
APMP	NPLI	17/07/2017
SIM	NIST	14/8/2017
EURAMET	CEM	30/10/2017
EURAMET	NPL	27/11/2017

Table 4: Original schedule of the comparison for the 1020 mm step gauge

RMO	Laboratory	Starting date
EURAMET	NPL	01/12/2015
EURAMET	LNE	04/01/2016
EURAMET	BEV	01/02/2016
EURAMET	VSL	28/03/2016
Non-NMI	Zeiss	25/4/2016
EURAMET	NPL	23/05/2016
EURAMET	CEM	01/08/2016
EURAMET	SP	29/08/2016
EURAMET	VTT MIKES	26/09/2016
EURAMET	INRIM	24/10/2016
EURAMET	NPL	28/11/2016
SIM	NRC-CNRC	30/01/2017
EURAMET	METAS	27/02/2017
EURAMET	TUBITAK-UME	27/03/2017
APMP	NMC/A*STAR	24/04/2017
APMP	NMIJ	22/05/2017
AFRIMETS	NMISA	17/07/2017
SIM	NIST	14/08/2017
SIM	CENAM	11/09/2017
EURAMET	NPL	09/10/2017
EURAMET (Informal)	PTB	06/11/2017
APMP	NIM	04/12/2017
EURAMET	NPL	08/1/2018

The original timetables for the circulation were not adhered to for a number of reasons, including equipment failures, logistical issues and lengthy customs delays. A number of laboratories overran their measurement slots for various reasons, and several exceeded the 6 week deadline for reporting results, some by several months.

The actual measurement schedules for the gauges are shown in Table 5 and Table 6.

Table 5: Actual schedule of the comparison for the 610 mm step gauge

RMO	Laboratory	Gauge Received	Gauge despatched	Report Received
EURAMET	NPL (Pilot)	01/12/2016	14/12/2016	15/12/2016
EURAMET	INRIM	09/11/2016	23/01/2017	05/07/2017
EURAMET	MKEH	28/01/2017	21/02/2017	24/04/2017
EURAMET	CMI		22/03/2017	12/04/2017
EURAMET	GUM	28/03/2017	16/04/2017	09/06/2017
EURAMET	INM	21/04/2017	19/05/2017	19/09/2017
APMP	NPLI	See Note 1	N/A	N/A
SIM	NIST	28/08/2017	05/10/2017	08/03/2018
EURAMET	CEM	29/10/2017	29/11/2017	07/03/2018
APMP	NPLI	01/02/2018	16/03/2018	01/05/2018
EURAMET	GUM (see note 2)	14/05/2018	09/06/2018	24/09/2018
GULFMET	SASO-NMCC	26/06/2018	15/07/2018	10/09/2018
SIM	NRC-CNRC	27/07/2018	25/09/2018	07/11/2018
EURAMET	VTT MIKES	04/10/2018	07/11/2018	12/11/2018
EURAMET	NPL (Pilot)	10/11/2018	N/A	N/A

Note 1: NPLI requested a change of date due to a possible clash with some facilities work and were rescheduled.

Note 2: GUM discovered that a failure of their measurement equipment and air conditioning had affected their first measurement set and requested a remeasurement.

Table 6: Actual schedule of the comparison for the 1020 mm step gauge

RMO	Laboratory	Gauge Received	Gauge despatched	Report Received
EURAMET	NPL(Pilot)	01/12/2016	14/12/2016	15/12/2016
EURAMET	LNE	16/12/2015	26/01/2016	15/03/2016
EURAMET	BEV	28/01/2016	14/03/2016	19/04/2016
EURAMET	VSL	07/04/2016	22/04/2016	See note 1
Non-NMI	Zeiss	26/04/2016	24/05/2016	25/05/2016
EURAMET	NPL(Pilot)	31/05/2016	01/08/2016	N/A
EURAMET	CEM	04/08/2016	29/08/2016	27/10/2016
EURAMET	SP	30/08/2016	22/09/2016	28/10/2016
EURAMET	VTT MIKES	26/09/2016	19/10/2016	02/12/2016
EURAMET	INRIM	24/10/2016	07/12/2016	See note 2
EURAMET	NPL(Pilot)	12/12/2016	20/01/2017	N/A
SIM	NRC-CNRC	02/02/2017	09/02/2017	See note 3
EURAMET	METAS	20/02/2017	20/03/2017	20/03/2017
EURAMET	TUBITAK-UME	27/03/2017	16/05/2017	20/06/2017
APMP	NMC/A*STAR	See note 4	N/A	N/A
APMP	NMIJ	26/05/2017	08/07/2017	28/08/2017
AFRIMETS	NMISA	09/10/2017	10/10/2017	See note 5
SIM	NIST	25/10/2017	15/11/2017	08/03/2018
SIM	CENAM	See note 6	N/A	N/A
EURAMET (Informal)	PTB	See note 7	N/A	N/A
APMP	NIM	See note 8	N/A	N/A
APMP	NMC/A*STAR	02/04/2018	08/05/2018	29/06/2018
SIM	CENAM	22/05/2018	20/06/2018	27/07/2018
APMP	NIM	24/07/2018	28/08/2018	12/10/2018
EURAMET	INRIM	14/09/2018	08/10/2018	See note 9
EURAMET	VSL	26/10/2018	10/12/2018	31/01/2019
EURAMET	NPL(Pilot)	14/12/2018	N/A	N/A

Note 1: VSL reported that the results obtained during this measurement window did not meet their internal quality criteria and would not have been issued to a normal customer, with additional time being requested to complete further measurements. Since this was not possible due to the demands of the schedule a remeasurement was requested and no results from this window were submitted.

Note 2: INRIM reported that they were unable to measure the 1020 mm gauge due to equipment issues. A remeasurement was requested.

Note 3: NRC-CNRC reported that they were unable to measure the 1020 mm gauge due to equipment issues. A remeasurement was requested, with the preference being given to switch to the 610 mm gauge.

Note 4: NMC-A*STAR requested a new measurement slot prior to receiving the gauge due to a delay in procuring new equipment. A new slot was arranged during the remeasurement period. TUBITAK-UME despatched the gauge directly to NMIJ.

Note 5: Due to internal logistical issues NMISA were unable to accept delivery of the artefact for several months. On delivery the gauge was immediately sent to the next participant. NMISA then began long term upgrade works on their equipment so were unable to complete measurements and withdrew from the comparison.

Note 6: The delay at NMISA meant that it was impossible to send the gauge to CENAM in the original slot for customs reasons. Therefore, a new slot was arranged.

Note 7: PTB notified that they would be unable to measure the gauge as planned prior to their slot and withdrew from the comparison.

Note 8: NIM notified that they were unable to fulfil their measurement slot prior to it commencing and requested rescheduling.

Note 9: INRIM were unable to make measurements due to a laboratory facilities upgrade. As they had submitted results for the 610 mm gauge INRIM withdrew from measuring the 1020 mm artefact.

Note 10: After draft A1 of the comparison report was circulated CENAM reported that their submitted results contained expanded uncertainties (k = 2) rather than standard uncertainties as required. The pilot accepted the late correction and the results for CENAM use the late submission standard uncertainties.

5 Artefacts

5.1 Description of artefacts

Two artefacts were used for the comparison. Artefact 1, shown in Figure 1, was a 1020 mm nominal length step gauge produced by Hexagon Metrology Inc. The artefact is a monolithic ceramic block with measurement and alignment features similar to step gauges manufactured by KOBA. Details of the artefact are shown in Table 7.

Figure 1: Ceramic 1020 mm step gauge

Table 7: Details of the 1020 mm artefact

Manufacturer	Hexagon Metrology Inc.
Model	HG-1020
Serial Number	GC14385
Material	Ceramic
Weight	5.4 kg
Thermal expansion coefficient	2.3×10^{-6} K^{-1} (calibrated value)

The dimension of the step gauge is 1080 mm in length, 55 mm in width and 55 mm in height. The main gauge represents a total length of 1020 mm with 20 mm steps and consists of 52 measurement faces. The details of the step gauge can be seen in Figure 2.

Dimensions of the artefact and reference for measurement are presented in Figure 3.

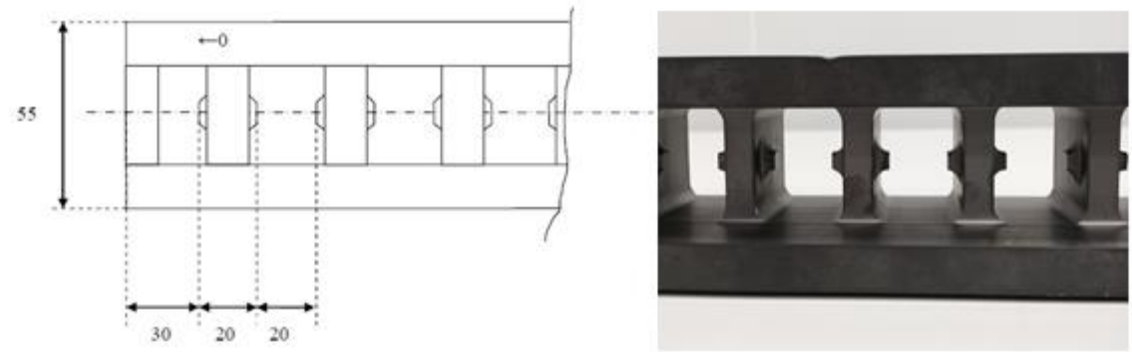


Figure 2: Details of the 1020 mm artefact

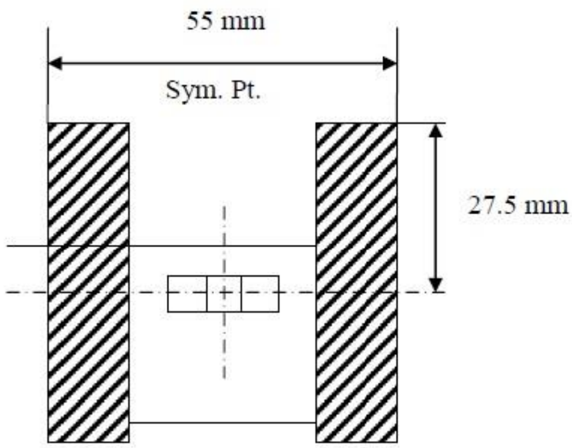


Figure 3: Dimensions and reference position for measurement of the 1020 mm artefact

Artefact 2, shown in Figure 4, was a 610 mm steel step gauge. The details of the artefact are shown in Table 8.

Figure 4: 610 mm step gauge

Table 8: Details of the 610 mm artefact

Manufacturer	Mitutoyo
Model	Precision Check Master, code no 515-742
Serial Number	022131
Material	Steel
Weight	7.2 kg
Thermal expansion coefficient	10.7×10^{-6} K^{-1}

The dimension of the step gauge is 630 mm in length, 50 mm in width and 80 mm in height. The main gauge represents a total length of 610 mm with 10 mm steps and consists of 52 measurement faces.

6 Analysis of results

6.1 Calculation of the KCRV

The key comparison reference value (KCRV) was calculated as the weighted mean of the participant results. The check for consistency of the comparison results with their associated uncertainties was made based on Birge ratio; the degrees of equivalence for each laboratory and each interval with respect to the KCRV were evaluated using En values, along the lines of the *WG-MRA-KC-report-template*.

Where the results of all participants for an interval were not consistent, the weighted mean of the largest consistent subset of participants was used as the reference value. This was determined for each interval separately.

6.2 Correlations

Three correlations between laboratories were identified.

1. UME-TUBITAK made measurements by substitution with a gauge previously calibrated at NPL and included the uncertainty of this calibration in their overall uncertainty budget.
2. NMC-A*STAR used a step gauge calibrated by NPL to perform an ISO 10360-2 verification test on their co-ordinate measurement machine (CMM). They then included the maximum permitted error (MPE) of the CMM, which was demonstrated during the ISO 10360-2 test as an uncertainty contribution for their submitted results.
3. NPLI also used a step gauge calibrated at NPL to calibrate their CMM. The uncertainty of this was included in a general machine/equipment term, along with other contributions so the effect of the correlation was hard to determine.

The second correlation is very weak while the first and third are likely quite strong.

Consideration was given to using a generalised weighted mean approach to account for the correlations but after investigation it was found that the high uncertainties of the correlated laboratories meant that the effect of this change on the calculated reference values was negligible. Given the significant increase in complexity of the analysis by the method of generalised weighted means and the negligibility of the change the pilot determined that a standard weighted mean was sufficiently rigorous.

6.3 1020 mm artefact analysis

6.3.1 Artefact stability

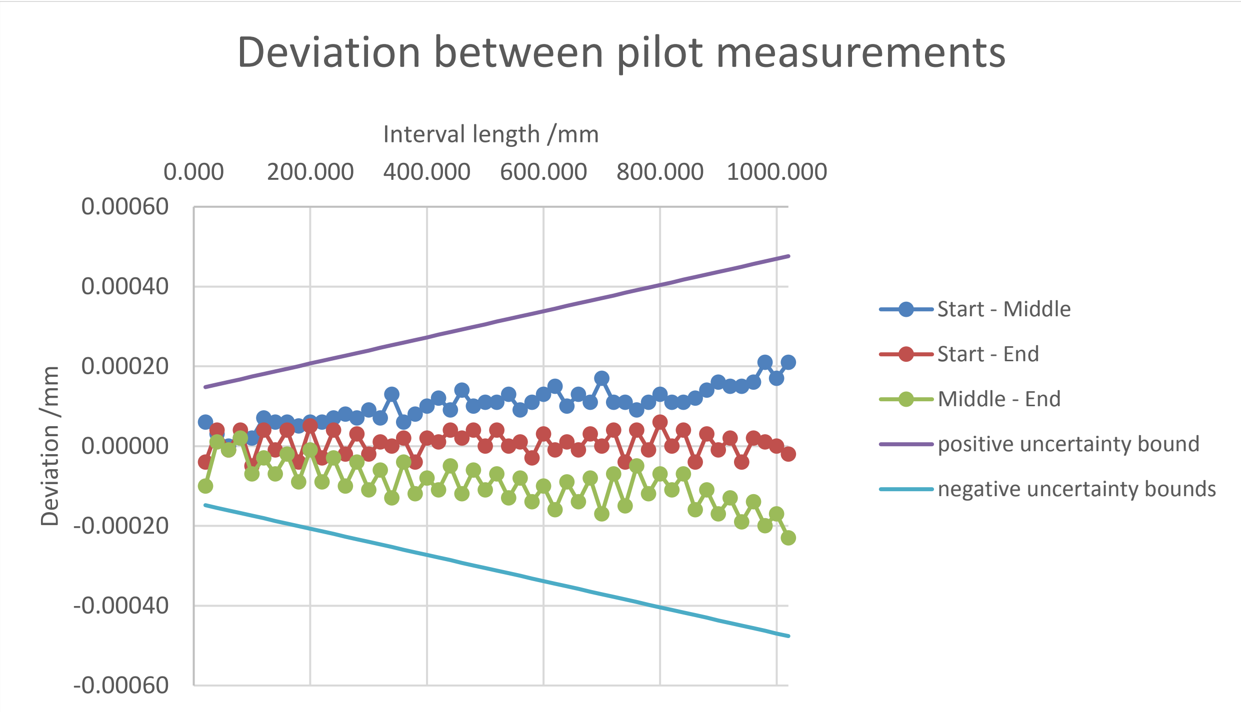


Figure 5: Deviation between pilot measurements of the 1020 mm artefact

The pilot laboratory made three measurements of the artefact during the comparison. The first prior to circulation, the second midway through and the third after the completion of circulation. The operator of these measurements did not have sight of other participants data while circulation was in progress, to ensure fairness.

Pilot measurements of the 1020 mm artefact were consistent with the gauge remaining stable throughout the comparison period. The deviations between the three measurements are shown in Figure 5. The uncertainty bounds shown are the uncertainty of the difference between two sets of measurements defined as

$$u_{(1-2)} = \sqrt{{u_1}^2 + {u_2}^2}$$

Where u is the expanded uncertainty of measurement at k = 2.

6.3.2 Participant measurement results

The reported measurement results for each participant who measured the 1020 mm artefact are shown in Table 9. The number of decimal places shown in the table is the number reported by the participants. In the case of LNE, results of intervals with a nominal length shorter than 800 mm were reported to 5 decimal places while those of intervals 800 mm longer were reported to 6 decimal places. All three NPL measurements are included. The data set labelled NPL1 was used as NPL's results for the purposes of demonstrating equivalence.

Table 9: 1020 mm artefact participant reported results

Nominal Length /mm	NPL1 /mm	LNE /mm	BEV /mm	CEM /mm	SP /mm	VTT MIKES /mm
20	19.992 54	19.992 31	19.995 4	19.992 43	19.992 54	19.992 544
40	39.993 55	39.993 60	39.993 9	39.993 48	39.993 61	39.993 535
60	59.987 74	59.987 53	59.990 8	59.987 54	59.987 83	59.987 757
80	79.993 91	79.993 93	79.994 0	79.993 82	79.993 97	79.993 917
100	99.989 70	99.989 49	99.992 5	99.989 60	99.989 80	99.989 739
120	119.996 56	119.996 57	119.996 8	119.996 42	119.996 60	119.996 532
140	139.986 71	139.986 39	139.989 9	139.986 48	139.986 76	139.986 698
160	159.994 57	159.994 51	159.995 0	159.994 48	159.994 67	159.994 581
180	179.983 75	179.983 47	179.987 1	179.983 56	179.983 83	179.983 762
200	199.994 64	199.994 59	199.995 2	199.994 53	199.994 72	199.994 601
220	219.984 44	219.984 16	219.987 2	219.984 26	219.984 56	219.984 453
240	239.997 26	239.997 16	239.997 7	239.997 16	239.997 37	239.997 256
260	259.989 07	259.988 71	259.992 4	259.988 87	259.989 18	259.989 045
280	280.000 96	280.000 86	280.001 8	280.000 85	280.001 07	280.000 952
300	299.986 18	299.985 86	299.989 1	299.986 00	299.986 33	299.986 222
320	319.993 07	319.992 91	319.993 7	319.993 08	319.993 25	319.993 114
340	339.988 64	339.988 28	339.991 8	339.988 40	339.988 77	339.988 649
360	360.007 42	360.007 18	360.008 3	360.007 37	360.007 62	360.007 481
380	379.989 69	379.989 31	379.993 2	379.989 46	379.989 85	379.989 682
400	399.999 15	399.999 02	400.000 4	399.999 09	399.999 26	399.999 181
420	419.991 27	419.990 94	419.996 0	419.991 08	419.991 46	419.991 282
440	439.995 82	439.995 61	439.996 6	439.995 75	439.995 93	439.995 897
460	459.990 88	459.990 57	459.994 4	459.990 58	459.990 98	459.990 851
480	480.000 30	480.000 15	480.001 4	480.000 19	480.000 36	480.000 304
500	499.983 40	499.983 12	499.986 8	499.983 06	499.983 44	499.983 351
520	519.995 67	519.995 50	519.996 4	519.995 60	519.995 75	519.995 716
540	539.984 11	539.983 72	539.987 5	539.983 81	539.984 21	539.984 076
560	559.991 87	559.991 71	559.993 0	559.991 82	559.992 00	559.991 935
580	579.988 09	579.987 81	579.991 5	579.987 83	579.988 17	579.988 079
600	599.993 09	599.992 86	599.994 2	599.992 93	599.993 12	599.993 062
620	619.982 40	619.982 08	619.986 0	619.982 07	619.982 46	619.982 347
640	639.989 19	639.988 96	639.990 4	639.989 06	639.989 25	639.989 016
660	659.979 76	659.979 45	659.982 8	659.979 40	659.979 82	659.979 775
680	679.992 70	679.992 53	679.993 6	679.992 56	679.992 73	679.992 659

Nominal Length /mm	NPL1 /mm	LNE /mm	BEV /mm	CEM /mm	SP /mm	VTT MIKES /mm
700	699.984 83	699.984 55	699.988 5	699.984 44	699.984 89	699.984 759
720	720.013 28	720.013 09	720.014 5	720.013 07	720.013 32	720.013 231
740	739.984 35	739.984 05	739.988 1	739.983 94	739.984 39	739.984 273
760	759.997 42	759.997 39	759.998 7	759.997 26	759.997 55	759.997 455
780	779.982 46	779.982 17	779.986 4	779.982 03	779.982 48	779.982 366
800	799.998 72	799.998 74	800.000 1	799.998 46	799.998 77	799.998 677
820	819.986 03	819.986 206	819.989 7	819.985 60	819.986 09	819.985 952
840	839.997 04	839.997 470	839.998 4	839.996 78	839.997 12	839.997 004
860	859.988 15	859.988 199	859.992 1	859.987 74	859.988 25	859.988 117
880	879.993 30	879.993 631	879.994 6	879.993 06	879.993 39	879.993 272
900	899.984 27	899.984 305	899.988 4	899.983 84	899.984 37	899.984 225
920	919.998 23	919.998 544	919.999 9	919.998 03	919.998 37	919.998 196
940	939.986 39	939.986 336	939.990 6	939.985 95	939.986 56	939.986 368
960	959.989 97	959.990 128	959.991 7	959.989 67	959.990 09	959.989 936
980	979.987 22	979.986 972	979.991 3	979.986 69	979.987 33	979.987 160
1000	999.994 02	999.994 068	999.995 8	999.993 71	999.994 18	999.993 995
1020	1019.986 06	1019.985 727	1019.990 4	1019.985 50	1019.986 24	1019.986 051

Nominal Length /mm	NPL2 /mm	METAS /mm	TUBITAK-UME /mm	NMIJ /mm	NIST /mm
20	19.992 48	19.992 49	19.994 2	19.992 42	19.992 45
40	39.993 52	39.993 50	39.994 5	39.993 41	39.993 53
60	59.987 74	59.987 72	59.989 5	59.987 56	59.987 70
80	79.993 89	79.993 89	79.994 7	79.993 74	79.993 91
100	99.989 68	99.989 73	99.991 4	99.989 51	99.989 74
120	119.996 49	119.996 53	119.997 3	119.996 28	119.996 53
140	139.986 65	139.986 66	139.988 4	139.986 37	139.986 66
160	159.994 51	159.994 59	159.995 4	159.994 29	159.994 60
180	179.983 70	179.983 75	179.985 3	179.983 37	179.983 74
200	199.994 58	199.994 62	199.995 3	199.994 24	199.994 59
220	219.984 38	219.984 45	219.986 0	219.984 00	219.984 42
240	239.997 19	239.997 28	239.998 0	239.996 82	239.997 24
260	259.988 99	259.989 06	259.990 8	259.988 55	259.989 06
280	280.000 89	280.000 98	280.001 8	280.000 44	280.000 97
300	299.986 09	299.986 17	299.987 8	299.985 56	299.986 17
320	319.993 00	319.993 15	319.993 8	319.992 56	319.993 14
340	339.988 51	339.988 62	339.990 1	339.987 98	339.988 64

Nominal Length /mm	NPL2 /mm	METAS /mm	TUBITAK-UME /mm	NMIJ /mm	NIST /mm
360	360.007 36	360.007 50	360.008 3	360.006 88	360.007 50
380	379.989 61	379.989 64	379.991 1	379.988 91	379.989 57
400	399.999 05	399.999 18	399.999 8	399.998 48	399.999 21
420	419.991 15	419.991 28	419.992 7	419.990 49	419.991 28
440	439.995 73	439.995 92	439.996 6	439.995 17	439.995 94
460	459.990 74	459.990 85	459.992 4	459.989 96	459.990 79
480	480.000 20	480.000 31	480.001 1	479.999 46	480.000 28
500	499.983 29	499.983 33	499.985 0	499.982 40	499.983 28
520	519.995 56	519.995 72	519.996 7	519.994 80	519.995 68
540	539.983 98	539.984 06	539.985 8	539.983 06	539.983 97
560	559.991 78	559.991 90	559.993 0	559.990 94	559.991 90
580	579.987 98	579.988 08	579.989 8	579.986 98	579.987 97
600	599.992 96	599.993 08	599.994 0	599.992 03	599.993 01
620	619.982 25	619.982 36	619.983 9	619.981 20	619.982 26
640	639.989 09	639.989 21	639.990 5	639.988 07	639.989 10
660	659.979 63	659.979 73	659.981 4	659.978 47	659.979 54
680	679.992 59	679.992 68	679.994 1	679.991 52	679.992 59
700	699.984 66	699.984 73	699.986 8	699.983 47	699.984 59
720	720.013 17	720.013 27	720.014 9	720.012 03	720.013 19
740	739.984 24	739.984 24	739.986 2	739.982 91	739.984 05
760	759.997 33	759.997 46	759.998 7	759.996 14	759.997 31
780	779.982 35	779.982 39	779.984 0	779.980 97	779.982 23
800	799.998 59	799.998 68	799.999 6	799.997 28	799.998 55
820	819.985 92	819.985 97	819.987 4	819.984 49	819.985 79
840	839.996 93	839.997 03	839.997 8	839.995 59	839.996 92
860	859.988 03	859.988 12	859.989 5	859.986 61	859.987 96
880	879.993 16	879.993 33	879.994 0	879.991 78	879.993 19
900	899.984 11	899.984 25	899.985 5	899.982 66	899.984 05
920	919.998 08	919.998 24	919.998 9	919.996 64	919.998 07
940	939.986 24	939.986 42	939.987 9	939.984 76	939.986 22
960	959.989 81	959.990 00	959.991 1	959.988 32	959.989 81
980	979.987 01	979.987 18	979.989 0	979.985 43	979.986 91
1000	999.993 85	999.994 02	999.995 3	999.992 27	999.993 79
1020	1019.985 85	1019.986 05	1019.988 1	1019.984 22	1019.985 77

Nominal Length /mm	NMC A*STAR /mm	CENAM /mm	NIM /mm	VSL /mm	NPL3 /mm
20	19.992 93	19.992 42	19.992 28	19.992 40	19.992 58
40	39.993 35	39.993 49	39.993 53	39.993 39	39.993 51
60	59.988 05	59.987 64	59.987 50	59.987 57	59.987 75
80	79.993 68	79.993 90	79.993 98	79.993 74	79.993 87
100	99.989 97	99.989 64	99.989 59	99.989 50	99.989 75
120	119.996 16	119.996 52	119.996 60	119.996 29	119.996 52
140	139.986 81	139.986 60	139.986 52	139.986 39	139.986 72
160	159.994 13	159.994 59	159.994 60	159.994 30	159.994 53
180	179.983 87	179.983 66	179.983 60	179.983 40	179.983 79
200	199.994 18	199.994 68	199.994 76	199.994 28	199.994 59
220	219.984 49	219.984 37	219.984 34	219.984 07	219.984 47
240	239.996 72	239.997 29	239.997 45	239.996 85	239.997 22
260	259.989 07	259.988 97	259.988 95	259.988 60	259.989 09
280	280.000 48	280.001 03	280.001 21	280.000 51	280.000 93
300	299.986 33	299.986 12	299.986 09	299.985 67	299.986 20
320	319.992 68	319.993 19	319.993 32	319.992 65	319.993 06
340	339.988 74	339.988 56	339.988 54	339.988 12	339.988 64
360	360.007 08	360.007 57	360.007 76	360.007 00	360.007 40
380	379.989 82	379.989 62	379.989 67	379.989 00	379.989 73
400	399.998 78	399.999 24	399.999 45	399.998 69	399.999 13
420	419.991 40	419.991 21	419.991 22	419.990 80	419.991 26
440	439.995 44	439.995 97	439.996 26	439.995 43	439.995 78
460	459.990 95	459.990 78	459.990 83	459.990 28	459.990 86
480	479.999 89	480.000 35	480.000 60	479.999 80	480.000 26
500	499.983 47	499.983 32	499.983 36	499.982 79	499.983 40
520	519.995 24	519.995 70	519.995 96	519.995 18	519.995 63
540	539.984 24	539.984 04	539.984 08	539.983 51	539.984 11
560	559.991 56	559.991 93	559.992 18	559.991 41	559.991 86
580	579.988 26	579.988 00	579.988 01	579.987 50	579.988 12
600	599.992 76	599.993 11	599.993 32	599.992 60	599.993 06
620	619.982 62	619.982 31	619.982 29	619.981 90	619.982 41
640	639.988 92	639.989 23	639.989 43	639.988 73	639.989 18
660	659.980 03	659.979 66	659.979 65	659.979 22	659.979 77
680	679.992 39	679.992 69	679.992 87	679.992 26	679.992 67
700	699.984 97	699.984 66	699.984 60	699.984 32	699.984 83
720	720.012 98	720.013 38	720.013 48	720.012 91	720.013 24
740	739.984 53	739.984 20	739.984 17	739.983 85	739.984 39
760	759.997 13	759.997 53	759.997 62	759.997 09	759.997 38
780	779.982 62	779.982 30	779.982 23	779.982 07	779.982 47
800	799.998 35	799.998 71	799.998 87	799.998 40	799.998 66

Nominal Length /mm	NMC A*STAR /mm	CENAM /mm	NIM /mm	VSL /mm	NPL3 /mm
820	819.986 18	819.985 83	819.985 79	819.985 73	819.986 03
840	839.996 70	839.997 12	839.997 24	839.996 82	839.997 00
860	859.988 45	859.988 09	859.988 00	859.987 96	859.988 19
880	879.993 12	879.993 42	879.993 49	879.993 14	879.993 27
900	899.984 68	899.984 23	899.984 02	899.984 12	899.984 28
920	919.998 07	919.998 31	919.998 39	919.998 15	919.998 21
940	939.986 89	939.986 36	939.986 29	939.986 37	939.986 43
960	959.990 01	959.990 06	959.990 18	959.989 96	959.989 95
980	979.987 87	979.987 09	979.986 97	979.987 17	979.987 21
1000	999.994 24	999.994 06	999.994 15	999.994 01	999.994 02
1020	1019.987 02	1019.985 97	1019.985 83	1019.986 11	1019.986 08

6.3.3 Participant measurement uncertainties

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 10. Where possible the model equations reported have been converted to 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 mm and the standard uncertainty u is expressed in µm.

Table 10: 1020 mm artefact participant measurement uncertainties

Participant	Measurement uncertainty	Participant	Measurement uncertainty
NPL	0.05 + 0.116 ×10^{-3} L µm	TUBITAK-UME	Q[0.174, 0.8696×10^{-3} L] µm
LNE	Q[0.138, 0.3×10^{-3} L] µm	NMIJ	Q[0.074, 0.19 L] µm *
BEV	No simple length dependent formula could be derived	NIST	Front Faces 0.035 + 0.43×10^{-4} L µm Back Faces 0.039 + 0.41×10^{-4} L µm
CEM	Q[0.04, 0.2×10^{-3} L] µm	NMC A*STAR	Q[0.254, 0.0014 L] µm
SP	Q[0.09, 0.7×10^{-4} L] µm	CENAM	Q[0.125, 0.175×10^{-3} L] µm
VTT MIKES	Q[0.04, 0.48×10^{-4} L] µm	NIM	Q[0.1, 0.32×10^{-3} L] µm
METAS	Q[0.07,0.12×10^{-3} L] µm	VSL	Q[0.049, 2.27×10^{-4} L] µm

*Although NMIJ calculated and reported this equation as being the specific estimate of the uncertainty of the measurements undertaken, the measurement uncertainties associated with NMIJ's submitted results were based on the higher values obtained from the equation found in NMIJ's current CMC for step gauges of Q[0.085,0.24*L*] µm (*k* = 1). This was because NMIJ was not willing to tighten the values of the corresponding CMC even if the smaller uncertainty shown in Table 10 were shown to be valid by the comparison.

Table 11 shows the reported standard uncertainties supplied by each participant for the measured intervals.

Table 11: 1020 mm artefact participant reported standard uncertainties (*k* = 1)

Nominal Length /mm	NPL /µm	LNE /µm	BEV /µm	CEM /µm	SP /µm	VTT MIKES /µm	METAS /µm
20	0.052	0.14	0.44	0.04	0.09	0.040	0.07
40	0.055	0.14	0.40	0.04	0.09	0.040	0.07
60	0.057	0.14	0.45	0.04	0.09	0.040	0.07
80	0.059	0.14	0.44	0.04	0.09	0.040	0.07
100	0.062	0.14	0.45	0.04	0.09	0.040	0.07
120	0.064	0.14	0.46	0.05	0.09	0.040	0.07
140	0.066	0.14	0.47	0.05	0.09	0.040	0.07
160	0.069	0.15	0.47	0.05	0.09	0.040	0.07
180	0.071	0.15	0.48	0.05	0.09	0.041	0.07
200	0.073	0.15	0.50	0.06	0.09	0.041	0.07
220	0.076	0.15	0.51	0.06	0.09	0.041	0.07
240	0.078	0.16	0.47	0.06	0.09	0.041	0.07
260	0.080	0.16	0.50	0.07	0.09	0.042	0.08
280	0.082	0.16	0.46	0.07	0.09	0.042	0.08
300	0.085	0.16	0.54	0.07	0.09	0.042	0.08
320	0.087	0.17	0.52	0.08	0.09	0.043	0.08
340	0.089	0.17	0.54	0.08	0.09	0.043	0.08
360	0.092	0.18	0.51	0.08	0.09	0.043	0.08
380	0.094	0.18	0.53	0.09	0.09	0.044	0.08
400	0.096	0.18	0.51	0.09	0.09	0.044	0.08
420	0.099	0.19	0.70	0.09	0.09	0.045	0.09
440	0.101	0.19	0.55	0.10	0.10	0.045	0.09
460	0.103	0.20	0.59	0.10	0.10	0.045	0.09
480	0.106	0.20	0.51	0.10	0.10	0.046	0.09
500	0.108	0.20	0.63	0.11	0.10	0.046	0.09
520	0.110	0.21	0.60	0.11	0.10	0.047	0.09
540	0.113	0.21	0.61	0.12	0.10	0.047	0.09
560	0.115	0.22	0.59	0.12	0.10	0.048	0.10
580	0.117	0.22	0.60	0.12	0.10	0.049	0.10
600	0.120	0.23	0.62	0.13	0.10	0.049	0.10
620	0.122	0.23	0.65	0.13	0.10	0.050	0.10

Nominal Length /mm	NPL /µm	LNE /µm	BEV /µm	CEM /µm	SP /µm	VTT MIKES /µm	METAS /µm
640	0.124	0.24	0.57	0.13	0.10	0.050	0.10
660	0.127	0.24	0.65	0.14	0.10	0.051	0.10
680	0.129	0.25	0.59	0.14	0.10	0.052	0.11
700	0.131	0.25	0.65	0.15	0.10	0.052	0.11
720	0.134	0.26	0.63	0.15	0.10	0.053	0.11
740	0.136	0.26	0.64	0.15	0.10	0.053	0.11
760	0.138	0.27	0.61	0.16	0.10	0.054	0.11
780	0.140	0.27	0.65	0.16	0.11	0.055	0.12
800	0.143	0.28	0.61	0.16	0.11	0.055	0.12
820	0.145	0.47	0.68	0.17	0.11	0.056	0.12
840	0.147	0.47	0.64	0.17	0.11	0.057	0.12
860	0.150	0.47	0.67	0.18	0.11	0.057	0.12
880	0.152	0.47	0.65	0.18	0.11	0.058	0.13
900	0.154	0.48	0.63	0.18	0.11	0.059	0.13
920	0.157	0.48	0.64	0.19	0.11	0.060	0.13
940	0.159	0.48	0.63	0.19	0.11	0.060	0.13
960	0.161	0.48	0.61	0.20	0.11	0.061	0.13
980	0.164	0.48	0.65	0.20	0.11	0.062	0.14
1000	0.166	0.48	0.61	0.20	0.11	0.063	0.14
1020	0.168	0.48	0.65	0.21	0.11	0.063	0.14

Nominal Length /mm	TUBITAK-UME /µm	NMIJ /µm	NIST /µm	NMC A*STAR /µm	CENAM /µm	NIM /µm	VSL /µm
20	0.37	0.09	0.040	0.26	0.128	0.10	0.06
40	0.37	0.09	0.037	0.26	0.130	0.10	0.06
60	0.37	0.09	0.041	0.27	0.132	0.10	0.06
80	0.37	0.09	0.038	0.28	0.135	0.10	0.07
100	0.38	0.09	0.043	0.29	0.137	0.10	0.07
120	0.38	0.09	0.040	0.31	0.139	0.11	0.07
140	0.39	0.10	0.045	0.32	0.141	0.11	0.08
160	0.39	0.10	0.042	0.34	0.144	0.11	0.08
180	0.40	0.10	0.046	0.36	0.146	0.12	0.08
200	0.41	0.10	0.044	0.38	0.148	0.12	0.09
220	0.41	0.11	0.048	0.40	0.150	0.12	0.09
240	0.42	0.11	0.045	0.43	0.152	0.12	0.10
260	0.43	0.11	0.050	0.45	0.154	0.13	0.10
280	0.44	0.11	0.047	0.47	0.156	0.13	0.11

Nominal Length /mm	TUBITAK-UME /µm	NMIJ /µm	NIST /µm	NMC A*STAR /µm	CENAM /µm	NIM /µm	VSL /µm
300	0.45	0.12	0.051	0.50	0.158	0.14	0.11
320	0.46	0.12	0.049	0.52	0.160	0.14	0.12
340	0.47	0.12	0.053	0.55	0.162	0.15	0.13
360	0.48	0.13	0.050	0.57	0.163	0.15	0.13
380	0.49	0.13	0.055	0.60	0.165	0.16	0.14
400	0.51	0.13	0.052	0.62	0.167	0.16	0.14
420	0.52	0.14	0.056	0.65	0.169	0.17	0.15
440	0.53	0.14	0.054	0.68	0.171	0.17	0.16
460	0.54	0.14	0.058	0.70	0.173	0.18	0.16
480	0.56	0.15	0.056	0.73	0.174	0.18	0.17
500	0.57	0.15	0.059	0.76	0.176	0.19	0.17
520	0.58	0.16	0.057	0.78	0.178	0.19	0.18
540	0.60	0.16	0.061	0.81	0.180	0.20	0.19
560	0.61	0.16	0.059	0.84	0.181	0.21	0.19
580	0.62	0.17	0.063	0.86	0.183	0.21	0.20
600	0.64	0.17	0.061	0.89	0.185	0.22	0.20
620	0.65	0.18	0.064	0.92	0.186	0.22	0.21
640	0.67	0.18	0.063	0.95	0.188	0.23	0.22
660	0.68	0.18	0.066	0.97	0.190	0.23	0.22
680	0.70	0.19	0.064	1.00	0.191	0.24	0.23
700	0.71	0.19	0.068	1.03	0.193	0.25	0.24
720	0.73	0.20	0.066	1.06	0.194	0.25	0.24
740	0.74	0.20	0.069	1.08	0.196	0.26	0.25
760	0.76	0.21	0.068	1.11	0.197	0.26	0.25
780	0.77	0.21	0.071	1.14	0.199	0.27	0.26
800	0.79	0.21	0.069	1.17	0.201	0.27	0.27
820	0.80	0.22	0.073	1.19	0.202	0.28	0.27
840	0.82	0.22	0.071	1.22	0.204	0.29	0.28
860	0.83	0.23	0.074	1.25	0.205	0.29	0.29
880	0.85	0.23	0.073	1.28	0.207	0.30	0.29
900	0.86	0.24	0.076	1.31	0.208	0.30	0.30
920	0.88	0.24	0.075	1.33	0.210	0.31	0.30
940	0.90	0.25	0.078	1.36	0.211	0.32	0.31
960	0.91	0.25	0.076	1.39	0.212	0.32	0.32
980	0.93	0.26	0.079	1.42	0.214	0.33	0.32
1000	0.94	0.26	0.078	1.45	0.215	0.34	0.33
1020	0.96	0.26	0.081	1.47	0.217	0.34	0.34

6.3.4 KCRV

The KCRV for each measured interval and the associated uncertainty on the 1020 mm gauge for this comparison are shown in Table 12. The reference value for each face is the weighted mean of the largest consistent subset of participants. The criteria for consistency was that the Birge ratio should be satisfied.

During the drafting of the report CEM and VSL found from preliminary results that their measurements had been affected by serious errors (see responses in sections 6.3.8.2 and 6.3.8.3 respectively for details). All VSL's results and half of CEM's results (the faces approached in the opposite direction to the datum face) were affected. These results are excluded from the KCRV calculation.

Note that the KCRV is applicable only to the specific step gauge measured during the comparison.

Table 12: KCRV values for the 1020 mm gauge

Interval	KCRV /mm	KCRV Uncertainty /µm	Interval	KCRV /mm	KCRV Uncertainty /µm
0 mm - 20 mm	19.992 489	0.020 9	0 mm - 540 mm	539.984 059	0.030 1
0 mm - 40 mm	39.993 522	0.018 2	0 mm - 560 mm	559.991 923	0.029 5
0 mm - 60 mm	59.987 711	0.021 3	0 mm - 580 mm	579.988 057	0.031 3
0 mm - 80 mm	79.993 890	0.018 5	0 mm - 600 mm	599.993 058	0.030 3
0 mm - 100 mm	99.989 709	0.021 8	0 mm - 620 mm	619.982 338	0.031 9
0 mm - 120 mm	119.996 511	0.019 8	0 mm - 640 mm	639.989 110	0.030 9
0 mm - 140 mm	139.986 656	0.022 5	0 mm - 660 mm	659.979 709	0.032 6
0 mm - 160 mm	159.994 562	0.020 3	0 mm - 680 mm	679.992 656	0.032 0
0 mm - 180 mm	179.983 742	0.023 8	0 mm - 700 mm	699.984 730	0.033 5
0 mm - 200 mm	199.994 610	0.021 9	0 mm - 720 mm	720.013 242	0.032 8
0 mm - 220 mm	219.984 436	0.024 3	0 mm - 740 mm	739.984 289	0.039 2
0 mm - 240 mm	239.997 256	0.022 2	0 mm - 760 mm	759.997 430	0.033 5
0 mm - 260 mm	259.989 050	0.025 4	0 mm - 780 mm	779.982 348	0.035 6
0 mm - 280 mm	280.000 968	0.023 5	0 mm - 800 mm	799.998 658	0.034 6
0 mm - 300 mm	299.986 192	0.025 8	0 mm - 820 mm	819.985 931	0.036 5
0 mm - 320 mm	319.993 133	0.024 5	0 mm - 840 mm	839.997 005	0.035 7
0 mm - 340 mm	339.988 639	0.026 5	0 mm - 860 mm	859.988 096	0.037 0
0 mm - 360 mm	360.007 490	0.024 8	0 mm - 880 mm	879.993 277	0.036 7
0 mm - 380 mm	379.989 655	0.027 2	0 mm - 900 mm	899.984 203	0.038 2
0 mm - 400 mm	399.999 194	0.025 7	0 mm - 920 mm	919.998 200	0.037 6
0 mm - 420 mm	419.991 291	0.028 1	0 mm - 940 mm	939.986 363	0.038 9
0 mm - 440 mm	439.995 904	0.027 1	0 mm - 960 mm	959.989 938	0.038 1
0 mm - 460 mm	459.990 845	0.028 8	0 mm - 980 mm	979.987 121	0.039 9
0 mm - 480 mm	480.000 304	0.027 7	0 mm - 1000 mm	999.993 966	0.039 3
0 mm - 500 mm	499.983 341	0.029 4	0 mm - 1020 mm	1019.986 081	0.046 8
0 mm - 520 mm	519.995 704	0.028 4			

6.3.5 Participant results by face

The following plots, Figures 6 through 56, show the deviation from the reference value of each participant for each interval measured. The NPL values used were the measurement results taken prior to circulation.

The uncertainties shown are the uncertainty in the deviation from the reference length x_{ref}, calculated to be

$$u_{(x_i - x_{ref})} = \sqrt{{u_{x_i}}^2 - {u_{x_{ref}}}^2}$$

if x_i, the participant reported length, is part of the largest consistent subset and thus contributes to x_{ref}. If a participant has not contributed to the reference value for a given interval, then the uncertainty is calculated as

$$u_{(x_i - x_{ref})} = \sqrt{{u_{x_i}}^2 + {u_{x_{ref}}}^2}$$

u_{x_i} and $u_{x_{ref}}$ are both expanded uncertainties at k = 2.

