EURAMET Supplementary Comparison, EURAMET.L-S20 (#1169)

Comparison of laser distance measuring instruments

Final Report

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Contents

1 Introduction

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

At the meeting in September 2010, the EUROMET TC Length decided to carry out a comparison of laser distance measuring instruments (EDMs), with the Central Office of Measures (GUM), Poland as the pilot laboratory. The results of this international comparison will support the Calibration and Measurement Capabilities (CMCs) declared by the NMIs in the CIPM Mutual Recognition Arrangement (MRA). Four EDMs of different quality classes had been used as artifacts (three of them were provided by BEV). The measurements were carried out over a distance up to 30, 40 or 50 m, depending on measurement capabilities of participants.

2 Organisation

Conditions for participation

The participating laboratories were NMIs required to fulfil the following conditions:

- signatory (or applicant) of the CIPM MRA;
- calibrating EDMs for their customers as a regular service;
- being well trained in handling EDMs;
- being capable of measuring at least within a 20 m range.

Participants

Institute	Address	Contact
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CEM	Centro Español de Metrologia C/del Alfar ,2 ES-28760 Tres Cantos, Madrid Spain	Emilio Prieto, Tel. +34 91 807 47 16 Fax. +34 91 807 48 07 eprieto@cem.minetur.es
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METAS	Federal Office of Metrology METAS Lindenweg 50 CH-3003 Bern-Wabern Switzerland	Oliver Stalder Tel. +41 31 32 33 355 Fax. +41 31 32 33 210 oliver.stalder@metas.ch

Two laboratories (VSL from Netherlands and NPL from United Kingdom) were originally on the list of participants. NPL has withdrawn since they did not provide calibration of EDMs as a regular service. VSL has withdrawn for lack of funds to take part in comparisons.

Time schedule

The comparison was carried out in the form of a circulation. The pilot laboratory performed measurements with the EDMs at the beginning, in the middle and at the end of the circulation in order to monitor their stability.

Laboratory	Country	Date
GUM	Poland	February 2011
MIKES	Finland	March 2011
SP	Sweden	April 2011
AS Metrosert	Estonia	May 2011
PTB	Germany	June 2011
GUM	Poland	August-September 2011
CMI	Czech Republic	October 2011
SMU	Slovakia	November 2011
INM	Romania	December 2011
INRIM	Italy	January 2012
CEM	Spain	February 2012
BEV	Austria	April 2012
JV	Norway	June 2012
METAS	Switzerland	July 2012
GUM	Poland	August 2012

Transportation

The transportation of the devices was not critical. In most cases courier services were used. The ATA carnet, issued outside the EU, was handled correctly in all cases.

3 Description of the standards

4 EDMs of different quality classes were used. For each of the two different manufacturers, two models of EDMs were selected.

Manufacturer, type	Serial no.	Dimensions	Uncertainty declared	Resolution
Bosch DLE 50	782511118	(100x58x32) mm	1,5 mm	1 mm
Bosch GLM 150	005051241	(120x66x37) mm	1 mm	0,1 mm
Leica DISTO D3a BT	902520011	(127x49x27) mm	1 mm	0,1 mm
Leica DISTO D8	500950167	(143x55x30) mm	1 mm	0,1 mm
Target plate	–	(275x198x3) mm	–	–
Technical protocol	–	–	–	–

Bosch DLE 50

Bosch GLM 150

Leica DISTO D3a BT

Leica DISTO D8

4 Handling and measurement instructions

Measurement instructions

Before calibration, the EDMs were inspected for damage. It was checked if their batteries had been discharged. If necessary, the batteries were replaced with new ones.

The Leica DISTO D8 was set to the “standard mode” (not “long range”).

The EDMs were calibrated with beam pointing horizontally and lying up display. It was mandatory to use the included target plate (no adhesive tape side, no division line area).

Each EDM was calibrated at a distance of 0,3 m and regularly spaced intervals every 5 m (as close as possible to these points) for the range up to 50 m. Laboratories with a maximum range of less than 50 meters performed measurements up to the highest possible measurable multiple of 5 meters.

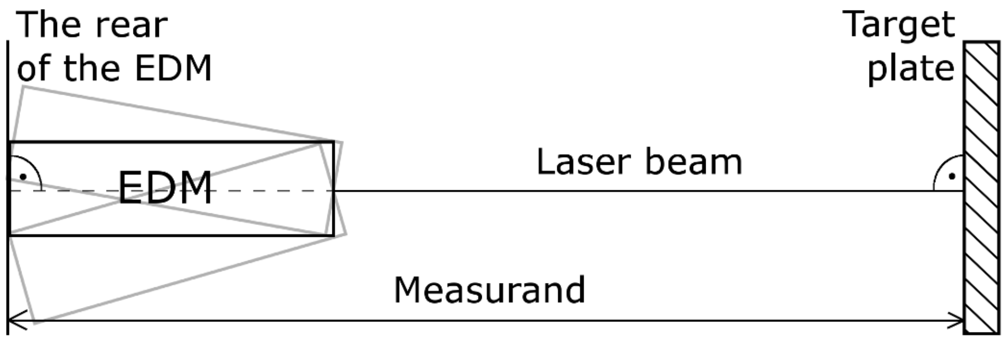
The measurement results were corrected to the reference temperature of 20°C.

The measurement results, instrument description and a detailed evaluation of the measurement uncertainty were reported using forms given in the protocol. All results were transmitted electronically, as well as a signed paper report.

Measurand

Typically, the laser beam is not perpendicular to the back of EDM. To achieve laser beam perpendicular to the target plate, angular position of the EDM body was corrected.

The measurand for this comparison was a distance from the point at the rear of the angularly corrected EDM farthest from the target plate to the target plate (see figure below).



5 Measurement equipment and methods used by the participants

The participating laboratories gave a short description in their measurement report related to the equipment and method used for EDMs’ calibration. These reports are given in Appendix 1. Most of the laboratories used a laser interferometer system for the length measurement, others used a reference tape and reference baseline (see table below).

Lab	Bench length	Reference
GUM	50 m	Laser interferometer
MIKES	30 m	Laser interferometer
SP	50 m	50 m steel tape
AS Metrosert	20 m	Laser interferometer
PTB	50 m	Laser interferometer
CMI	30 m	Laser interferometer
SMU	40 m	50 m steel tape
INM	50 m	Laser interferometer
INRIM	25 m	Laser interferometer
CEM	50 m	Reference baseline calibrated by total station
BEV	50 m	Laser interferometer
JV	50 m	Laser interferometer
METAS	50 m	Laser interferometer

6 Measurement results

In the tables below, the measurement results and the expanded measurement uncertainties are given for all laboratories and the four EDMs.

BOSCH DLE 50

NMI	Country	300 mm		5000 mm		10000 mm		15000 mm		20000 mm		25000 mm		30000 mm		35000 mm		40000 mm		45000 mm		50000 mm	
		L (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)
MIKES	FI	299,09	0,91	5000,08	0,91	9999,84	0,91	14999,71	0,91	20000,16	0,91	24999,93	0,91	29998,62	0,91								
SP	SE	299,90	0,91	5000,10	0,91	10000,10	0,92	15000,00	0,94	19999,90	0,97	25000,60	1,00	30000,30	1,04	35000,20	1,08	40000,50	1,13	45000,70	1,19	50000,00	1,24
Metrosert	EE	300,20	0,29	4999,70	0,61	9999,60	0,73	14999,60	0,84	19999,40	0,84												
PTB	DE	299,70	0,41	5000,10	0,43	10000,20	0,51	14999,90	0,62	19999,90	0,74	24999,60	0,88	29999,60	1,02	34999,50	1,16	39999,20	1,31	44998,40	1,46	50000,00	1,61
GUM	PL	299,26	1,22	4999,83	1,24	9999,80	1,23	14999,82	1,23	19999,81	1,43	25000,04	1,32	29999,82	1,35	34999,85	1,40	39999,68	1,97	44999,06	1,88	50000,29	1,68
CMI	CZ	299,66	1,21	5000,16	1,21	9999,93	1,21	15000,00	1,21	19999,87	1,21	24999,67	1,21	29999,94	1,21								
SMU	SK	299,75	0,72	4999,44	0,78	9999,69	0,89	14999,70	0,95	19999,60	1,10	24999,24	1,17	30000,28	1,29	35000,34	1,42	40000,51	1,57				
INM	RO	300,00	0,82	5000,20	0,83	10000,40	0,83	15000,00	0,84	20000,00	0,86	25000,00	0,88	29998,80	0,90	34998,60	0,93	39996,80	0,96	44996,20	0,99	49996,40	1,02
INRIM	IT	299,84	0,22	4999,82	0,25	10000,04	0,30	15000,82	0,63														
CEM	ES			4999,40	1,50	9999,70	1,50	14999,30	1,50	19999,20	1,50	24999,90	1,50	29999,00	1,50	35001,00	1,50	40000,20	1,50	44998,20	1,50	49999,30	1,50
BEV	AT	299,59	0,93	4999,98	0,90	10000,04	0,91	14999,94	0,91	19999,89	0,95	24999,83	1,01	30000,00	1,03	34999,93	1,06	40000,17	1,22	44999,69	1,37	49999,96	1,57
JV	NO	299,52	0,76	4999,75	0,78	10000,29	0,84	14999,36	0,94	20000,44	1,06	25000,72	1,20	30000,53	1,34	35002,48	1,50	40002,19	1,66	45000,65	1,83	50001,72	2,00
METAS	CH	300,00	0,60	5000,00	0,61	10000,00	0,61	15000,00	0,61	19998,80	0,81	25000,00	1,02	29999,30	1,12	34999,80	1,12	39999,00	1,72	45000,30	2,02	49999,00	1,93

Table 1. Measurement results for BOSCH DLE 50 EDM and expanded measurement uncertainties (k=2). The results reported by laboratories were corrected to nominal length of the measured distances.

BOSCH GLM 150

NMI	Country	300 mm		5000 mm		10000 mm		15000 mm		20000 mm		25000 mm		30000 mm		35000 mm		40000 mm		45000 mm		50000 mm	
		L (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)
MIKES	FI	300,52	0,81	4999,76	0,81	9999,94	0,81	14999,93	0,81	19999,65	0,81	24999,69	0,81	30000,48	0,81								
SP	SE	300,50	0,71	5000,30	0,71	10000,00	0,71	15000,00	0,91	19999,90	0,91	24999,60	0,91	30000,10	0,91	35000,20	0,92	40000,20	0,92	45000,20	0,92	50000,70	0,93
Metrosert	EE	299,40	0,84	4999,60	0,84	10000,00	1,31	15000,20	1,31	20000,40	1,85												
PTB	DE	300,84	0,44	5000,18	0,44	10000,10	0,41	15000,10	0,42	19999,60	0,43	24999,80	0,44	30000,20	0,45	35000,30	0,47	40000,50	0,49	45000,70	0,51	50000,70	0,53
GUM	PL	300,43	0,56	4999,67	0,69	9999,83	0,66	14999,61	0,88	19999,42	0,80	24999,74	0,89	30000,12	0,80	35000,32	0,81	40000,37	0,84	45000,48	0,83	50000,69	0,91
CMI	CZ	299,98	0,81	4999,50	0,81	9999,52	0,81	14999,24	0,81	19999,00	0,81	24999,13	0,81	29999,96	0,81								
SMU	SK	300,60	0,43	4999,60	0,64	9999,33	0,68	14999,89	0,91	20000,04	0,97	24999,54	1,15	29999,92	1,21	35000,73	1,37	40000,95	1,49				
INM	RO	300,36	0,38	4999,86	0,39	9999,76	0,40	14999,80	0,81	19999,40	0,82	25000,00	0,84	30000,00	0,86	35000,00	0,89	40000,40	0,92	45000,00	0,95	49999,80	0,99
INRIM	IT	300,76	0,10	4999,57	0,18	9999,54	0,28	14999,63	0,36	19999,20	0,35	24999,21	0,37										
CEM	ES			4999,80	1,10	9999,80	1,10	14999,40	1,10	19999,20	1,10	24999,20	1,10	29999,10	1,10	35000,80	1,10	39999,40	1,10	44999,40	1,10	49999,20	1,10
BEV	AT	300,44	0,70	4999,76	0,70	9999,72	0,70	14999,88	0,92	19999,03	0,92	24999,13	0,92	29999,68	0,92	34999,94	0,92	39999,99	0,92	45000,01	0,92	50000,07	0,92
JV	NO	300,49	0,46	4999,86	0,48	10000,03	0,55	14999,89	1,00	19999,22	1,00	24999,74	1,00	29999,66	1,00	35000,00	1,00	40000,54	1,03	45000,60	1,08	50001,00	1,14
METAS	CH	300,30	0,14	4999,70	0,13	9999,80	0,31	14999,80	0,81	19999,30	1,01	24999,30	0,62	29999,50	0,82	34999,50	0,83	39999,80	0,84	44999,50	0,85	50000,00	0,86

Table 2. Measurement results for BOSCH GLM 150 EDM and expanded measurement uncertainties (k=2). The results reported by laboratories were corrected to nominal length of the measured distances.

Leica DISTO D3a BT

NMI	Country	300 mm		5000 mm		10000 mm		15000 mm		20000 mm		25000 mm		30000 mm		35000 mm		40000 mm		45000 mm		50000 mm	
		L (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)
MIKES	FI	300,40	0,55	5000,58	0,55	10000,58	0,55	15000,11	0,55	20000,28	0,55	25000,62	0,55	30000,40	0,55								
SP	SE	300,60	0,71	5000,30	0,71	10000,70	0,71	15000,30	0,71	20000,50	0,71	25000,80	0,72	30000,70	0,72	35000,40	0,73	40000,60	0,73	45000,90	0,74	50000,40	0,75
Metrosert	EE	300,10	0,34	5000,00	0,39	10000,10	0,44	15000,10	0,50	20000,10	0,50												
PTB	DE	300,66	0,39	5000,02	0,39	10000,61	0,40	15000,32	0,42	20000,55	0,44	25000,64	0,47	30000,47	0,51	35000,48	0,55	40001,21	0,59	45000,70	0,63	50000,79	0,67
GUM	PL	300,54	0,77	5000,17	0,76	10000,56	0,77	15000,24	0,78	20000,43	0,82	25000,74	0,77	30000,37	0,80	35000,52	0,85	40001,04	0,82	45000,89	0,80	50000,81	0,80
CMI	CZ	300,35	0,48	5000,00	0,48	10000,43	0,48	15000,12	0,48	20000,17	0,48	25000,50	0,48	29999,97	0,48								
SMU	SK	300,36	0,36	4999,94	0,56	10000,16	0,61	15000,23	0,70	20000,00	0,88	24999,77	0,99	30000,63	1,09	34999,87	1,20	39999,93	1,33				
INM	RO	300,36	0,32	4999,86	0,33	10000,04	0,35	15000,18	0,37	20000,12	0,40	25000,10	0,44	29999,72	0,49	34999,74	0,53	39999,88	0,58	44999,64	0,63	49997,34	0,68
INRIM	IT	300,58	0,21	4999,94	0,24	10000,58	0,27	15000,73	0,29														
CEM	ES			4999,76	0,93	10000,25	0,93	15000,14	0,93	19999,51	0,93	25000,35	0,93	30000,12	0,93	34999,56	0,93	40000,27	0,93	44999,55	0,93	49998,87	0,93
BEV	AT	300,16	0,56	4999,90	0,56	10000,17	0,56	15000,20	0,56	20000,05	0,56	25000,10	0,56	30000,04	0,56	35000,01	0,56	40000,33	0,56	45000,42	0,56	50000,38	0,56
JV	NO	300,55	0,71	5000,16	0,71	10000,49	0,74	15000,52	0,79	20000,51	0,84	25000,68	0,91	30000,57	0,99	35000,53	1,07	40001,30	1,16	45001,88	1,25	50000,64	1,35
METAS	CH	300,10	0,11	5000,00	0,07	10000,00	0,13	14999,90	0,14	19999,80	0,15	25000,00	0,22	29999,70	0,44	34999,70	0,37	40000,00	0,65	44999,70	0,66	50000,00	0,76

Table 3. Measurement results for LEICA D3a and expanded measurement uncertainties (k=2). The results reported by laboratories were corrected to nominal length of the measured distances.

Leica DISTO D8

NMI	Country	300 mm		5000 mm		10000 mm		15000 mm		20000 mm		25000 mm		30000 mm		35000 mm		40000 mm		45000 mm		50000 mm	
		L (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)	*L* (mm)	*U* (mm)
MIKES	FI	300,35	0,38	4999,75	0,38	10000,74	0,38	15000,51	0,38	20000,85	0,38	25001,18	0,38	30000,83	0,38								
SP	SE	300,70	0,71	4999,90	0,71	10000,70	0,71	15000,40	0,71	20000,70	0,71	25000,90	0,72	30000,90	0,72	35001,00	0,73	40001,10	0,74	45000,80	0,75	50001,20	0,76
Metrosert	EE	300,00	0,61	4999,70	0,44	10000,20	0,61	14999,90	0,61	20000,40	0,78												
PTB	DE	300,47	0,43	4999,74	0,43	10000,59	0,43	15000,22	0,43	20000,50	0,43	25000,74	0,43	30000,65	0,43	35001,09	0,43	40001,50	0,43	45001,13	0,43	50001,62	0,43
GUM	PL	299,92	0,71	4999,70	0,61	10000,12	0,62	15000,53	0,63	20000,92	0,68	25000,61	0,73	30000,92	0,63	35001,28	0,73	40001,51	0,63	45001,41	0,66	50001,73	0,62
CMI	CZ	299,49	0,29	4999,49	0,29	9999,86	0,29	14999,83	0,48	20000,54	0,29	25000,64	0,30	30000,58	0,30								
SMU	SK	299,70	0,39	4999,52	0,58	9999,88	0,68	15000,01	0,78	20000,42	0,86	25000,11	1,05	30000,63	1,17	35000,83	1,28	40000,92	1,43				
INM	RO	300,32	0,36	4999,56	0,37	10000,40	0,38	15000,28	0,41	20000,46	0,44	25000,52	0,47	30000,60	0,51	35000,90	0,56	40001,40	0,60	45001,28	0,65	50001,50	0,70
INRIM	IT	300,65	0,19	4999,50	0,21	10000,31	0,34	15000,62	0,28	20000,52	0,31	25001,54	0,46										
CEM	ES			4999,70	0,93	10000,24	0,93	15000,28	0,93	20000,22	0,93	25000,20	0,93	30000,04	0,93	35000,19	0,93	40000,34	0,93	44999,73	0,93	49999,71	0,93
BEV	AT	299,68	0,65	4999,53	0,65	9999,89	0,65	14999,45	0,65	20000,37	0,65	25000,52	0,65	30000,49	0,65	35000,54	0,65	40000,84	0,65	45000,74	0,65	50000,79	0,65
JV	NO	300,28	0,46	4999,89	0,46	10000,69	0,46	15000,48	0,46	20000,91	0,47	25001,08	0,48	30000,94	0,49	35001,26	0,50	40001,87	0,51	45001,80	0,53	50001,37	0,55
METAS	CH	300,40	0,23	4999,70	0,16	10000,50	0,22	15000,50	0,24	20000,50	0,26	25000,60	0,24	30000,60	0,35	35000,50	0,45	40000,60	0,31	45000,50	0,33	50000,70	0,36

Table 4. Measurement results for LEICA D8 and expanded measurement uncertainties (k=2). The results reported by laboratories were corrected to nominal length of the measured distances.

7 Measurement uncertainties

The participants were asked to report detailed measurements uncertainty budgets evaluated according to the ISO Guide. In table 5, the majority of the contributions are summarized, as they had been reported by the participants.

		MIKES		SP		Metrosert		PTB		GUM		CMI		SMU	
		Leica D8		Leica D8		D3		D8				D8			
		absolute	relative	absolute	relative	absolute	relative	absolute	relative	absolute	relative	absolute	relative	absolute	relative
1.	**EDM**														
1.1	Resolution	1,90E-01		3,00E-02		2,89E-02				2,89E-02		5,77E-02		2,50E-02	
1.2	Repeatability			6,00E-02	2,00E-03	2,31E-01		1,00E-01		3,32E-01		2,30E-01		2,80E-01	
2.	**Inteferometer/tape**														
2.1	ref. index/expansion coefficent		3,00E-05	1,00E-03	2,00E-04		2,51E-02		1,13E-04		3,00E-04	5,00E-06	5,53E-04		5,15E-03
2.2	others		1,01E-04	9,49E-02	1,41E-03	1,74E-03	1,20E-03	1,20E-03	2,50E-05	2,89E-03	3,00E-06		4,00E-04	1,15E-01	1,36E-02
3.	**Geometry**														
3.1	Abbe error		9,00E-05			2,89E-02		5,80E-02		1,88E-03		1,11E-02			
3.2	Cosine error - interferometer/tape								2,10E-04		1,15E-05		5,60E-07		5,00E-03
3.3	Cosine error - EDM		1,80E-05	1,70E-01			5,80E-03				2,89E-04		1,39E-03		7,80E-03
3.4	Parallelism			2,60E-01								2,76E-02		9,00E-02	
3.5	Zero point	incl. in 1.		9,00E-02		5,77E-02		1,70E-01		2,89E-02		2,24E-02		5,00E-02	
3.6	Others							6,20E-05				3,60E-02			
4.	**Others**														2,00E-06

		INM		INRIM		CEM		BEV		JV		METAS			
		D8				D8		D8		D8		D8			
		absolute	relative	absolute	relative	absolute	relative	absolute	relative	absolute	relative	absolute	relative		
1.	**EDM**														
1.1	Resolution	2,90E-02				3,00E-02		2,89E-02		2,90E-02		2,99E-02			
1.2	Repeatability	1,10E-01		4,00E-01		7,00E-02		1,33E-01		1,90E-01		1,50E-01			
2.	**Inteferometer/tape**														
2.1	ref. index/expansion coefficent	2,00E-04	2,50E-07	1,35E-03		3,76E-01		1,00E-03		7,50E-02			5,79E-03		
2.2	others			1,52E-02									1,00E-04		
3.	**Geometry**														
3.1	Abbe error	1,00E-01		5,42E-02		1,90E-01		5,00E-02		5,00E-02		2,40E-03			
3.2	Cosine error - interferometer/tape		1,80E-09		1,13E-07					1,00E-03			1,00E-04		
3.3	Cosine error - EDM					4,00E-02							1,45E-02		
3.4	Parallelism	1,00E-01	6,00E-06	2,89E-02		1,08E-02							1,50E-01		
3.5	Zero point									1,63E-01					
3.6	Others					1,44E-01		2,00E-01							
4.	**Others**				3,00E-06			8,00E-02							

Table 5. Summary of the most frequently reported measurements uncertainty contributions in mm, taken from uncertainty budgets reported by the participating laboratories.

8 Stability of the EDMs

Repeatability measurements showed that in the short period (less than 60 min.) indications of the EDMs did not reveal any drift. Large differences (~ 1.5 mm) were also noted, between the mean values of the subsequent measurement series performed within 48 hours. Considering this effect in uncertainty budget and on the basis of measurements made at the beginning, in the middle and at the end of the comparison, one cannot determine the drift of the results.

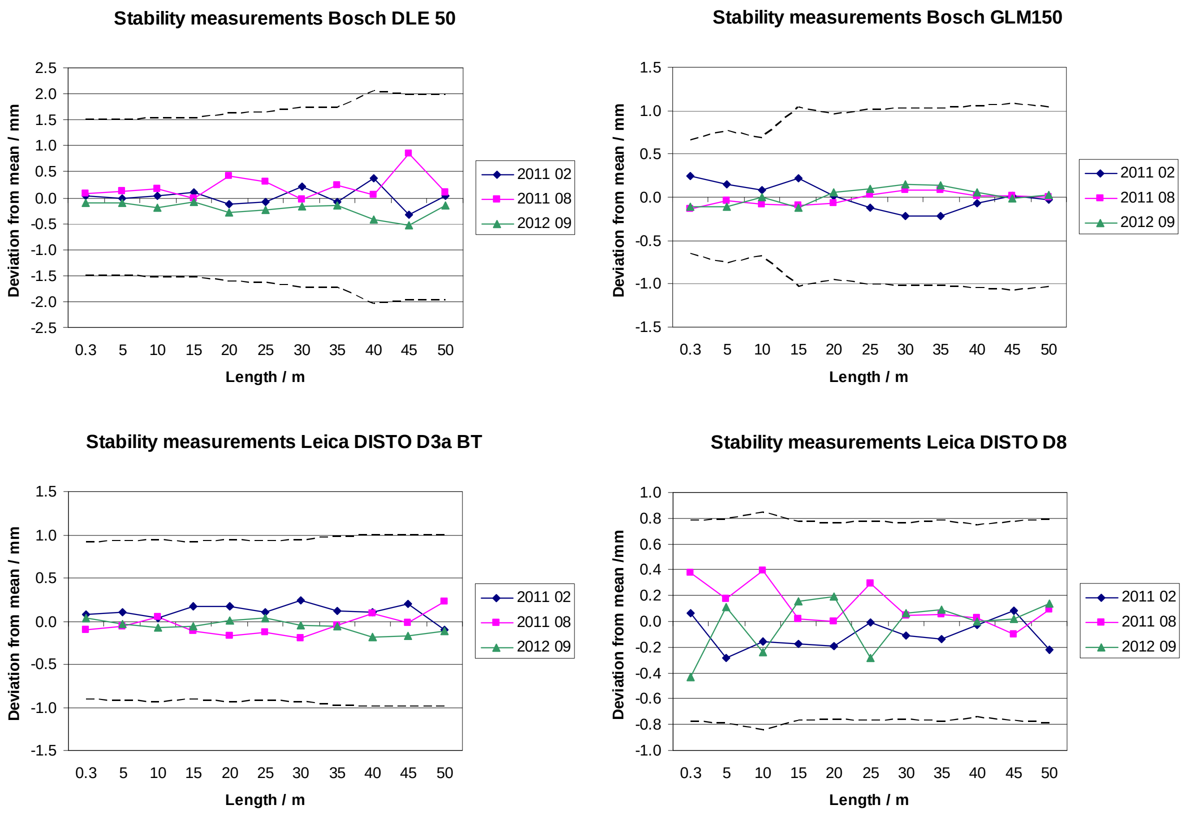


Fig. 1. Measurements of the pilot laboratory monitoring the stability of all four EDMs at each of the measuring distances, bounded by the expanded measurements uncertainty (for k=2; dashed line). The solid curves represent deviation from the arithmetic mean of the three measurements.

The test of the stability of the EDMs showed significant changes in the mean results in timescale months or even days. A detailed analysis of the observed problems will be presented by way of example with Leica DISTO D8 and for a 10 m distance. This EDM has been chosen because it is theoretically the best of the compared models, with resolution of 0.1 mm over whole range. Depending on the measured distance, the EDM is characterized by some measurement uncertainty. Typically, the standard deviation increases along the distance. Distance of 10 m was selected to minimize the impact of the uncertainty on a single measurement. The more the distance from the target increases, the weaker the reflected signal becomes and the more the uncertainty of a single measurement increases, while for very short distances the reflected signal is so strong that it can also have a negative impact on the results.

Stability over few minutes time interval

The studies performed showed that deviations from expected value are well characterized by normal distribution. Results of those studies are presented in the figure below. Probability density of deviations from expected value for Leica D8 for 10 m is consistent with a normal distribution with standard deviation s = 0.19 (blue marks – experimental, red line – fitted model).

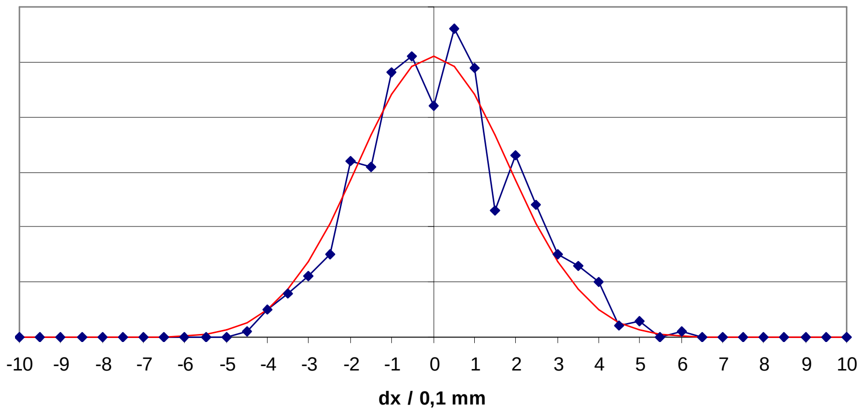


Fig. 2. Distribution of results over few minutes time interval.

Stability over tens of minutes time interval

Several series of measurements were made with a duration from 15 minutes to 30 minutes, at a constant distance and under constant measurement conditions. For most of the series, changes in the average value of indications of EDMs have been observed at the level of about 0.2 mm. However, for one of the series, change exceeds 0.5 mm (see figure below). This value leads to u = 0,15 mm.

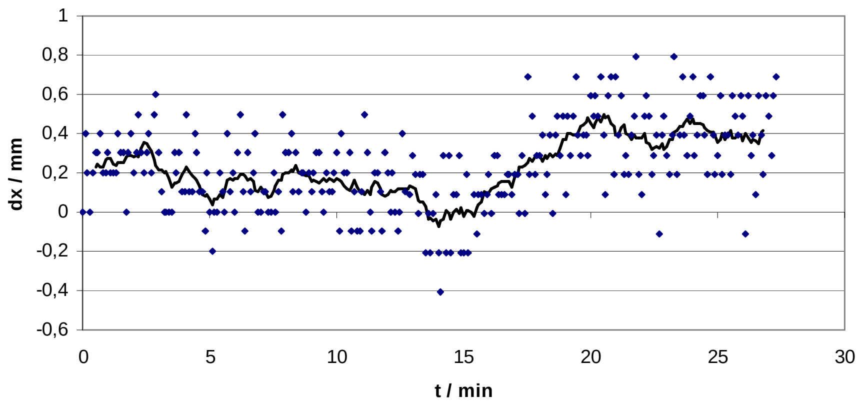


Fig. 3. Stability of results over tens of minutes time interval.

Stability in the timescale of days and months

The measurements were performed in three series of measurements over an interval of a few days. The cycle of measurements was repeated twice within a few months. The first three measuring series were carried out in February 2011, then in August 2011 and the last one in September 2012.

In the figure below, the standard deviations of individual measurements of distance are shown with error bars. The dashed lines represent minimum and maximum values of individual measurements in the series of measurements.

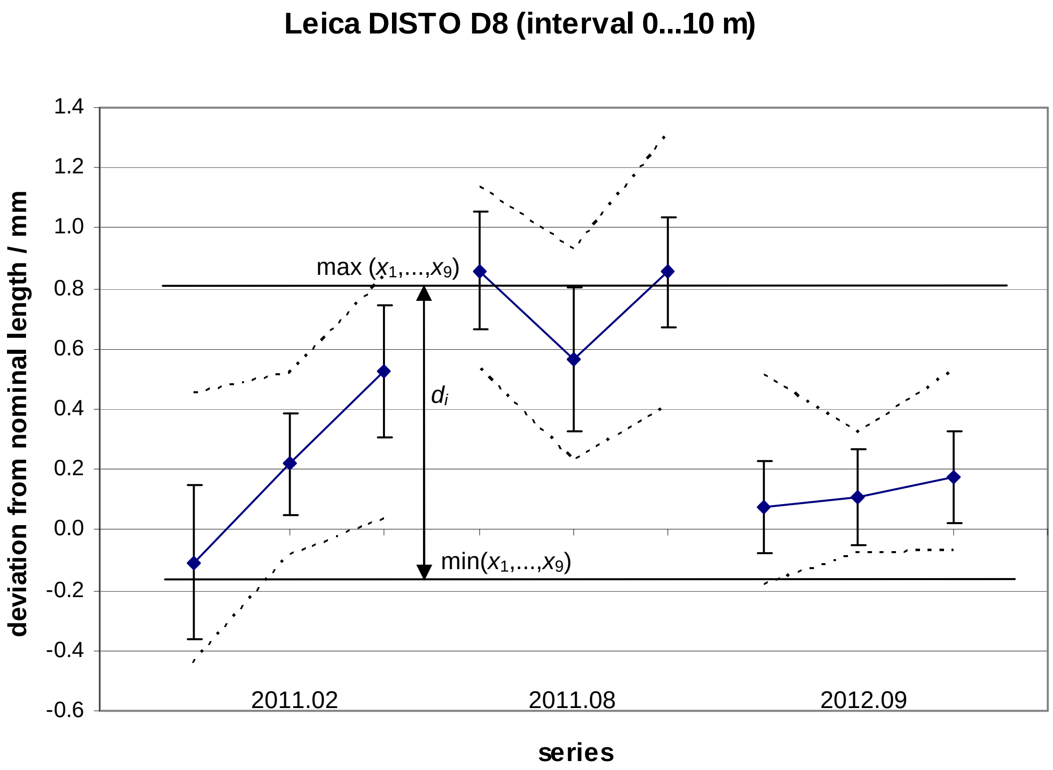


Fig. 4. Results of all series of measurements for Leica DISTO D8 for a distance of 10 m.

Having analyzed the graph, one can see that the maximum and minimum values in each series performed at an interval of several months do not overlap. The mean value in one of the series is not even in a range limited by minimum and maximum for the other series.

Such a large differences between the average values appear over a time scale longer than few days. This means that the laboratory couldn't observe this variability when briefly examining the instrument.

In the figure below, probability density of all results from all measurement series was presented.

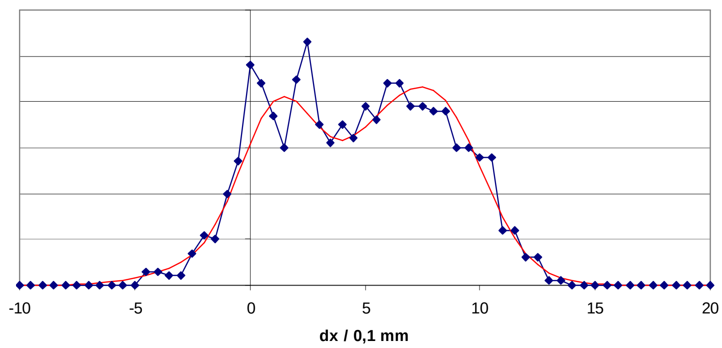


Fig. 5. Distribution of all results from all measurement series.

Continuous red curve represents the sum of the theoretical normal distributions for each series of measurements. Theoretical curve is consistent with the observed distribution.