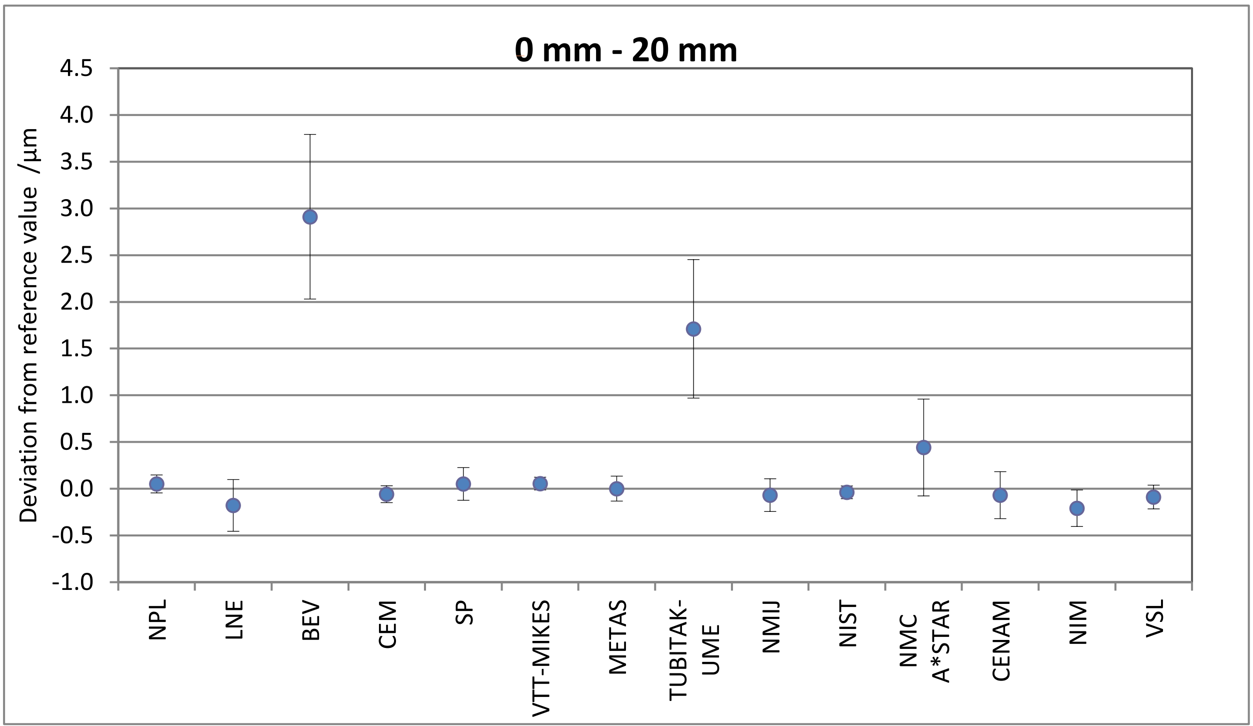


Figure 6: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

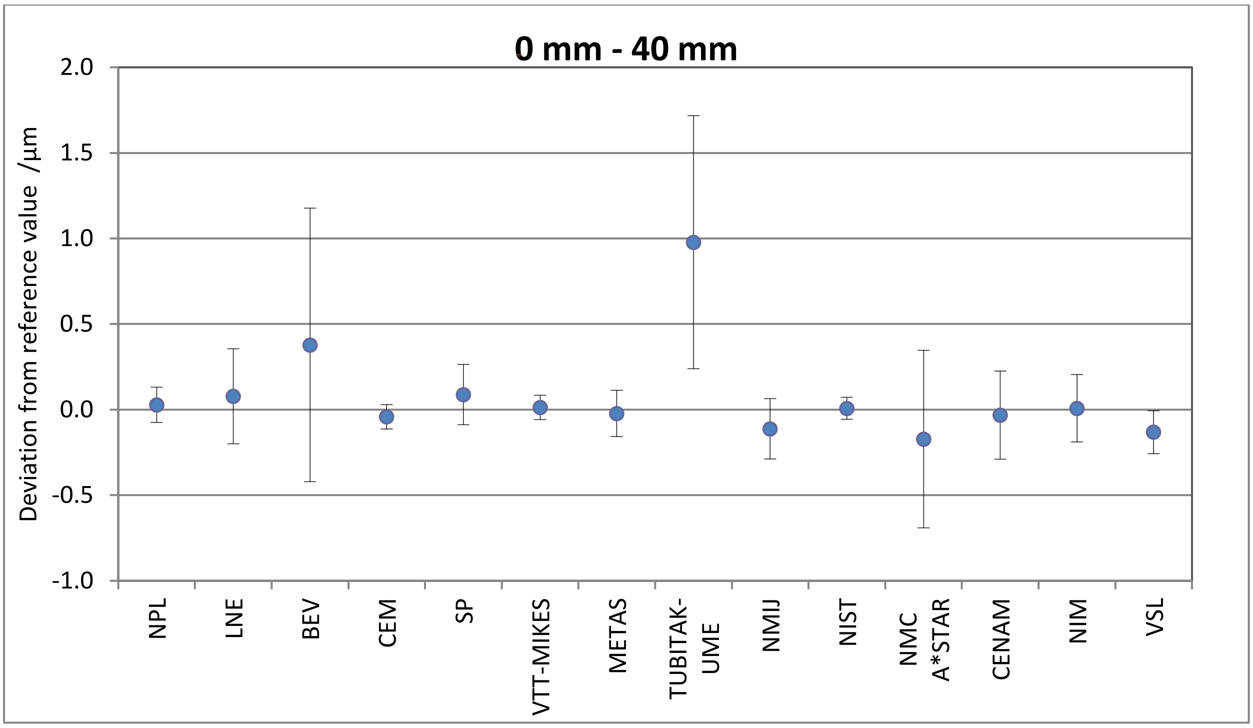


Figure 7: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

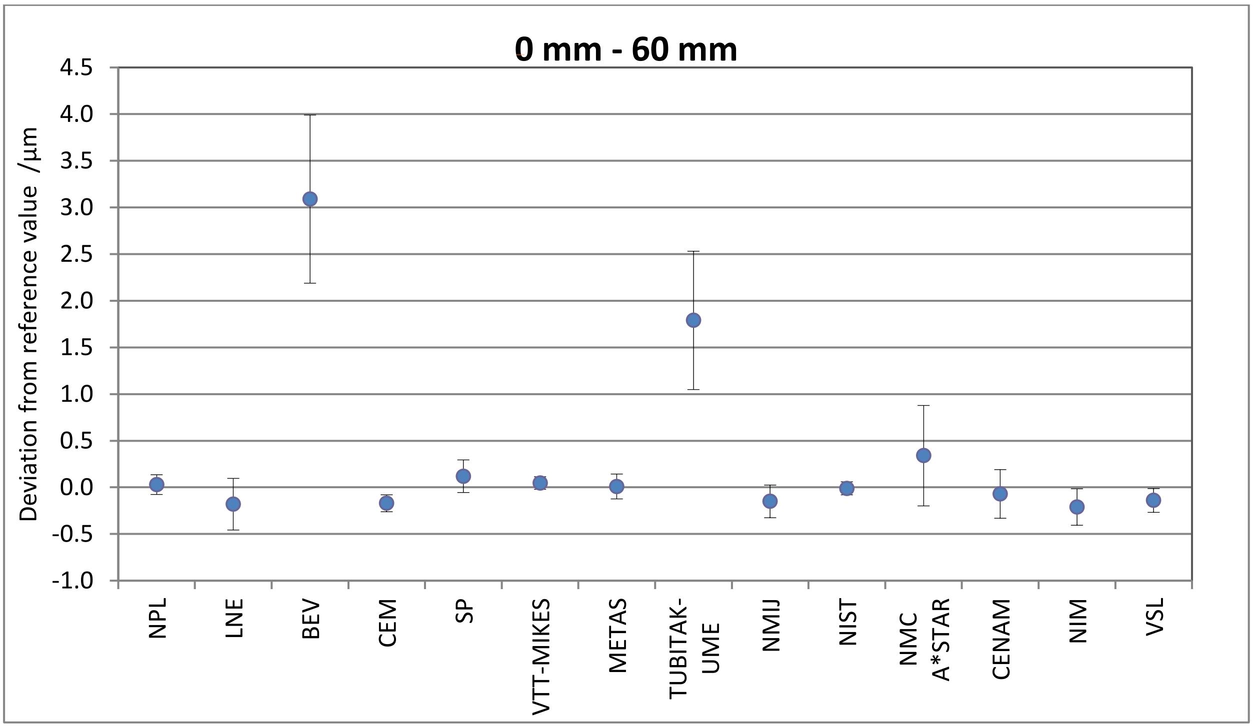


Figure 8: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

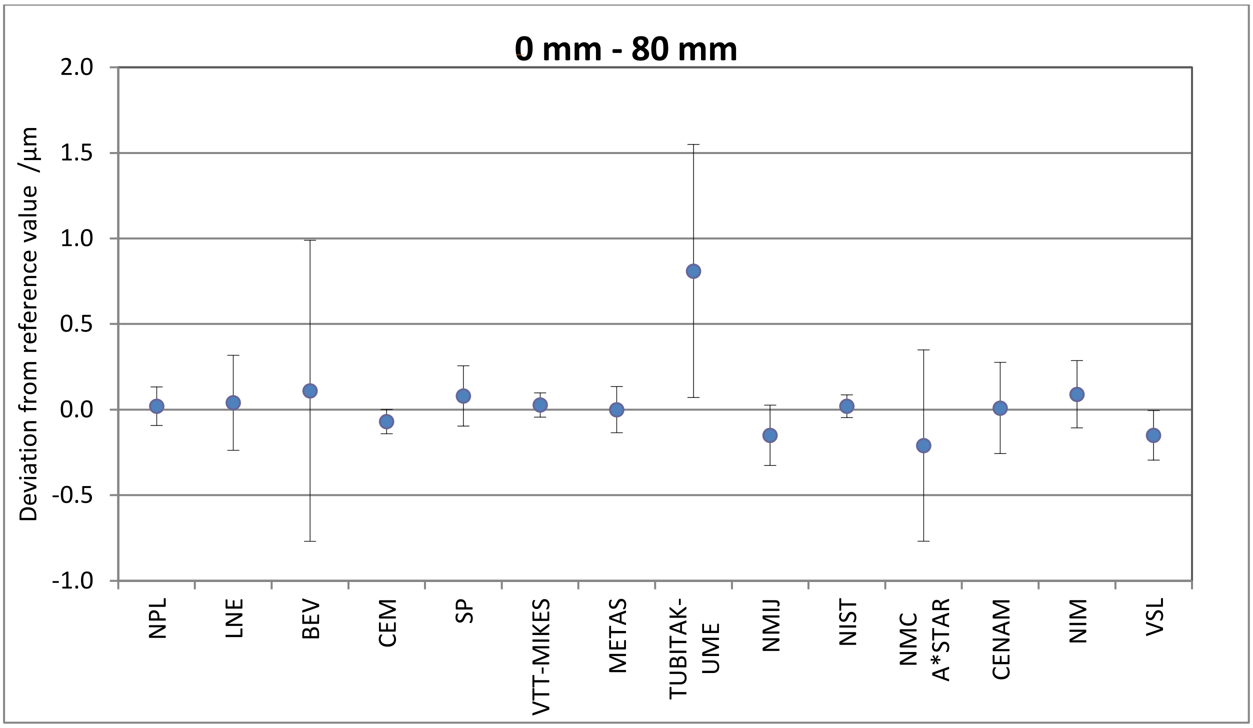


Figure 9: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

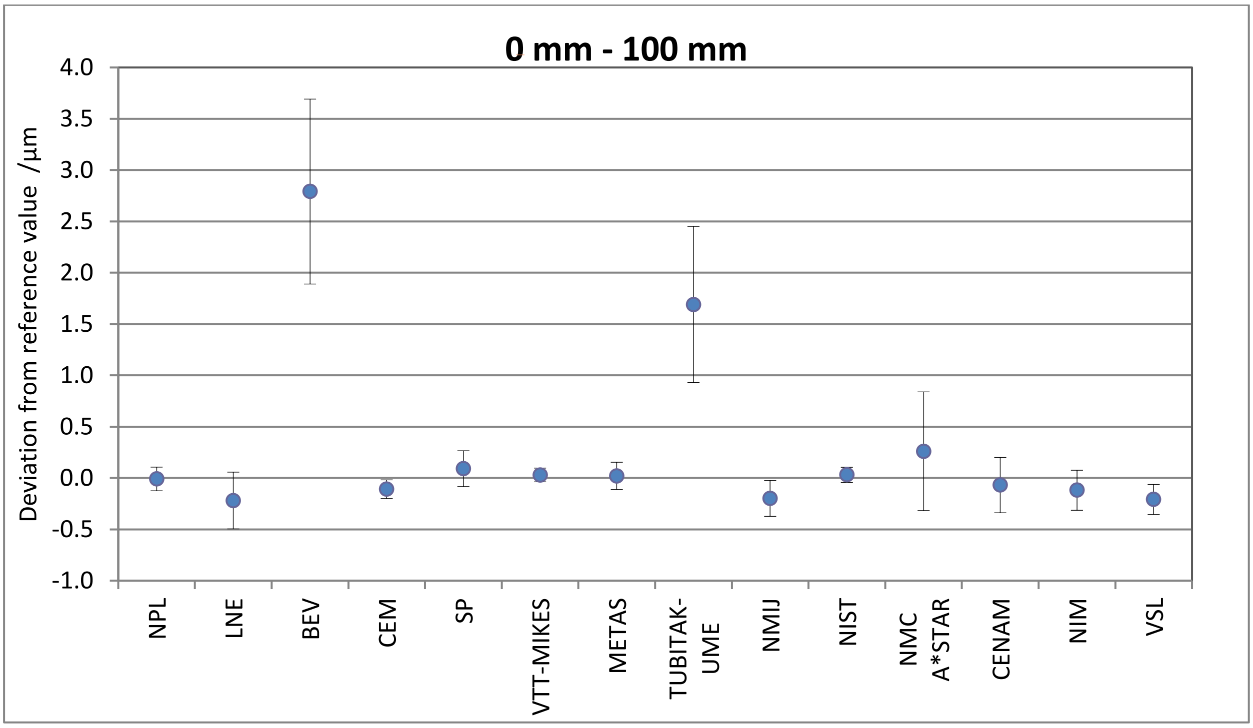


Figure 10: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

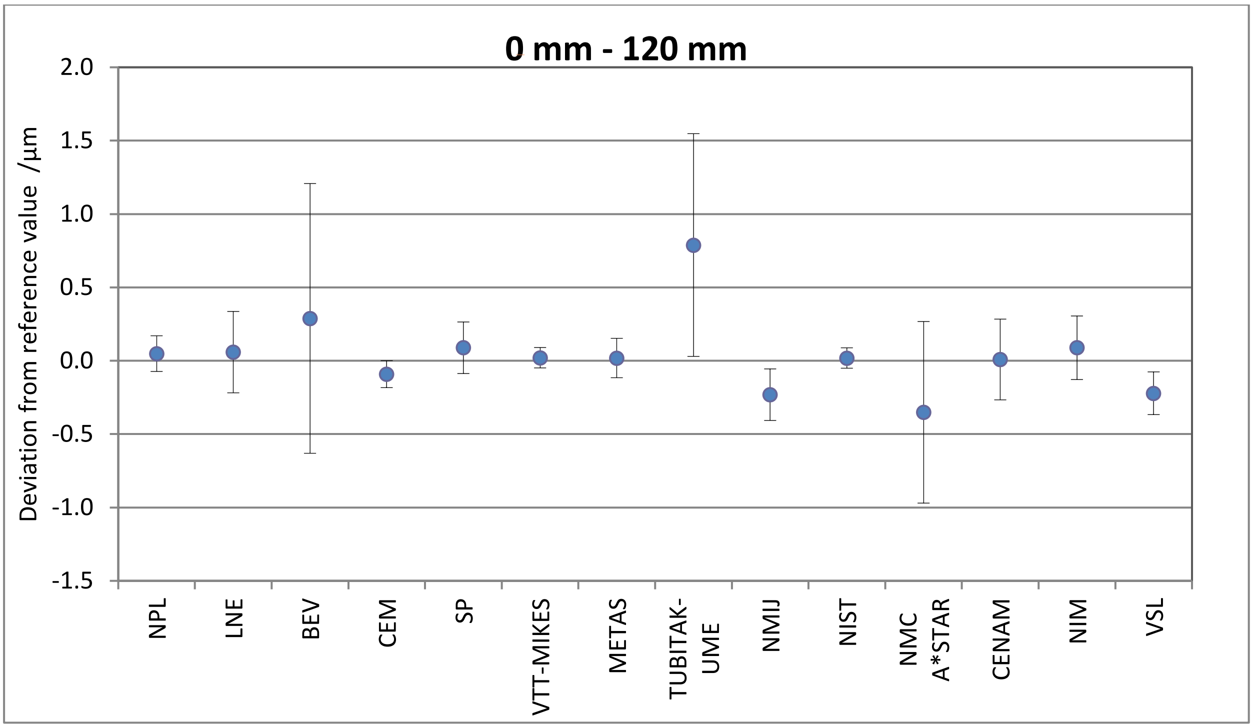


Figure 11: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

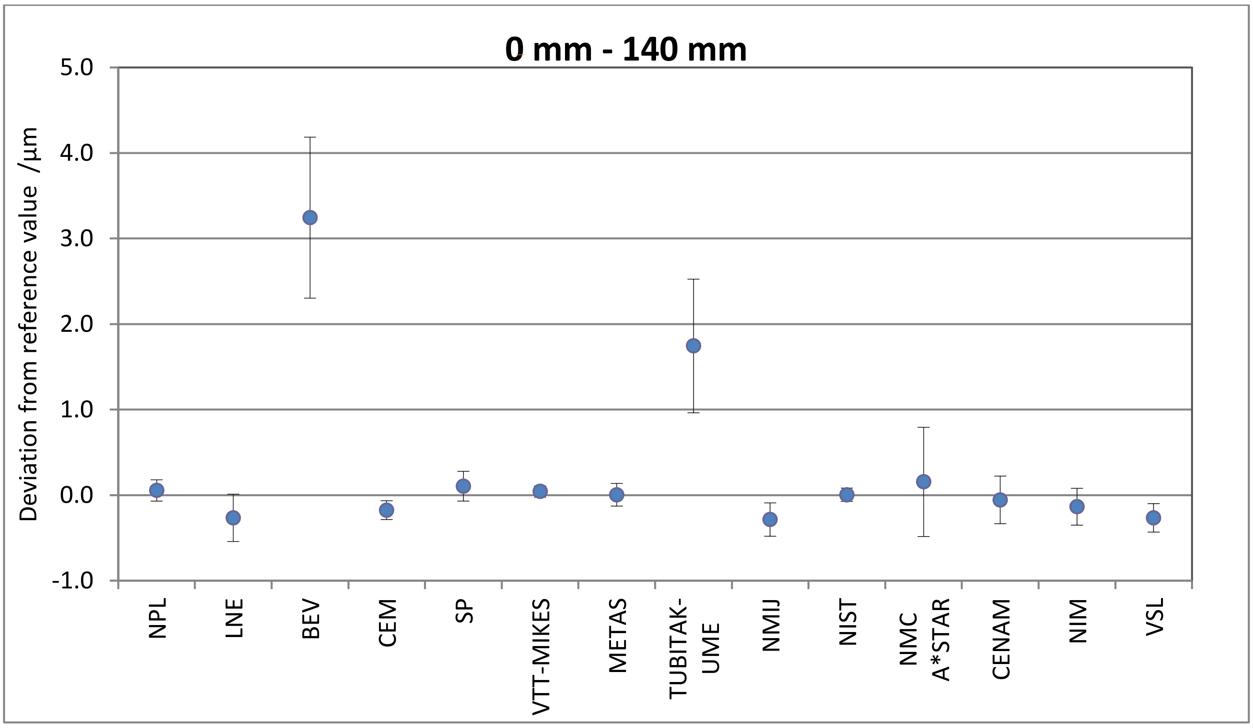


Figure 12: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

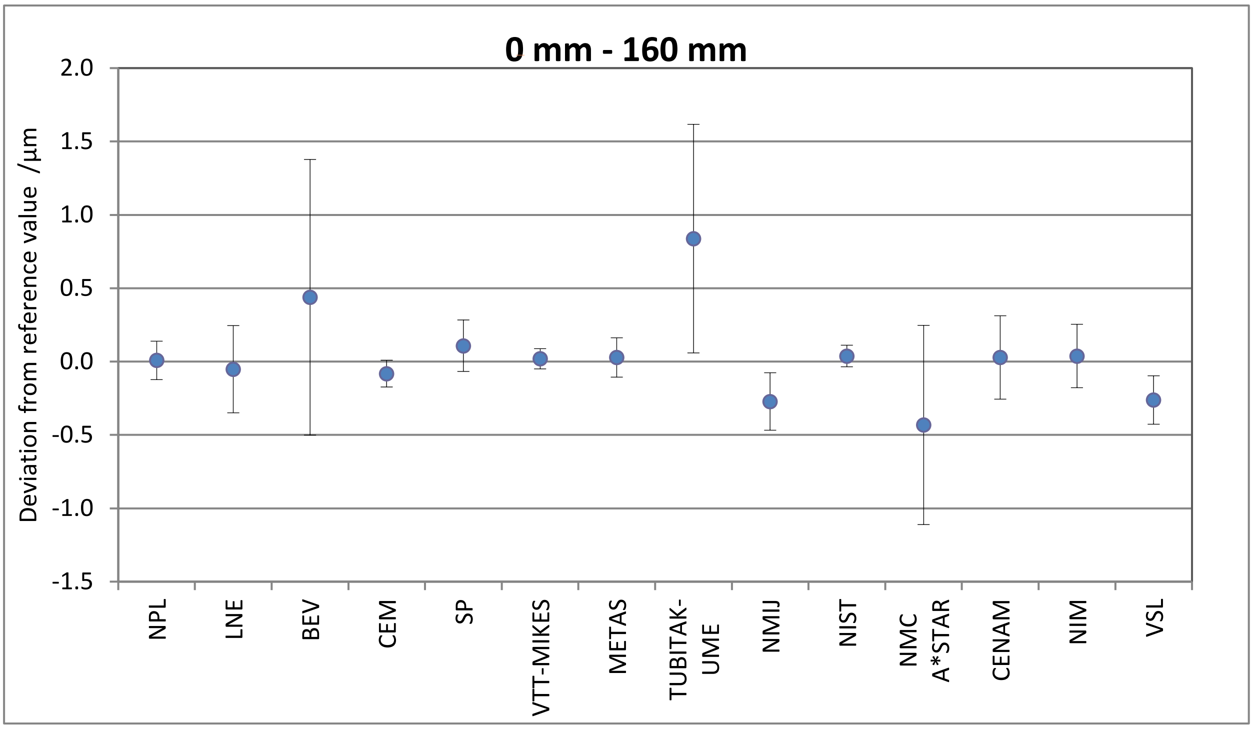


Figure 13: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

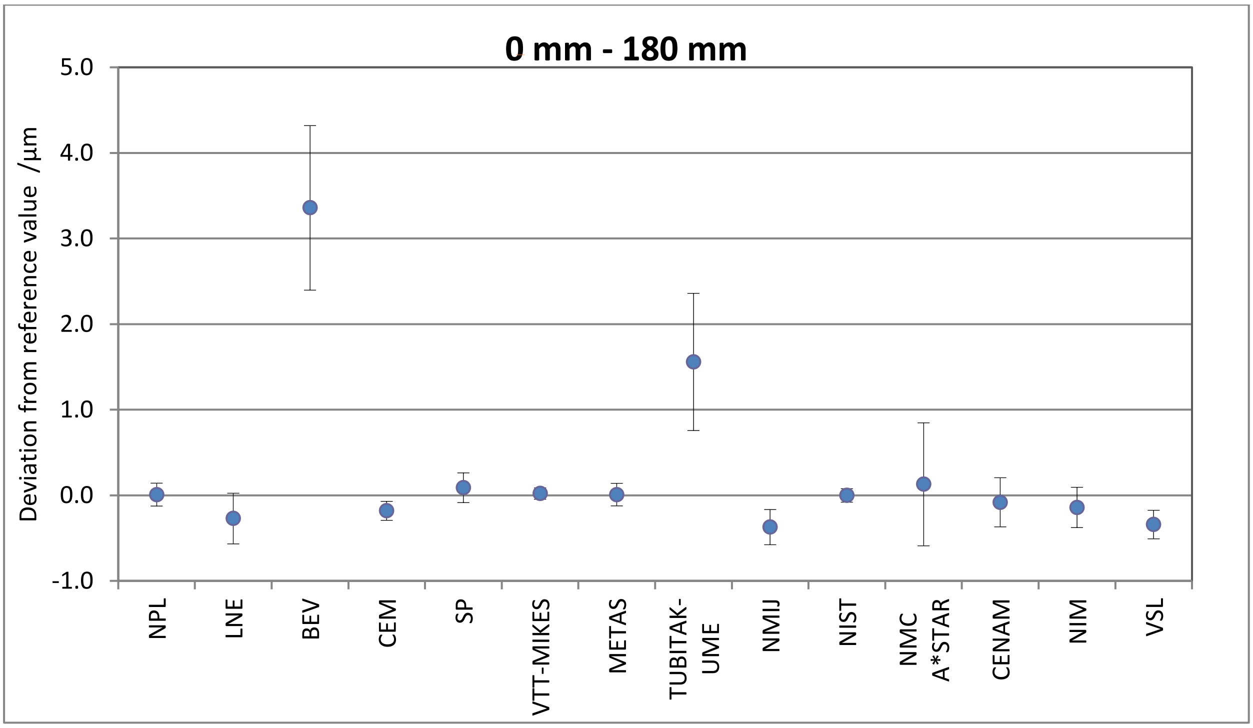


Figure 14: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

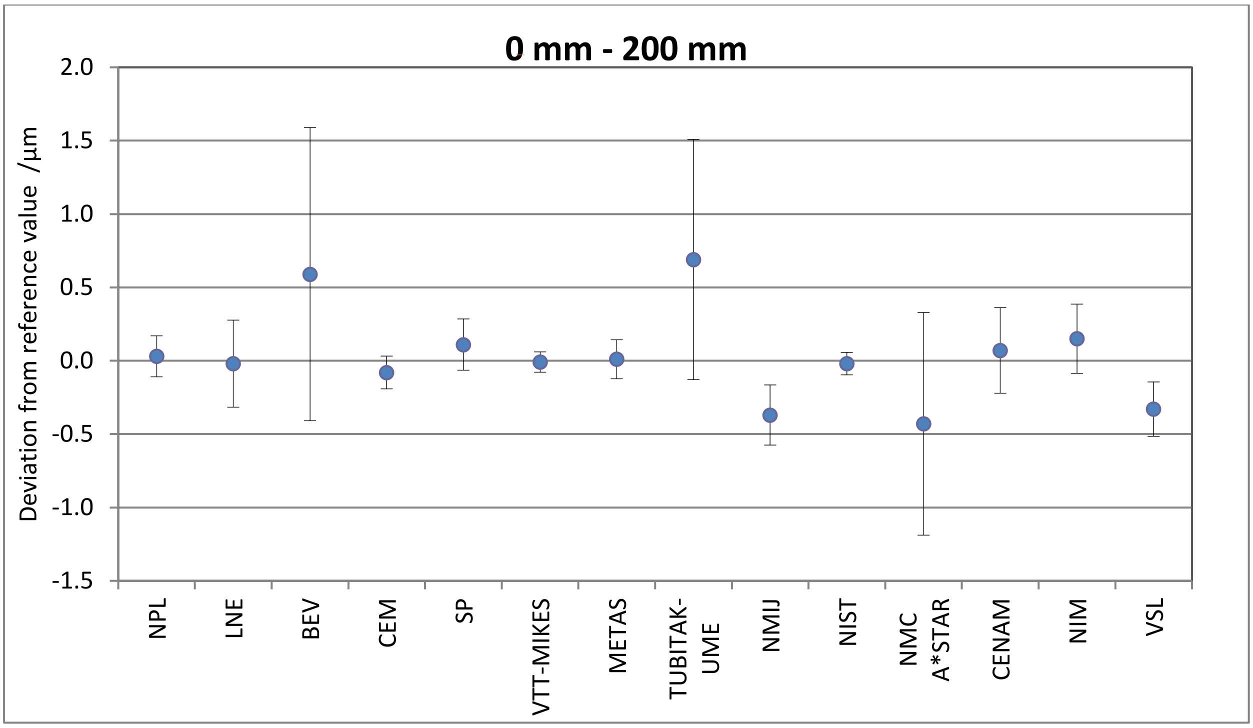


Figure 15: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

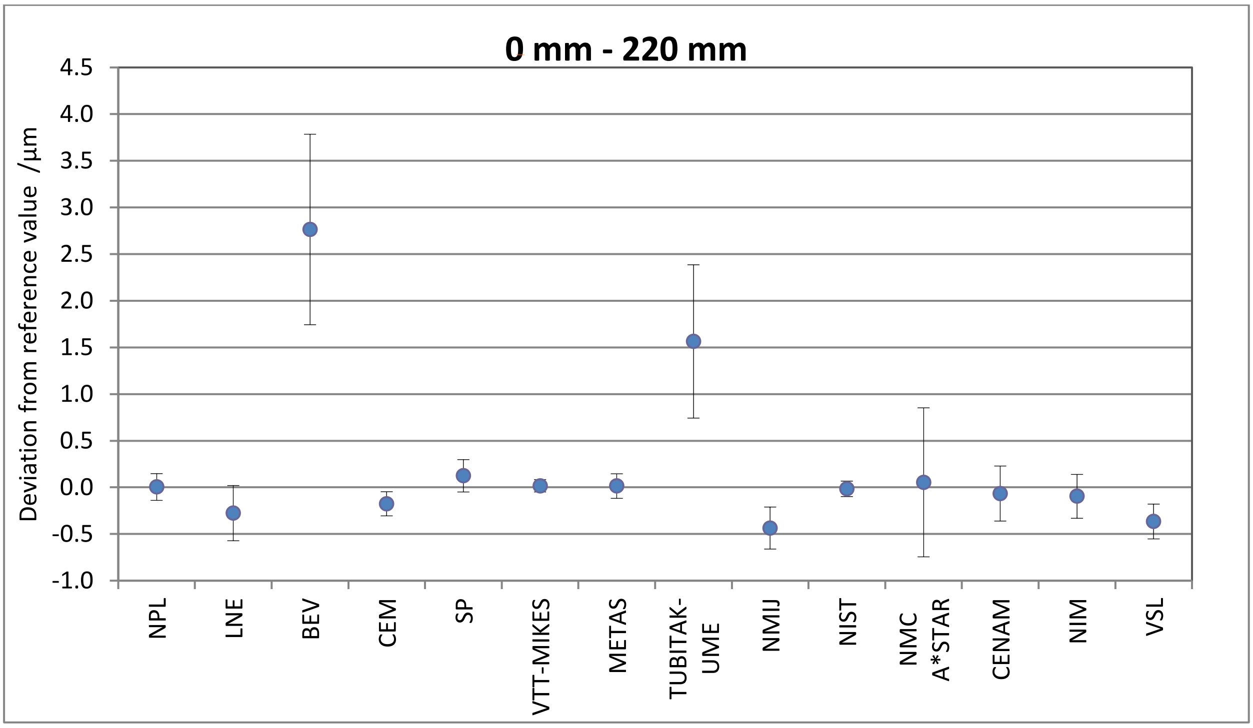


Figure 16: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

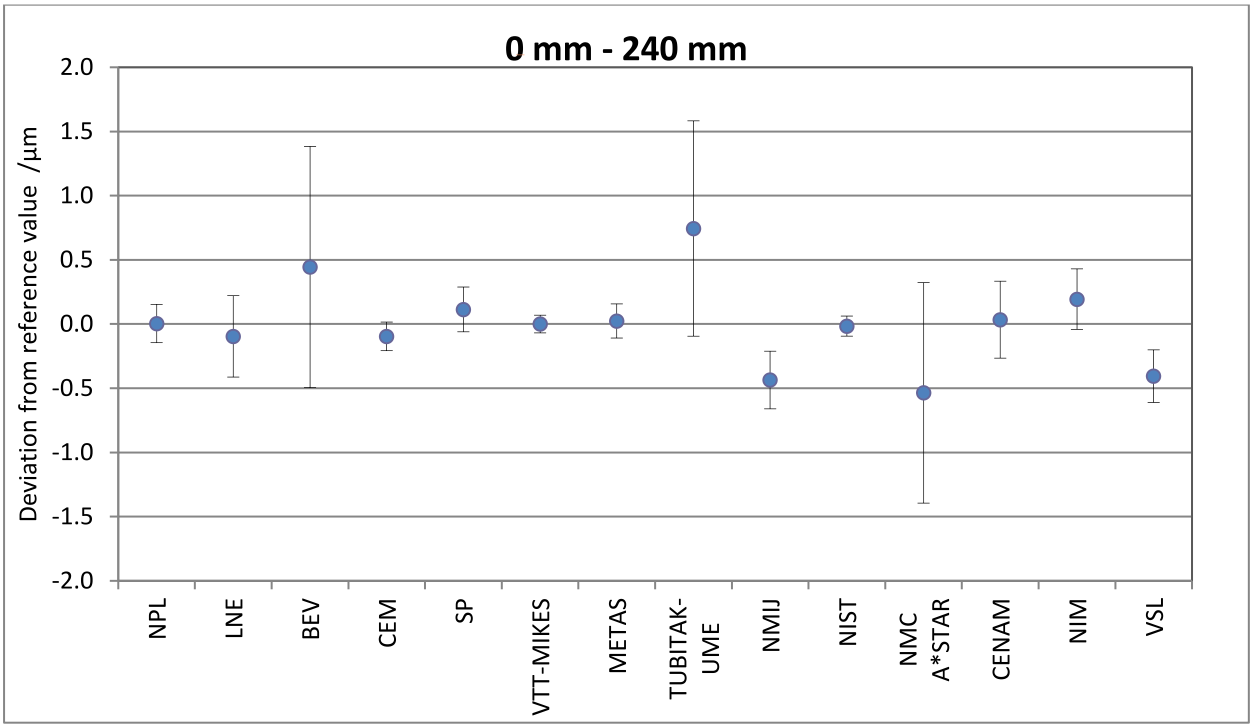


Figure 17: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

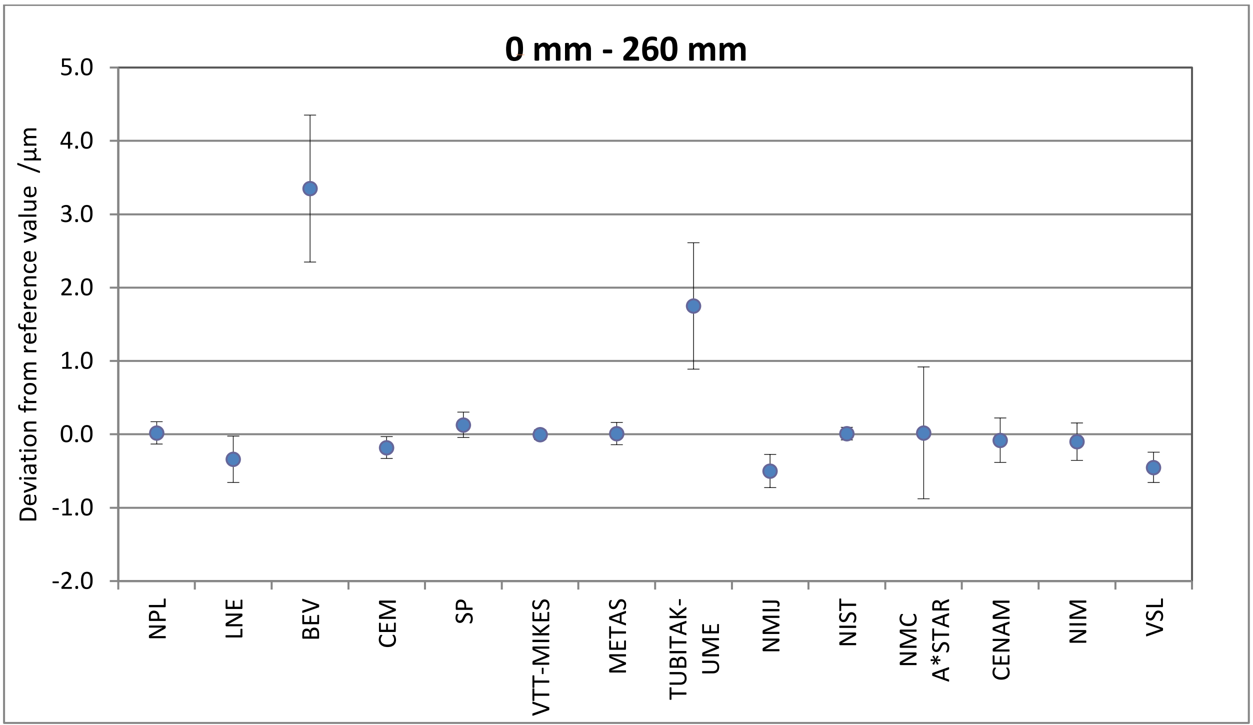


Figure 18: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

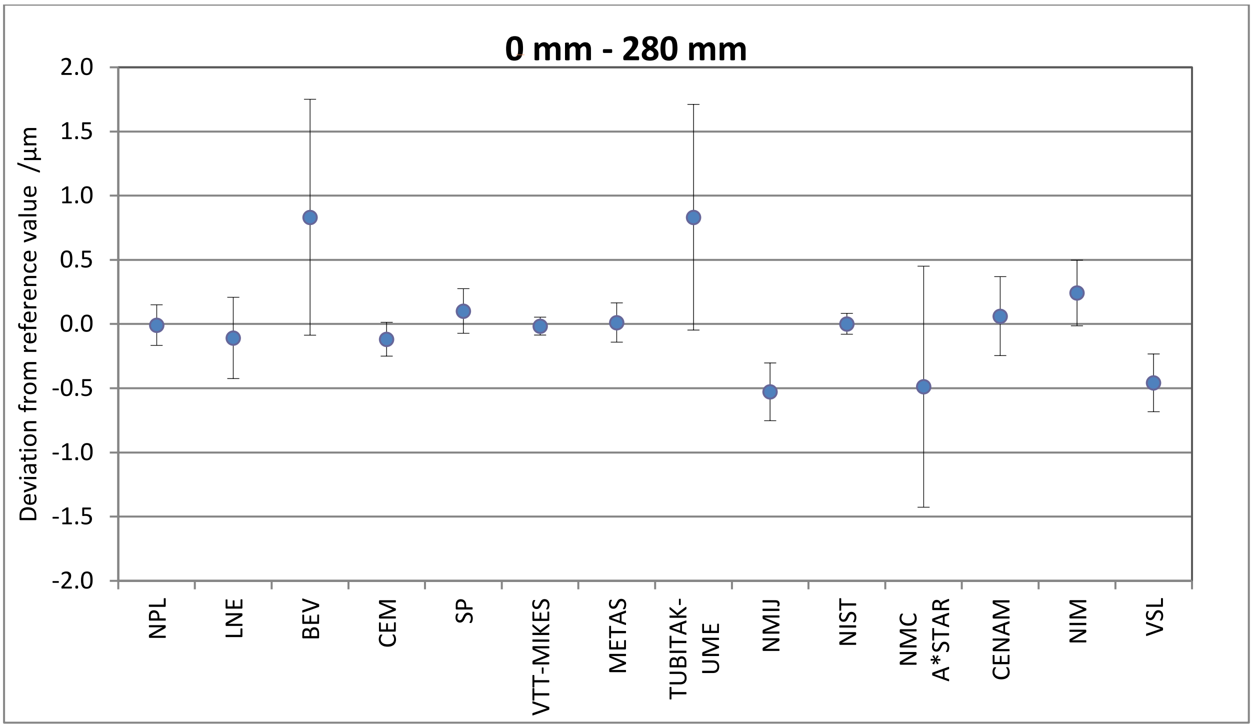


Figure 19: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

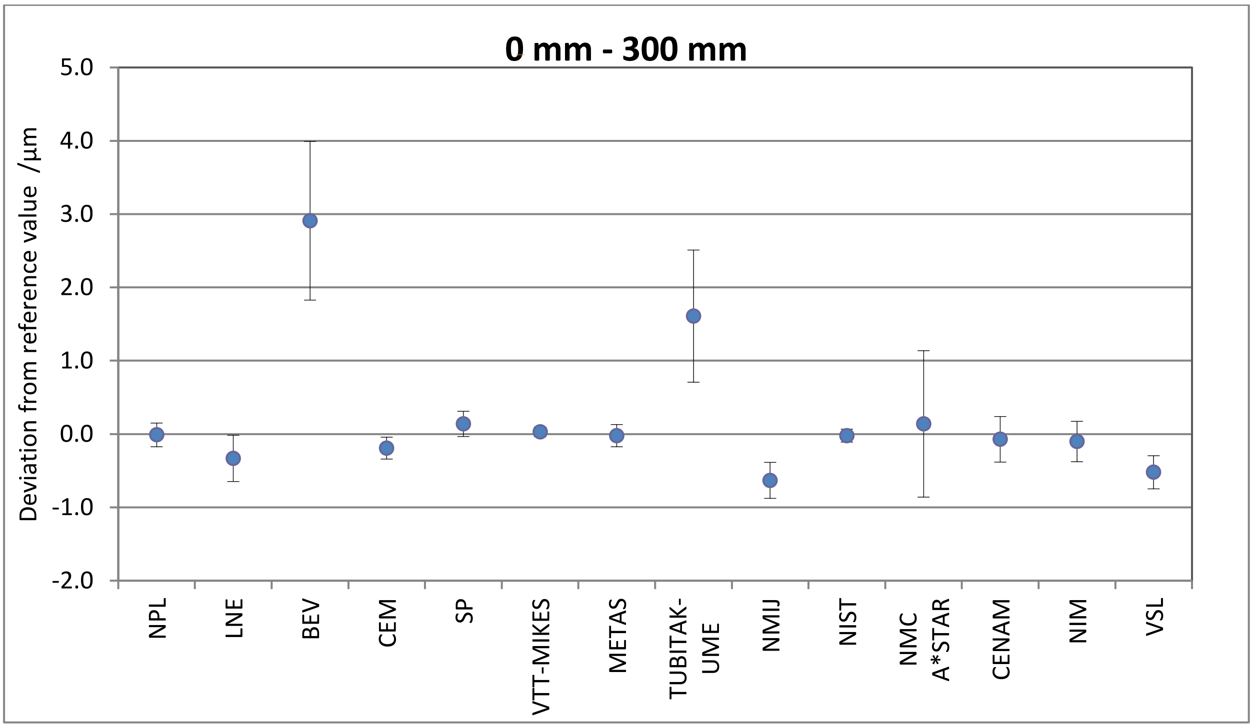


Figure 20: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

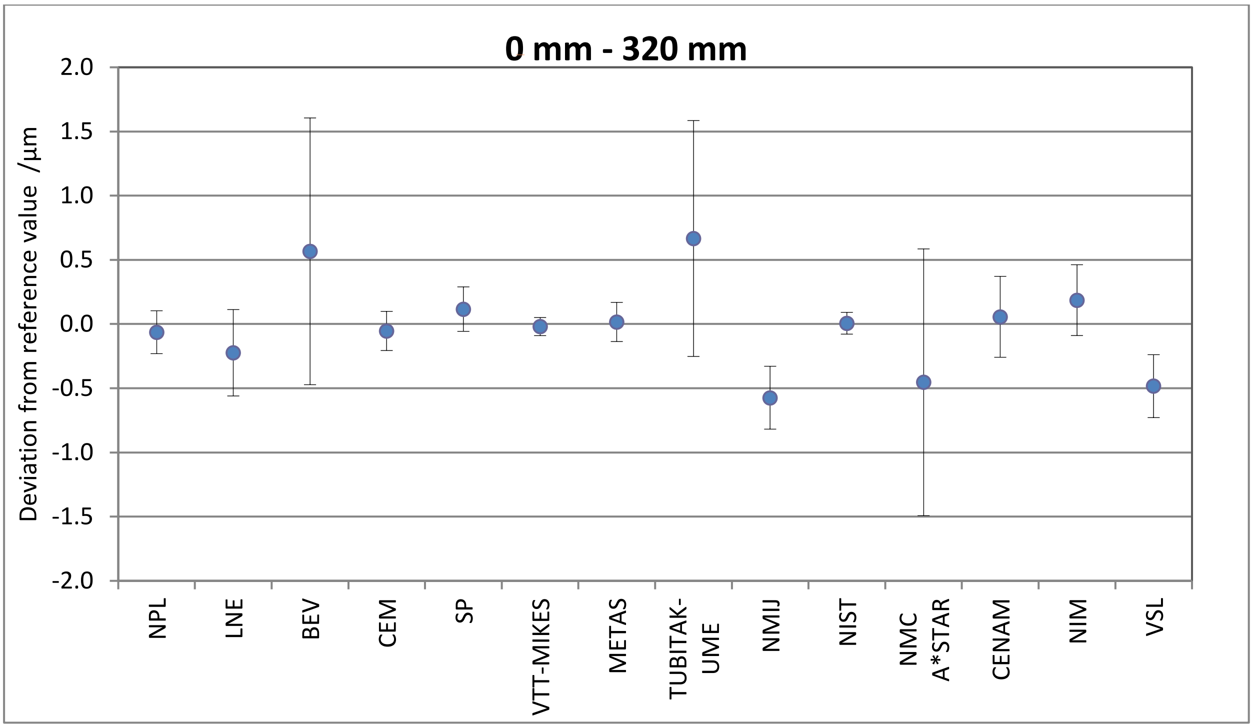


Figure 21: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

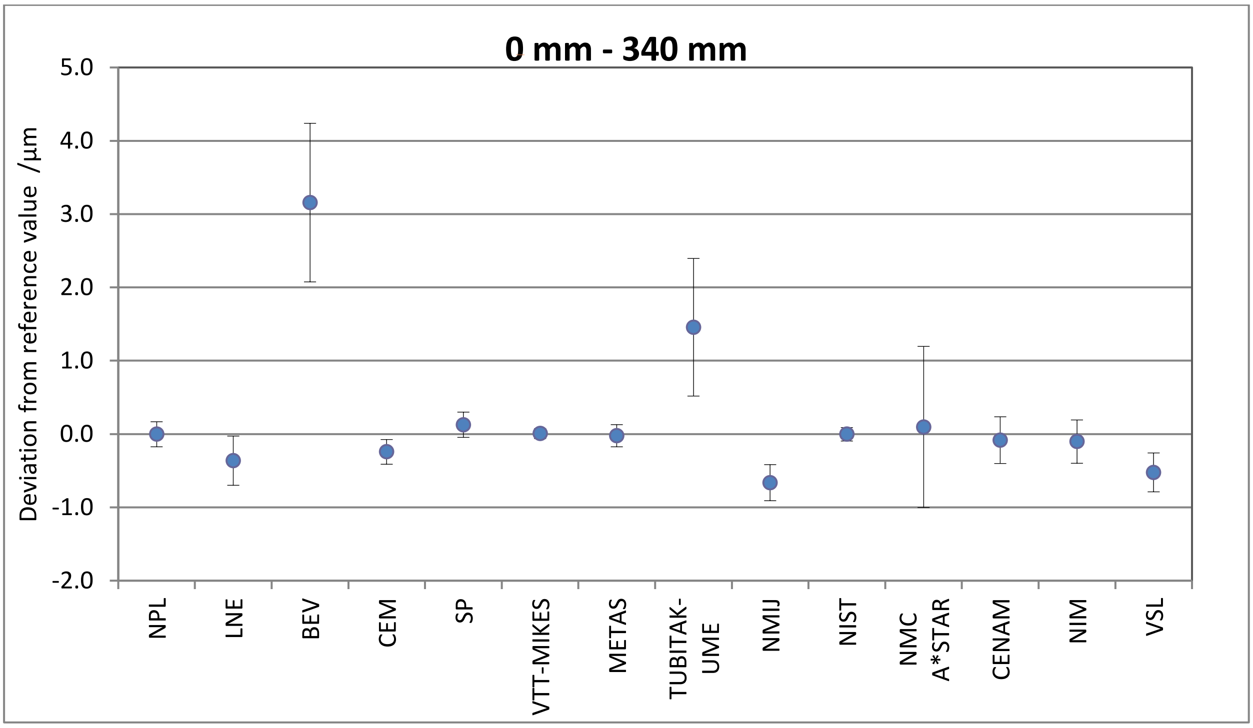


Figure 22: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

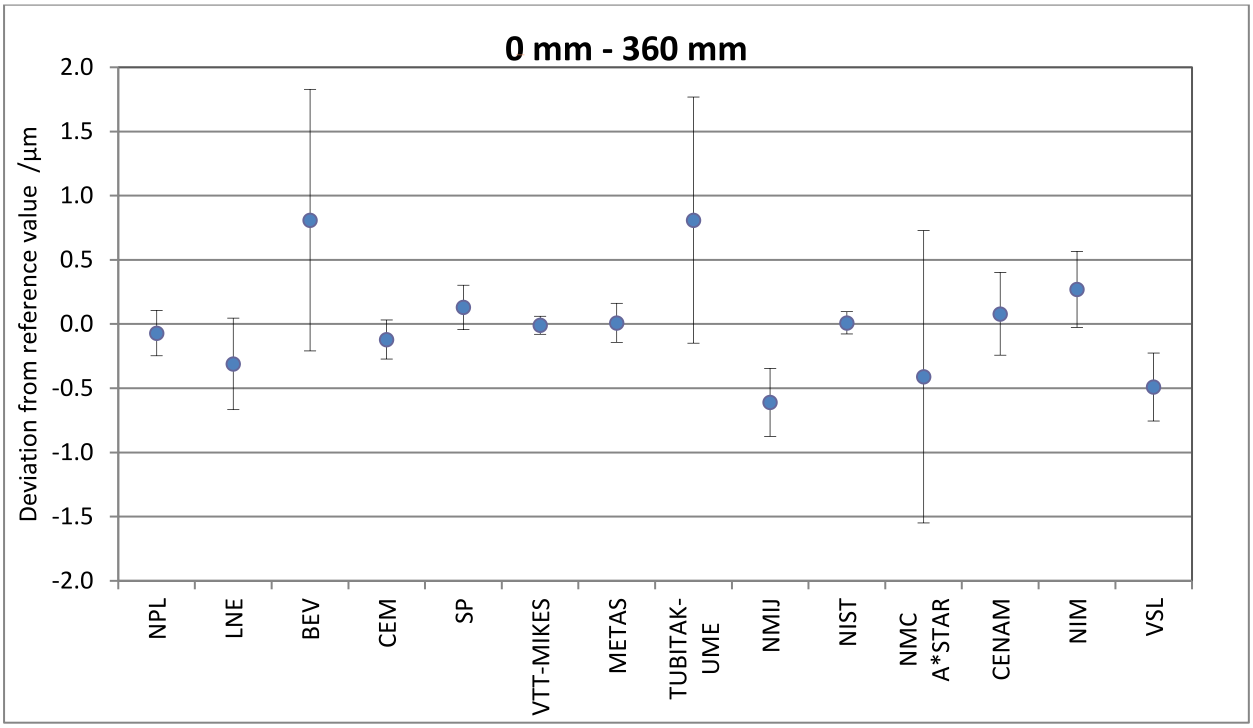


Figure 23: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

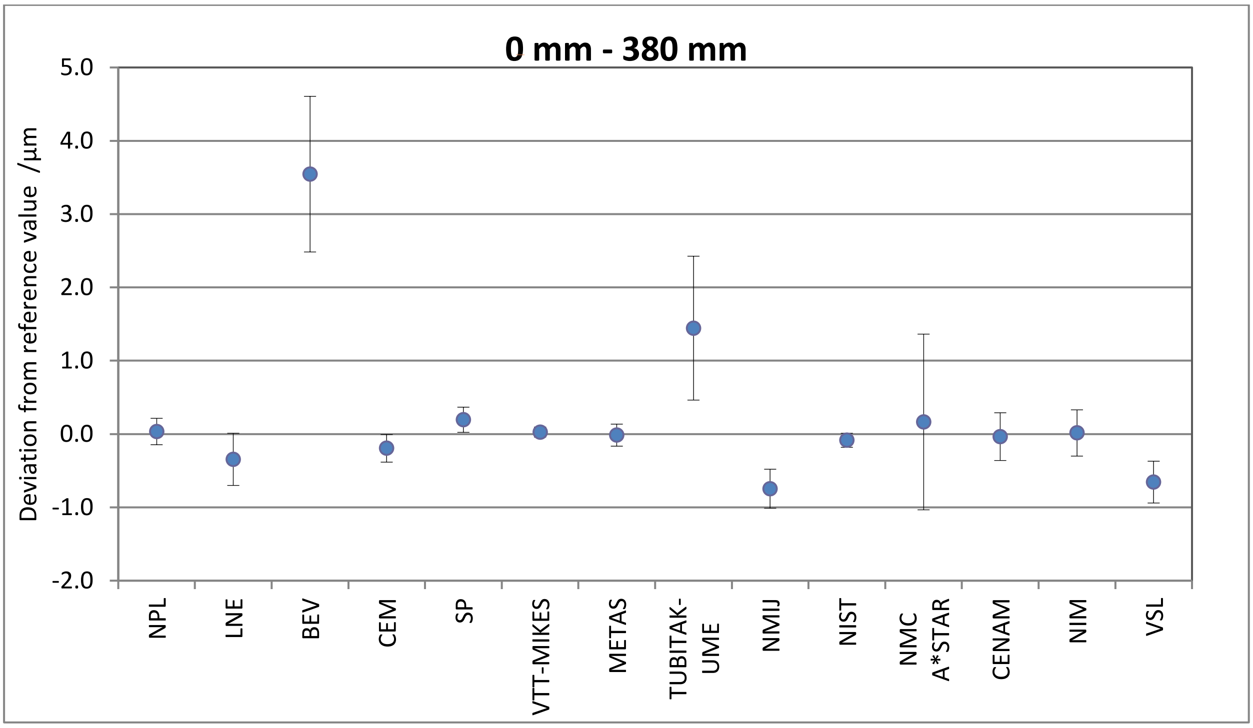


Figure 24: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

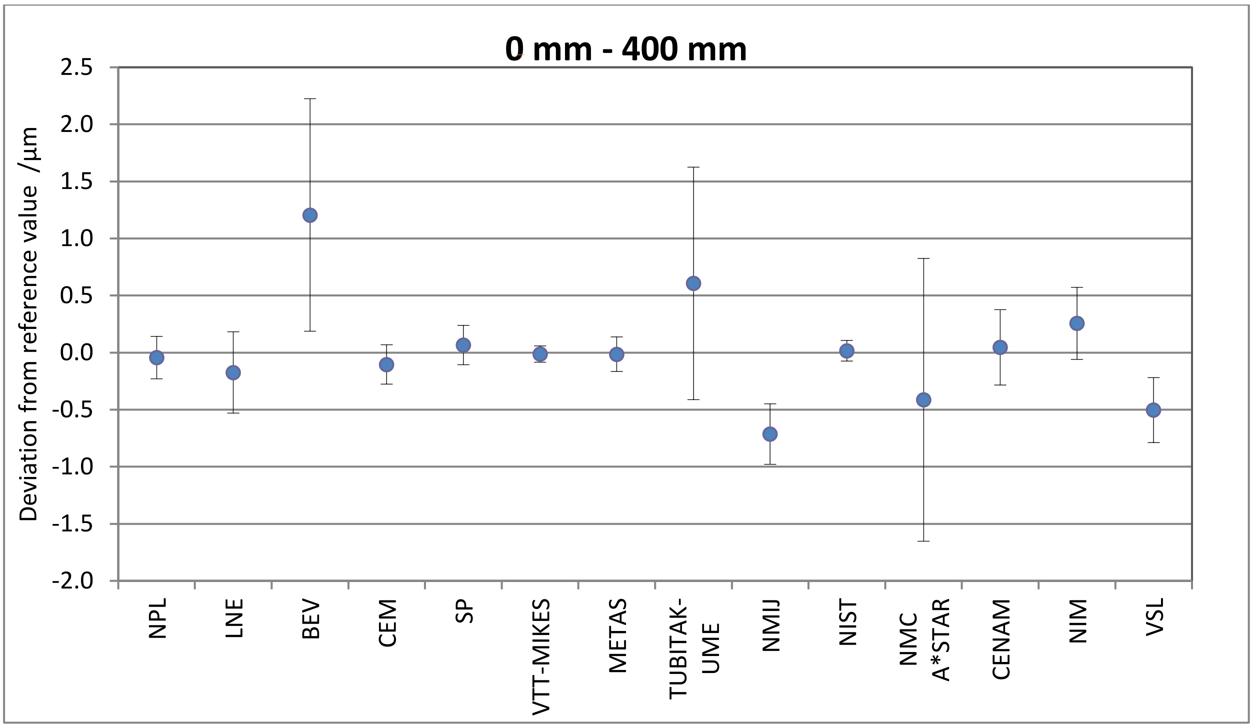


Figure 25: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

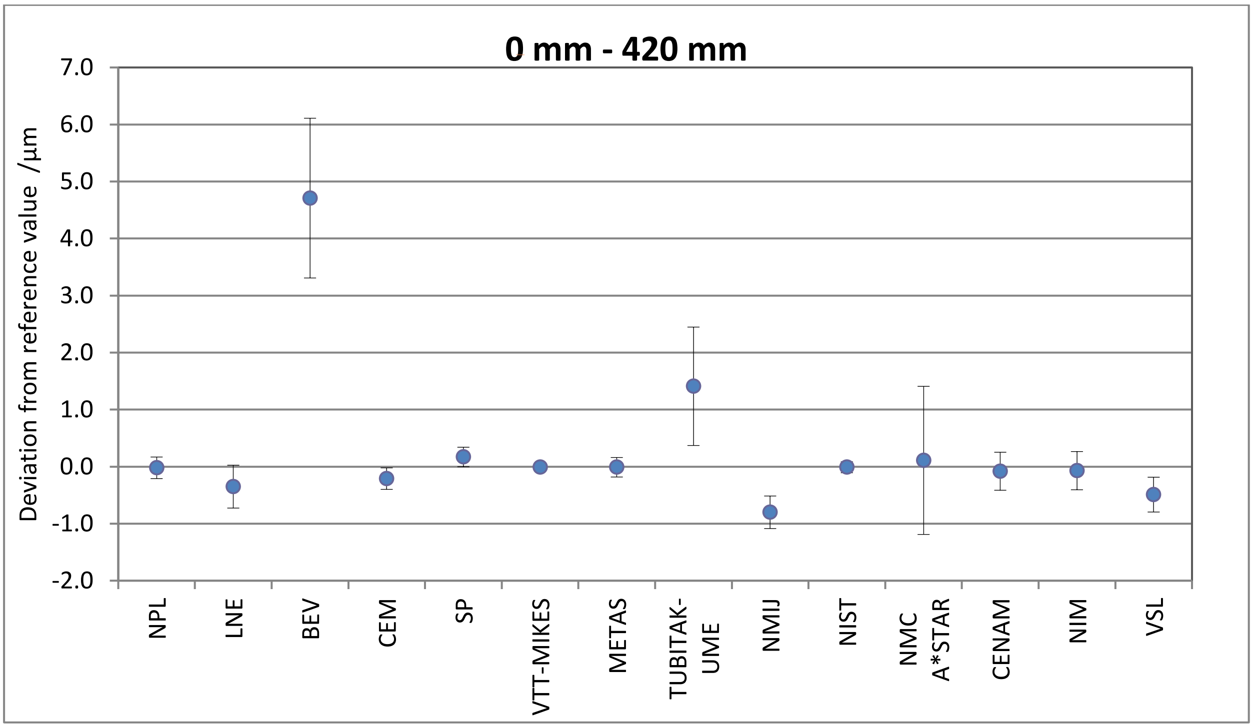


Figure 26: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

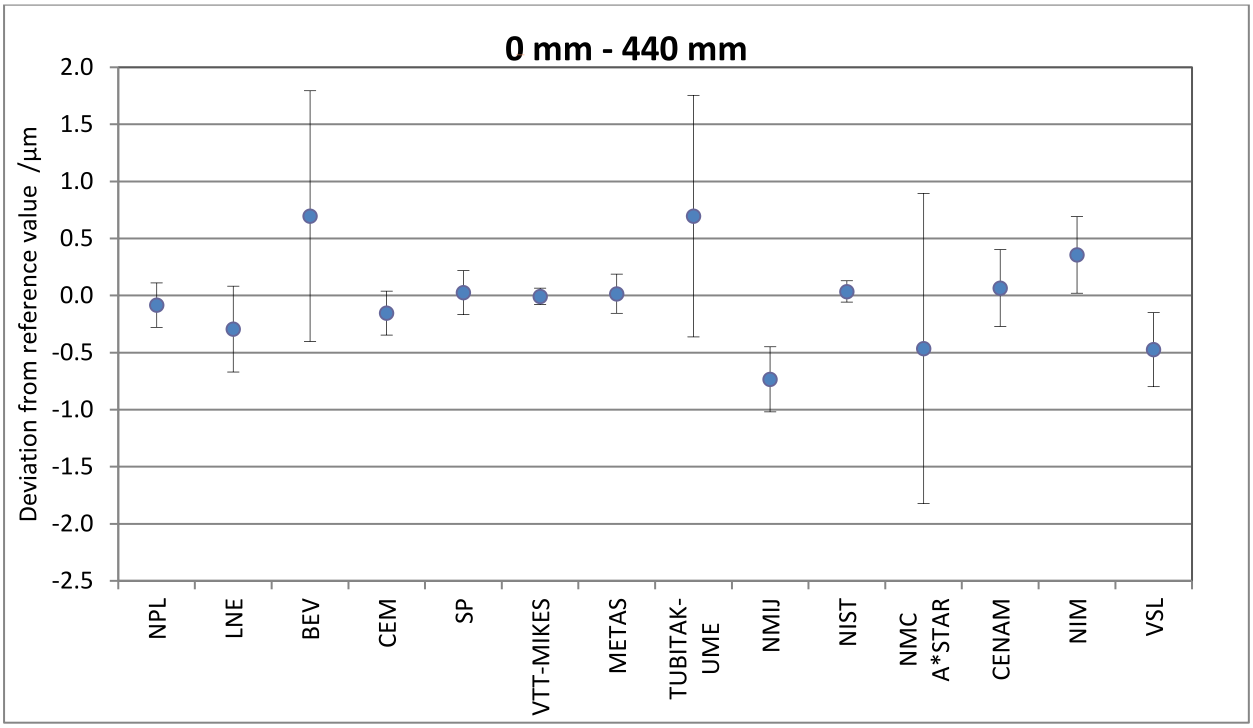


Figure 27: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

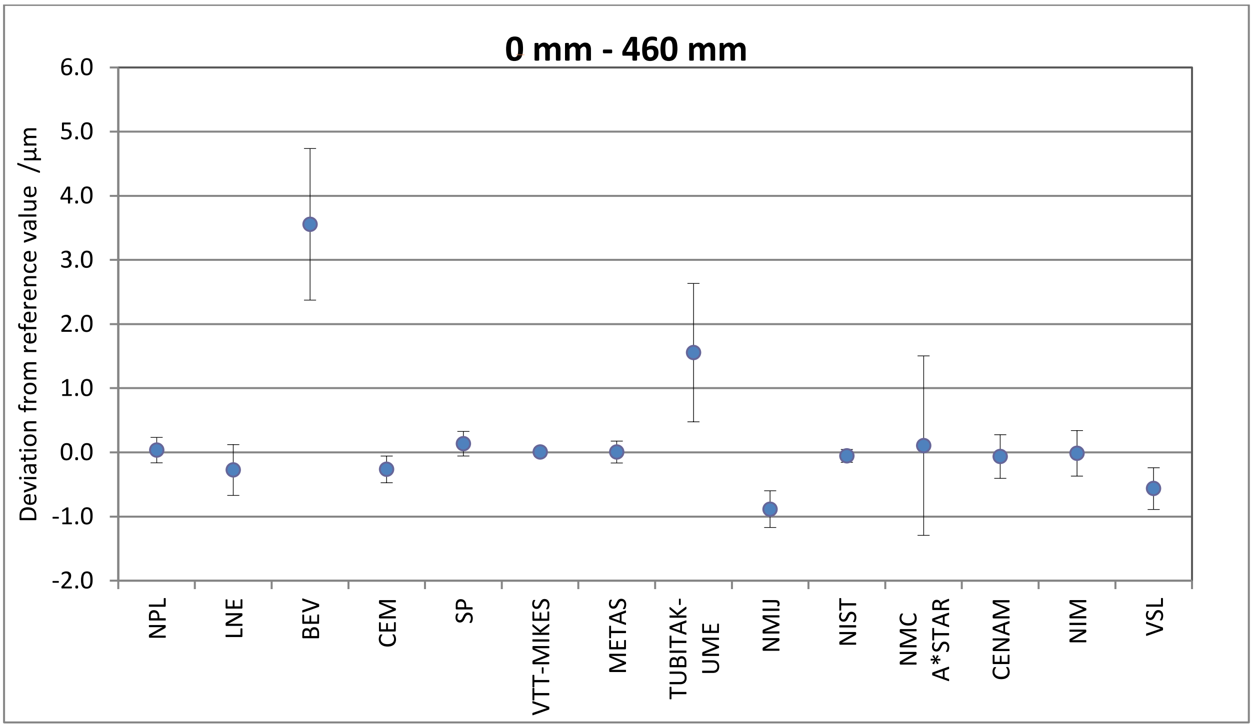


Figure 28: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

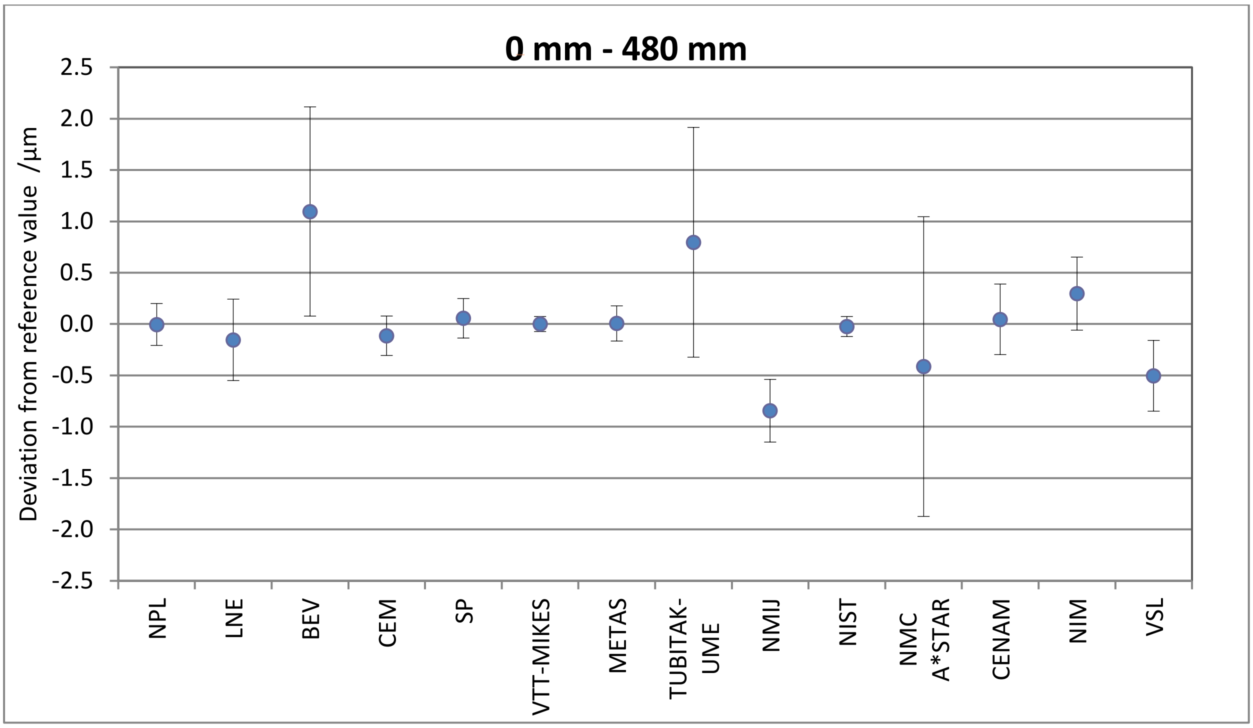


Figure 29: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

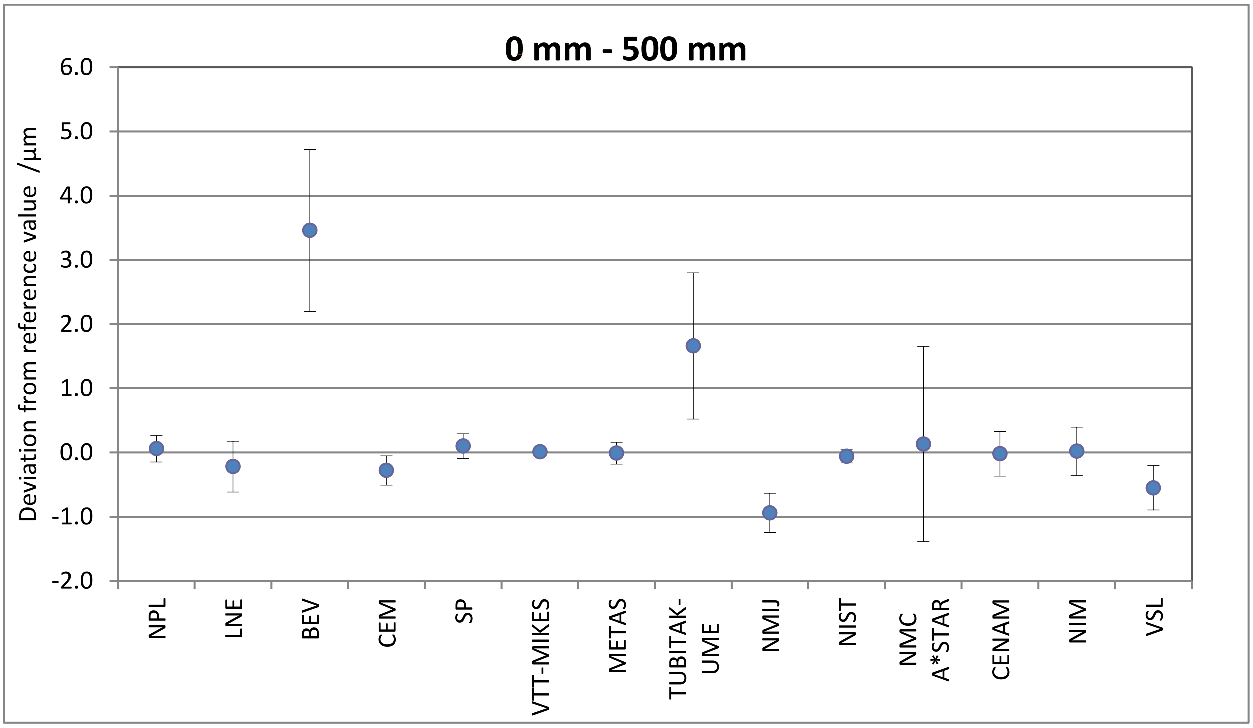


Figure 30: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

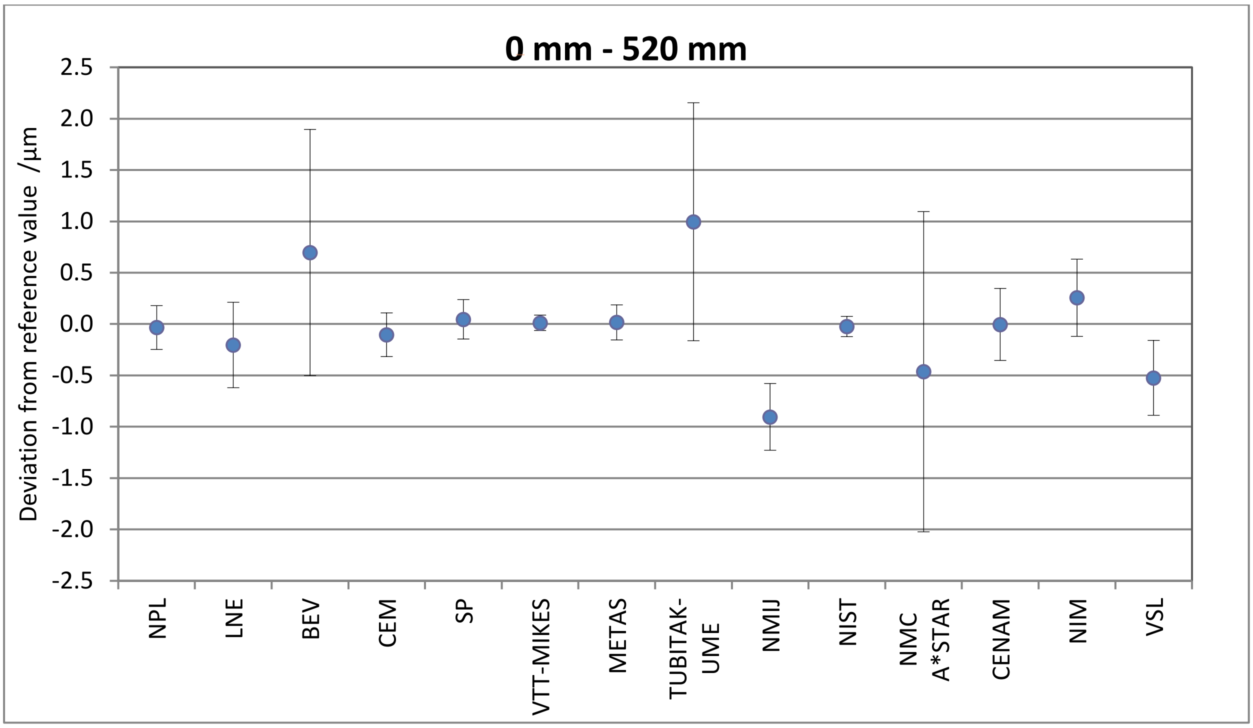


Figure 31: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

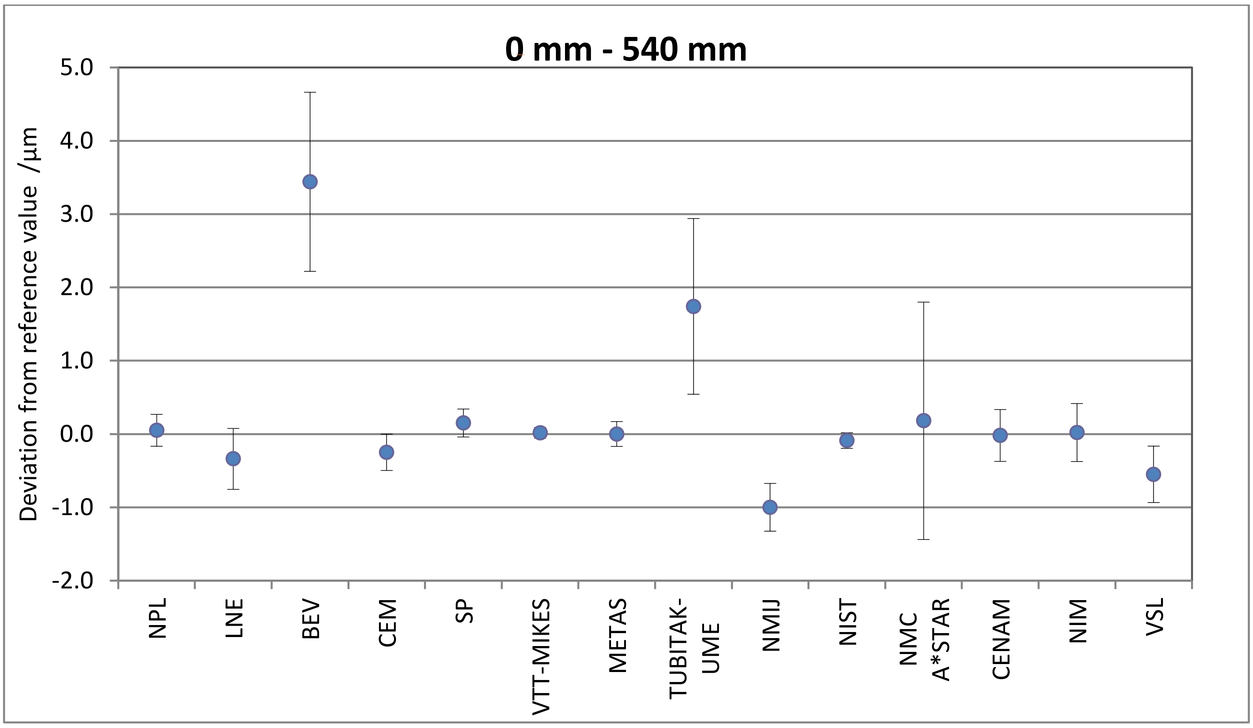


Figure 32: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

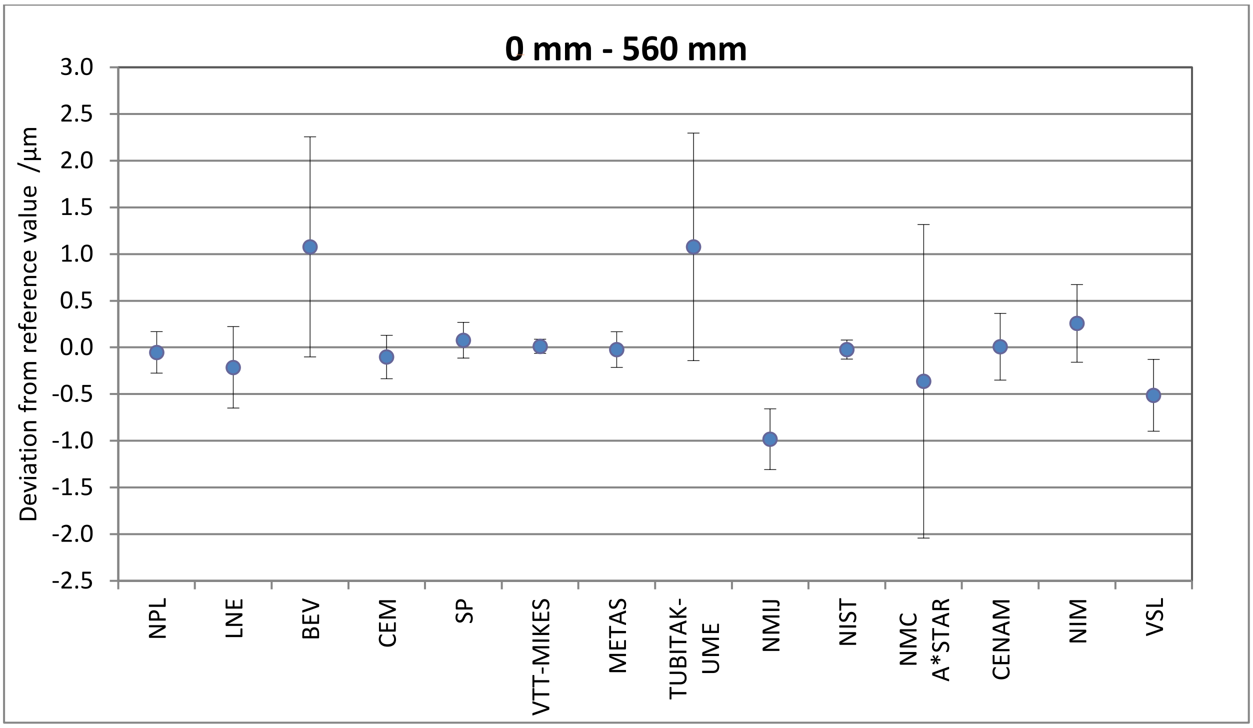


Figure 33: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

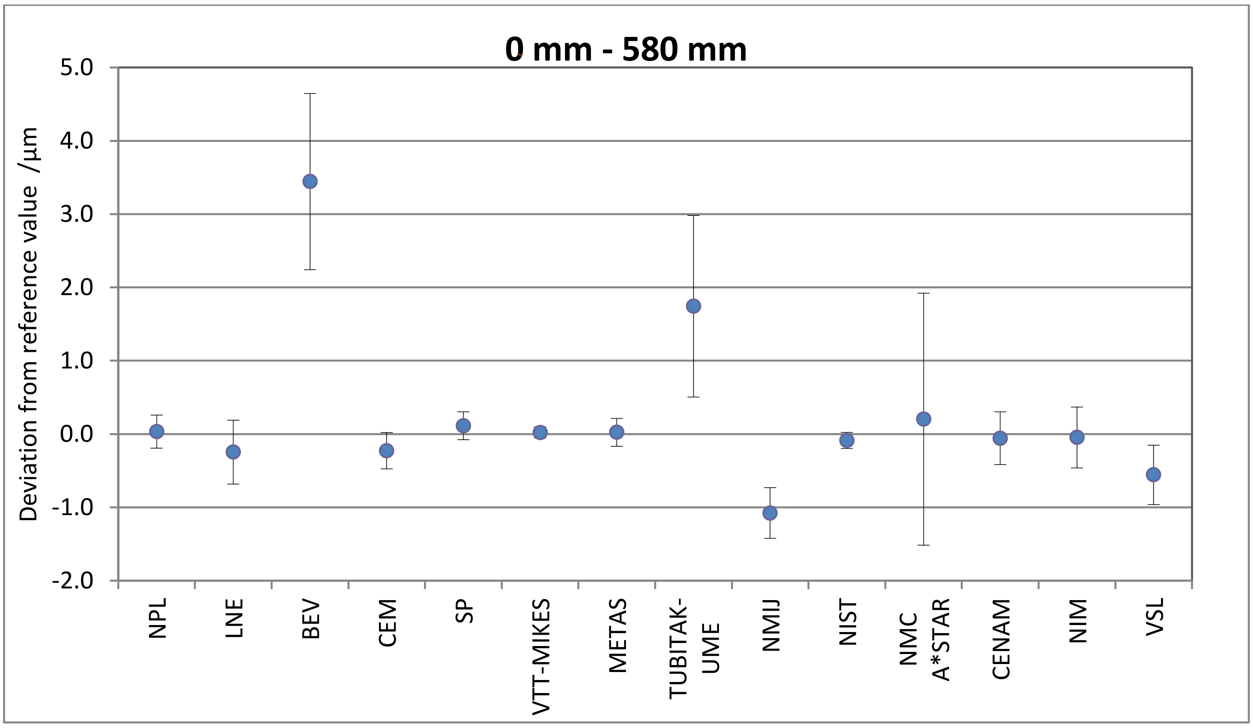


Figure 34: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

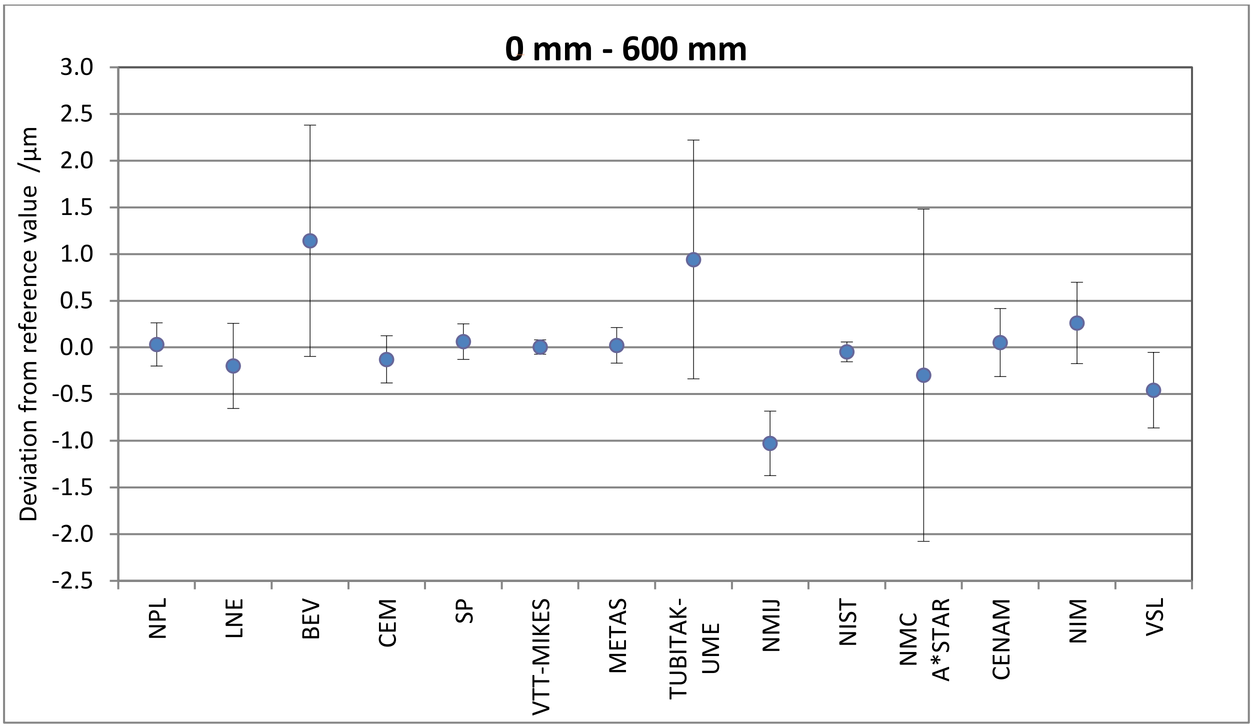


Figure 35: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

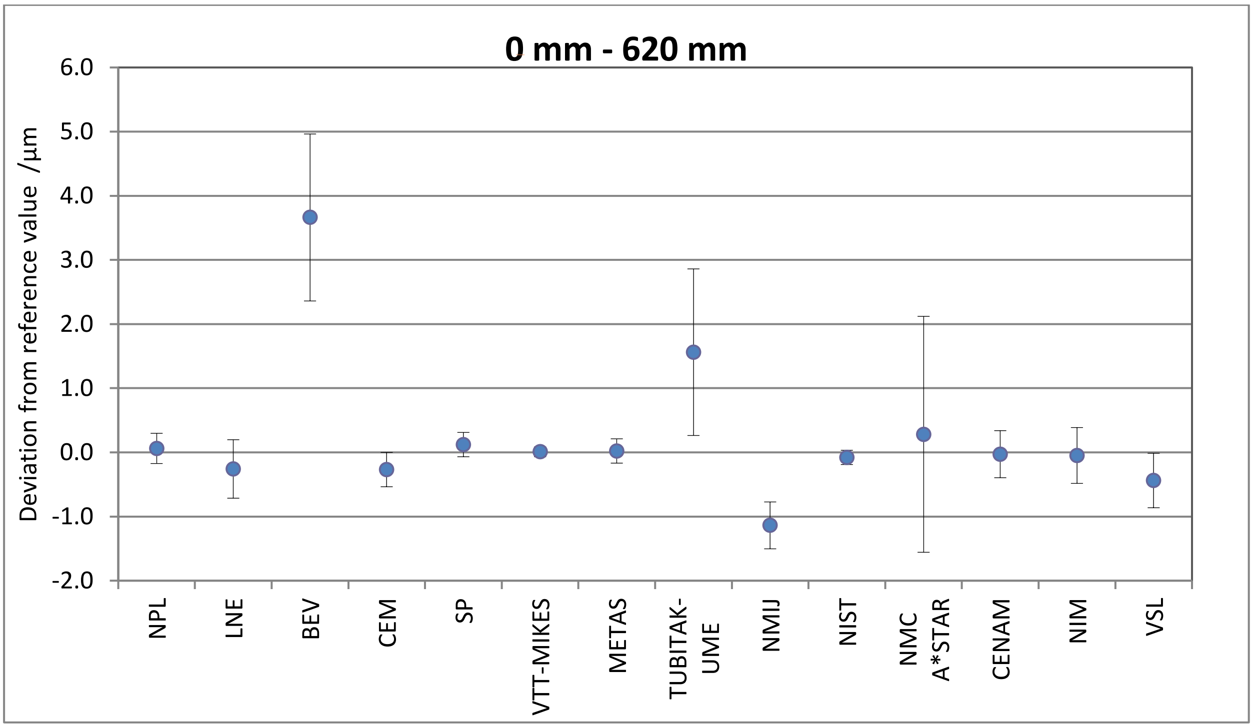


Figure 36: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

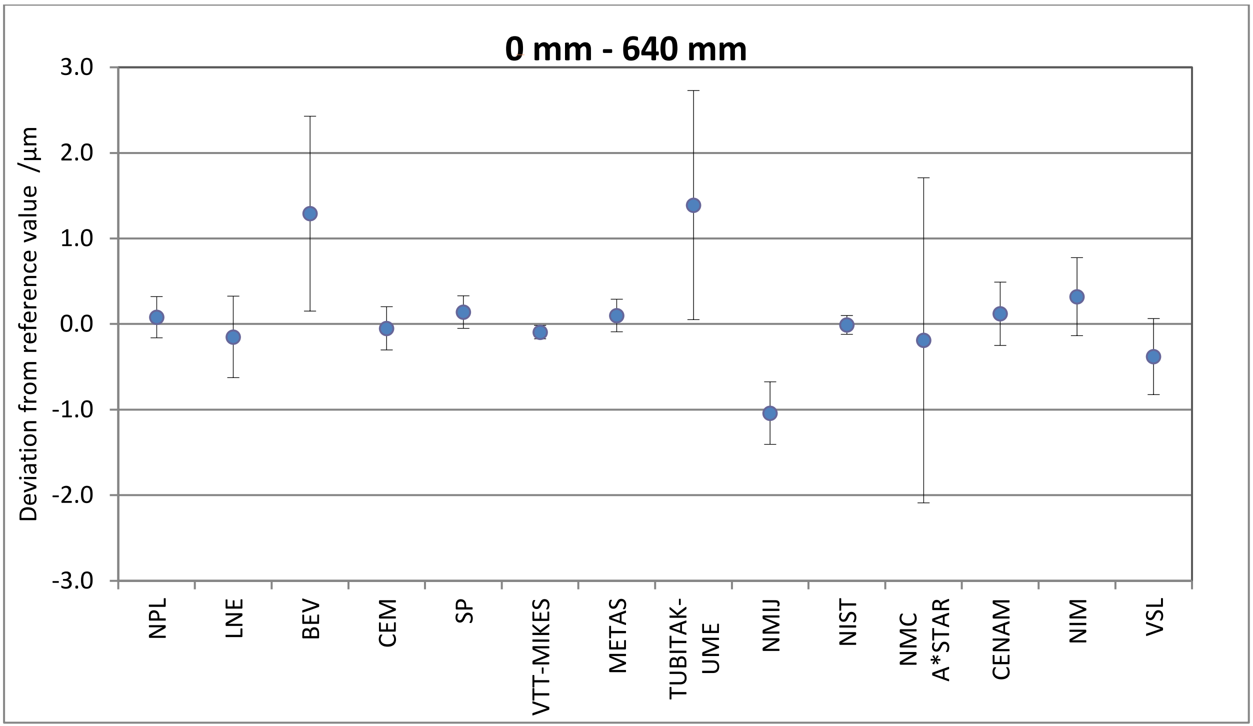


Figure 37: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

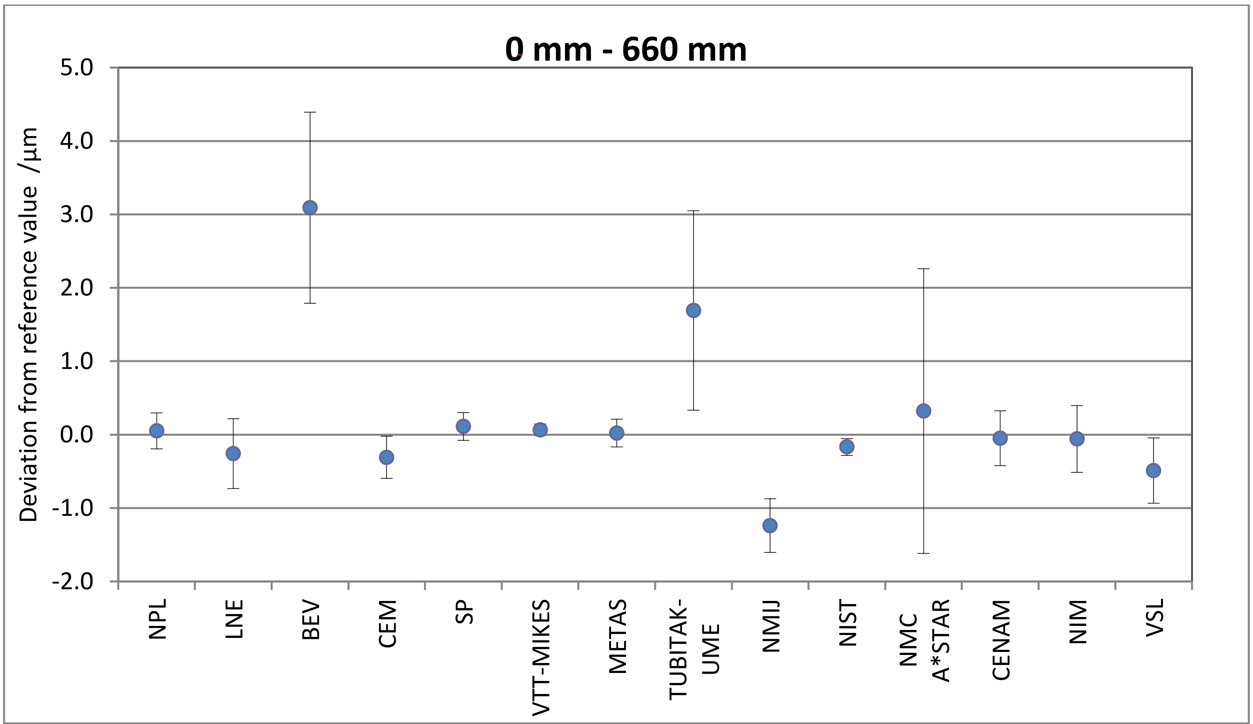


Figure 38: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

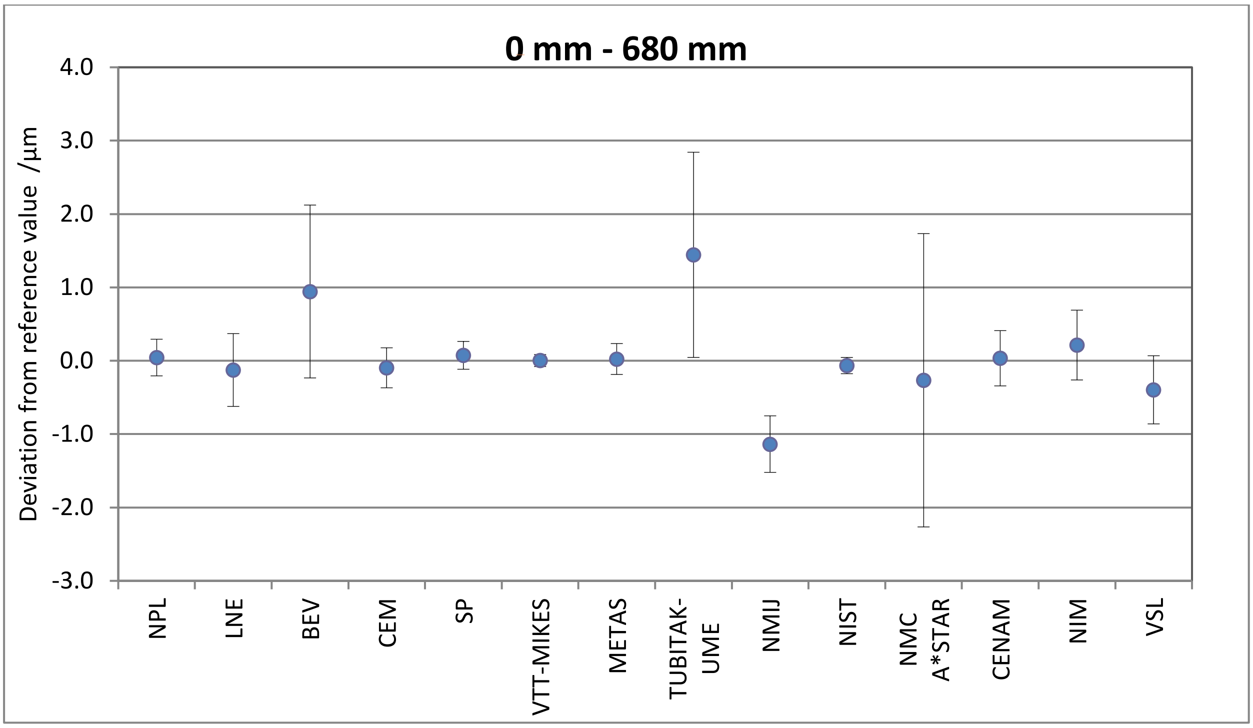


Figure 39: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

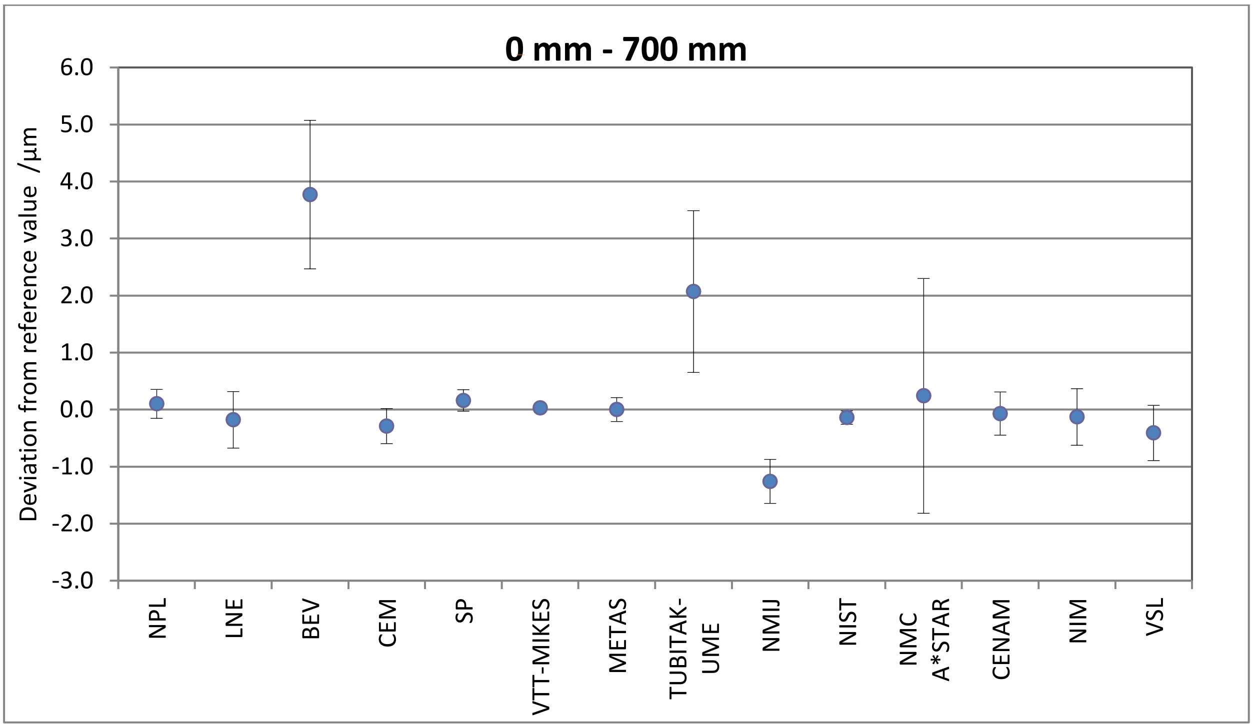


Figure 40: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

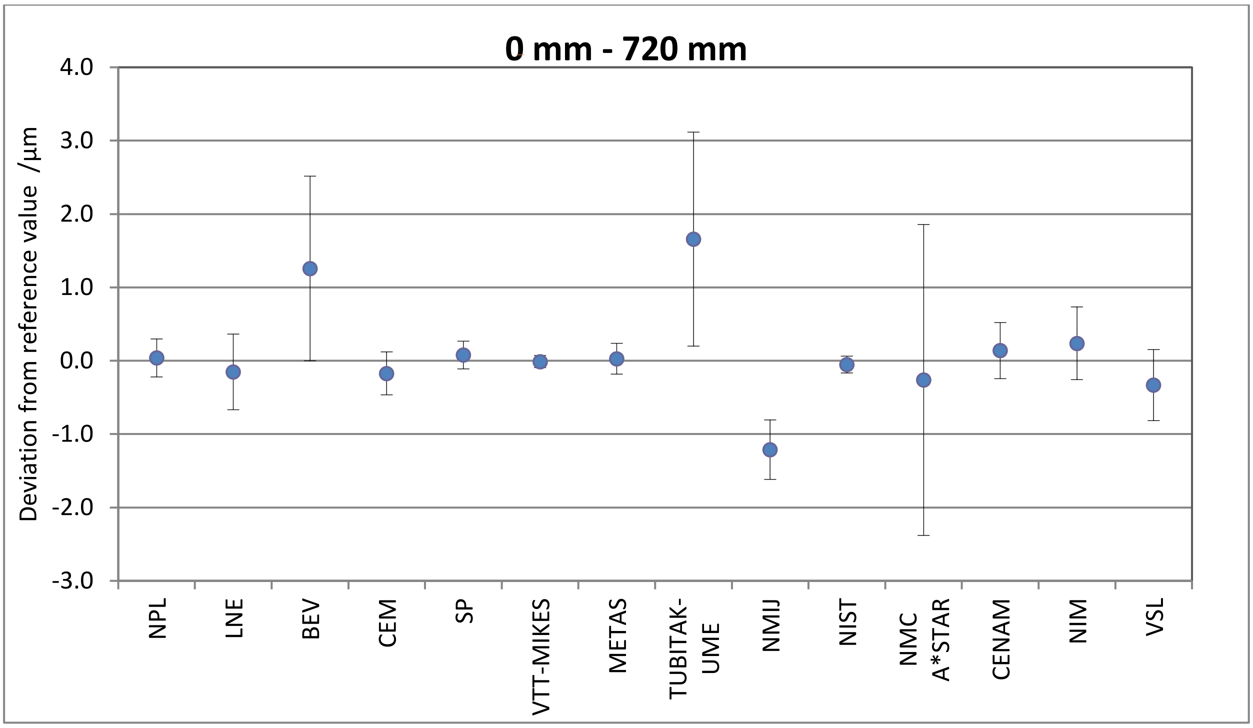


Figure 41: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

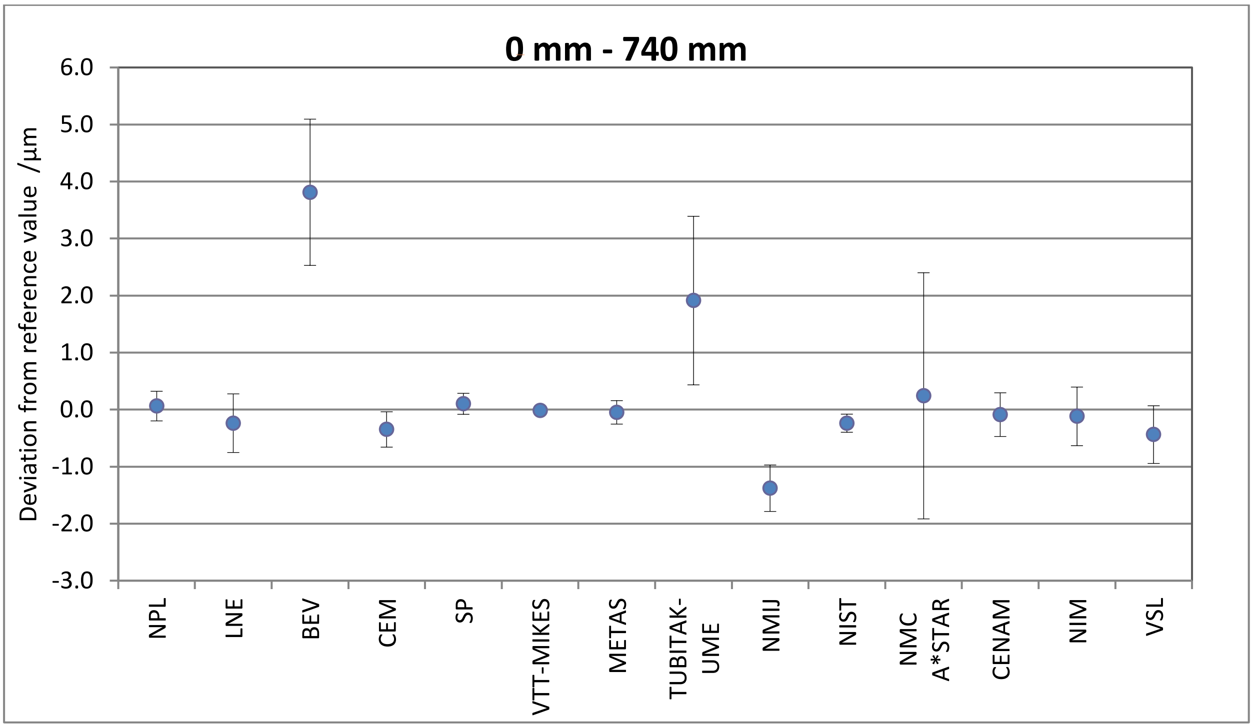


Figure 42: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

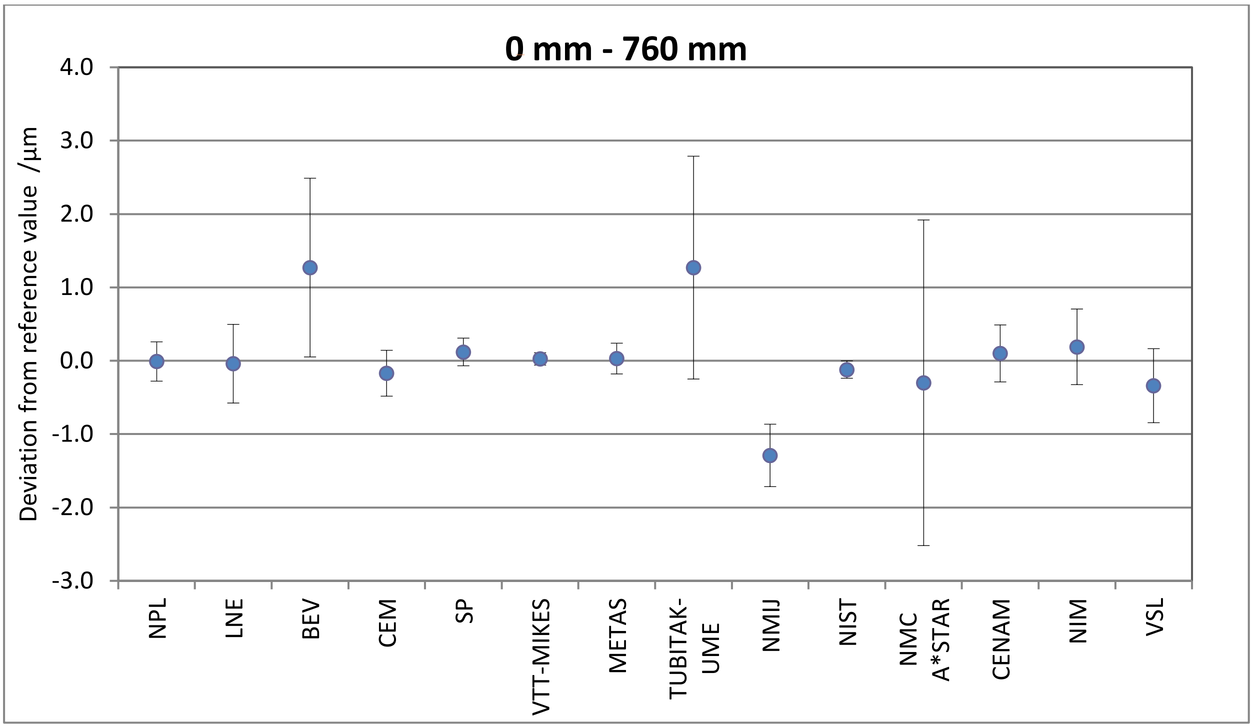


Figure 43: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

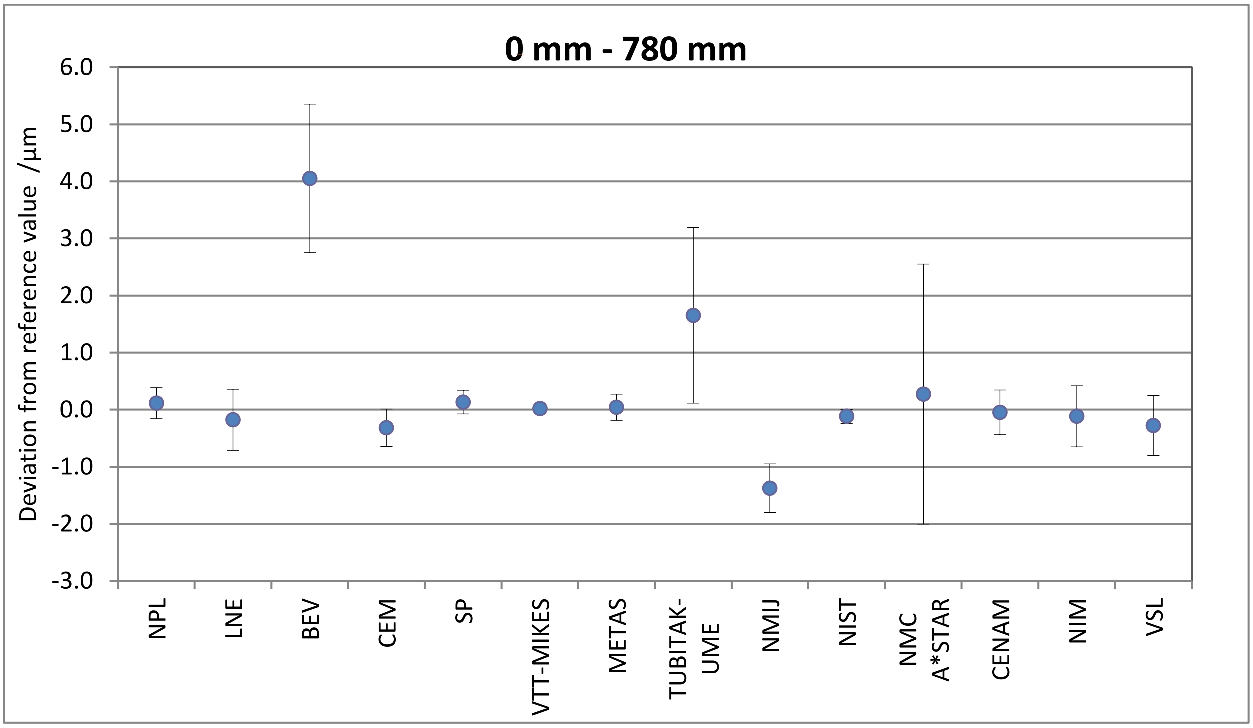


Figure 44: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

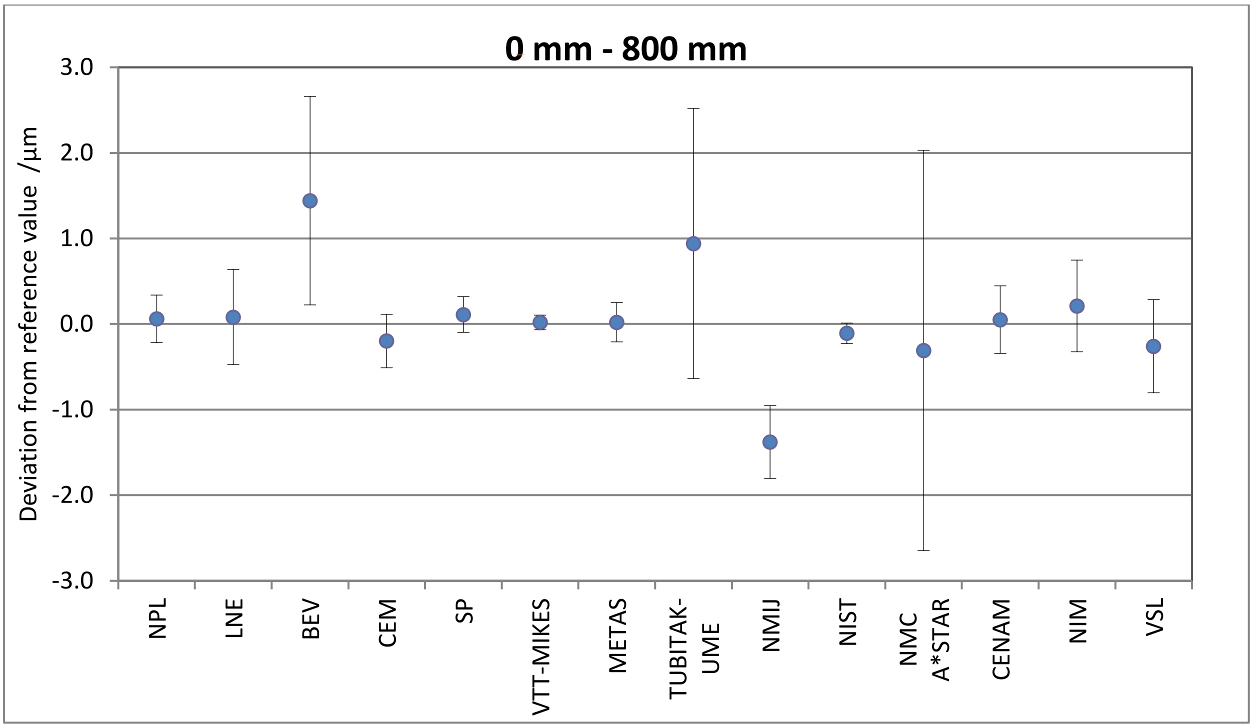


Figure 45: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

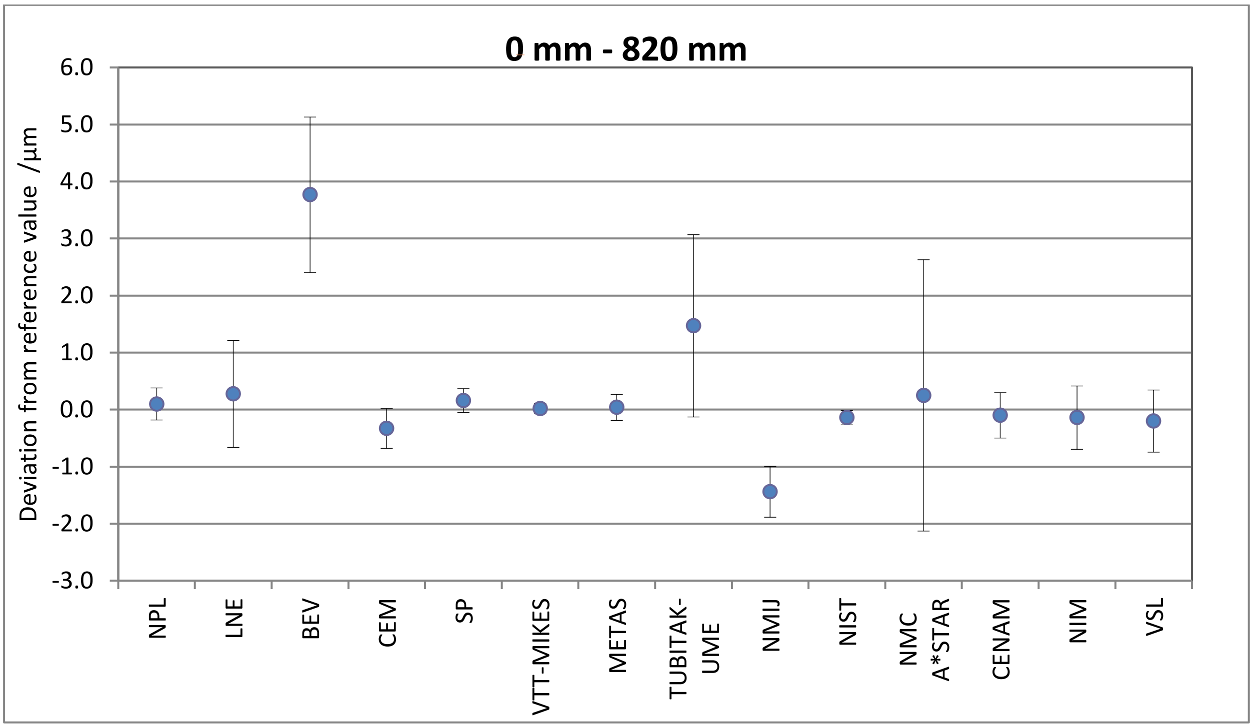


Figure 46: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

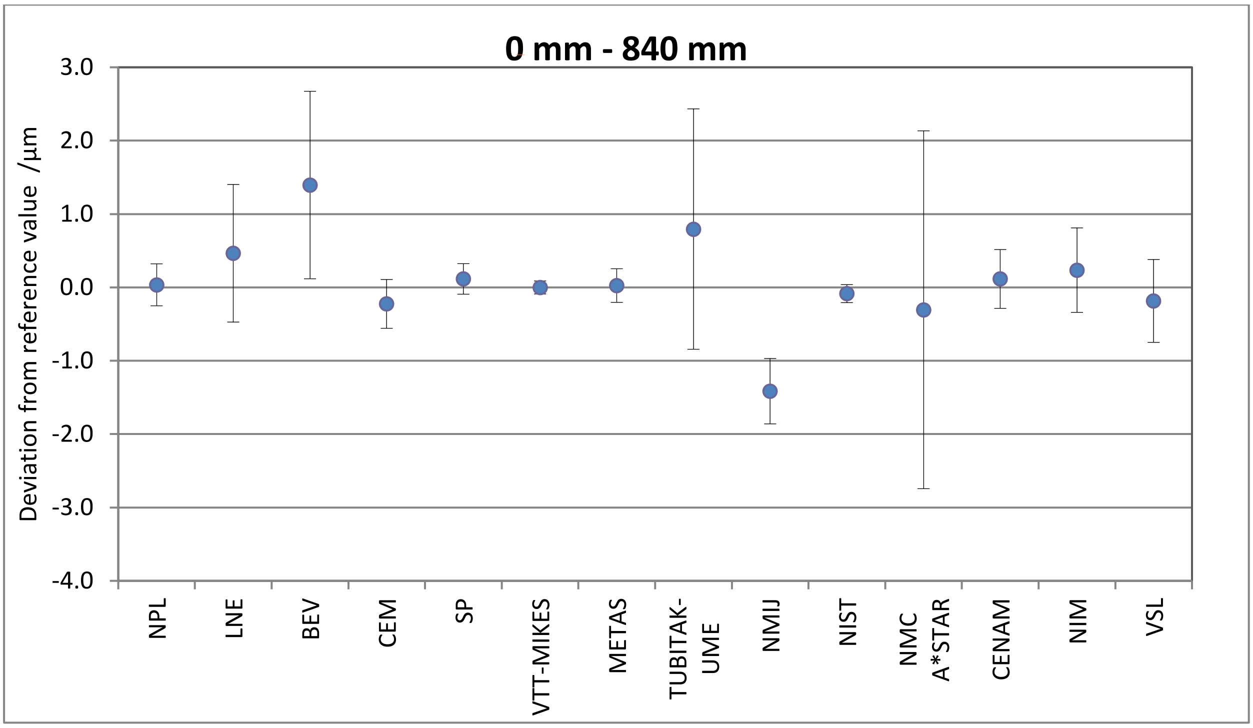


Figure 47: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

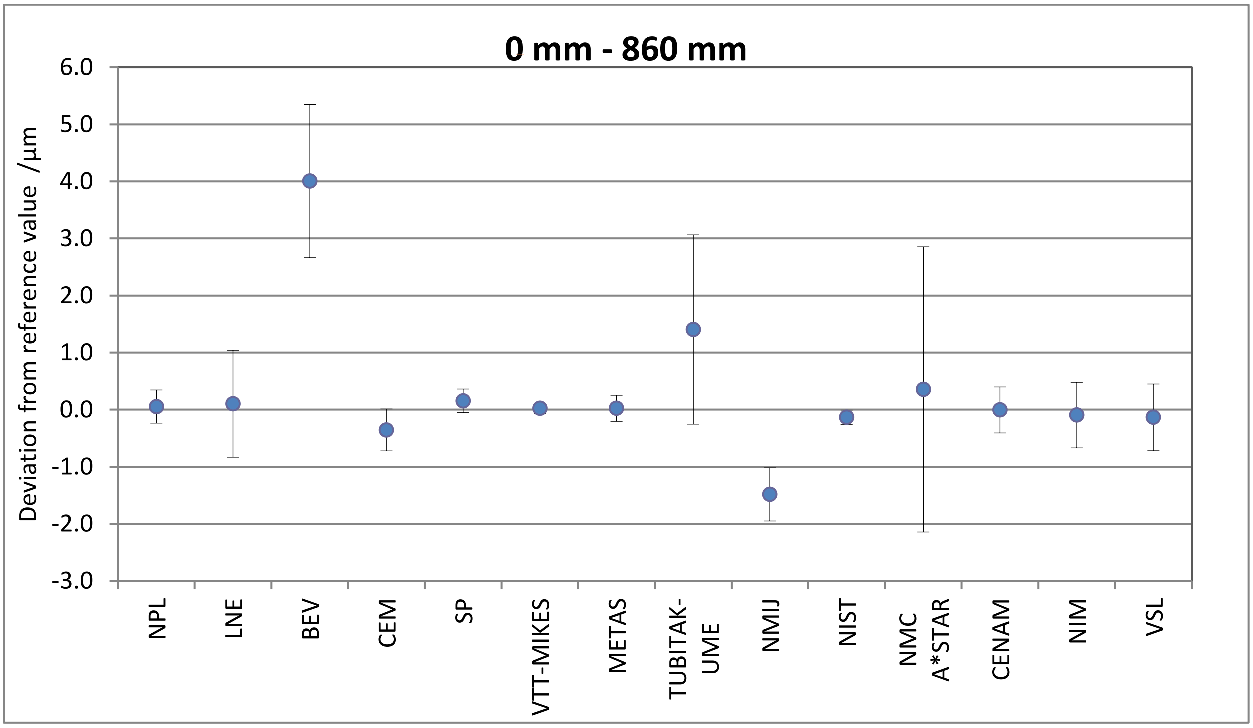


Figure 48: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

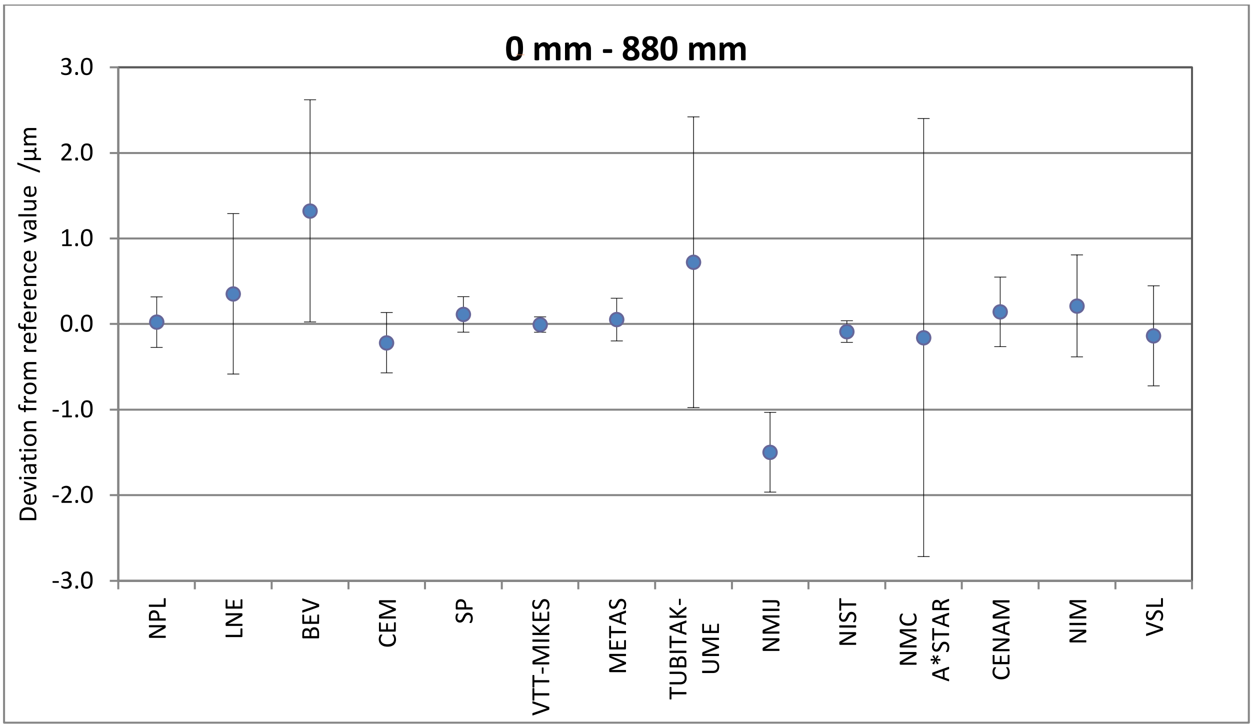


Figure 49: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

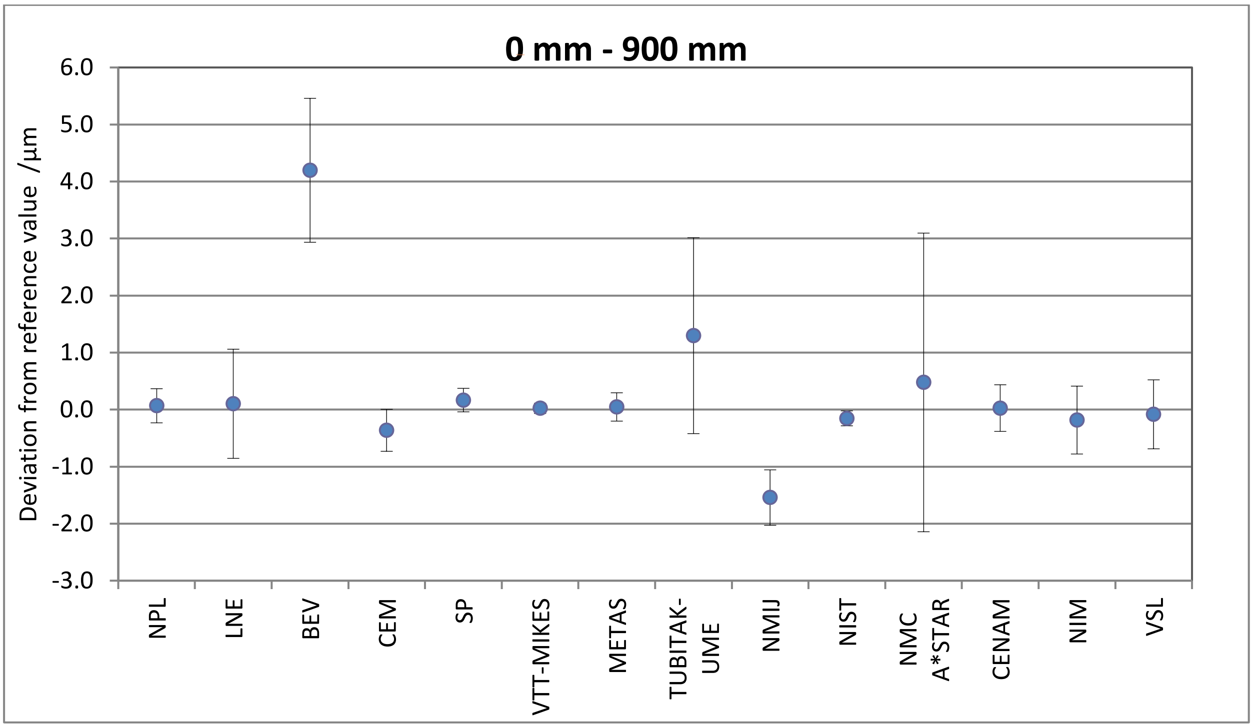


Figure 50: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

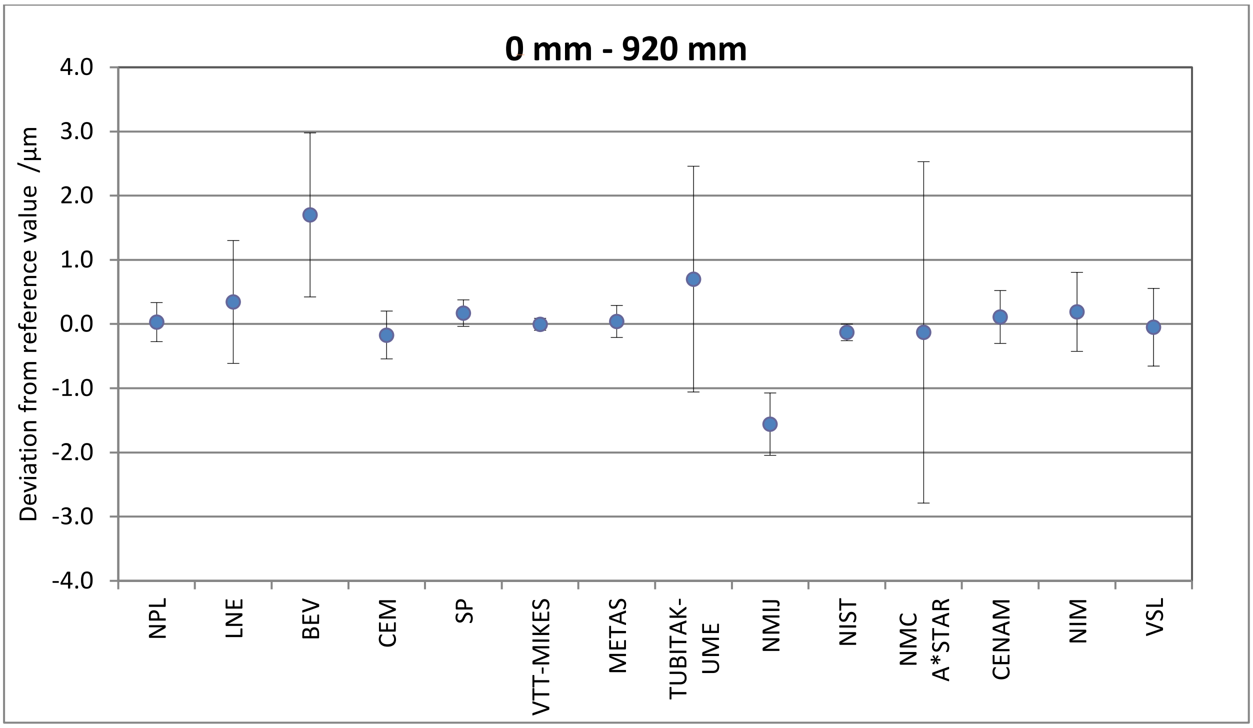


Figure 51: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

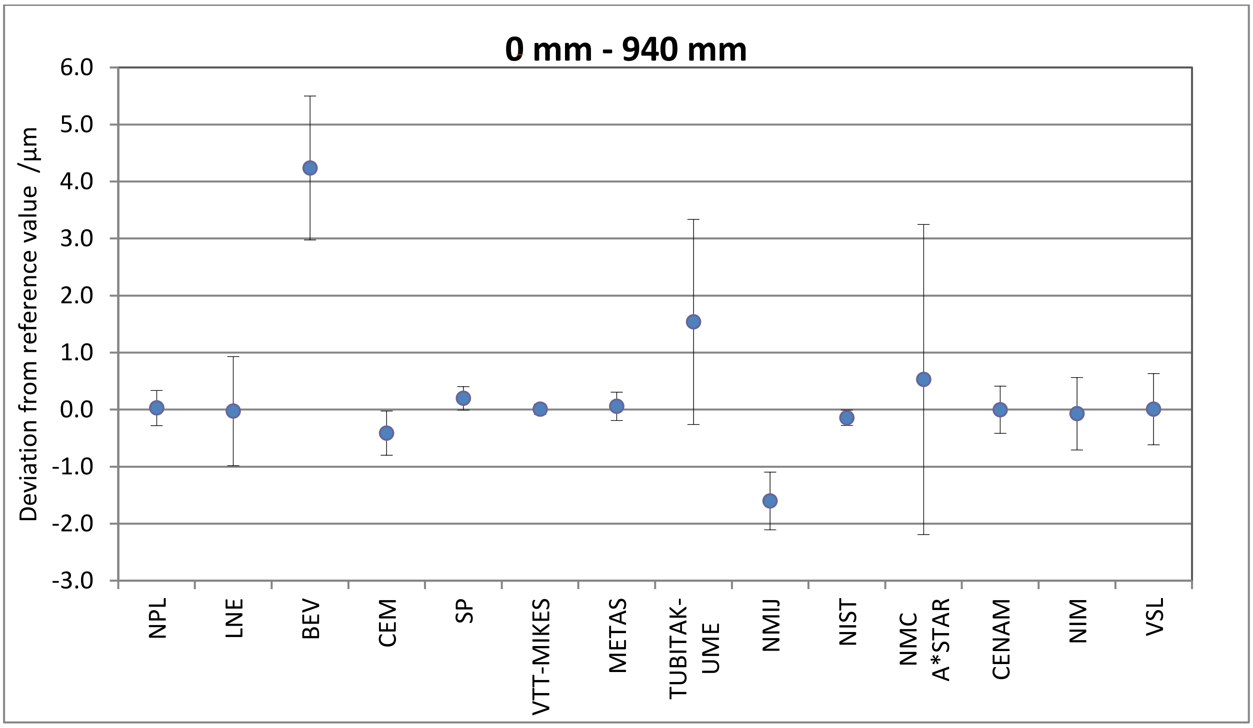


Figure 52: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

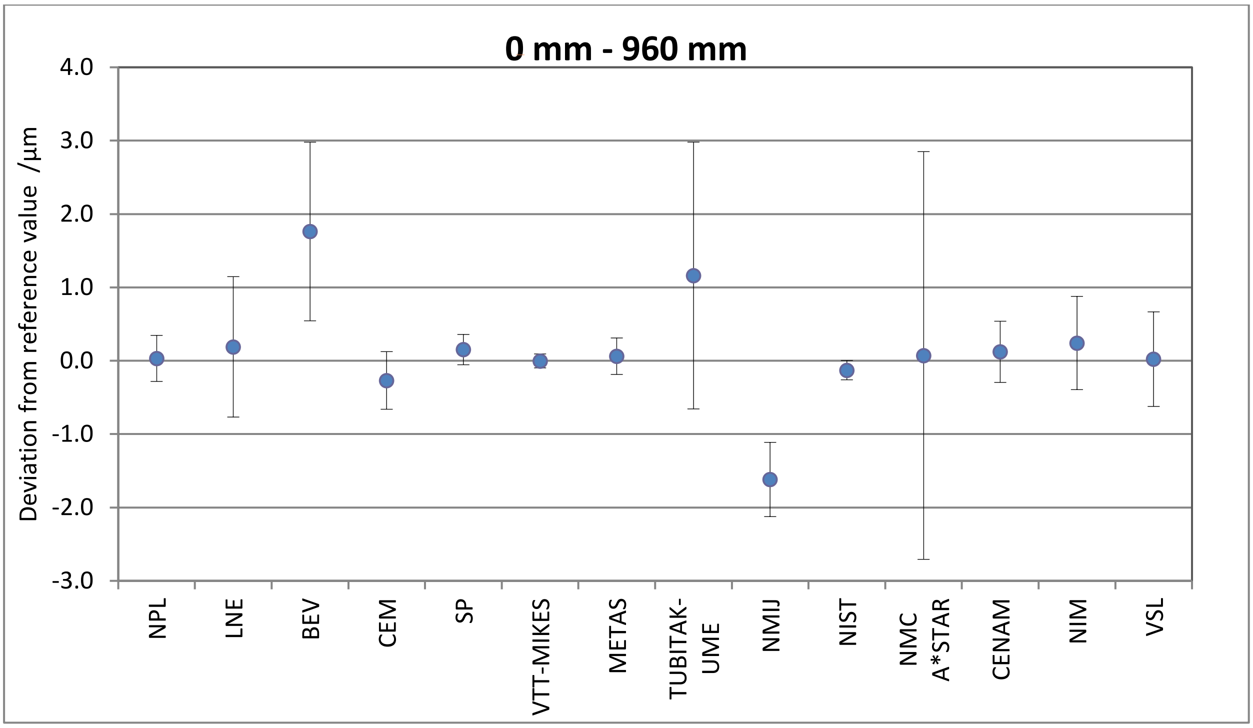


Figure 53: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

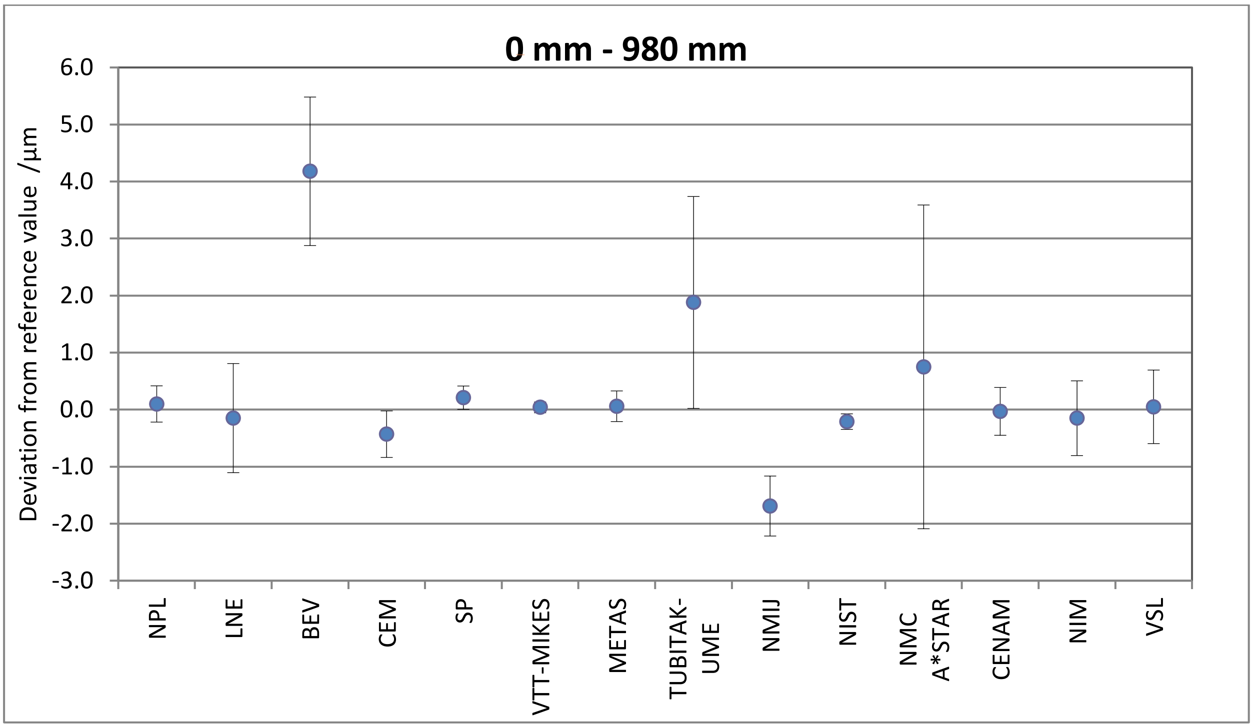


Figure 54: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

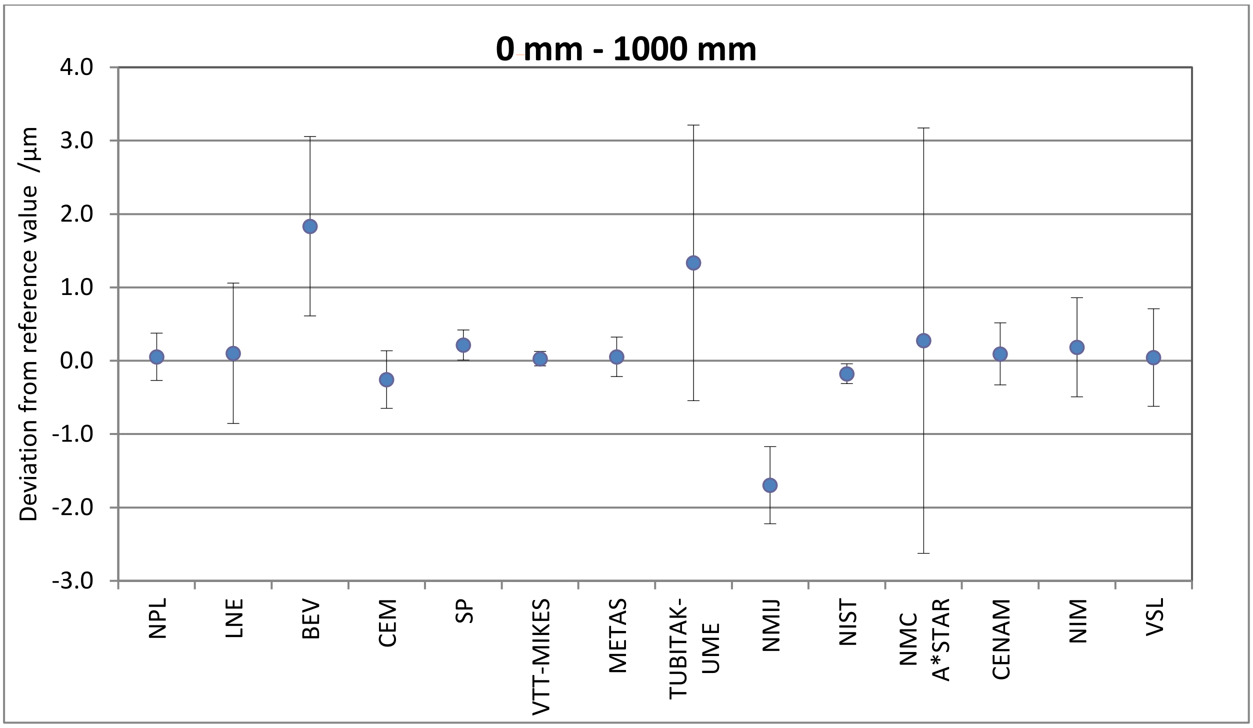


Figure 55: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

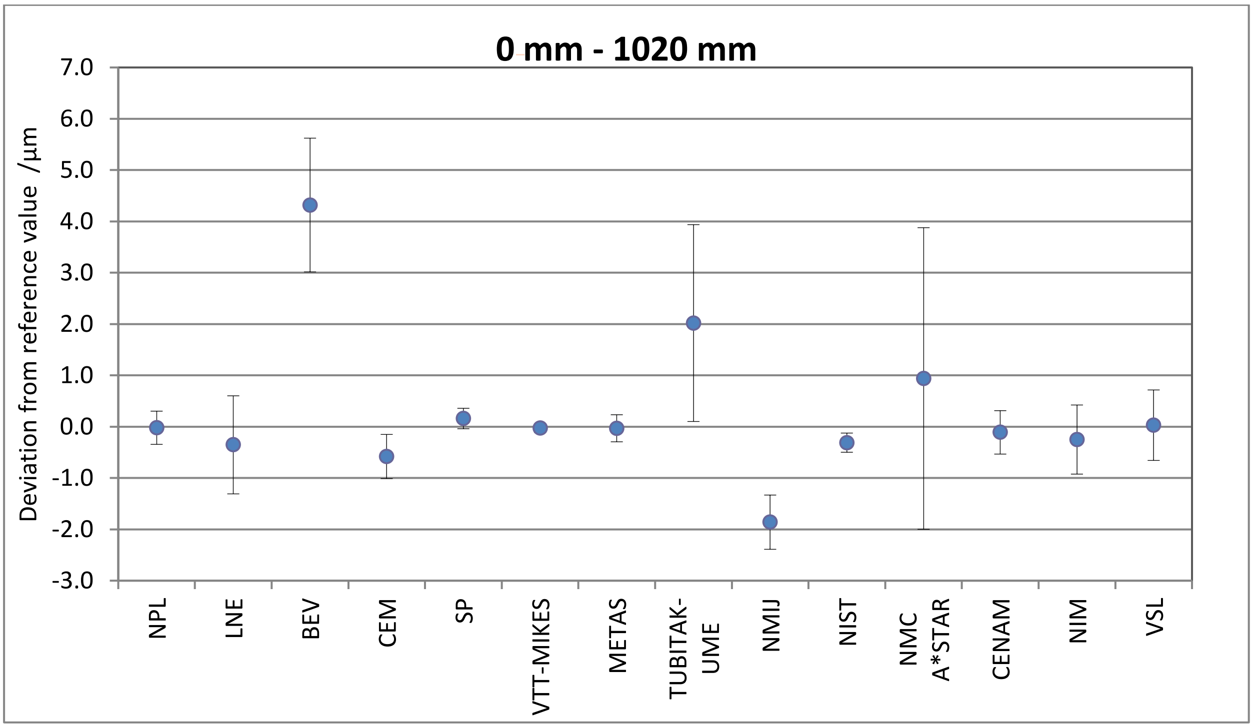


Figure 56: 1020 mm artefact, participant deviations from KCRV for this interval (*k* = 2)