Estimation of uncertainty of artifact

The reproducibility of EDM is affected by random changes of mean values in time scale of days. To determine d_i for a given EDM and a given distance, the results from all nine series of measurements $(x_1,...,x_9)$ were used,

$$d_i = \max(x_1,...,x_9) - \min(x_1,...,x_9)$$

where i is an index of measurement distance.

Set of eleven d_i was determined for each EDM. The figure below presents those results.

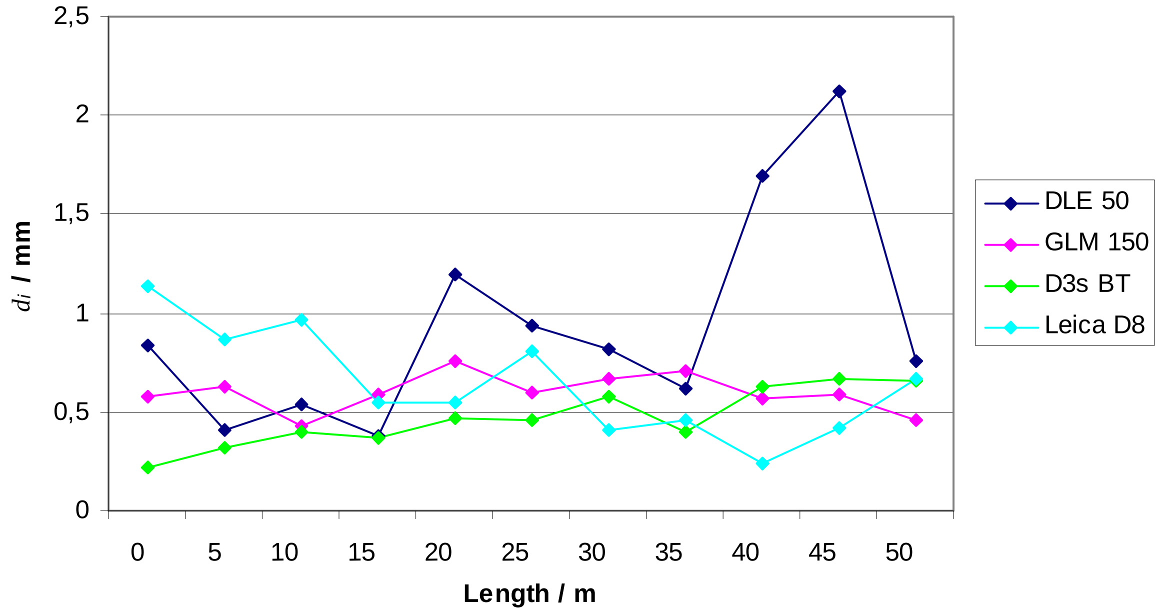


Fig. 6. d_i values for all distances for each EDM.

The value of d_i varies widely. This is especially noticeable in Bosh DLE 50 where for the neighboring distances, the d_i values can differ by several times. Each EDM is characterized by a different trend.

The model assumes that long-term stability is characterized by rectangular distribution with domain described by maximal d_i and expected value estimated based on all of the measurements. Dispersion of individual measurements (short-term stability) is described by normal distribution.

The max value of d_i was used to estimate uncertainty $u(d_{art})$ related to random changes of EDM results. In order to disentangle $u(d_{art})$, one should try to subtract the observed short term stability from $\max(d_i)$ and influences of the different alignments like zero point u_{zero}, cosine error u_{cos} and parallelism u_{paral} [3]

$$u^2(d_{art}) = \left(\frac{\max(d_i)}{2\sqrt{3}}\right)^2 - u_{zero}^2 - u_{\cos}^2 - u_{paral}^2$$

In the case of Leica DISTO D8, we obtain $\max(d_i)$ = 1,133 which corresponds to $u(d_{art})$ = 0,324 mm.

Table below contains values of $u(d_{art})$ estimated for all the four EDMs.

Table 6. Values of $u(d_{art})$ for all the four EDMs.

EDM	$u(d_{art})$ (mm)
Bosch DLE 50	0,308
Bosch GLM 150	0,197
Leica DISTO D3a BT	0,149
Leica DISTO D8	0,324

Additional stability test of EDMs

The suspected main factors responsible for the change of EDMs indications are:

1) Effects of electronics – resulting from unstable operation of the EDM.
2) Effects of mechanics – impact of transport of the EDM between laboratories.
3) Effects of geometry – alignment repeatability of the EDM during measurements.

Two additional experiments were conducted in order to determine which factors have the greatest impact on the results. Leica DISTO D3a BT was used for these tests.

a) Static test

During the measurements the EDM was immobilized on a bench. Measurements were made at a distance of 10 m in a controlled environment. The measurement results are presented in the figure below.

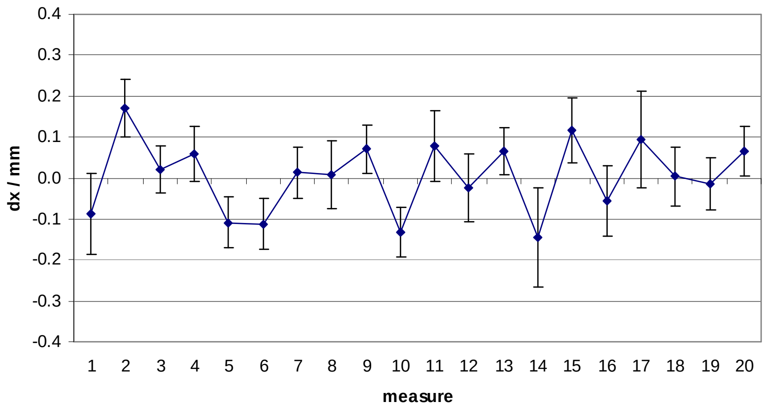


Fig. 7. Static stability test results.

Each point represents the mean value of 15-20 measurements. This test covers about 6 hours of EDM work. The standard deviation is s = 0,09 mm.

b) Dynamic test

Measurements were made at a distance of 10 m in a controlled environment. After each series of measurements the EDM was removed from the bench, shaken and squeezed. The aim was to simulate the conditions during transportation. This test covers about 6 hours of EDM work. Measurement results are presented in the figure below.

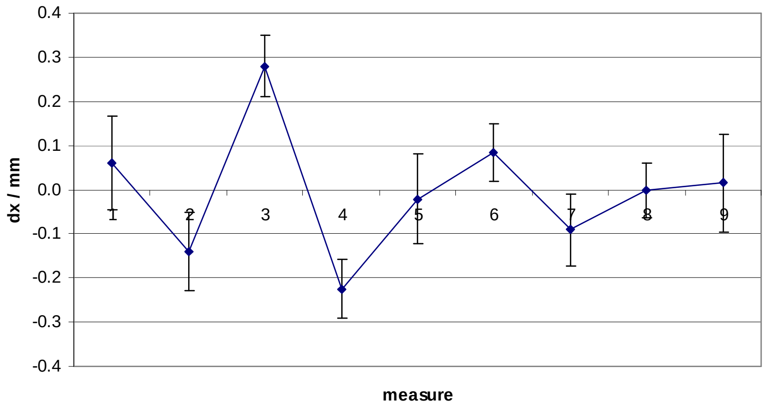


Fig. 8. Dynamic stability test results.

The standard deviation for this test is s = 0,15 mm and is greater than in the static test.

The average standard deviation of three measurement series was estimated using the data from the comparison. The value s = 0,09 mm is similar to the result in the static test.

The estimated uncertainty associated with the artifact for this EDM is u_{art} = 0,15 mm (see table above). The same value u = 0,15 mm was estimated from the stability test in the scale of tens of minutes. Both values are close to the value of standard deviation for the dynamic test.

These results may lead to the conclusion that the level of the effects of electronics, mechanics and geometry have a similar impact on the long-term stability. Due to this fact, it is difficult to identify which of these factors has the greatest impact on the observed measurement results.

9 Reference values

The standard approach is to use weighted mean for determining the reference value x_{ref} [1,2]. This is calculated by the mean of all measurement values x_i weighted by the inverse square of the standard uncertainties $u(x_i)$ associated with the measurements and using these values, the largest consistent subset of the sample is determined. However, checking the consistency of the sample without taking into account the uncertainty associated with the artifact, leads to erroneous recognition of the consistent subset. We propose to add u_{art} to the uncertainty of each laboratory at the beginning of the calculation.

$$u_c^2(x_i) = u^2(d_{art}) + u^2(x_i)$$

Thereby, the uncertainty associated with the artifact will be taken into account during the consistency check.

$$x_{ref} = \frac{\sum_{i=1}^{n} \frac{x_i}{u_c^2(x_i)}}{\sum_{i=1}^{n} \frac{1}{u_c^2(x_i)}} .$$

The pilot laboratory contributed only by its first measurements to the reference values. The weighted mean approach requires the individual uncertainties from the laboratories to be estimated according to a common approach (as they should be, since all participants were requested to estimate the uncertainties according to the *ISO Guide*). The standard uncertainty $u(x_{ref})$ of the reference value is calculated by combining the individual uncertainties:

$$u^2(x_{ref}) = \frac{1}{\sum_{i=1}^{n} \frac{1}{u_c^2(x_i)}} .$$

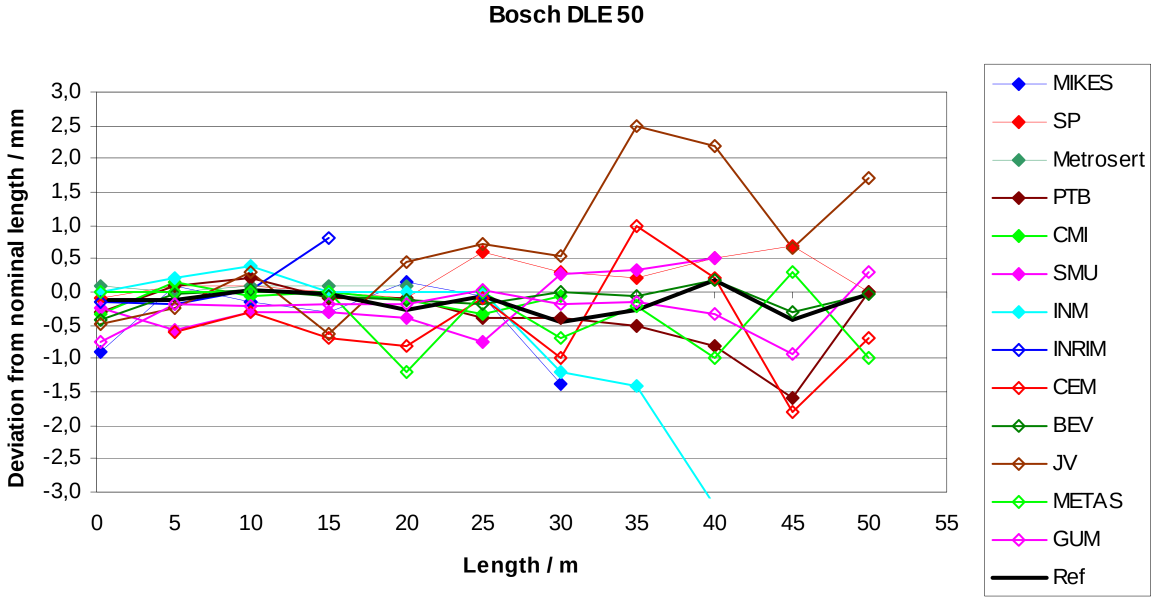
The χ^2 test was applied in order to estimate x_{ref} from the largest consistent subset [1].

Table 7. Reference values and associated standard uncertainties based on weighted mean.

Distance	Bosch DLE 50		Bosch GLM 150		Leica DISTO D3a BT		Leica DISTO D8	
mm	x_{ref}	$u(x_{ref})$	x_{ref}	$u(x_{ref})$	x_{ref}	$u(x_{ref})$	x_{ref}	$u(x_{ref})$
300	299,694	0,138	300,475	0,084	300,353	0,071	300,177	0,113
5000	4999,900	0,139	4999,774	0,090	5000,020	0,074	4999,659	0,111
10000	10000,041	0,146	9999,776	0,096	10000,285	0,077	10000,336	0,114
15000	14999,945	0,154	14999,781	0,120	15000,176	0,080	15000,258	0,117
20000	19999,804	0,175	19999,423	0,124	20000,112	0,086	20000,581	0,118
25000	24999,955	0,186	24999,526	0,128	25000,321	0,094	25000,754	0,124
30000	29999,586	0,193	29999,956	0,138	30000,140	0,103	30000,675	0,129
35000	34999,779	0,235	35000,051	0,156	35000,022	0,119	35000,844	0,153
40000	40000,185	0,279	40000,250	0,159	40000,476	0,132	40001,167	0,151
45000	44999,576	0,315	45000,208	0,165	45000,391	0,155	45000,974	0,156
50000	49999,983	0,324	50000,344	0,169	50000,319	0,156	50001,137	0,157

10 Deviations from reference values

The following figures show results from NMIs for all of the distances. Reference value is represented by a bold black line.



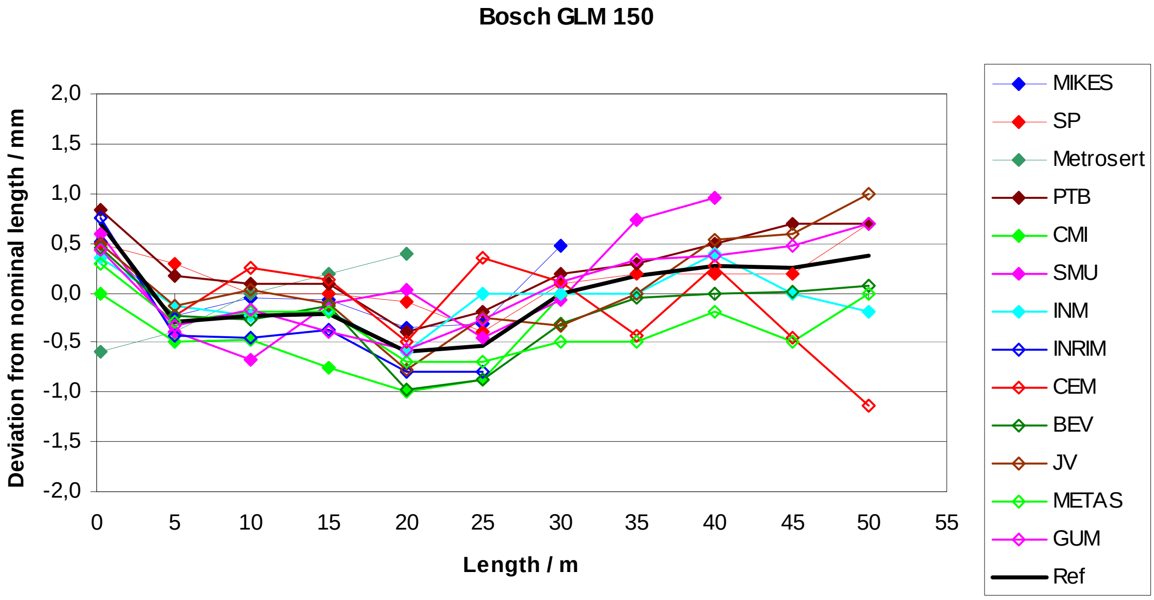
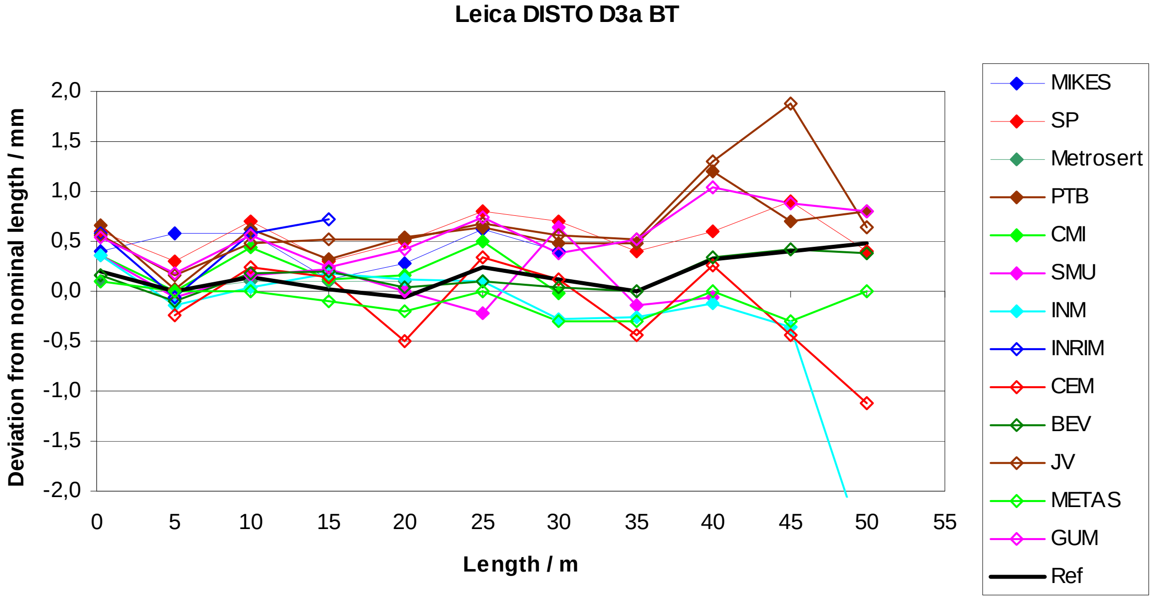


Fig. 9. Deviations from reference values.