6.3.6 Participant deviations by length

6.3.6.1 NPL

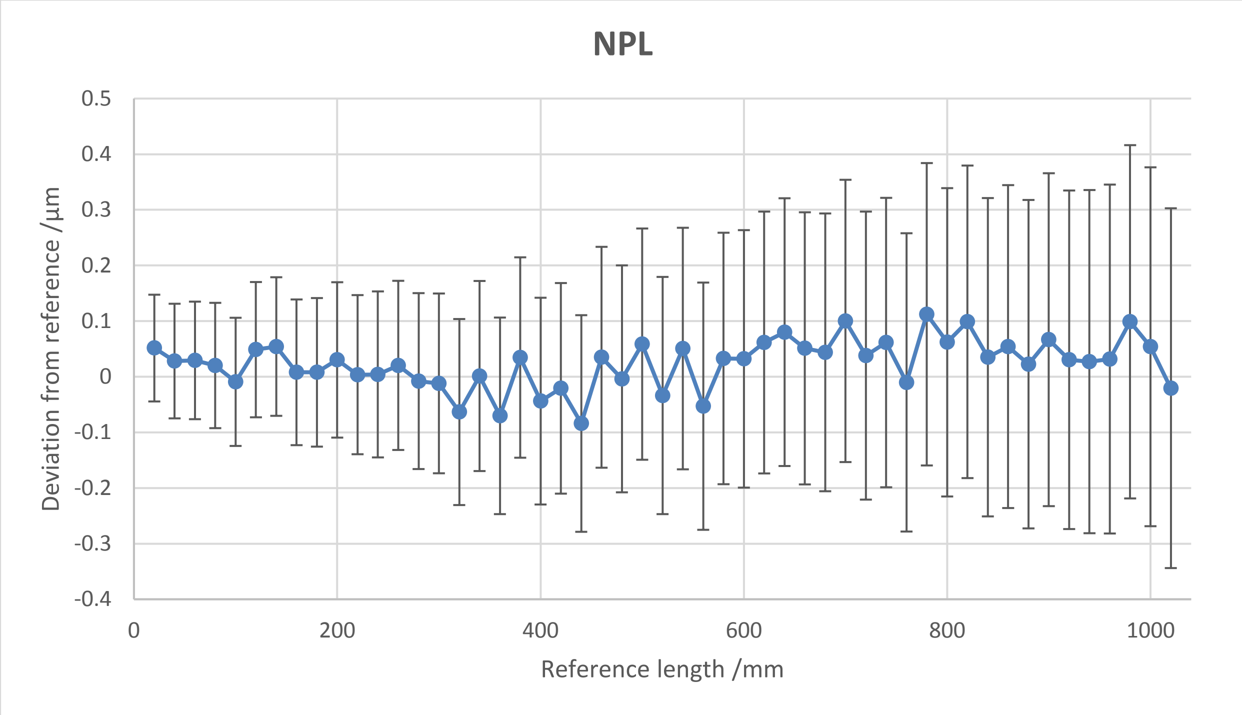


Figure 57

6.3.6.2 LNE

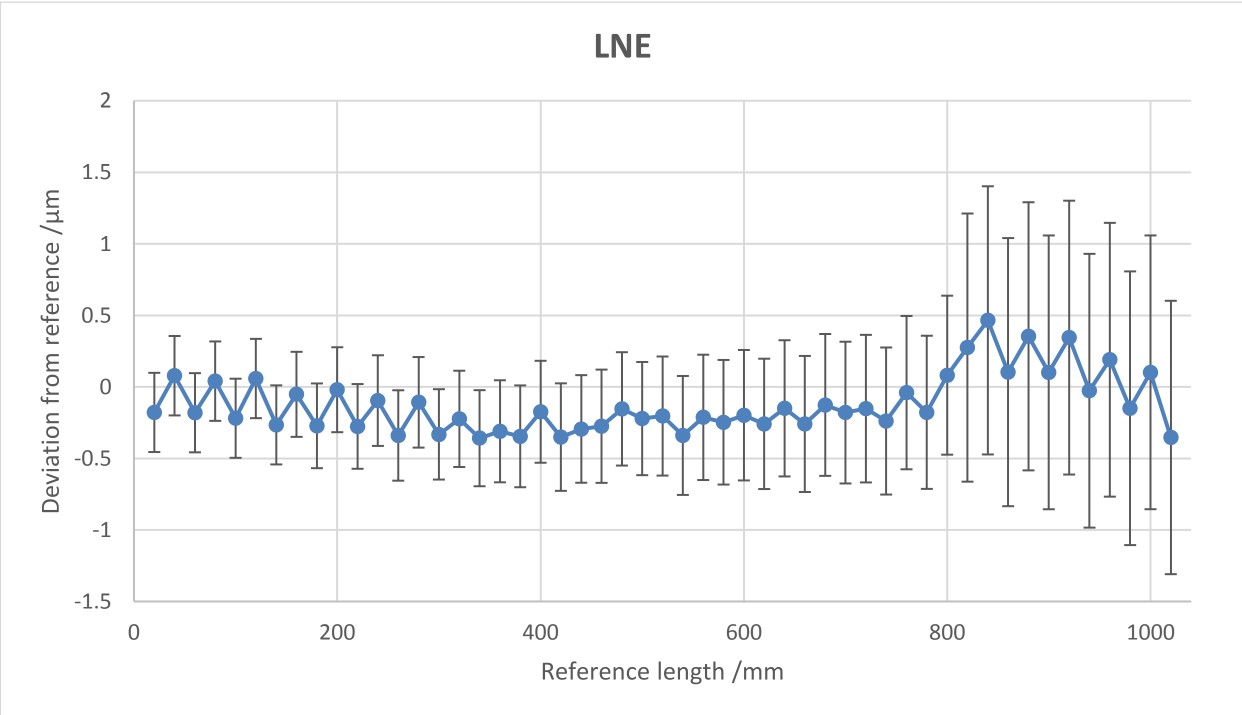


Figure 58

6.3.6.3 BEV

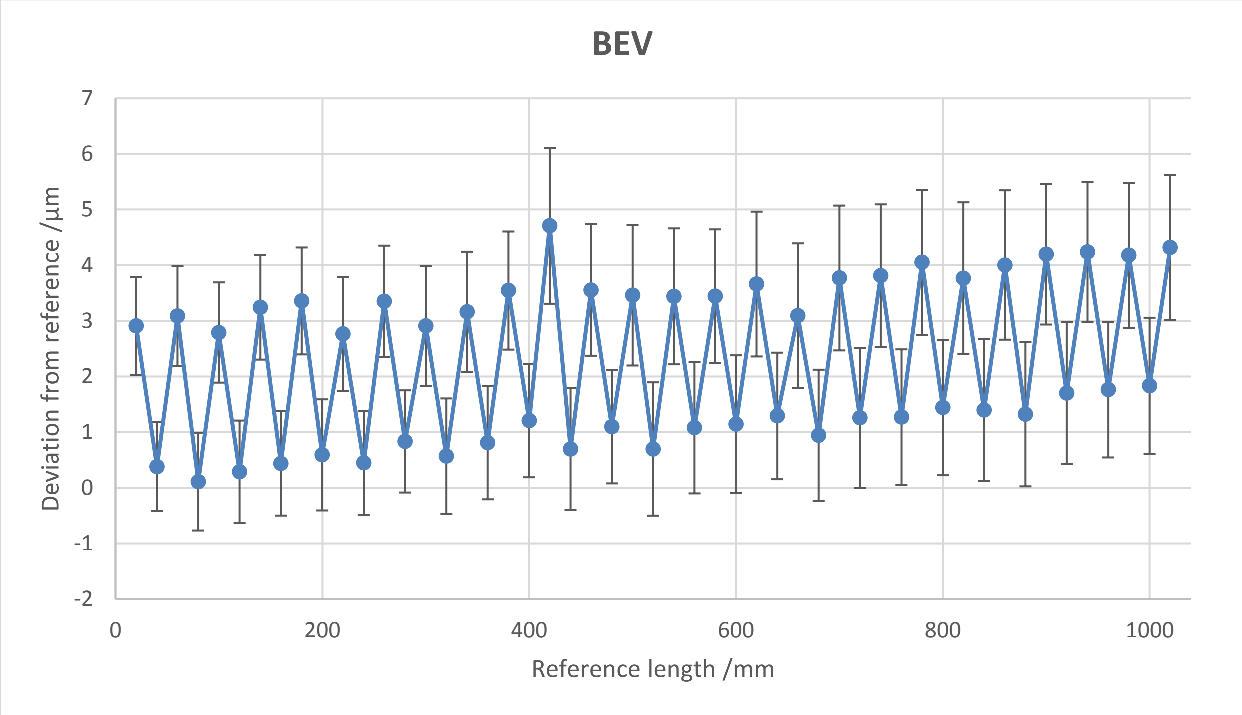


Figure 59

6.3.6.4 CEM

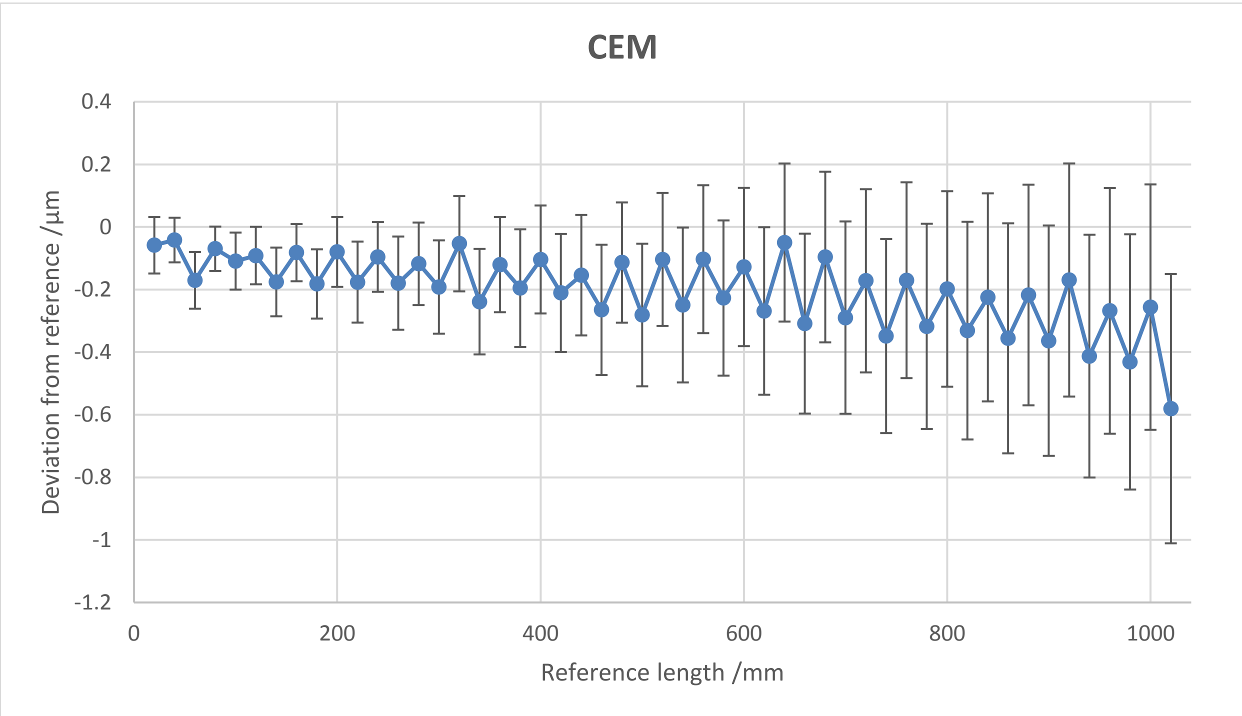


Figure 60

6.3.6.5 SP

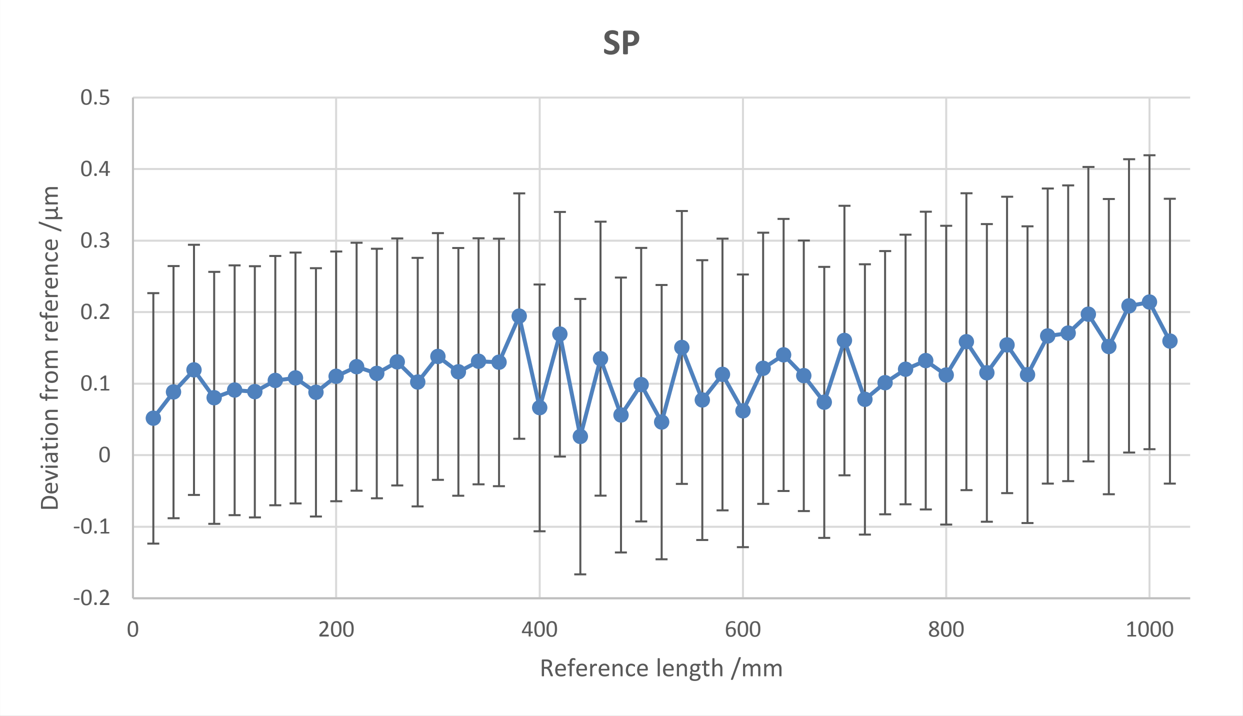


Figure 61

6.3.6.6 VTT MIKES

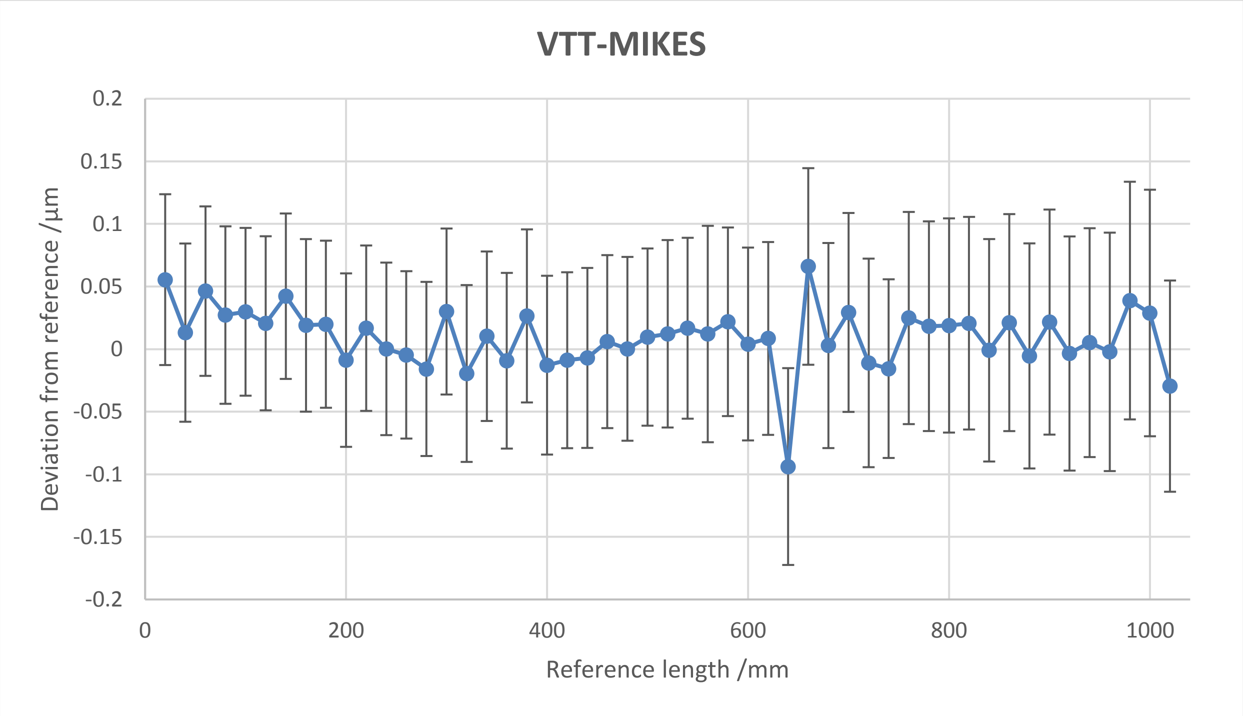


Figure 62

6.3.6.7 METAS

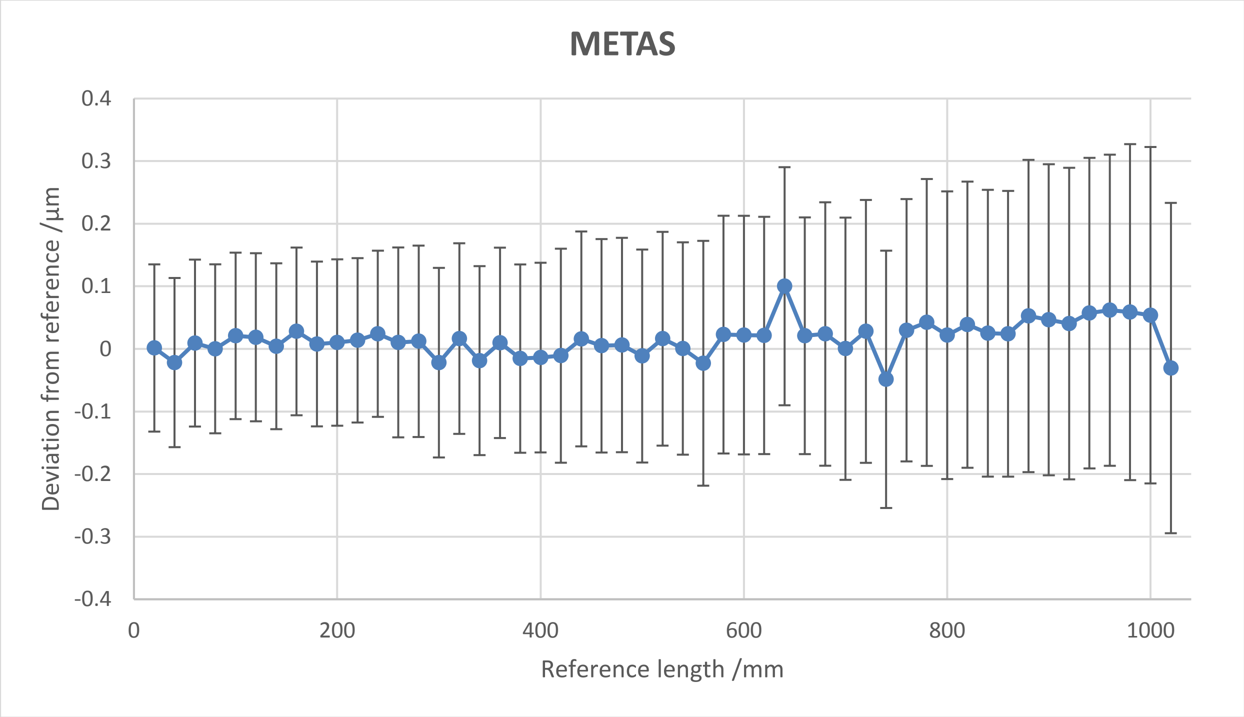


Figure 63

6.3.6.8 VSL

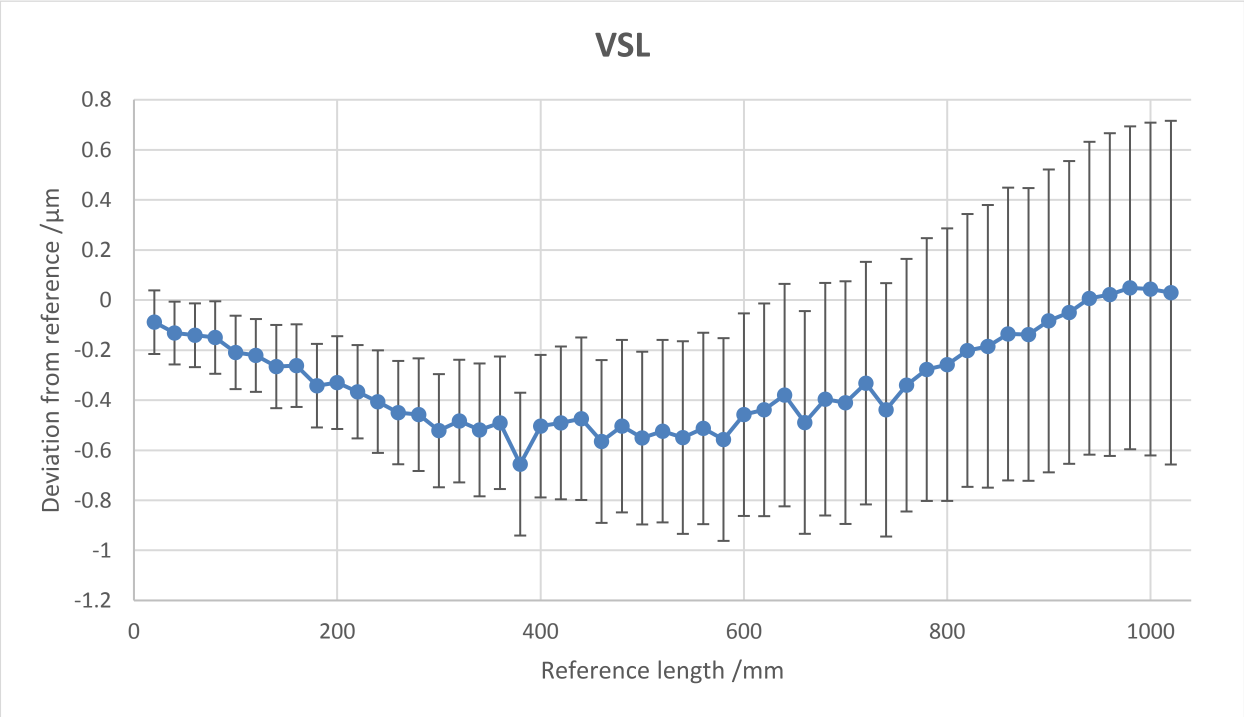


Figure 64

6.3.6.9 TUBITAK-UME

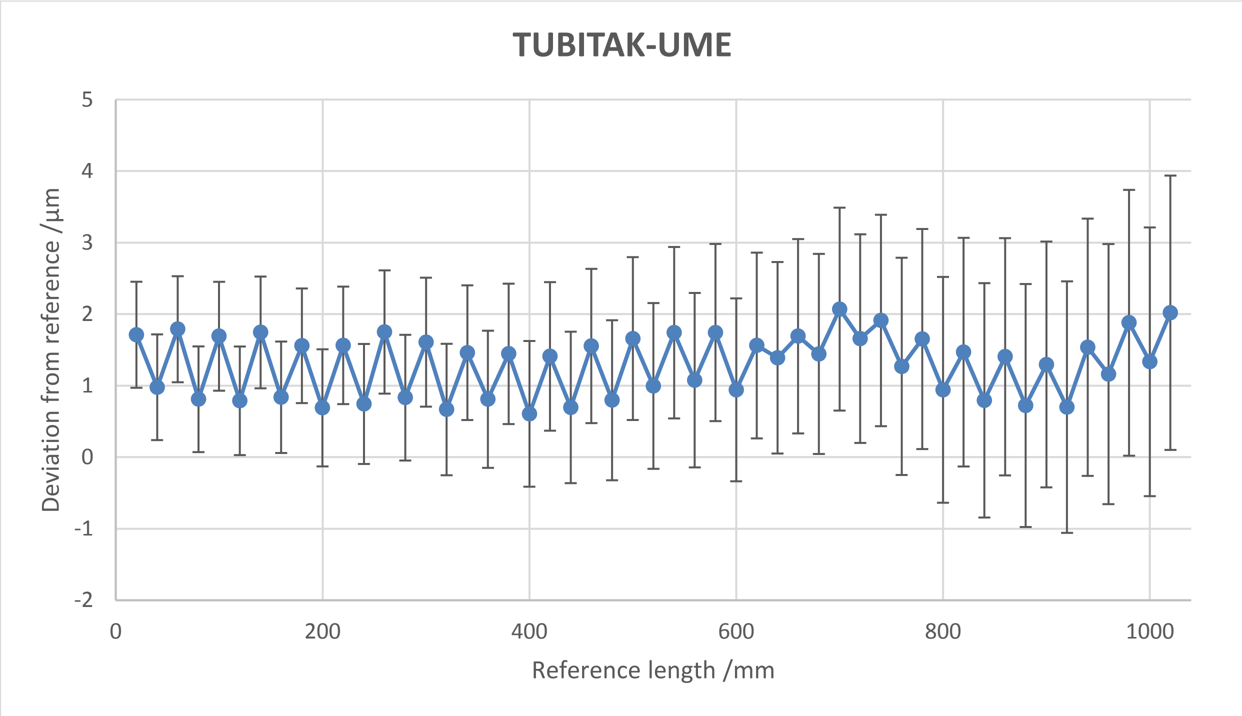


Figure 65

6.3.6.10 NMIJ

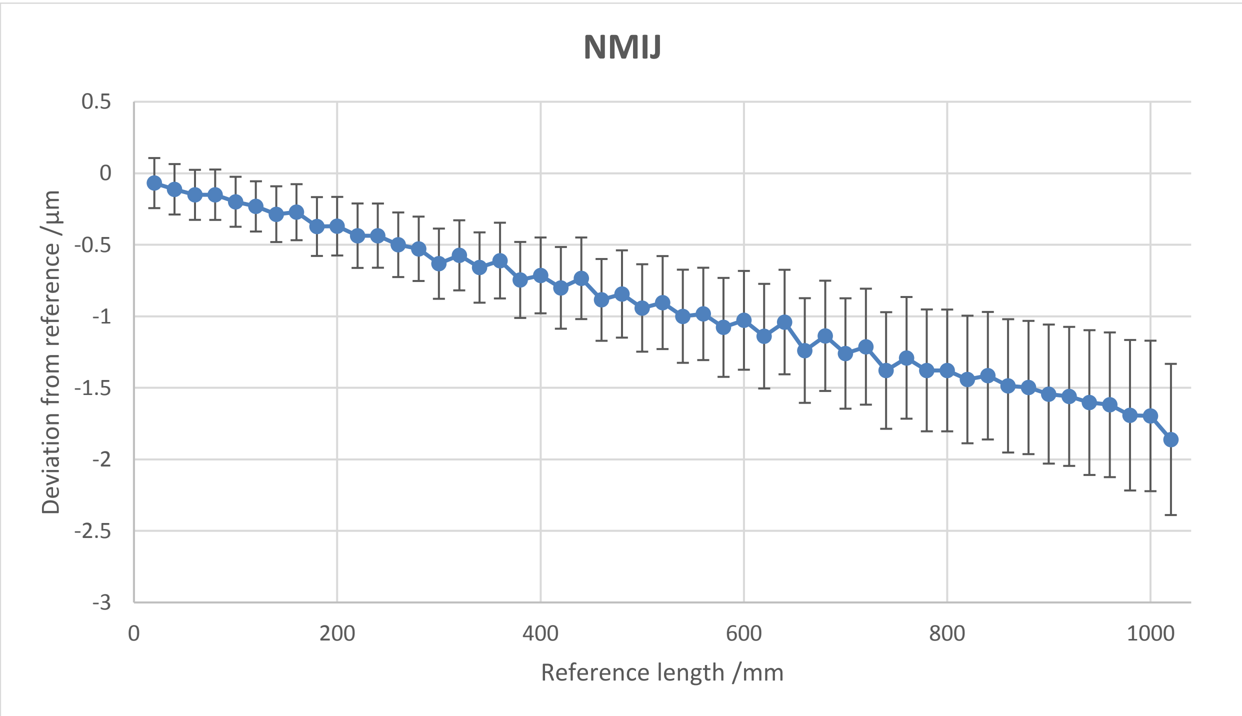


Figure 66

6.3.6.11 NIST

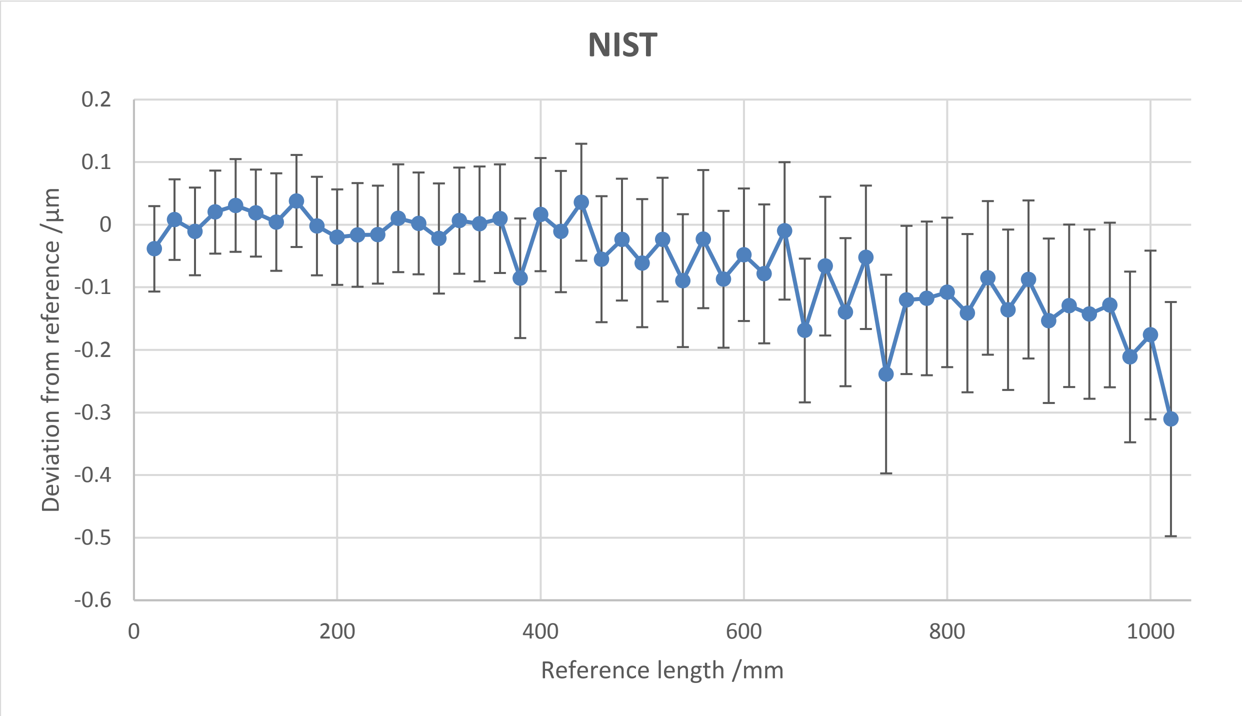


Figure 67

6.3.6.12 NMC A*STAR

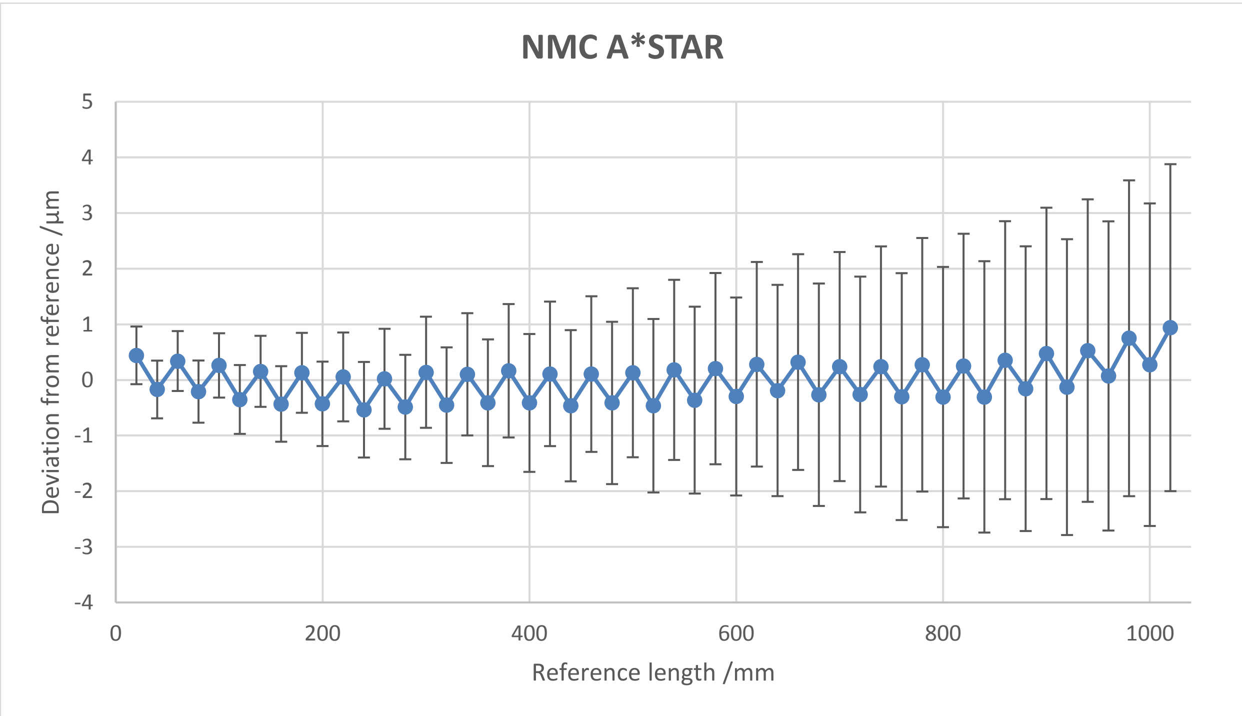


Figure 68

6.3.6.13 CENAM

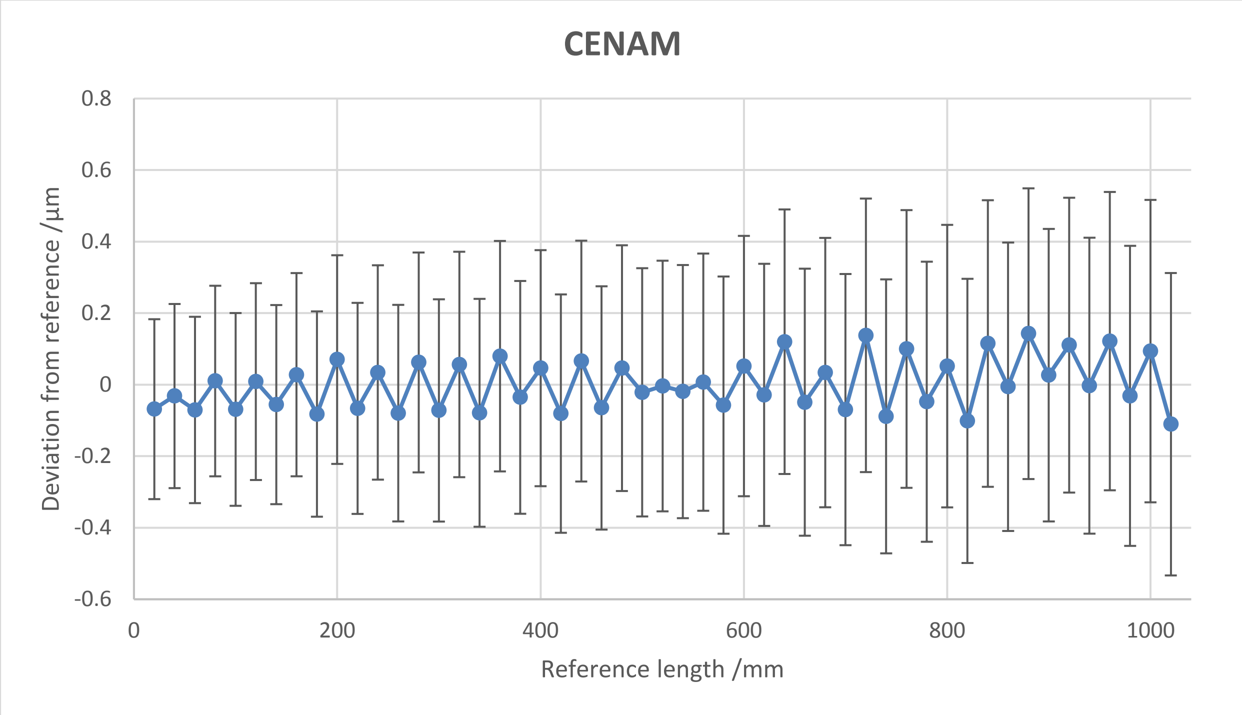


Figure 69

6.3.6.14 NIM

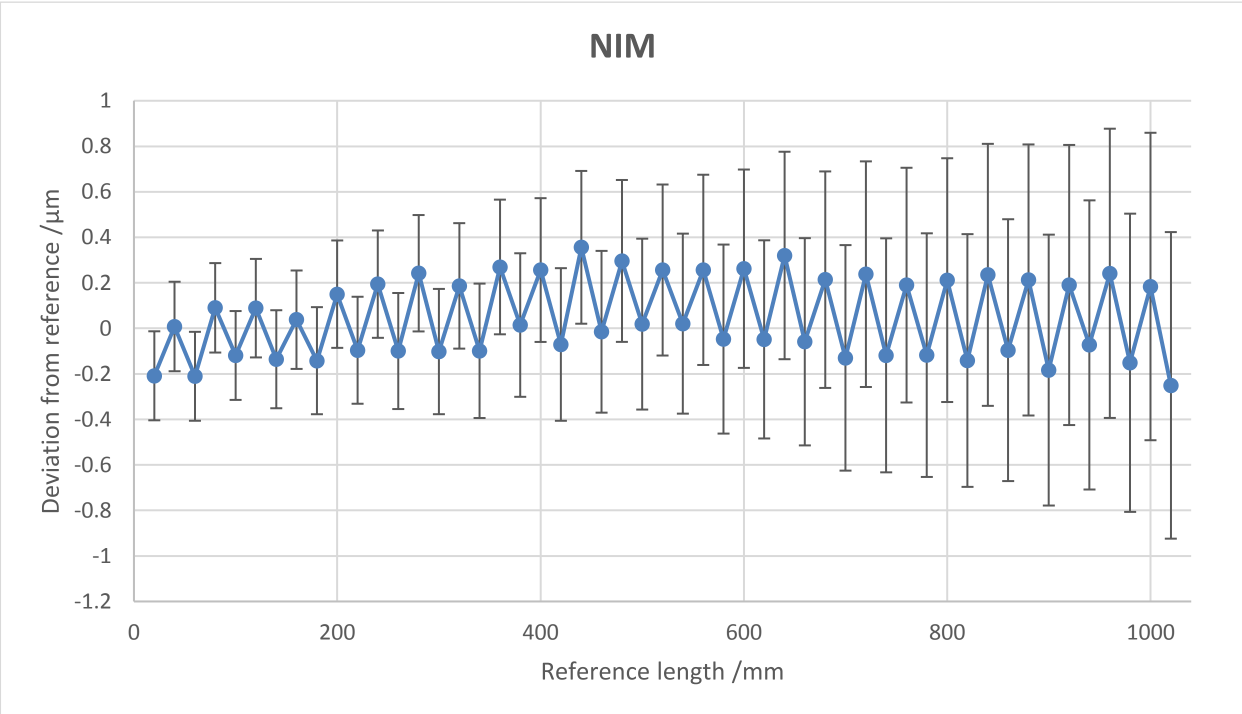


Figure 70

6.3.7 Participant *En* values

The *En* values for each participant's measurement of each interval relative to the reference value are shown in Table 13. The expanded uncertainties used to calculate this value were obtained by multiplying the standard uncertainty of the deviation from the reference value by a coverage factor, $k = 2$. This gives a coverage probability of approximately 95 %. If $En > 1$ then equivalence to the reference is not demonstrated. Values were this is the case are shown in red font.

Length /mm	NPL	LNE	BEV	CEM	SP	VTT MIKES	METAS	VSL	TUBITAK -UME	NMIJ	NIST	NMC A*STAR	CENAM	NIM
20	0.54	0.64	3.30	0.65	0.29	0.81	0.01	0.70	2.31	0.39	0.56	0.85	0.27	1.07
40	0.27	0.28	0.47	0.59	0.50	0.18	0.16	1.05	1.32	0.63	0.13	0.33	0.12	0.04
60	0.28	0.65	3.43	1.88	0.68	0.68	0.07	1.10	2.41	0.86	0.15	0.63	0.27	1.08
80	0.18	0.14	0.13	0.98	0.46	0.38	0.00	1.03	1.10	0.85	0.30	0.38	0.04	0.46
100	0.08	0.79	3.10	1.20	0.52	0.44	0.16	1.43	2.22	1.14	0.42	0.45	0.26	0.61
120	0.40	0.21	0.31	0.99	0.50	0.30	0.14	1.52	1.04	1.32	0.27	0.57	0.03	0.41
140	0.44	0.96	3.45	1.60	0.60	0.64	0.03	1.60	2.23	1.47	0.05	0.24	0.20	0.63
160	0.06	0.18	0.47	0.90	0.62	0.27	0.21	1.59	1.08	1.39	0.52	0.64	0.10	0.18
180	0.06	0.92	3.49	1.64	0.51	0.30	0.06	2.05	1.94	1.81	0.03	0.18	0.29	0.60
200	0.22	0.07	0.59	0.71	0.63	0.13	0.08	1.78	0.84	1.81	0.26	0.57	0.24	0.64
220	0.03	0.93	2.71	1.36	0.71	0.25	0.10	1.96	1.90	1.94	0.20	0.07	0.22	0.41
240	0.03	0.30	0.47	0.86	0.65	0.00	0.18	1.98	0.89	1.94	0.20	0.62	0.11	0.82
260	0.13	1.07	3.35	1.21	0.76	0.07	0.07	2.18	2.03	2.21	0.12	0.02	0.26	0.39
280	0.05	0.34	0.91	0.89	0.59	0.23	0.08	2.04	0.95	2.35	0.03	0.52	0.20	0.95
300	0.07	1.05	2.69	1.29	0.80	0.45	0.15	2.31	1.78	2.57	0.25	0.14	0.23	0.37
320	0.38	0.66	0.55	0.35	0.67	0.28	0.11	1.97	0.73	2.34	0.08	0.44	0.18	0.68
340	0.01	1.07	2.92	1.42	0.76	0.15	0.12	1.95	1.55	2.68	0.01	0.09	0.25	0.33
360	0.40	0.87	0.79	0.79	0.75	0.13	0.06	1.85	0.84	2.31	0.11	0.36	0.25	0.91
380	0.19	0.97	3.34	1.04	1.13	0.38	0.10	2.30	1.47	2.81	0.89	0.14	0.11	0.05
400	0.24	0.49	1.18	0.60	0.38	0.18	0.09	1.77	0.60	2.69	0.18	0.33	0.14	0.81
420	0.11	0.93	3.36	1.12	0.99	0.13	0.06	1.61	1.36	2.80	0.11	0.08	0.24	0.21
440	0.43	0.78	0.63	0.80	0.13	0.10	0.09	1.46	0.66	2.57	0.38	0.34	0.20	1.06
460	0.18	0.69	3.01	1.27	0.70	0.09	0.03	1.74	1.44	3.10	0.55	0.08	0.19	0.04
480	0.02	0.39	1.08	0.59	0.29	0.00	0.04	1.46	0.71	2.77	0.24	0.28	0.13	0.83
500	0.28	0.56	2.74	1.24	0.52	0.14	0.07	1.60	1.46	3.08	0.60	0.08	0.06	0.05
520	0.16	0.49	0.58	0.49	0.24	0.16	0.10	1.44	0.86	2.78	0.24	0.30	0.01	0.68
540	0.23	0.82	2.82	1.01	0.79	0.23	0.00	1.43	1.45	3.07	0.84	0.11	0.05	0.05
560	0.24	0.49	0.91	0.44	0.39	0.14	0.12	1.34	0.88	3.05	0.21	0.22	0.02	0.62
580	0.15	0.57	2.87	0.92	0.59	0.29	0.12	1.38	1.41	3.12	0.80	0.12	0.16	0.11
600	0.14	0.43	0.92	0.51	0.33	0.05	0.12	1.13	0.74	2.98	0.45	0.17	0.14	0.60
620	0.26	0.57	2.81	1.00	0.64	0.11	0.11	1.03	1.20	3.11	0.71	0.15	0.08	0.11
640	0.33	0.31	1.13	0.20	0.74	1.19	0.53	0.85	1.04	2.85	0.09	0.10	0.32	0.70
660	0.21	0.54	2.37	1.07	0.59	0.84	0.11	1.10	1.24	3.39	1.47	0.17	0.13	0.13
680	0.18	0.25	0.80	0.35	0.39	0.03	0.11	0.85	1.03	2.95	0.60	0.13	0.09	0.45
700	0.40	0.36	2.90	0.94	0.85	0.37	0.00	0.85	1.46	3.26	1.18	0.12	0.18	0.26
720	0.15	0.29	1.00	0.59	0.41	0.13	0.13	0.69	1.14	2.99	0.45	0.12	0.36	0.48

Length /mm	NPL	LNE	BEV	CEM	SP	VTT MIKES	METAS	VSL	TUBITAK -UME	NMIJ	NIST	NMC A*STAR	CENAM	NIM
740	0.24	0.46	2.97	1.12	0.55	0.22	0.24	0.87	1.29	3.38	1.50	0.11	0.23	0.23
760	0.04	0.07	1.04	0.54	0.64	0.29	0.14	0.67	0.84	3.03	1.01	0.14	0.26	0.37
780	0.41	0.33	3.11	0.97	0.64	0.22	0.18	0.53	1.07	3.23	0.96	0.12	0.12	0.22
800	0.22	0.15	1.18	0.63	0.54	0.22	0.10	0.47	0.60	3.24	0.91	0.13	0.13	0.40
820	0.35	0.29	2.77	0.95	0.76	0.24	0.17	0.37	0.92	3.23	1.12	0.10	0.25	0.25
840	0.12	0.50	1.09	0.68	0.55	0.01	0.11	0.33	0.49	3.17	0.69	0.13	0.29	0.41
860	0.19	0.11	2.98	0.97	0.74	0.24	0.11	0.23	0.85	3.19	1.06	0.14	0.01	0.17
880	0.08	0.38	1.02	0.62	0.54	0.06	0.21	0.24	0.43	3.21	0.69	0.06	0.35	0.36
900	0.22	0.11	3.32	0.99	0.81	0.24	0.19	0.14	0.75	3.18	1.17	0.18	0.06	0.31
920	0.10	0.36	1.33	0.46	0.82	0.04	0.16	0.08	0.40	3.21	1.00	0.05	0.27	0.31
940	0.09	0.03	3.36	1.06	0.96	0.06	0.23	0.01	0.85	3.17	1.06	0.19	0.01	0.11
960	0.10	0.20	1.45	0.68	0.74	0.02	0.25	0.03	0.64	3.20	0.98	0.03	0.29	0.38
980	0.31	0.16	3.21	1.06	1.02	0.41	0.22	0.08	1.01	3.21	1.55	0.26	0.07	0.23
1000	0.17	0.11	1.50	0.65	1.04	0.29	0.20	0.07	0.71	3.23	1.31	0.09	0.22	0.27
1020	0.06	0.37	3.31	1.35	0.80	0.35	0.12	0.04	1.05	3.52	1.66	0.32	0.26	0.37

Table 13: *En* values for 1020 mm artefact

A summary of the number of measurements for each institution made that did not demonstrate equivalence to the comparison reference value is shown in Table 14. Given that the expanded uncertainty provides an approximately 95% probability of a measured value being within the uncertainty range of the true value (which in the case of this comparison can be considered to be 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 therefore considered to have demonstrated the validity of their submitted uncertainty.

	Number of intervals where *En* > 1	Percentage of intervals where *En* > 1	Uncertainty validity demonstrated?
NPL	0	0.00	YES
LNE	3	5.88	NO
BEV	36	70.59	NO
CEM	19	37.25	NO
SP	3	5.88	NO
VTT MIKES	1	1.96	YES
METAS	0	0.00	YES
VSL	31	60.78	NO
TUBITAK-UME	29	56.86	NO
NMIJ	47	92.16	NO
NIST	11	21.57	NO
NMC A*STAR	0	0.00	YES
CENAM	0	0.00	YES
NIM	3	5.88	NO

Table 14: Summary of participant *En* values for the 1020 mm artefact

6.3.8 Participant responses

Following the circulation of the results the pilot received responses regarding discrepancies from several participants. Details of these are included below.

6.3.8.1 BEV

BEV sent the following response on 13 August 2019:

After we received the first Draft A report, we had an intensive investigation on our (makeshift) setup for the step gauge calibration. Essentially it is a workaround based on a linear length measuring machine with a modified attachment originally to be intended for thread measurement. It has to be operated purely manually. So there is no way to identify faulty recordings of the probe diameter determination afterwards. Unfortunately it is not obvious if errors were introduced and even a history of this parameter is of no help. The variation between successive set-ups are very large. The length dependent error is more displeasing to me since this could affect also different kind of calibrations on this machine.

After presenting the results to my management we decided to stop the service of step gauge calibration (and ball bars too) completely. We have already withdrawn the relevant CMCs completely. Also we performed the necessary steps to check the calibrations performed for customers (one every other year) since the last key comparison. Moreover, a possible impact on other calibrations (and CMCs) were analysed.

To conclude we will not revive this service with the current setup. Taking into account the low consumer demand it is moreover unlikely to install a state-of-the-art facility in the near future.

6.3.8.2 CEM

CEM sent the following response on 27 September 2019

*On this comparison, instead of using the two typical **fixed supports** we use for normal calibrations of steps (supposing the measurement line is connecting the centre of the first and last faces), we used **adjustable supports** with certain degrees of freedom, searching for a better alignment of the full step, this probably causing a small cosine error (see the tendency to measure shorter with the length) and also a bad local correction when reading the right faces on each individual step.*

Apparently, our data are not very bad looking at the graphs but when looking at Draft A2, table 6.3.5, we see such (bad but not very high) E_n *values in specific alternate faces.*

I think this is most due, not to the measured value, always very close to the reference value, but to the small uncertainty we claim, very sensitive with respect to the problems I have described before.

Probably adding a new uncertainty component due to such misalignment would cause U segment cutting the reference-value line in the graphs and getting correct E_n *values.*

6.3.8.3 VSL

VSL reported a lengthy investigation into their results. The following summary was provided on 6 November 2019.

The VSL results on the 1020 mm step gauge were obtained using a supporting method for the step gauge that is not conform our normal supporting method. Once the analysis results were distributed by the pilot and the large errors with respect to the reference value became known, investigation of the measurement process indeed showed an erroneous supporting method. Further study also excluded all other potential origins (i.e. alignment, temperature, Abbe correction, analysis software) for the observed error. Since the *gauge was no longer available to confirm the origin of our results, subsequent FEM analysis of the set-up with the erroneous support has confirmed, at least qualitatively, that the erroneous support was indeed the sole cause of our results.*

6.3.8.4 NIST

NIST reported the following issue on 1 July 2019.

At the time of the step gauge intercomparison circulation, the NIST M48 CMM had just recently undergone some process improvements, mostly to the thermal airflow around the machine volume. These were really successful, and our gradients are quite low on the machine table now. We decided to submit a tightened uncertainty budget based on the new air flow conditions. It was our hope to lower our 1D uncertainty in the near future based on the extraordinary thermal performance on the CMM table.

Unfortunately, during the error mapping of the machine motions just prior to the key comparison, an HP receiver on an unused wavelength tracker was left powered on. The unit is inside the laser beam path housing of the machine. This created a beam path temperature gradient of about 80 millidegrees that was not addressed, and mostly directly affected the rear portion of the machine scale during the error mapping process. Then of course, during use of the machine for gauge measurements, the gradient was once again not corrected, as our beam path temp sensors are not placed back at that specific rear area of the optics. So, most of the error occurred again; effectively doubled. It only really affected the rear 300mm of machine volume and shows up in long step gauge data. So, we would appear low relative to the true gauge length due to this effective machine scale issue.

In short, the mistake was detected in subsequent gauge measurements and was easily corrected. But only after our K5 results were submitted to you.

Subsequent to this, a data set with a revised uncertainty budget was received by the pilot on 15 October 2019. This data set could not be accepted as a formal submission to the intercomparison but the deviation from the KCRV (shown in Figure 71) and *E*n values for the revised data set were calculated by the pilot. The results showed one result with an *E*n value greater than 1. This means that the revised uncertainty's validity is demonstrated.

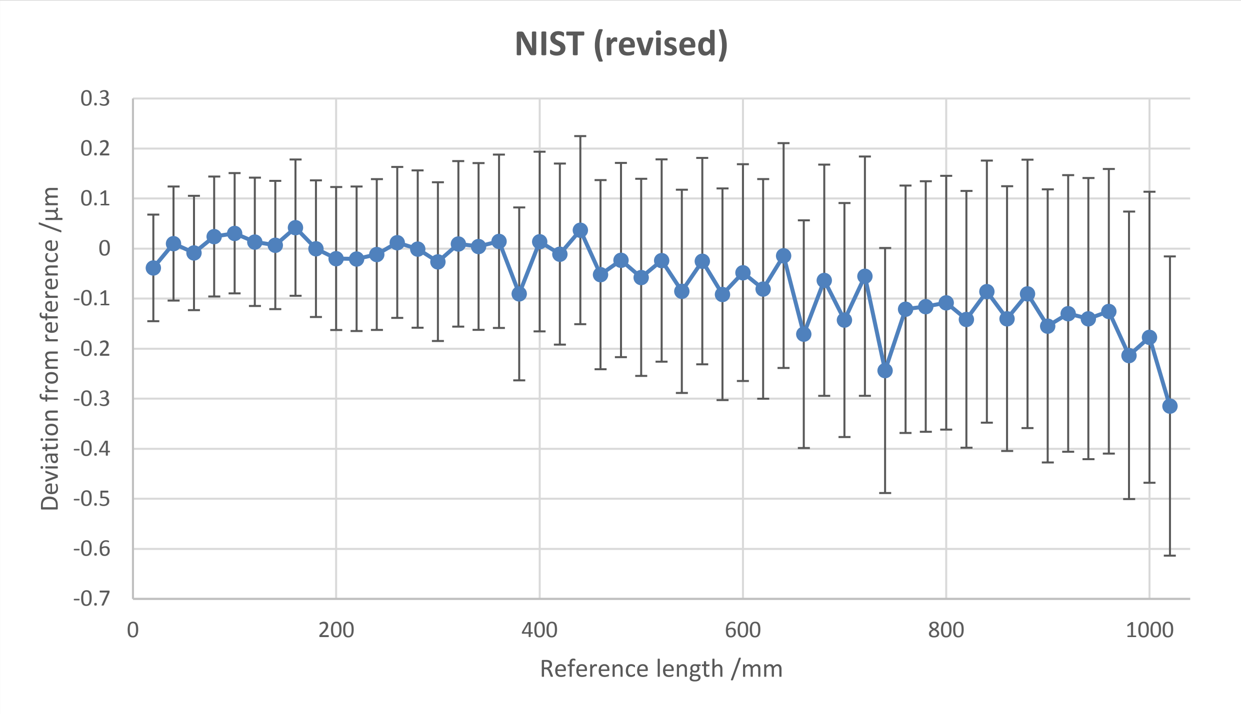


Figure 71

6.3.8.5 <u>SP</u>

Following a recalculation of *E*n values after the detection of an error in the analysis software SP results showed 3 discrepant faces (prior to this it was believed only 1 face was discrepant). After this was communicated to them SP sent the following response on 28 February 2020.

We have tried to remember and look back at what we did about 4 years ago. The step gauge used in this intercomparison is of a type, which was not familiar to us. We had no previous experience with this type. Therefore we could not rely entirely on our past experience with step gauges, but, among other things, had to recalculate parts of our uncertainty estimates.

Looking at the uncertainty estimations we made at the time, we realize that there is one component we may have underestimated. It regards the quality of the measuring surfaces of the step gauge, in combination with our ability to precisely hit the center point of the surface. We tried to estimate this uncertainty component by changing the direction of the step gauge in our setup, using the difference between the directions as an estimator of this effect.

However, the uncertainty has been estimated as a pool of the values for each surface. This, we now realize, may lead to an underestimation for those surfaces, where the difference is somewhat larger than the pooled value. We now believe, we should have used the maximum difference as an estimator instead.

SP submitted a data set with the revised uncertainty on 2 March 2020. The revised uncertainty model equation is Q[0.22, 1.4×10^{-4}] µm. *E*n values and deviations from the KCRV were calculated. The deviations are shown in Figure 72. All *E*n values for the revised data set were less than 1 so the revised uncertainty's validity is demonstrated.

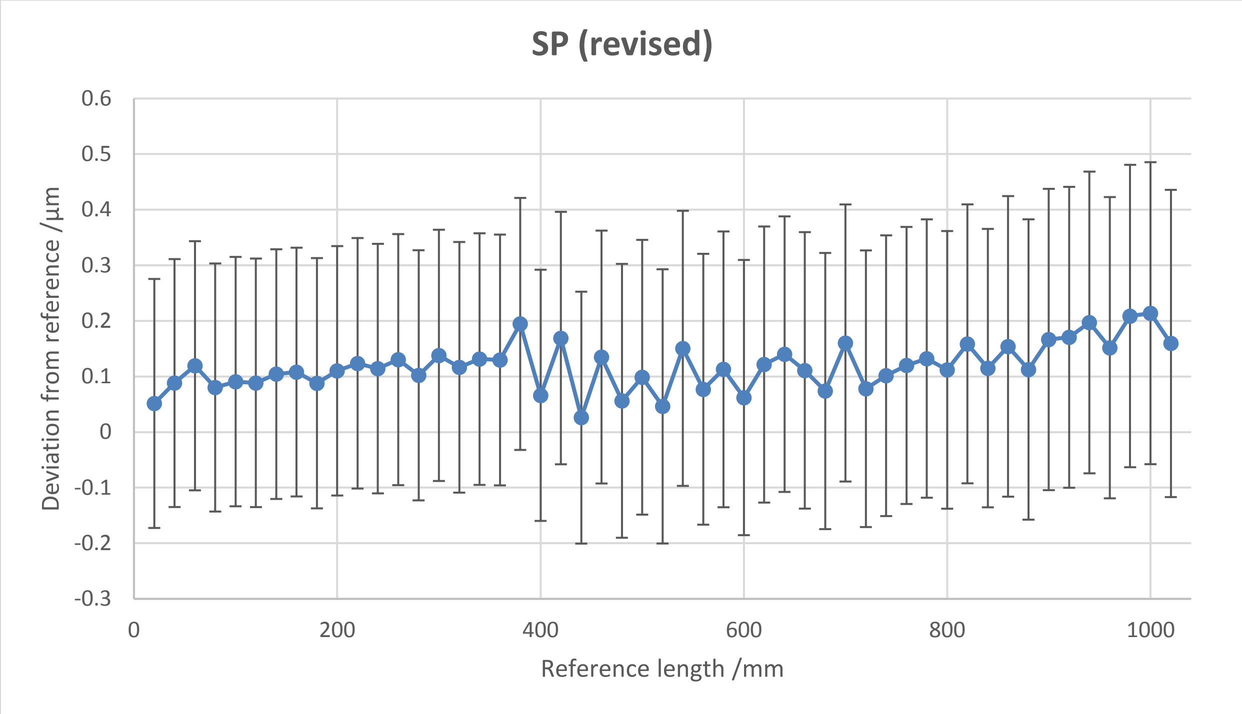


Figure 72

6.3.8.6 NIM

NIM communicated with the Pilot shortly after the draft A1 to raise concerns about an apparent probe ball issue present in those results. During the report draft stages NIM made a series of investigations into the issue, the findings of which are summarised below.

We noticed the errors between opposite faces of the step gauges in the past comparisons. That's why we tried to calibrate the reference sphere by ourselves with a new length measuring machine. The calibration result of diameter had a 0.13µm difference from the values we used before. We decided to use the correction in the comparison just before sent out the comparison report because we did not have time to verify it. When we got the comparison data in Feb 2019, we knew that the correction of the sphere was wrong.

We drew back the correction and [have kept] traceability of the sphere by [the previous method] since that time point.

We checked the comparison values with the CMC of our calibration service which was issued in our certificates: $U=0.2\mu m+0.5\times10^{-6}L$, k=2. With the correction of [the probe ball] diameter, only one E*n values was [greater than] 1.*

The pilot checked the revised data set and concurred with NIM's conclusion that only one result had an *E*n value greater than 1 and so the uncertainty supplied is valid. The revised deviation by length plot is shown in Figure 73.

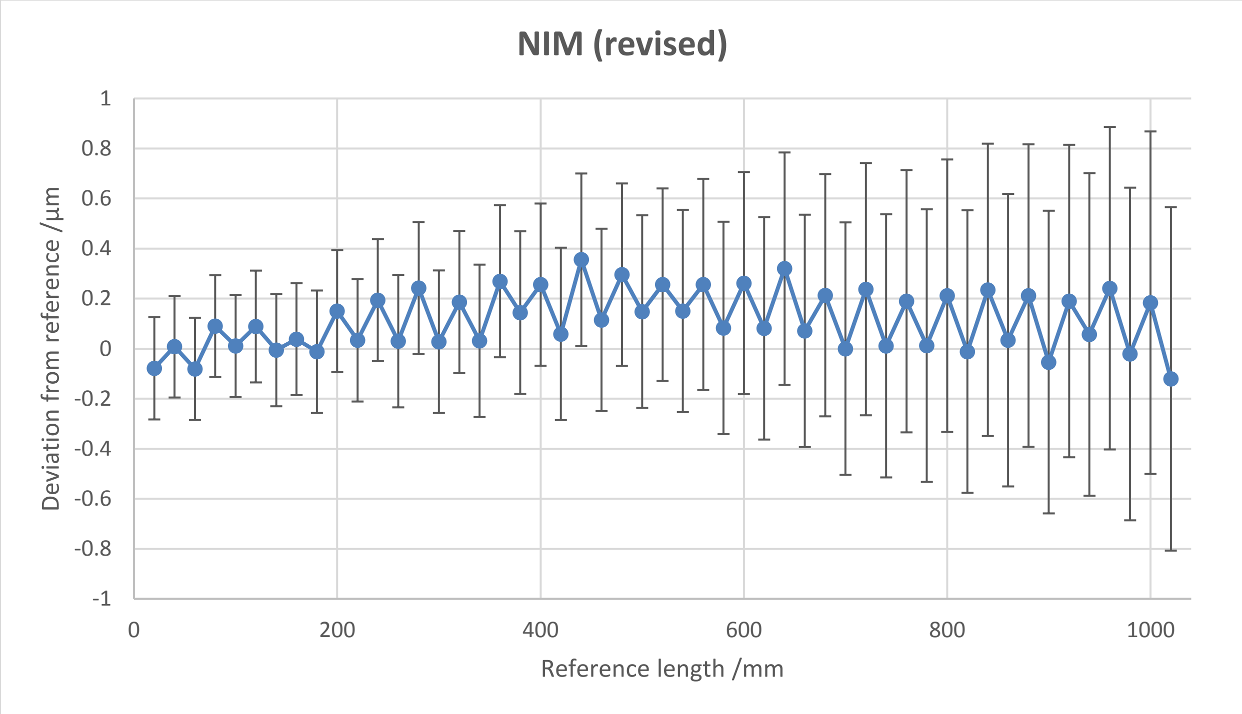


Figure 73

6.4 610 mm artefact Analysis

6.4.1 Artefact Stability

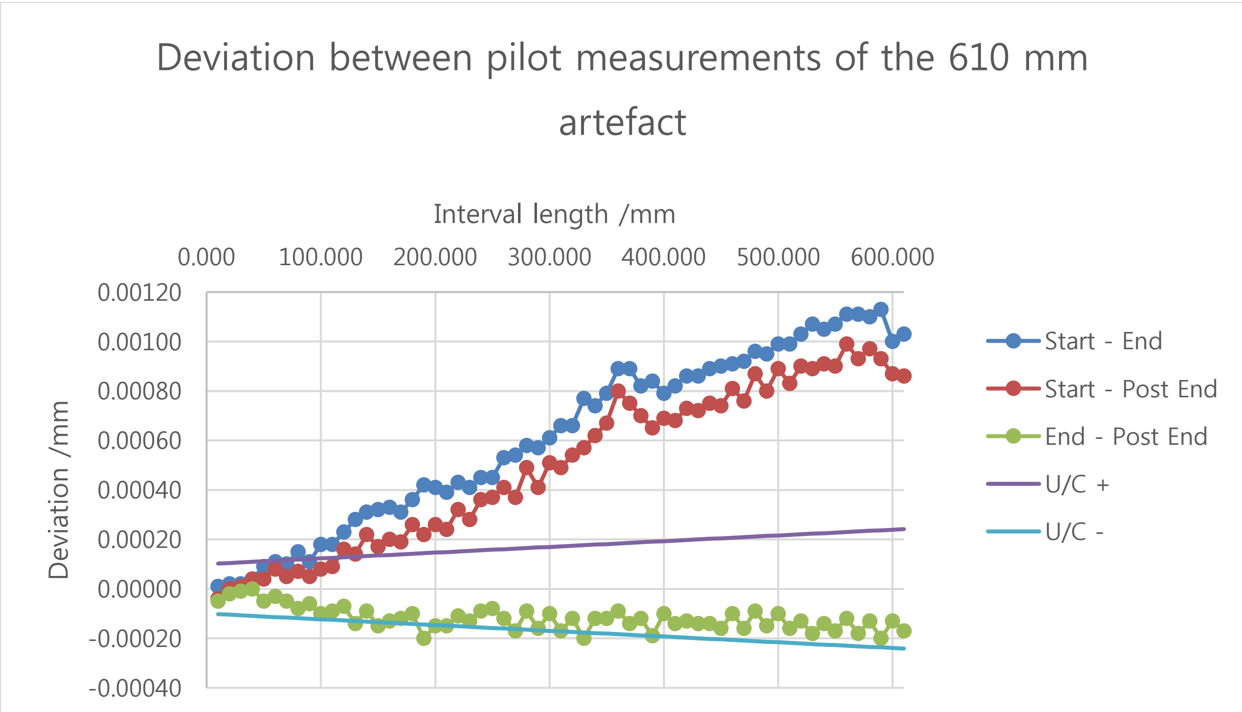


Figure 74: Deviation between pilot measurements of the 610 mm artefact

The pilot measured the 610 mm artefact at the start and at the end of the circulation. The deviations observed between the measurements were significantly greater than the pilot's uncertainty showing that the artefact had changed length at some point during the circulation. An additional measurement was made several months after the circulation had completed (this is referred to as Post End in Figure 74).

This measurement showed consistency with the end of circulation measurement, suggesting that the change was not due to long term drift.

In addition to the pilot, three other participants had measured both artefacts acting as linking laboratories. These were NIST, VTT MIKES and CEM. To determine if the issue was with the pilot measurements a test reference value was calculated from the weighted mean of the linking laboratory results and the start and end pilot measurements. Deviations from this value were calculated and are displayed in Figure 75.

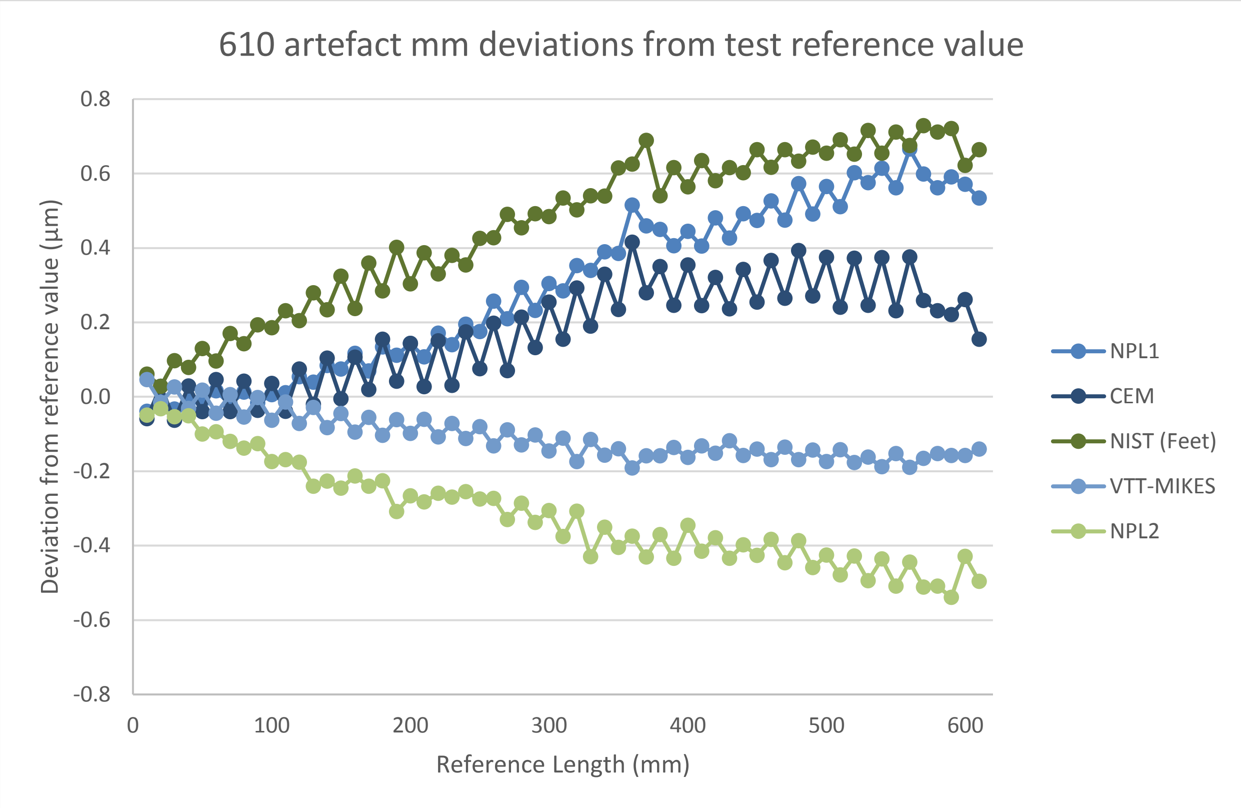


Figure 75: deviations of linking labs from test reference value

It can be clearly seen that there is no consistency between these results given that maximum reported uncertainty for any of these laboratories is 0.3 µm at k = 2. Since these laboratories, apart from CEM, demonstrated equivalence of measurement performance over the same range as this artefact (NIST had some results that did not demonstrate equivalence, but these were at longer ranges than this artefact) it must be concluded that the artefact has changed during the comparison.

It is noticeable that there appears to be some agreement in values between groups of participants. NIST and NPL1 (the start measurement) seem to show the same trends, as do VTT MIKES and NPL2. CEM show a trend that initially follows that of NIST and NPL1 but differs after 360 mm.

A check of the schedule shows that the order of these measurements was NPL, NIST, CEM, VTT MIKES NPL. Approximately a year passed between NPL's initial measurement and NIST's measurement, during which time the artefact appears to have been stable. There was then a further year before VTT MIKES made their measurements. During that year it appears that the gauge underwent a change in length, possibly as a one-off event, although this is unclear. However, the gauge has not continued to change as shown by the post end measurement taken at NPL 11 months after VTT MIKES' measurement.

It is therefore clear that the 610 mm artefact did not remain stable during the circulation. The change does not appear to be a linear drift. No obvious damage to the gauge was reported by any participant. However, NRC did report the following on the receiving the gauge.

It should be noted that when the step gauge was received the two machine screws which are inserted through the bottom of the wooden case to secure the step gauge in place were severely bent. It is not clear how or when this may have occurred, or whether the event which caused such damage also affected the step gauge itself.

The damaged screws are shown in Figure 76.

Figure 76: Photograph of damaged retaining screws from NRC

The pilot concurred with NRC's assessment of the damage, as no particular change in the gauge could be attributed to the observed damage. In addition, it appears that a previous length change, effecting only the section of the gauge furthest from the datum face, may have occurred prior to CEM's measurement. Provisional results indicate that at least one other laboratory shows very similar deviations to CEM. Therefore, even if the cause of the damage to the screws did change the length of the step gauge it cannot be ruled out that another event also took place which did not produce visible damage in this way.

In these circumstances the protocol for this comparison required that EURAMET TC-L determine how to proceed. This question was be put to the meeting of EURAMET TC-L in October 2019.

The decision was taken that the comparison should be treated as a series of smaller comparisons. Equivalence would be demonstrated by a participant if they showed agreement with a laboratory who had demonstrated their equivalence in the 1020 mm circulation. The selection criteria as to which linking laboratory each lab should show agreement was based on proximity with the schedule.

The measured value from the linking laboratory selected would be the reference value for the group. This is appropriate because the uncertainties of the linking laboratories are significantly smaller than most of the 610 mm participants, so a weighted mean would be dominated by the value anyway.

6.4.2 Groupings

Examination of the form of deviations from a provisional reference value showed similar trends in deviations for all participants up to NPLI and a different but consistent trend in those who measured after NPLI. Therefore, the comparison was split into two groups, NPLI and those which measured before it and those which measured after. The reference participant for each group was selected using the criteria of having the lowest uncertainty of those who measured in the relevant time period and having successfully demonstrated equivalence in the 1020 mm circulation without any issues. In consequence, by this reason, the other possible linking participants, NIST and CEM, are not included in this analysis, even as normal participants. So, the participants finally considered in groups 1 and 2 are shown in Table 12 and Table 13 respectively.

RMO	Laboratory
EURAMET	NPL (Reference)
EURAMET	INRIM
EURAMET	MKEH
EURAMET	CMI
EURAMET	INM
APMP	NPLI

Table 15: List of participants in Group 1

RMO	Laboratory
EURAMET	GUM
GULFMET	SASO-NMCC
SIM	NRC-CNRC
EURAMET	VTT MIKES (reference)

Table 16: List of participants in Group 2

6.4.3 Group 1 reference value

The reference value for Group 1, shown in Table 17, is the initial measurement made by NPL.

Table 17: 610 mm artefact group 1 reference value

Interval	Reference value /mm	Reference value Uncertainty /µm	Interval	Reference value /mm	Reference value Uncertainty /µm
0 mm - 10 mm	10.000 140	0.051 2	0 mm - 320 mm	319.998 400	0.087 1
0 mm - 20 mm	20.000 420	0.052 3	0 mm - 330 mm	329.998 440	0.088 3
0 mm - 30 mm	30.000 560	0.053 5	0 mm - 340 mm	339.998 190	0.089 4
0 mm - 40 mm	40.000 430	0.054 6	0 mm - 350 mm	349.998 250	0.090 6
0 mm - 50 mm	50.000 540	0.055 8	0 mm - 360 mm	359.998 130	0.091 8
0 mm - 60 mm	60.000 470	0.057 0	0 mm - 370 mm	369.998 170	0.092 9
0 mm - 70 mm	70.000 530	0.058 1	0 mm - 380 mm	379.997 990	0.094 1
0 mm - 80 mm	80.000 280	0.059 3	0 mm - 390 mm	389.998 010	0.095 2
0 mm - 90 mm	90.000 120	0.060 4	0 mm - 400 mm	399.997 740	0.096 4
0 mm - 100 mm	100.000 060	0.061 6	0 mm - 410 mm	409.997 780	0.097 6
0 mm - 110 mm	110.000 190	0.062 8	0 mm - 420 mm	419.997 610	0.098 7
0 mm - 120 mm	119.999 890	0.063 9	0 mm - 430 mm	429.997 640	0.099 9
0 mm - 130 mm	129.999 960	0.065 1	0 mm - 440 mm	439.997 360	0.101 0
0 mm - 140 mm	139.999 750	0.066 2	0 mm - 450 mm	449.997 410	0.102 2
0 mm - 150 mm	149.999 840	0.067 4	0 mm - 460 mm	459.997 230	0.103 4
0 mm - 160 mm	159.999 580	0.068 6	0 mm - 470 mm	469.997 260	0.104 5
0 mm - 170 mm	169.999 620	0.069 7	0 mm - 480 mm	479.997 120	0.105 7
0 mm - 180 mm	179.999 490	0.070 9	0 mm - 490 mm	489.997 130	0.106 8
0 mm - 190 mm	189.999 610	0.072 0	0 mm - 500 mm	499.996 980	0.108 0
0 mm - 200 mm	199.999 350	0.073 2	0 mm - 510 mm	509.997 010	0.109 2
0 mm - 210 mm	209.999 400	0.074 4	0 mm - 520 mm	519.996 860	0.110 3
0 mm - 220 mm	219.999 260	0.075 5	0 mm - 530 mm	529.996 950	0.111 5
0 mm - 230 mm	229.999 340	0.076 7	0 mm - 540 mm	539.996 770	0.112 6
0 mm - 240 mm	239.999 070	0.077 8	0 mm - 550 mm	549.996 800	0.113 8
0 mm - 250 mm	249.999 080	0.079 0	0 mm - 560 mm	559.996 520	0.115 0
0 mm - 260 mm	259.998 940	0.080 2	0 mm - 570 mm	569.996 560	0.116 1
0 mm - 270 mm	269.998 990	0.081 3	0 mm - 580 mm	579.996 530	0.117 3
0 mm - 280 mm	279.998 750	0.082 5	0 mm - 590 mm	589.996 560	0.118 4
0 mm - 290 mm	289.998 800	0.083 6	0 mm - 600 mm	599.996 530	0.119 6
0 mm - 300 mm	299.998 650	0.084 8	0 mm - 610 mm	609.996 600	0.120 8
0 mm - 310 mm	309.998 670	0.086 0			

6.4.4 Group 1 Participant results

Group 1 Participant results are shown in Table 18.

Note that due to an equipment limitation INM only measured up to the 500 mm interval.

Table 18: Group 1 participant results

Nominal Length /mm	INRIM /mm	MKEH /mm	CMI /mm	INM /mm	NPLI /mm
10	10.000 10	10.000 1	10.000 18	10.000 61	10.000 08
20	20.000 47	20.000 5	20.000 39	19.999 98	20.000 50
30	30.000 54	30.000 9	30.000 58	30.000 92	30.000 60
40	40.000 50	40.000 9	40.000 42	40.000 67	40.000 54
50	50.000 52	50.001 1	50.000 54	50.000 90	50.000 53
60	60.000 54	60.001 2	60.000 44	60.000 33	60.000 52
70	70.000 55	70.001 2	70.000 55	70.000 53	70.000 54
80	80.000 38	80.001 2	80.000 26	80.000 26	80.000 36
90	90.000 15	90.000 9	90.000 11	90.000 54	90.000 16
100	100.000 19	100.001 1	100.000 03	100.000 04	100.000 19
110	110.000 22	110.000 9	110.000 17	110.000 24	110.000 20
120	120.000 02	120.000 8	119.999 84	119.999 60	119.999 94
130	130.000 00	130.000 6	129.999 95	129.999 84	129.999 89
140	139.999 88	140.000 6	139.999 66	139.999 86	139.999 80
150	149.999 89	150.000 8	149.999 81	149.999 59	149.999 88
160	159.999 71	160.000 7	159.999 52	159.999 43	159.999 68
170	169.999 71	170.000 4	169.999 58	169.999 24	169.999 59
180	179.999 65	180.000 7	179.999 39	179.999 29	179.999 52
190	189.999 69	190.000 3	189.999 57	189.999 04	189.999 62
200	199.999 52	200.000 5	199.999 25	199.998 79	199.999 43
210	209.999 50	210.000 6	209.999 38	209.998 69	209.999 40
220	219.999 44	220.000 3	219.999 18	219.998 71	219.999 37
230	229.999 45	230.001 4	229.999 31	229.998 59	229.999 41
240	239.999 28	240.000 6	239.998 98	239.998 61	239.999 20
250	249.999 20	250.000 6	249.999 02	249.998 70	249.999 09
260	259.999 13	260.000 6	259.998 83	259.998 21	259.999 00
270	269.999 14	270.000 4	269.998 92	269.998 23	269.999 04
280	279.998 96	280.000 0	279.998 61	279.998 13	279.998 84
290	289.998 97	290.000 2	289.998 74	289.997 92	289.998 87
300	299.998 88	300.000 4	299.998 55	299.997 85	299.998 74
310	309.998 82	309.999 7	309.998 62	309.997 47	309.998 69

Nominal Length /mm	INRIM /mm	MKEH /mm	CMI /mm	INM /mm	NPLI /mm
320	319.998 61	319.999 3	319.998 32	319.997 67	319.998 50
330	329.998 60	329.999 6	329.998 36	329.997 70	329.998 48
340	339.998 41	339.999 3	339.998 09	339.997 16	339.998 29
350	349.998 41	349.999 4	349.998 20	349.997 17	349.998 22
360	359.998 33	359.999 1	359.997 98	359.997 31	359.998 10
370	369.998 34	369.999 1	369.998 08	369.997 34	369.998 08
380	379.998 19	379.998 7	379.997 88	379.996 93	379.998 01
390	389.998 17	389.998 9	389.997 97	389.997 39	389.997 92
400	399.997 95	399.998 5	399.997 68	399.996 94	399.997 71
410	409.997 94	409.998 9	409.997 71	409.996 92	409.997 66
420	419.997 78	419.998 5	419.997 52	419.997 00	419.997 49
430	429.997 78	429.998 5	429.997 60	429.996 62	429.997 38
440	439.997 54	439.998 2	439.997 30	439.996 67	439.997 15
450	449.997 52	449.998 2	449.997 36	449.996 35	449.997 09
460	459.997 41	459.997 9	459.997 15	459.996 03	459.996 97
470	469.997 41	469.998 1	469.997 28	469.996 17	469.996 91
480	479.997 28	479.998 1	479.997 07	479.995 96	479.996 77
490	489.997 28	489.998 1	489.997 16	489.996 28	489.996 74
500	499.997 15	499.998 3	499.996 97	499.996 37	499.996 58
510	509.997 14	509.998 0	509.997 08		509.996 57
520	519.997 04	519.998 2	519.996 91		519.996 43
530	529.997 07	529.997 8	529.997 06		529.996 44
540	539.996 96	539.998 2	539.996 86		539.996 29
550	549.996 94	549.997 8	549.996 96		549.996 29
560	559.996 68	559.998 0	559.996 62		559.996 00
570	569.996 69	569.997 7	569.996 71		569.995 96
580	579.996 69	579.998 0	579.996 66		579.995 96
590	589.996 68	589.997 7	589.996 75		589.996 00
600	599.996 70	599.998 0	599.996 68		599.996 10
610	609.996 74	609.997 9	609.996 80		609.996 01

6.4.5 Group 1 participant measurement uncertainties

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 19. Where possible the model equations reported have been converted to 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 mm and the standard uncertainty u is expressed in µm.

Table 19: Group 1 participant measurement uncertainties

Participant	Measurement uncertainty
INRIM	Q[0.035, 0.275×10^{-3} L] µm
MKEH	Q[0.33, 1.4×10^{-3} L] µm
CMI	Q[0.1, 0.3×10^{-3} L] µm
INM	Q[0.47, 1.0×10^{-3} L] µm
NPLI	Q[0.225,0.8×10^{-3} L] µm

Table 20 shows the reported standard uncertainties supplied by each Group 1 participant for the measured intervals.