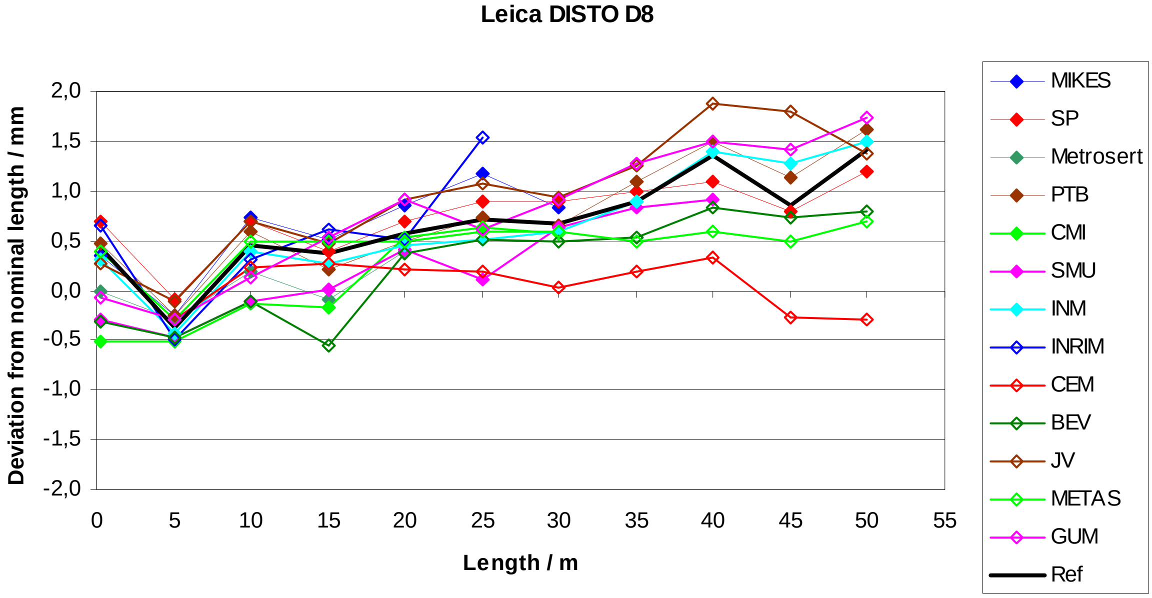


Fig. 9. Deviations from reference values (continued).

The deviations D_i from reference value x_{ref} are calculated by

$$D_i = x_i - x_{\text{ref}} .$$

For calculating the expanded uncertainty of these deviations $U(D_i)$, the corresponding uncertainties $u(x_i)$ and $u(x_{\text{ref}})$ cannot simply be geometrically added, because the values x_i and x_{ref} are correlated. Due to the random changes described in section 6, uncertainty $u(d_{\text{art}})$ was added [2]. It can be shown, that the expanded uncertainty $U(D_i)$ is given by

$$U(D_i) = 1{,}96\sqrt{u^2(x_i) - u^2(x_{\text{ref}}) + u^2(d_{\text{art}})}$$

when x_i belongs to the largest consistent subset and

$$U(D_i) = 1{,}96\sqrt{u^2(x_i) + u^2(x_{\text{ref}}) + u^2(d_{\text{art}})}$$

otherwise. The deviations from the reference values are given in various figures and tables below. The uncertainty bars in the figures correspond to the expanded uncertainties $U(D_i)$ (k = 1,96).

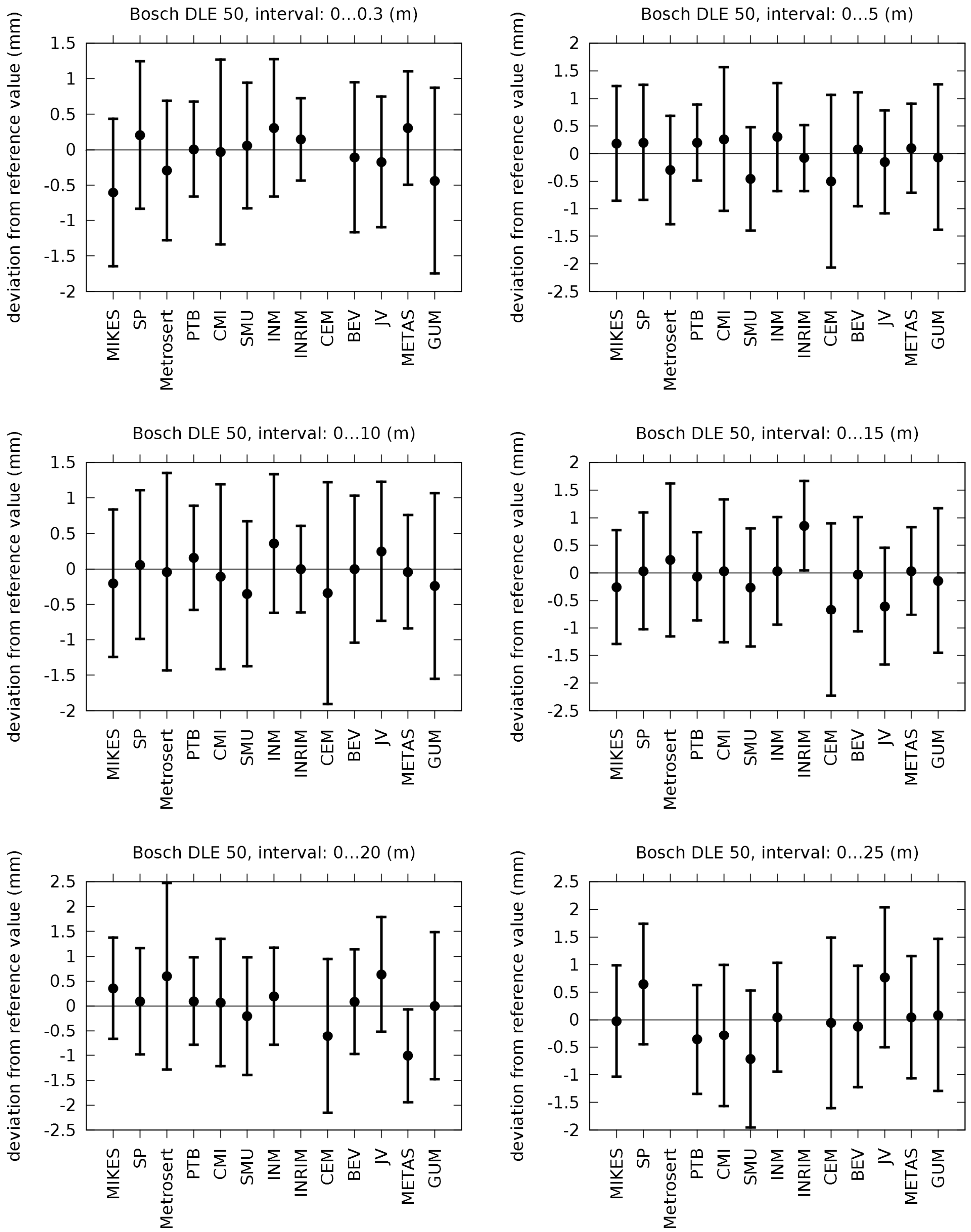


Fig. 10. Deviations from reference values.

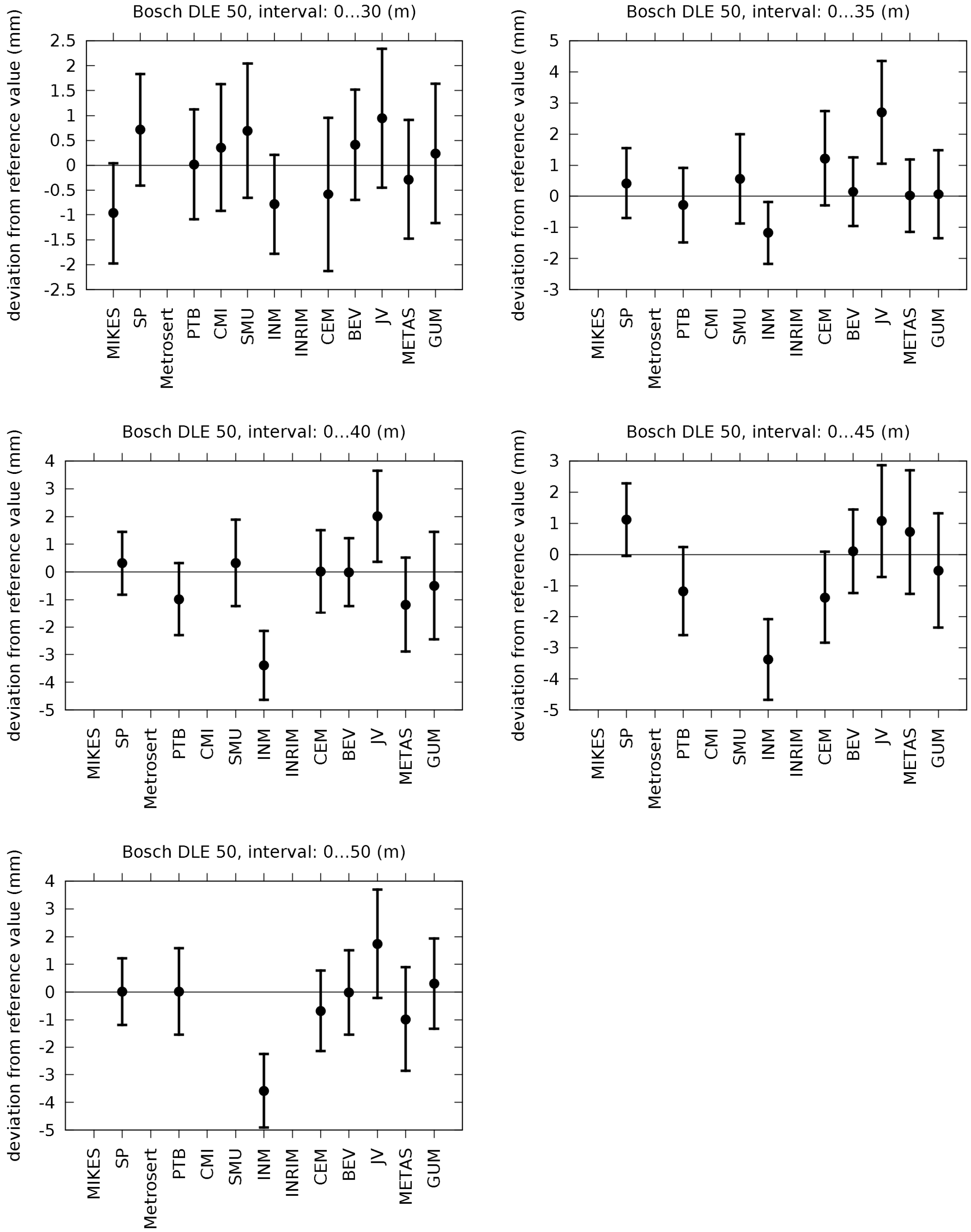


Fig. 10. Deviations from reference values (continued).

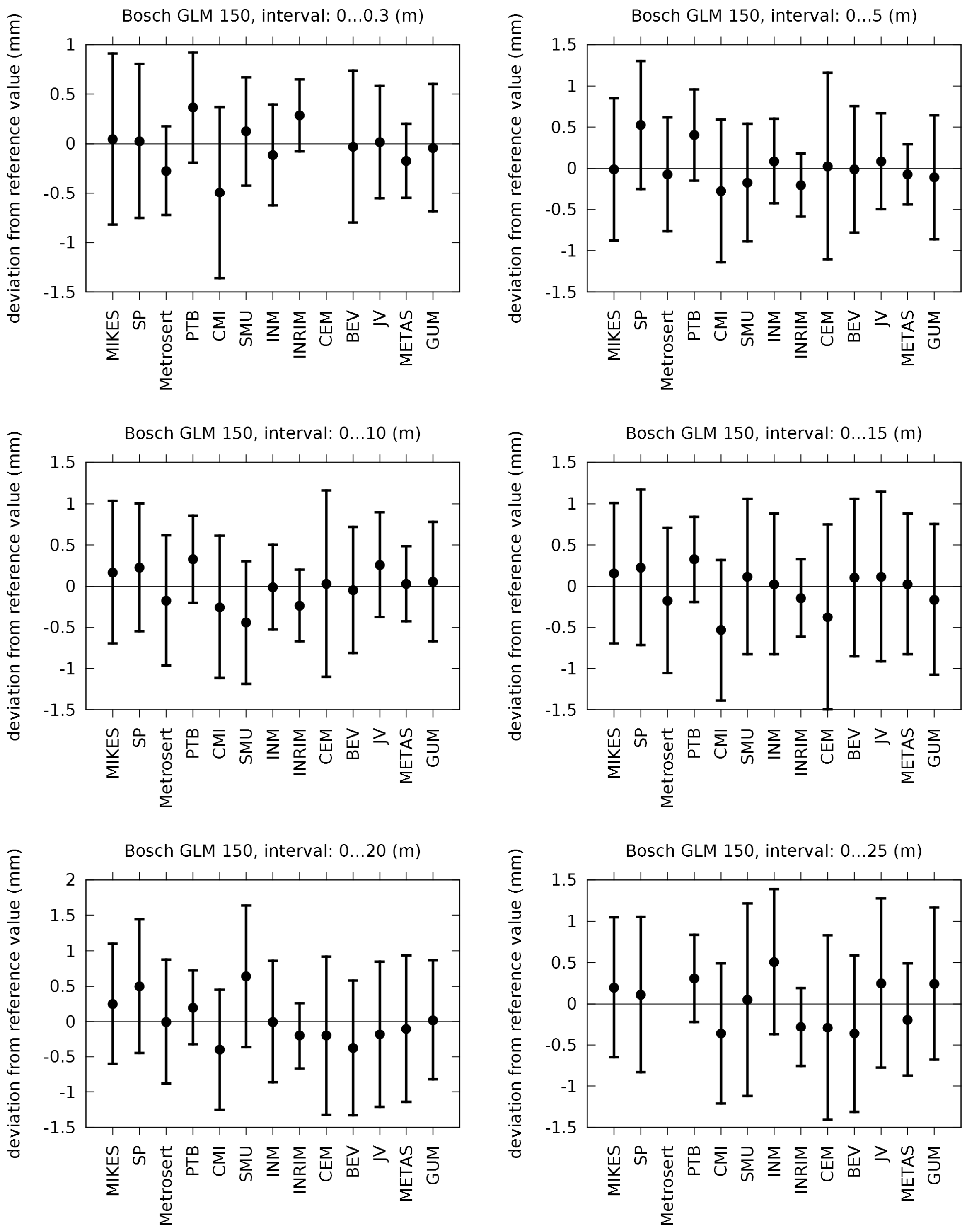


Fig. 10. Deviations from reference values (continued).

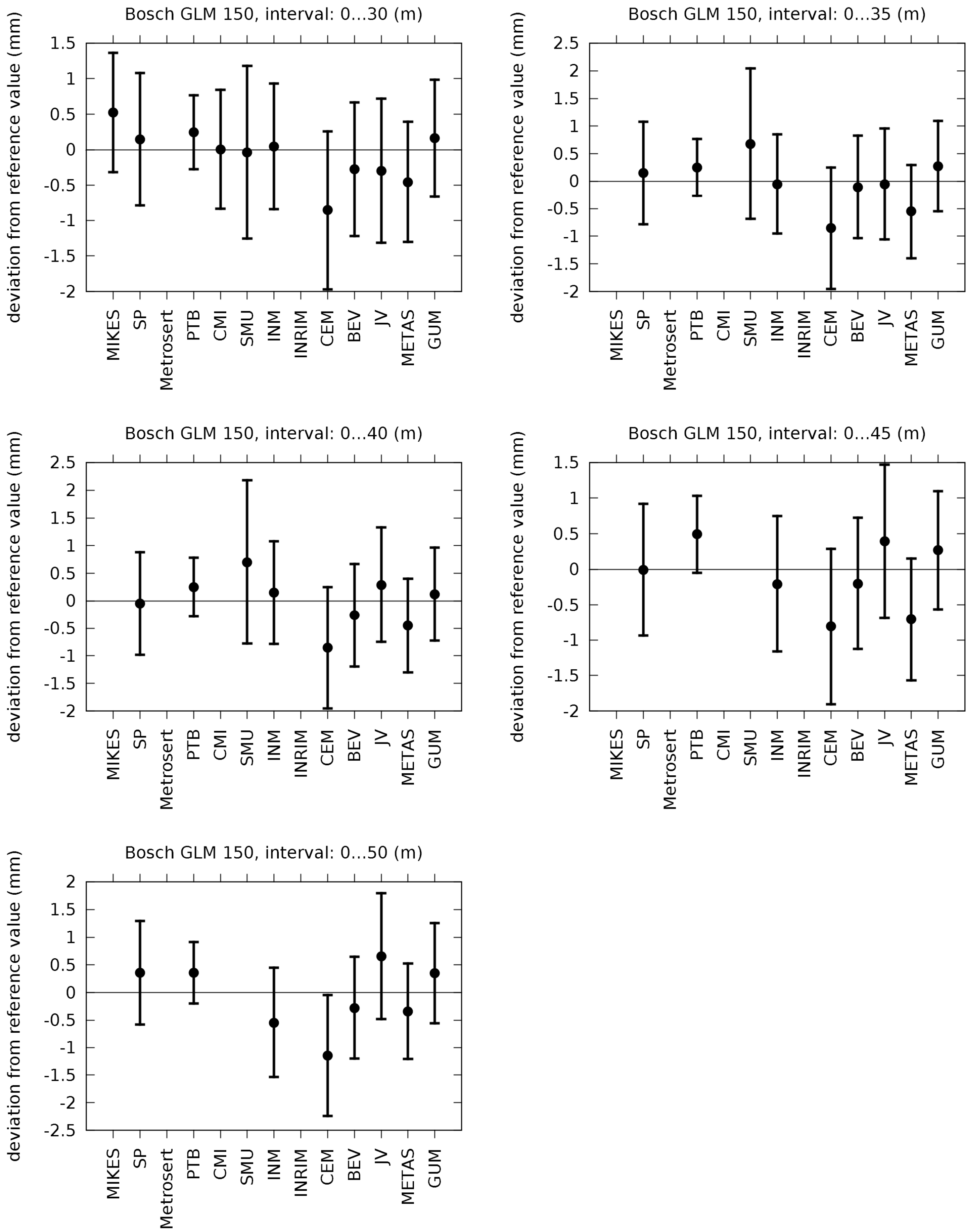


Fig. 10. Deviations from reference values (continued).