Table 20: Group 1 reported standard uncertainties

Nominal Length /mm	INRIM /µm	MKEH /µm	CMI /µm	INM /µm	NPLI /µm
10	0.04	0.34	0.10	0.47	0.23
20	0.04	0.34	0.10	0.47	0.23
30	0.05	0.34	0.10	0.47	0.23
40	0.04	0.34	0.10	0.47	0.23
50	0.04	0.34	0.10	0.47	0.23
60	0.04	0.35	0.10	0.47	0.23
70	0.05	0.35	0.10	0.48	0.23
80	0.04	0.36	0.10	0.48	0.23
90	0.05	0.36	0.10	0.48	0.24
100	0.04	0.37	0.10	0.48	0.24
110	0.05	0.37	0.11	0.48	0.24
120	0.05	0.38	0.11	0.49	0.24
130	0.05	0.38	0.11	0.49	0.25
140	0.05	0.39	0.11	0.49	0.25
150	0.06	0.40	0.11	0.49	0.25
160	0.06	0.41	0.11	0.50	0.26
170	0.06	0.41	0.11	0.50	0.26
180	0.06	0.42	0.11	0.50	0.27
190	0.07	0.43	0.12	0.51	0.27
200	0.07	0.44	0.12	0.51	0.28

Nominal Length /mm	INRIM /µm	MKEH /µm	CMI /µm	INM /µm	NPLI /µm
210	0.07	0.45	0.12	0.51	0.28
220	0.07	0.46	0.12	0.52	0.29
230	0.08	0.47	0.12	0.52	0.29
240	0.08	0.48	0.12	0.52	0.30
250	0.08	0.49	0.12	0.53	0.30
260	0.08	0.50	0.13	0.53	0.31
270	0.09	0.51	0.13	0.54	0.31
280	0.09	0.52	0.13	0.54	0.32
290	0.09	0.53	0.13	0.55	0.32
300	0.09	0.54	0.13	0.55	0.33
310	0.09	0.55	0.14	0.56	0.33
320	0.09	0.56	0.14	0.56	0.34
330	0.10	0.57	0.14	0.57	0.35
340	0.10	0.59	0.14	0.57	0.35
350	0.10	0.60	0.14	0.58	0.36
360	0.11	0.61	0.15	0.59	0.37
370	0.11	0.62	0.15	0.59	0.37
380	0.11	0.63	0.15	0.60	0.38
390	0.11	0.65	0.15	0.60	0.38
400	0.12	0.66	0.16	0.61	0.39
410	0.12	0.67	0.16	0.61	0.40
420	0.14	0.68	0.16	0.62	0.40
430	0.14	0.69	0.16	0.63	0.41
440	0.14	0.71	0.17	0.63	0.42
450	0.14	0.72	0.17	0.64	0.42
460	0.14	0.73	0.17	0.65	0.43
470	0.15	0.74	0.17	0.65	0.44
480	0.15	0.76	0.18	0.66	0.45
490	0.15	0.77	0.18	0.67	0.45
500	0.15	0.78	0.18	0.67	0.46
510	0.16	0.79	0.18		0.47
520	0.16	0.81	0.19		0.47
530	0.16	0.82	0.19		0.48
540	0.16	0.83	0.19		0.49
550	0.17	0.85	0.19		0.49
560	0.17	0.86	0.20		0.50
570	0.17	0.87	0.20		0.51
580	0.17	0.89	0.20		0.52
590	0.18	0.90	0.20		0.52
600	0.18	0.91	0.21		0.53

Nominal Length /mm	INRIM /µm	MKEH /µm	CMI /µm	INM /µm	NPLI /µm
610	0.18	0.92	0.21		0.54

6.4.6 Group 1 participant deviations by face

The following plots, Figures 77 through 142, show the deviation from the reference value of each participant for each interval measured. The uncertainties shown are the uncertainty in the deviation from the reference length x_{ref}, calculated to be

$$u_{(x_i - x_{ref})} = \sqrt{{u_{x_i}}^2 + {u_{x_{ref}}}^2}$$

Where x_i is the the participant reported length and u_{x_i} and $u_{x_{ref}}$ are both expanded uncertainties at *k* = 2. This calculation is used because in this case none of the participant results displayed contributed to the reference value.

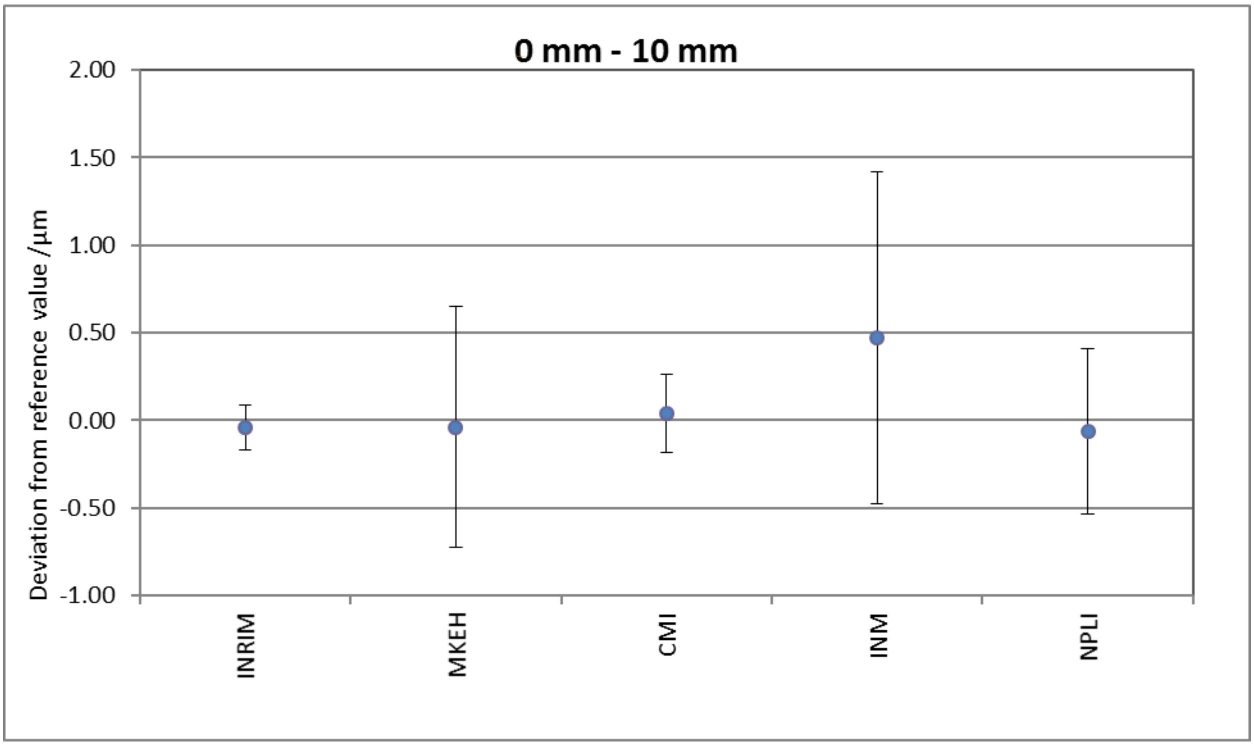


Figure 77: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

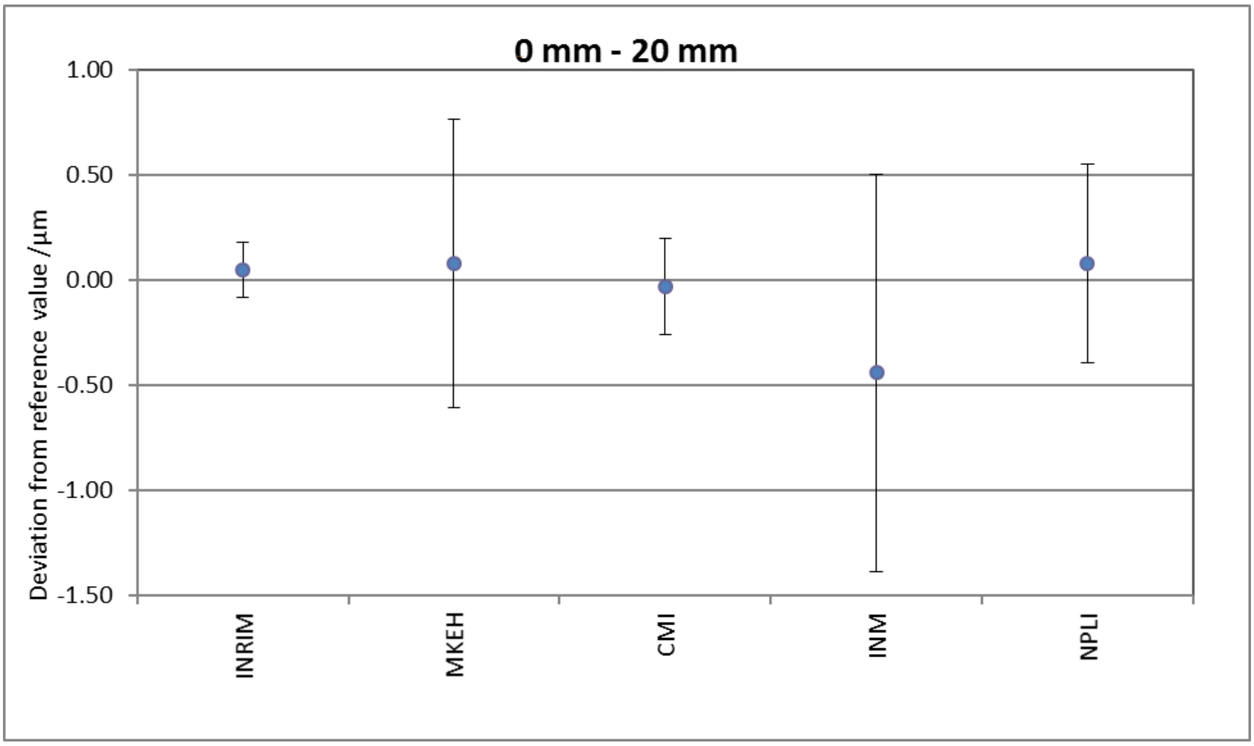


Figure 78: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

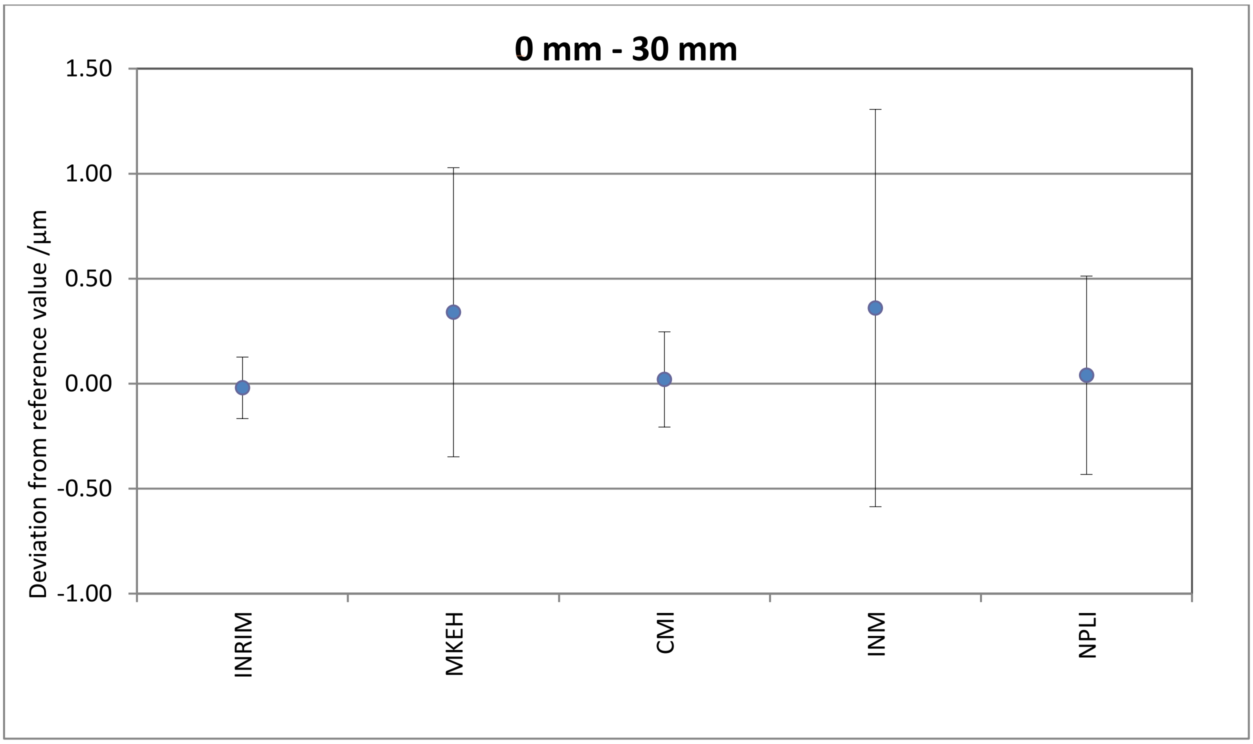


Figure 79: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

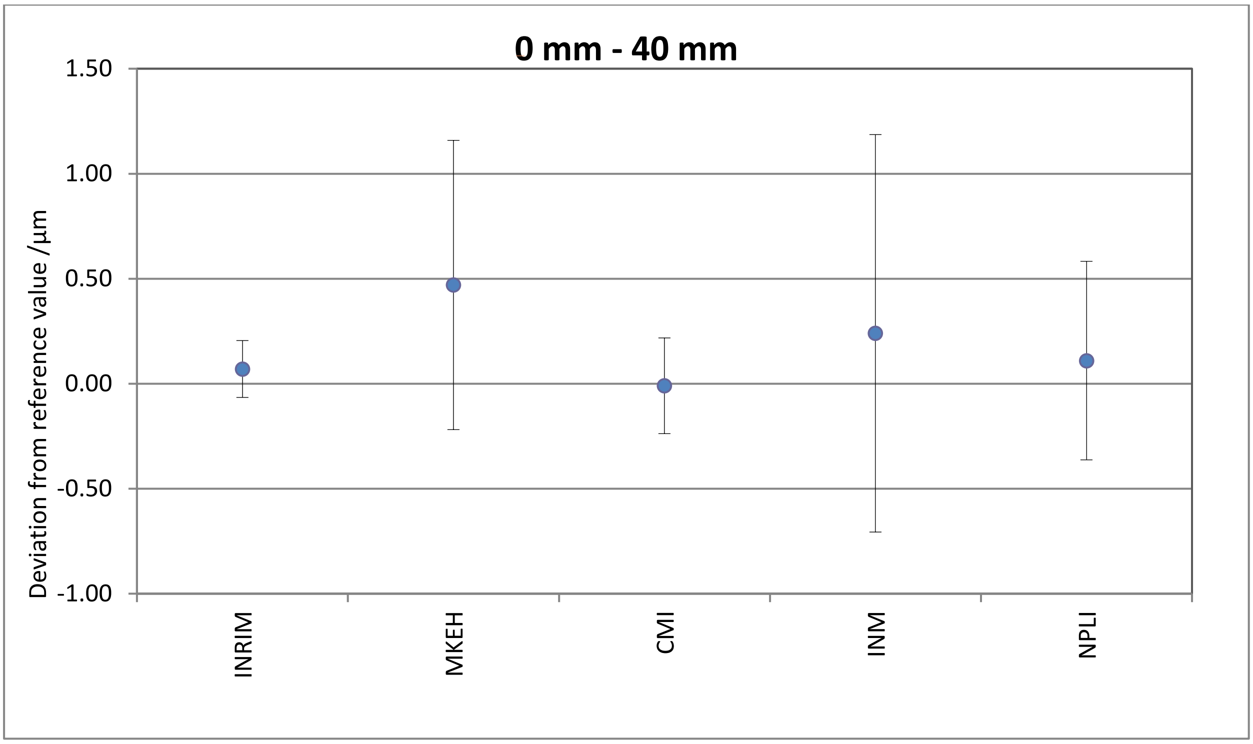


Figure 80: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

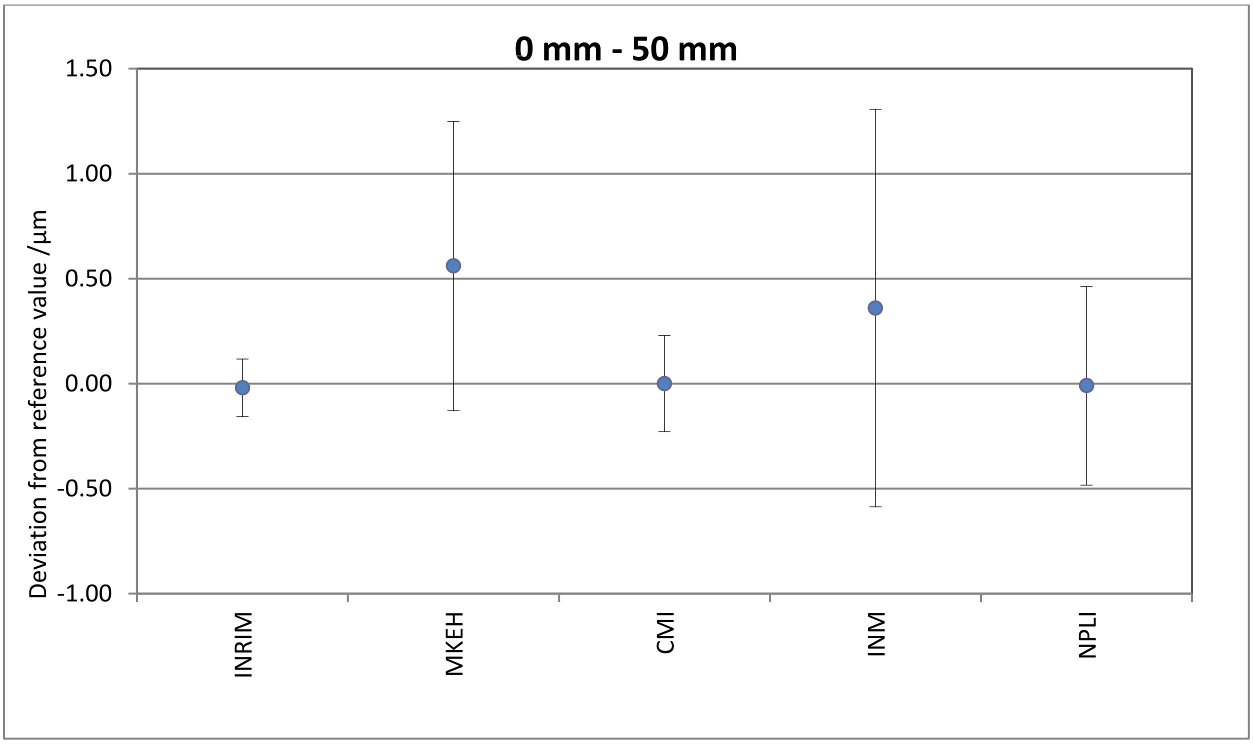


Figure 81: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

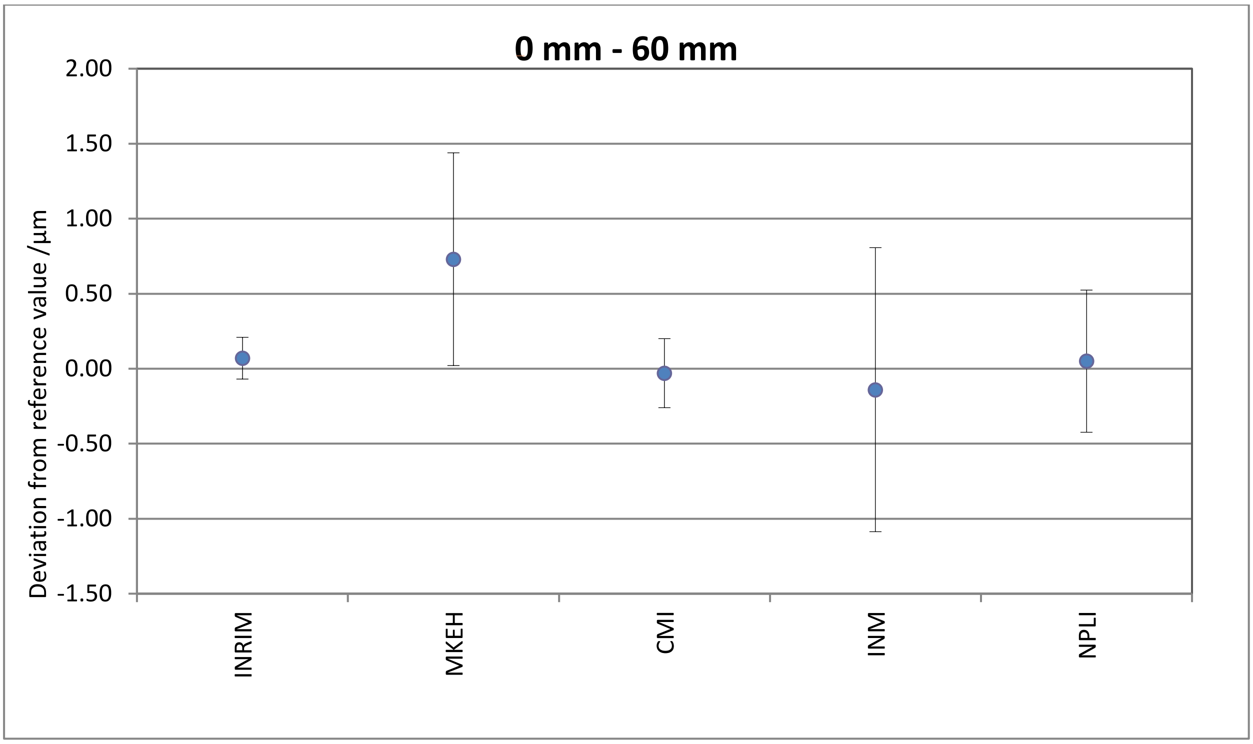


Figure 82: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

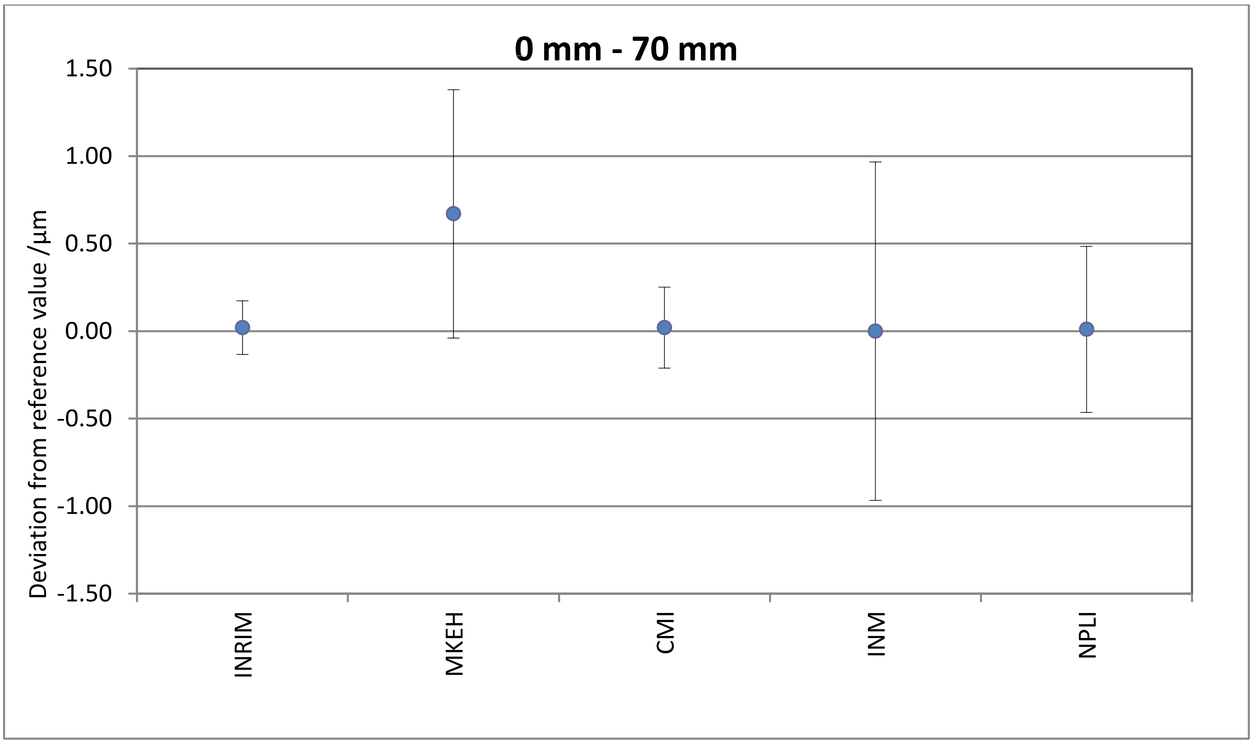


Figure 83: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

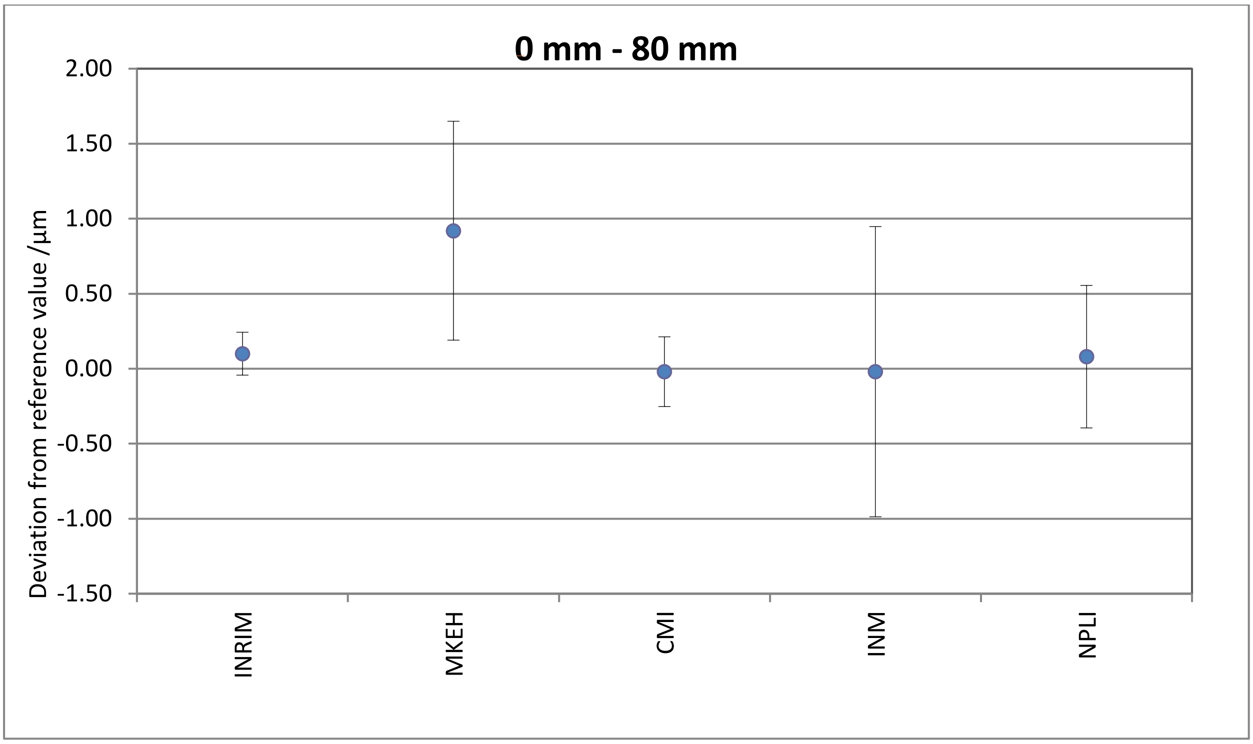


Figure 84: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

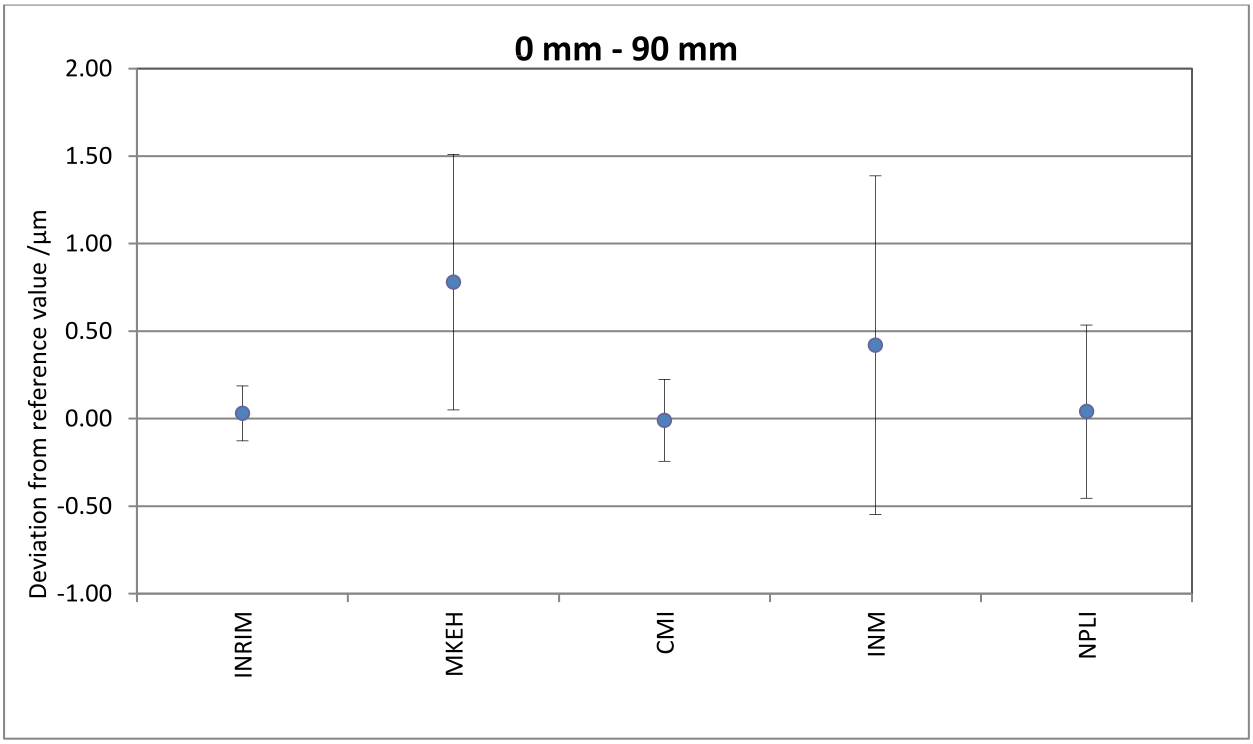


Figure 85: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

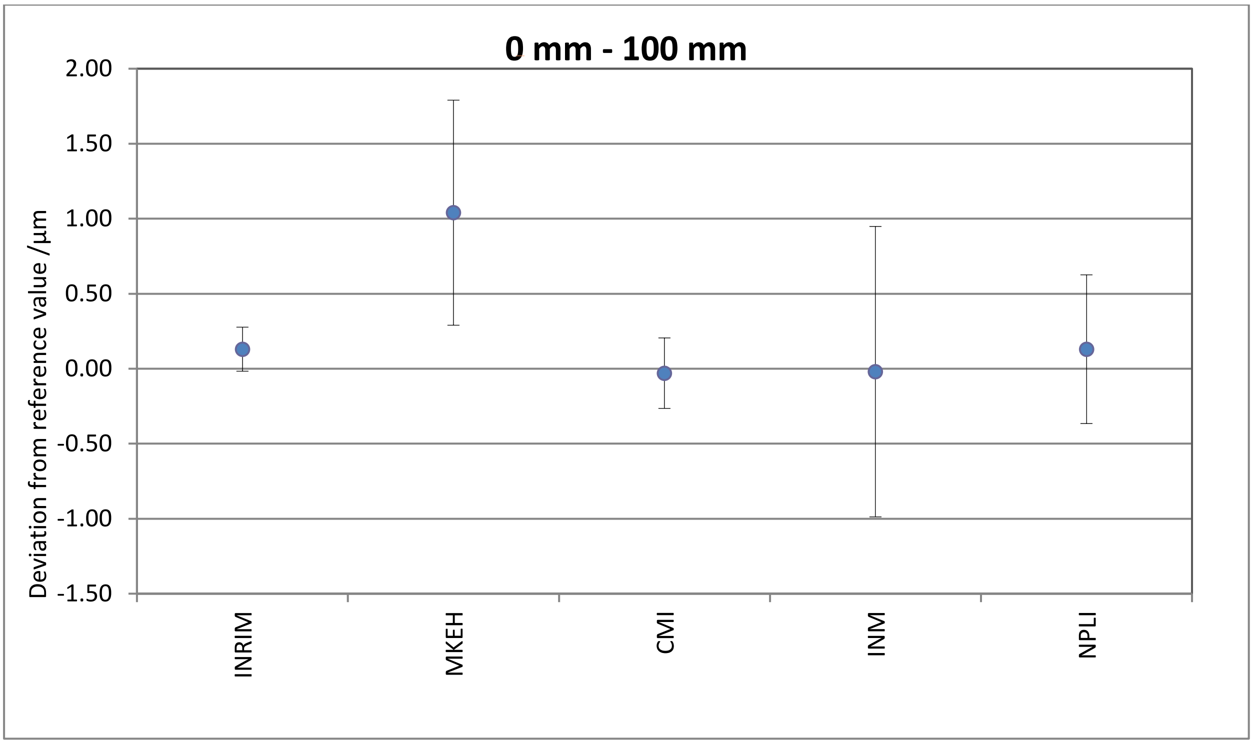


Figure 86: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

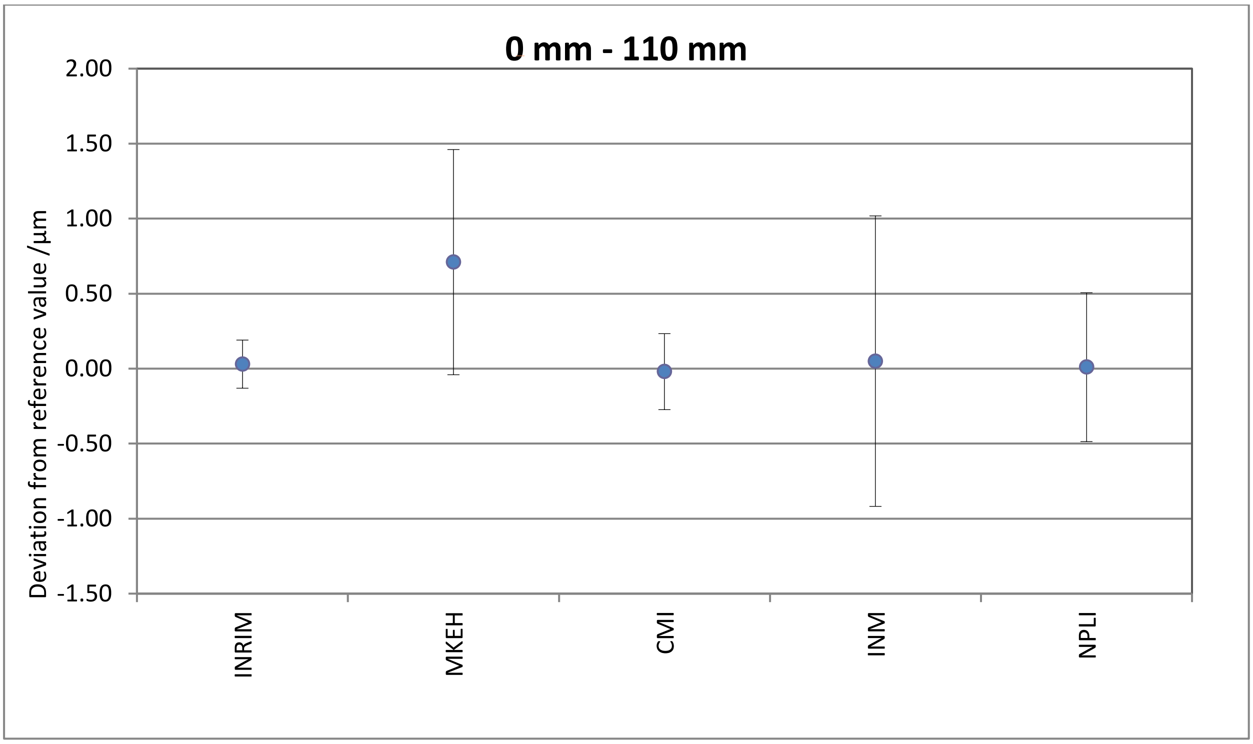


Figure 87: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

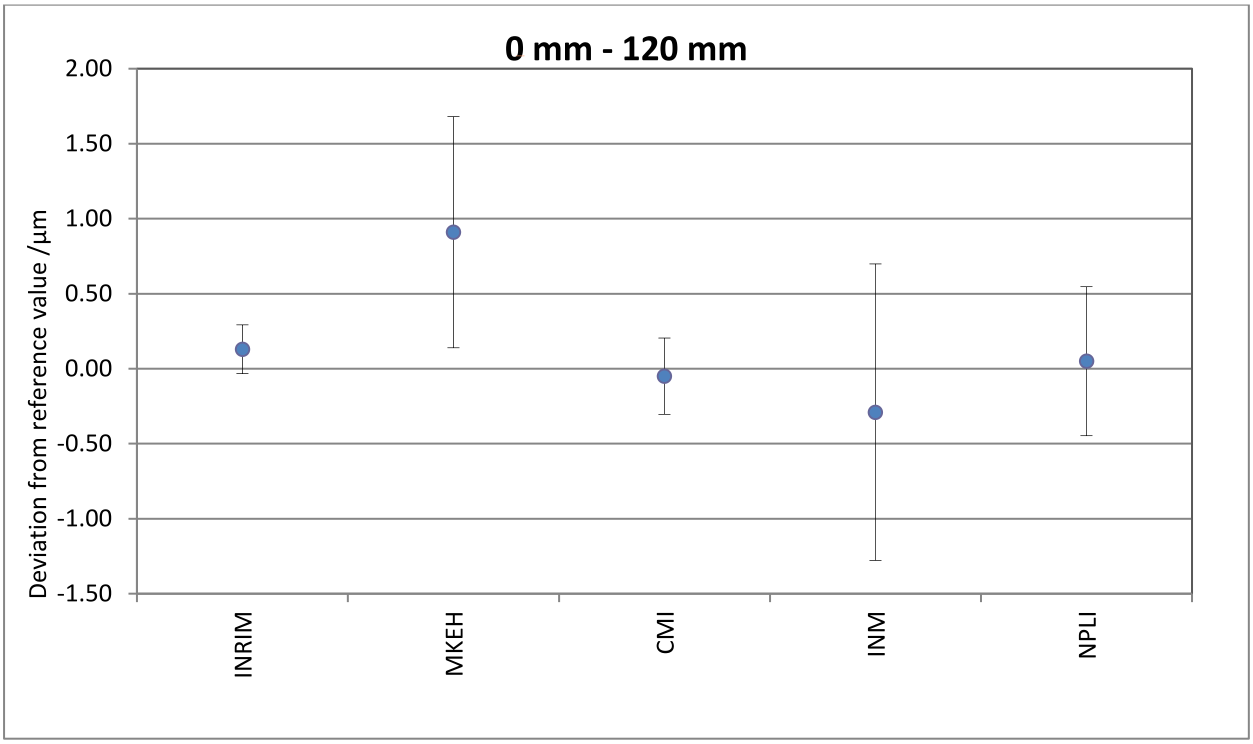


Figure 88: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

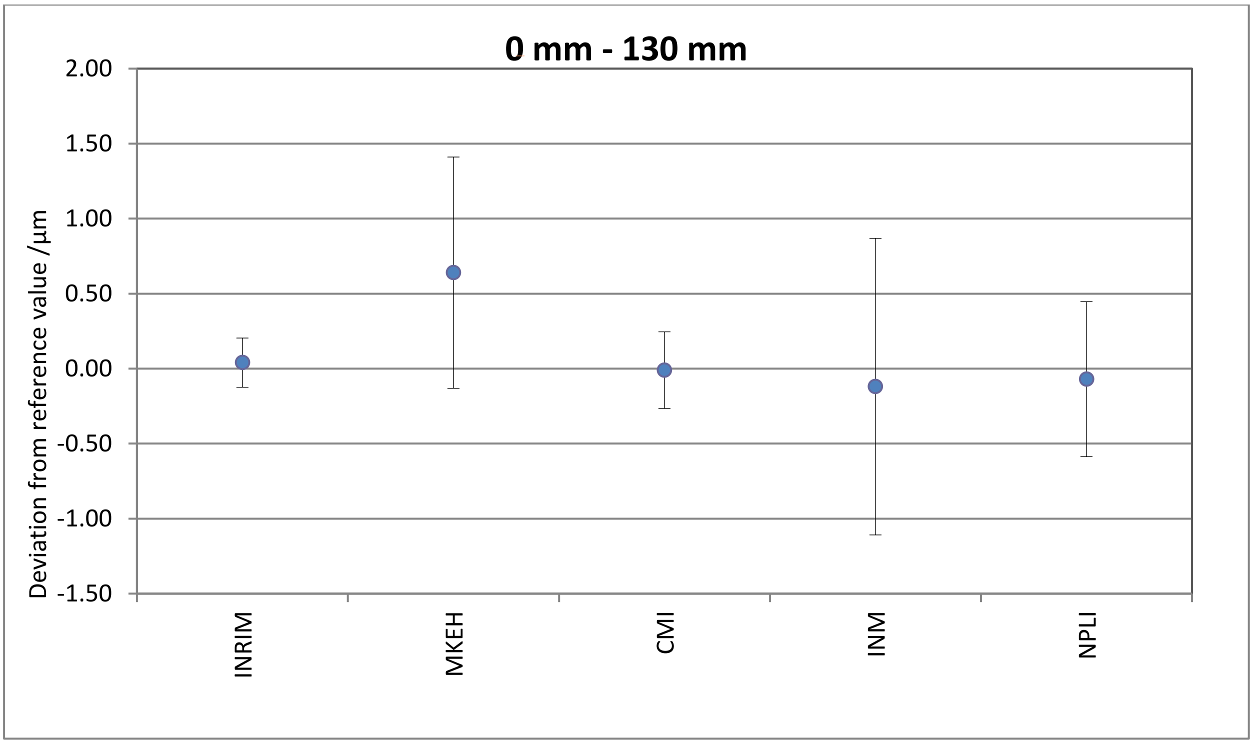


Figure 89: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

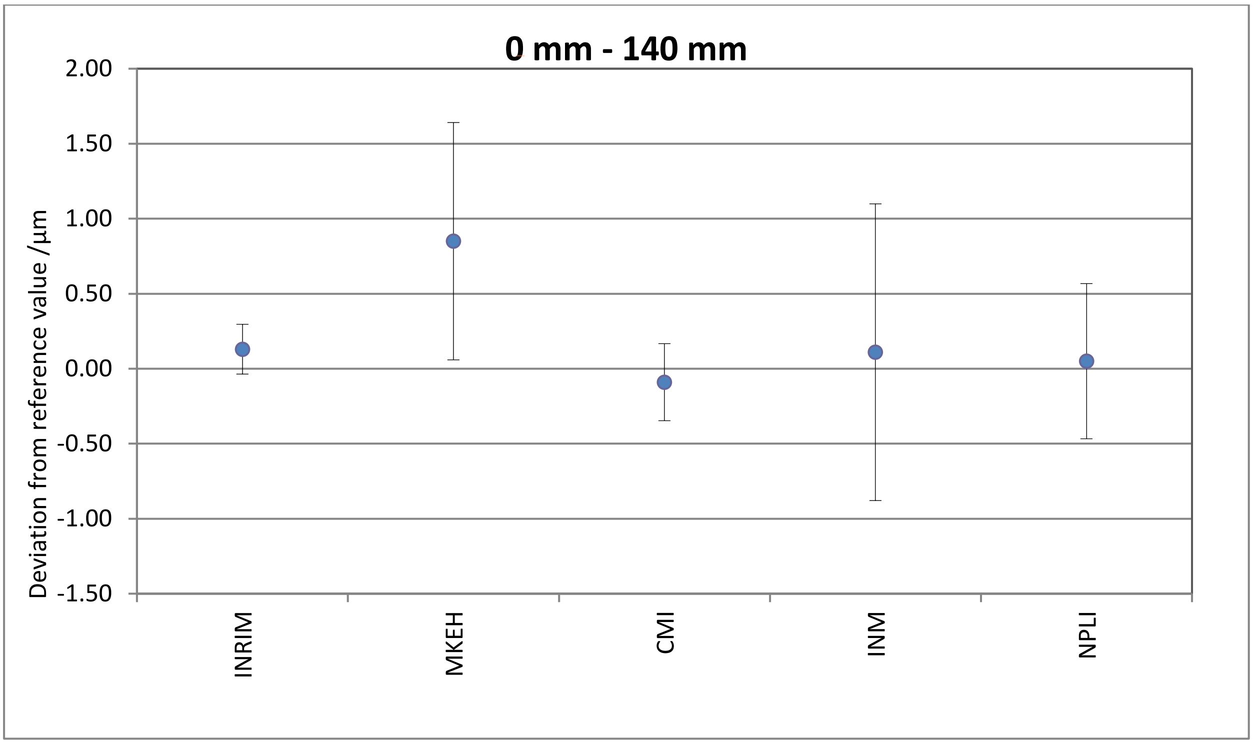


Figure 90: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

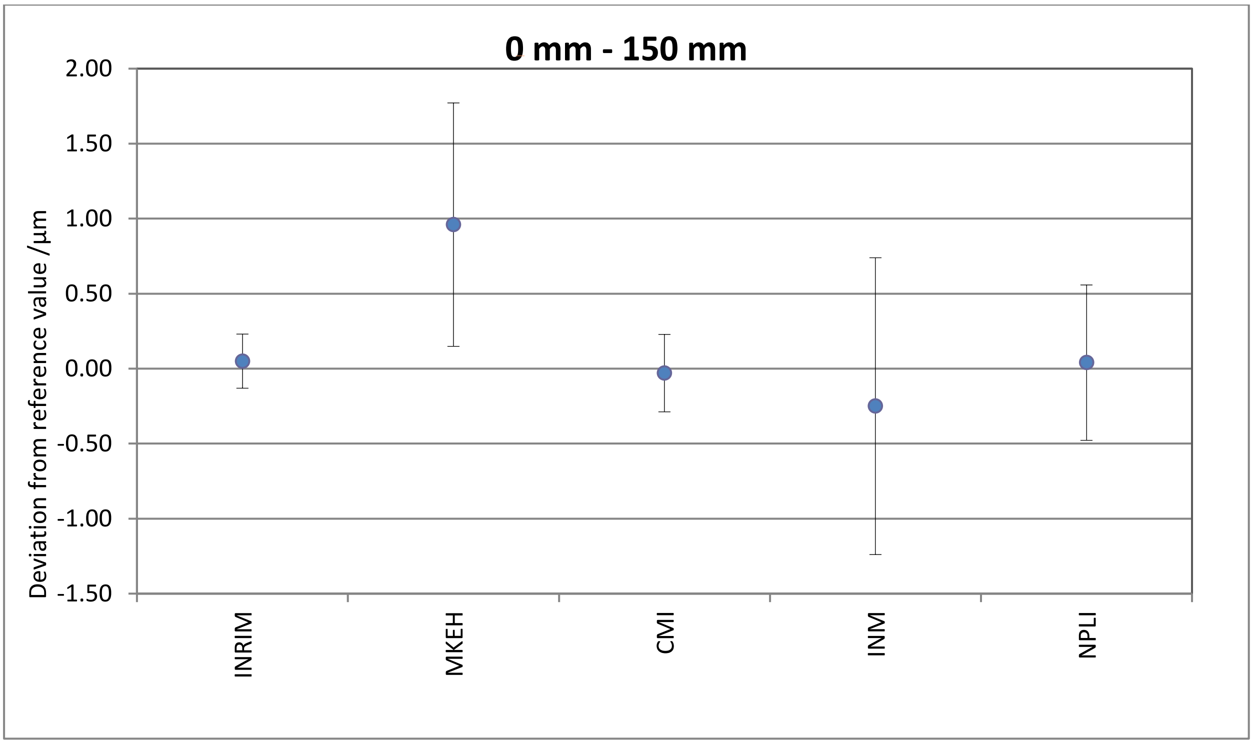


Figure 91: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

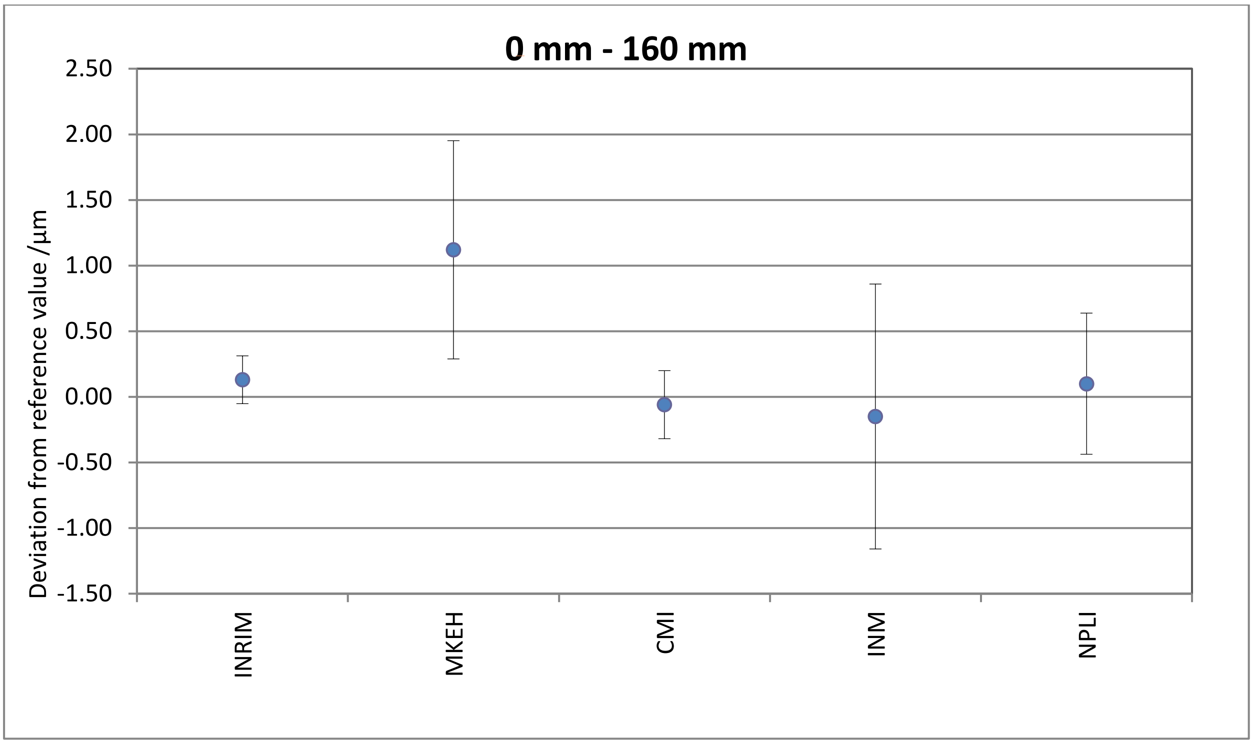


Figure 92: 610 mm artefact, group 1 participant deviations from reference value for this interval (k = 2)

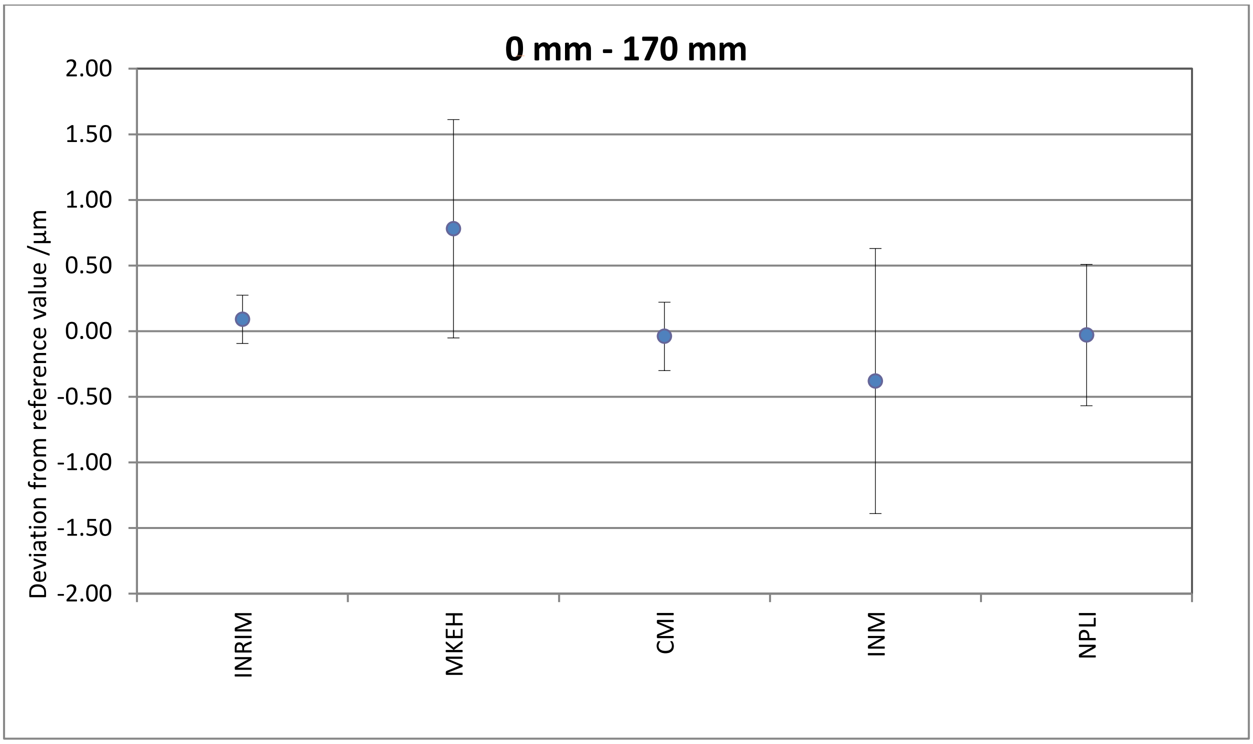


Figure 93: 610 mm artefact, group 1 participant deviations from reference value for this interval (k = 2)