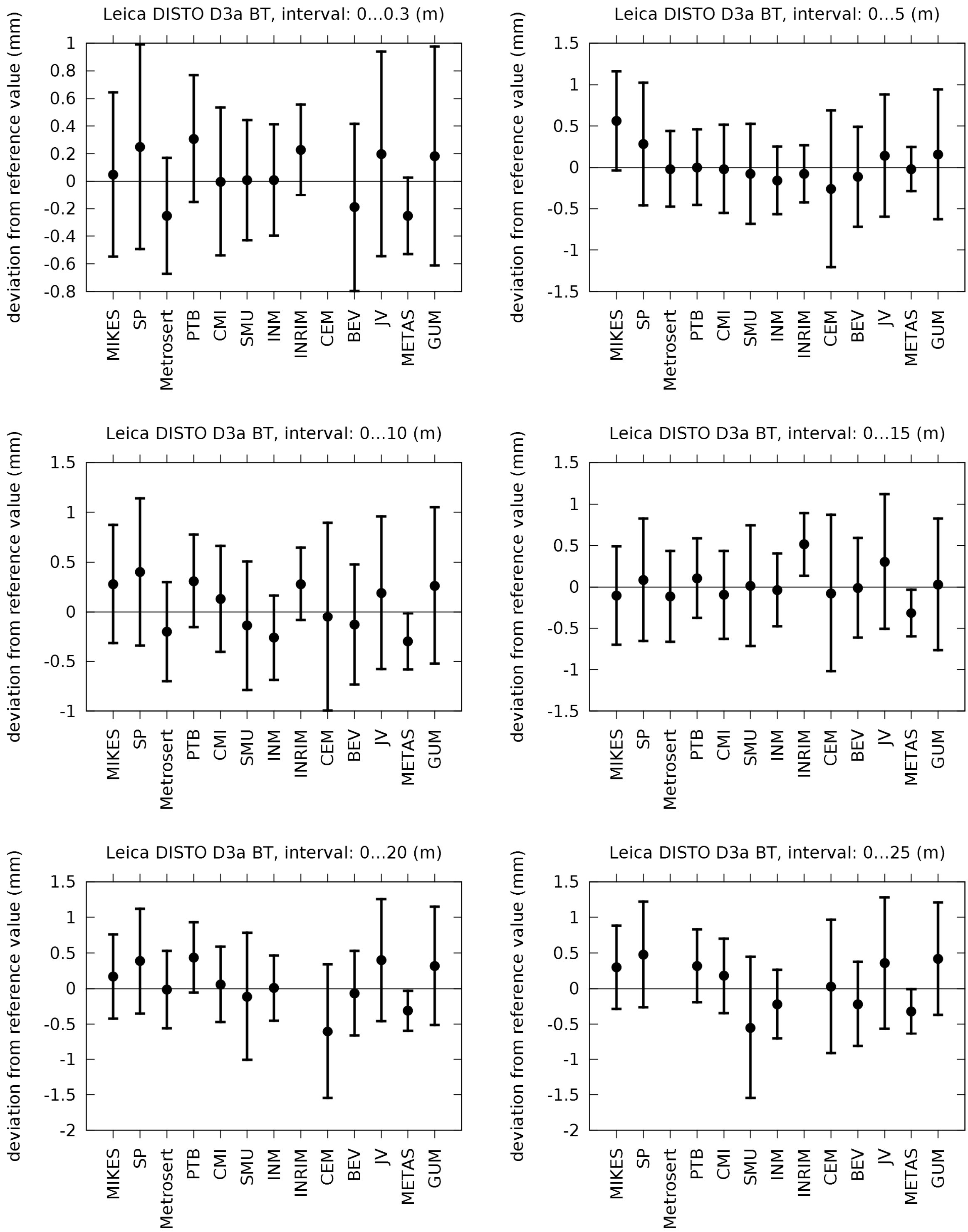


Fig. 10. Deviations from reference values (continued).

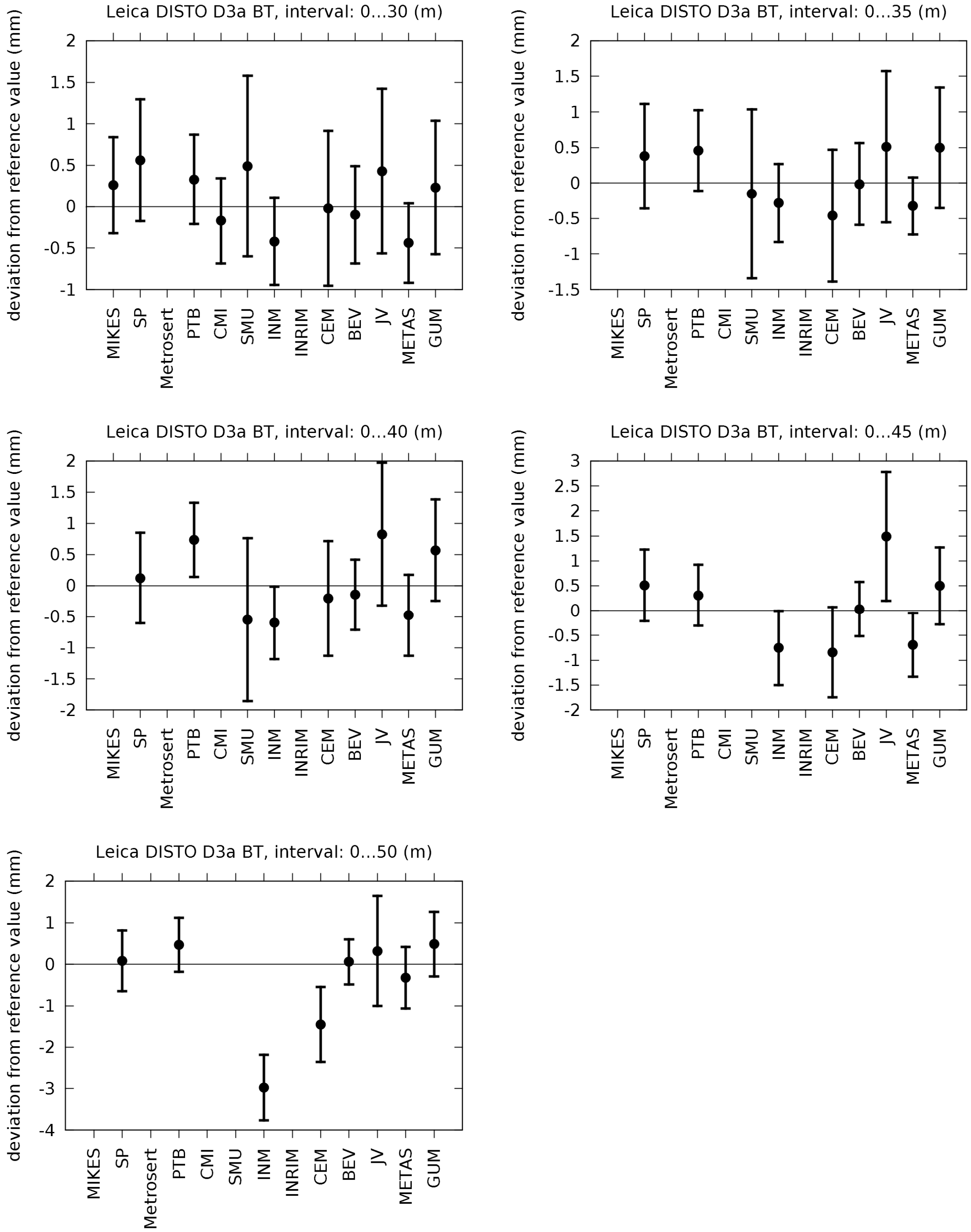


Fig. 10. Deviations from reference values (continued).

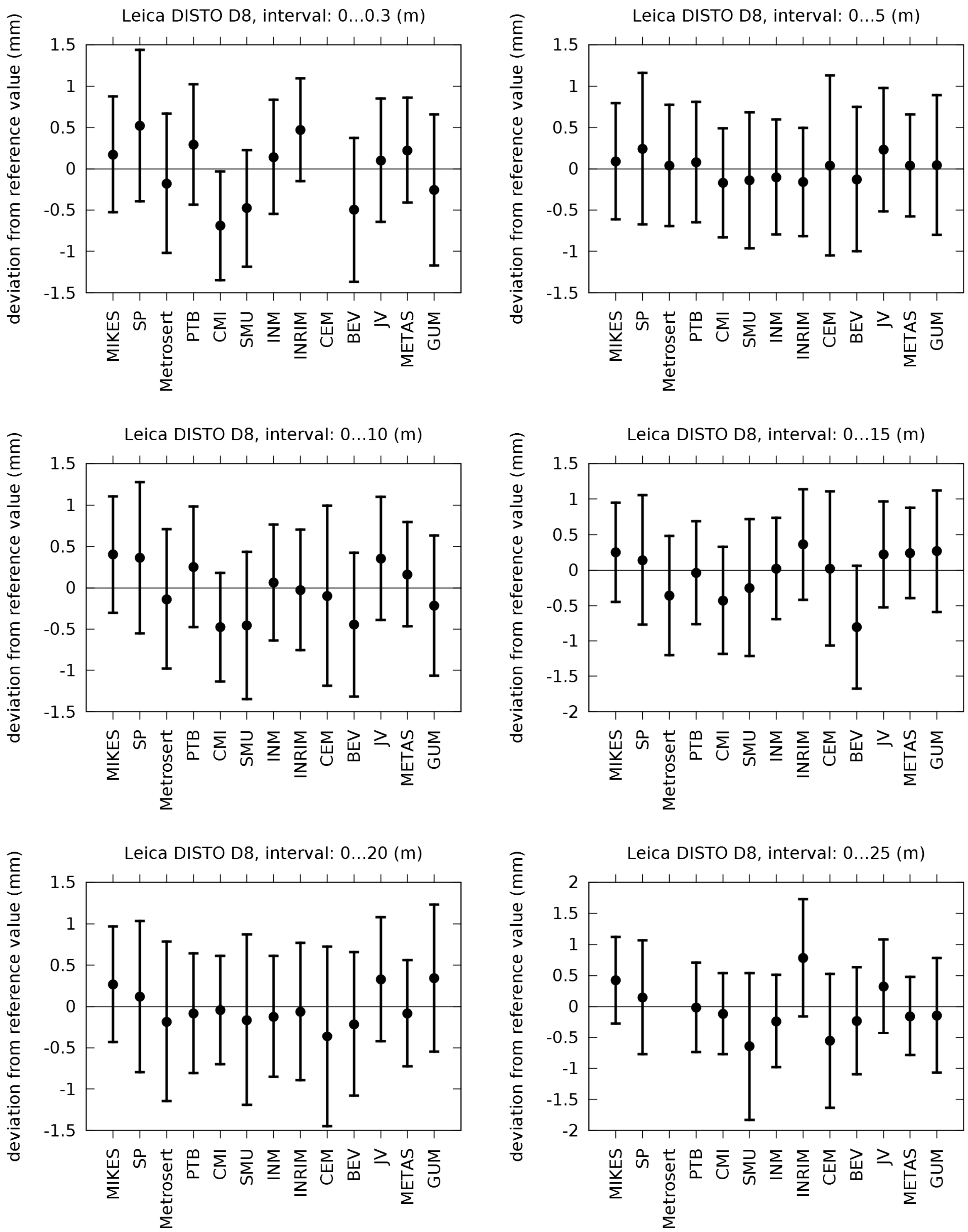


Fig. 10. Deviations from reference values (continued).

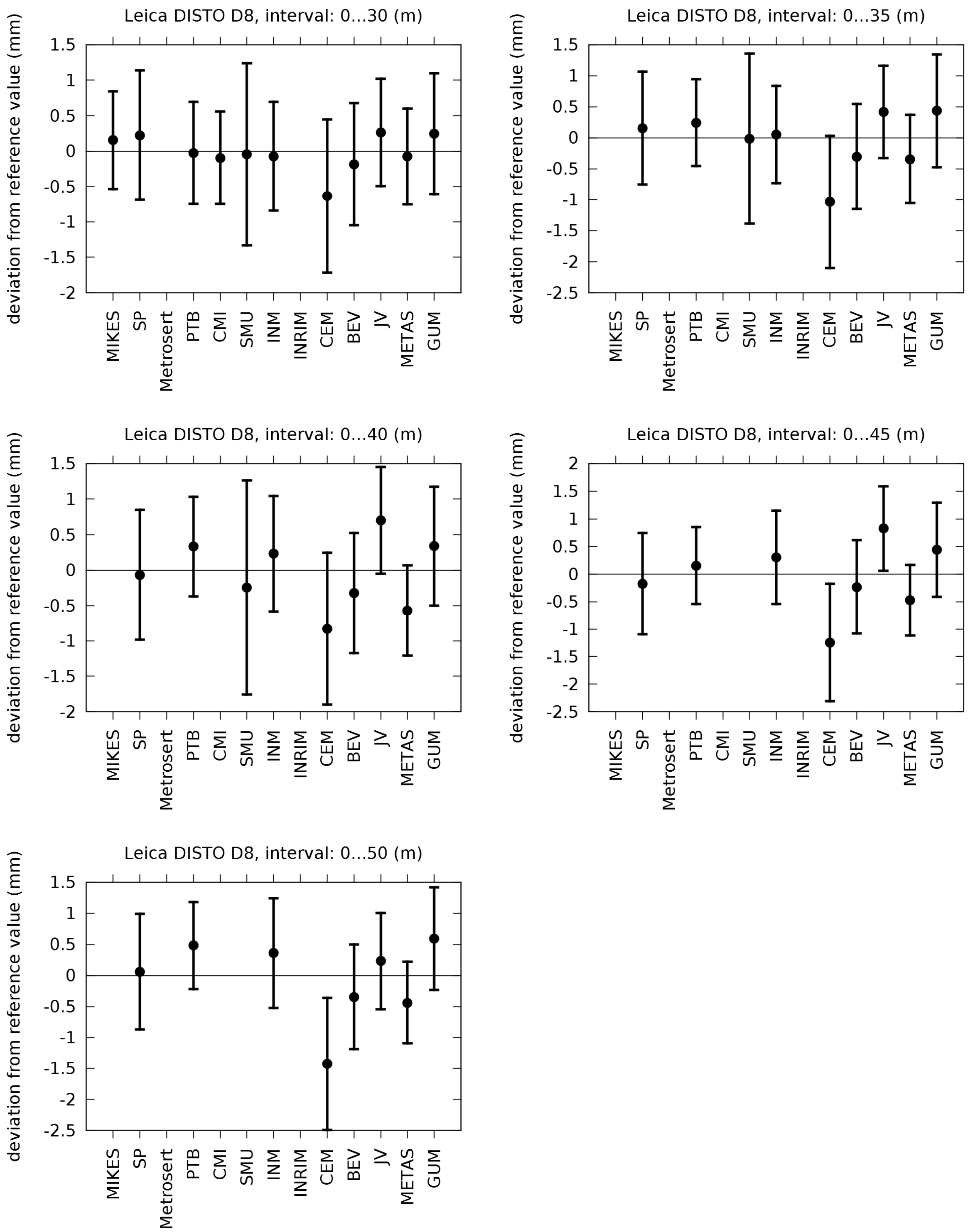


Fig. 10. Deviations from reference values (continued).

BOSCH DLE 50

NMI	Country	300 mm		5000 mm		10000 mm		15000 mm		20000 mm		25000 mm		30000 mm		35000 mm		40000 mm		45000 mm		50000 mm	
		D (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)
MIKES	FI	-0,78	1,49	0,20	1,49	-0,18	1,48	-0,25	1,48	0,42	1,47	-0,02	1,46	-0,94	1,46								
SP	SE	0,03	1,49	0,22	1,49	0,08	1,49	0,04	1,49	0,16	1,51	0,65	1,52	0,74	1,54	0,46	1,55	0,31	1,55	1,11	1,57	0,02	1,60
Metrosert	EE	0,33	1,23	-0,18	1,33	-0,42	1,38	-0,36	1,44	-0,34	1,43												
PTB	DE	-0,17	1,26	0,22	1,26	0,18	1,29	-0,06	1,32	0,16	1,37	-0,35	1,44	0,04	1,53	-0,24	1,60	-0,99	1,68	-1,19	1,78	0,02	1,89
GUM	PL	-0,62	1,69	-0,05	1,69	-0,22	1,68	-0,14	1,68	0,07	1,82	0,09	1,73	0,26	1,75	0,10	1,77	-0,50	2,22	-0,53	2,12	0,31	1,94
CMI	CZ	-0,21	1,68	0,28	1,68	-0,09	1,68	0,04	1,67	0,13	1,66	-0,28	1,66	0,38	1,65								
SMU	SK	-0,12	1,38	-0,44	1,41	-0,33	1,47	-0,26	1,50	-0,14	1,59	-0,71	1,63	0,72	1,71	0,60	1,79	0,32	1,89				
INM	RO	0,13	1,44	0,32	1,44	0,38	1,44	0,04	1,44	0,26	1,44	0,05	1,44	-0,76	1,45	-1,14	1,45	-3,39	1,60	-3,39	1,64	-3,58	1,67
INRIM	IT	-0,03	1,21	-0,06	1,21	0,02	1,22	0,86	1,33														
CEM	ES			-0,48	1,89	-0,32	1,89	-0,66	1,88	-0,54	1,88	-0,05	1,87	-0,56	1,87	1,26	1,85	0,01	1,83	-1,39	1,81	-0,68	1,80
BEV	AT	-0,29	1,50	0,09	1,48	0,01	1,48	-0,02	1,48	0,15	1,49	-0,12	1,52	0,44	1,53	0,18	1,53	-0,01	1,62	0,10	1,71	-0,02	1,86
JV	NO	-0,35	1,41	-0,13	1,41	0,27	1,44	-0,60	1,49	0,70	1,56	0,77	1,65	0,97	1,75	2,74	1,94	2,00	1,96	1,06	2,08	1,74	2,22
METAS	CH	0,13	1,33	0,12	1,33	-0,02	1,33	0,04	1,32	-0,94	1,41	0,05	1,53	-0,26	1,59	0,06	1,58	-1,19	2,01	0,71	2,24	-0,98	2,16

Table 8. Deviations from the reference value (given at the top of the table) and expanded uncertainties (k=1,96) of such deviations for BOSCH DLE 50.

BOSCH GLM 150

NMI	Country	300 mm		5000 mm		10000 mm		15000 mm		20000 mm		25000 mm		30000 mm		35000 mm		40000 mm		45000 mm		50000 mm	
		D (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)
MIKES	FI	-0,18	0,90	0,05	0,90	0,18	0,89	0,13	0,88	0,25	0,88	0,22	0,88	0,50	0,87								
SP	SE	-0,20	0,81	0,59	0,81	0,24	0,81	0,20	0,97	0,50	0,97	0,13	0,97	0,12	0,96	0,03	0,96	-0,07	0,96	-0,05	0,96	0,33	0,96
Metrosert	EE	-1,30	0,93	-0,11	0,92	0,24	1,35	0,40	1,34	1,00	1,85												
PTB	DE	0,14	0,60	0,47	0,60	0,34	0,57	0,30	0,56	0,20	0,57	0,33	0,58	0,22	0,57	0,13	0,57	0,23	0,58	0,45	0,59	0,33	0,61
GUM	PL	-0,27	0,69	-0,04	0,79	0,06	0,76	-0,18	0,94	0,02	0,87	0,26	0,95	0,13	0,85	0,15	0,86	0,10	0,88	0,23	0,87	0,32	0,94
CMI	CZ	-0,72	0,90	-0,21	0,90	-0,24	0,89	-0,56	0,88	-0,40	0,88	-0,34	0,88	-0,02	0,87								
SMU	SK	-0,10	0,60	-0,11	0,76	-0,43	0,78	0,09	0,97	0,64	1,03	0,07	1,19	-0,06	1,24	0,56	1,38	0,68	1,50				
INM	RO	-0,34	0,56	0,15	0,57	0,00	0,57	0,00	0,88	0,00	0,89	0,53	0,91	0,02	0,92	-0,17	0,94	0,13	0,96	-0,25	0,99	-0,57	1,02
INRIM	IT	0,06	0,43	-0,14	0,46	-0,22	0,49	-0,17	0,52	-0,20	0,52	-0,26	0,53										
CEM	ES			0,09	1,16	0,04	1,15	-0,40	1,15	-0,20	1,14	-0,27	1,14	-0,88	1,14	0,63	1,13	-0,87	1,13	-0,85	1,13	-1,17	1,12
BEV	AT	-0,25	0,81	0,05	0,80	-0,04	0,80	0,08	0,98	-0,37	0,98	-0,35	0,98	-0,30	0,97	-0,23	0,96	-0,28	0,96	-0,24	0,96	-0,31	0,95
JV	NO	-0,21	0,62	0,15	0,63	0,27	0,68	0,09	1,05	-0,18	1,05	0,27	1,05	-0,32	1,04	-0,17	1,04	0,27	1,06	0,35	1,11	0,63	1,16
METAS	CH	-0,40	0,46	-0,01	0,44	0,04	0,51	0,00	0,88	-0,10	1,06	-0,17	0,72	-0,48	0,88	-0,67	0,88	-0,47	0,89	-0,75	0,89	-0,37	0,90

Table 9. Deviations from the reference value (given at the top of the table) and expanded uncertainties (k=1,96) of such deviations for BOSCH GLM 150.

Leica DISTO D3a BT

NMI	Country	300 mm		5000 mm		10000 mm		15000 mm		20000 mm		25000 mm		30000 mm		35000 mm		40000 mm		45000 mm		50000 mm	
		D (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)
MIKES	FI	0,20	0,65	0,58	0,66	0,45	0,65	0,08	0,65	0,34	0,65	0,38	0,64	0,28	0,63								
SP	SE	0,40	0,79	0,30	0,79	0,57	0,79	0,27	0,79	0,56	0,78	0,56	0,79	0,58	0,78	0,41	0,78	0,28	0,77	0,51	0,77	-0,08	0,77
Metrosert	EE	-0,10	0,50	0,00	0,54	-0,03	0,57	0,07	0,61	0,16	0,61												
PTB	DE	0,46	0,53	0,02	0,54	0,48	0,54	0,29	0,55	0,61	0,59	0,40	0,58	0,35	0,60	0,49	0,63	0,89	0,74	0,31	0,67	0,31	0,70
GUM	PL	0,34	0,84	0,17	0,83	0,43	0,83	0,22	0,84	0,49	0,87	0,50	0,83	0,25	0,85	0,52	0,89	0,72	0,85	0,49	0,82	0,32	0,82
CMI	CZ	0,15	0,60	0,00	0,60	0,30	0,60	0,09	0,60	0,23	0,59	0,26	0,59	-0,15	0,58								
SMU	SK	0,16	0,51	-0,06	0,66	0,03	0,70	0,20	0,78	0,06	0,94	-0,47	1,03	0,51	1,12	-0,12	1,22	-0,39	1,33				
INM	RO	0,16	0,48	-0,14	0,49	-0,09	0,50	0,15	0,51	0,18	0,53	-0,14	0,56	-0,40	0,59	-0,25	0,61	-0,44	0,63	-0,75	0,78	-3,14	0,82
INRIM	IT	0,38	0,44	-0,06	0,44	0,45	0,47	0,70	0,49														
CEM	ES			-0,24	0,99	0,12	0,98	0,11	0,98	-0,43	0,98	0,11	0,98	0,00	0,97	-0,43	0,97	-0,05	0,95	-0,84	0,95	-1,61	1,03
BEV	AT	-0,04	0,66	-0,10	0,66	0,04	0,66	0,18	0,66	0,10	0,66	-0,14	0,65	-0,08	0,64	0,02	0,64	0,01	0,61	0,03	0,61	-0,10	0,60
JV	NO	0,35	0,79	0,16	0,79	0,36	0,81	0,49	0,86	0,57	0,90	0,44	0,96	0,45	1,03	0,54	1,10	0,98	1,17	1,49	1,31	0,16	1,34
METAS	CH	-0,10	0,38	0,00	0,38	-0,13	0,39	-0,13	0,39	-0,14	0,39	-0,24	0,41	-0,42	0,55	-0,29	0,48	-0,32	0,69	-0,69	0,70	-0,48	0,78

Table 10. Deviations from the reference value (given at the top of the table) and expanded uncertainties (k=1,96) of such deviations for Leica DISTO D3a BT.

Leica DISTO D8

NMI	Country	300 mm		5000 mm		10000 mm		15000 mm		20000 mm		25000 mm		30000 mm		35000 mm		40000 mm		45000 mm		50000 mm	
		D (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)	*D* (mm)	*U* (mm)
MIKES	FI	-0,08	0,73	0,11	0,74	0,30	0,73	0,15	0,73	0,28	0,73	0,47	0,73	0,16	0,73								
SP	SE	0,27	0,94	0,26	0,94	0,26	0,94	0,04	0,94	0,13	0,94	0,19	0,94	0,23	0,94	0,11	0,94	-0,26	0,94	-0,06	0,95	-0,22	0,95
Metrosert	EE	-0,43	0,87	0,06	0,77	-0,24	0,87	-0,46	0,87	-0,17	0,99												
PTB	DE	0,04	0,76	0,10	0,76	0,15	0,76	-0,14	0,76	-0,07	0,76	0,03	0,76	-0,02	0,75	0,20	0,74	0,14	0,74	0,27	0,74	0,20	0,73
GUM	PL	-0,51	0,94	0,07	0,87	-0,32	0,87	0,16	0,88	0,35	0,92	-0,10	0,95	0,25	0,88	0,39	0,94	0,14	0,87	0,55	0,89	0,31	0,85
CMI	CZ	-0,94	0,71	-0,15	0,70	-0,58	0,71	-0,53	0,79	-0,03	0,69	-0,07	0,69	-0,09	0,69								
SMU	SK	-0,73	0,75	-0,12	0,85	-0,56	0,92	-0,35	0,99	-0,15	1,05	-0,60	1,21	-0,04	1,31	-0,06	1,40	-0,44	1,53				
INM	RO	-0,11	0,72	-0,08	0,73	-0,04	0,73	-0,08	0,75	-0,11	0,76	-0,19	0,78	-0,07	0,80	0,01	0,82	0,04	0,84	0,42	0,88	0,08	0,91
INRIM	IT	0,22	0,66	-0,14	0,67	-0,13	0,71	0,26	0,69	-0,05	0,70	0,83	0,79										
CEM	ES			0,06	1,11	-0,20	1,11	-0,08	1,11	-0,35	1,11	-0,51	1,11	-0,63	1,11	-0,70	1,10	-1,02	1,09	-1,13	1,13	-1,71	1,14
BEV	AT	-0,75	0,90	-0,10	0,90	-0,55	0,90	-0,91	0,90	-0,20	0,90	-0,19	0,89	-0,18	0,89	-0,35	0,88	-0,52	0,88	-0,12	0,88	-0,63	0,87
JV	NO	-0,15	0,78	0,25	0,78	0,25	0,77	0,12	0,77	0,34	0,78	0,37	0,78	0,27	0,79	0,37	0,78	0,51	0,78	0,94	0,85	-0,05	0,80
METAS	CH	-0,03	0,67	0,06	0,65	0,06	0,67	0,14	0,67	-0,07	0,68	-0,11	0,67	-0,07	0,71	-0,39	0,75	-0,76	0,74	-0,36	0,69	-0,72	0,77

Table 11. Deviations from the reference value (given at the top of the table) and expanded uncertainties (k=1,96) of such deviations for Leica DISTO D8.

11 E_n Tables

Results with $E_n > 1$ are marked with red color in Tables below. E_n values are calculated by $D_i / U(D_i)$ with D_i and $U(D_i)$ as given on page 19.

Table 12. BOSCH DLE50

Lab.	Distance (mm)										
	300	5000	10000	15000	20000	25000	30000	35000	40000	45000	50000
MIKES	-0,58	0,17	-0,19	-0,23	0,35	-0,02	-0,96				
SP	0,20	0,19	0,06	0,05	0,09	0,59	0,64	0,37	0,28	0,97	0,01
Metrosert	-0,30	-0,31	-0,03	0,18	0,32						
PTB	0,01	0,29	0,22	-0,06	0,11	-0,36	0,01	-0,23	-0,75	-0,83	0,01
GUM	-0,33	-0,05	-0,18	-0,09	0,00	0,06	0,17	0,05	-0,26	-0,28	0,19
CMI	-0,03	0,20	-0,09	0,04	0,05	-0,22	0,28				
SMU	0,06	-0,49	-0,34	-0,23	-0,17	-0,57	0,51	0,39	0,21		
INM	0,32	0,31	0,37	0,06	0,20	0,05	-0,79	-1,19	-2,72	-2,60	-2,69
INRIM	0,25	-0,13	0,00	0,96							
CEM		-0,32	-0,22	-0,41	-0,39	-0,04	-0,38	0,80	0,01	-0,94	-0,47
BEV	-0,10	0,07	0,00	-0,01	0,08	-0,11	0,37	0,13	-0,01	0,08	-0,01
JV	-0,19	-0,16	0,25	-0,55	0,55	0,60	0,68	1,63	1,22	0,60	0,89
METAS	0,38	0,12	-0,05	0,07	-1,07	0,04	-0,24	0,02	-0,70	0,37	-0,52

Table 13. BOSCH GLM150

Lab	Distance (mm)										
	300	5000	10000	15000	20000	25000	30000	35000	40000	45000	50000
MIKES	0,05	-0,02	0,19	0,18	0,27	0,19	0,62				
SP	0,03	0,68	0,29	0,23	0,51	0,08	0,15	0,16	-0,05	-0,01	0,38
Metrosert	-0,61	-0,11	-0,22	-0,21	-0,03						
PTB	0,66	0,74	0,62	0,62	0,34	0,53	0,47	0,48	0,47	0,91	0,64
GUM	-0,07	-0,14	0,07	-0,18	0,00	0,23	0,20	0,33	0,14	0,32	0,38
CMI	-0,57	-0,32	-0,30	-0,64	-0,50	-0,47	0,00				
SMU	0,23	-0,24	-0,60	0,12	0,62	0,01	-0,03	0,50	0,47		
INM	-0,22	0,17	-0,03	0,02	-0,03	0,54	0,05	-0,06	0,16	-0,22	-0,55
INRIM	0,79	-0,52	-0,50	-0,26	-0,34	-0,42					
CEM		0,02	0,02	-0,34	-0,20	-0,29	-0,77	-0,77	-0,77	-0,74	-1,04
BEV	-0,04	-0,02	-0,07	0,10	-0,42	-0,42	-0,29	-0,11	-0,28	-0,22	-0,30
JV	0,03	0,15	0,40	0,11	-0,20	0,21	-0,29	-0,05	0,28	0,36	0,58
METAS	-0,47	-0,20	0,05	0,02	-0,12	-0,33	-0,54	-0,65	-0,53	-0,82	-0,40

Table 14. Leica DISTO D3a BT

Lab	Distance (mm)										
	300	5000	10000	15000	20000	25000	30000	35000	40000	45000	50000
MIKES	0,08	0,94	0,50	-0,11	0,28	0,51	0,45				
SP	0,33	0,38	0,56	0,17	0,53	0,65	0,76	0,51	0,17	0,71	0,11
Metrosert	-0,60	-0,04	-0,37	-0,14	-0,02						
PTB	0,67	0,00	0,70	0,30	0,89	0,62	0,61	0,81	1,24	0,50	0,72
GUM	0,23	0,19	0,35	0,08	0,38	0,53	0,29	0,58	0,70	0,64	0,63
CMI	-0,01	-0,04	0,27	-0,11	0,11	0,34	-0,33				
SMU	0,02	-0,13	-0,19	0,07	-0,13	-0,55	0,45	-0,13	-0,42		
INM	0,02	-0,39	-0,58	0,01	0,02	-0,45	-0,80	-0,51	-1,02	-1,01	-3,78
INRIM	0,70	-0,20	0,63	1,01							
CEM		-0,28	-0,04	-0,04	-0,64	0,03	-0,02	-0,50	-0,22	-0,93	-1,60
BEV	-0,32	-0,19	-0,19	0,04	-0,11	-0,37	-0,17	-0,02	-0,25	0,05	0,12
JV	0,27	0,19	0,27	0,42	0,46	0,39	0,43	0,48	0,72	1,15	0,24
METAS	-0,91	-0,08	-1,02	-0,98	-1,11	-1,03	-0,92	-0,80	-0,73	-1,08	-0,43

Table 15. Leica DISTO D8

Lab	Distance (mm)										
	300	5000	10000	15000	20000	25000	30000	35000	40000	45000	50000
MIKES	0,25	0,13	0,58	0,36	0,38	0,61	0,22				
SP	0,57	0,26	0,40	0,16	0,13	0,16	0,25	0,17	-0,07	-0,19	0,07
Metrosert	-0,21	0,06	-0,16	-0,43	-0,19						
PTB	0,40	0,11	0,35	-0,05	-0,11	-0,02	-0,04	0,35	0,47	0,22	0,69
GUM	-0,28	0,05	-0,25	0,31	0,39	-0,15	0,29	0,48	0,41	0,52	0,72
CMI	-1,04	-0,26	-0,72	-0,57	-0,06	-0,17	-0,15				
SMU	-0,67	-0,17	-0,51	-0,26	-0,16	-0,54	-0,04	-0,01	-0,16		
INM	0,21	-0,14	0,09	0,03	-0,17	-0,31	-0,10	0,07	0,29	0,36	0,41
INRIM	0,76	-0,24	-0,04	0,47	-0,07	0,83					
CEM		0,04	-0,09	0,02	-0,33	-0,51	-0,59	-0,97	-0,77	-1,16	-1,34
BEV	-0,57	-0,14	-0,51	-0,93	-0,24	-0,27	-0,21	-0,36	-0,38	-0,28	-0,41
JV	0,14	0,31	0,47	0,30	0,44	0,43	0,35	0,56	0,93	1,08	0,30
METAS	0,35	0,07	0,26	0,38	-0,13	-0,24	-0,11	-0,48	-0,89	-0,74	-0,66

12 Conclusions

It was the first comparison of EDMs. For most of the laboratories, it was an important opportunity to validate their measurement instrumentation and procedure. It allowed to become aware of potential problems and to take corrective actions in changing the procedure.