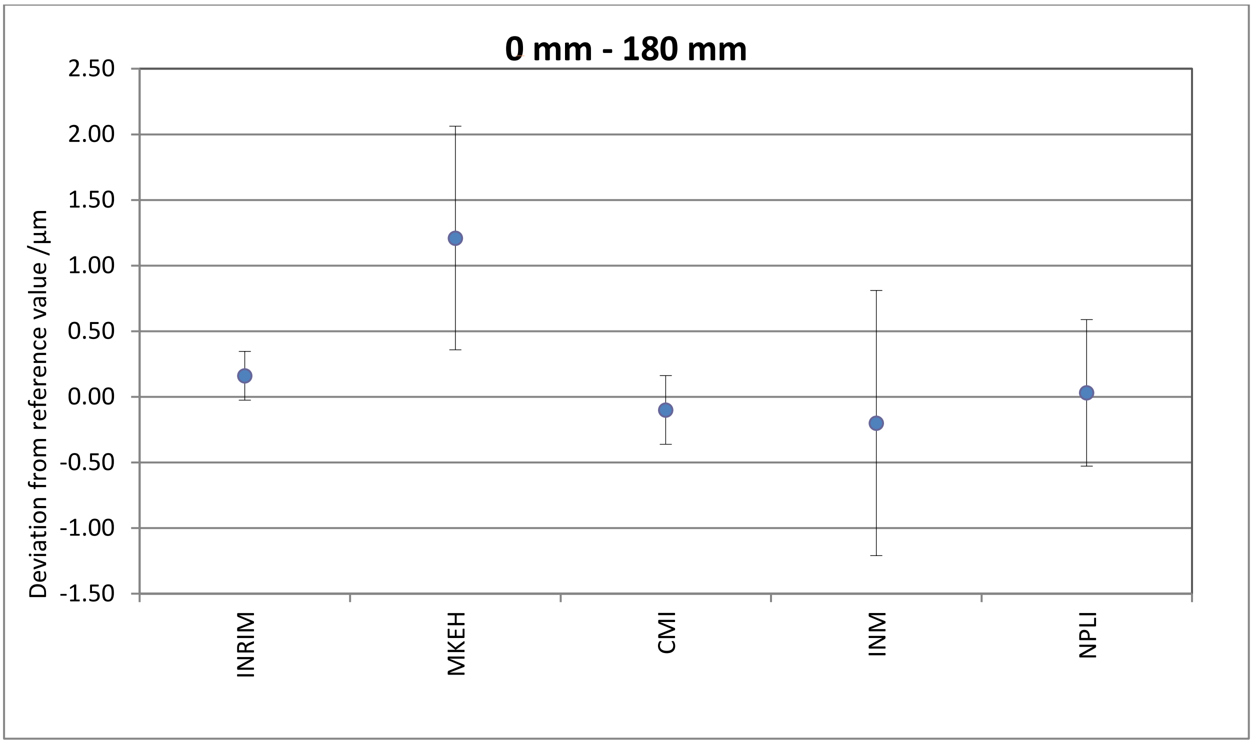


Figure 94: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

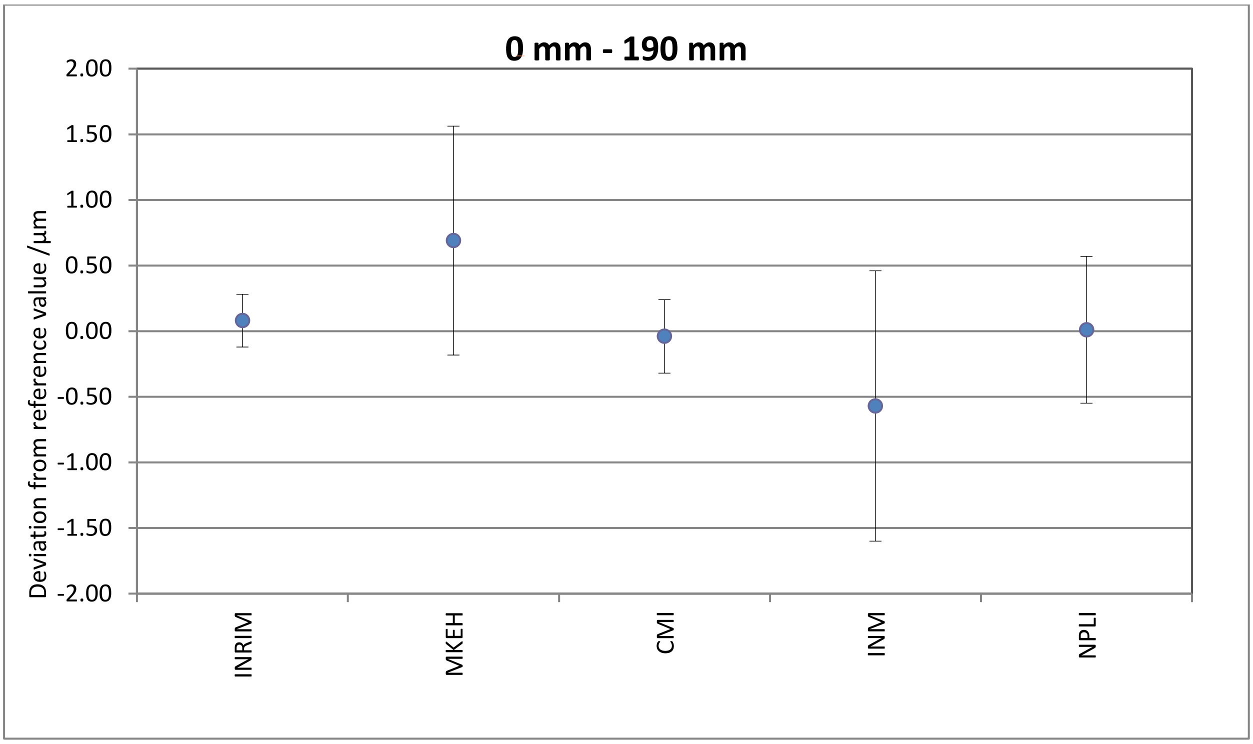


Figure 95: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

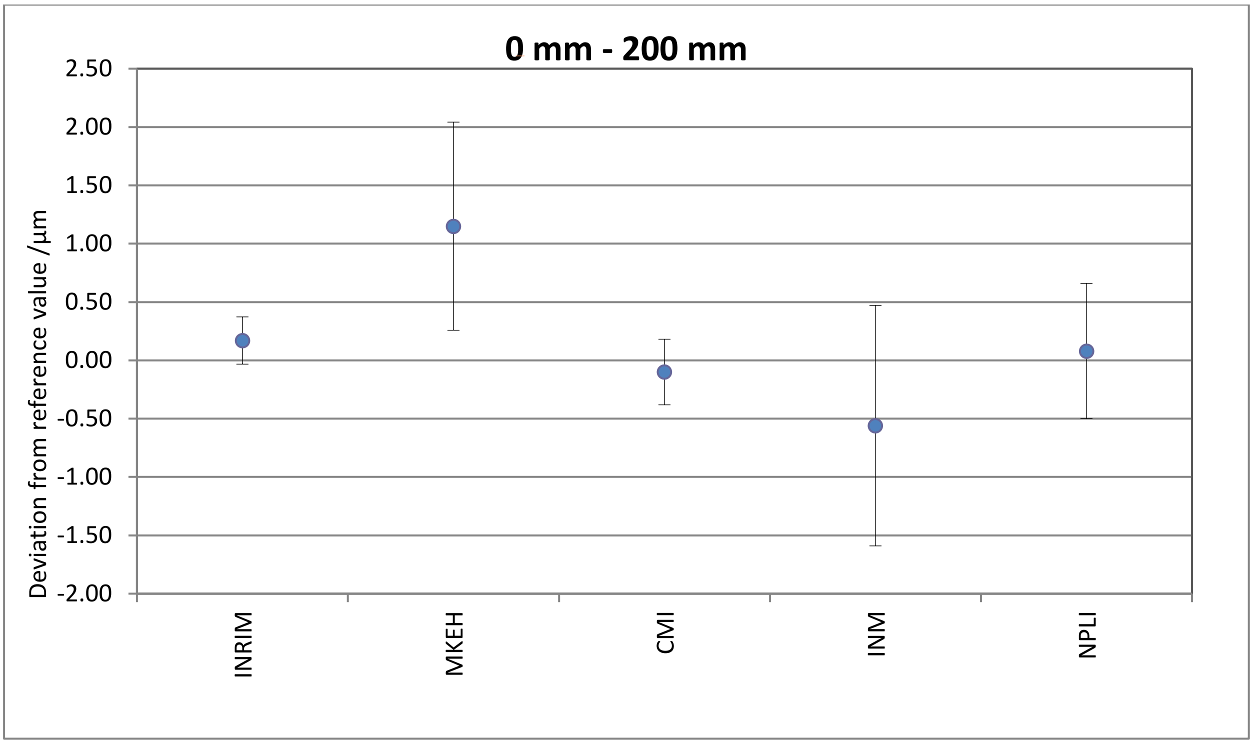


Figure 96: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

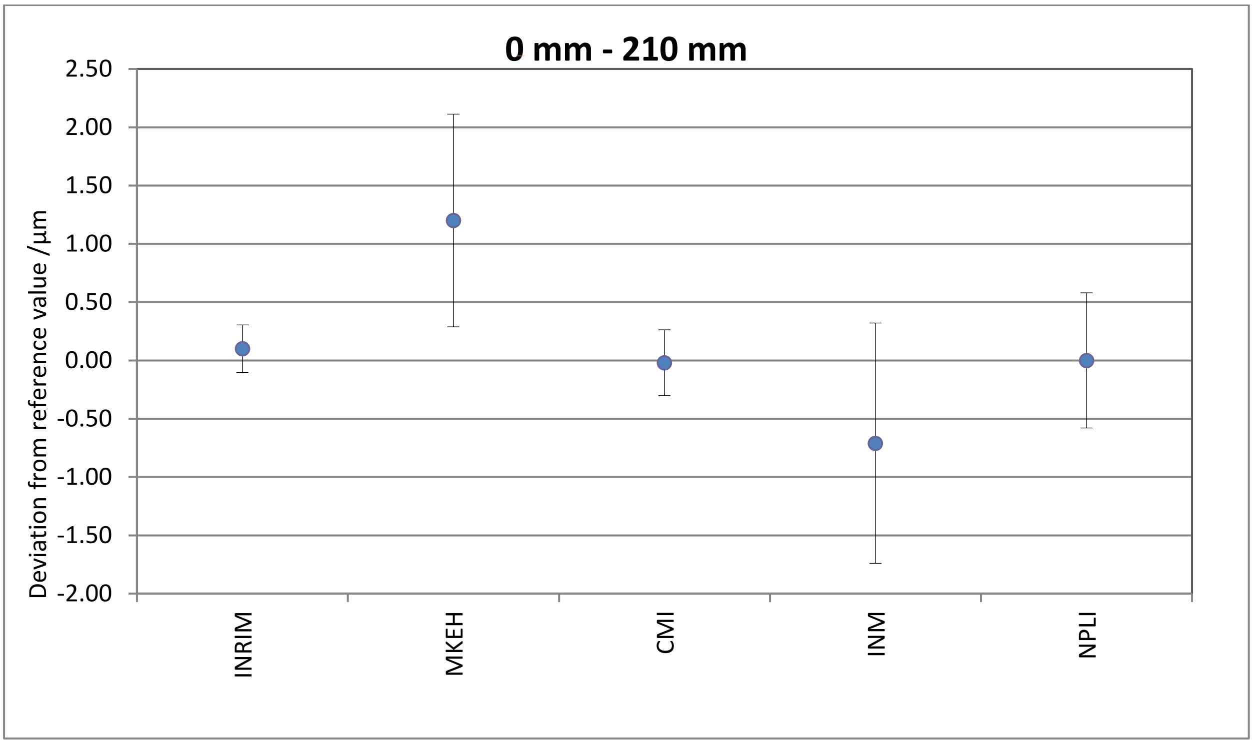


Figure 97: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

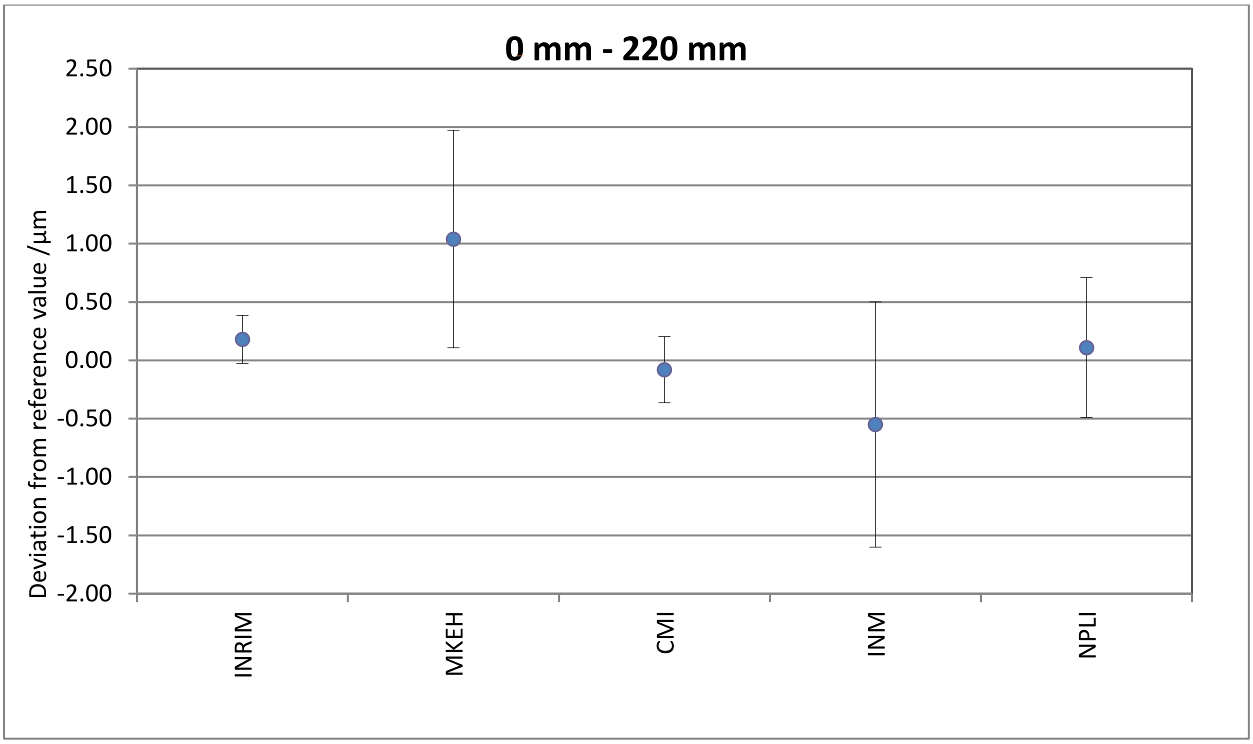


Figure 98: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

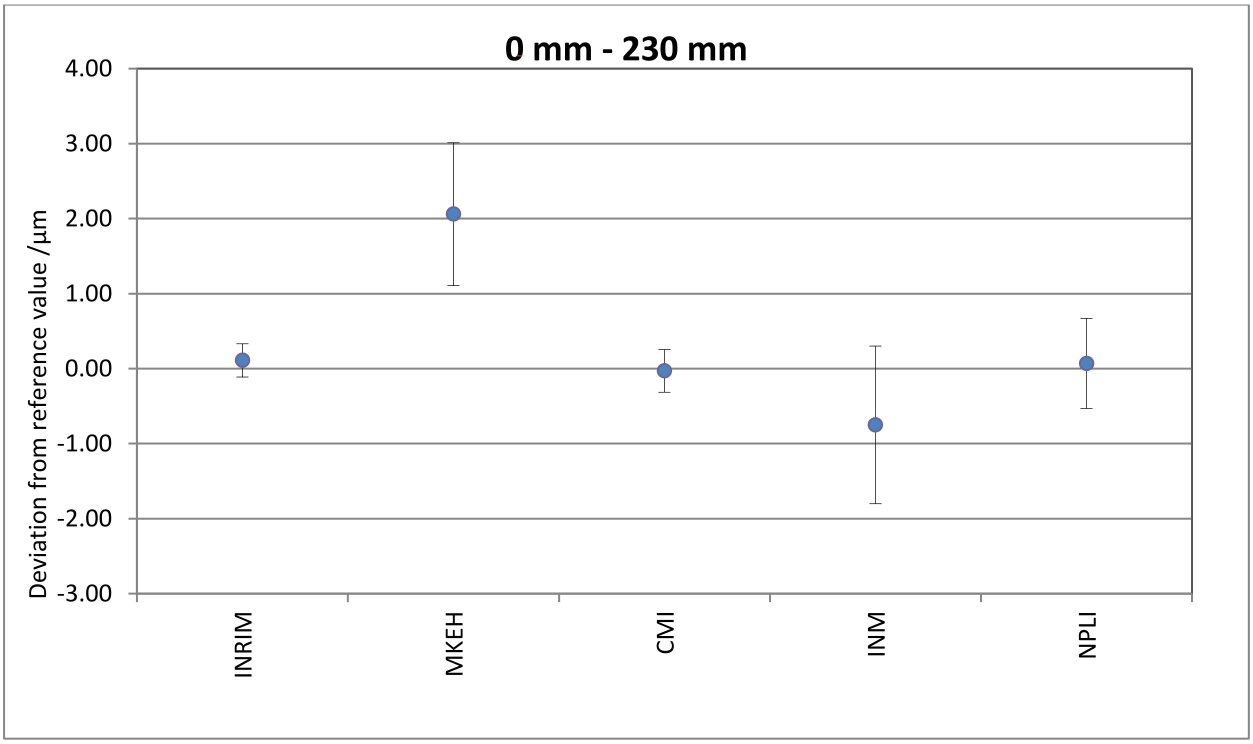


Figure 99: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

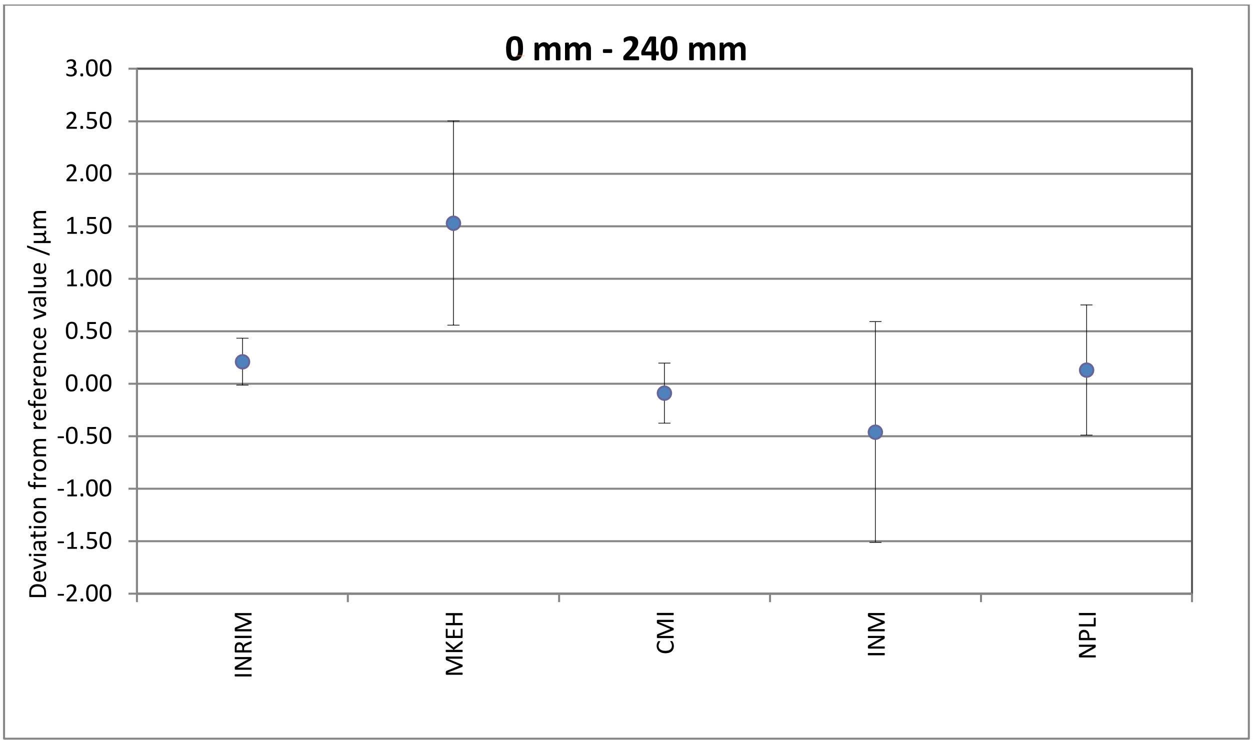


Figure 100: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

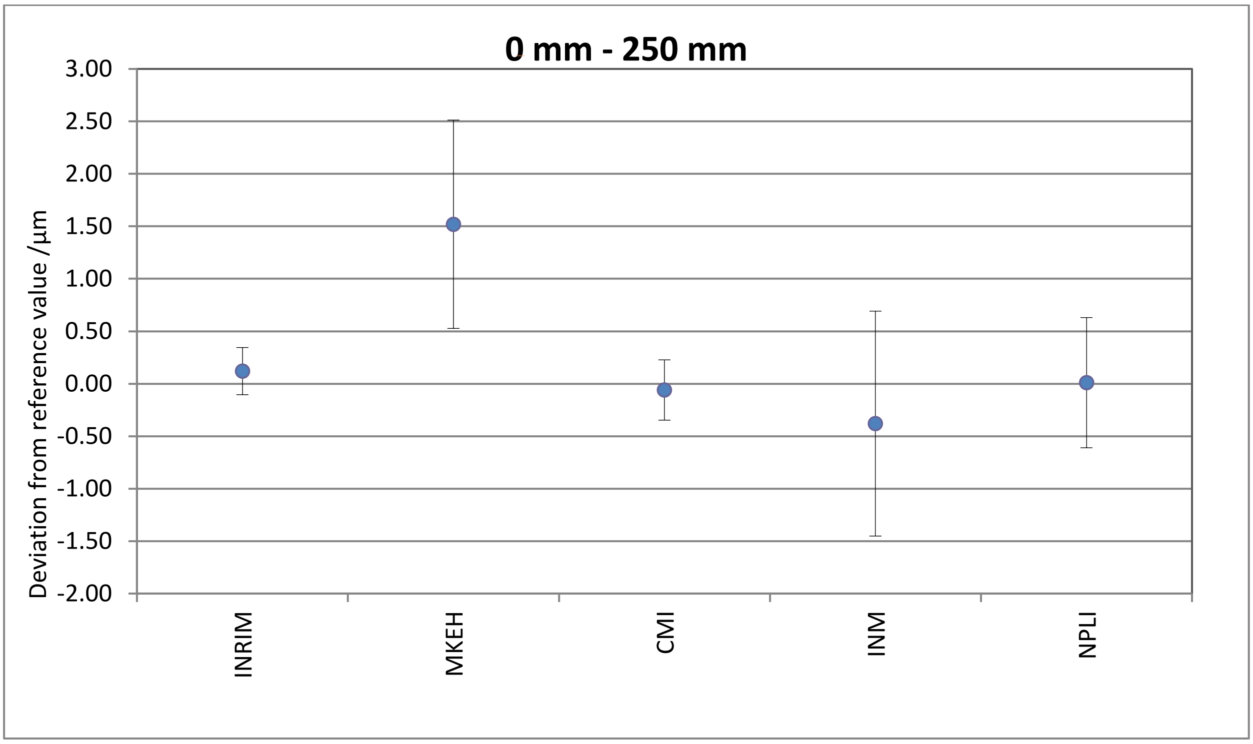


Figure 101: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

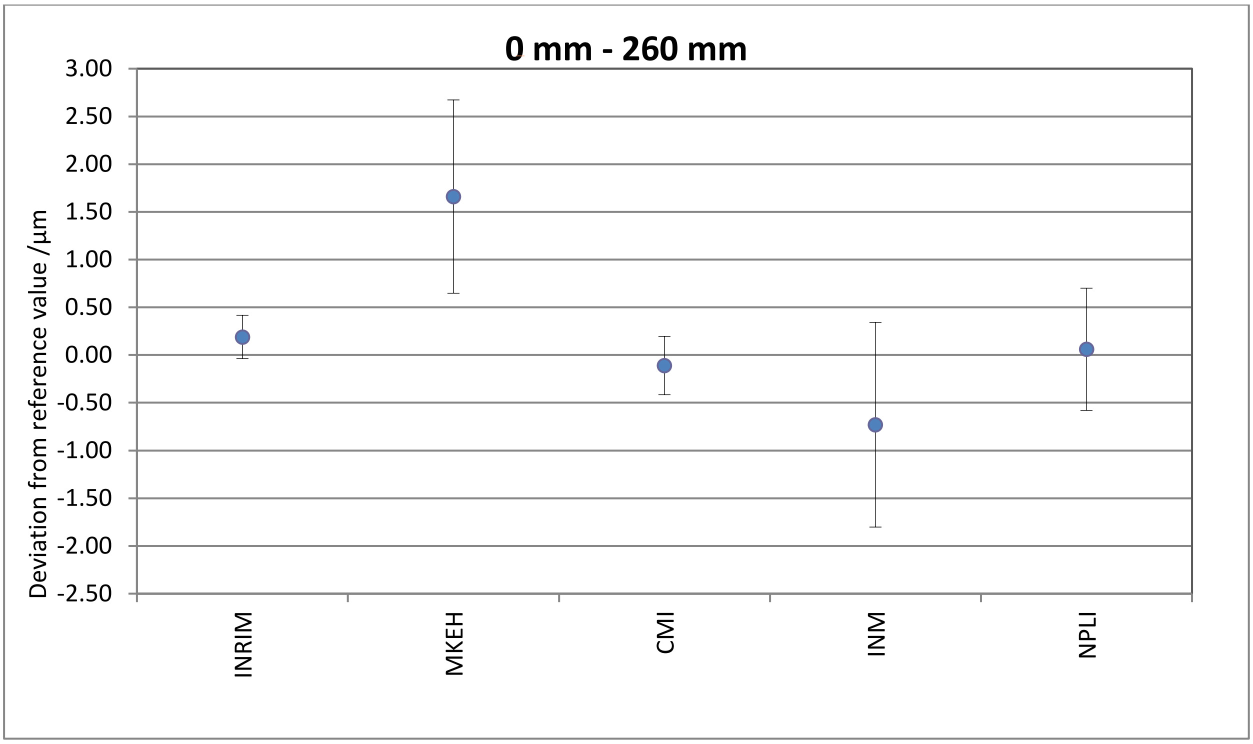


Figure 102: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

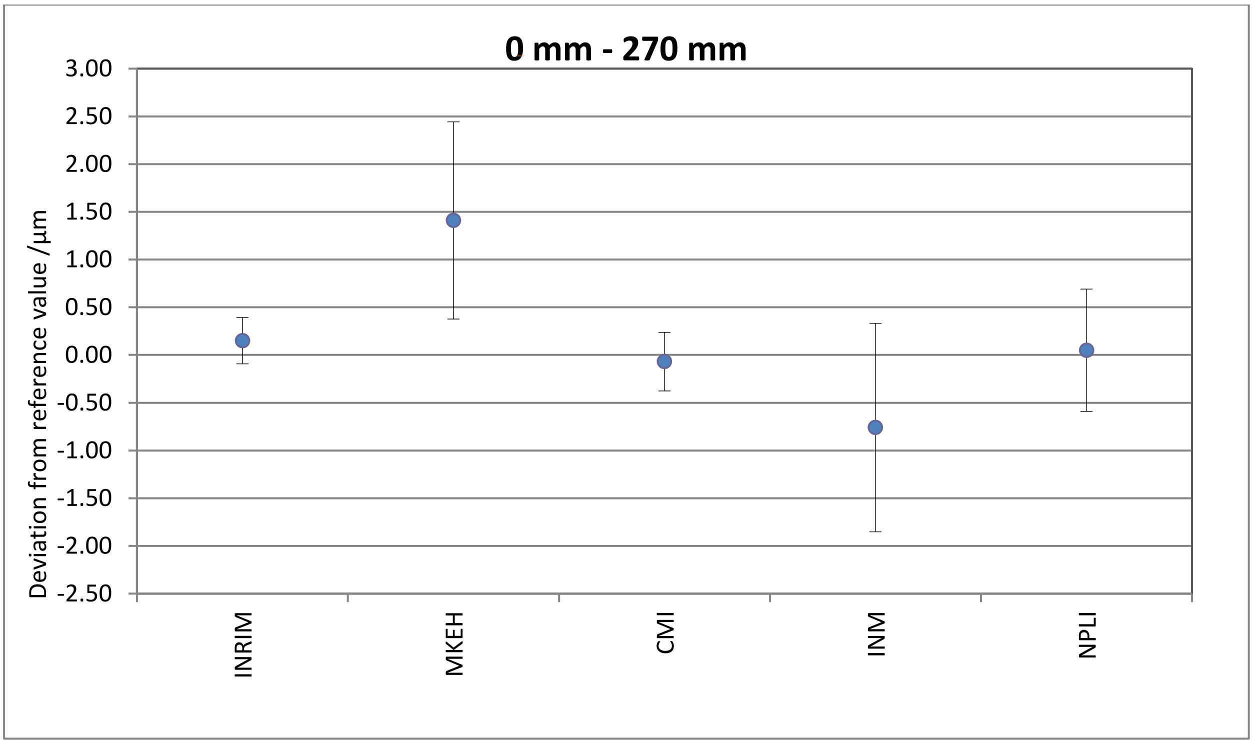


Figure 103: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

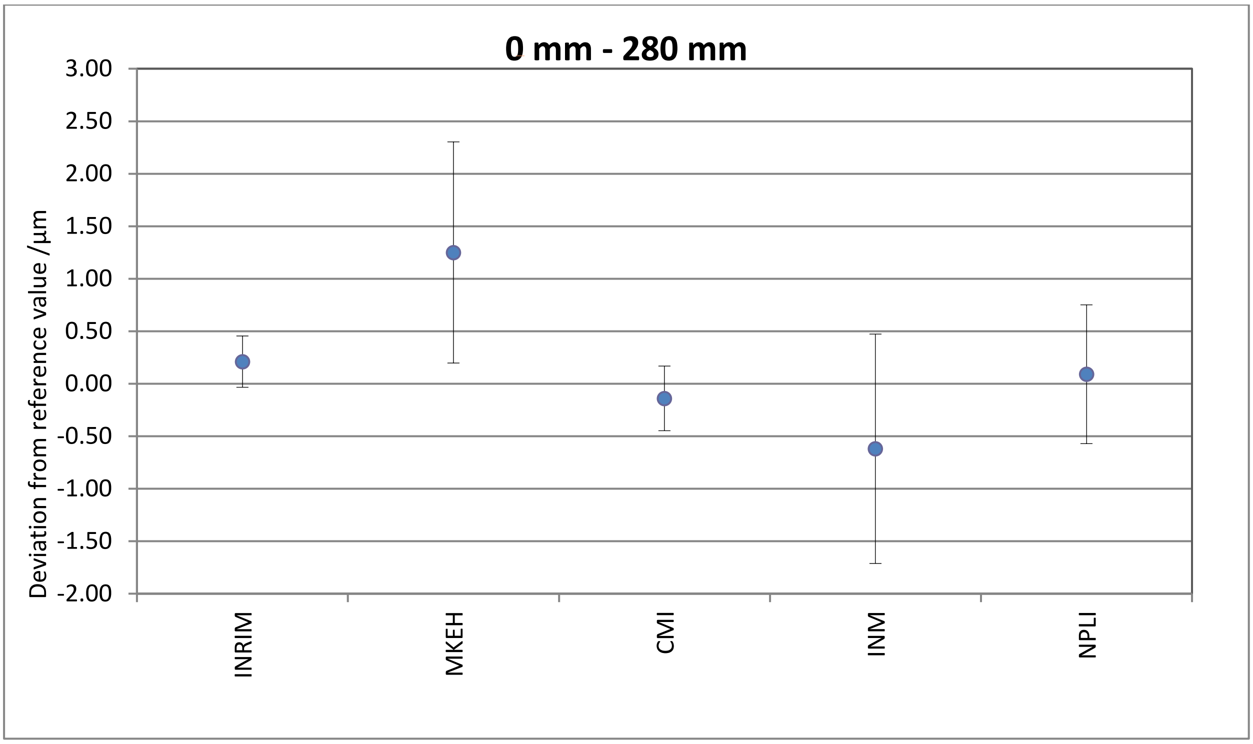


Figure 104: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

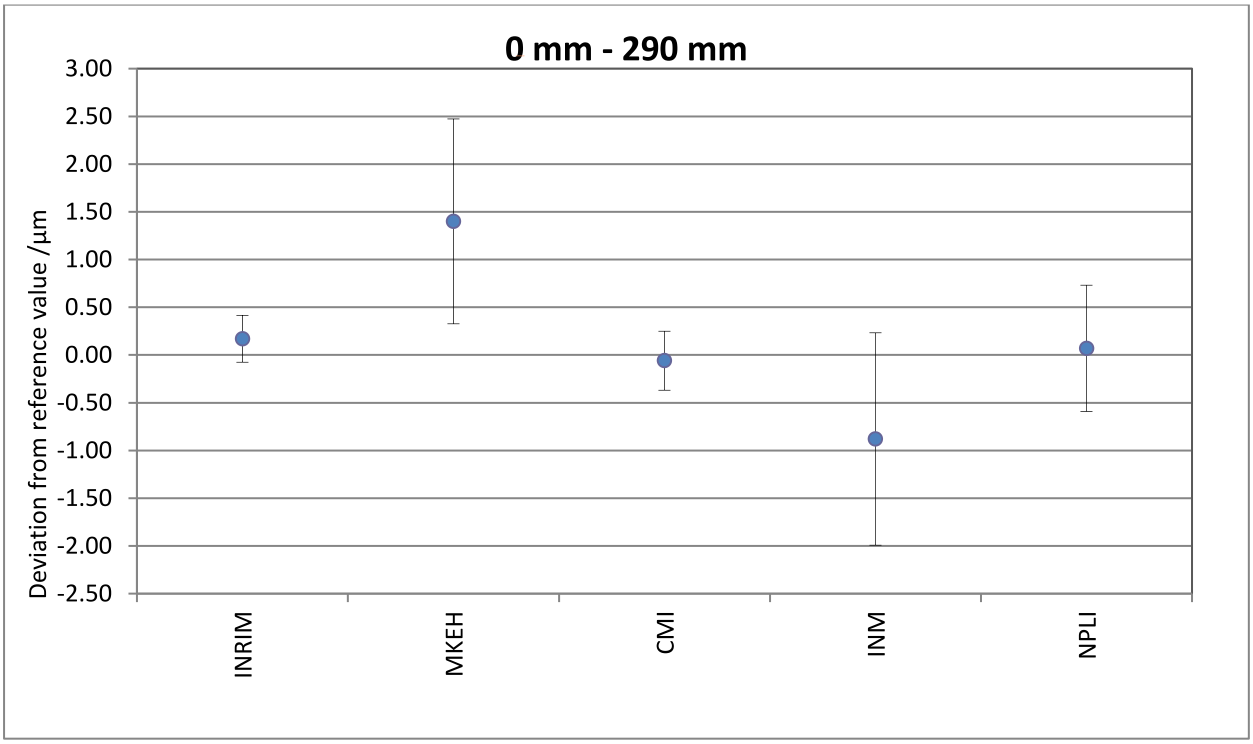


Figure 105: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

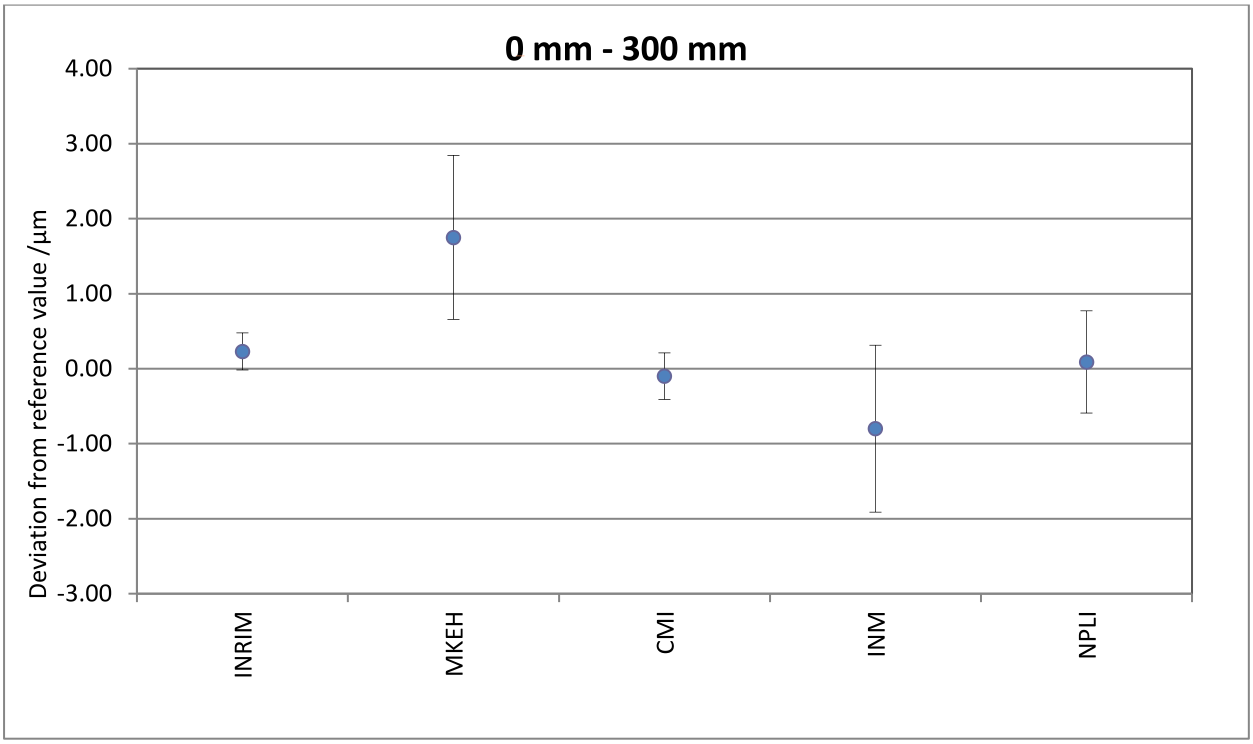


Figure 106: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

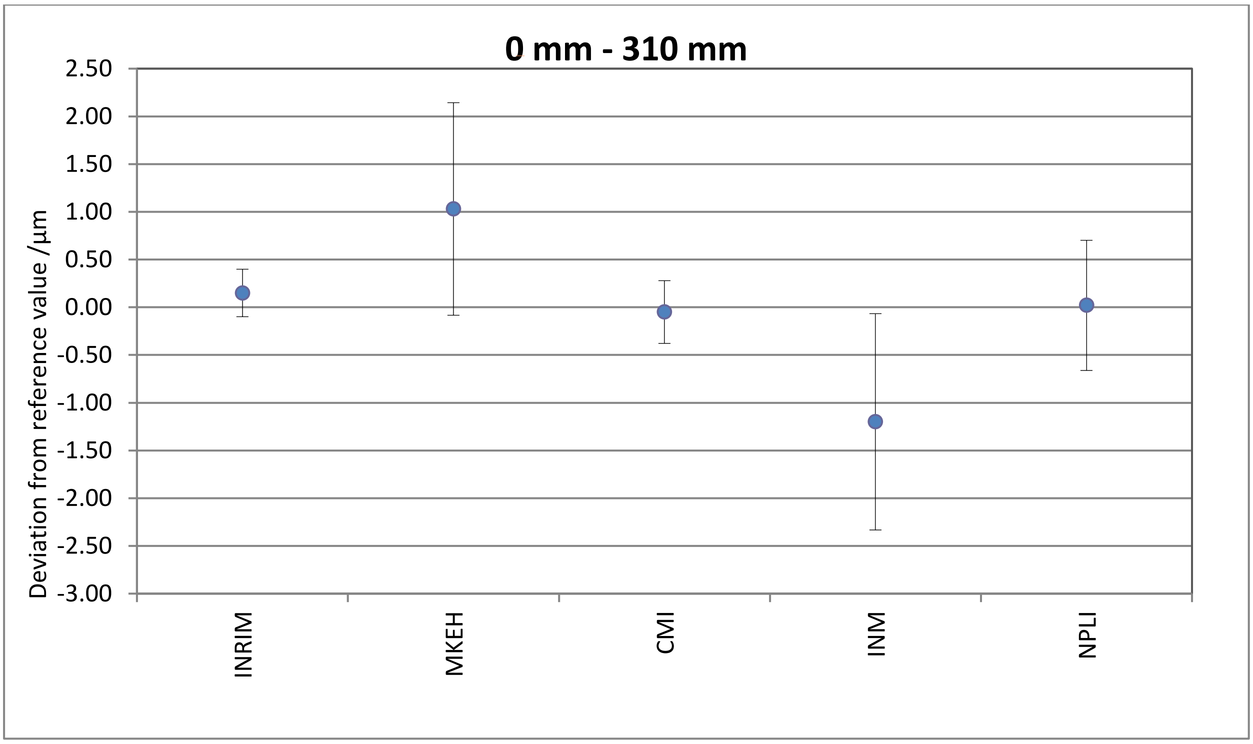


Figure 107: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

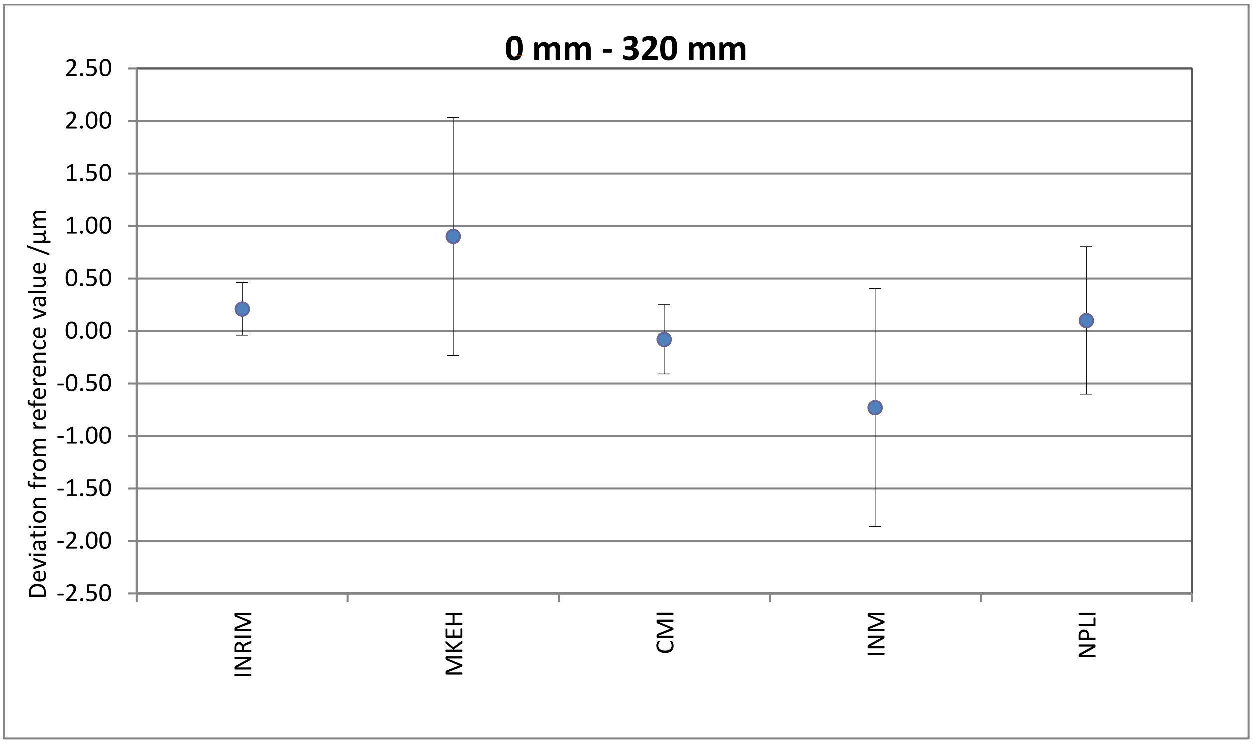


Figure 108: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

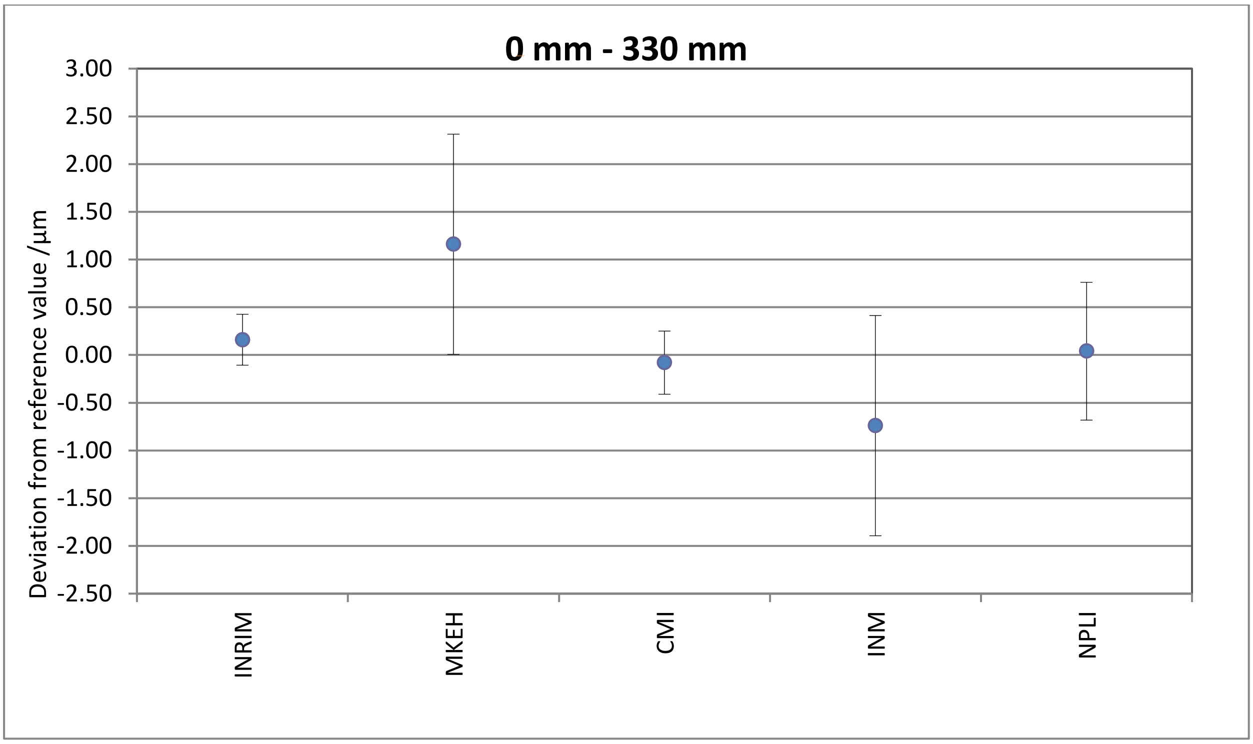


Figure 109: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

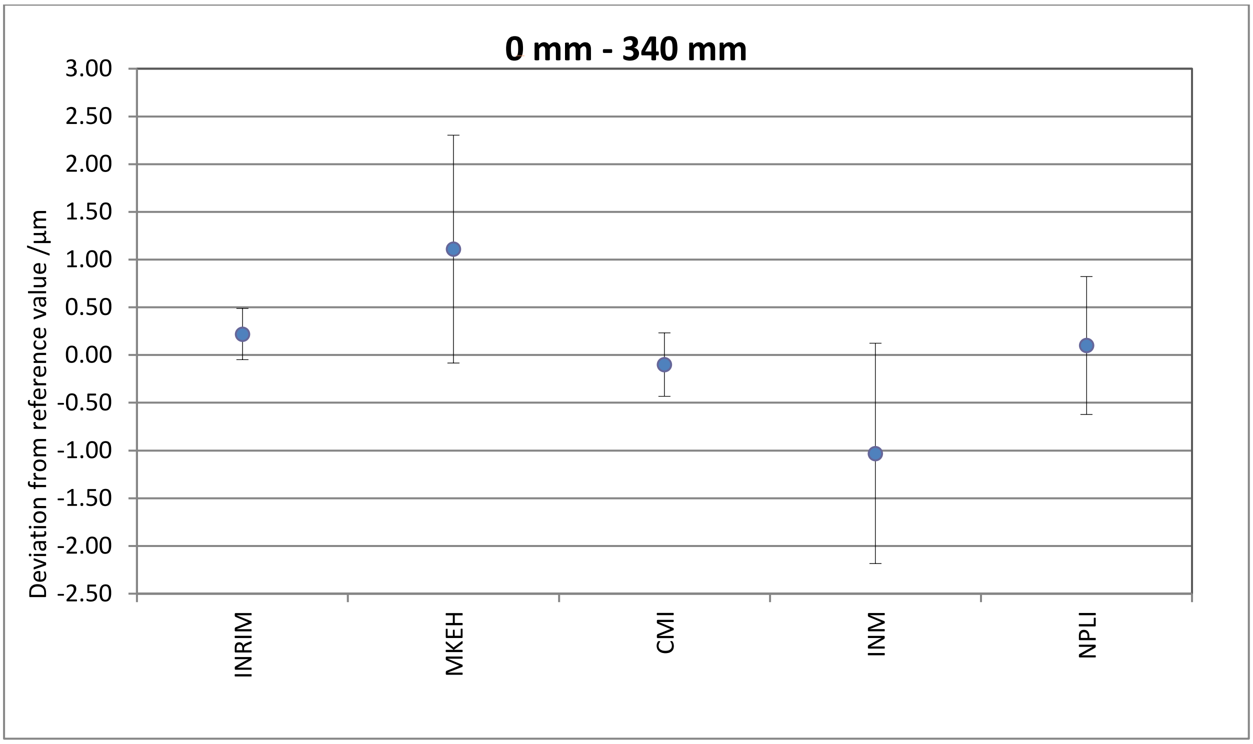


Figure 110: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

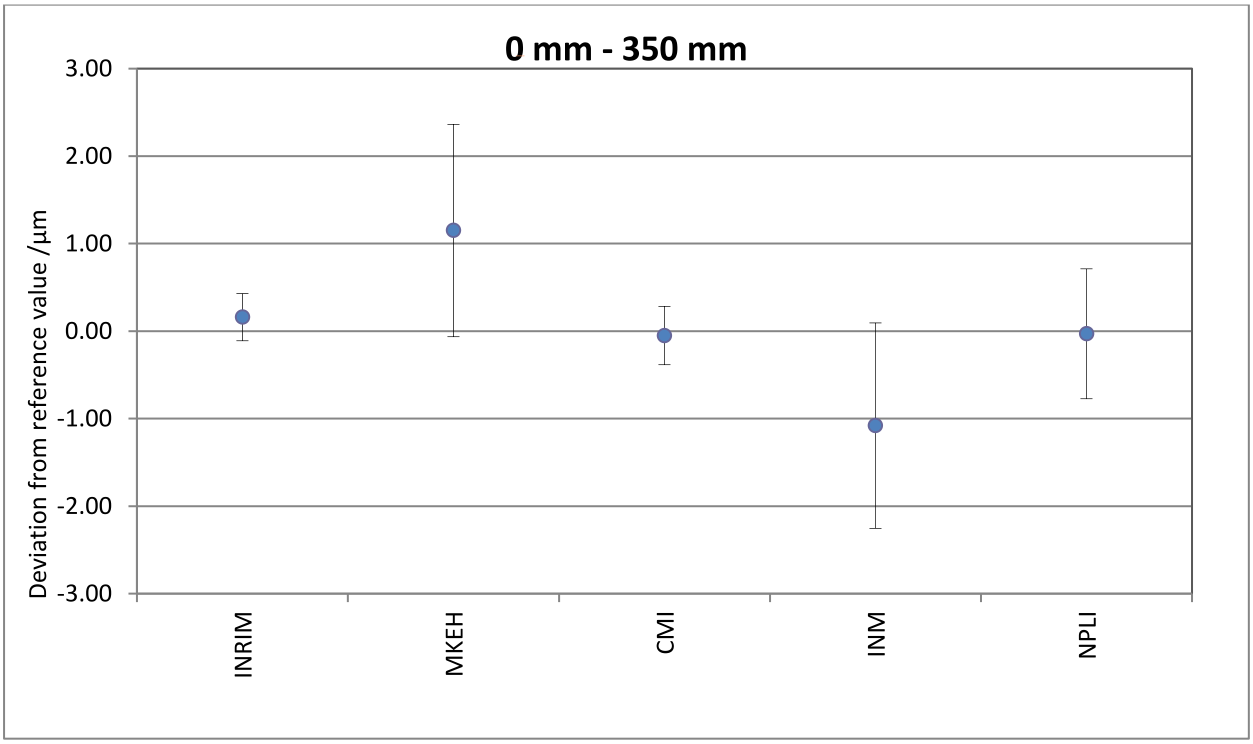


Figure 111: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

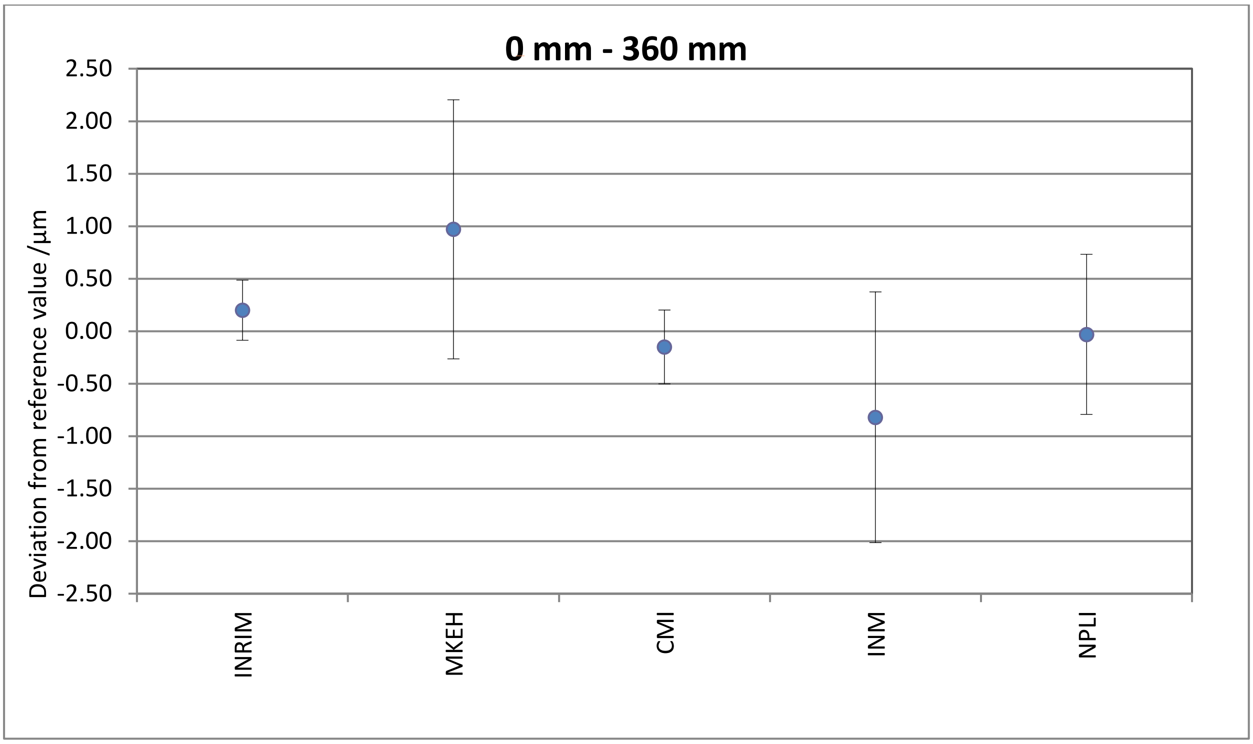


Figure 112: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

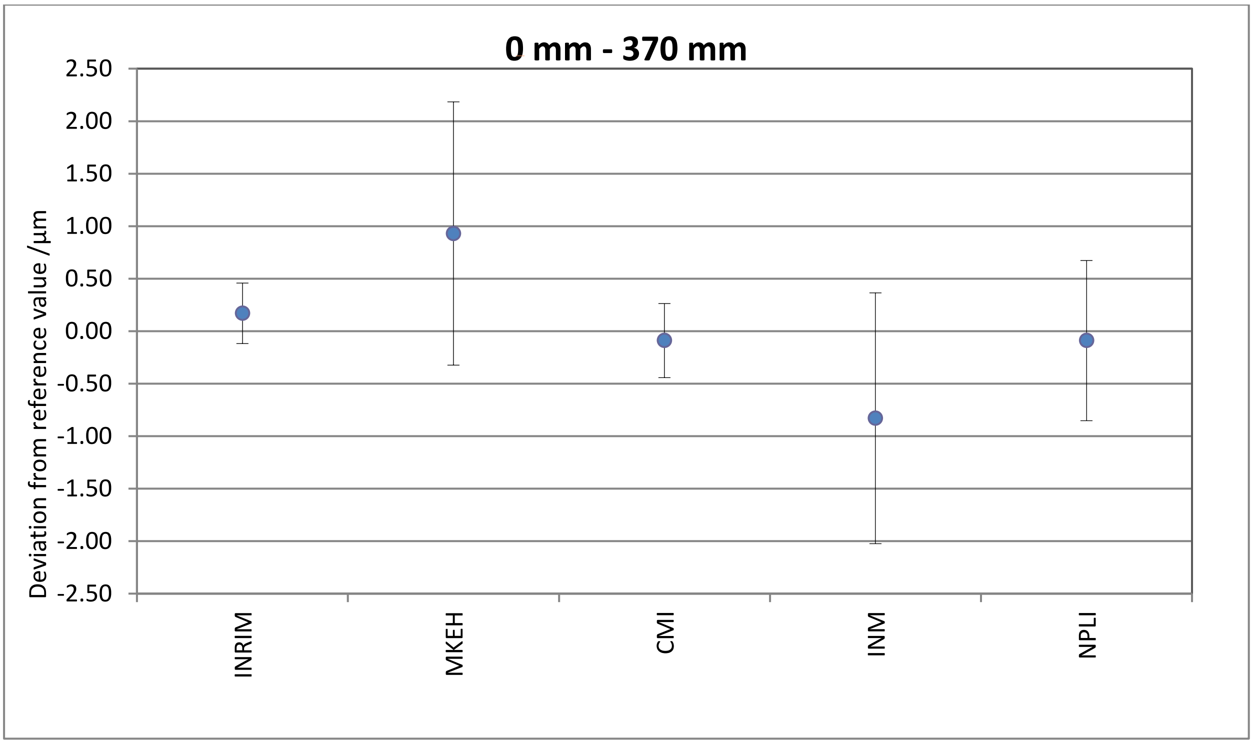


Figure 113: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

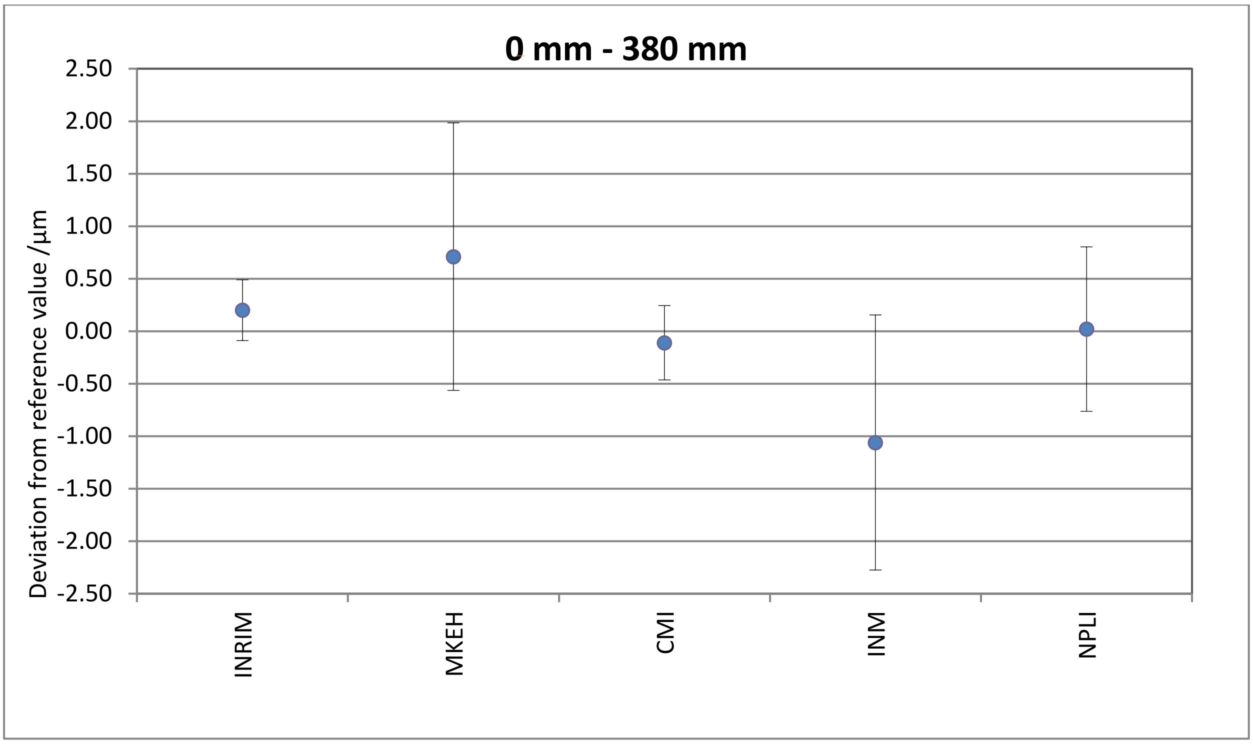


Figure 114: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

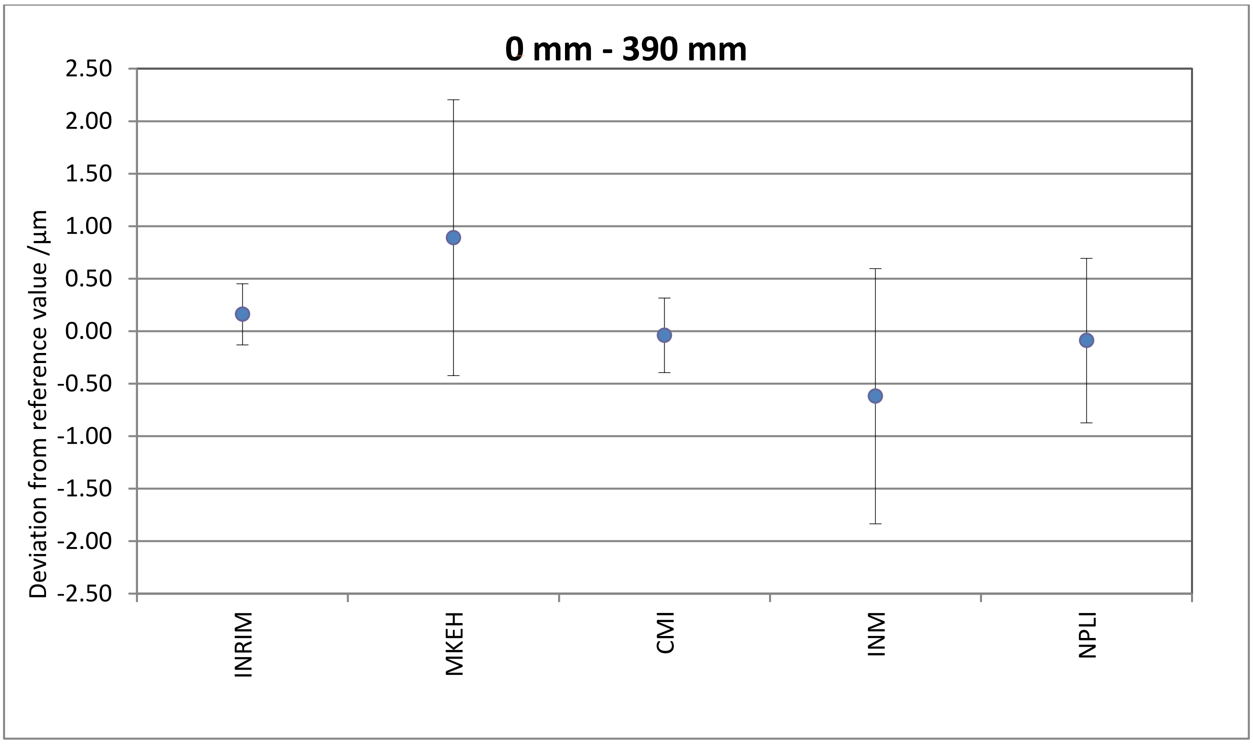


Figure 115: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

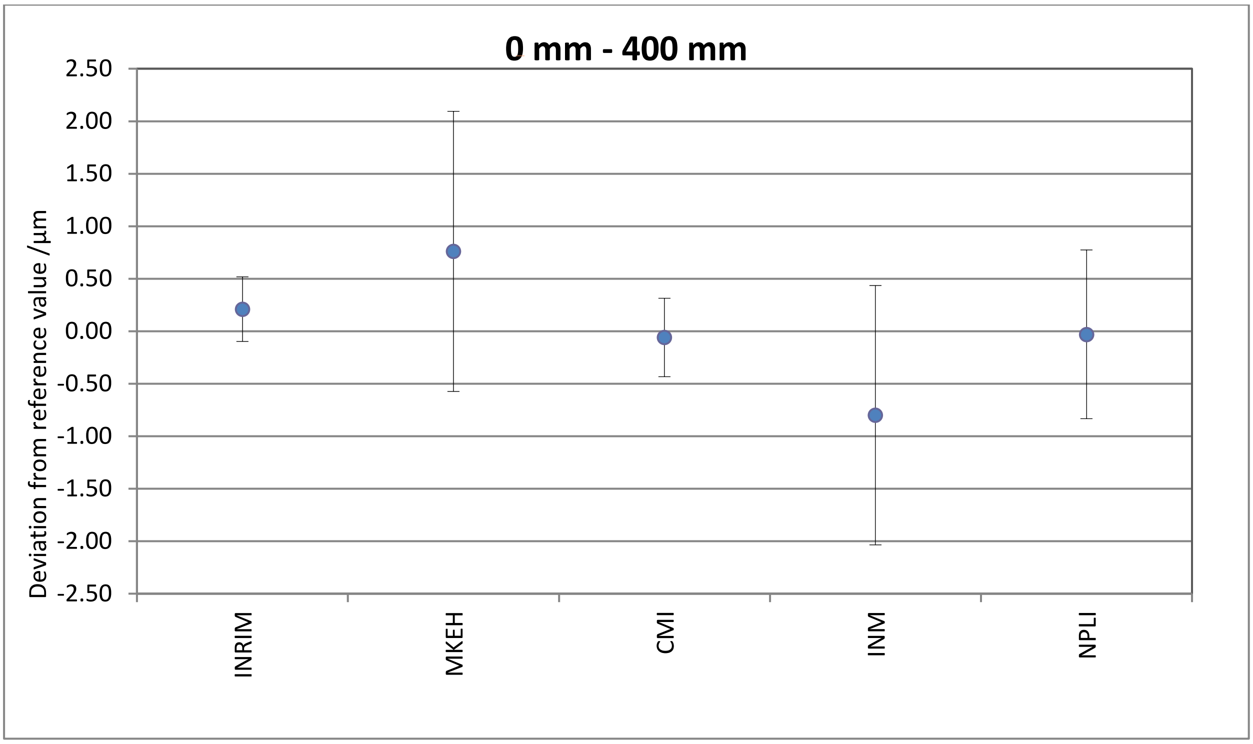


Figure 116: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

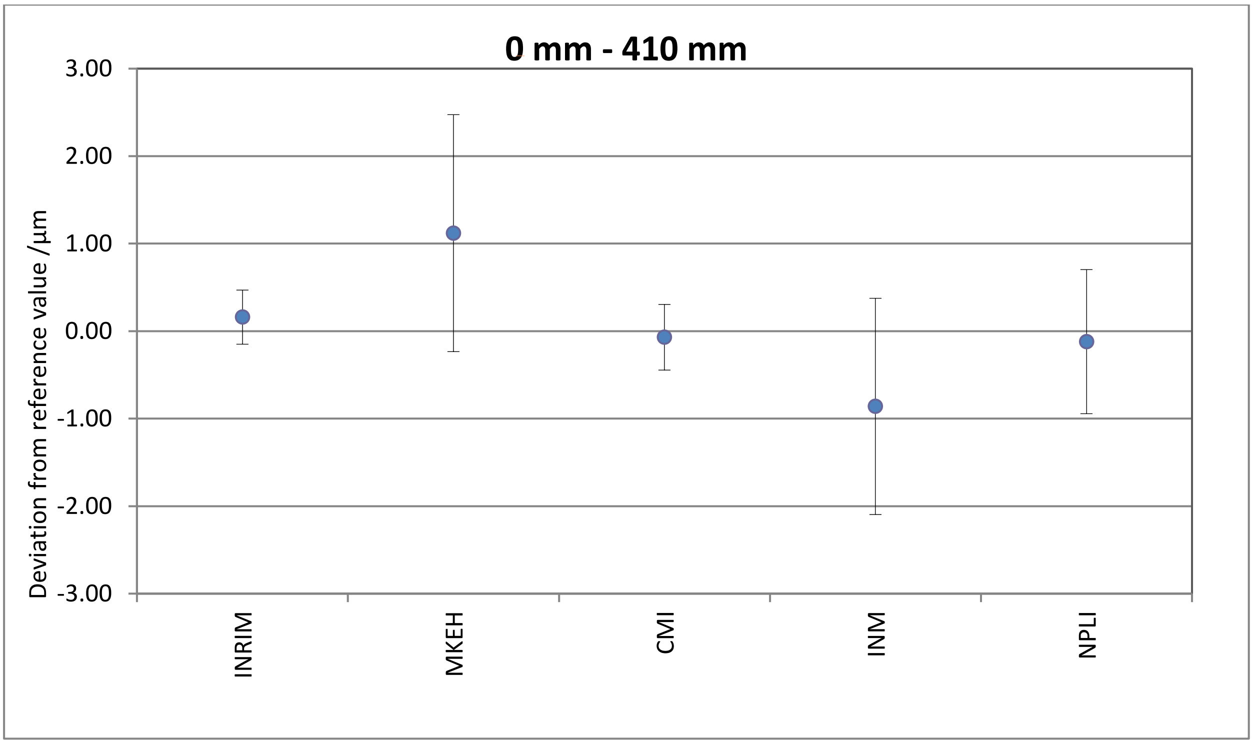


Figure 117: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

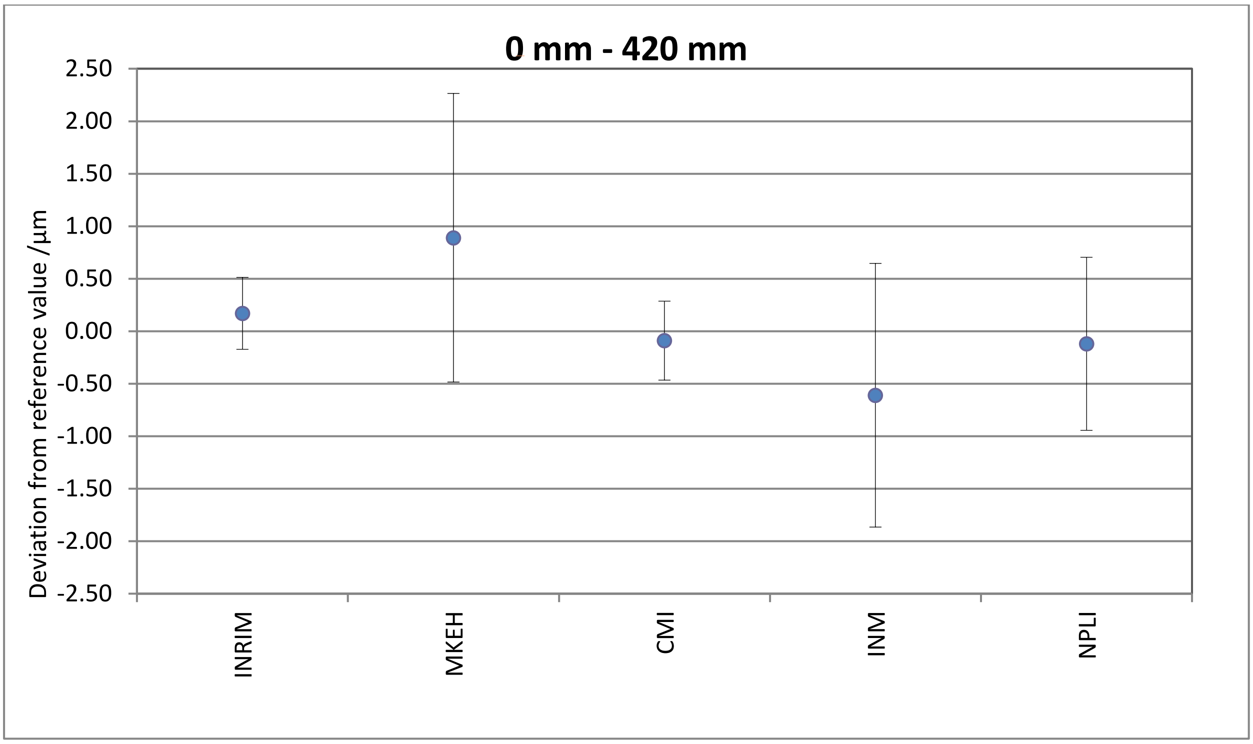


Figure 118: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

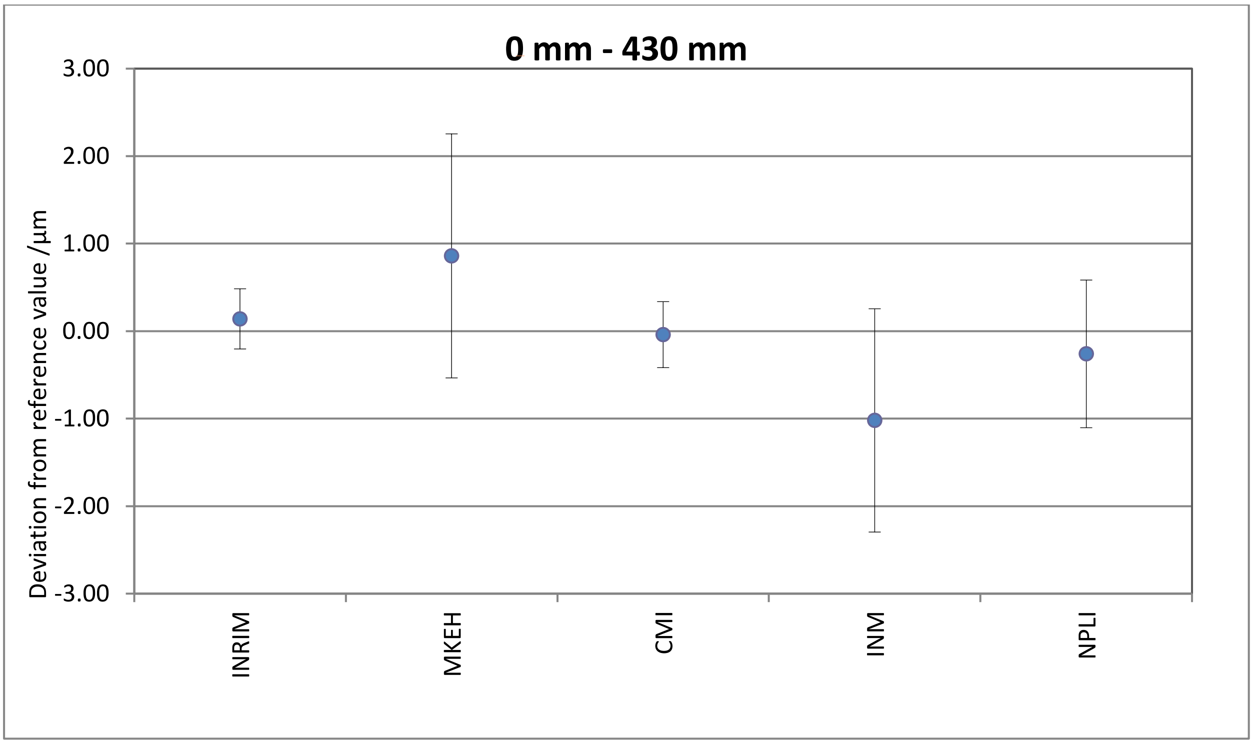


Figure 119: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

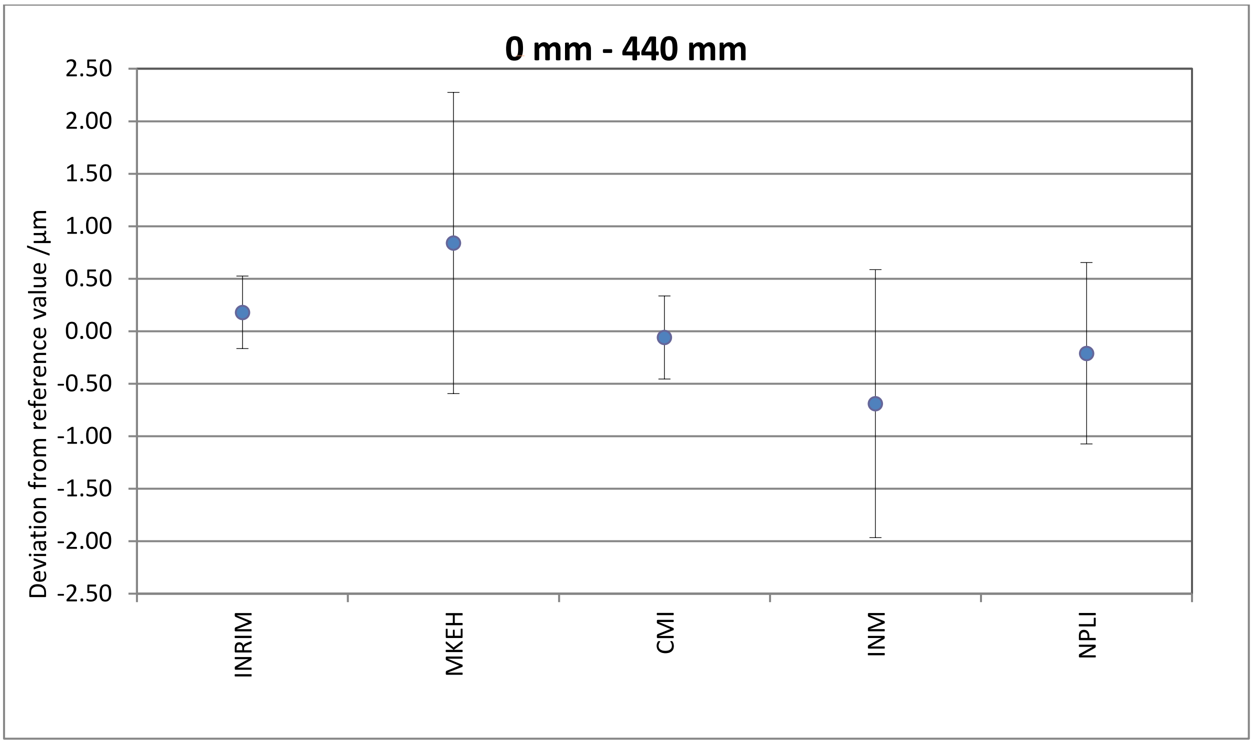


Figure 120: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

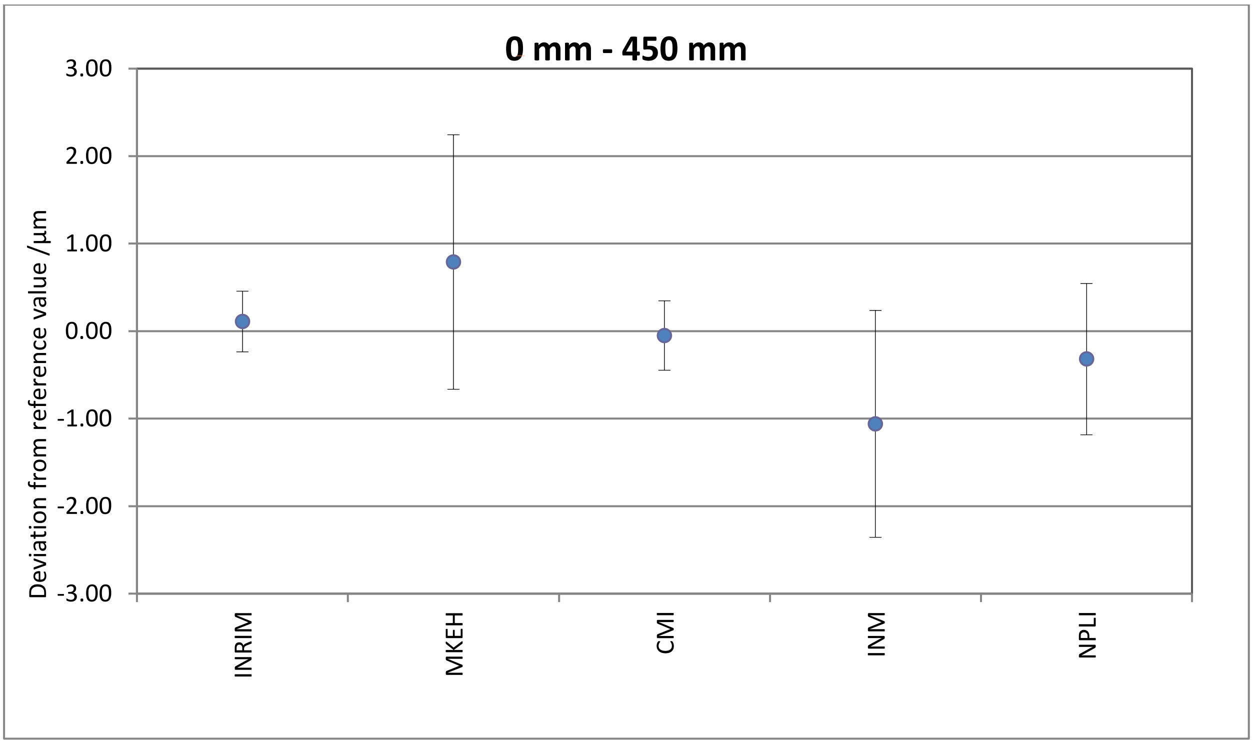


Figure 121: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

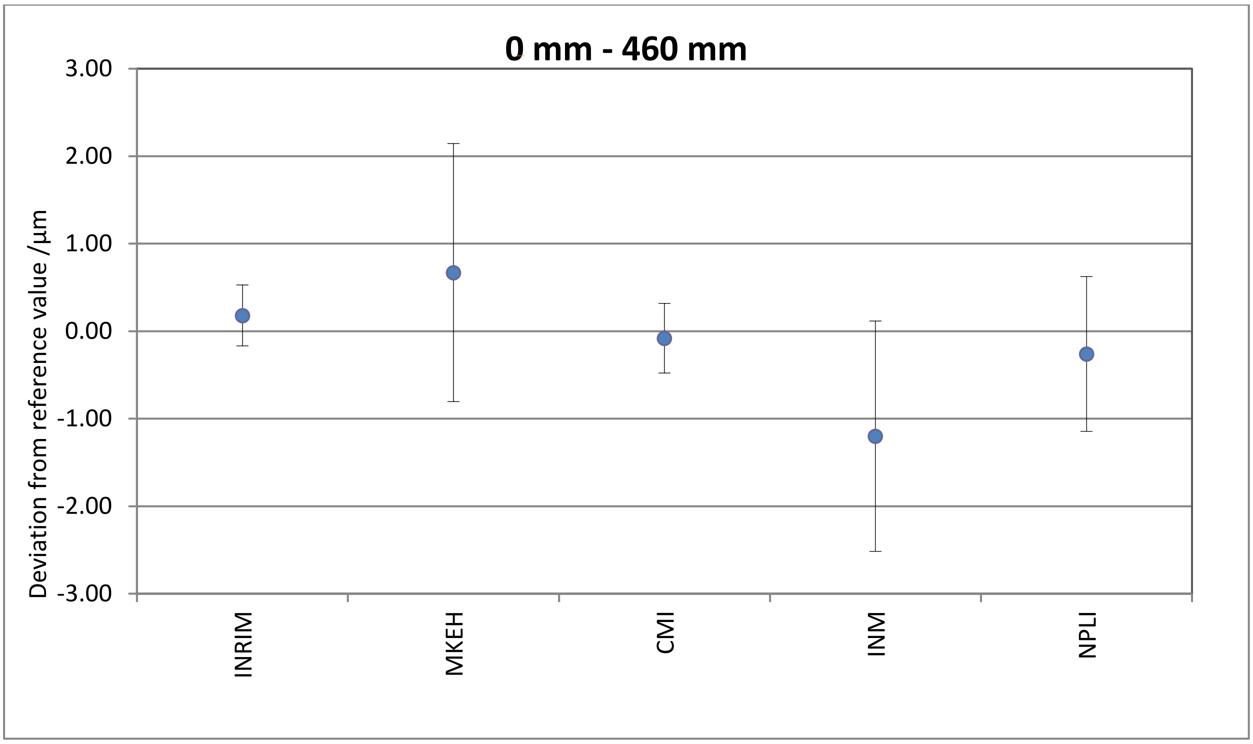


Figure 122: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

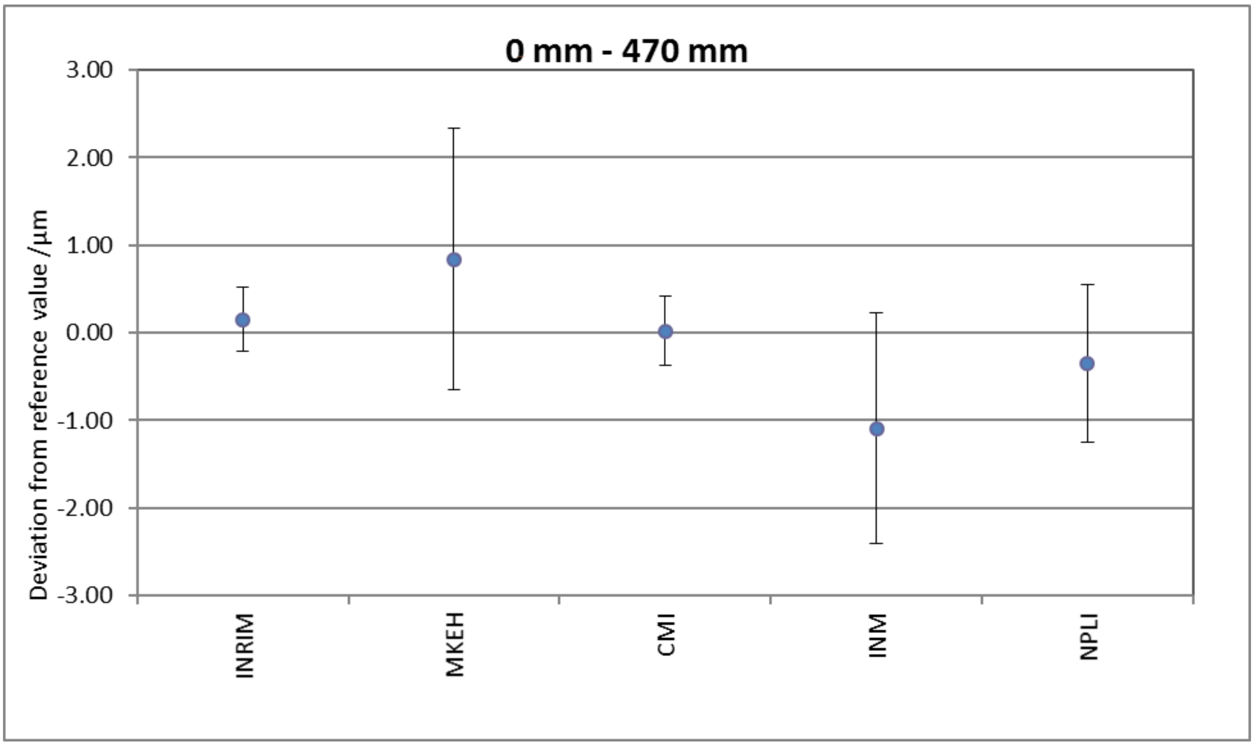


Figure 123: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

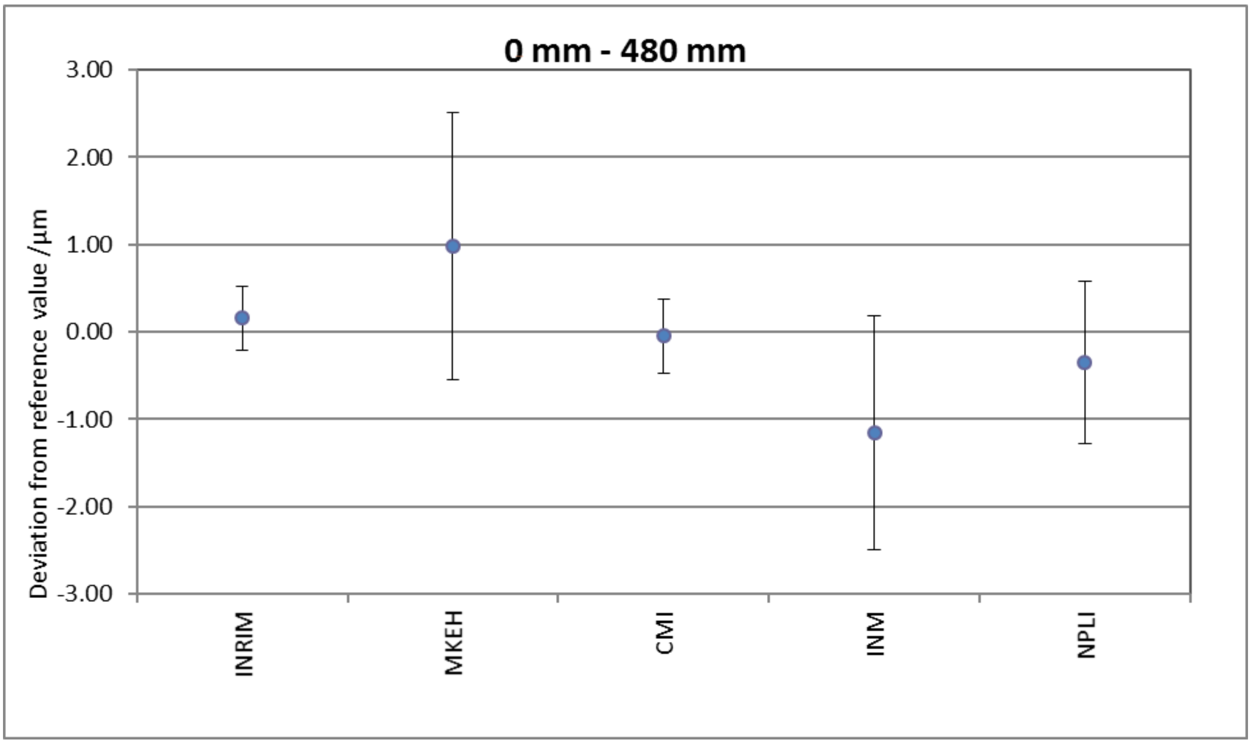


Figure 124: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

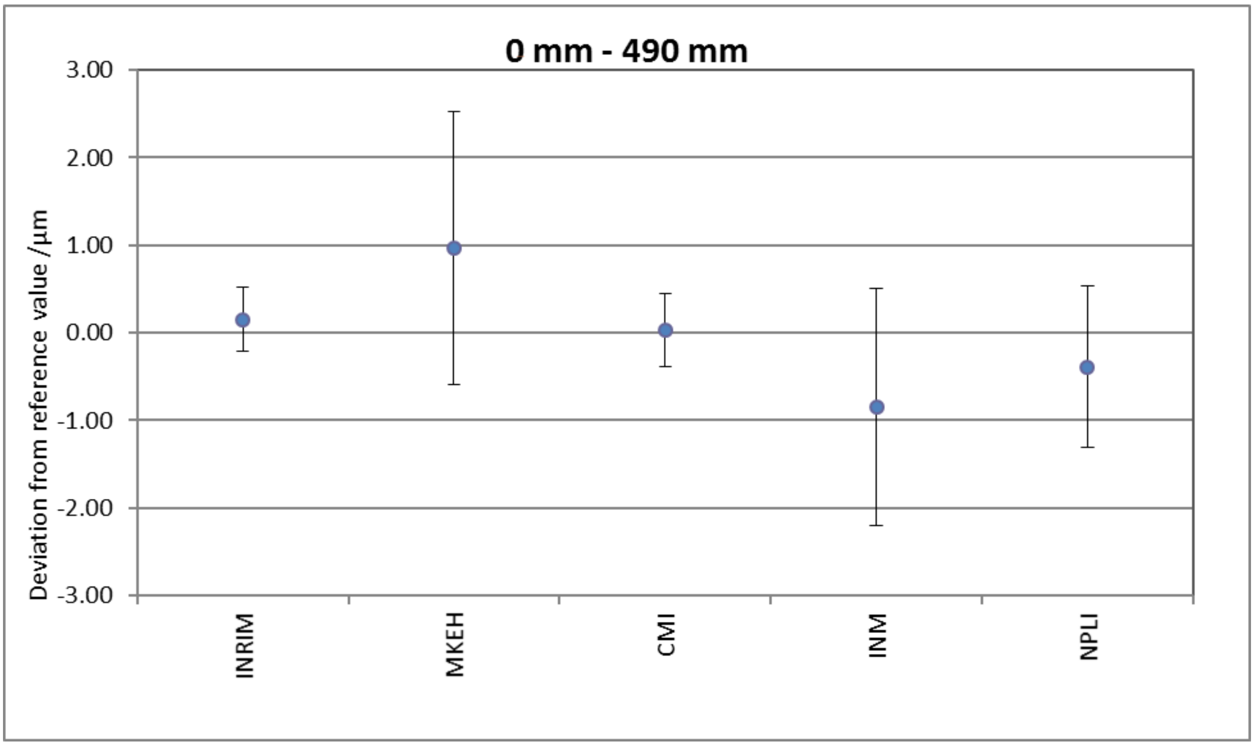


Figure 125: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

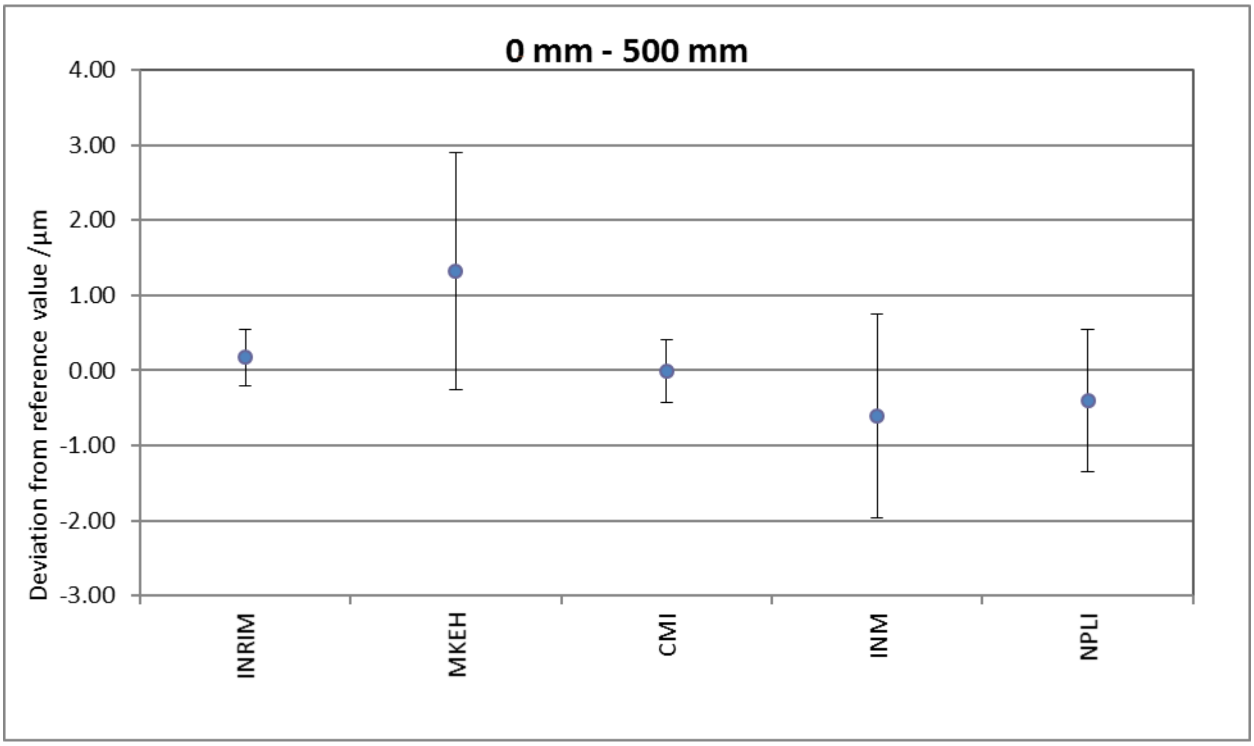


Figure 126: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

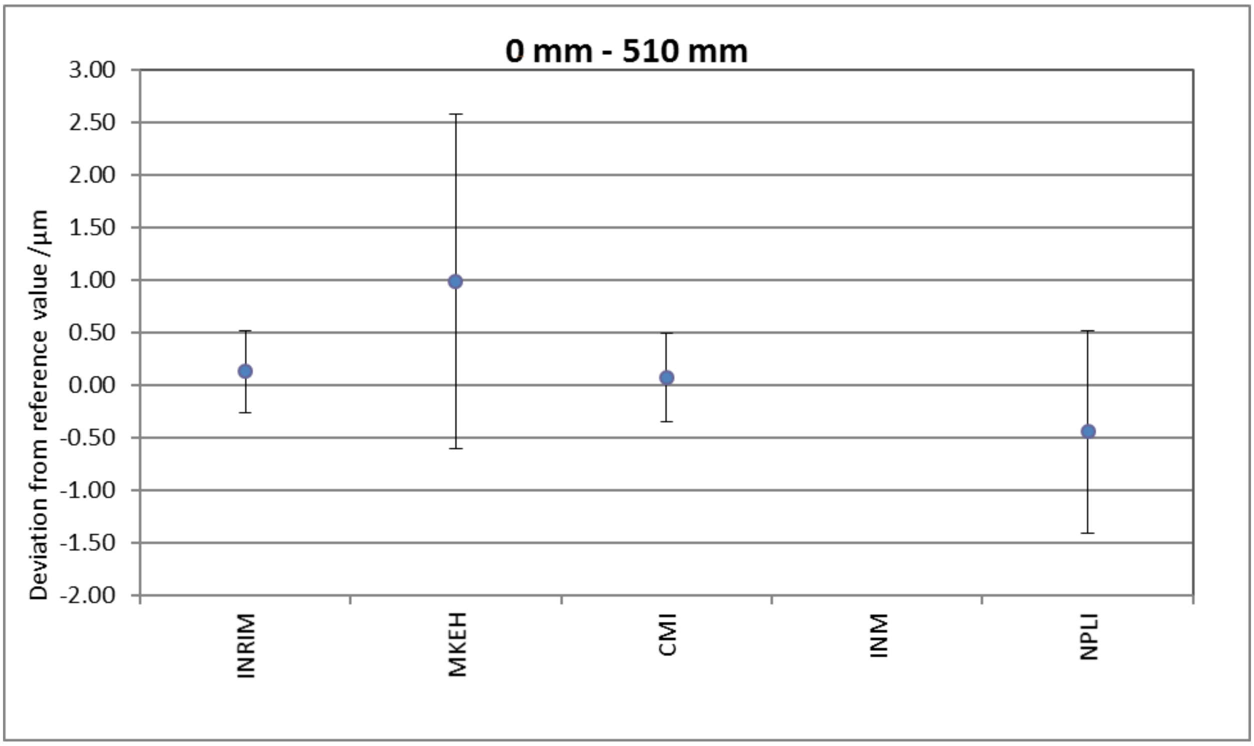


Figure 127: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

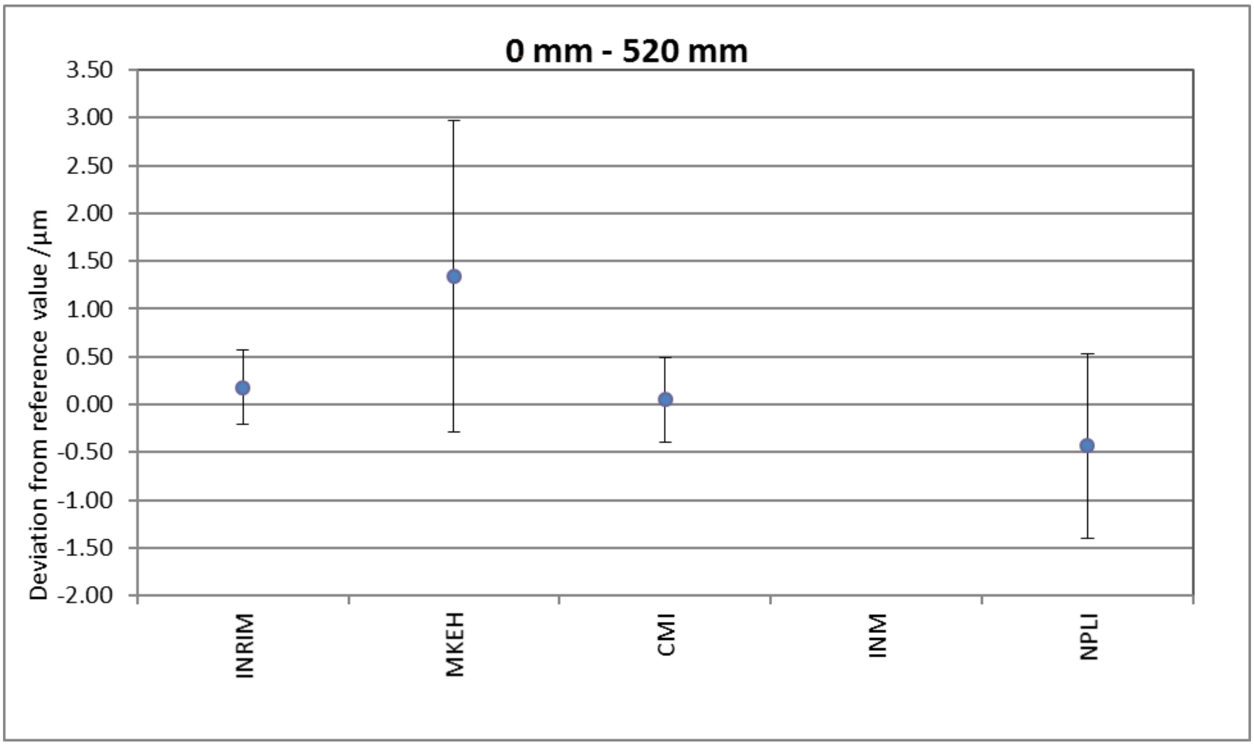


Figure 128: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

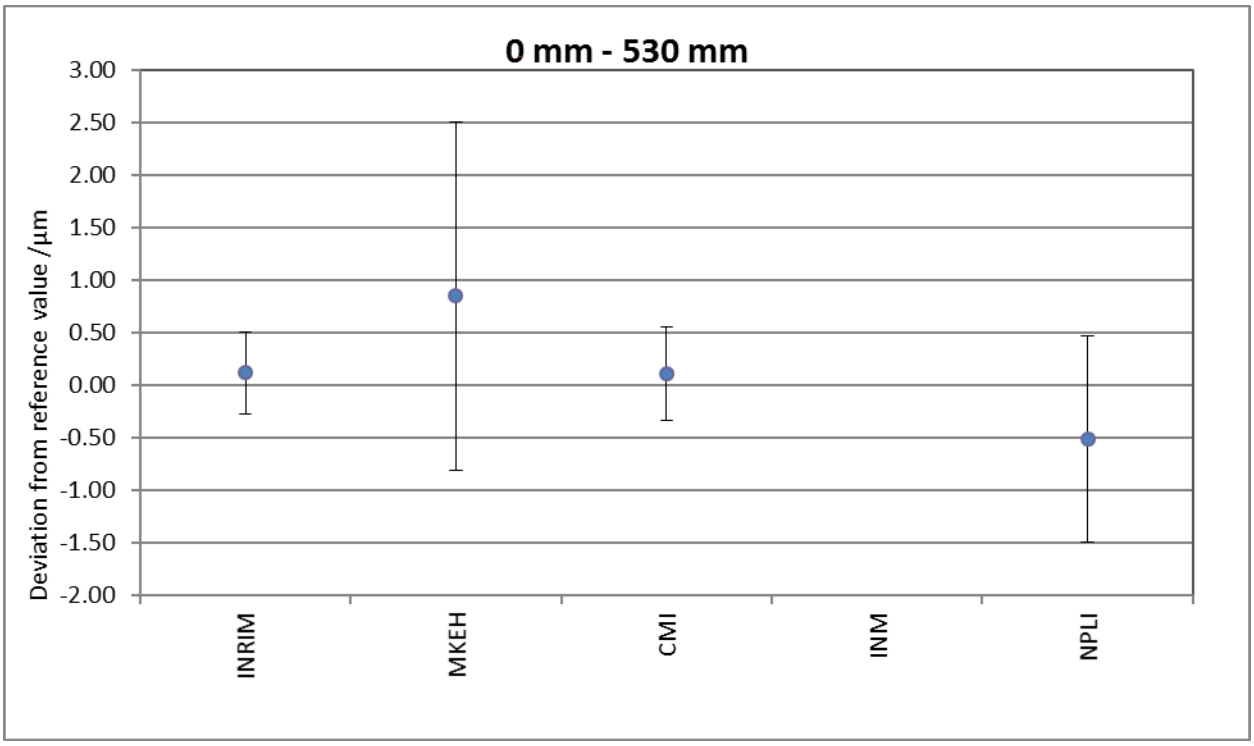


Figure 129: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

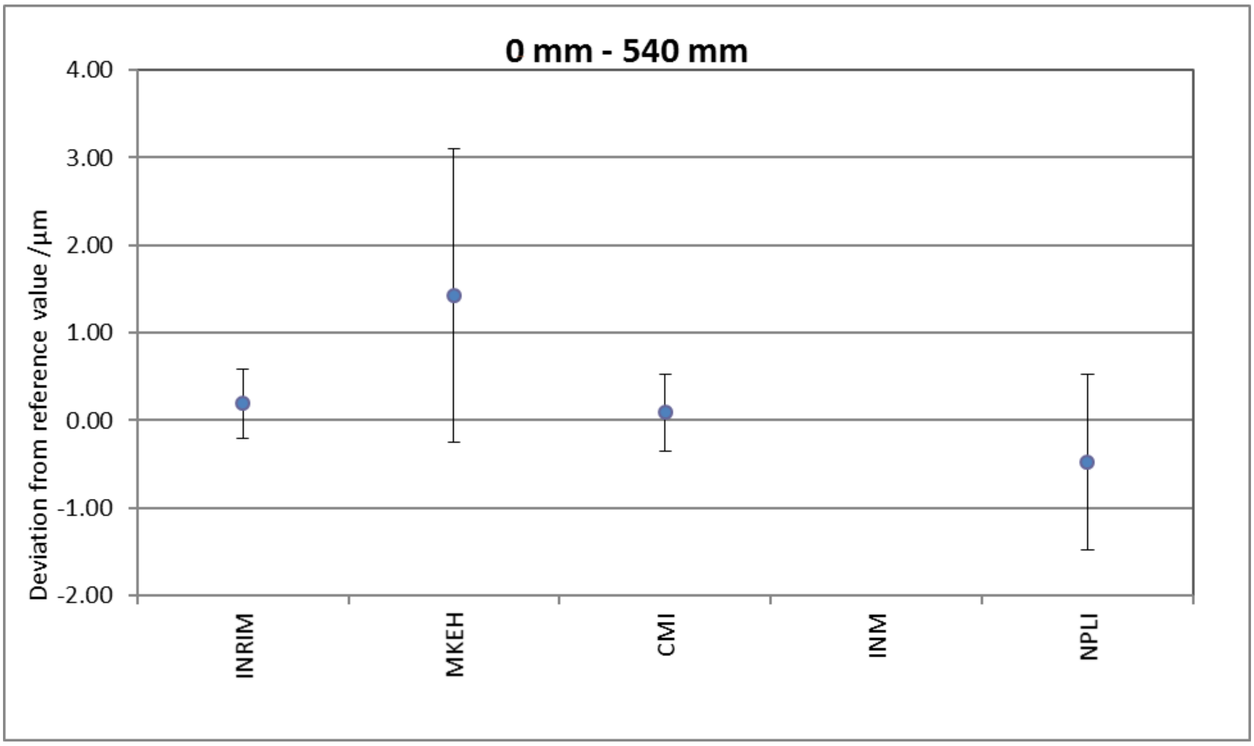


Figure 130: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

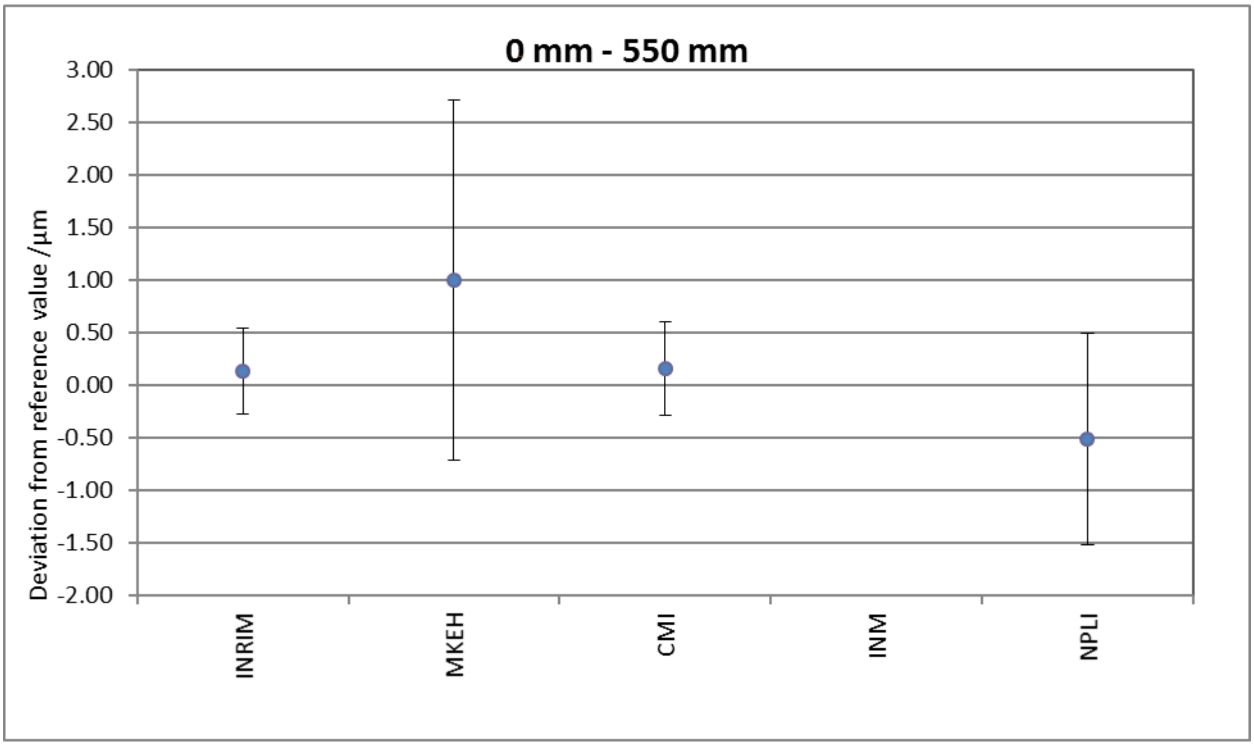


Figure 131: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

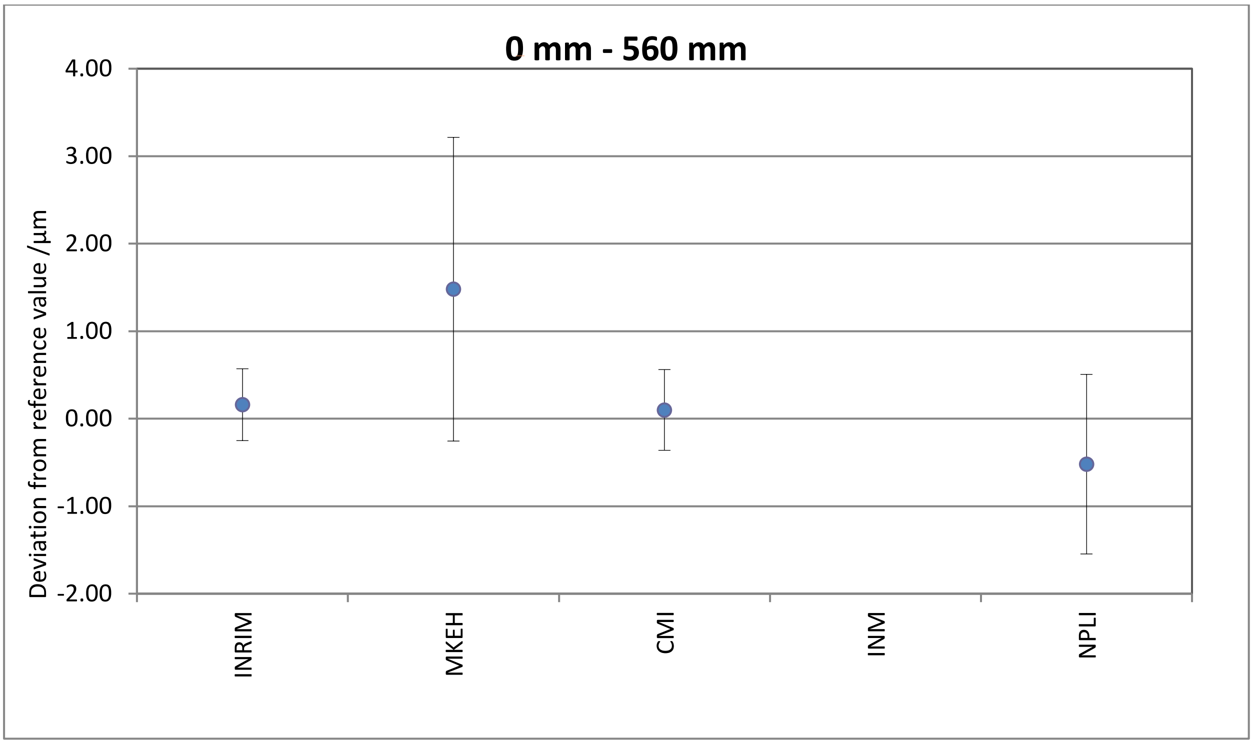


Figure 132: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

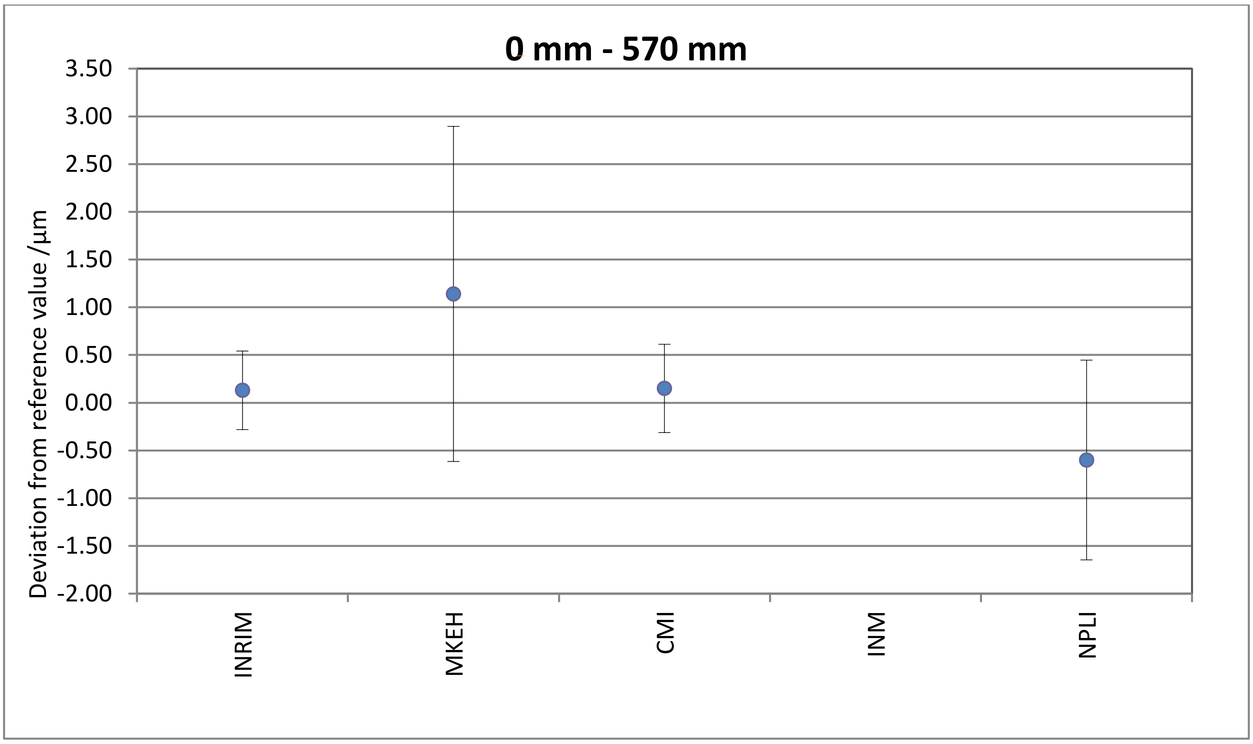


Figure 133: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

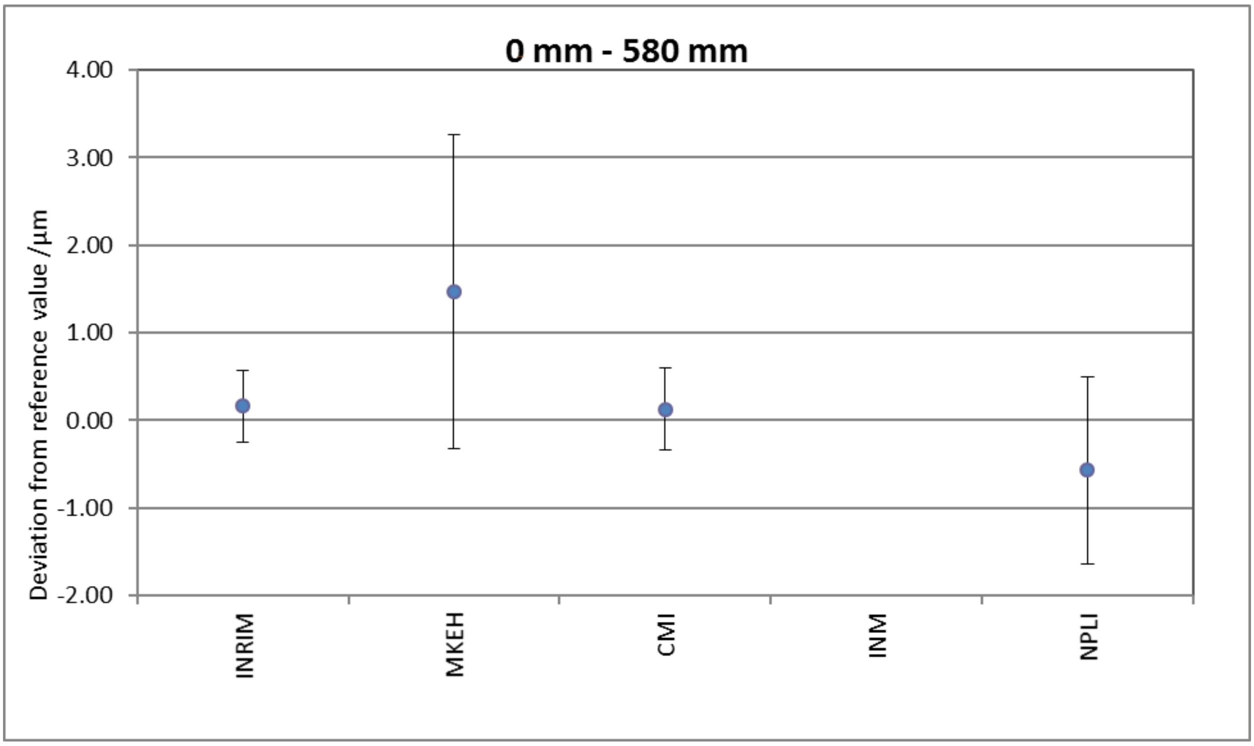


Figure 134: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

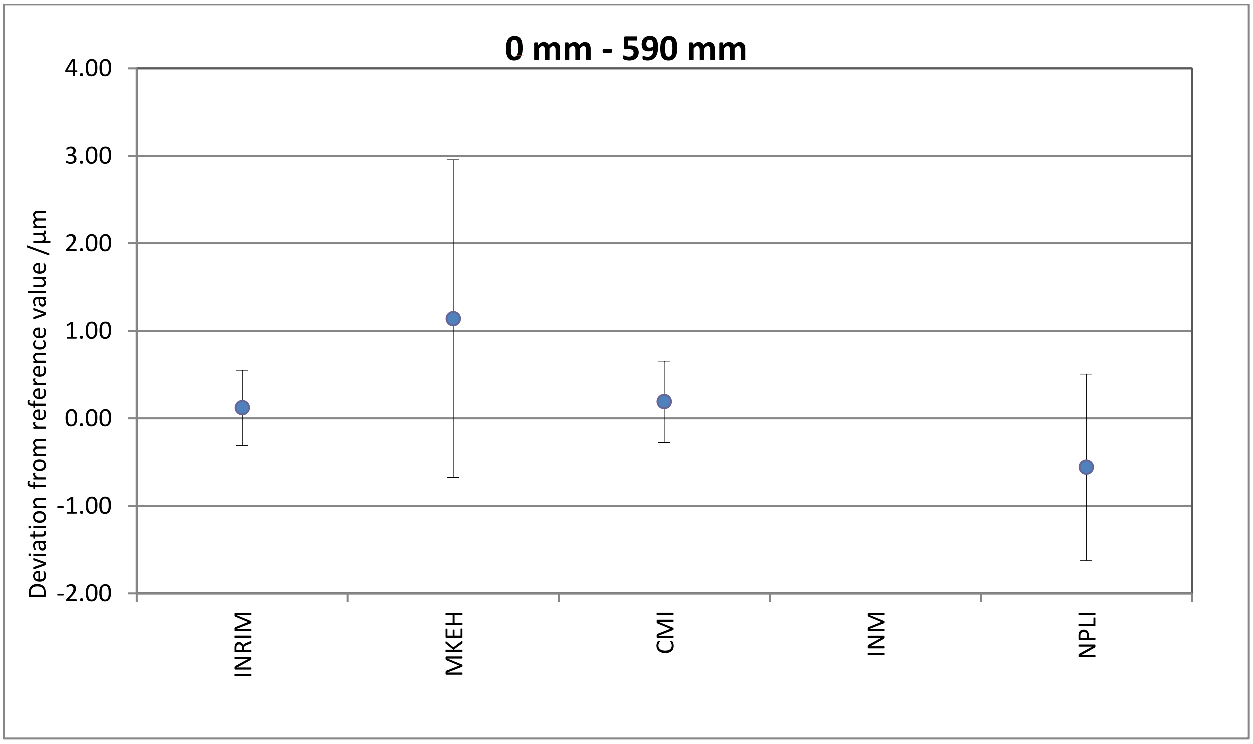


Figure 135: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

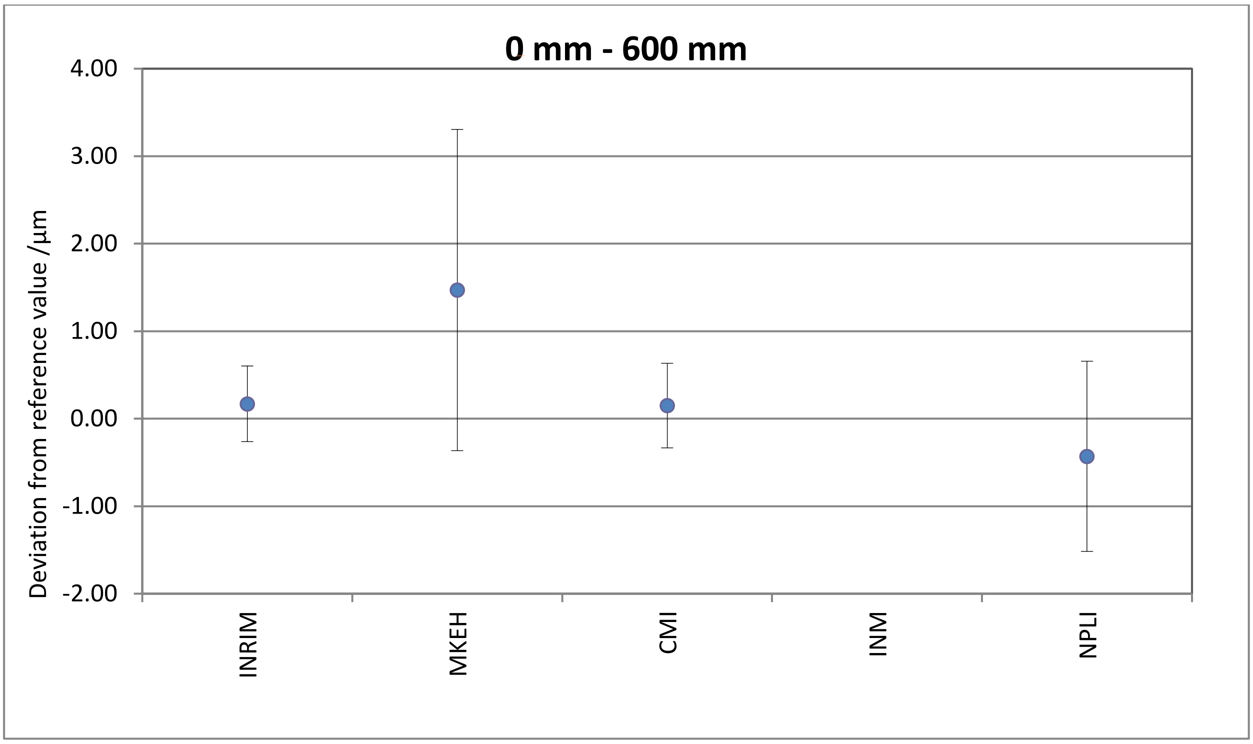


Figure 136: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

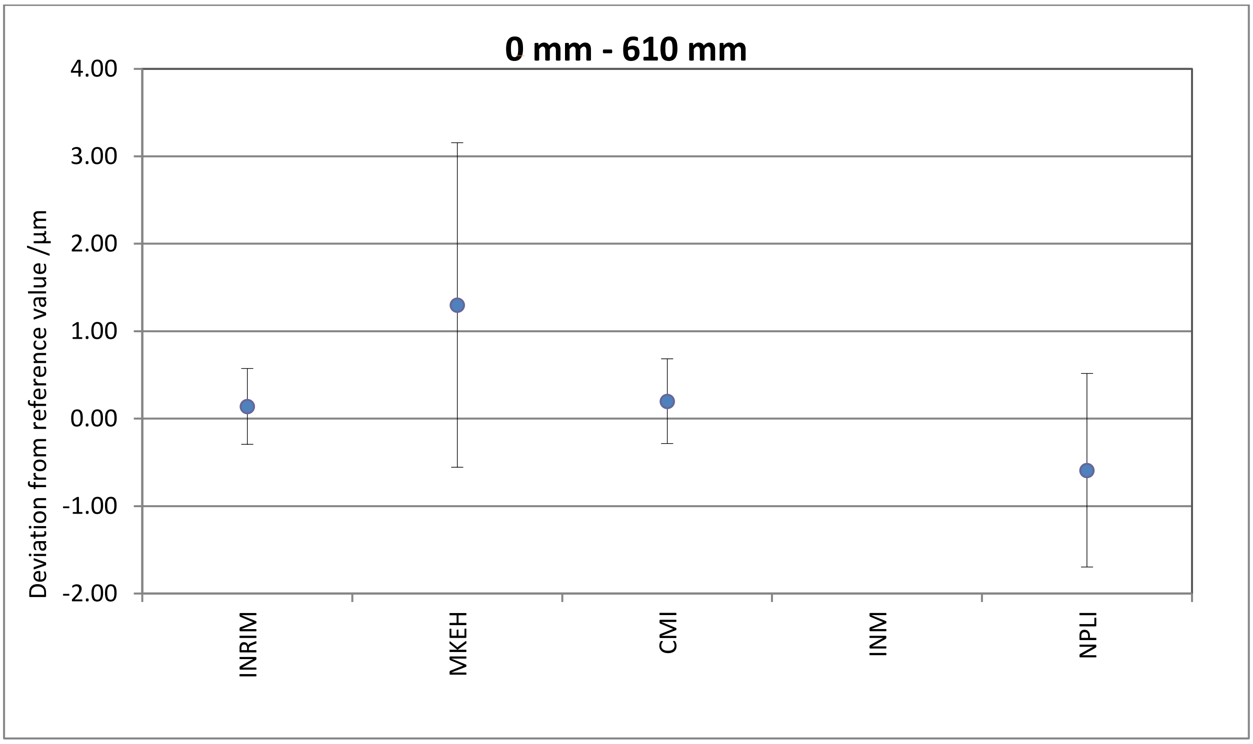


Figure 137: 610 mm artefact, group 1 participant deviations from reference value for this interval (*k* = 2)