For the evaluation of the reference value, the weighted mean approach has been chosen, although the consistency check according to procedure A of Ref. [1] failed in many cases. A more complicated procedure for the evaluation of the reference value was proposed which slightly changes the uncertainty of the reference value.

In total, there were 23 E_n values larger than 1. This represents 4.7 % of the full set of 482 results. It is less than the 5 % of possible values being out of the expanded uncertainty of the reference value for k=2.

The uncertainty of the results mainly comes from the uncertainty of the reproducibility. It is difficult to distinguish between Lab's calibration and measurement capability.

The comparison shows a global compliance with declared CMCs, independently of whether some participant can have a high percentage of values not compliant with its CMC due to the influence of the artifact and the estimation of its uncertainty.

13 References

[1] M. G. Cox, The evaluation of key comparison data, *Metrologia* 39, 589 – 595 (2002)

[2] R. Thalmann. EUROMET 677 – Steel Tape Measures, *Final report* (2004)

[3] F. Pollinger, personal communication

Appendix 1: Description of the measurement equipment as reported by the laboratories

A1.1. MIKES, Finland

Short description of measurement bench

MIKES interferometric bench is situated in an underground laboratory with air temperature and humidity control. Typically air temperature is 20 ± 0.1 °C and humidity 45 ± 2 % RH. The linear guide, on the top of the concrete beam, comprises two parallel round shafts with adjustable fixtures every 1 m. A carriage with ball bush bearings is moved along the rail and location of it is measured with reference interferometer HP-5529A. Temperature of air is measured with 6 pt100 sensors and Keithley 2010 multimetre with 4-wire resistance mode. Air pressure and humidity are measured with Vaisala PTU200. Updated Edlén equation by Bönsch & Potulski is used for calculation of refractive index of air.

For EDM calibration on the other end, than laser interferometer, is a fixed reference plate which is adjusted perpendicular to the laser beam. Next to the reference plate is an adjustable base for EDM instrument with which it can be adjusted to point parallel and coincident with measurement arm of the interferometer. A target plate, adjusted perpendicular to laser beam, is fixed to the carriage. The calibration followed Abbe principle with some millimetre uncertainty in offset adjustment.

First, reference interferometer is set to zero when the target plate and reference plate are in contact, then EDM is positioned and adjusted in its base. The rear surface of the EDM is also slightly pressed against reference surface behind it. Then the readings from both instruments are collected at selected locations. For this calibration there is no fine adjustment of the target position so there are typically deviations of up to few millimetres from nominal locations. Results are averages of 3-4 measurements.

Additional remarks

The CMC entry, MIKES has for EDM calibrations, is based on calibration of length scales of high quality total stations and laser trackers. This type of EDMs used in this comparison are not accurate enough for truly testing of MIKES calibration measurement capability.

A1.2. SP, Sweden

Short description of measurement bench

The bench consists of a simple aluminium U−shaped profile with polished steel pins acting as supports for the tape. The bench is a little over 50 m long, and works as support for the reference tape and the calibrated EDMs simultaneously.

Length measurement instrument

Comparison with reference steel tape.

Temperature measurement system, number and location of sensors

The tape temperature is continuously registered in 6 points equally distributed along the bench. The air temperature is monitored during the measurements, but not used for corrections.

Additional remarks

The EDM support is placed approximately 2 cm vertically above the tape. No visual aid is used.

A1.3. AS Metrosert, Estonia

Short description of measurement bench

The 21-m bench is located in the designated corridor-like laboratory room. The lab is air-conditioned and the stability of temperature is typically ±0,5 ºC. There are three humidity and temperature sensors in room for stability and gradient monitoring.

Two stainless steel rails running in parallel are made of 3-m long rods. The rails lay without fixed attachment on metal supports which are mounted on concrete base. The base rests on pillars made of bricks.

Length measurement instrument

Laser-interferometer system Renishaw ML10 was used as length measurement instrument.

Laser interferometer gets temperature, humidity and pressure data from it’s own measurement system EC10.

Additional remarks

Due to the length of the bench, only measurements up to 20 m could be made. Five measurement series were made with each EDM.

A1.4. PTB, Germany

Short description of measurement bench:

The measurements were performed on the 50 m geodetic base of the PTB. The comparator consists of a 50 m rail. The laboratory is equipped with a network of 21 temperature sensors, spaced by 2.5 m along the bench. As depicted in fig. 1, the EDM is mounted at one end of the comparator, the reflector is fixed vertically on the carriage. A large retroreflector is mounted approximately 150 mm below the EDM reflector on the carriage, reflecting the beam of the reference interferometer. The deviation of the length due to tilting carriage (Abbe error) has been investigated along the bench by comparison of two interferometers. It remains smaller than 100 µm. The distance of the first position of 300 mm with respect to the back side of the EDM is determined by a gauge block of 300 mm length and a thickness of 10 mm. This procedure is depicted for one of the comparison standards in figure 2.

For the calibration the desired positions are programmed. After the carriage reaches a measurement position, the operator waits for another 30 s for the carriage to settle. In control experiments the remaining movement between positioning and measurement remained smaller than 2 µm. The operator then activates the measurement of the EDM, reads the indicated position and writes it down. The procedure is repeated for twelve times at every position, the mean of the 12 measurements represents the “indicated distance by the EDM”. All measurements of a single run at one position are performed within approximately one minute. The complete measurement was repeated for four times.


Length measurement instrument:

The reference length is determined by a frequency-calibrated laser interferometer (Agilent 5519A). The reference interferometer is set up in Michelson geometry, the signals being digitalised by a Heidenhain IK 121 card. The index of refraction is determined by the external weather station of the geodetic base consisting of 21 Pt-100 temperature sensors, spaced 2.5 m along the bench, two humidity sensors (Testo 650) and two pressure sensors (Setra 370 and DPI 141). The environmental parameters are used to determine the index of refraction for the reference measurement, deploying the modification of the Edlén equation by Bönsch and Potulski.

A1.5. CMI, Czech Republic

Description of measurement bench

The EDMs were measured on 30 m long measuring bench equipped by laser interferometer (LI) Renishaw ML10 (pic. 1 and 2), calibrated traceable to national standard of length and quantities of environmental sensors. The target plate and retroreflector of the LI were fixed on a moving part of the bench and each EDM was fixed in horizontal position by clamps (pic. 3). LI and EDM are placed on opposite ends of bench, the Abbe offset was <10 mm for some of them and <50mm for all. The value of LI was reset (to zero) at position corresponding to the rear of the EDM (using 3D measuring arm FARO Quantum, with uncertainty about 27µm). The perpendicularities of the EDM stop as well as target plate to the beam were also checked by FARO). Each EDM was 3x replaced and aligned, the measurement (reading) was repeated 6 times for each alignment and position, the mean value of these 3x6 measurements is stated in tables with results. The uncertainty claimed covers the statistical uncertainty of single readings. Only in case of Leica D8 (the best performing EDM in this comparison) we state also the uncertainty corresponding to the mean of 6 readings in last column (this uncertainty is smaller and better illustrates our CMC).

Length measurement instrument

- Laser interferometer Renishaw.
- Laser 633 nm Type ML10.
- Compensator EC10.
- 3D measuring arm FARO Quantum.
- 3D measuring arm FARO Quantum.


A1.6. SMU, Slovakia

Short description of measurement bench

No bench is available at the SMU, the measurements are being carried out in the underground corridor of the laboratory building with length of 42,8 m.

The 50 m steel measuring tape KINEX was used as the reference, laid on the floor and pulled by the force 50 N (the same force as had been applied during its calibration at the SMU). The calibration of reference tape was done at the SMU, using ULM3m Zeiss with laser interferometer Agilent 5529 B (i.e. per 3 m parts).

Three mercury thermometers with the resolution of 0.1 °C were used along the measurement path, each of them laid onto the tape and located at 6.67 m, 19.90 m (instead of 20 m, because of this was one of measuring points) and 33.3 m respectively. Each of them thus corresponded approximately to one third of the measured steel tape section.

Regarding the 0.3 m measuring point, the ULM3m Zeiss length measuring machine was used, with the 300 mm gauge block as the reference.

Length measurement instrument

We used our own target plate, being fixed perpendicularly (within uncertainty stated) to the construction equipped with nonius and the camera holder, transported manually along the steel tape. The second construction was fixed to the tape by such a way that zero line of the tape corresponded to the rear of EDM (within uncertainty stated).

The position of the target is read on the monitor and 20 repeated readings of the EDM data took place in each measuring point (multiples of 5 m up to 40 m).

Concerning 0.3 m, the 300 mm gauge block was fit between the target plate and the construction with EDM. The distance of the EDM rear from the target plate corresponded to the length of gauge block (within uncertainty stated).

Additional remarks

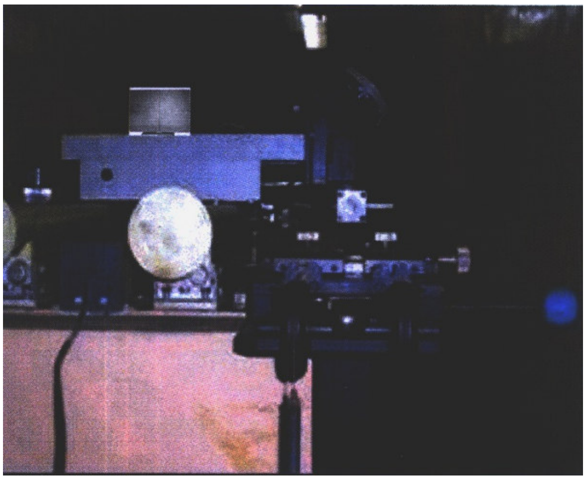
The identical measurement method was used, as we use to do within our calibration service, although the results reporting is different – we provide the regression line, calculated from the measurement of irregularly distributed points and corresponding uncertainty (k = 2) in the form of [a, bL] mm (i.e. the same coefficients for each length in the range (0 – 42) m).

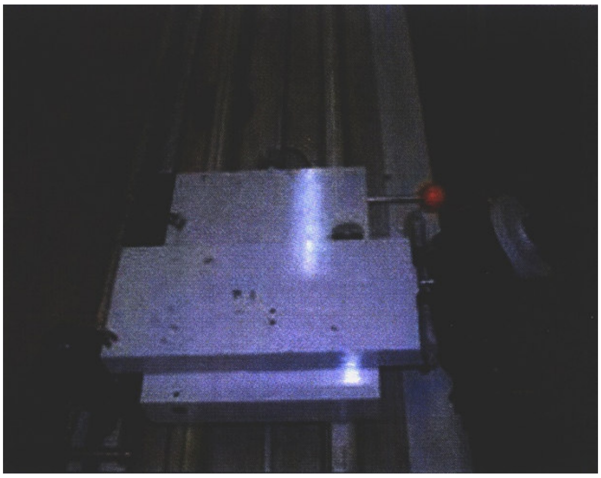
SMU hasn’t got this category in CMC tables.

A1.7. INM, Romania

Short description of measurement bench

Geodesic base located in the basement of the laboratory, with nominal length equal to 50 m, having a mobile carriage thet support both laser He-Ne retroreflector and the target of the laser distance measuring instrument; in the front of geodesic base exists a support where are aligned both laser interferometer and the laser distance measuring instruments.





Length measurement instrument

Laser interferometer type Hewlett Packard, model 5526 A, with nominal length equal to 50 m, resolution 0,001 mm,

U = 0.2 µm +0,5·10^{-6}L.

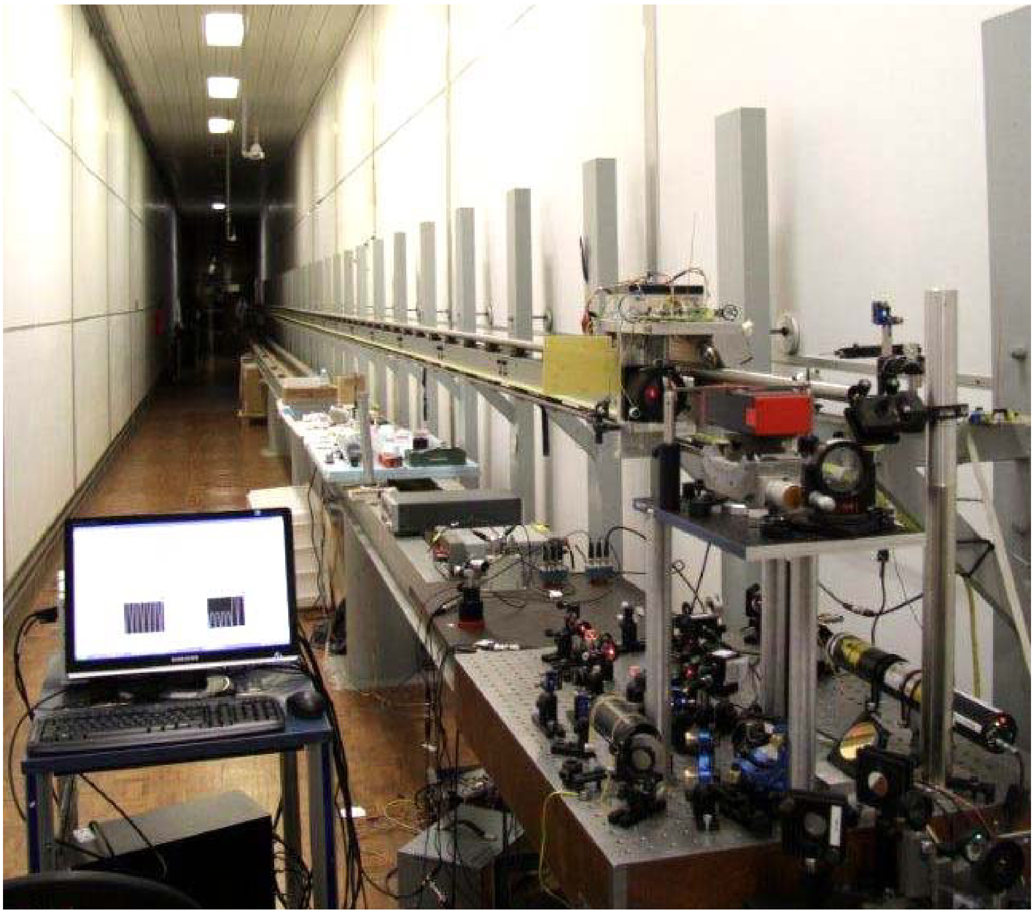
Additional remarks

During the measurements the maximum gradient of temperature was equal to 0,5 °C.

A1.8. INRIM, Italy

Short description of measurement bench

The facility for long distance measurements is located in a corridor of the gallery devoted to dimensional metrology. The structure consists in a 28 m long rail fixed to a series of pillars which rest directly on the ground released from the vibrations of floor and wall. The measuring system is based on a heterodyne interferometer, whose mobile arm consists of a hollow retro-reflector mounted on a structure that can run along the rail, so-called "carriage". A photograph of the facility is presented in Fig.1



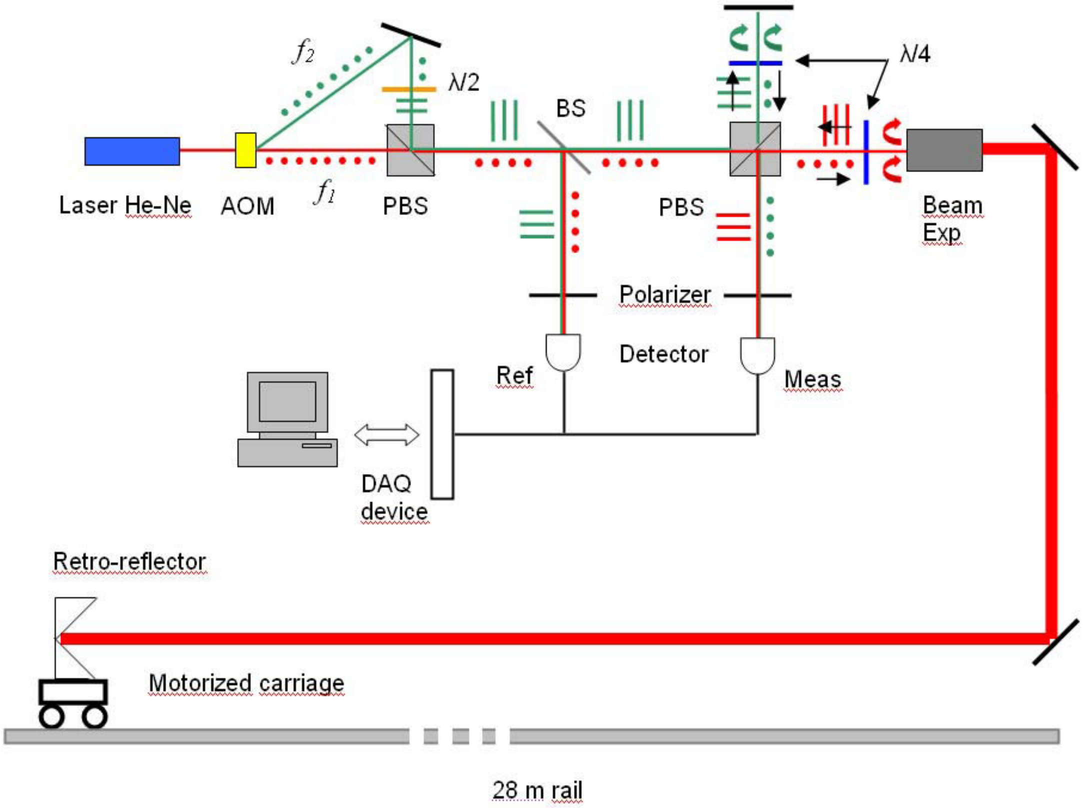
The carriage is moved by a micro-step motor: the motor driver receives a digital pulse and converts it into an electrical pulse to run the motor. Each pulse causes a rotation of the motor shaft of one step, which amounts to 1/1000 of a complete revolution of the shaft. If the pulse frequency increases, the rotation becomes continuous, with a speed that is directly proportional to the pulse frequency. The speed ranges between few µm/s up to 2,7 m/s with a resolution of 0,3 µm/s.