6.4.7 Group 1 participant deviations by length

6.4.7.1 INRIM

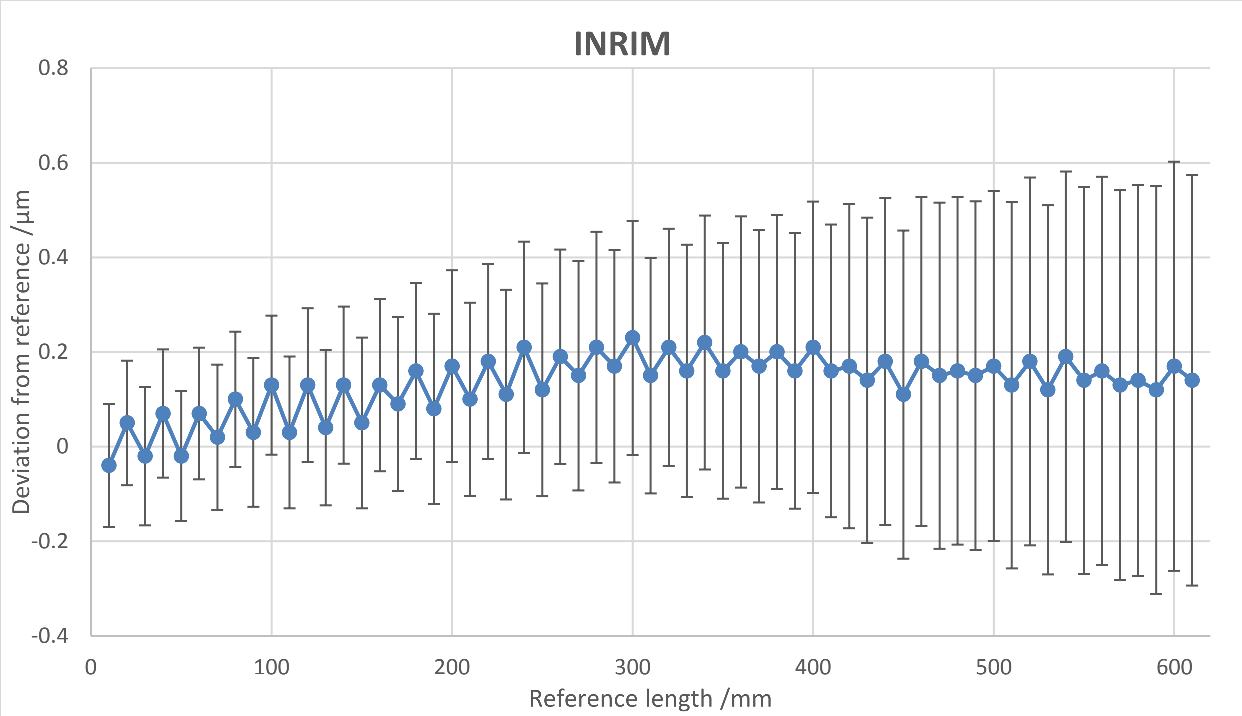


Figure 138

6.4.7.2 MKEH

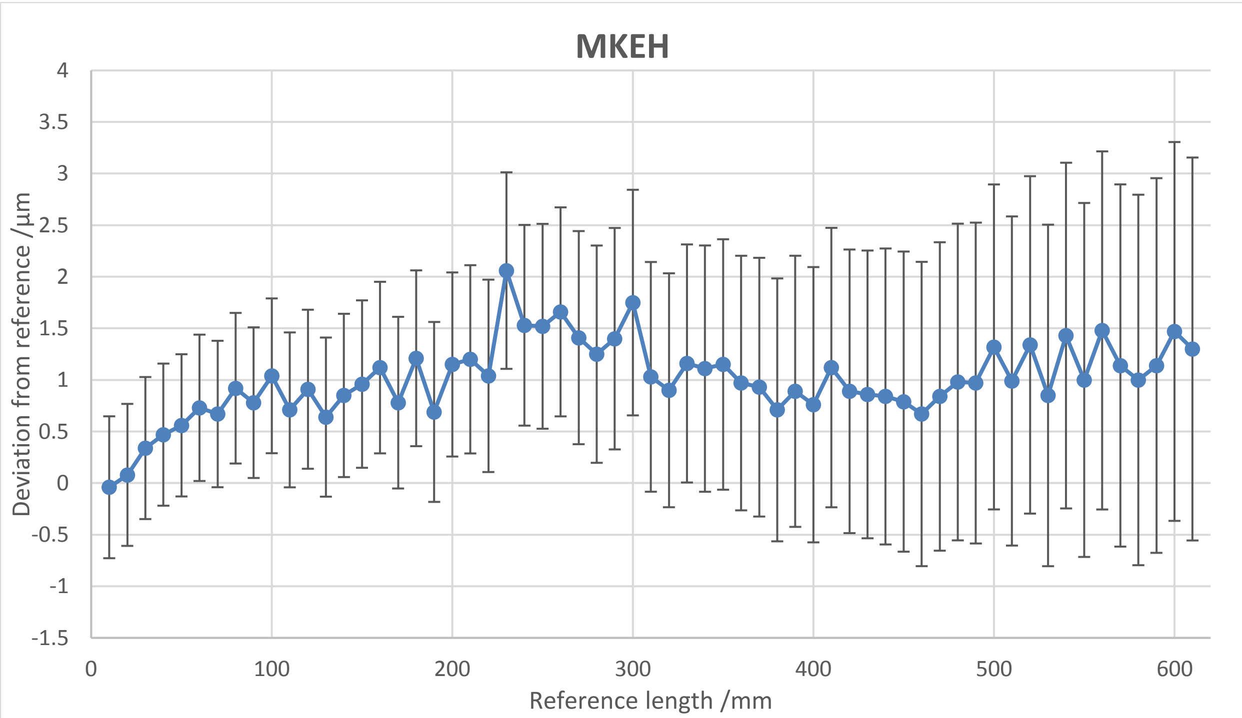


Figure 139

6.4.7.3 CMI

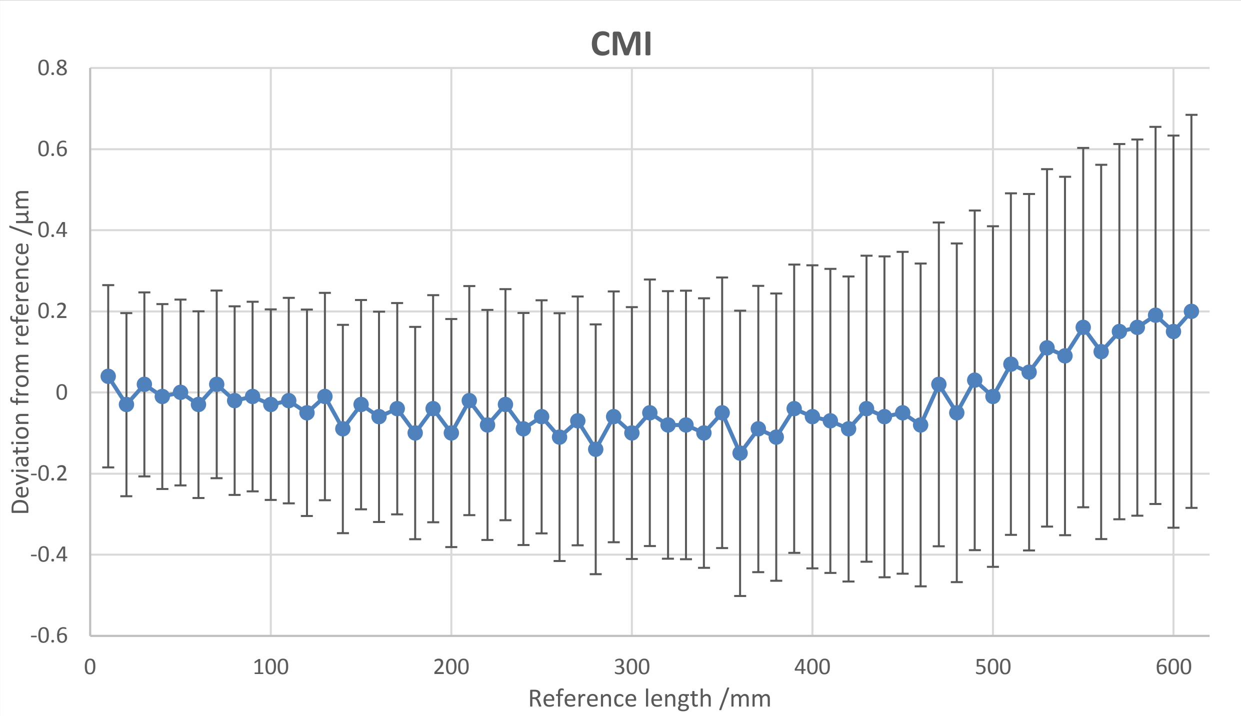


Figure 140

6.4.7.4 INM

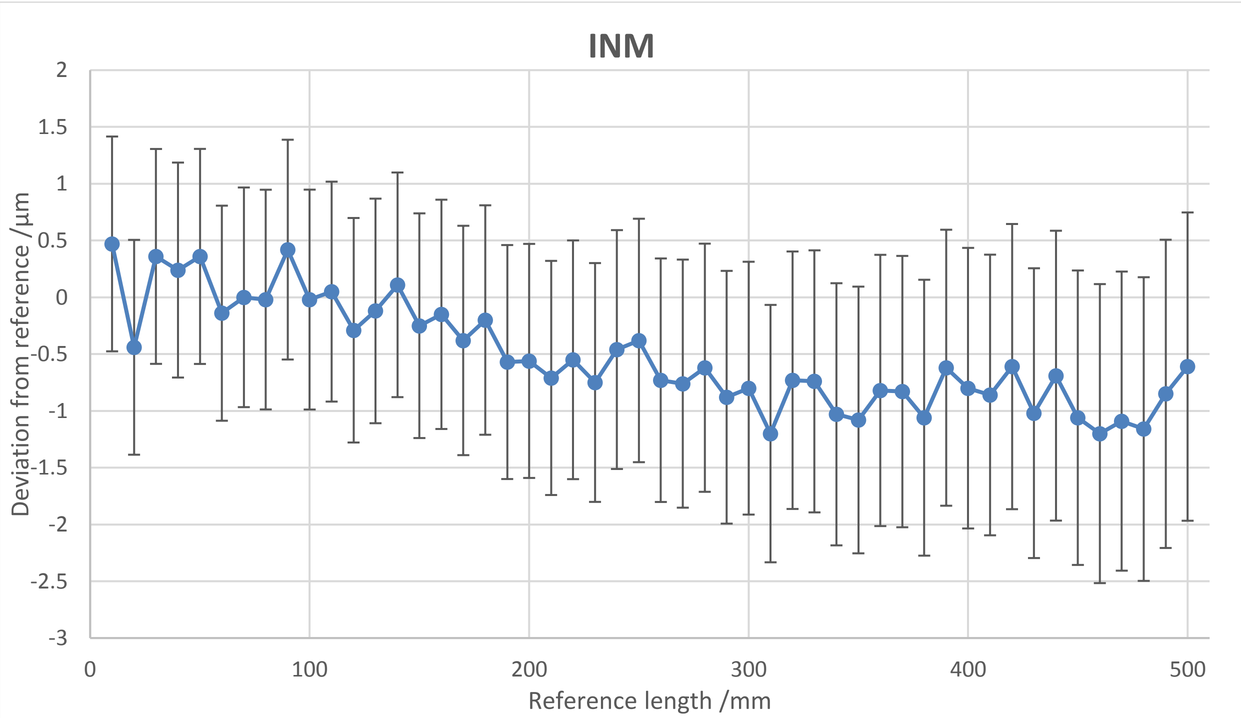


Figure 141

6.4.7.5 NPLI

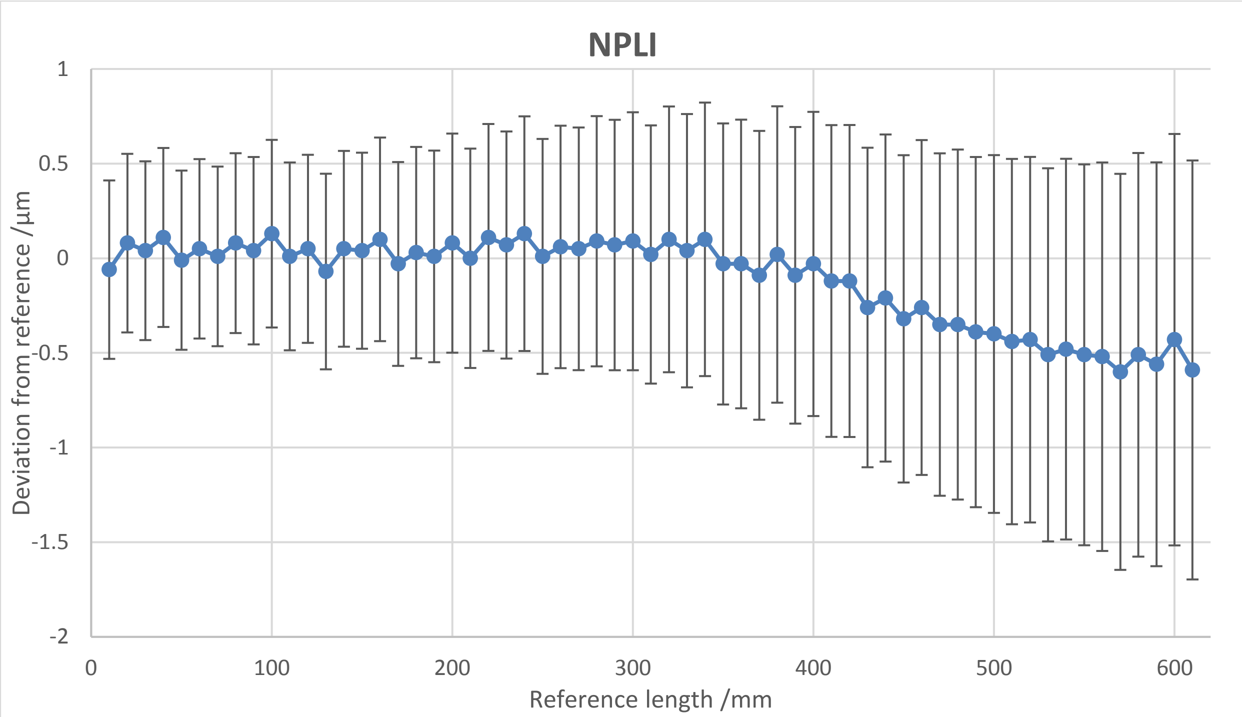


Figure 142

6.4.8 Group 1 Participant *En* values

The *En* values for each participant's measurement of each interval relative to the reference value are shown in Table 21. The expanded uncertainties used to calculate this value were obtained by multiplying the standard uncertainty of the deviation from the reference value by a coverage factor, *k* = 2. This gives a coverage probability of approximately 95 %. If *En* > 1 then equivalence to the reference is not demonstrated. Values were this is the case are shown in red font.

Length /mm	INRIM	MKEH	CMI	INM	NPLI
10	0.31	0.06	0.18	0.50	0.13
20	0.38	0.12	0.13	0.47	0.17
30	0.14	0.49	0.09	0.38	0.08
40	0.52	0.68	0.04	0.25	0.23
50	0.15	0.81	0.00	0.38	0.02
60	0.50	1.03	0.13	0.15	0.11
70	0.13	0.94	0.09	0.00	0.02
80	0.70	1.26	0.09	0.02	0.17
90	0.19	1.07	0.04	0.43	0.08
100	0.88	1.39	0.13	0.02	0.26
110	0.19	0.95	0.08	0.05	0.02

Length /mm	INRIM	MKEH	CMI	INM	NPLI
120	0.80	1.18	0.20	0.29	0.10
130	0.24	0.83	0.04	0.12	0.14
140	0.78	1.07	0.35	0.11	0.10
150	0.28	1.18	0.12	0.25	0.08
160	0.71	1.35	0.23	0.15	0.19
170	0.49	0.94	0.15	0.38	0.06
180	0.86	1.42	0.38	0.20	0.05
190	0.40	0.79	0.14	0.55	0.02
200	0.84	1.29	0.36	0.54	0.14
210	0.49	1.32	0.07	0.69	0.00
220	0.87	1.12	0.28	0.52	0.18
230	0.50	2.16	0.11	0.71	0.12
240	0.94	1.57	0.31	0.44	0.21
250	0.53	1.53	0.21	0.35	0.02
260	0.84	1.64	0.36	0.68	0.09
270	0.62	1.37	0.23	0.70	0.08
280	0.86	1.19	0.45	0.57	0.14
290	0.69	1.30	0.19	0.79	0.11
300	0.93	1.60	0.32	0.72	0.13
310	0.60	0.93	0.15	1.06	0.03
320	0.84	0.79	0.24	0.64	0.14
330	0.60	1.01	0.24	0.64	0.06
340	0.82	0.93	0.30	0.89	0.14
350	0.59	0.95	0.15	0.92	0.04
360	0.70	0.79	0.43	0.69	0.04
370	0.59	0.74	0.26	0.69	0.12
380	0.69	0.56	0.31	0.87	0.03
390	0.55	0.68	0.11	0.51	0.11
400	0.68	0.57	0.16	0.65	0.04
410	0.52	0.83	0.19	0.70	0.15
420	0.50	0.65	0.24	0.49	0.15
430	0.41	0.62	0.11	0.80	0.31
440	0.52	0.59	0.15	0.54	0.24
450	0.32	0.54	0.13	0.82	0.37
460	0.52	0.45	0.20	0.91	0.29
470	0.41	0.56	0.05	0.83	0.39
480	0.44	0.64	0.12	0.87	0.38
490	0.41	0.62	0.07	0.63	0.42
500	0.46	0.84	0.02	0.45	0.42
510	0.34	0.62	0.17		0.46
520	0.46	0.82	0.11		0.45
530	0.31	0.51	0.25		0.52
540	0.49	0.85	0.20		0.48

Length /mm	INRIM	MKEH	CMI	INM	NPLI
550	0.34	0.58	0.36		0.51
560	0.39	0.85	0.22		0.51
570	0.32	0.65	0.32		0.57
580	0.39	0.82	0.28		0.53
590	0.28	0.63	0.41		0.53
600	0.39	0.80	0.31		0.40
610	0.32	0.70	0.41		0.53

Table 21: *E*n values for 610 mm artefact Group 1 participants

A summary table of the number of measurements for each institution made that did not demonstrate equivalence to the comparison reference value is shown in Table 22. Given that the expanded uncertainty provides an approximately 95% probability of a measured value being within the uncertainty range of the true value (which in the case of this comparison can be considered to be 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 *E*n > 1 is therefore considered to have demonstrated the validity of their submitted uncertainty.

	Number of intervals where *E*n > 1	Percentage of intervals where *E*n > 1	Uncertainty validity demonstrated?
INRIM	0	0.00	YES
MKEH	21	34.43	NO
CMI	0	0.00	YES
INM	1	2.00	YES
NPLI	0	0.00	YES

Table 22: Summary of participant *E*n values for the 610 mm artefact Group 1 participants

6.4.9 Group 2 reference value

The reference value for Group 2 is the measurement made by VTT-MIKES. This is shown in Table 23.

Table 23: 610 mm artefact group 2 reference value

Interval	Reference value /mm	Reference value Uncertainty /µm	Interval	Reference value /mm	Reference value Uncertainty /µm
0 mm - 10 mm	10.000 225	0.023 0	0 mm - 320 mm	319.997 873	0.030 0
0 mm - 20 mm	20.000 417	0.023 0	0 mm - 330 mm	329.997 985	0.030 0

0 mm - 30 mm	30.000 620	0.023 0	0 mm - 340 mm	339.997 644	0.030 0
0 mm - 40 mm	40.000 409	0.023 0	0 mm - 350 mm	349.997 725	0.031 0
0 mm - 50 mm	50.000 568	0.023 0	0 mm - 360 mm	359.997 424	0.031 0
0 mm - 60 mm	60.000 410	0.023 0	0 mm - 370 mm	369.997 552	0.032 0
0 mm - 70 mm	70.000 556	0.023 0	0 mm - 380 mm	379.997 381	0.032 0
0 mm - 80 mm	80.000 213	0.023 0	0 mm - 390 mm	389.997 468	0.032 0
0 mm - 90 mm	90.000 134	0.023 0	0 mm - 400 mm	399.997 133	0.033 0
0 mm - 100 mm	99.999 991	0.024 0	0 mm - 410 mm	409.997 243	0.033 0
0 mm - 110 mm	110.000 165	0.024 0	0 mm - 420 mm	419.996 977	0.034 0
0 mm - 120 mm	119.999 764	0.024 0	0 mm - 430 mm	429.997 096	0.034 0
0 mm - 130 mm	129.999 892	0.024 0	0 mm - 440 mm	439.996 710	0.035 0
0 mm - 140 mm	139.999 583	0.024 0	0 mm - 450 mm	449.996 795	0.035 0
0 mm - 150 mm	149.999 721	0.024 0	0 mm - 460 mm	459.996 535	0.036 0
0 mm - 160 mm	159.999 368	0.025 0	0 mm - 470 mm	469.996 650	0.036 0
0 mm - 170 mm	169.999 495	0.025 0	0 mm - 480 mm	479.996 378	0.036 0
0 mm - 180 mm	179.999 252	0.025 0	0 mm - 490 mm	489.996 496	0.037 0
0 mm - 190 mm	189.999 437	0.025 0	0 mm - 500 mm	499.996 241	0.037 0
0 mm - 200 mm	199.999 108	0.026 0	0 mm - 510 mm	509.996 357	0.038 0
0 mm - 210 mm	209.999 232	0.026 0	0 mm - 520 mm	519.996 081	0.038 0
0 mm - 220 mm	219.998 982	0.026 0	0 mm - 530 mm	529.996 212	0.039 0
0 mm - 230 mm	229.999 128	0.027 0	0 mm - 540 mm	539.995 968	0.039 0
0 mm - 240 mm	239.998 763	0.027 0	0 mm - 550 mm	549.996 086	0.040 0
0 mm - 250 mm	249.998 824	0.027 0	0 mm - 560 mm	559.995 665	0.040 0
0 mm - 260 mm	259.998 551	0.027 0	0 mm - 570 mm	569.995 796	0.041 0
0 mm - 270 mm	269.998 691	0.028 0	0 mm - 580 mm	579.995 691	0.041 0
0 mm - 280 mm	279.998 326	0.028 0	0 mm - 590 mm	589.995 811	0.042 0
0 mm - 290 mm	289.998 465	0.029 0	0 mm - 600 mm	599.995 801	0.042 0
0 mm - 300 mm	299.998 200	0.029 0	0 mm - 610 mm	609.995 925	0.043 0
0 mm - 310 mm	309.998 274	0.029 0			

6.4.10 Group 2 Participant results

Group 2 Participant results are shown in Table 24.

Table 24: Group 2 participants results

Nominal Length /mm	GUM /mm	SASO-NMCC /mm	NRC-CNRC /mm
10	9.998 7	10.000 17	10.000 21
20	19.998 1	20.000 39	20.000 48
30	29.999 0	30.000 55	30.000 67
40	39.998 1	40.000 38	40.000 46
50	49.998 6	50.000 50	50.000 59
60	59.998 0	60.000 35	60.000 46

Nominal Length /mm	GUM /mm	SASO-NMCC /mm	NRC-CNRC /mm
70	69.998 8	70.000 47	70.000 59
80	79.997 8	80.000 16	80.000 25
90	89.998 7	90.000 03	90.000 18
100	99.997 8	99.999 92	100.000 05
110	109.998 6	110.000 07	110.000 22
120	119.997 7	119.999 71	119.999 85
130	129.998 4	129.999 79	129.999 97
140	139.997 6	139.999 49	139.999 67
150	149.998 2	149.999 62	149.999 80
160	159.997 5	159.999 27	159.999 46
170	169.998 0	169.999 38	169.999 55
180	179.997 4	179.999 15	179.999 34
190	189.998 1	189.999 29	189.999 52
200	199.997 5	199.999 00	199.999 21
210	209.997 9	209.999 06	209.999 30
220	219.997 3	219.998 83	219.999 09
230	229.997 9	229.998 89	229.999 24
240	239.997 2	239.998 58	239.998 88
250	249.997 5	249.998 59	249.998 91
260	259.996 5	259.998 33	259.998 66
270	269.996 6	269.998 42	269.998 77
280	279.996 6	279.998 10	279.998 42
290	289.996 8	289.998 18	289.998 54
300	299.996 5	299.997 93	299.998 27
310	309.996 9	309.997 99	309.998 34
320	319.996 7	319.997 62	319.997 97
330	329.996 8	329.997 67	329.998 05
340	339.996 6	339.997 35	339.997 67
350	349.996 8	349.997 36	349.997 75
360	359.996 5	359.997 06	359.997 47
370	369.996 7	369.997 13	369.997 58
380	379.996 6	379.996 95	379.997 40
390	389.996 7	389.996 99	389.997 48
400	399.996 3	399.996 67	399.997 17
410	409.996 6	409.996 76	409.997 29
420	419.996 2	419.996 52	419.997 04
430	429.996 8	429.996 60	429.997 12
440	439.996 2	439.996 25	439.996 75
450	449.996 7	449.996 28	449.996 84
460	459.996 4	459.996 05	459.996 57

Nominal Length /mm	GUM /mm	SASO-NMCC /mm	NRC-CNRC /mm
470	469.996 5	469.996 09	469.996 65
480	479.996 4	479.995 90	479.996 40
490	489.996 6	489.995 96	489.996 52
500	499.996 3	499.995 72	499.996 30
510	509.996 7	509.995 82	509.996 37
520	519.995 8	519.995 62	519.996 12
530	529.996 5	529.995 71	529.996 26
540	539.996 0	539.995 52	539.996 00
550	549.996 5	549.995 58	549.996 08
560	559.995 7	559.995 21	559.995 71
570	569.996 2	569.995 32	569.995 80
580	579.995 3	579.995 24	579.995 74
590	589.996 4	589.995 32	589.995 79
600	599.995 3	599.995 35	599.995 87
610	609.996 5	609.995 42	609.995 96

6.4.11 Group 2 participant measurement uncertainties

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 25. Where possible the model equations reported have been converted to 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 mm and the standard uncertainty u is expressed in µm.

Table 25: Group 2 participant measurement uncertainties

Participant	Measurement uncertainty
GUM	Q[0.42, 0.48×10^{-3} L] µm
SASO-NMCC	Q[0.231, 0.99×10^{-3} L] µm
NRC-CNRC	Q[0.08,0.27×10^{-3} L] µm

Table 26 shows the reported standard uncertainties supplied by each Group 2 participant for the measured intervals.

Table 26: Group 2 reported standard uncertainties

Nominal Length /mm	GUM /µm	SASO-NMCC /µm	NRC-CNRC /µm
10	0.429 4	0.23	0.08
20	0.429 5	0.23	0.08
30	0.429 6	0.23	0.08
40	0.429 8	0.23	0.08
50	0.430 1	0.24	0.08
60	0.430 4	0.24	0.08
70	0.430 7	0.24	0.08
80	0.431 1	0.24	0.08
90	0.431 6	0.25	0.08
100	0.432 1	0.25	0.08
110	0.432 7	0.26	0.09
120	0.433 3	0.26	0.09
130	0.433 9	0.26	0.09
140	0.434 7	0.27	0.09
150	0.435 4	0.27	0.09
160	0.436 3	0.28	0.09
170	0.437 1	0.29	0.09
180	0.438 1	0.29	0.09
190	0.439 0	0.30	0.10
200	0.440 1	0.30	0.10
210	0.441 1	0.31	0.10
220	0.442 3	0.32	0.10
230	0.443 5	0.32	0.10
240	0.444 7	0.33	0.10
250	0.446 0	0.34	0.10
260	0.447 3	0.35	0.11
270	0.448 7	0.35	0.11
280	0.450 1	0.36	0.11
290	0.451 5	0.37	0.11
300	0.453 0	0.38	0.11
310	0.454 6	0.39	0.12
320	0.456 2	0.39	0.12
330	0.457 9	0.40	0.12
340	0.459 5	0.41	0.12

Nominal Length /mm	GUM /µm	SASO-NMCC /µm	NRC-CNRC /µm
350	0.461 3	0.42	0.12
360	0.463 1	0.43	0.13
370	0.464 9	0.43	0.13
380	0.466 8	0.44	0.13
390	0.468 7	0.45	0.13
400	0.470 6	0.46	0.13
410	0.472 6	0.47	0.14
420	0.474 6	0.48	0.14
430	0.476 7	0.49	0.14
440	0.478 8	0.49	0.14
450	0.481 0	0.50	0.15
460	0.483 2	0.51	0.15
470	0.485 4	0.52	0.15
480	0.487 6	0.53	0.15
490	0.489 9	0.54	0.15
500	0.492 3	0.55	0.16
510	0.494 7	0.56	0.16
520	0.497 1	0.57	0.16
530	0.499 5	0.58	0.16
540	0.502 0	0.58	0.17
550	0.504 5	0.59	0.17
560	0.507 0	0.60	0.17
570	0.509 6	0.61	0.17
580	0.512 2	0.62	0.18
590	0.514 9	0.63	0.18
600	0.517 5	0.64	0.18
610	0.520 2	0.65	0.18

6.4.12 Group 2 participant deviations by face

The following plots, Figures 143 through 203, show the deviation from the reference value of each participant for each interval measured. The uncertainties shown are the uncertainty in the deviation from the reference length x_{ref}, calculated to be

$$u_{(x_i - x_{ref})} = \sqrt{{u_{x_i}}^2 + {u_{x_{ref}}}^2}$$

Where x_i is the the participant reported length and u_{x_i} and $u_{x_{ref}}$ are both expanded uncertainties at *k* = 2. This calculation is used because in this case none of the participant results displayed contributed to the reference value.

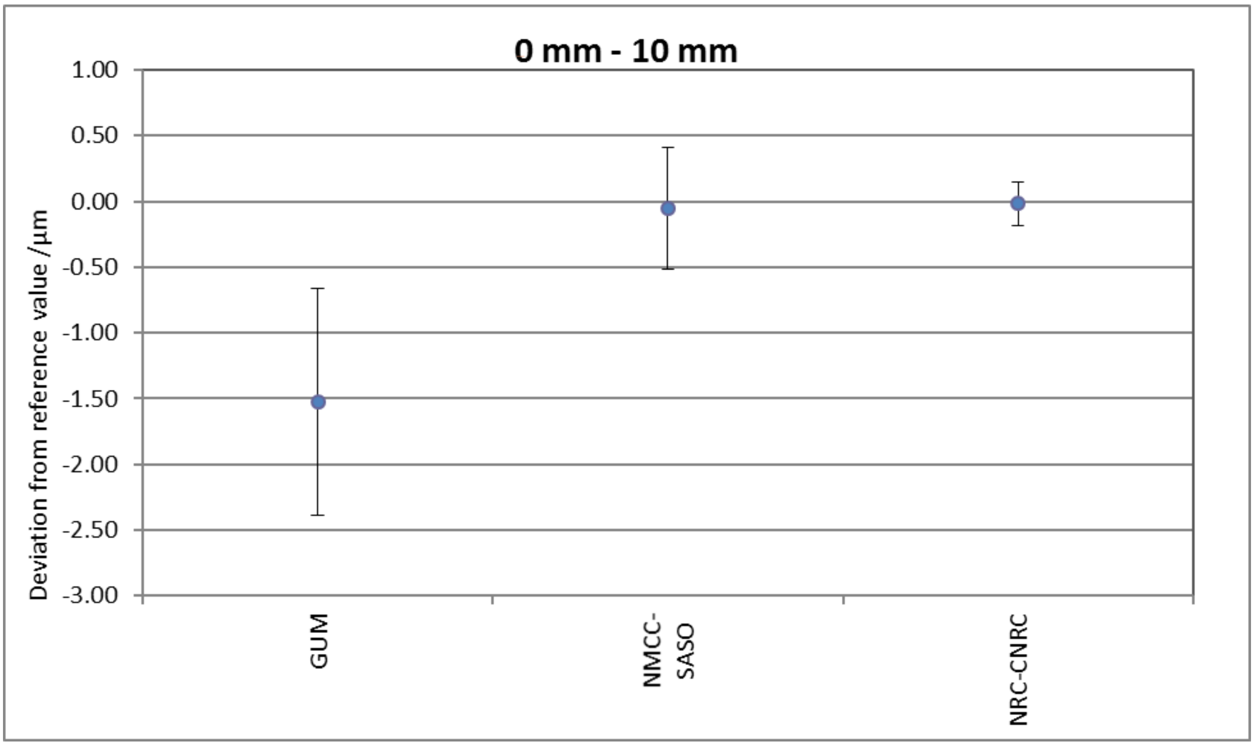


Figure 143: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

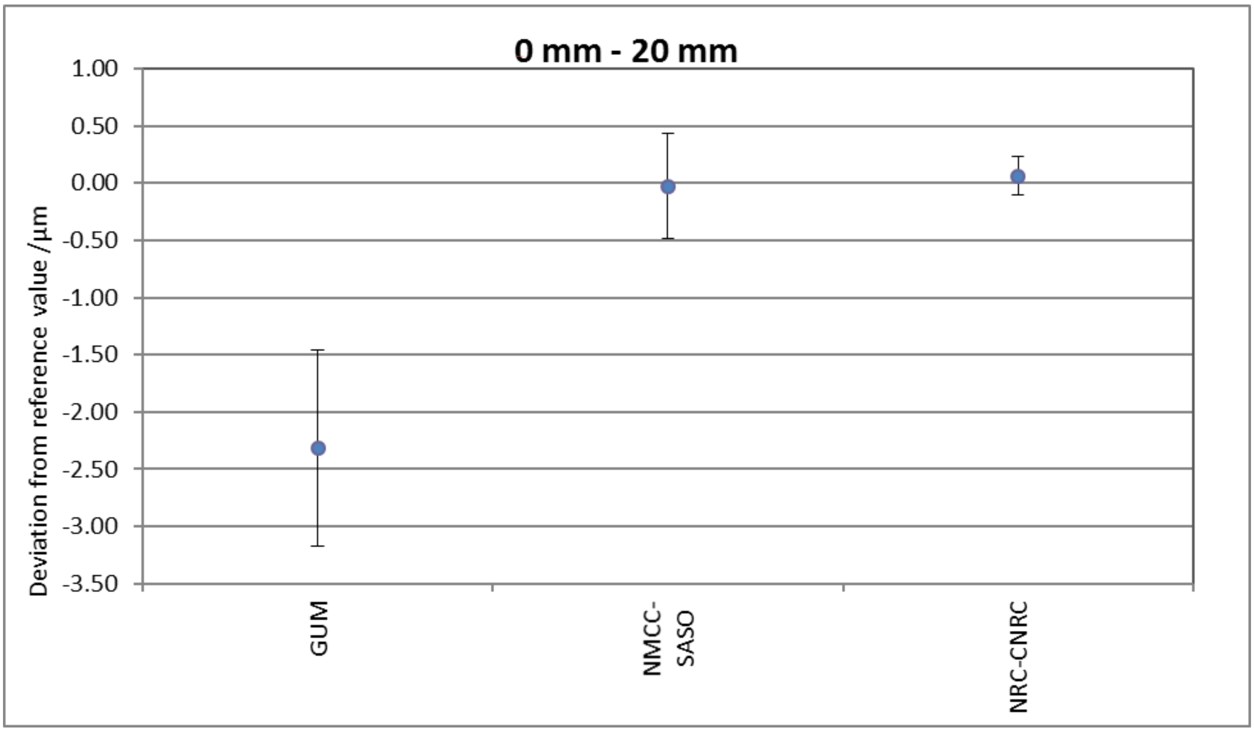


Figure 144: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

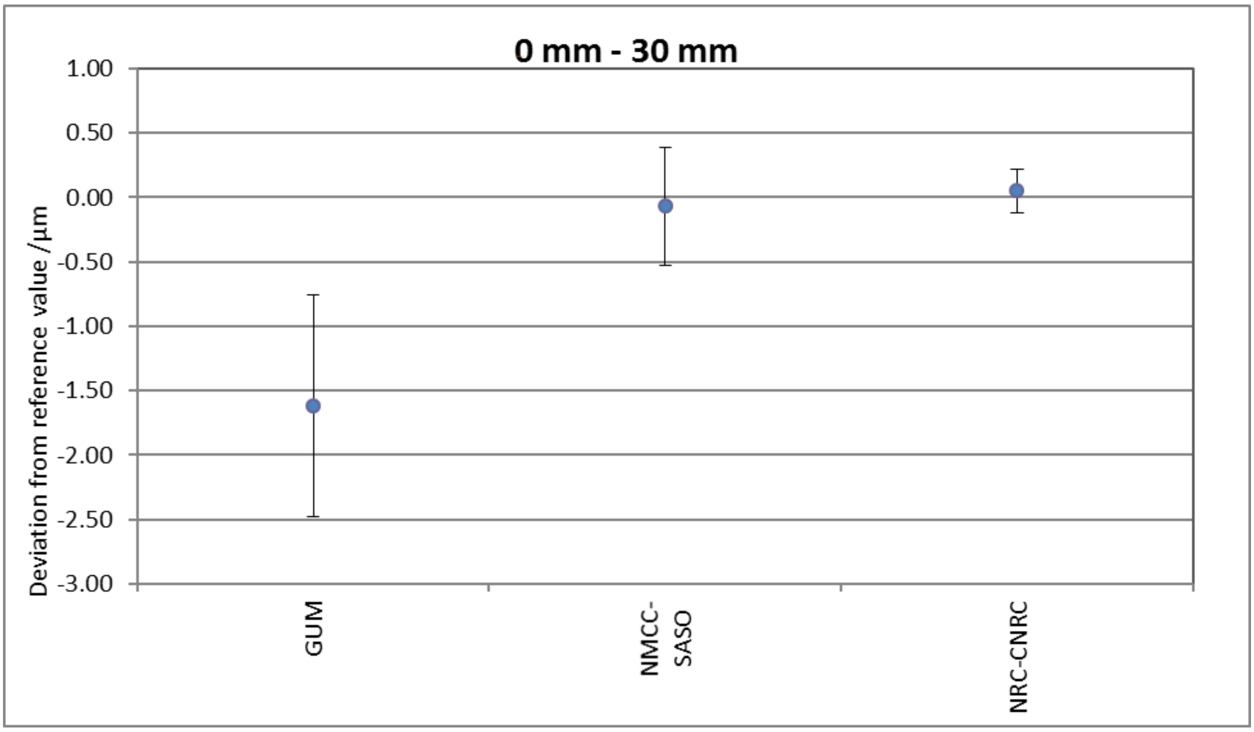


Figure 145: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

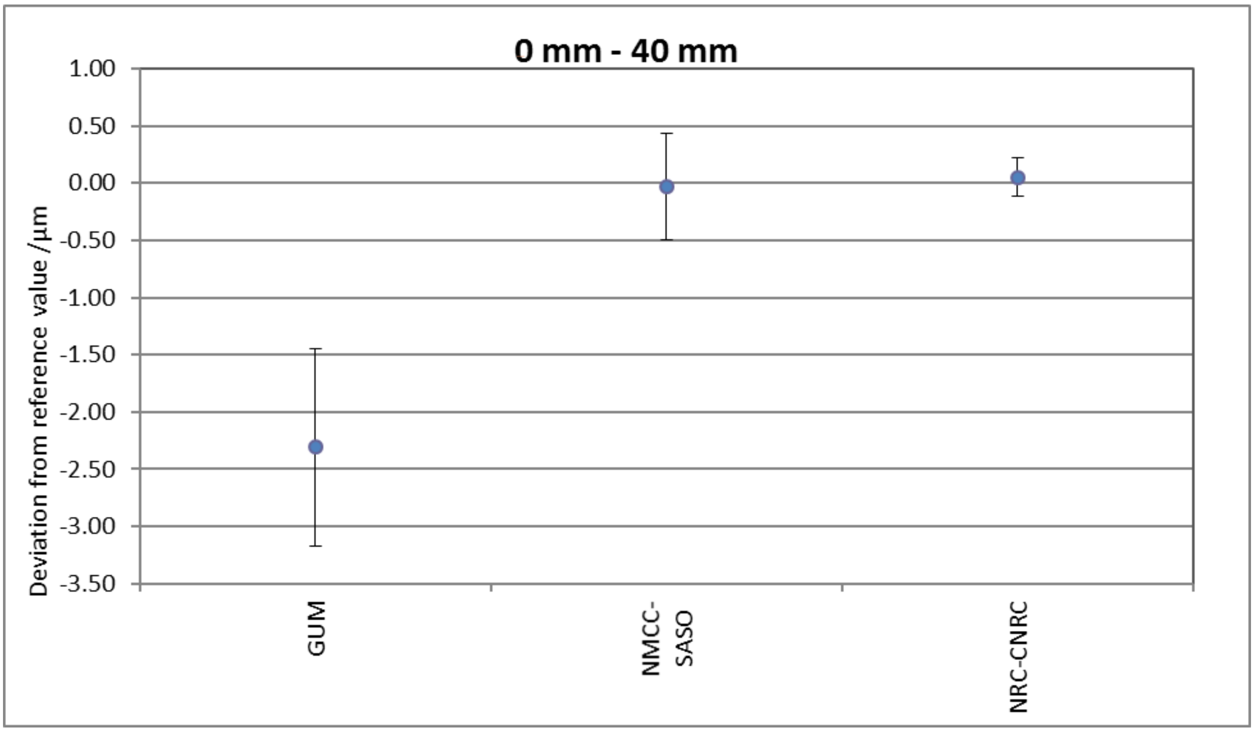


Figure 146: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

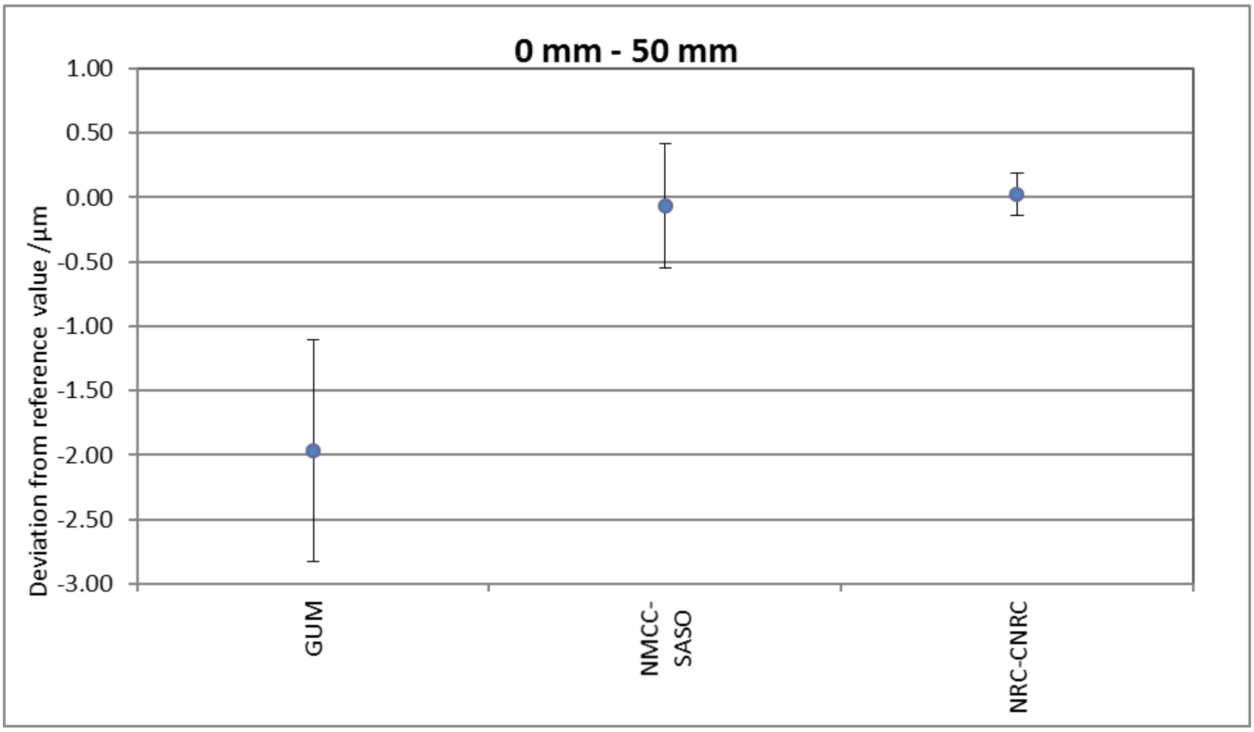


Figure 147: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

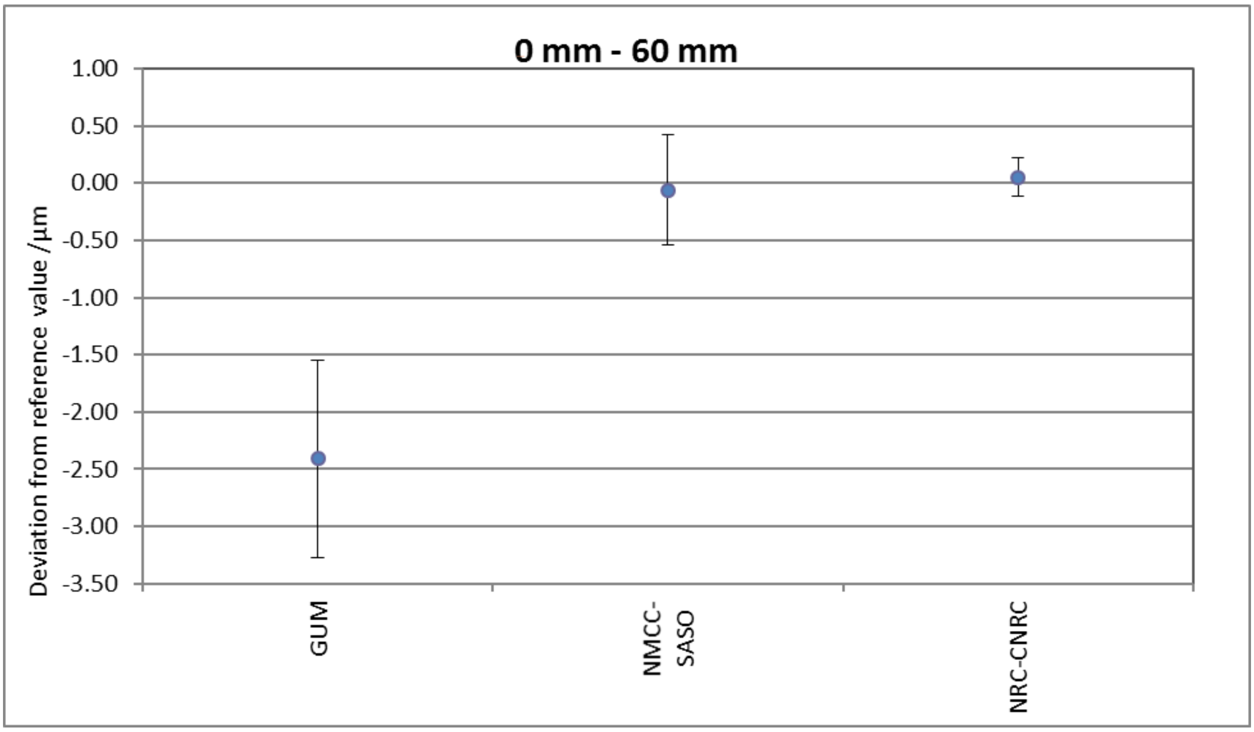


Figure 148 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

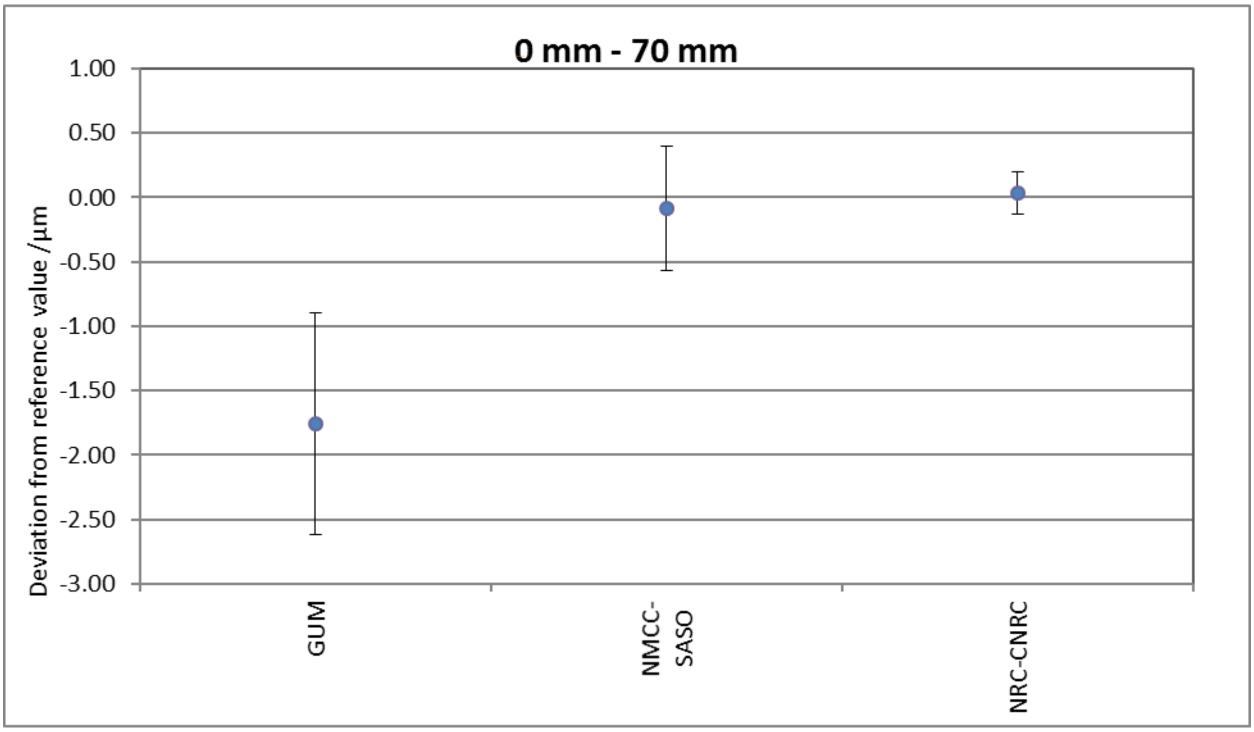


Figure 149: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

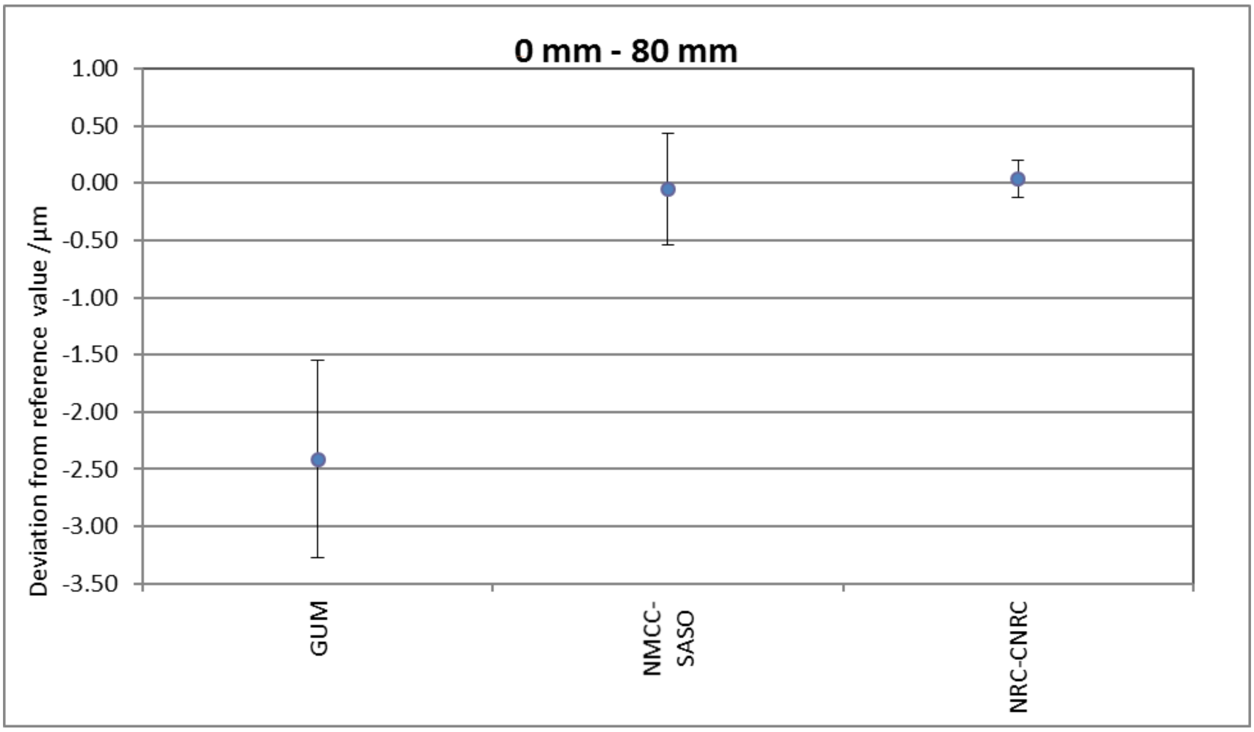


Figure 150: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

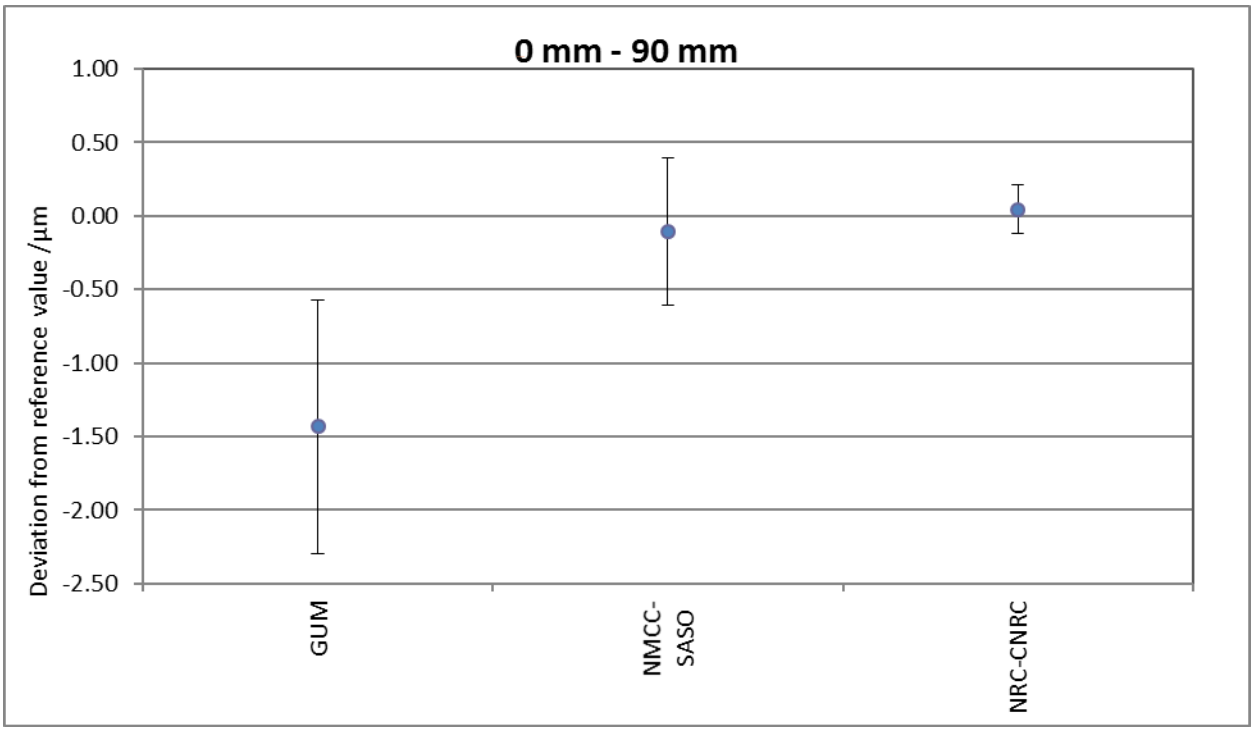


Figure 151: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

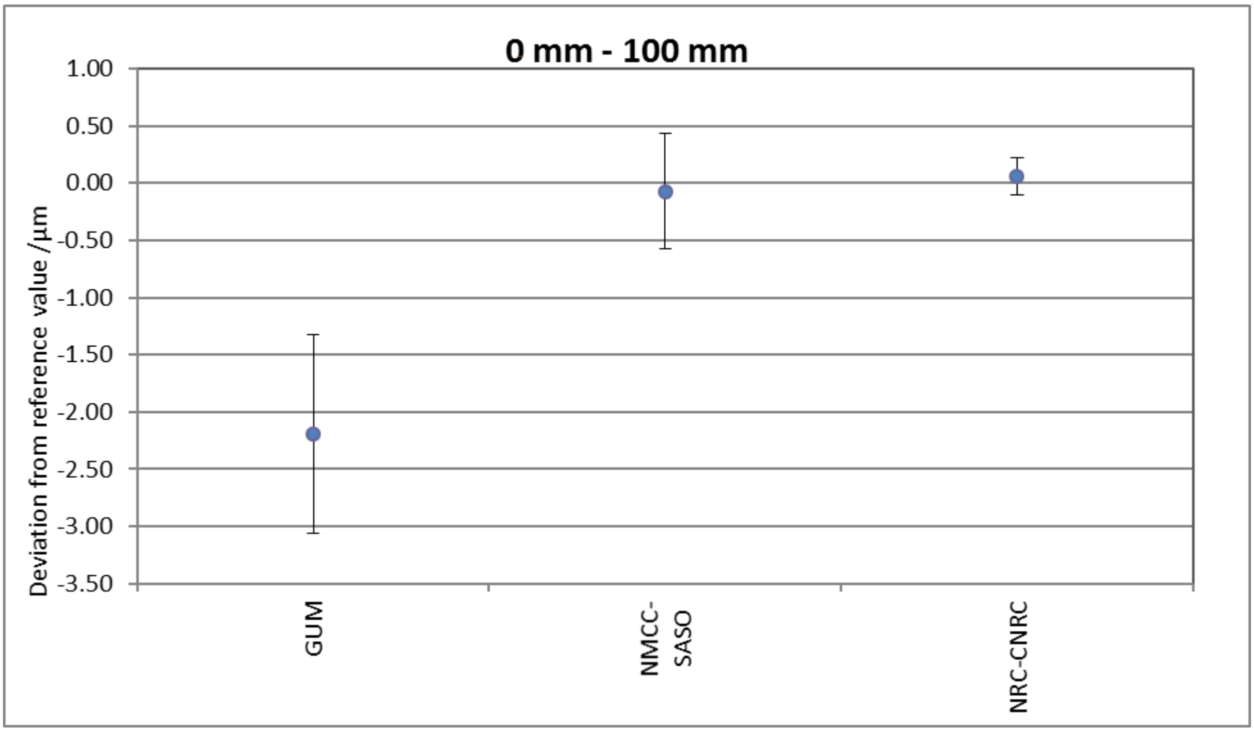


Figure 152: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

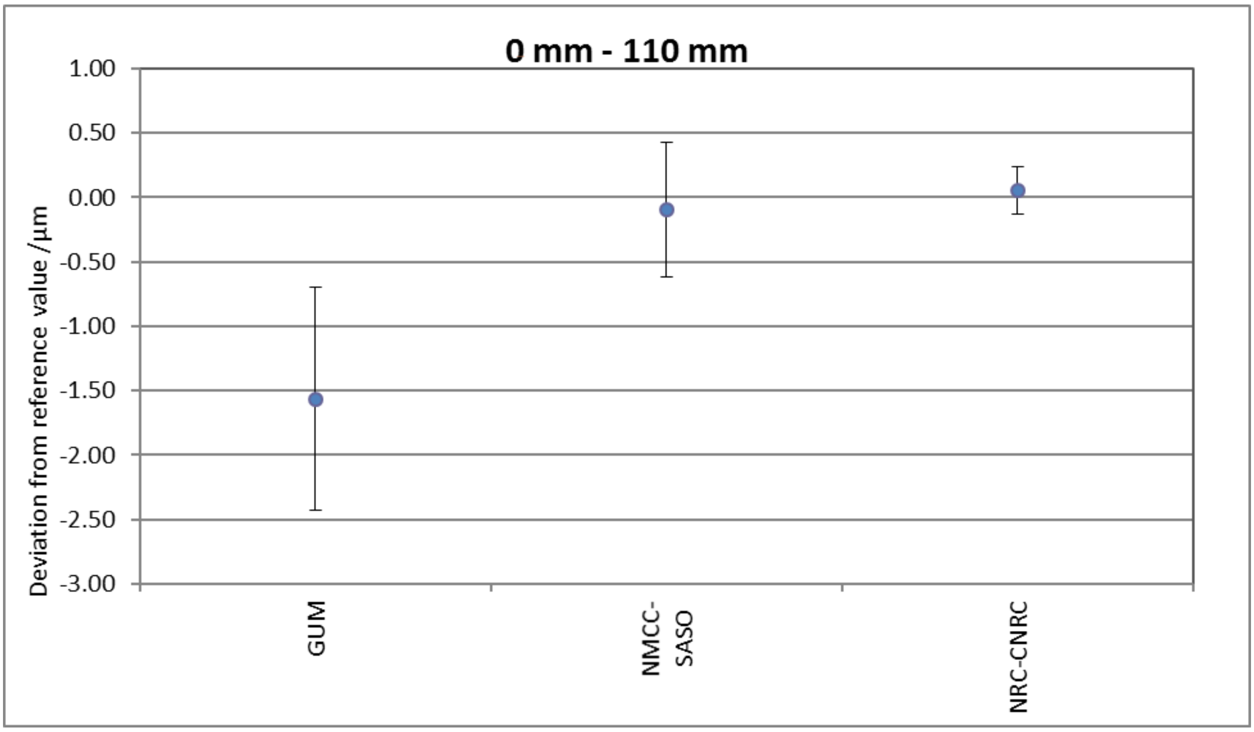


Figure 153: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

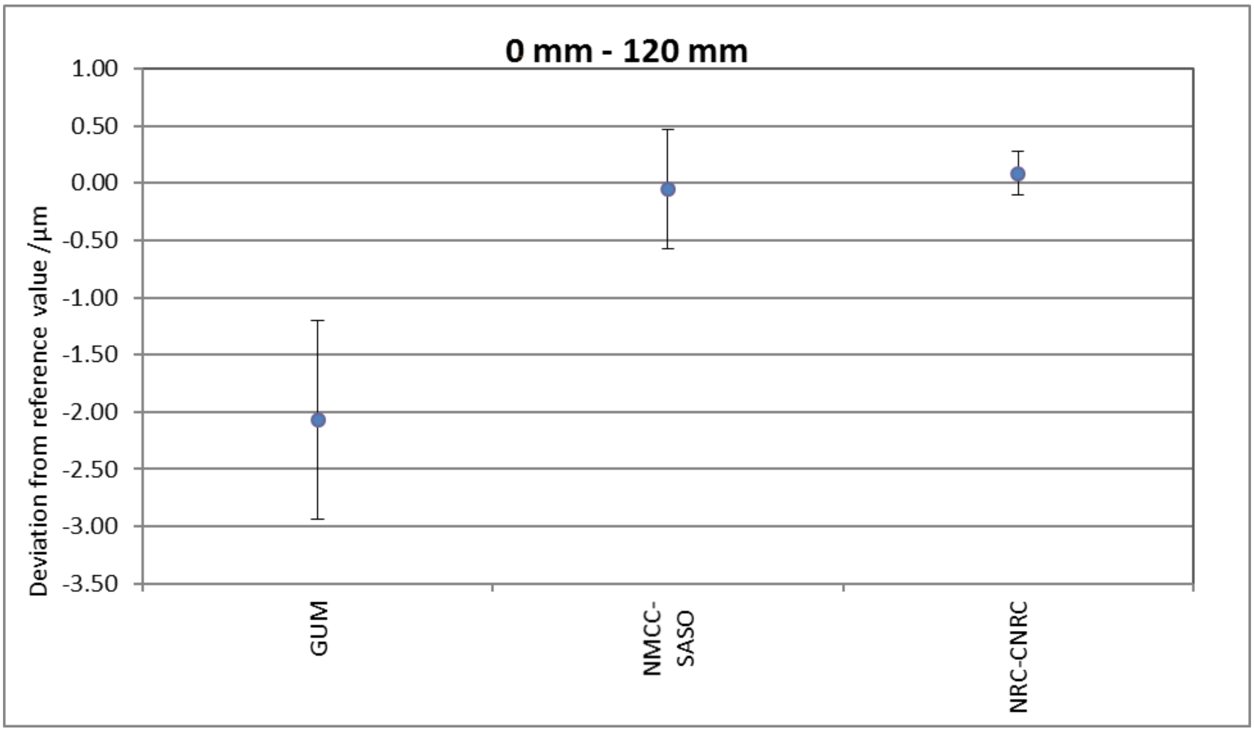


Figure 154: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

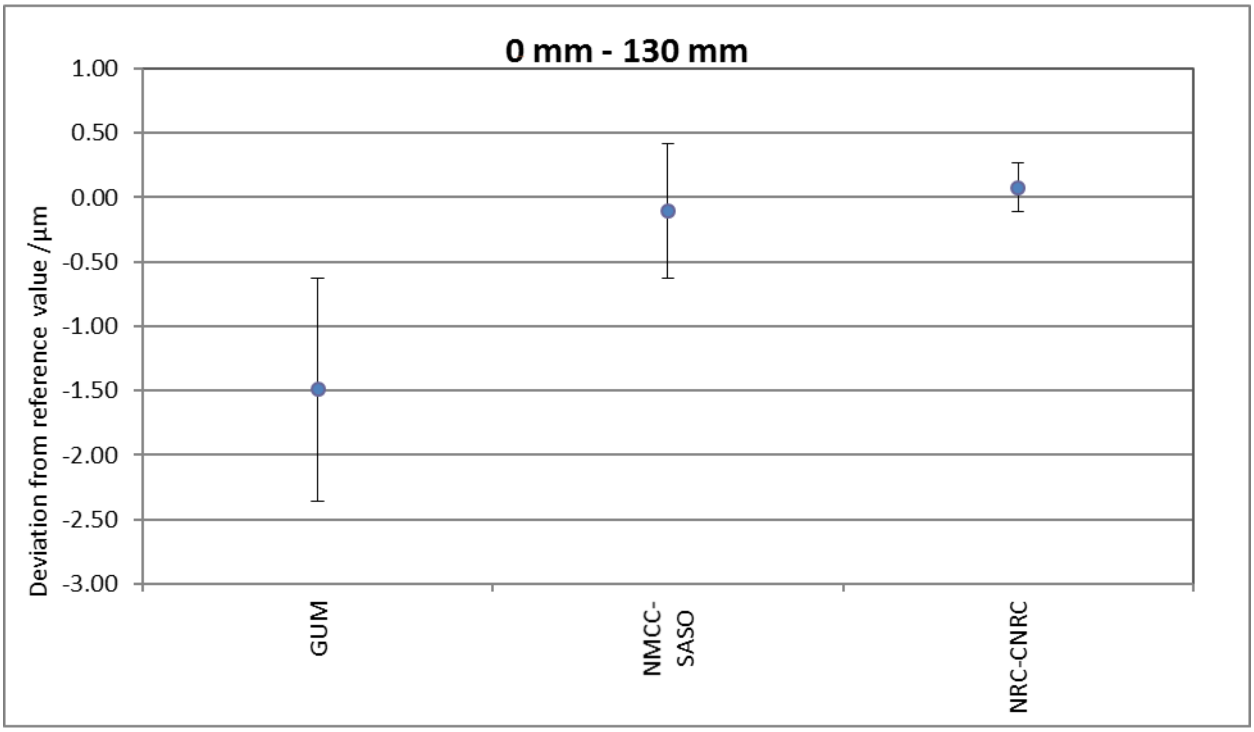


Figure 155: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

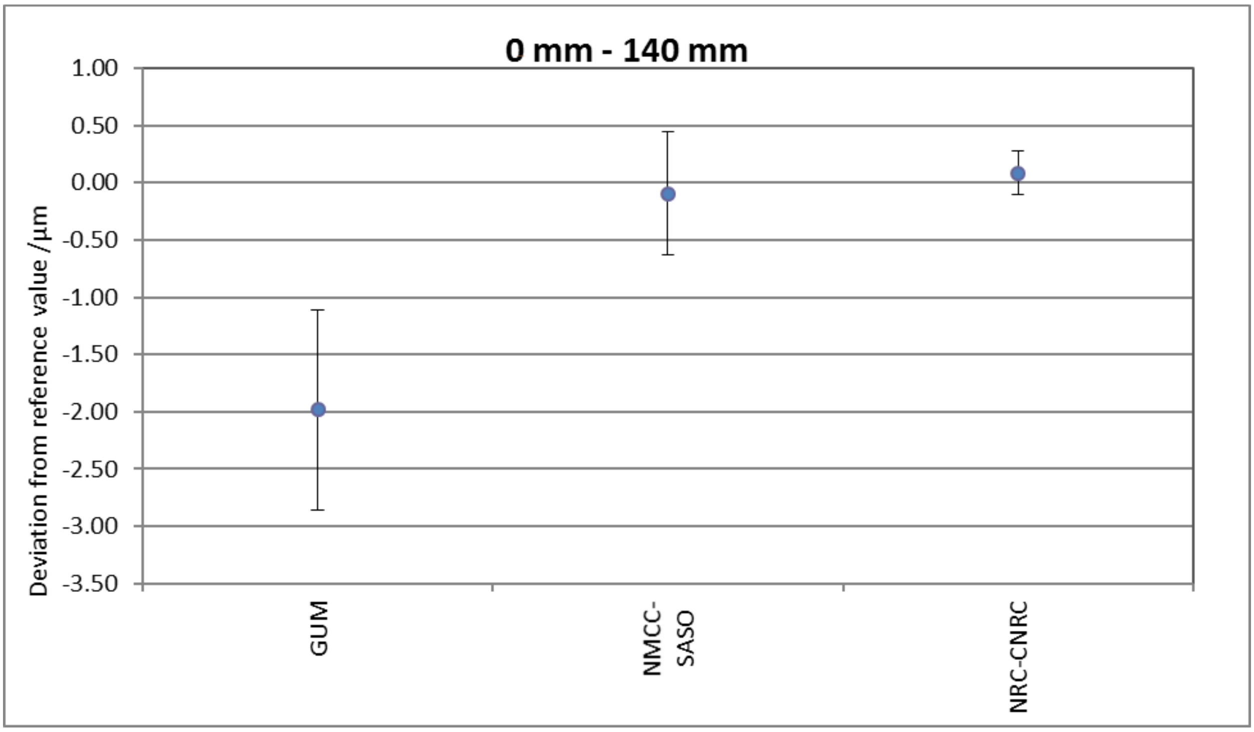


Figure 156: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

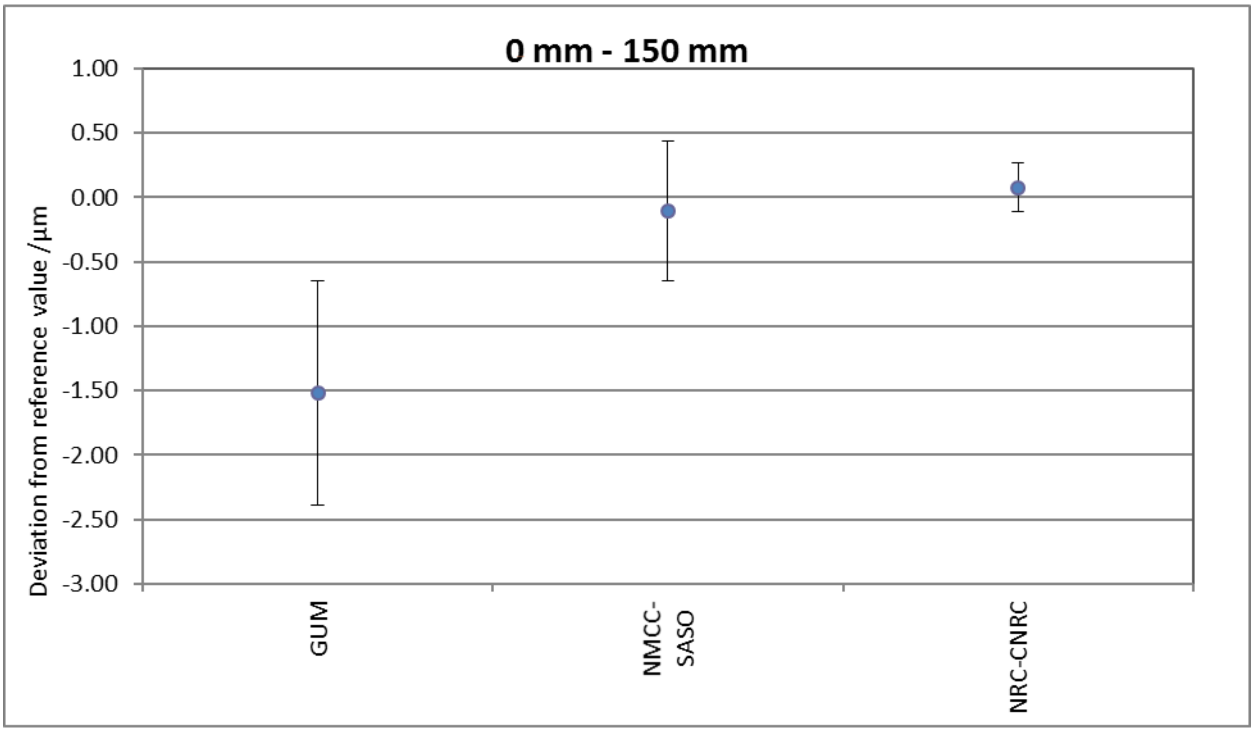


Figure 157: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

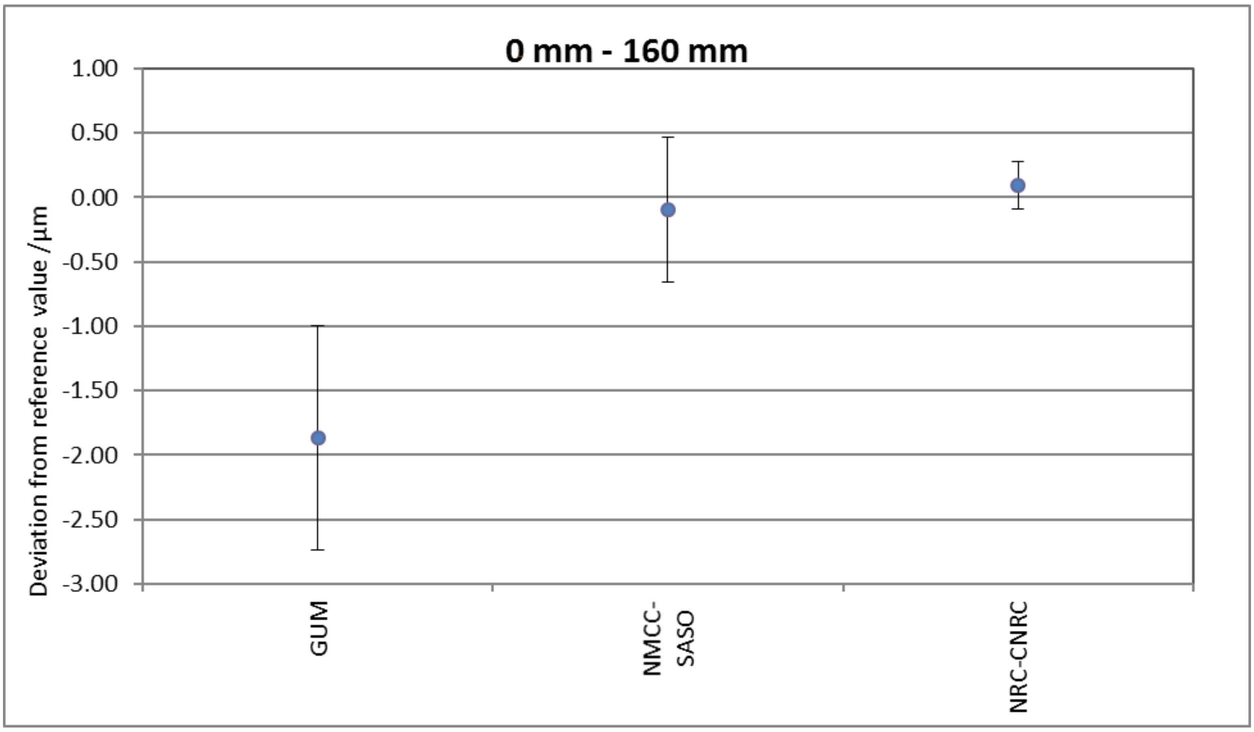


Figure 158: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

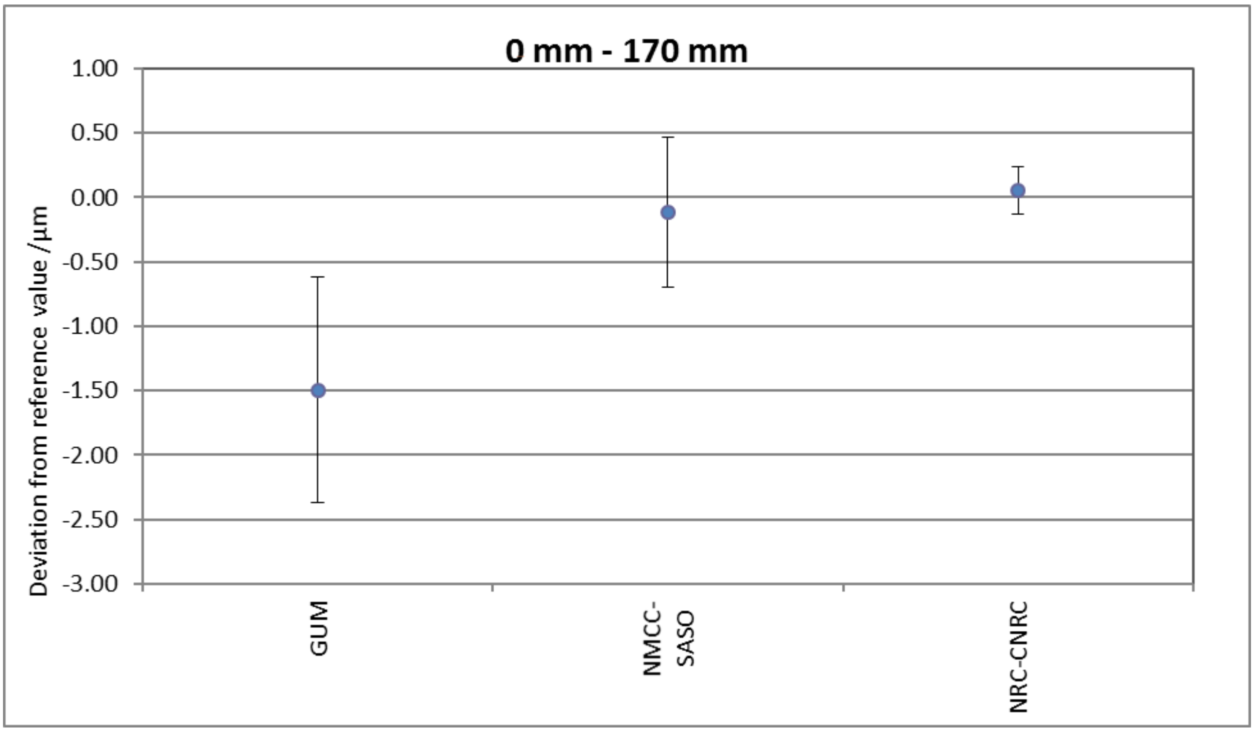


Figure 159: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

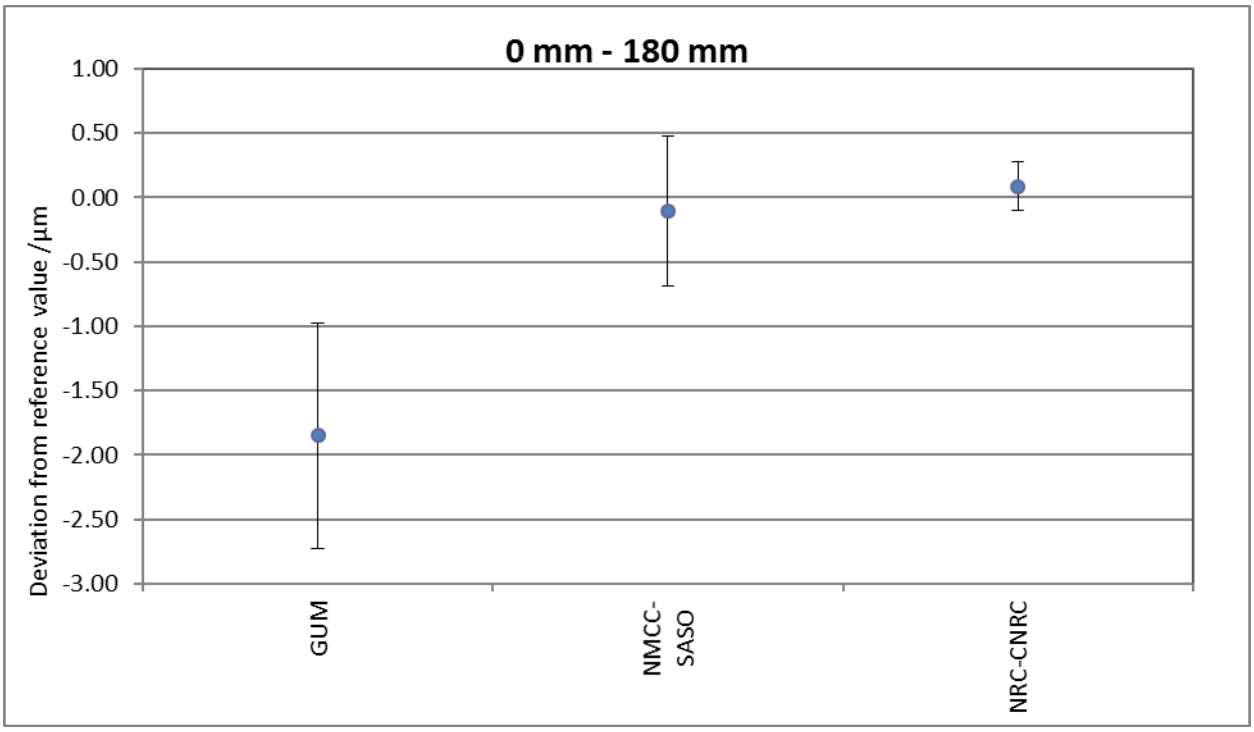


Figure 160: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

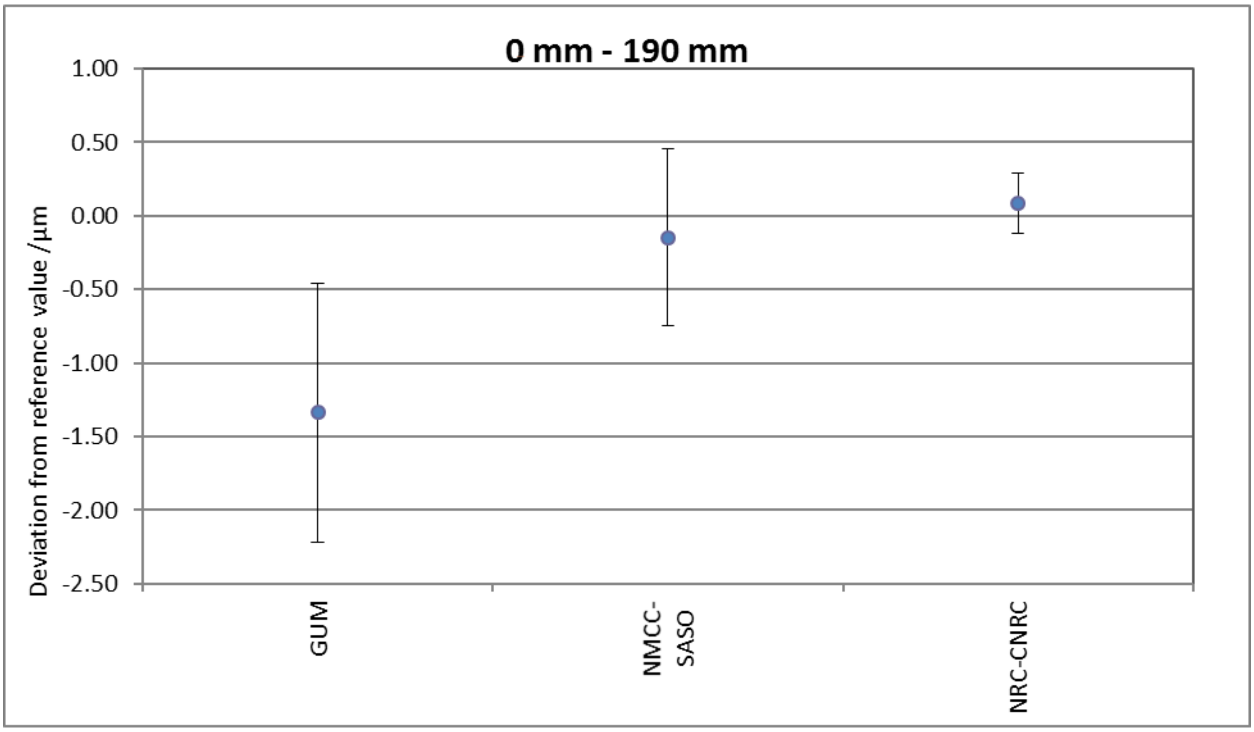


Figure 161: 610 mm artefact, group 2 participant deviations from reference value for this interval (k = 2)

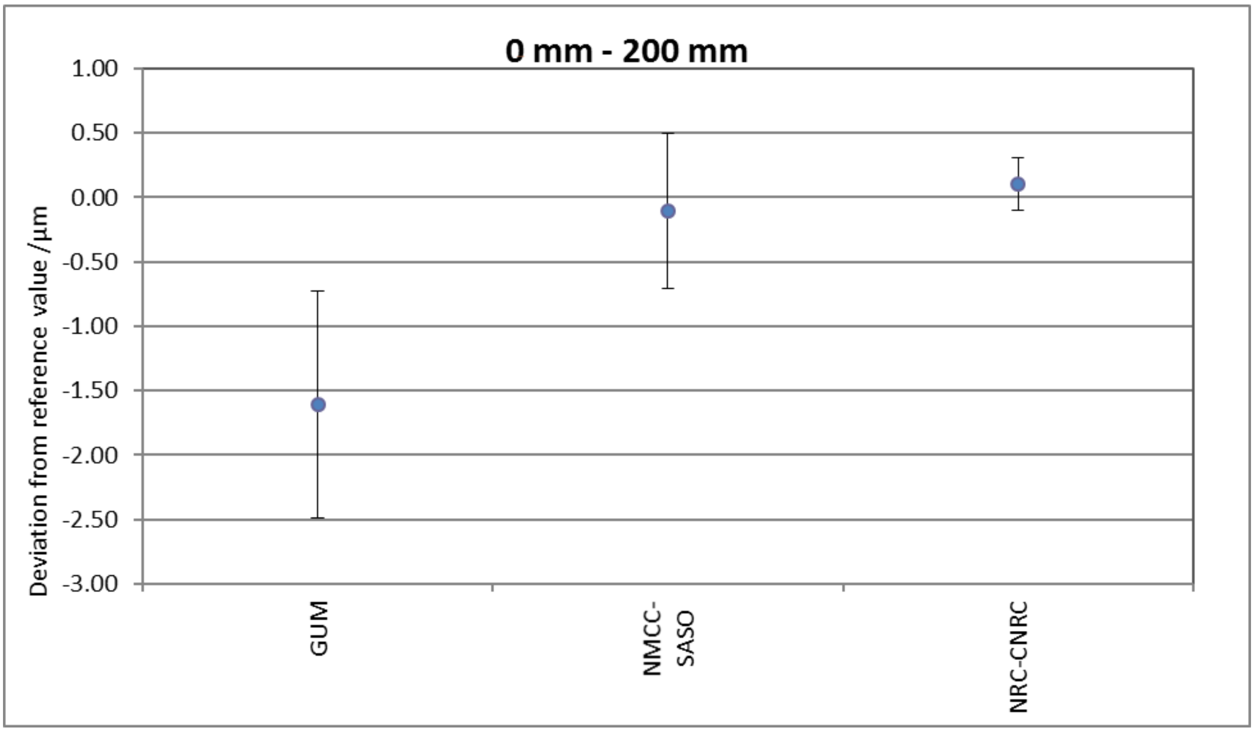


Figure 162: 610 mm artefact, group 2 participant deviations from reference value for this interval (k = 2)

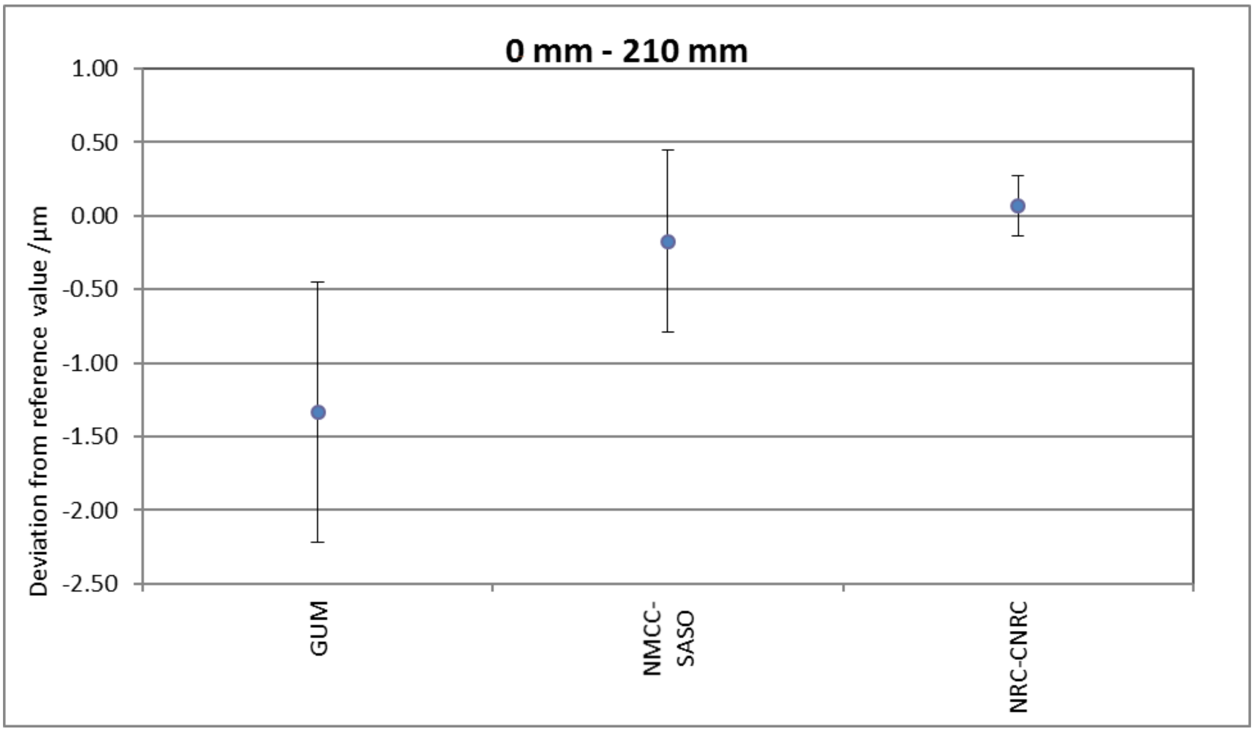


Figure 163: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

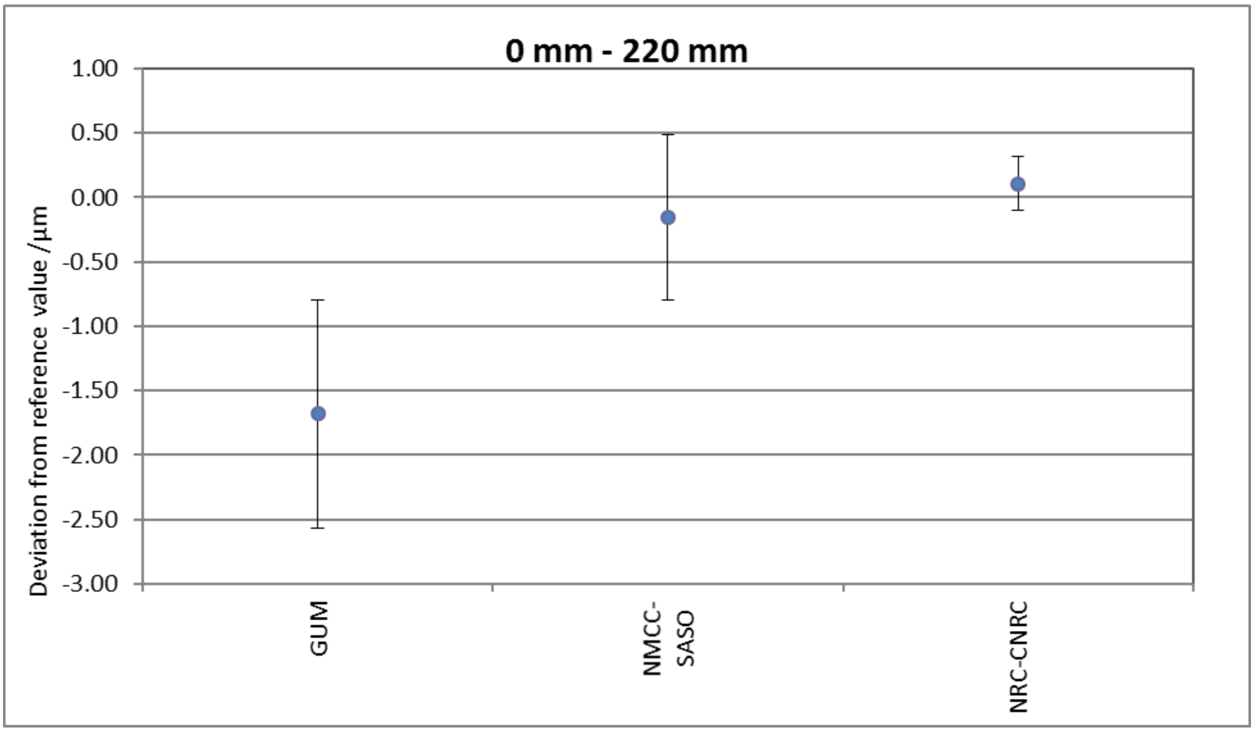


Figure 164: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

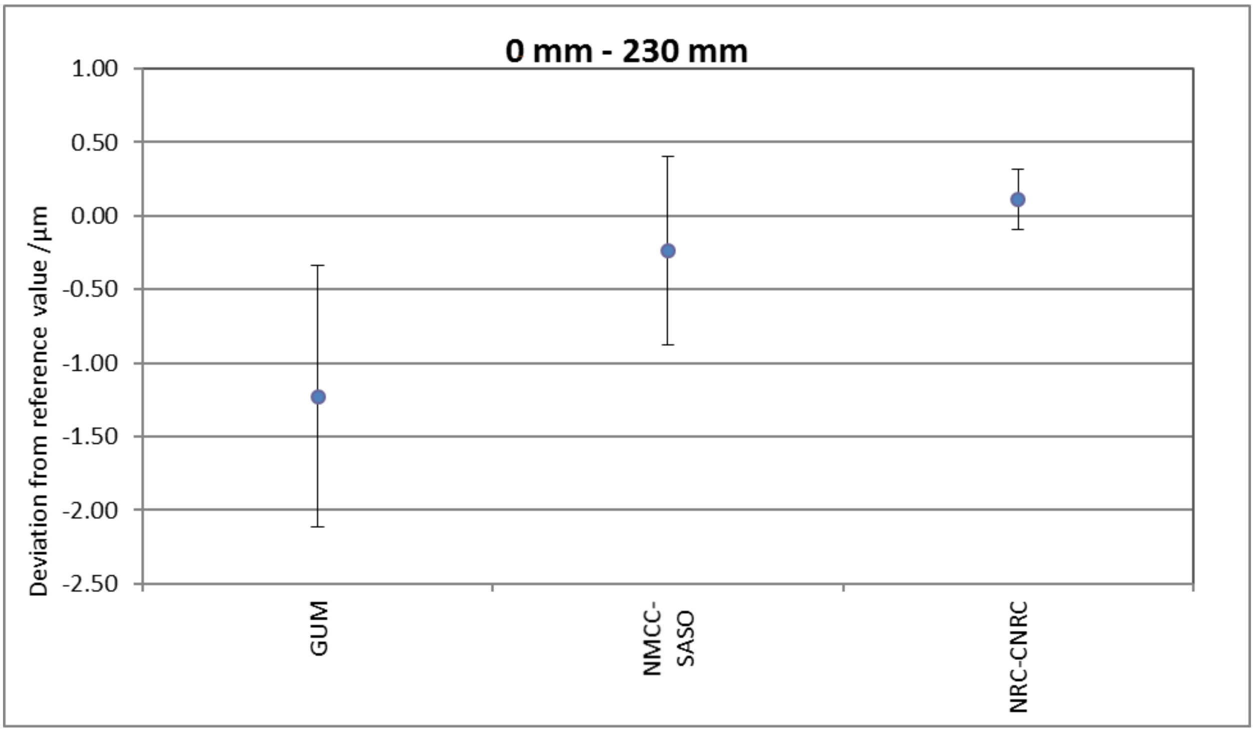


Figure 165: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

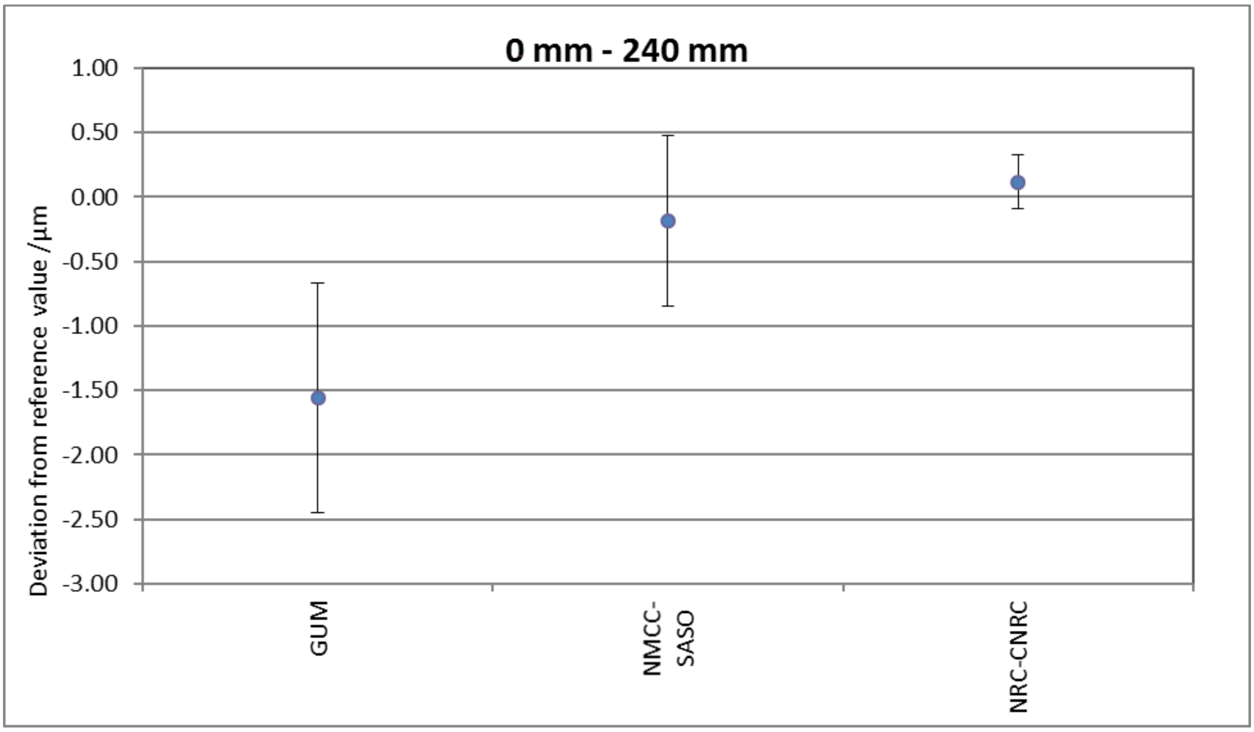


Figure 166: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

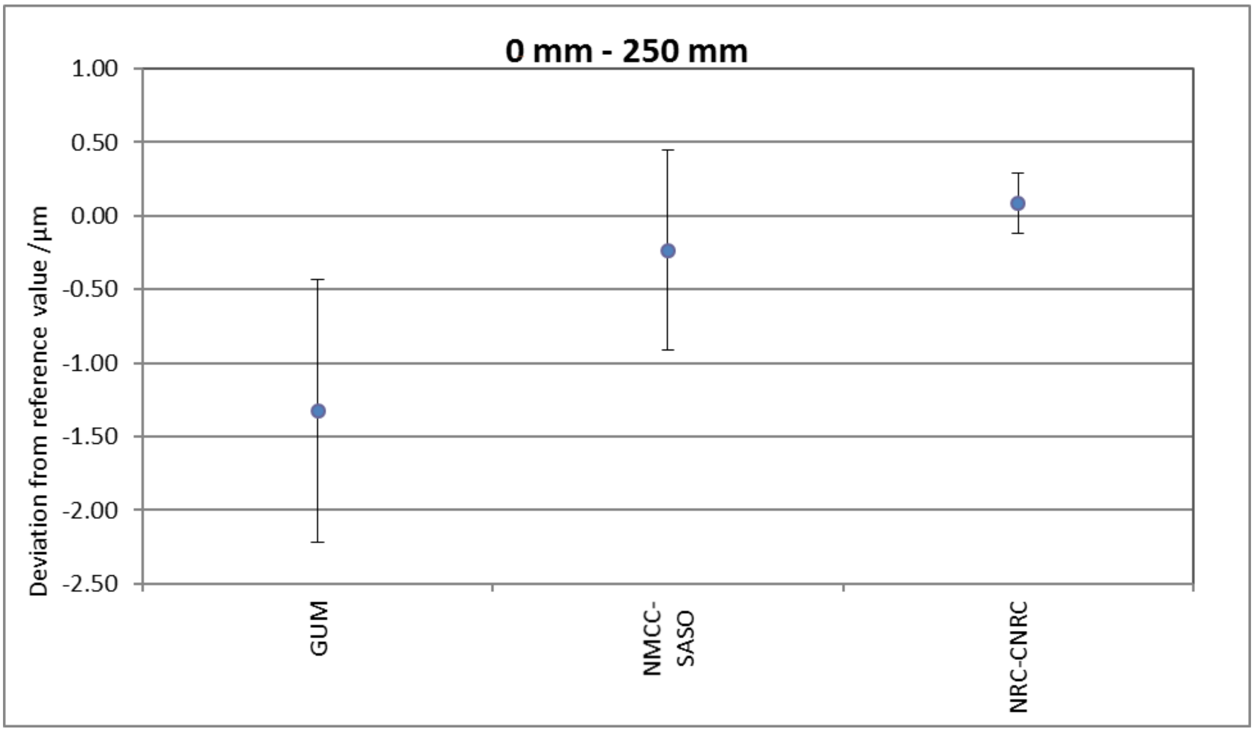


Figure 167: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

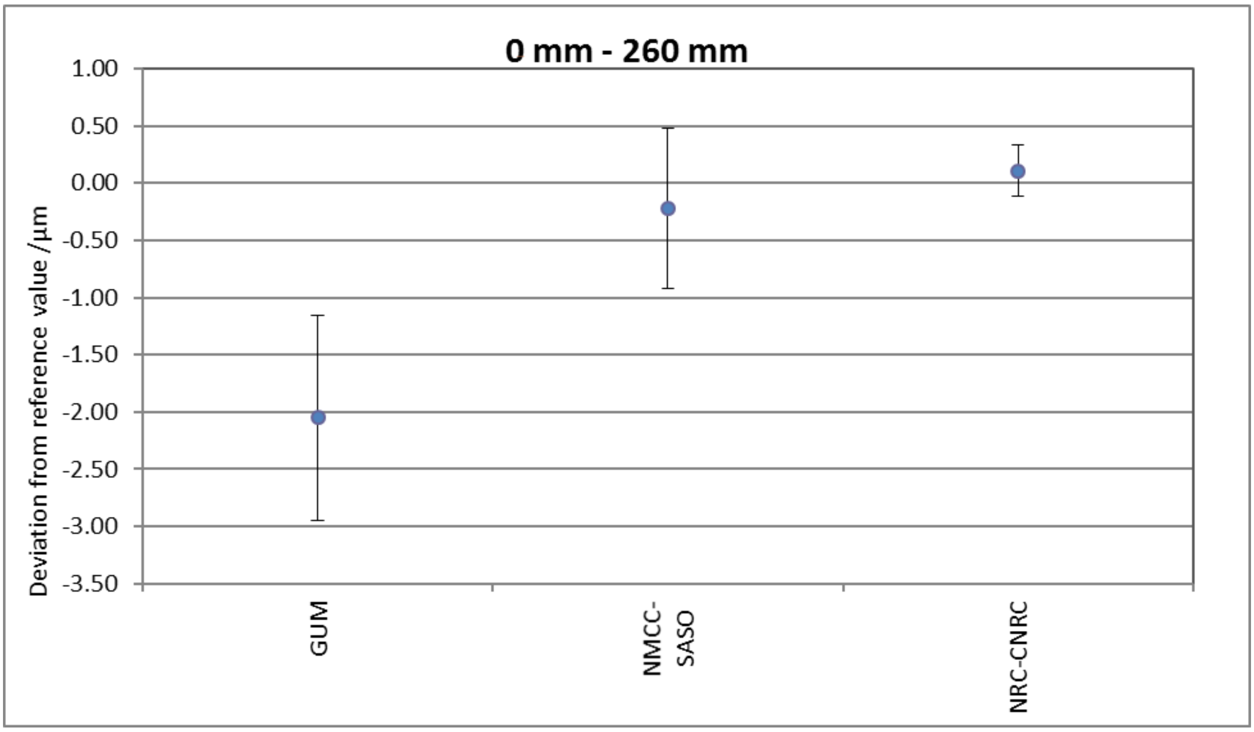


Figure 168: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

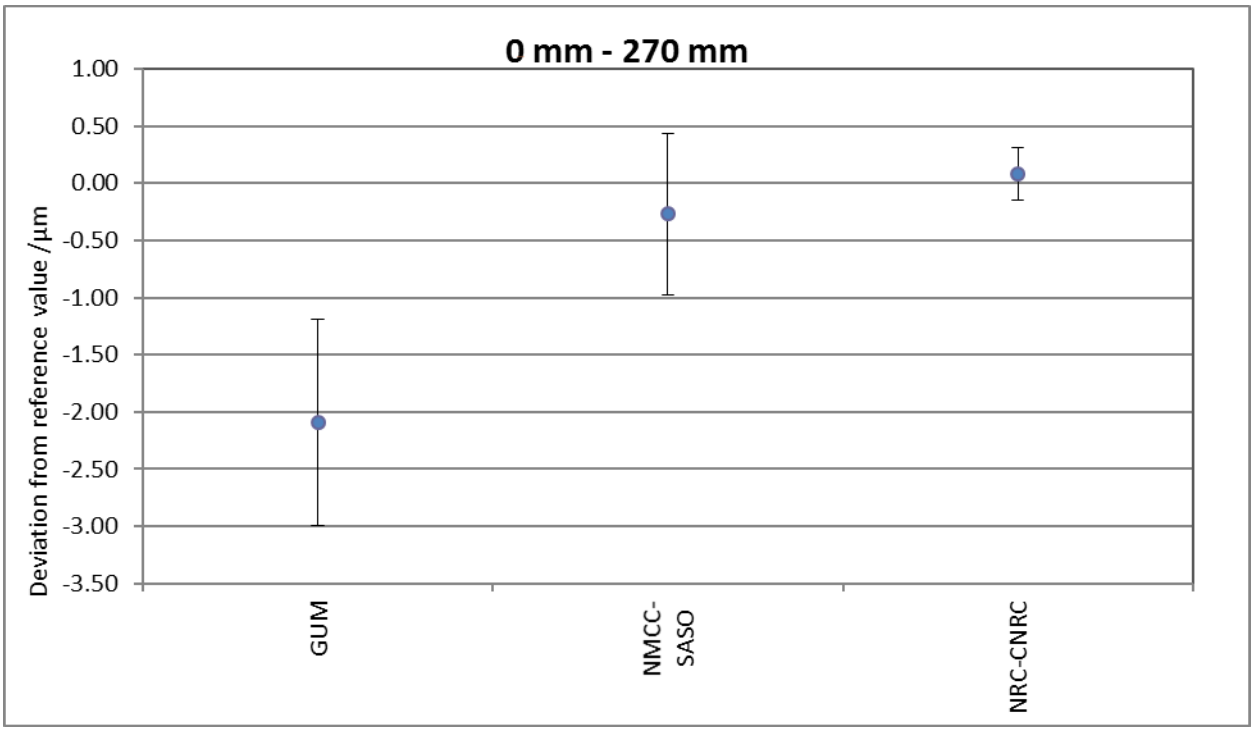


Figure 169: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

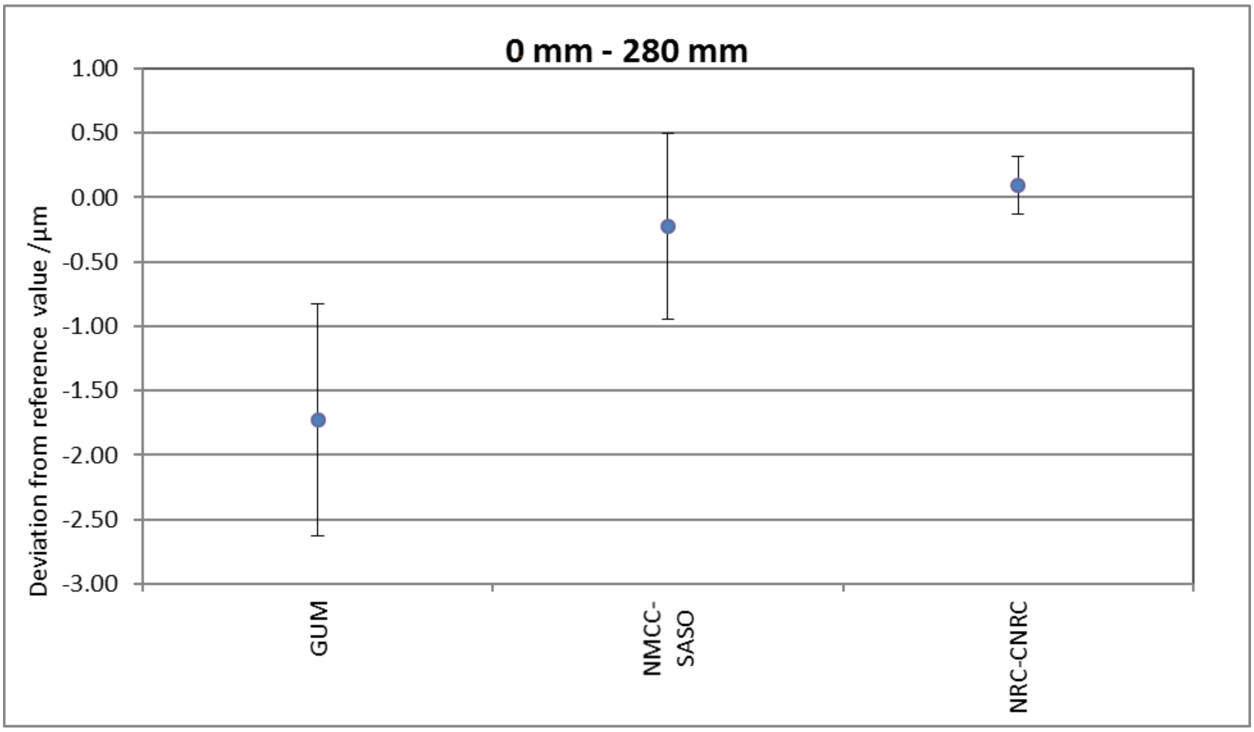


Figure 170: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

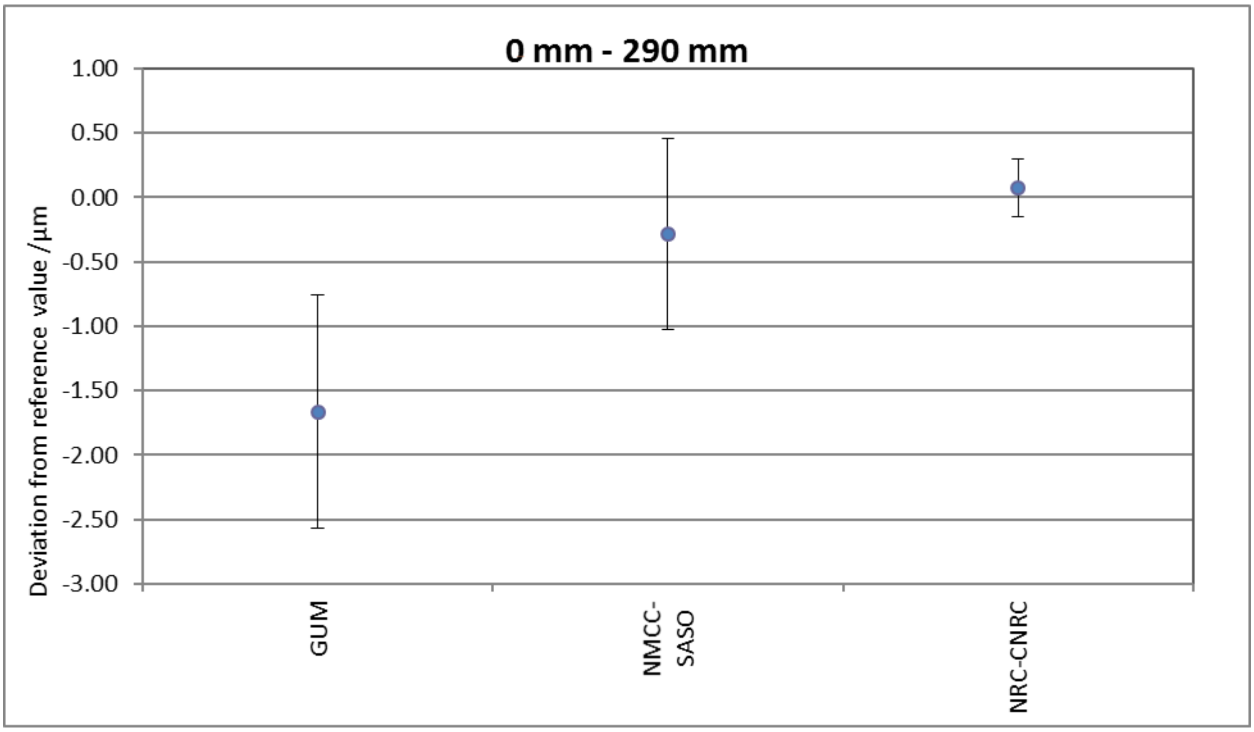


Figure 171: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

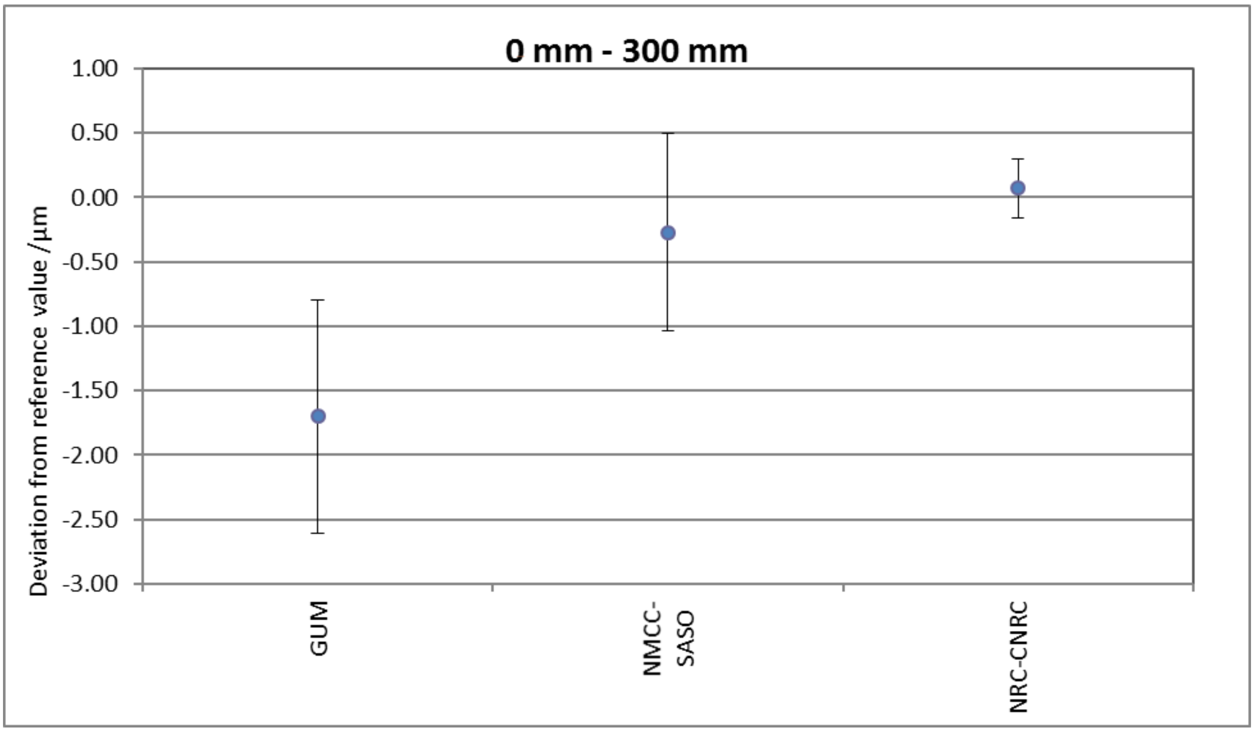


Figure 172: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

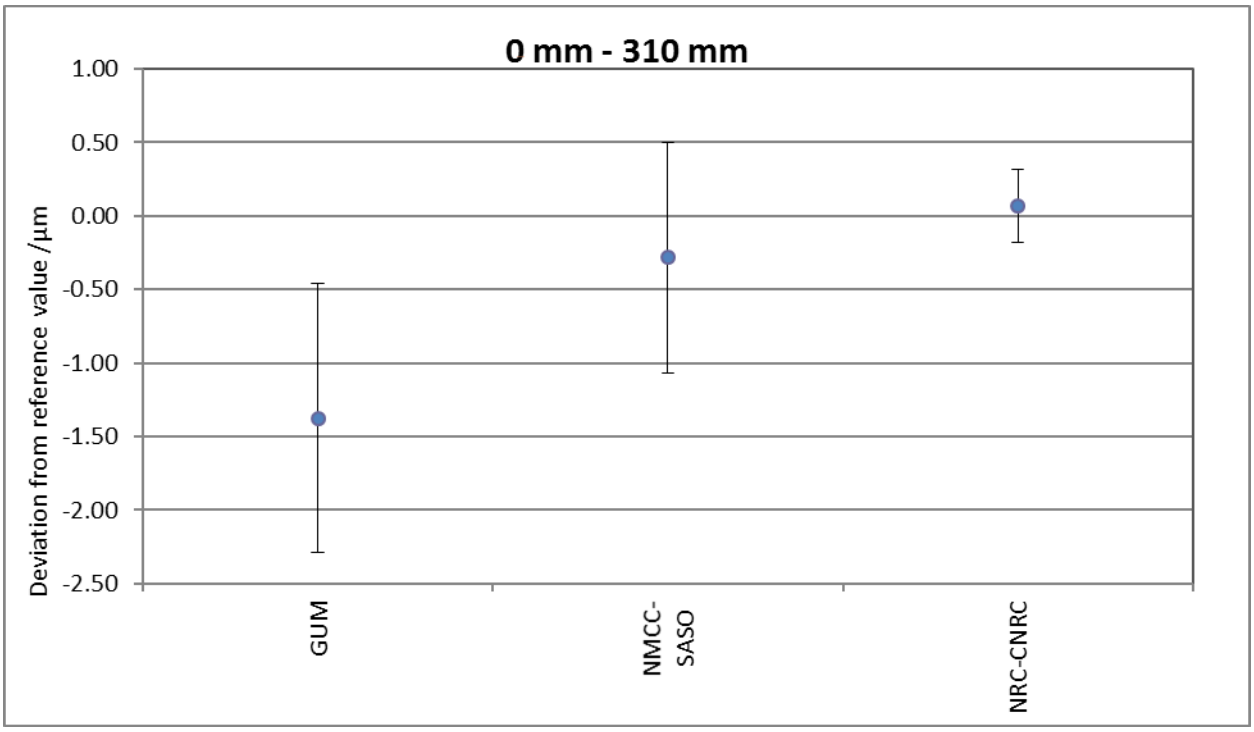


Figure 173: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

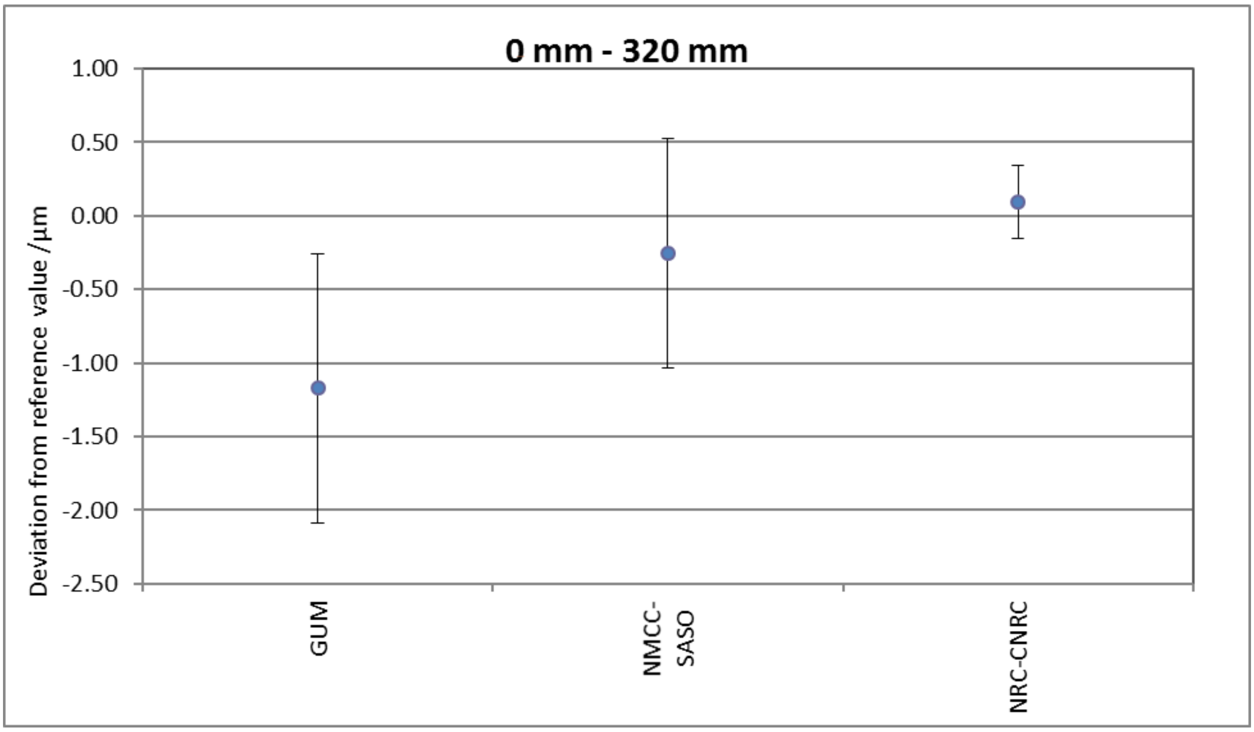


Figure 174: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

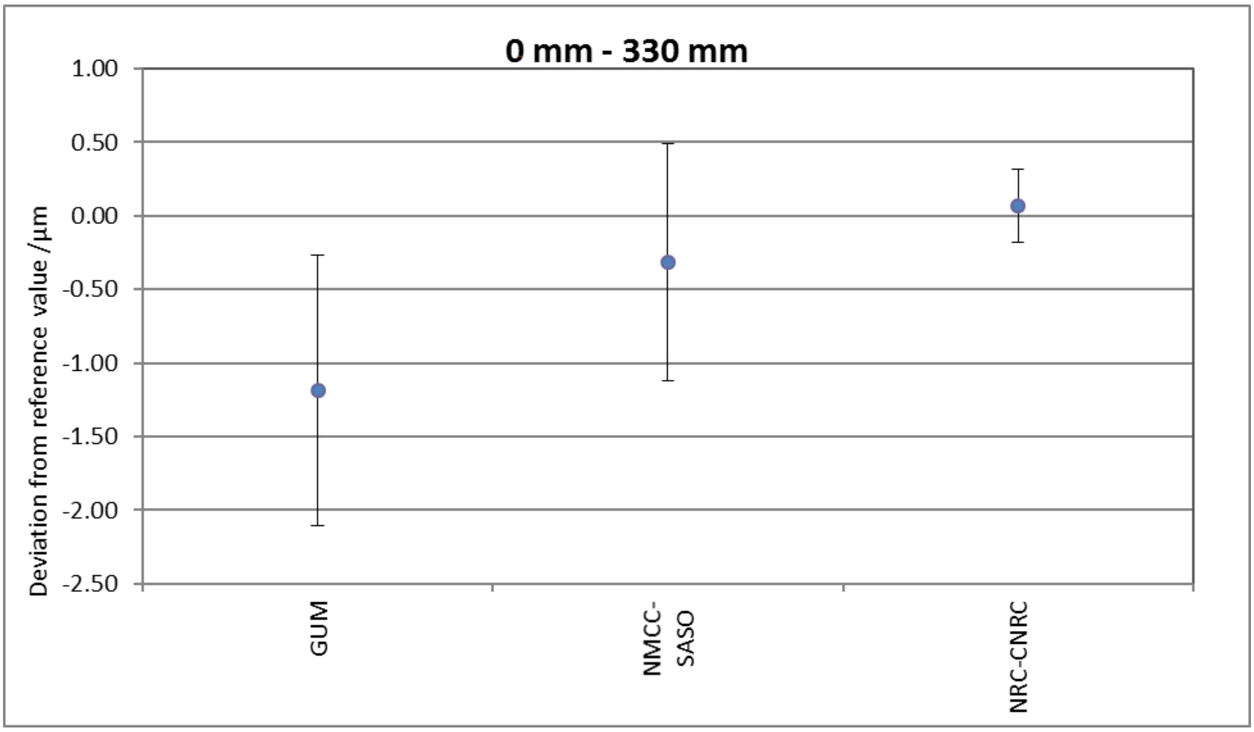


Figure 175: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

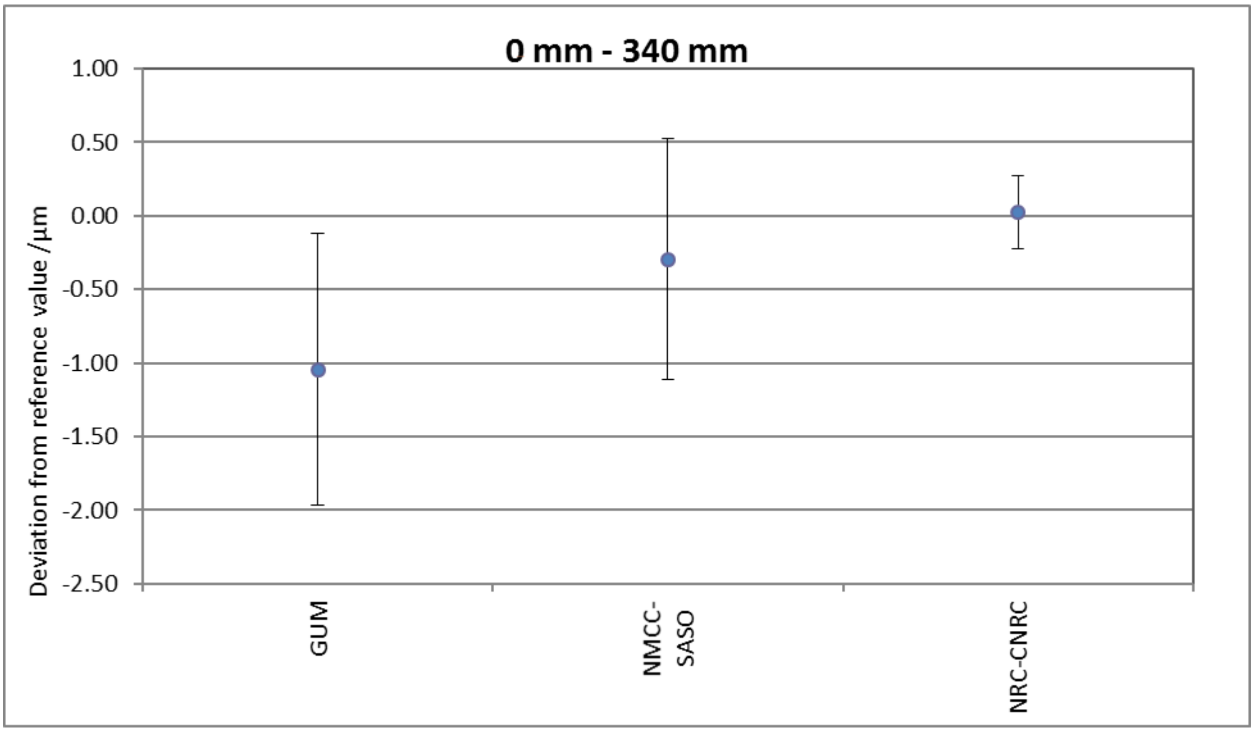


Figure 176: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

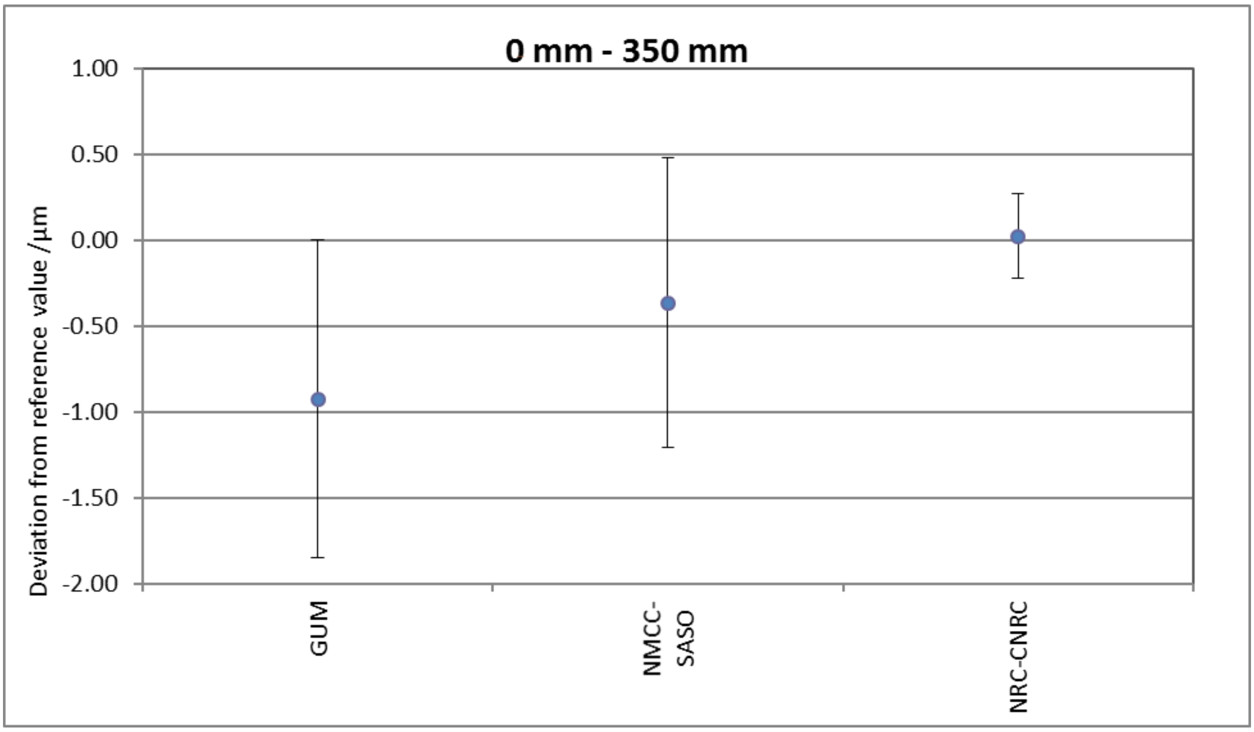


Figure 177: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

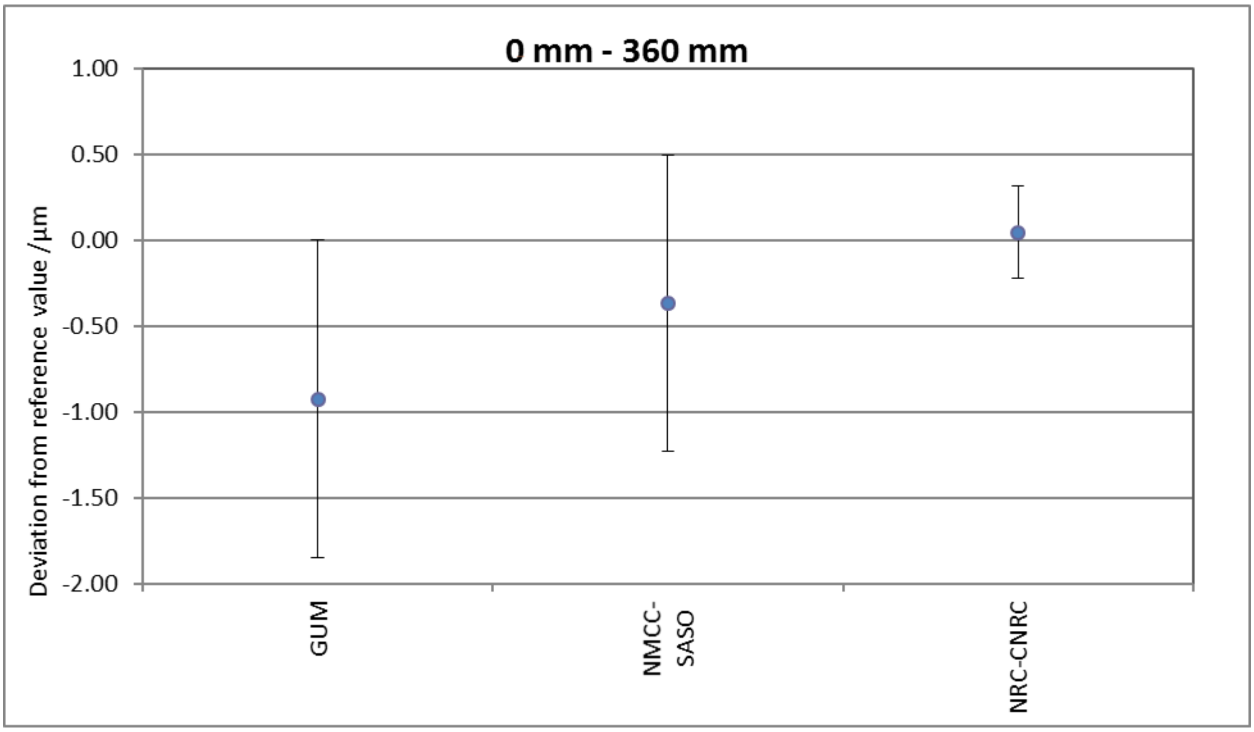


Figure 178: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

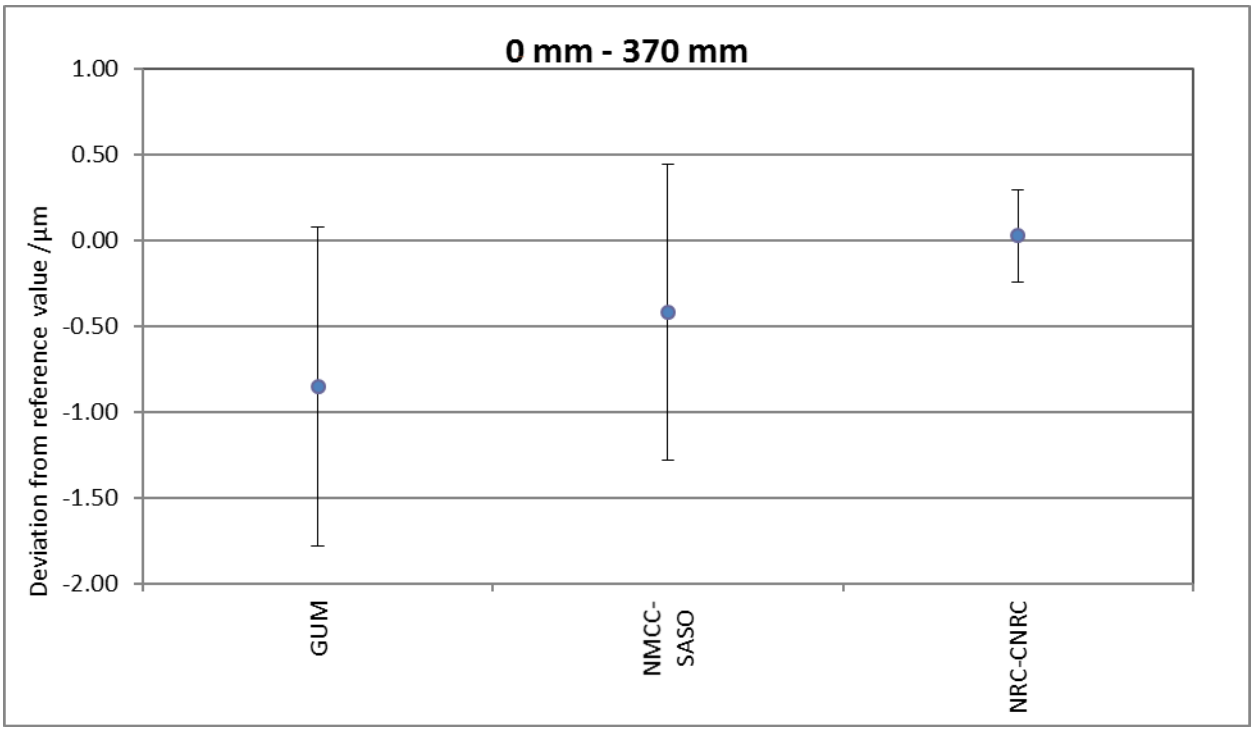


Figure 179: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

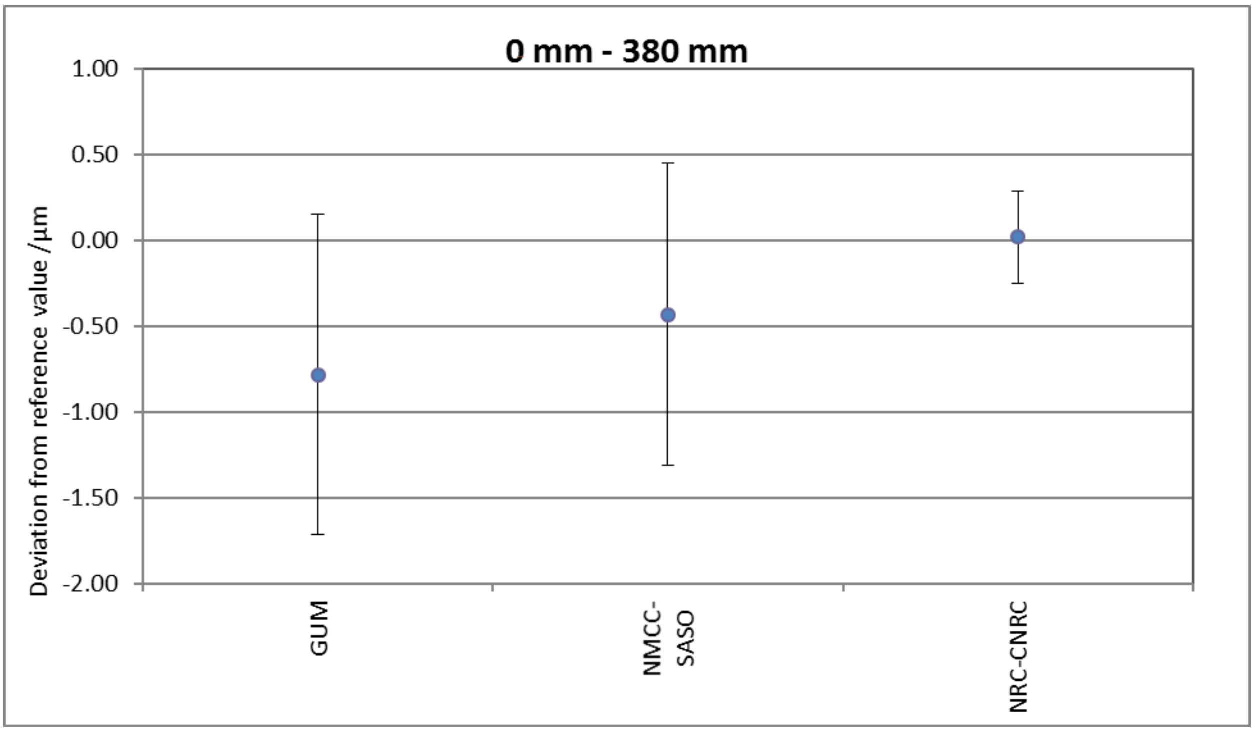


Figure 180: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

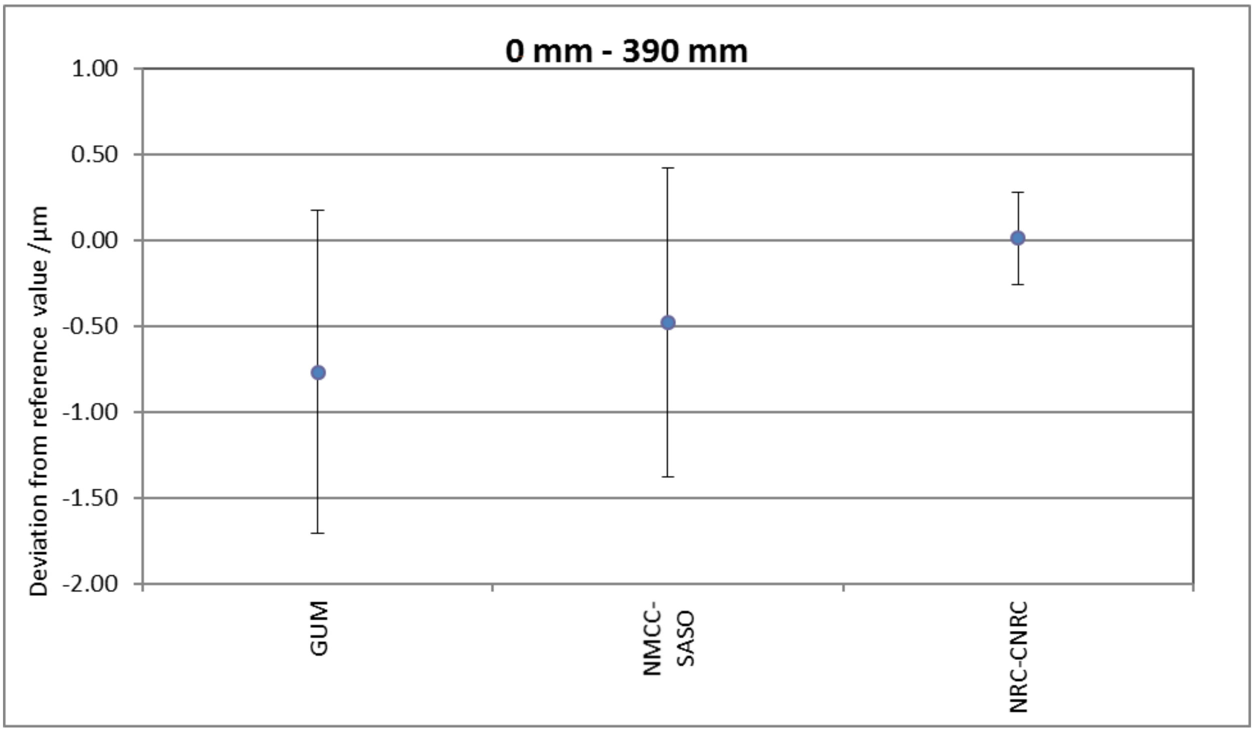


Figure 181: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

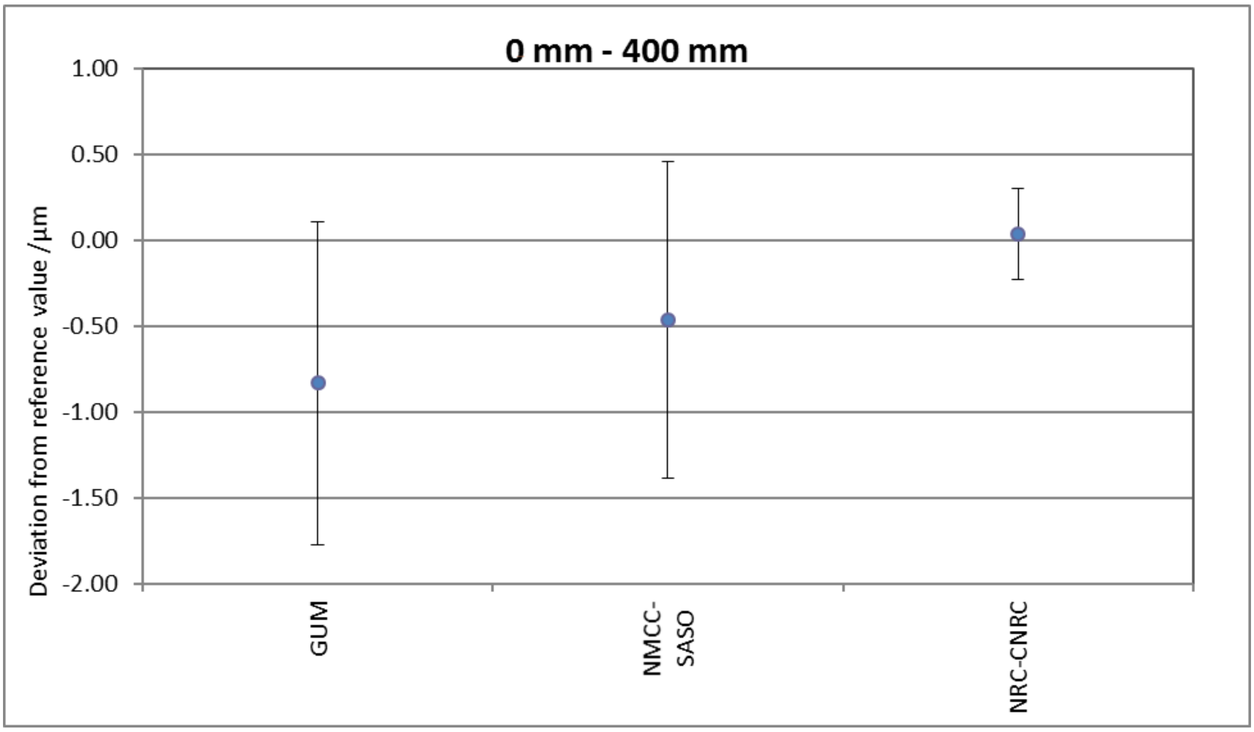


Figure 182: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

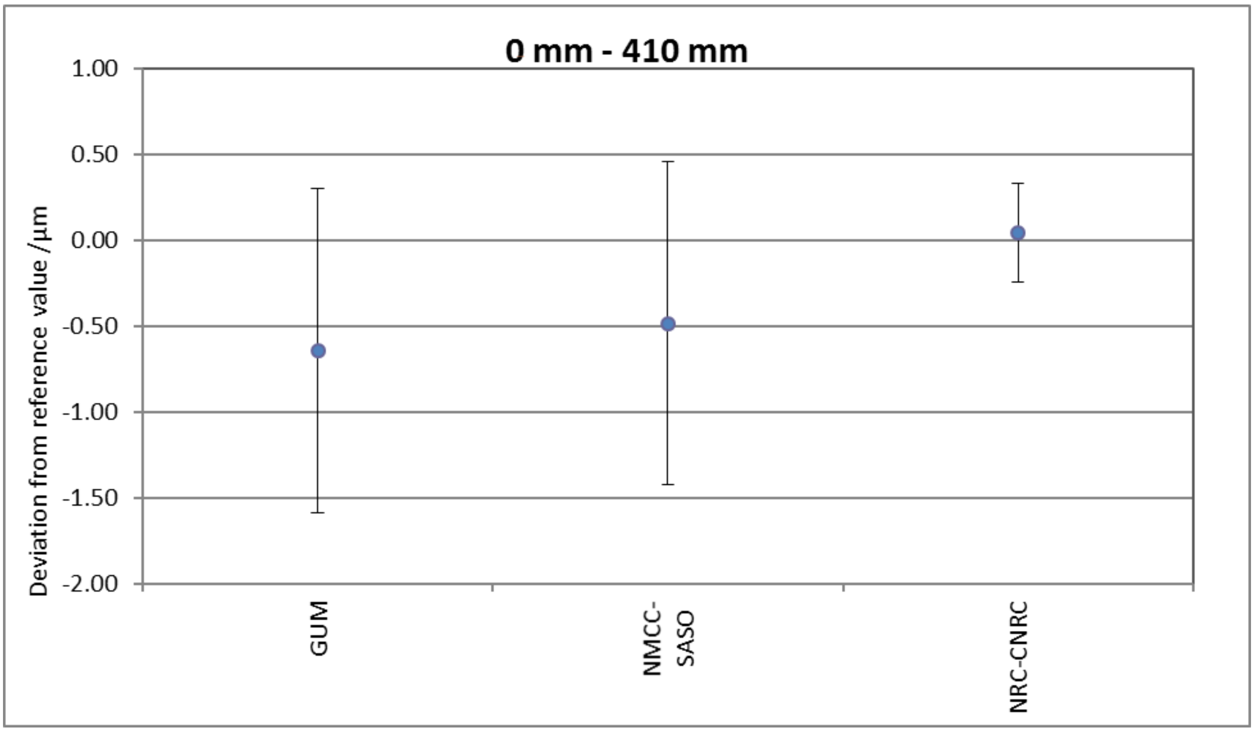


Figure 183: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

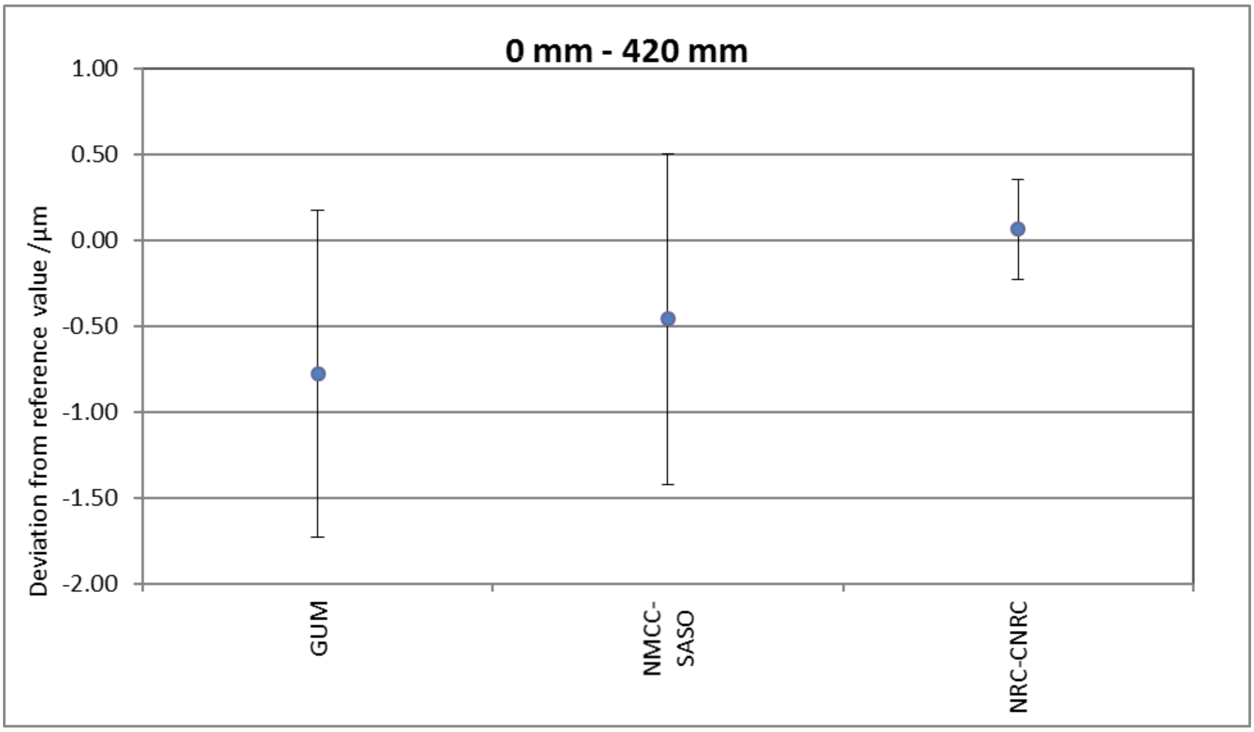


Figure 184: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

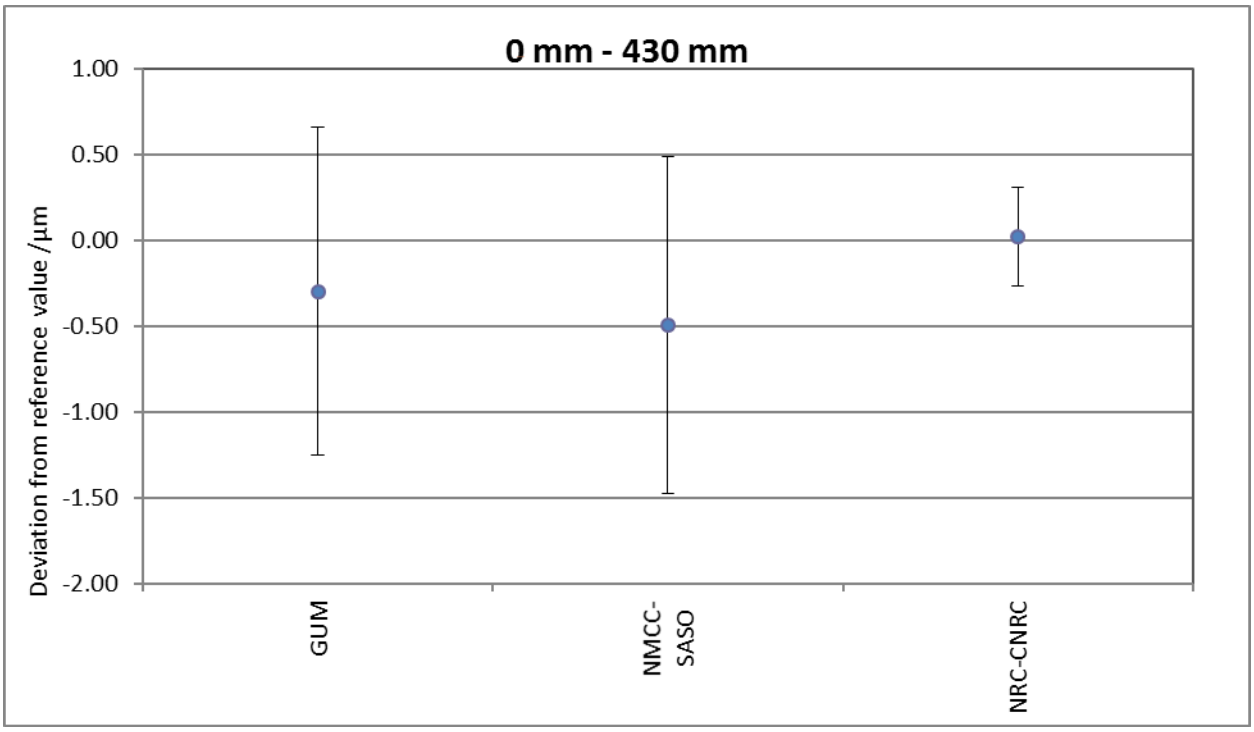


Figure 185: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

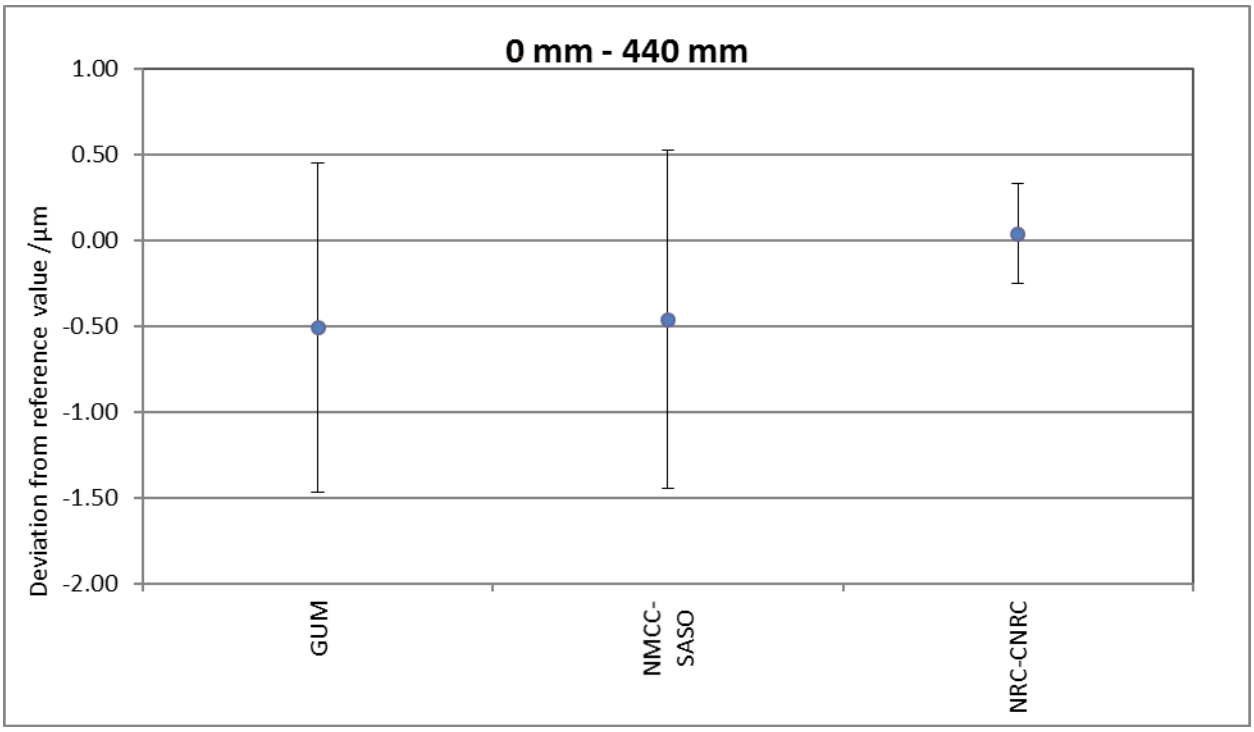


Figure 186: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

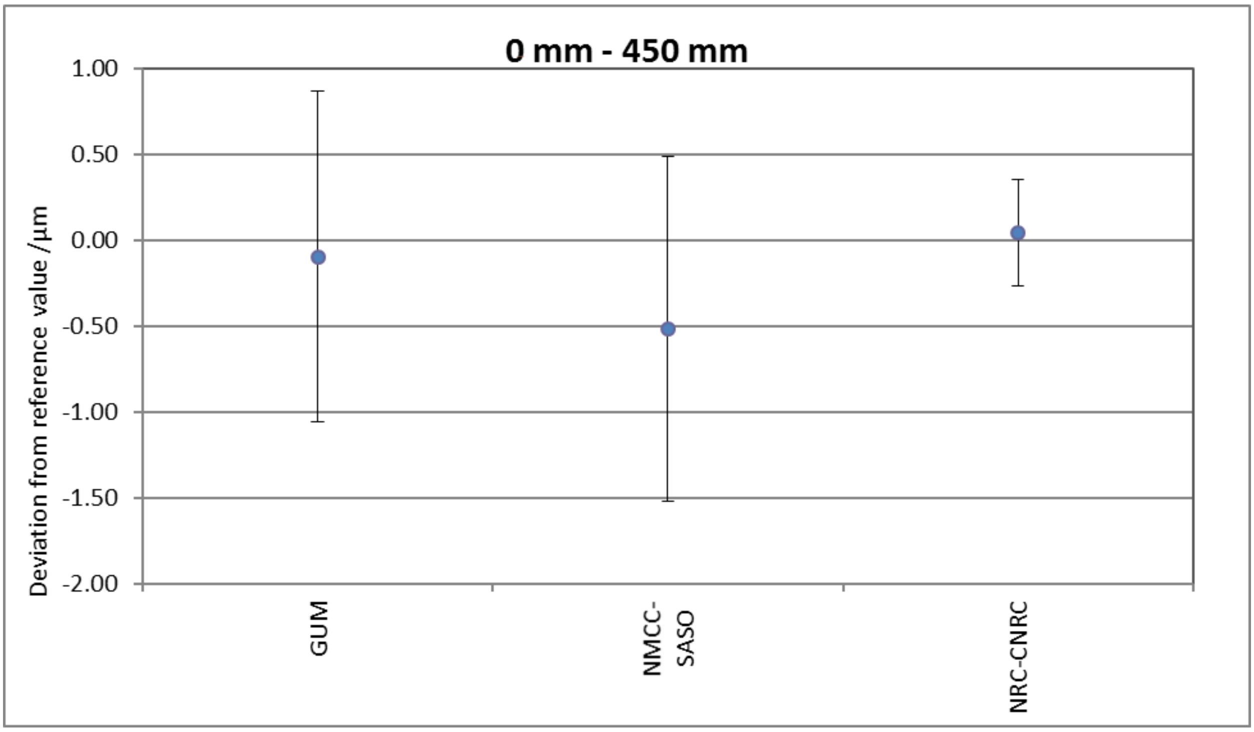


Figure 187: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

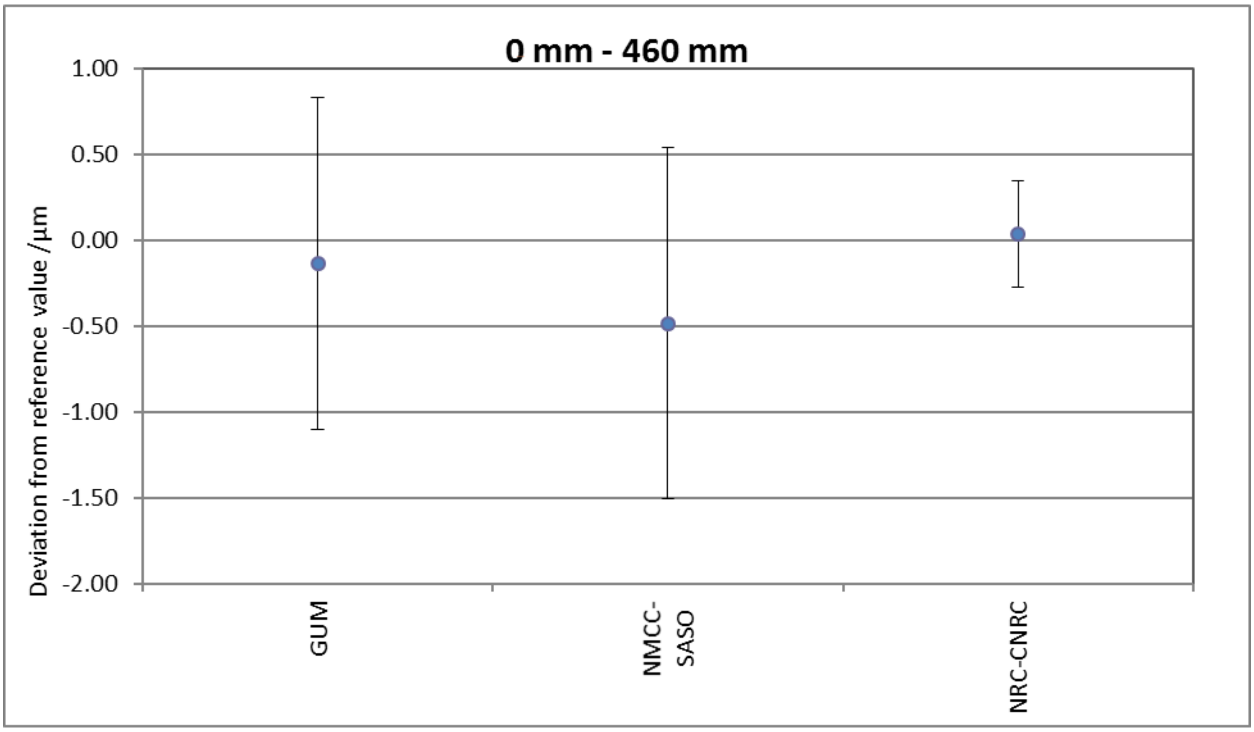


Figure 188: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

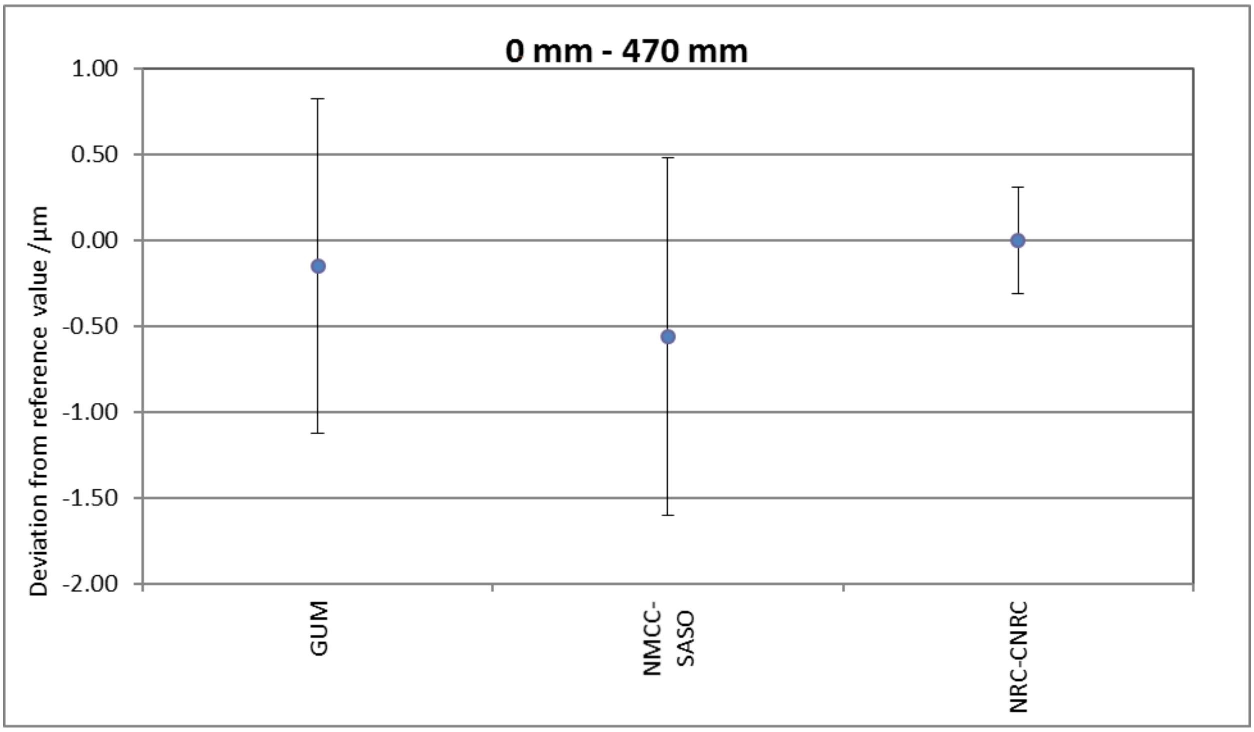


Figure 189: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

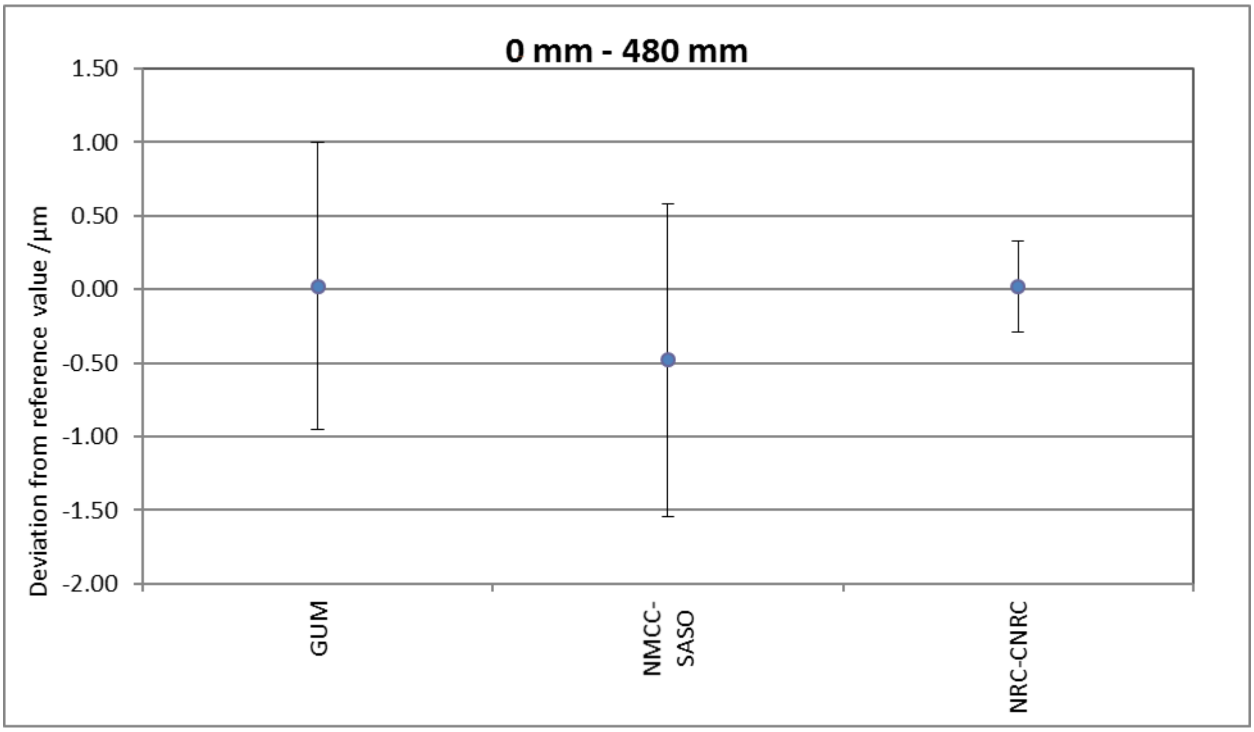


Figure 190: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

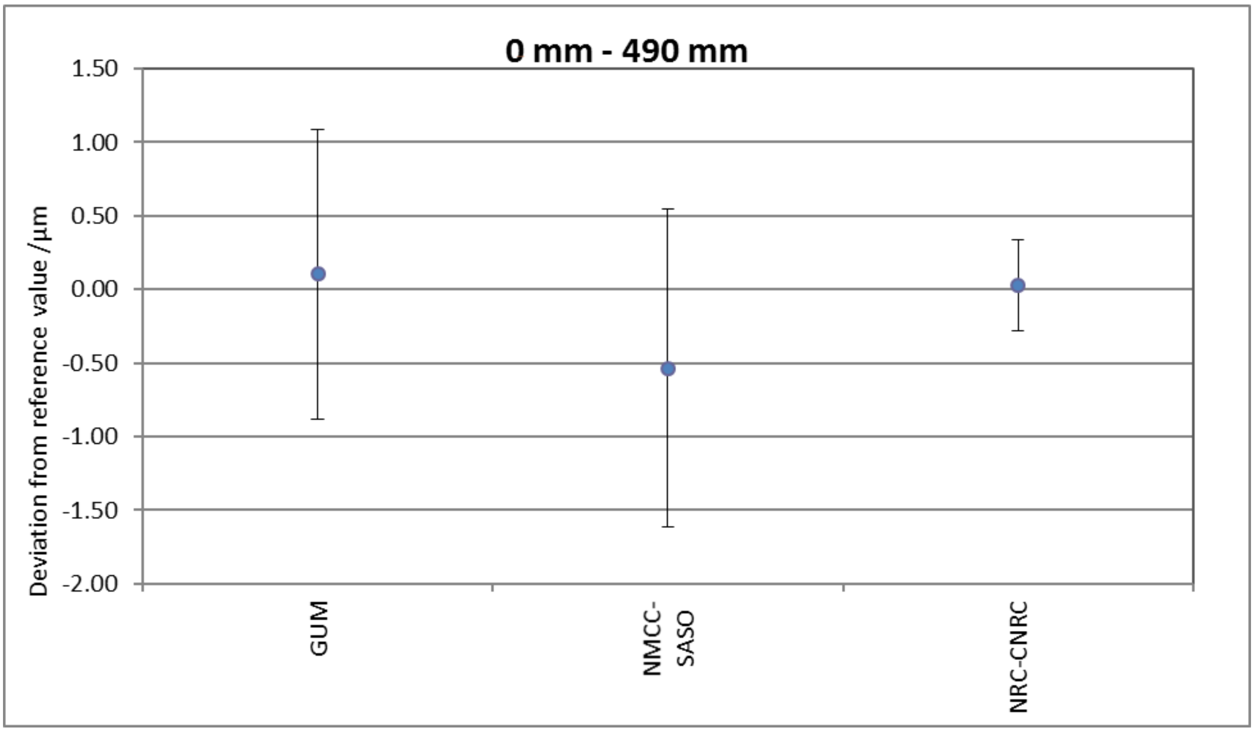


Figure 191: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

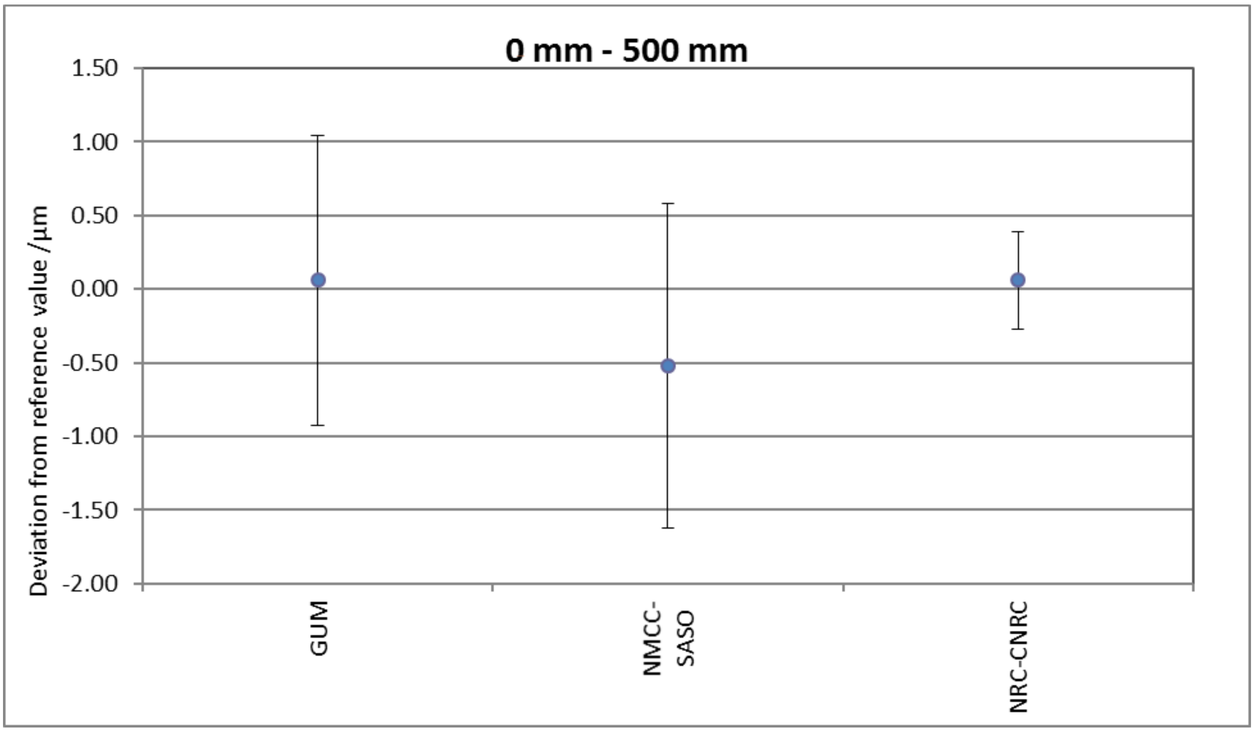


Figure 192: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

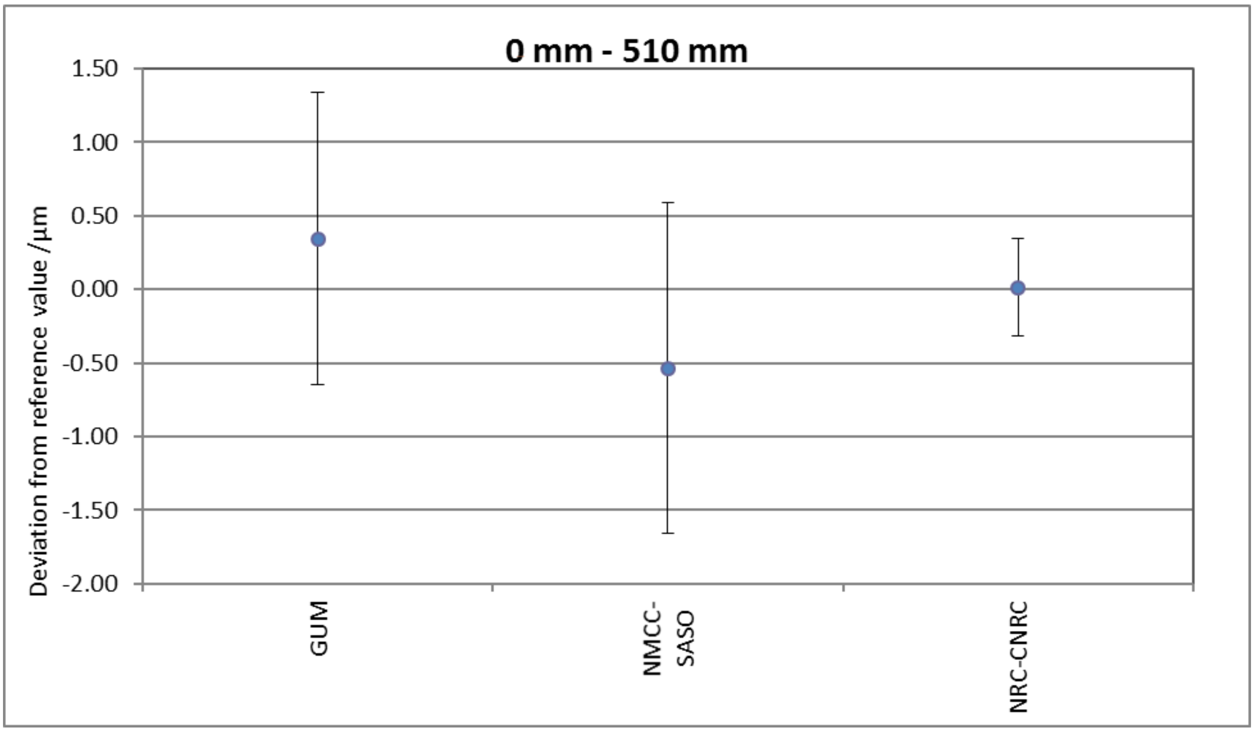


Figure 193: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

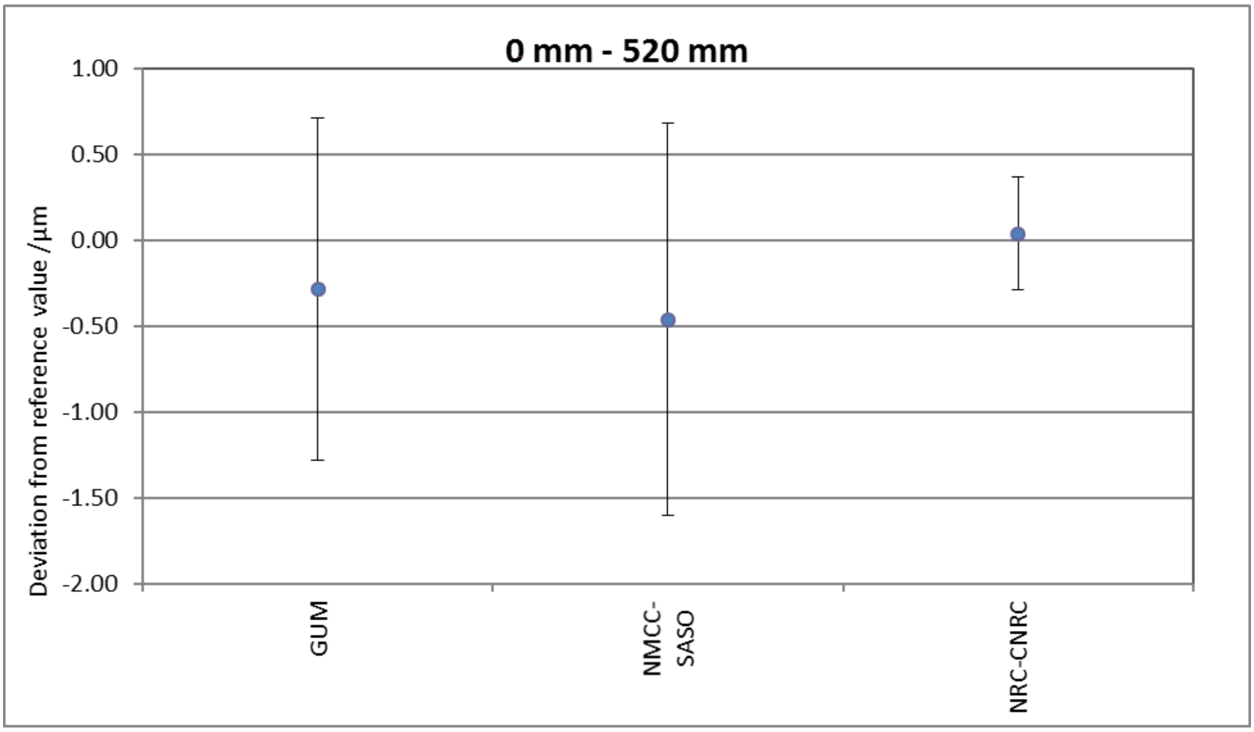


Figure 194: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

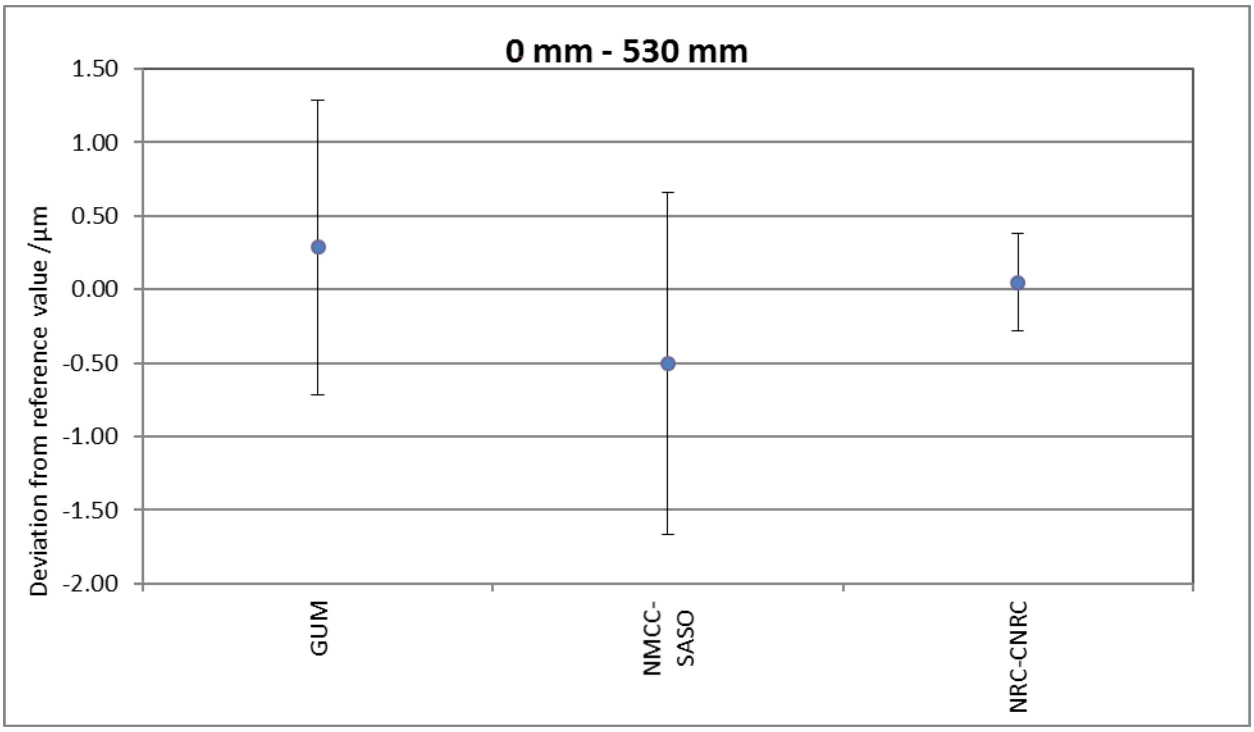


Figure 195: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

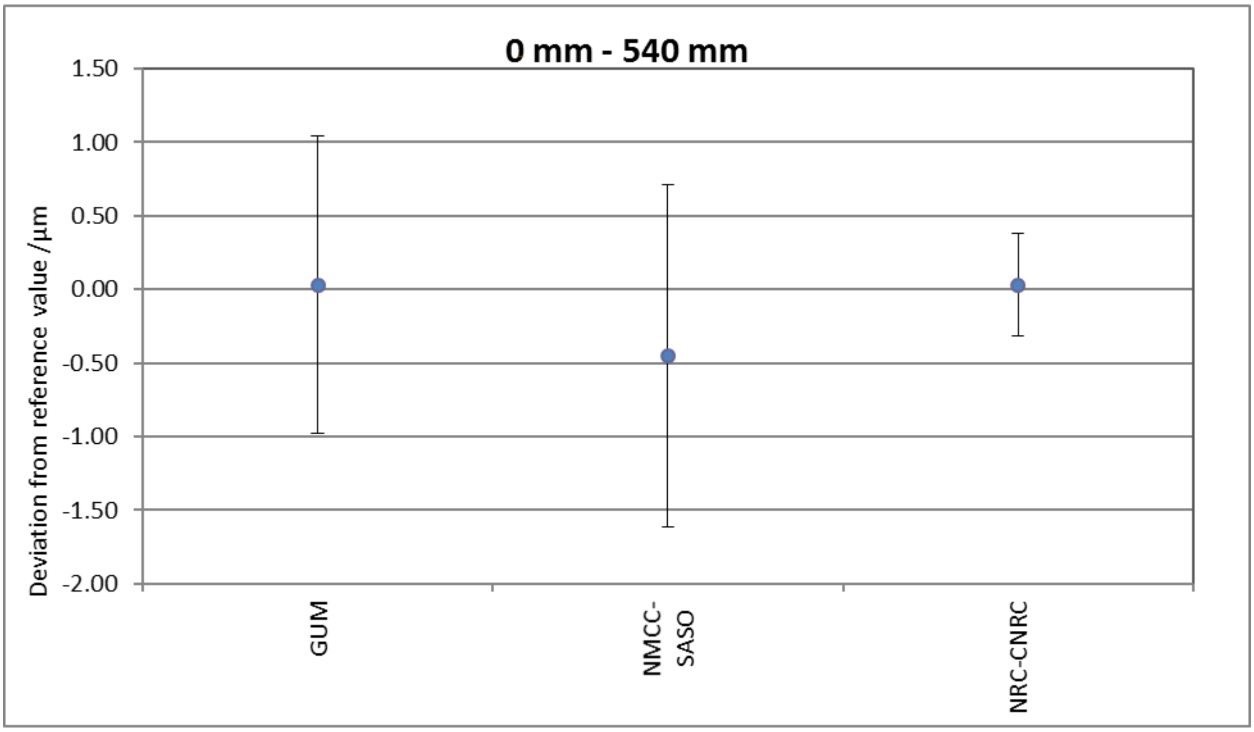


Figure 196: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

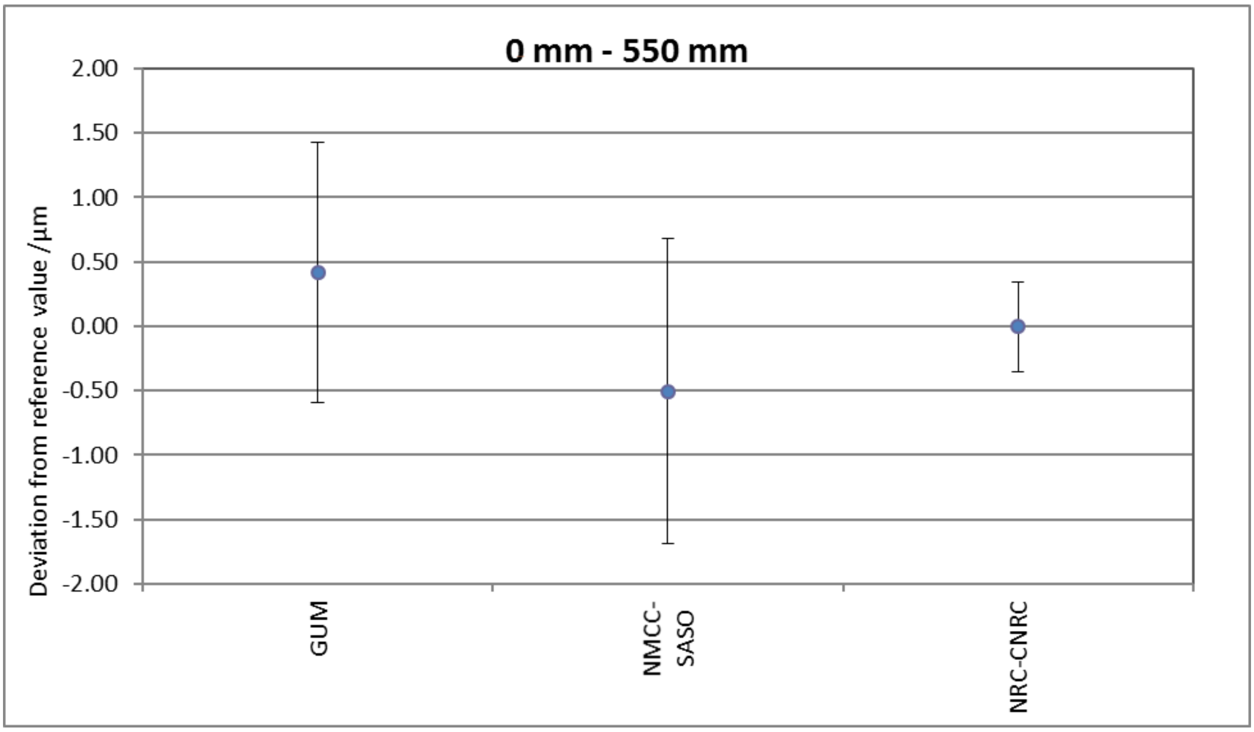


Figure 197: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

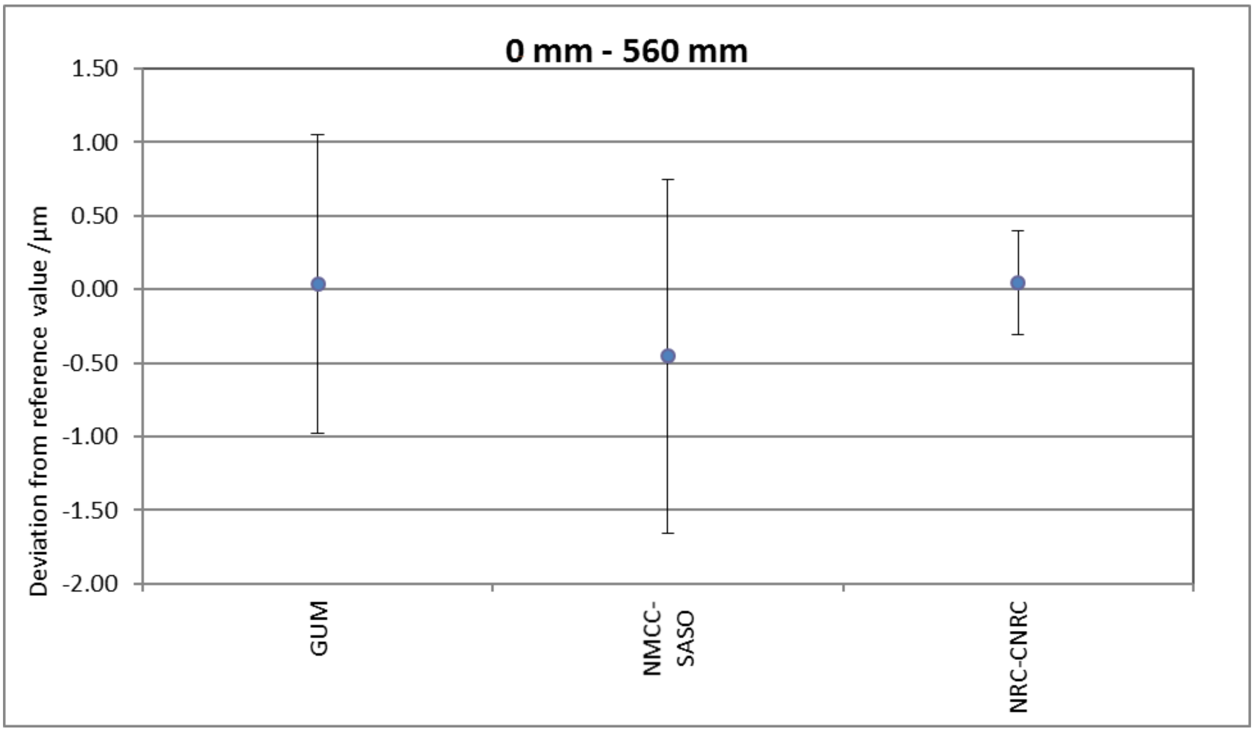


Figure 198: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

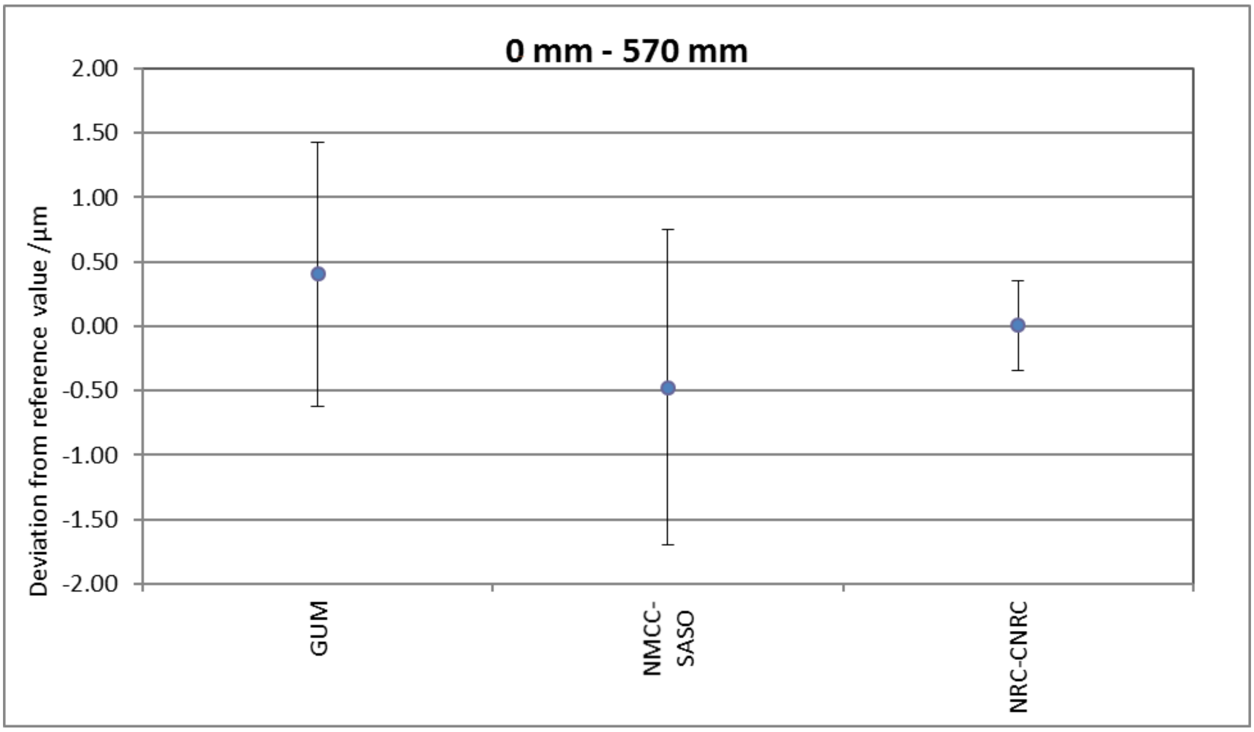


Figure 199: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

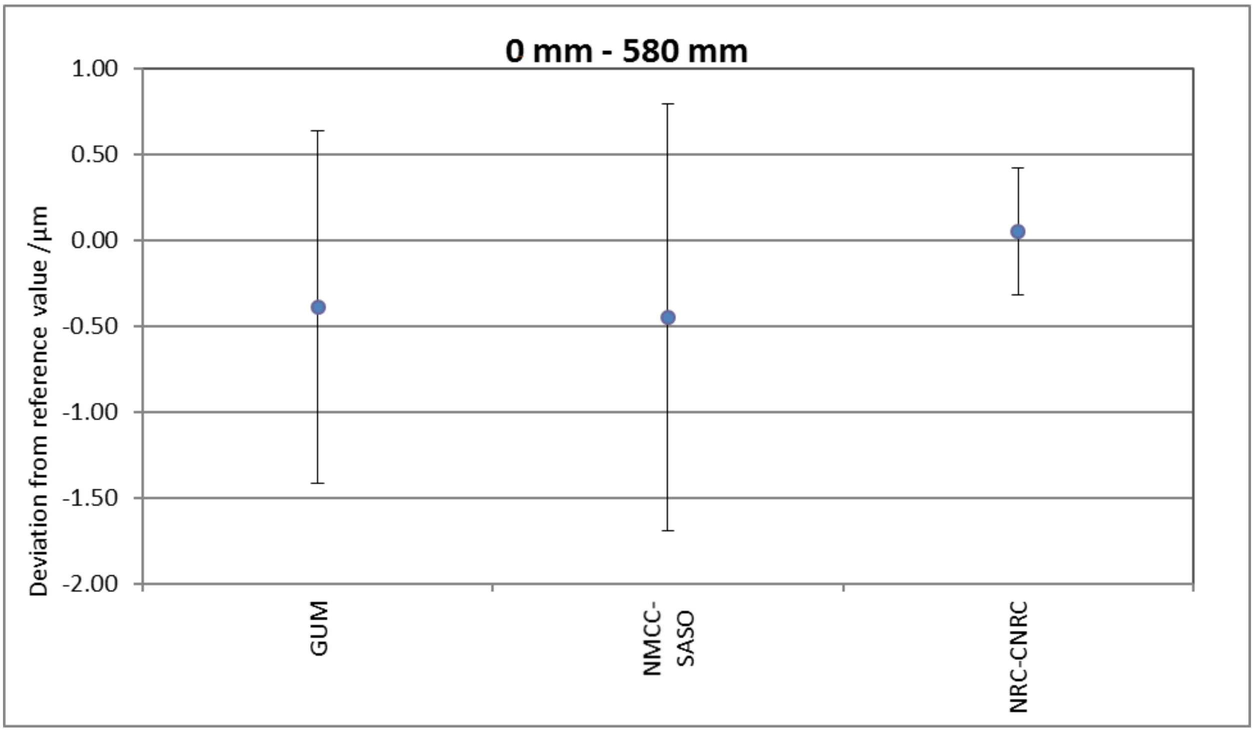


Figure 200: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

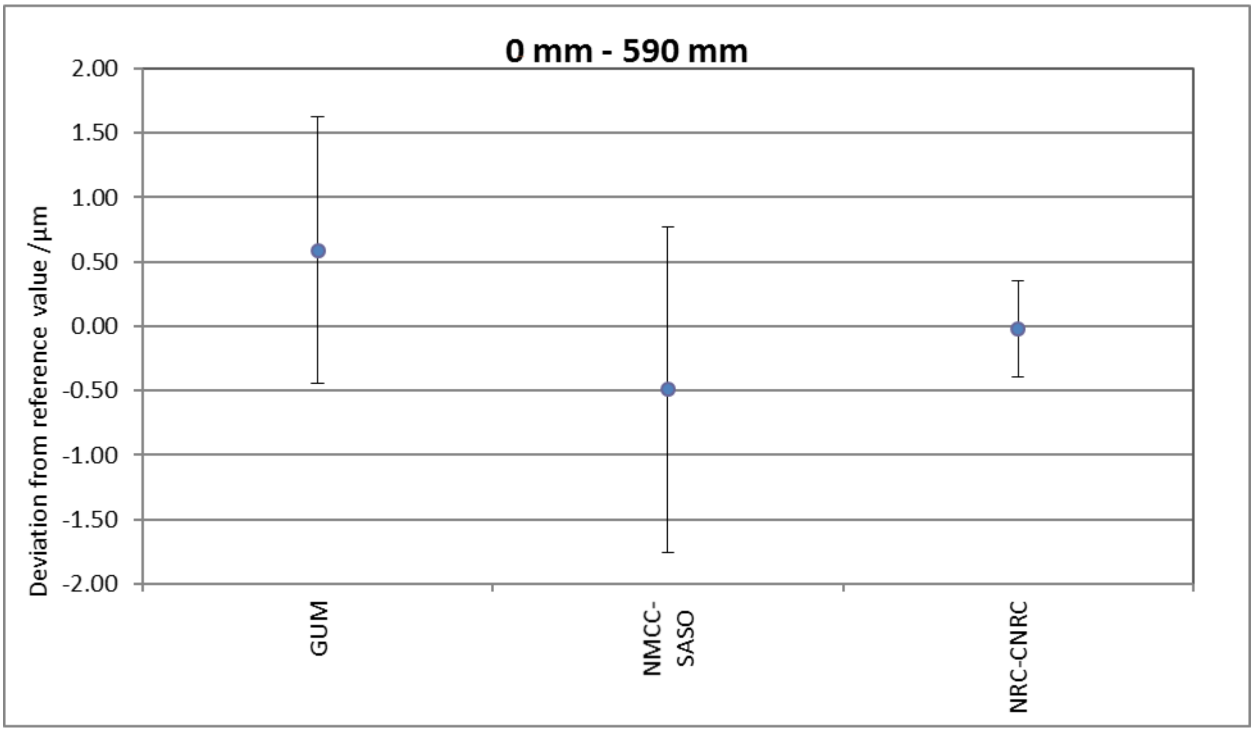


Figure 201: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

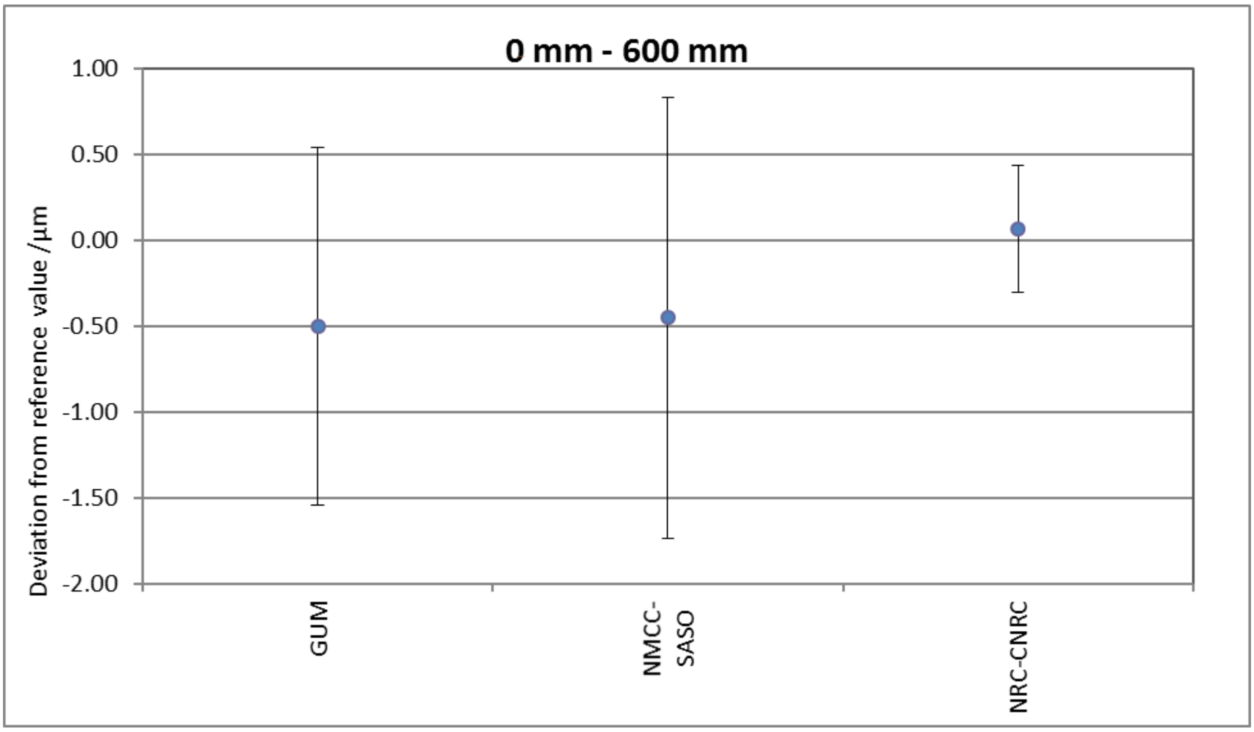


Figure 202: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

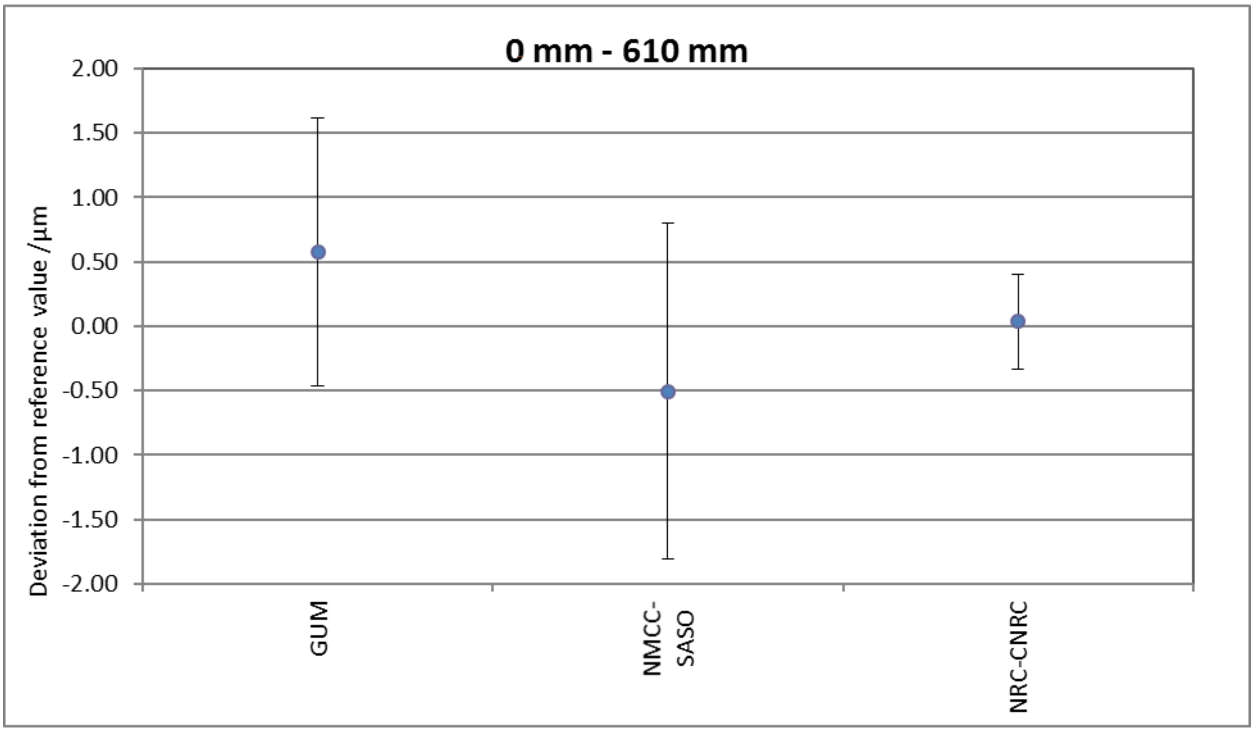


Figure 203: 610 mm artefact, group 2 participant deviations from reference value for this interval (*k* = 2)

6.4.13 Group 2 participant deviation by length

6.4.13.1 GUM

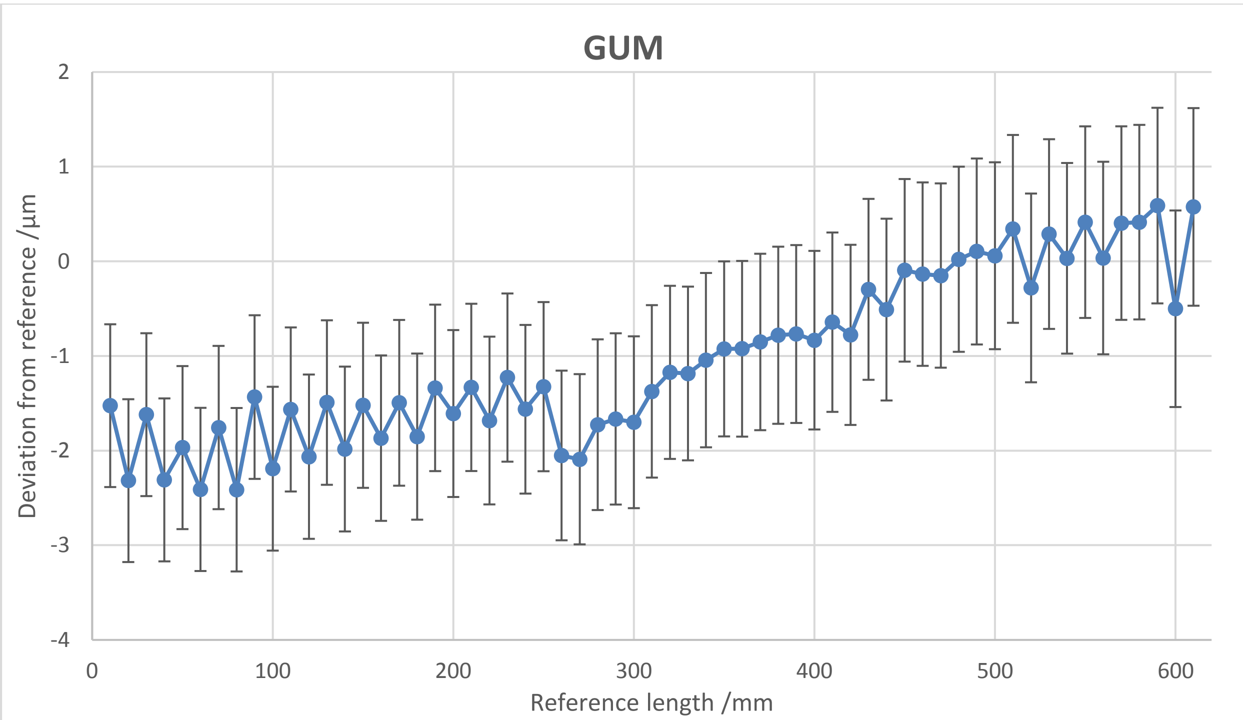


Figure 204

6.4.13.2 SASO-NMCC

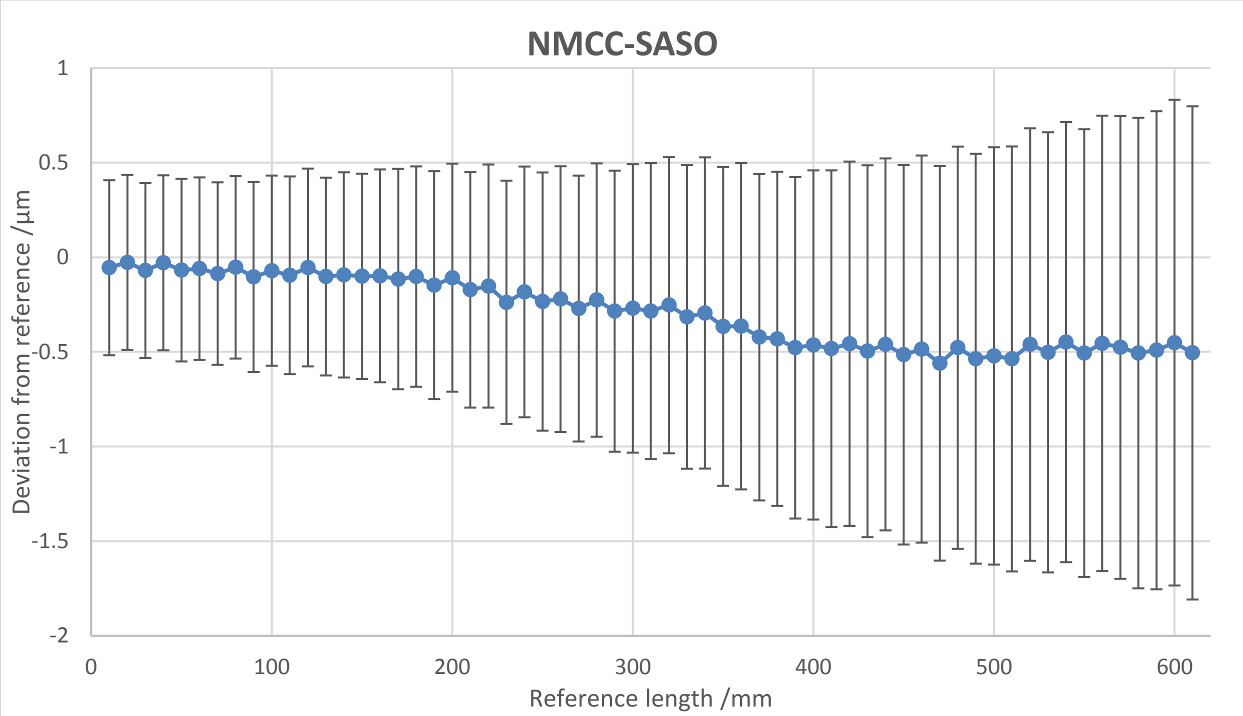


Figure 205

6.4.13.3 NRC-CNRC

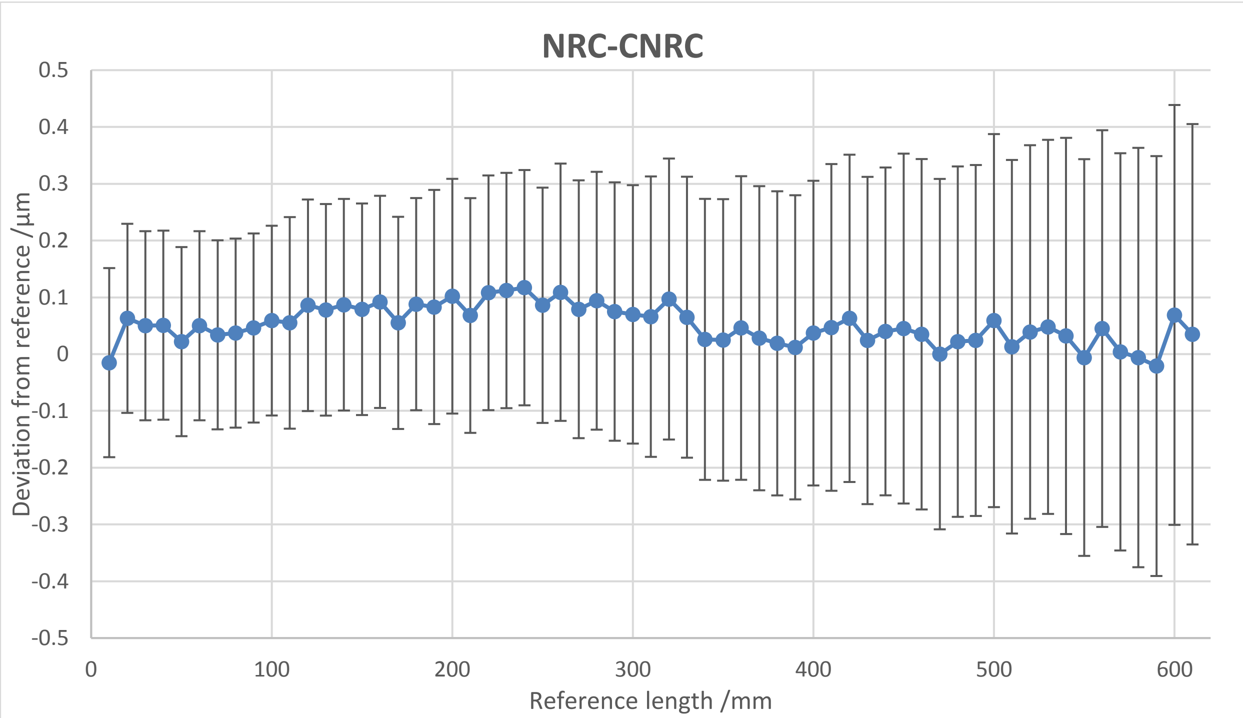


Figure 206

6.4.14 Group 2 Participant *En* values

The *En* values for each participant's measurement of each interval relative to the reference value are shown in Table 27. The expanded uncertainties used to calculate this value were obtained by multiplying the standard uncertainty of the deviation from the reference value by a coverage factor, $k = 2$. This gives a coverage probability of approximately 95 %. If $En > 1$ then equivalence to the reference is not demonstrated. Values were this is the case are shown in red font.

Length /mm	GUM	SASO-NMCC	NRC-CNRC
10	1.77	0.12	0.09
20	2.69	0.06	0.38
30	1.88	0.15	0.30
40	2.68	0.06	0.31
50	2.28	0.14	0.13
60	2.80	0.12	0.30
70	2.04	0.18	0.20
80	2.79	0.11	0.22
90	1.66	0.21	0.28
100	2.53	0.14	0.35
110	1.81	0.18	0.30
120	2.38	0.10	0.46
130	1.72	0.20	0.42
140	2.28	0.17	0.47
150	1.74	0.19	0.42
160	2.14	0.17	0.49
170	1.71	0.20	0.29
180	2.11	0.18	0.47
190	1.52	0.24	0.40
200	1.82	0.18	0.49
210	1.51	0.28	0.33
220	1.90	0.24	0.52
230	1.38	0.37	0.54
240	1.75	0.28	0.56
250	1.48	0.34	0.42
260	2.29	0.31	0.48
270	2.33	0.39	0.35
280	1.91	0.31	0.41
290	1.84	0.38	0.33
300	1.87	0.35	0.31
310	1.51	0.36	0.27
320	1.28	0.32	0.39
330	1.29	0.39	0.26
340	1.13	0.36	0.11
350	1.00	0.43	0.10

Length /mm	GUM	SASO-NMCC	NRC-CNRC
360	1.00	0.42	0.17
370	0.91	0.49	0.10
380	0.83	0.49	0.07
390	0.82	0.53	0.04
400	0.88	0.50	0.14
410	0.68	0.51	0.16
420	0.82	0.47	0.22
430	0.31	0.50	0.08
440	0.53	0.47	0.14
450	0.10	0.51	0.15
460	0.14	0.47	0.11
470	0.15	0.54	0.00
480	0.02	0.45	0.07
490	0.11	0.50	0.08
500	0.06	0.47	0.18
510	0.35	0.48	0.04
520	0.28	0.40	0.12
530	0.29	0.43	0.15
540	0.03	0.39	0.09
550	0.41	0.43	0.02
560	0.03	0.38	0.13
570	0.40	0.39	0.01
580	0.38	0.36	0.13
590	0.57	0.39	0.06
600	0.48	0.35	0.19
610	0.55	0.39	0.09

Table 27: *E*n values for 610 mm artefact Group 2 participants

A summary of the number of measurements for each institution made that did not demonstrate equivalence to the comparison reference value is shown in Table 28. Given that the expanded uncertainty provides an approximately 95% probability of a measured value being within the uncertainty range of the true value (which in the case of this comparison can be considered to be 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 *E*n > 1 is therefore considered to have demonstrated the validity of their submitted uncertainty.

	Number of intervals where *En* > 1	Percentage of intervals where *En* > 1	Uncertainty validity demonstrated?
GUM	35	57.38	NO
SASO-NMCC	0	0.00	YES
NRC-CNRC	0	0.00	YES

Table 28: Summary of participant *En* values for the 610 mm artefact Group 2 participants

6.4.15 Participant responses

No responses from participants in the 610 mm artefact were provided for inclusion in the published report.

7 Conclusions

A summary of the equivalence (En) values for all participants is shown in Table 29.

Participant	Submitted standard uncertainty /µm	Max *En*	Percentage of intervals where *En* > 1	Submitted uncertainty validity demonstrated?
NPL	$0.05 + 0.116 \times 10^{-3} L$	0.54	0.00	YES
LNE	$Q[0.138, 0.3 \times 10^{-3} L]$	1.07	5.88	NO
BEV	No simple length dependent formula could be derived	3.49	70.59	NO
CEM	$Q[0.04, 0.2 \times 10^{-3} L]$	1.88	37.25	NO
SP	$Q[0.09, 0.7 \times 10^{-4} L]$	1.13	5.88	NO
VTT MIKES	$Q[0.04, 0.48 \times 10^{-4} L]$	1.19	1.96	YES
METAS	$Q[0.07, 0.12 \times 10^{-3} L]$	0.53	0.00	YES
VSL	$Q[0.049, 2.27 \times 10^{-4} L]$	2.31	60.78	NO
TUBITAK-UME	$Q[0.174, 0.8696 \times 10^{-3} L]$	2.41	56.86	NO
NMIJ	$Q[0.074, 0.19 L]$	3.52	92.16	NO
NIST	Front Faces $0.035 + 0.43 \times 10^{-4} L$ Back Faces	1.66	21.57	NO

Participant	Submitted standard uncertainty /µm	Max *En*	Percentage of intervals where *En* > 1	Submitted uncertainty validity demonstrated?
	$0.039 + 0.41\times10^{-4}\,L$			
NMC A*STAR	Q[0.254, 0.0014 L]	0.85	0.00	YES
CENAM	Q[0.125, $0.175\times10^{-3}\,L$]	0.36	0.00	YES
NIM	Q[0.1, $0.32\times10^{-3}\,L$]	1.08	5.88	NO
INRIM	Q[0.035, $0.275\times10^{-3}\,L$]	0.94	0.00	YES
MKEH	Q[0.33, $1.4\times10^{-3}\,L$]	2.16	34.43	NO
CMI	Q[0.1, $0.3\times10^{-3}\,L$]	0.45	0.00	YES
INM	Q[0.47, $1.0\times10^{-3}\,L$]	1.06	2.00	YES
NPLI	Q[0.225,$0.8\times10^{-3}\,L$]	0.57	0.00	YES
GUM	Q[0.42, $0.48\times10^{-3}\,L$]	2.80	57.38	NO
SASO-NMCC	Q[0.231, $0.99\times10^{-3}\,L$]	0.54	0.00	YES
NRC-CNRC	Q[0.08,$0.27\times10^{-3}\,L$]	0.56	0.00	YES

Table 29: Summary of intercomparison results

Those laboratories who have demonstrated the validity of their submitted uncertainty may be concluded to have demonstrated the validity of their claimed measurement capability (CMC) currently registered in the CIPM key comparison database (KCDB) where the submitted uncertainty is less than or equal the current CMC.

Among those laboratories which did not demonstrate validity were several laboratories, particularly those who measured the 1020 mm artefact, which submitted uncertainties that differed from their claimed measurement capability (CMC) currently registered in the CIPM key comparison database (KCDB). This may have been due to the unusual design of the 1020 mm artefact, the introduction of new or improved equipment or the creation of a new service which does not currently have a CMC. It can therefore not be concluded directly that the failure to demonstrate the validity of the submitted uncertainty to this comparison invalidates a laboratory's CMC, which may be based on different equipment or a more usual artefact material. However, where the validity of the uncertainty submitted has not been demonstrated it is certainly the case that an investigation should be done to establish the root cause of the non-validity and what corrections are required. The determination of the validity of CMC claims will be done under the auspices of the Consultative Committee for Length's Working Group on the CIPM MRA (CCL-WG-MRA), following its usual procedures. This process will identify any corrective actions required in view of the results of this comparison and ensure these are carried out.

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

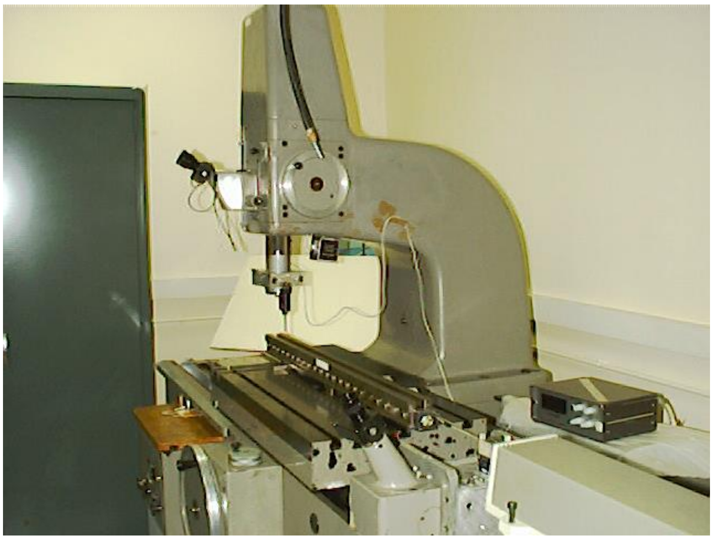
The methodology statements from participants are shown below. Not all participants supplied a methodology statement.

8.1 NPL

The measurements were made using an NPL designed laser interferometer system. This interferometer system, known at NPL as 'The Step Gauge Rig' is an instrument specifically designed for the measurement of precision step gauges. It features interferometric measurement of a moving probe, from two opposing directions simultaneously, with both measurements referred to one end of the step gauge. The Step Gauge Rig is mounted on a Leitz PMM 12106 high accuracy Coordinate Measuring Machine to provide probe positioning and is located in a temperature and humidity-controlled room, with nominal control of ±0.2 °C and ±5 % RH. The instrument uses two interferometers, one close to the datum face and one remote from it. Both interferometers are referenced to a double side mirror close to the near interferometer. The near interferometer is mounted on an Invar plate which is in sprung contact with the 'zero' end of the step gauge. This compensates for any thermal expansion of the mounting rig. A conventional CMM probe is used but with a double-sided mirror mounted onto the probe stem. This allows the position of the CMM probe to be measured with respect to the step gauge end face, from two directions simultaneously, to compensate for air path variations. Both interferometers allow both displacement and tilt measurement, so any tilting of the probe stem can be compensated for. Measurements are made of air temperature (at several locations), pressure and humidity, and the refractive index correction is calculated from this data. Probe ball diameter is calibrated by using the probe to measure a small reference gauge block (pre-calibrated by interferometry) which is mounted at the measurement axis height of the system. Temperature measurements were made using a total of five calibrated PRTs; two PRTs in contact with and located at either end of the gauge, two PRTs monitoring the air temperature close to the measurement line at both ends of the gauge and one PRT in contact with a reference gauge block used for probe ball diameter calibration.

8.2 LNE

We use a length Measuring machine designed by SIP (SIP F1A) as shown by the following photo



This machine has an X movement on which the axe of the step gauge is aligned and a vertical movement, in order to enter to the center line.

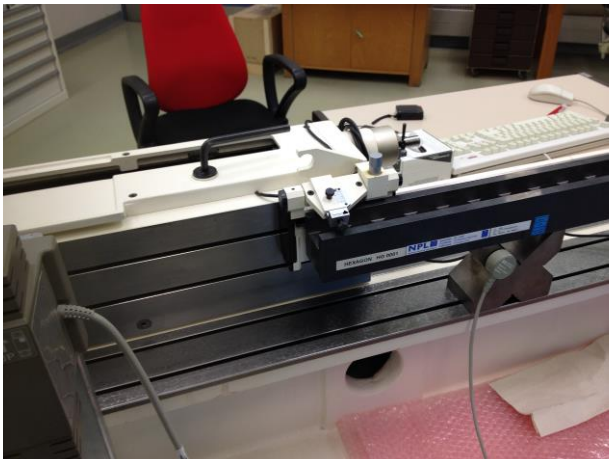
On this vertical axe an inductive probe Cary 1-Dim is mounted. Traceability is insured by the laser interferometer and for measuring probe diameter we use a gauge bridge calibrated by interferometry.

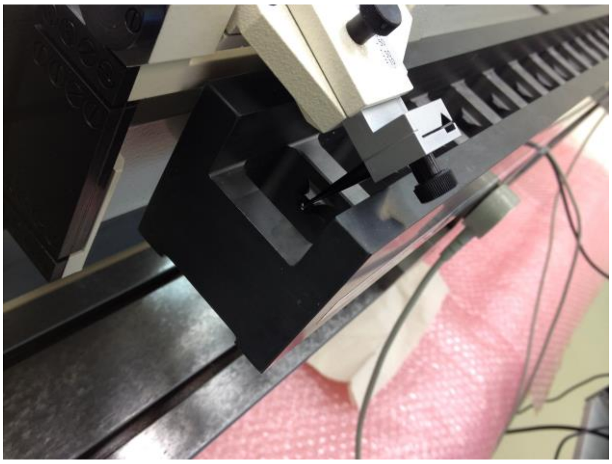
8.3 BEV

SIP 3002 length measuring machine with a standard laser interferometer (modified instrument without internal scale). The probing system is a modified system, normally used for screw pitch determination. The probing element was a steel ball with a nominal diameter of 2 mm. The Abbe principle is not fulfilled in this instrument (170 mm); this makes a considerable contribution to the measurement uncertainty.

Traceability path (scale, interferometer, calibration std.): HP 5529A Laser interferometer system with standard linear interferometer and Agilent 10751D air sensor. All systems calibrated by the BEV. For the gap measurements a setting ring (20 mm) traceable to METAS (CH) is used. Three surface temperature sensors (Agilent 10757), magnetically fixed to the artefact holder.

With the described setup only the distance of equally oriented faces are accessible. Consequently, two sets of distances were determined in the first step, denoted L_i and R_i, respectively. To combine these two sets, at least one additional gap measurement is necessary. In fact, four different gaps were measured according to the method normally used in ring (or gap) gage calibrations. The four results were adjusted in a classical way.





8.4 CEM

<u>*Make and type of instrument*</u>

Custom-built length comparator CEM-TEK 1200 equipped with laser-interferometer, two beam pseudo-Abbe measurement principle and alignment with respect to outer frame.

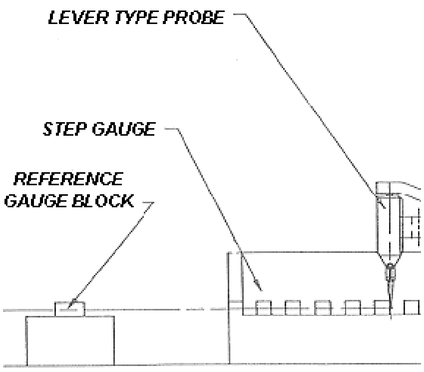
Interferometric Comparator CEM-TEK 1200

View of the step gauge on the comparator and detail of the lever type probe at the first face

Fine alignment of the step is made using horizontal and vertical micrometers situated under the Airy supporting points.

__Description of the measuring technique:__

Probing of both faces of gauges by using a lever type inductive probe situated vertically on a movable portic. Contact point situated in the measurement axis and within the plane formed by the two laser beams (minimized Abbe error). The probe moves up and down together with the retro-reflectors (flat mirrors) to avoid collisions against gauges when passing from one to another (see Fig.).



Probing in all gauges' faces is realized according to the following phases:

a) Approximation to the face, in a pre-programmed way, stopping at distances predefined, around 5 mm from the face, by security.

b) Location of the contact point by moving the probe against the face until being within the measuring range of the probe (± 20 μm), coincident with the range of the piezoelectric actuator. This 'location' phase makes up to three attempts at different velocities, in order to optimize the time of the process. Firstly, at a relatively high speed the system tries to locate the change of the probe saturation for, just in the same instant, stop immediately the axis. Again, the process is repeated at a lower speed and in the opposite sense. This iterative process is repeated until getting in the probe a non-saturated measure.

c) Measurement phase. The closed loop of the piezoelectric actuator tries to situate the probe as close as possible to its zero value. When this happens, within some pre-defined proximity and time windows, the servo-piezo control sends to the laser interferometer the shooting signal for taking the length readings.

Determination of the probe constant (deflexion and diameter of the tip) is made with the help of a 10 mm reference gauge block situated on the table supporting the step gauge, in line with this one.

Light sources / wavelengths used or traceability path:

Zeeman stabilized Laser Source HP 5517C, s/n 3002A00568, λ_0 = 632.991 365 64 nm, calibrated against reference laser CEM-2 (He-Ne iodine stabilized red laser AXIS Winters (ISL -1c), model 210-901-000, n/s 116)

Method used for determination of refractive index of the air :

Initial measurement of ambient conditions and applying of the Edlen's formulae. Then, using of a tracker (relative refractometer) to maintain updated the correction value.

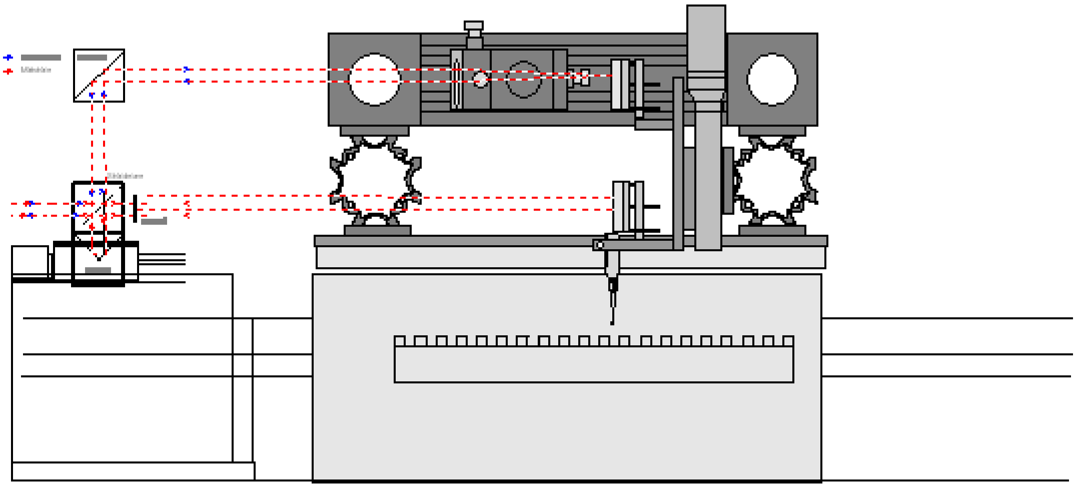
Range of artefact temperature during measurements & description of temperature measurement method:

20 °C ± 0.2 °C

Temperature is measured using Pt 100 probes, a Tinsley bridge and a Wilkinson standard resistor.

8.5 SP

The measurements were made in a specially designed (non-commercial) measuring bench, based on a movable carriage with an air-flow bearing on a granite surface. A laser interferometer with a tilt compensating beam path measures the distance to the inductive probe system. The probe constant is determined prior to each series by means of a calibrated gauge block and the environment data is collected for each measuring point.



Traceability path:

The laser interferometer is calibrated directly against the Swedish primary length standard (I^2-stabilized HeNe laser). The probe is calibrated through the laser.

Description of the measuring technique:

The alignment of the step gauge was made on the side-walls using a dial test indicator with 0,01 mm resolution (analogue). The step gauge was supported in the Bessel points.

The measurements were carried out along an axis which passes through the centre of the measuring face No. 0 and is parallel to both the bottom face and the side alignment face.

A computer controlled program measures each surface with a probe deviation < 1 µm. The result is the combination of laser and probe reading and corrected for environment data and the probe constant.

Range of artefact temperature during measurements & description of temperature measurement method: Measurements were made in temperature range of (20,0 ± 0,25) ˚C. The temperature was measured with 5 pcs of PT100 sensors attached to the frame of the object at equal distances.

8.6 VTT MIKES

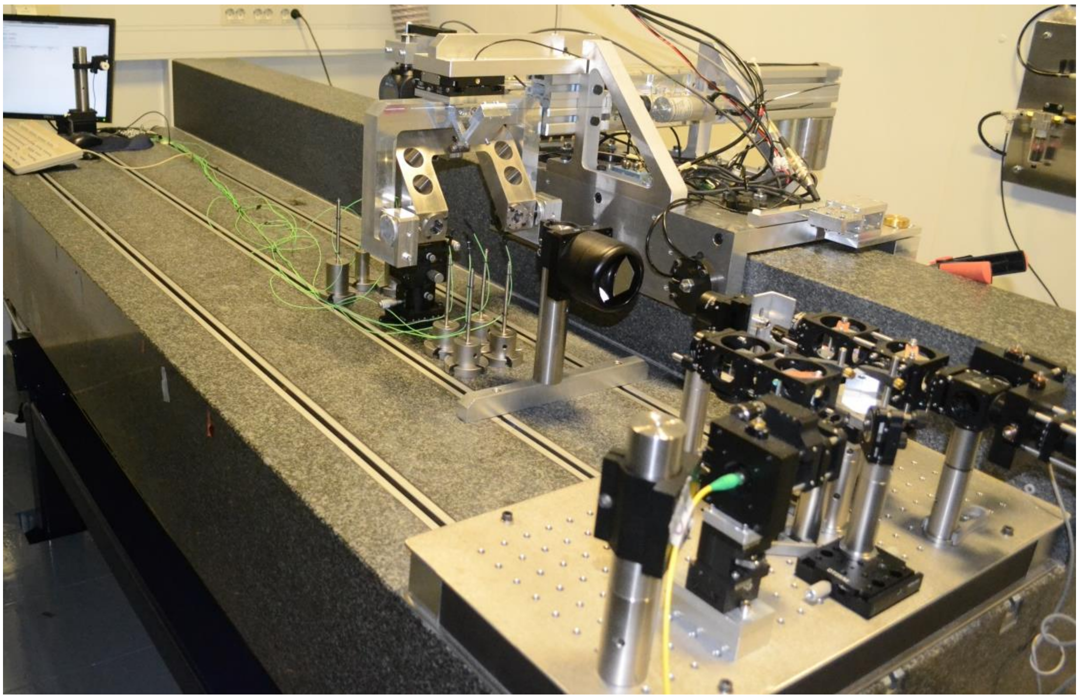


Figure 1. VTT MIKES step gauge interferometer.

The VTT MIKES interferometer for step gauge calibration is constructed on a vibration isolated stone table to eliminate mechanical disturbances. The instrument is located on a highly accurately controlled laboratory room[i]. The interferometer has two parallel beams in measuring arm allowing the adjustment of the measuring probe ball (Mahr Millimar 1320/1) to the actual effective measuring line to minimize the Abbé error. The beams are reflected back by two corner cubes fixed to the same stiff measuring head frame with the probe. The beams have been adjusted parallel with carriage movement using quadratic detectors. The reference arm reflector is situated close to step gauge to minimise the dead path. The probe ball (d=5 mm) is of sapphire to avoid magnetic effects during probing. The measuring head is constructed so that it's possible to lift the probe ~13 mm by tilting it without disturbing the interferometer signals. The measuring head is fixed to a carriage with air bearings and can be moved on stone guide using a stepper motor. The straightness of carriage movement has been measured to be <4". Fine tuning of the measuring head & probe ball position in measurement direction is made with a piezo actuator. The position of the probe is measured using a homodyne laser interferometer. As counter is used Heidenhein IK220 PC counter card. During probing the measuring head and probe is moved by piezo actuator to have few micrometres deep bending of probe ball and simultaneously analogue voltage signal from probe electronics and interferometer readings are recorded. The edge position is extrapolated to zero force. The standard deviation of the probing is 20 nm. The probe is lifted up and down using a linear actuator and Kevlar line. Ambient conditions (air and material temperature, air pressure and humidity) are measured continuously online. Humidity and pressure are measured using Vaisala PTU200 meter. Three pt100 sensors are used for material temperature measurement and four for air temperature measurement. The temperature sensors are connected via 4-wire scanner to Isotech TTI-2 High Accuracy Thermometer. All sensors and laser wavelength are calibrated against higher accuracy reference standards of VTT MIKES. Refractive index of air is calculated using updated Edlen's equation by Bönsch [ii].

The calibration sequence is fully controlled by a PC. Before measurement the positioning of the step gauge is done with integrated 2D-CMM using 3D edge detector and Heidenhein linear encoder scales with <1 µm resolution. The probe ball diameter is calibrated using a stack of three calibrated gauge blocks wrung so that both external and internal measurements can be done. For high accuracy measurement the same step gauge is measured four times: in two different positions with two orientations. Each measurement consists of several (n=~3) back and forth measurements of full scale. The average of 4 runs gives the final results.

During the EURAMET.L-K5 measurement the average temperature of material sensors varied between 19.95 °C and 20.02 °C. The typical deviation between sensors was ±15 mK. The average air temperature varied between 19.94 °C and 20.00 °C during the measurement with ±20 mK deviations between sensors.

[i] A. Lassila, M. Kari, H. Koivula, U. Koivula, J. Kortström, E. Leinonen, J. Manninen, J. Manssila, T. Mansten, T. Meriläinen, J. Muttilainen, J. Nissilä, R. Nyblom, K. Riski, J. Sarilo and H. Isotalo, Design and performance of an advanced metrology building for MIKES, *Measurement* 44 (2011) 399–425

[ii] G. Bönsch and E. Potulski, Measurement of the refractive index of air and comparison with modified Edlen's formula *Metrologia* 35 (1998) 133–9

8.7 METAS

Make and type of instrument

Length measurement machine SIP LMM5, based partly on the co-ordinate measuring machine SIP CMM5. [1]

Traceability path (scale, interferometer, calibration std.):

Laser interferometer Keysight 5519A with plane mirror interferometer.
Laser calibrated against METAS MeP stabilized Laser.

The probe constant is determined on a 5 mm gauge block.

Description of the measuring technique:

The measurements at the nominal height of the faces have been repeated several times with the gauge block in its original and inverted (first measurement face on the opposite side) position. The reported result represents the average of the measurement series. Additional measurements were carried out at heights 0.2 mm above and below the mid height and 0.5 mm left and right from the centre in order to check for the sensitivity of alignment of the measurement position. The measurement range being limited to 700 mm, the step gauge was measured in two positions with an overlap of 400 mm in the centre of the length.

The measurement strategy consisted of taking the first measurement surface (1a) as zero. For eliminating temperature drift effects, the zero has been set again every 3 or 5 gauge blocks, resulting in measurement sequences such as 1a, 1b, 2a, 2b, 3a, 3b, 1a, 4a, 4b, 5a, 5b, 6a, 6b, 1a, 7a, ...

For the probe, we used an inductive Cary 1-dim probe with a Ø4 mm diamond coated sphere. The probe constant (essentially the probe diameter, including any eventual further effect) was determined using a 5 mm gauge block. The probing force was extrapolated to zero.

The measuring machine in its configuration used for step gauges does not satisfy the Abbe principle. Therefore a correction has been introduced to take into account the calibrated pitch error of the horizontal axis.

Range of artefact temperature during measurements & description of temperature measurement method:

Material temperature range during all measurement series: (19.95 – 20.01)°C

Temperature sensors: Thermistors (10 kΩ @ 25°C) with digital multimeter and reference resistance standard.

[1] R. Thalmann, A new high precision length measuring machine, Congrès International de Métrologie, Besançon 1997

8.8 VSL

Description of the measurement instrument

The measurements on the step gauge were carried out using the following equipment:

Probing system	: Coordinate Measuring Machine
Model	: UC550
Manufacturer	: Zeiss
Measuring volume	: (1200x550x450) mm^3
Software	: UMESS-Basic + UX (2001)

The CMM is equipped with a 1D Interferometer in order to ensure direct traceability and a higher accuracy for 1D measurements.

1D Measurement	: Laser interferometer
Model	: 5528 A
Manufacturer	: Hewlett Packard

The laser system has a double pass (flat mirror) configuration. The CMM is only used as an accurate positioning and probing machine.

In order to correct the Abbe error due to the difference in the probing position of the CMM and the measuring position of the laser interferometer and the angular movements (pitch) of the CMM while probing the step gauge, an autocollimator was used to measure the angular movement during the measurements. The raw measurement data was corrected off-line for the Abbe error due to the difference in pitch angle between the zero step (= reference) and the step to be measured.

Angular measurement	: Autocollimator
Model	: Elcomat 2000
Manufacturer	: Moller-Wedel

Traceability path (scale, interferometer, calibration std.):

Traceability is ensured by using a stabilized HeNe laser for the length measurements. This laser was directly calibrated to the national primary length standard.

The probe constant (effective stylus diameter) was determined on a 10 mm gauge block which is calibrated by interferometry.

The autocollimator was calibrated with a traceable small angle generator.

Description of the measuring technique:

Alignment.
First the centre line of measurement of the laser system was aligned to be parallel to the mechanical Y-axis of the CMM. Subsequently, the step gauge was aligned to be parallel to the mechanical Y-axis of the CMM; for this alignment the outer faces of the step gauge have been used at the positions of the 0 mm step and the 1020 mm step. The maximum difference in the X- and Z-coordinates between the two alignment positions was 5 µm.
The centre line of measurement in the horizontal plane (X-Y plane of the CMM) was positioned at the symmetry points between the side walls at the positions of the 0 mm step and the 1020 mm step on 27.5 mm from the top of the step gauge; in the vertical plane (Y-Z plane of the CMM) it was positioned on 27.5 mm from the alignment points on the top of the step gauge.
The step gauge was supported at the Bessel points.

Measurements.
The step gauge was measured 10 times in order to determine the reproducibility of the process. At the beginning, the end and in between of the 10 measurement runs de probe constant has been determined 4 times.
After each probe constant determination, the alignment procedure of the step gauge was repeated.
The measurements have been performed by manual operation of the CMM.
To control drift during a measurement run the CMM was returned to the 0 mm step 5 times; after each return the step gauge temperature and environmental conditions were refreshed.

Description of temperature measurement method & characteristics of the step gauge temperature:
The temperature measurements have been performed using thermistors connected to an Agilent 34970A data acquisition/switch unit. The Agilent 34970A was controlled and read by a home-made application for temperature measurement running on a laptop.
The temperature of the step gauge was measured with 4 sensors evenly distributed over the step gauge with two sensors on both ends of the step gauge body.
The average value of the 4 sensors was used to correct the measured length to the reference temperature of 20 °C. The drift of the average temperature and the temperature gradient on the step gauge during the measurements was accounted for in the uncertainty.
The following temperature characteristics apply:

Description	Temperature /°C
Range of the average temperature	: 20.019 – 19.961
Maximum drift during the measurements between 2 consecutive returns to the 0 mm step	: 0.011
Maximum gradient between 2 consecutive sensors	: 0.023

8.9 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.

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 0.25 µm.

Measurement method

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) °C.

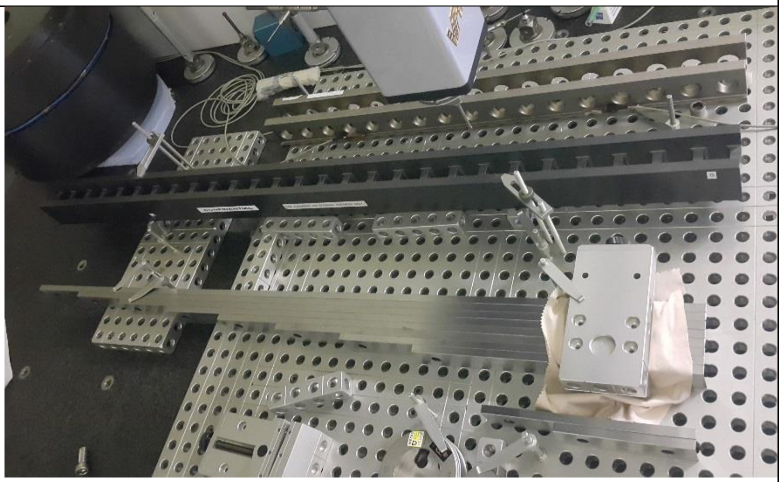
Setting standards: Step Gauge and a set of gauge blocks which have dimensions starting from 50 mm up to 1000 mm long are used to compare the results. Gauge blocks are just used for the verification of the results that are taken from the step gauge using substitution method. UME results given in the comparison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

Temperature measurements: Temperature in the laboratory is registered to be in (20±0.3) °C and better than (20±0.1) °C in working volume.

The temperature is kept within (20±0.1) °C 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.

Measurement set-up view: clamping of the artefacts and references:



8.10 NMIJ

Outline

Leitz PMM 121006 CMM equipped with laser interferometer is used to calibrate the step gauge. The laser interferometer has four paths for measurement of step gauge. A contact probe tip and a pair of plane mirrors for the laser interferometer are attached to the analogue probing system of the CMM. Temperature of step gauge is measured by an independent thermometer. Refractive index of air is compensated on Ciddor’s equation by measuring environmental condition such as air temperature, air pressure, and air humidity. A short gauge block is used to compensate effective diameter of the probe tip.

Traceability path (scale, interferometer, calibration standard.):

laser frequency	: calibrated by NMIJ
gauge block	: calibrated by NMIJ
thermometer	: calibrated by NMIJ
barometer	: calibrated by NMIJ
dew-point meter	: calibrated by NMIJ

Description of the measuring technique:
Gravity center of four paths of the laser interferometer is aligned to be considered with the center line of the step gauge. Reading of the laser interferometer is recorded when contacting force of the probe tip reaches to specific value. Atmospheric condition and temperature of the step gauge are measured before and after a series of measurement of length of the step gauge. A series of measurement consists of forward and backward measurement of every center point of the gauge surface.

Range of artefact temperature during measurements & description of temperature measurement method:
Totally eight channels of temperature sensors are adhered to the step gauge to measure gauge temperature. Temperature of the step gauge during measurement was from 20.179 °C to 20.241 °C.

8.11 NIST

Measurement instrument is a Moore M48 Coordinate Measuring Machine that uses an internal stabilized HeNe red laser as the scale for each axis. The machine is housed in a thermally controlled laboratory with T = 20.00 °C ± 0.03 °C at all times; humidity control to 40% ± 2%. Gradient control around the structure of the machine is kept to within 0.010 °C, and the artefact gradients on the CMM table are controlled to within 0.005 °C using an ambient air redirect assembly to move room supply air under the bridge of the CMM. The CMM motion is corrected using a rigid body error map generated from the twenty-one individually assessed rigid body errors. The CMM scales are directly mapped using an external HeNe laser whose frequency is traceable to the NIST iodine stabilized HeNe master laser system.

The CMM probe is a live body Movomatic Tridim design with a short-term repeatability of 5 to 8 nanometres in any one measurement axis. Once in contact, the probe overtravels to a pre-determined applied force and collects data as it retracts, with a final position value at a pre-set triggering force. The data is collected using thermal drift eliminating designs and redundant systematic determination of the step gauge origin puck location within the machine coordinate system during the full measurement process. The probe diameter is calibrated using multiple master precision spheres that have marked diameters determined using the NIST Strang Interferometer. This instrument also uses a traceable HeNe laser as the length scale.

Gauge material corrections, rigidity of fixturing, and performance of the step gauge is tested by conducting full measurement sequences at different probe triggering forces, then extrapolating any bi-directional trends to a zero applied force condition. NIST-owned step gauge control artefacts are present and measured alongside all client step gauges.

Historical data from the NIST control step gauges is used for assessing the reproducibility of the measurement process between rigid-body error mapping exercises and the variability of fixturing using different reference surfaces.

8.12 NMC A*STAR

The CMM (Carl Zeiss PRISMO ULTRA 9/13/7) with Calypso programme was used to conduct the comparison measurements at NMC/A*STAR. Through the precision 3D touching probe with its air-bearing 3-axis moving platform, 3D dimensional measurement can be realized with the accuracy in the order of micrometres. The 3-axis encode calibration is completed by a calibrated step gauge traceable to NPL. The artefacts with temperature sensor (19.6 °C) was located along the Y axis on CMM platform in the system. The measurement results are corrected and referred to values at 20°C. The measurement line is the straight line designated between reference points on “0 mm” face and “1020 mm” face. The reference points on “0 mm” face and “1020 mm” face were defined by intersection of the mid plane between the outer side walls, a plane parallel to that of the top surface of the gauge structure but offset downwards by 27.5 mm and the plane of “0 mm” and “1020 mm” measurement face respectively. Below is a photo of the CMM system at NMC.

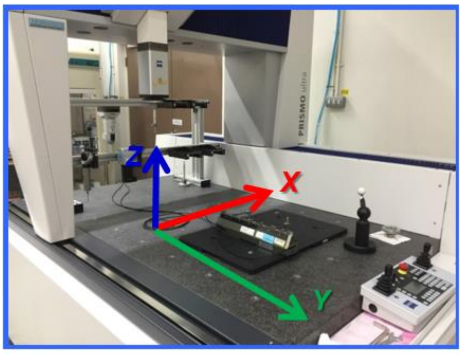
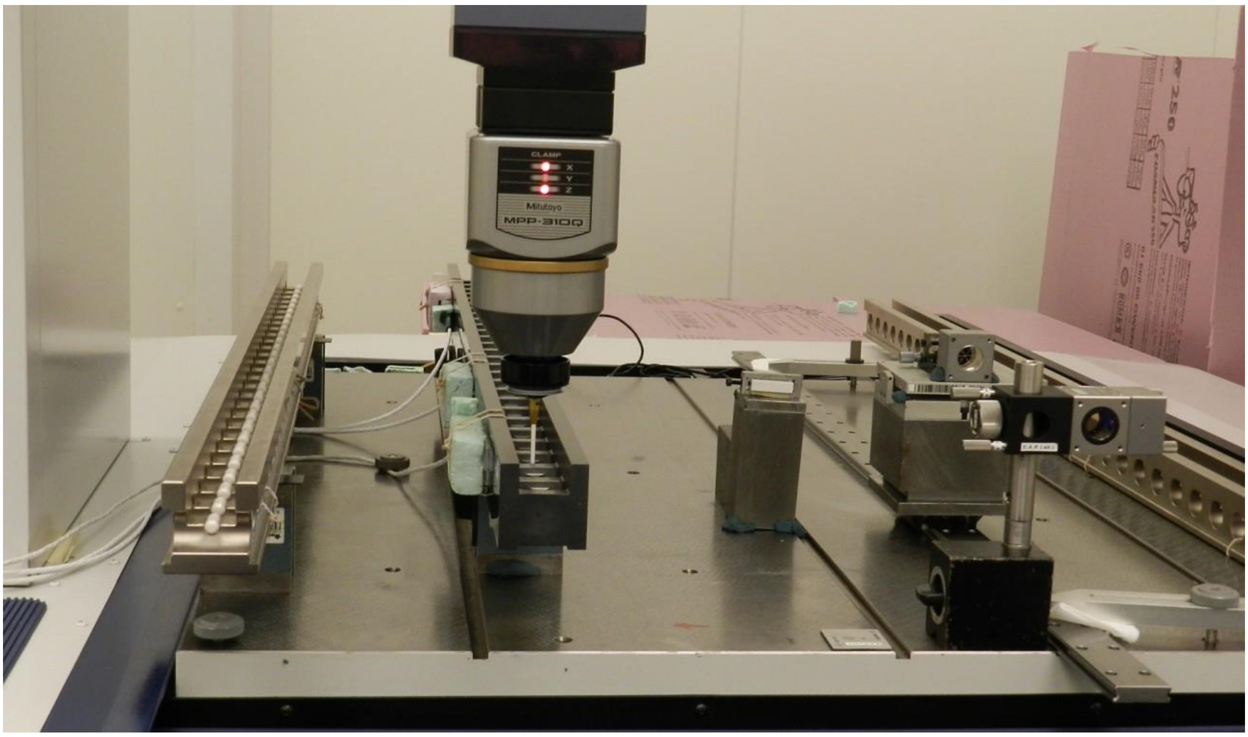


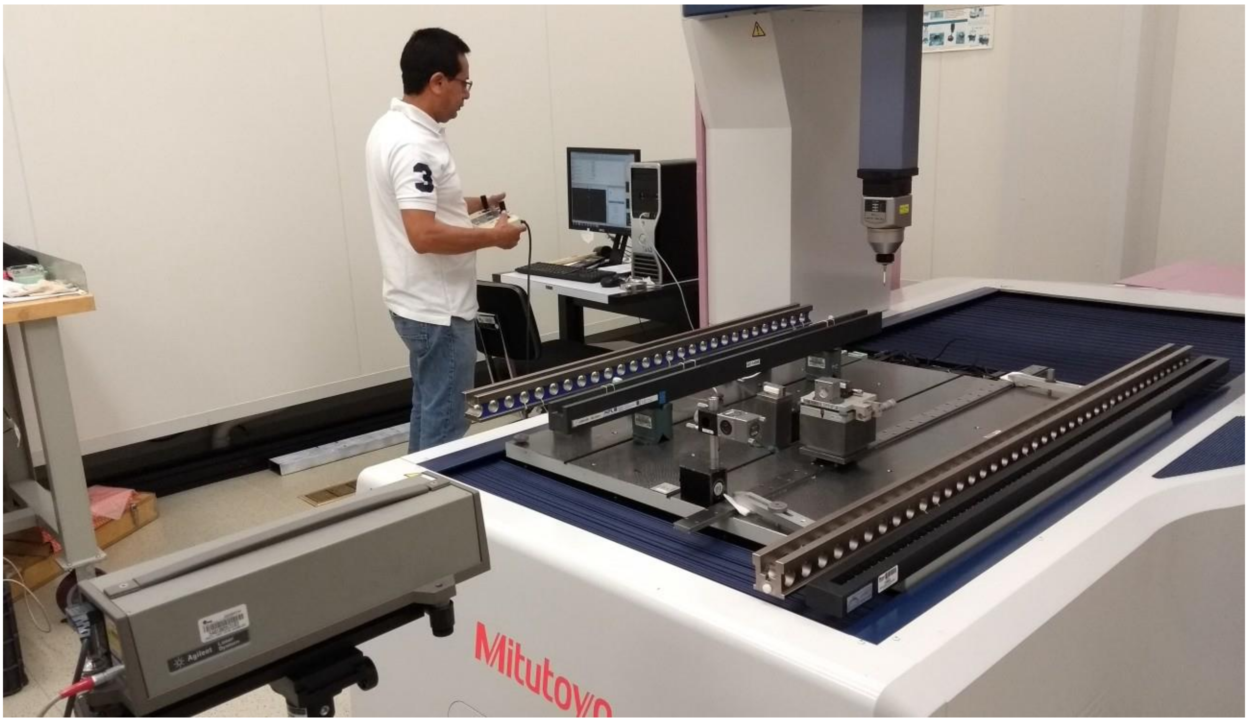
Photo of the CMM

Artefact in measurement

8.13 CENAM

Instrument used:
CMM Legex 9106 SN 30155141
Laser Interferometer Agilent 5519A SN US43061297
Ceramic Gauge Block (20 mm) Mitutoyo SN 090360
Thermometer ASL F200 SN 015769 with 3 sensors for material and one for the air
Barometer Mensor CP62400 SN 41000FPR
Average of measurement temperatures 19.83 °C
Maximum variations of the temperature in the step gauge 0.02 °C
Used method: substitution method using a measurement line in the CMM with multi-positions. The effective diameter and scale factor are compensated in the same line. The scale factor is determined using a precision guide equipped with a laser interferometer.





8.14 INRIM

The measuring apparatus is based on a Moore Measuring Machine, modified at INRIM (formerly IMGC), equipped with a laser interferometer and a proportional contact probe (CARY mod. I-DIM).

Tab. 1. Instrument/room identification.

Instrument	Manufacturer	Model
Universal Measuring Machine	Moore	n. 3
LVDT Probe (stylus 25 mm with ruby sphere dia. 3 mm)	CARY	I-DIM
Gage block	Cary	10 mm
Laser interferometer	HP	5517A
Barometer	Rosemount	A F1B1A1A
Hygrometer	Michell	S3000
Thermometer (with six PT100 Minco)	Corradi	RP7000
Laboratory with filtered air (not classified clean room class)	-	-

Traceability path (scale, interferometer, calibration std.):

The laser interferometer (λ_0) is calibrated with reference to the national length standard (laser He-Ne ($^{127}I_2$)).

A calibrated gage block is used for the characterization (probe diameter, displacement sensitivity) of the contact probe.

The measurements of the ambient parameters (temperature, pressure and humidity) and of the temperature of step gauge are traceable to the national standards.

Description of the measuring technique:

In the measurement procedure the contact probe is used to determine the positions (left- and right-sides) of the faces of the blocks/cylinders aligned along the measuring axis of the 1D interferometric comparator. The position of the face is obtained from combined interferometer and probe readings when the probe is in contact with the gauge face. The probe-surface load is of about 3 mN. A differential interferometric set-up is used for displacement measurements [1].

The diameter of the probing sphere (made of ruby) and the sensitivity of the LVDT probe are calibrated using a certified gage block mounted on the moving table/support of the Moore Machine. This measurement is repeated within and between the measurement runs on the step-gauge.

The measurement results have been appropriately corrected to the reference temperature of 20 °C using the given value of the thermal expansion coefficient.

The equipment configuration from bottom up was: Moore carriage, tilt stage and height adapters up to Abbe condition in vertical/lateral and base support of the step gauge (Bessel support points).

The applied procedure is the following:

The step gauge is placed on the base support and is aligned (visually) with the displacement axis and the measuring (laser) axis. Then, the step gauge is aligned along the vertical and y lateral axes, to minimize the Abbe offset between the laser beam and the center of the end face of blocks/cylinders.

The step gauge is further aligned by touching with the probe the lateral reference surfaces of the blocks according to the moving range of the measuring machine moving forth and back several times the axis of the measuring machine

For the determination of the center of the gauges/cylinders we used a sphere of know diameter placed in the upper surface of the step-gauge and aligned to its external lateral side. Then, we search with the probe the center of the sphere in the Y and Z directions and so we know the position of the upper and side surfaces of the step-gauge, from which we may position the measuring line at the center of the gauge/cylinder.

With the automatic control of the Moore machine, no manual handling of the step gauge is required to reset the equipment between each set of measurements.

Due to the x-axis range of 440 mm of the 1D comparator the gauge of 620 mm length has been calibrated in two steps: the first step from the block “0” (left face) up to the block “21” (right face) of 420 mm nominal length, and the second step by re-orienting of 180° the step gauge and measuring from the block “9” of 180 mm nominal length (left face) up to the full length of 620 mm (right face of the block “30”).

The adopted measurement strategy is:

1. The positions of the left- and right-side faces of the blocks/cylinders (step gauge aligned along the x-axis) from 4 measurement runs (forth and back paths for each run);
2. The positions of the left- and right-side faces of the cylinders/gauges (step gauge rotated of 180° in the xy plane) from 6 measurement runs (forth and back paths for each run);

For each run the deviation from the nominal length is obtained from the average of forward and backward measurements of the face positions.

Range of artefact temperature during measurements & description of temperature measurement method:

The range of artefact temperature during the measurement runs was from 19.99 °C to 20.08 °C. The temperatures of the ambient air (2 thermometers along the measuring path) and of the artefact (2 thermometers) are measured with a bridge-type temperature analyser operating with up to six PT100 resistance thermometers. Temperatures are taken about every 10 minutes during the full measurement run (about 2 hours).

References

1. G.B. Picotto, R. Bellotti, M. Pometto and M. Santiano, The INRIM 1D comparator with a new interferometric set-up for measurement of diameter gauges and linear artefacts, Proc. MacroScale 2011, Physikalisch-Technische Bundesanstalt (PTB), 2013. doi: 0.7795/810.20130620o

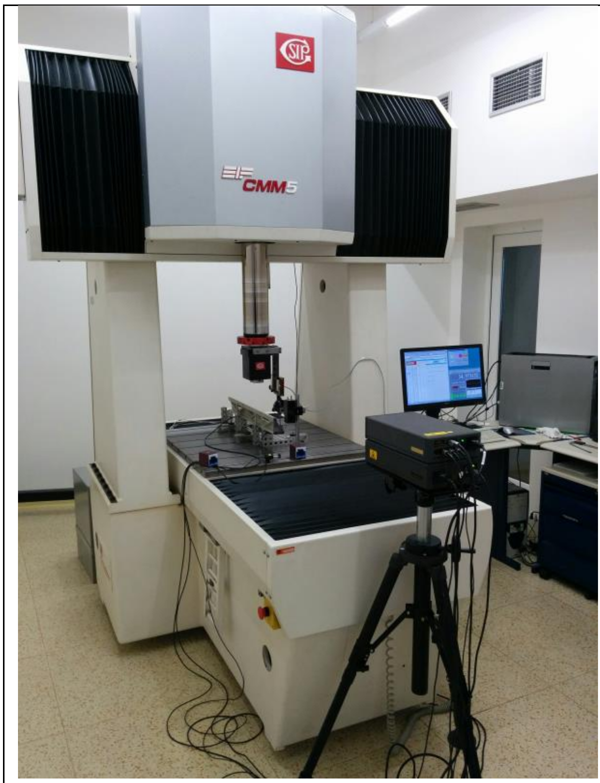
8.15 MKEH

The measurements have been performed with a co-ordinate measuring machine, manufacturer SIP, Geneva, type CMM5. The measuring range is (700 x 700 x 550) mm, the probe resolution is 0,1 µm.

The traceability was assured by calibrated gauge blocks. The gauge blocks with the sizes up to 100 mm was calibrated by MKEH by comparative method. The gauge blocks with the nominal sizes 125-600 mm was calibrated by interference method by NPL and METAS.

8.16 CMI

In CMI the coordinate measuring machine SIP CMM5 is used. For the calibrations of step gauges the CMM is equipped with a probe with plane mirror. Laser interferometer is used as reference and machine serves only to move the gauge. The probe consists of the plane mirror, the parallelogram and the high resolution inductive linear sensor. During measurement, software captures in one moment pair of points from sensor and laser interferometer. This is repeated ten times with small movements and the probing point with zero force is calculated.



8.17 INM

Make and type of instruments:

Laser interferometer type Hewlett – Packard, type 5526 A

One coordinate machine SIP - MUL 1000 and contacting probe

Standard gauge block of nominal length 20 mm

The measuring technique:

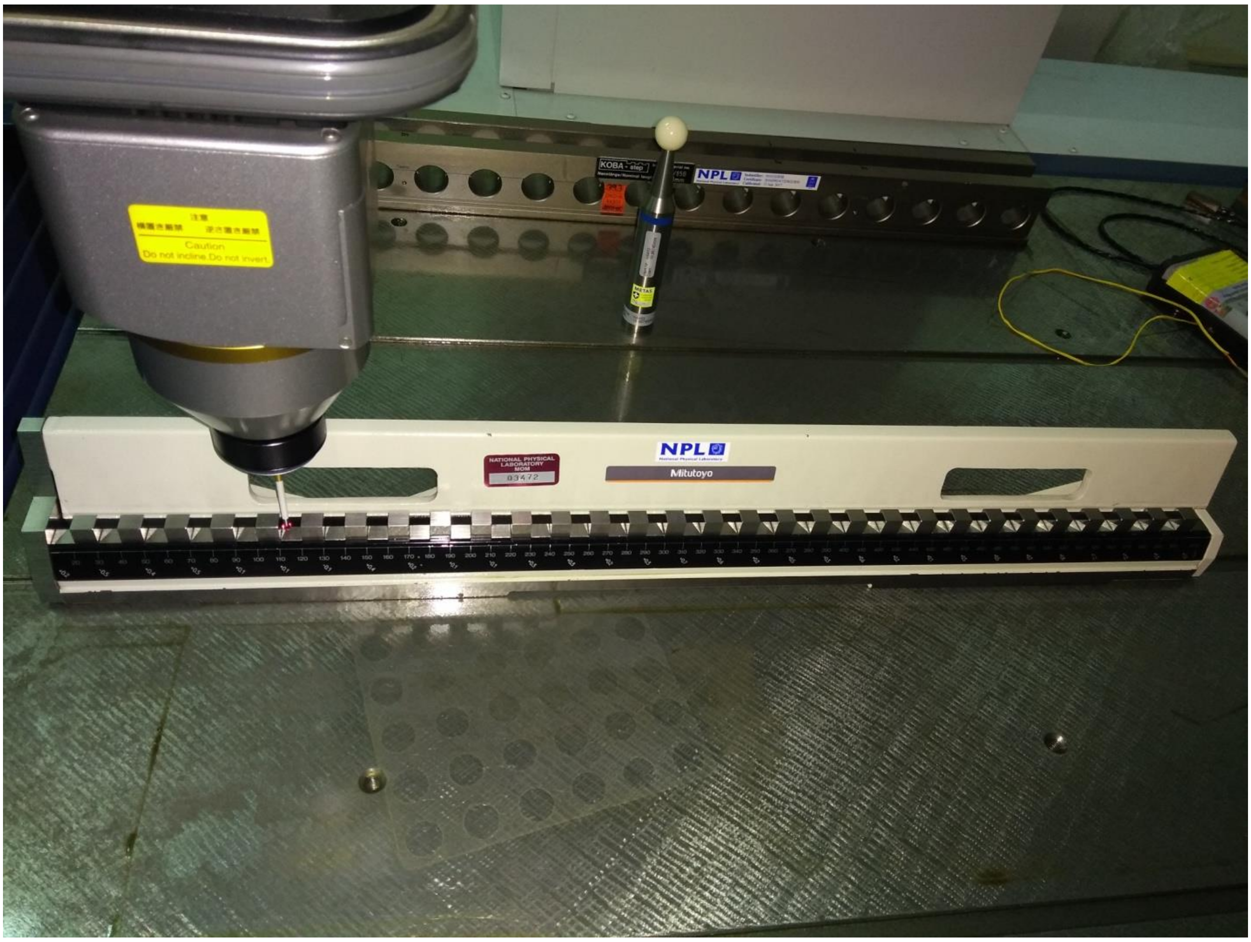
comparative method,

the distances of the centres of the front and back faces of the individual gauges of the step-gauge with respect to the centre of the front face of the first gauge is determined in horizontal position.

8.18 NPLI

Coordinate Measuring Machine has been used to measure 610mm artefact. Details of the machine are: 3D-CMM, Model : LEGEX 9106, Make: Mitutoyo, Range: X-axis :900mm, Y-axis :1000mm,Z-axis:600mm

The measurement was done by using a tactile probe head CMM. A reference step gauge, calibrated at NPL was used to provide traceability y.



8.19 SASO-NMCC

Zeiss Prismo ultra with VAST Gold Head Coordinate Measuring Machine has been used for calibration of the step gauge using 5 mm diameter probe.

Measurement method

The step gauge was measured by comparison method. The reference in this comparison was gauge blocks, which are traceable to SASO-NMCC. The reference gauges and step gauge were fixed on X-axis of CMM. Temperature in the laboratory is within range of (20±0.3) °C and 2 sensor (Pt100) is located on step gauge.

8.20 NRC-CNRC

The instrument used for step gauge calibration at NRC is a Mitutoyo Legex 707 CMM equipped with probing system MPP310. A ruby stylus of tip diameter 5 mm and 30 mm shank length was used. The step gauge was supported on truncated cylinders placed under the Bessel points and nominally aligned to the X-axis of the CMM. A calibrated gauge block 600 mm in length was used to evaluate and correct for scaling errors along the X-axis of the CMM. This gauge block was supported by truncated cylinders at the Airy points, nominally aligned to the X-axis of the CMM, and measured as part of the step gauge measurement protocol. A calibrated gauge block 20 mm in length was used to determine the bi-directional probing error. All measurements are corrected to the reference temperature of 20 °C by the CMM software using calibrated thermistors read by a Fluke 1529 digital thermometer. During calibration the temperature of the step gauge was between 19.985 °C and 20.015 °C.