Since the carriage must move back and forth automatically for a distance of almost 30 m, a remote control to send pulses to the motor driver was implemented. It consists of two parts: a radio command, which allows to set some general parameters of the carriage movement, such as the movement direction and mode of travel (slow or fast), and a fast command, which is performed by an amplitude modulated laser beam placed at the beginning of the track oriented towards the carriage. A photo detector placed above the carriage receives the modulated laser beam which is transformed into pulses to be sent to the driver of the motor. The modulation of the laser beam is implemented by a LabView program that controls a digital output of the data acquisition device.

Length measurement instrument

The length measurement instrument is based on a heterodyne incremental interferometer. The main beam of the interferometer with frequency f_1 is generated by a frequency stabilized

He-Ne laser calibrated with respect to the INRIM length standard and sent to the measurement arm; the second beam is a portion of the first one diffracted by an acousto-optic modulator (AOM) with frequency $f_2 = f_1 + 80$ MHz. The reference detector acquires the beat note signal at 80 MHz, while the measurement detector acquires a signal at 80 MHz, whose phase is varied due to the displacement of the retro-reflector moving on the rail. In figure 2 the optical design of the interferometer is presented.



Two different measuring techniques have been implemented:

1. the "phase measuring" technique, based on fringes counting, with a relative uncertainty of $5\cdot10^{-7}$ but limited at the maximum carriage speed of 3 cm/s;
2. the "Doppler frequency measurement" technique, for higher carriage speed, based on the measurement of the Doppler frequency shift while the carriage runs.

The second technique was validated by means of the comparison with the first technique at low speed with an agreement of the order of $3\cdot10^{-6}$: hence, the Doppler frequency method could be considered validated within 0,1 mm over the whole rail path with the advantage of reducing the time needed to cover long distances, so it was used for the EDM comparison.

In order to obtain the distance covered by the carriage, according to technique 2, the Doppler frequency is measured by a commercial high-performance counter (a Pendulum CNT-90) without dead time based on time stamping, then it is converted in speed and integrated over time, according to the following formula:

$$d = \frac{1}{2}\int (f'-f)\frac{\lambda}{n_{air}}dt = \frac{1}{2n_{air}}(f'-f)\lambda t$$

where d is the distance covered by the carriage, f is the frequency of the measuring signal with the carriage at rest, f' the frequency of the measuring signal with the carriage moving, λ_i is the wavelength of the laser in vacuum, n - air is the air refractive index and t_i is the integration time. The difference $f'-f$ is just the Doppler frequency due to the moving carriage.

The time interval measurement resolution of the instrument is 100 ps and the time base is connected to the INRIM UTC, so that the measurements of the Doppler frequency and the integration time are extremely accurate. The environmental parameters, such as air temperature, atmospheric pressure, partial pressure of water, were monitored during the measurement process in order to calculate the value of air refractive index according to the Edlen’s formula.

Comparison set-up

The different technical solutions adopted for the EDMs and for the target plate positioning are discussed in this paragraph and sketched in figure 3.

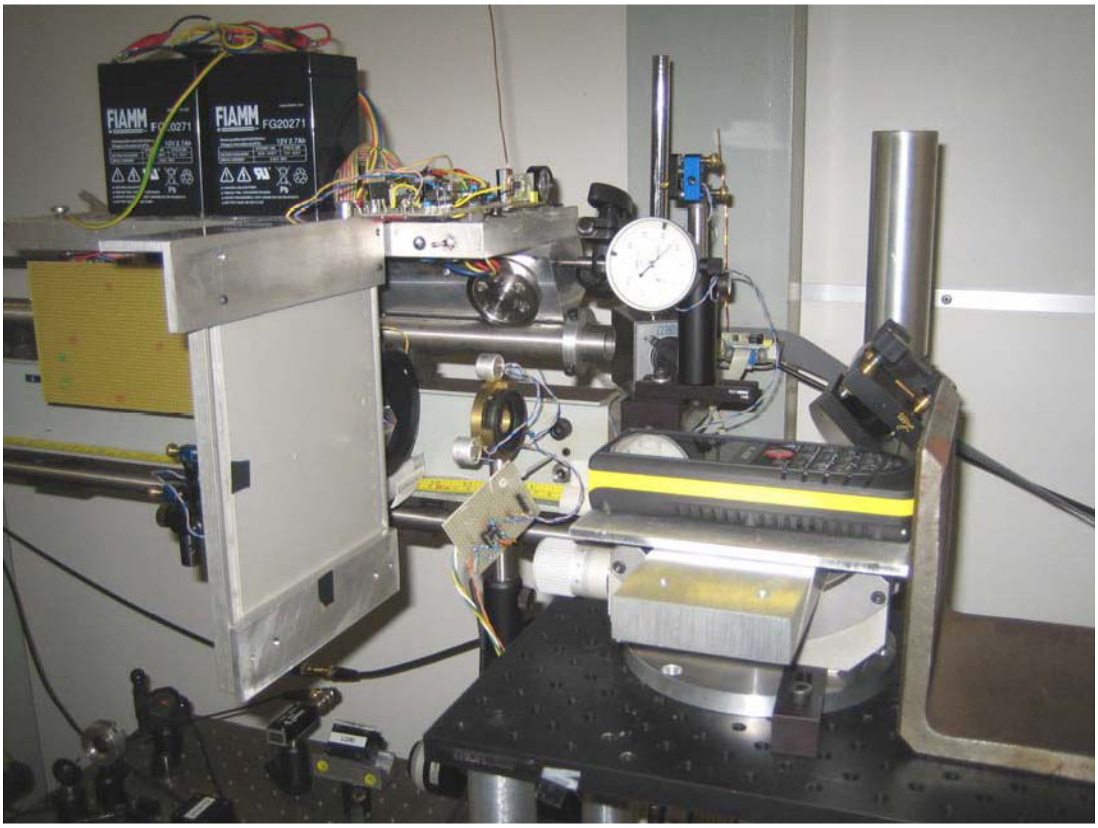


Fig. 3: picture of the EDM and target positioning area.

Target plate positioning

In order to use the provided target plate, an ad-hoc mounting was manufactured at INRIM: it consists in a sort of picture frame, made in aluminum, which slightly clamps the target folded in half and gives it the necessary stiffness to be a reproducible target. The upper part of the frame is L-shaped and allows it to be fixed to the carriage structure by means of two screws. The rear part of the target mounting is depicted in figure 4. The target mounting was considered necessary because of the poor stiffness and planarity of the plastic target. With the aluminium frame a planarity better than 0,1 mm was guaranteed. The target plate is placed few centimetres next to the retro-reflector and normal to the interferometer beam axis, since the EDM laser should be as close and parallel as possible to the reference beam.

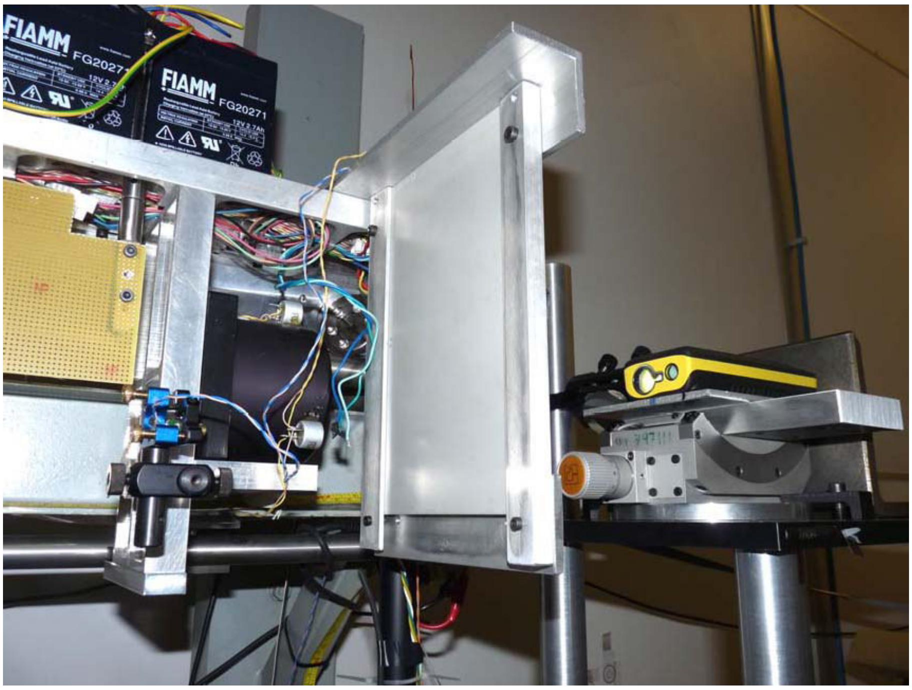


Fig. 4: picture of the rear part of the target plate mounting

EDMs' positioning

The EDMs are placed on a cradle-like platform, which is able to adjust the inclination of the EDM along the longitudinal axis (pitch angle). The platform height allows the EDMs to be at approx the same height as the interferometer beam. A crucial role was played by the stop-wall placed behind the platform, since it represents the "zero point" for all the length measurement. Hence a particular effort was devoted to align the stop-wall so that it was normal to the interferometer beam axis and parallel to the target plate.

Fig. 5: detail of EDMs' positioning: the cradle-like platform and the stop-wall are well visible.

Target and stop-wall alignment

In order to have the stop-wall parallel to the target plate and normal to the interferometer beam axis, the following procedure has been used:

1) the stop-wall and the target plate were roughly placed, trying to set them parallel and normal to the rail by eye (i.e. within few millimeters).

2) in order to check if the target was normal to the rail, one EDM was positioned on the platform: the pitch and yaw angles of the EDM were adjusted by observing the position of the EDM laser spot on the target plate when the target is moved along the rail: fixed position means laser beam parallel to the carriage movement. Then the target was moved until the end of the rail and a thin mirror was kept in contact with it: hence, observing the EDM laser reflected by the mirror, it was possible to adjust the target tilt acting on the screws until the laser beam is reflected back to the source.

3) finally, in order to check the parallelism between the stop-wall and the target, a tool made by a laser pointing orthogonally to its base was used: the base was leant against the stop-wall and the laser was centered on the target, when the target is near, then the target was moved until the end of the rail: hence, observing the spot of the laser on the target, it was possible to adjust the stop-wall orientation.

The residual misalignment errors, which we were not able to eliminate, were kept into account in the uncertainty budget.

Measurement of the first 30 cm

Due to the geometry of our set-up, it was not possible to perform the first point of measurement by means of the interferometer, indeed, the carriage (hence the target) is not able to go in contact with the stop-wall.

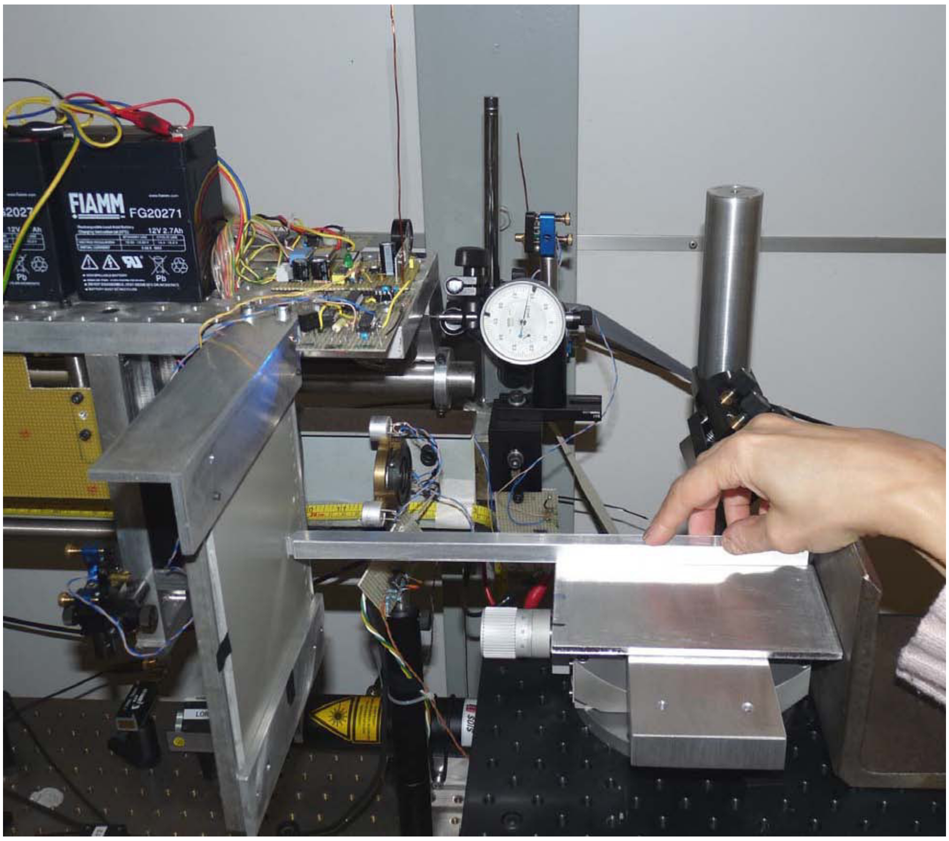


Fig. 6: measurement of the first 30 cm: the ruler touching the stop-wall and the target and the mechanical probe (in the back) touching the carriage are visible.

So, a ruler made of aluminum with rounded ends and nominal length equal to 30 cm was adopted to set the distance between the target plate and the stop-wall for the first point of measurement, as it is shown in figure 6. The ruler, whose length was measured by a CMM machine, was inserted between the target and the stop-wall, leaning against the latter, and the carriage was carefully moved towards the stop-wall until the target lightly touched the ruler. A mechanical probe, that touches the carriage structure when carriage is in the "30 cm" position, was used as a reference measurement to check the repeatability of this distance after each measurement set.

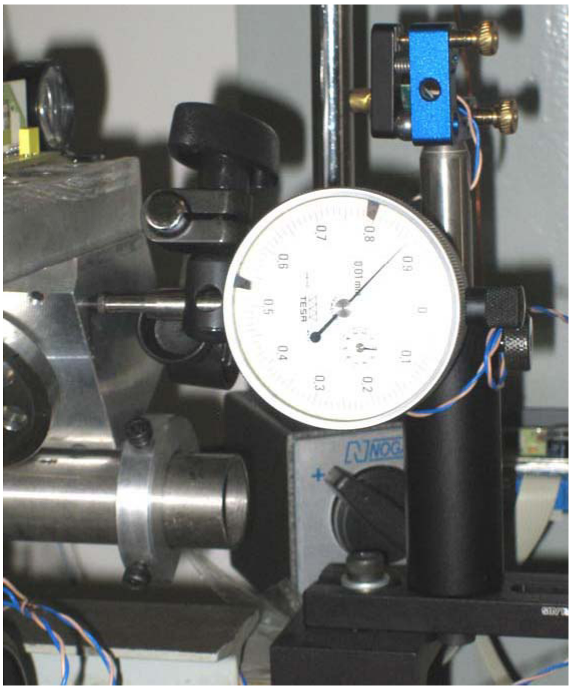


Fig. 7: detail of the mechanical probe touching the carriage

Environmental parameters

The environmental parameters, such as air temperature, atmospheric pressure and humidity, were monitored during the whole measurement process, in order to calculate the value of air refractive index according to the Edlen's formula.

Among these parameters, the temperature distribution along the mobile arm of the interferometer was our main concern mainly for two reasons:

1. the temperature control of the gallery was not perfectly working during the measurement period, so temperature drifts had to be monitored,
2. longitudinal temperature gradients due to non uniform heating and to the presence of electronic instruments were pretty high.

To the purpose, 14 thermometers were uniformly dislocated along the rail and automatically recorded for all the measurement period. Both temporal drifts and gradients along the path have been taken in account in the uncertainty budget. In any case maximum temperature differences along the rail are within 1 °C. In fig 8 an extract from the acquisition file is shown.

Unfortunately, the air conditioning system did not work well during the measurement campaign, hence the measurements were performed at a mean temperature of 20,9 °C.

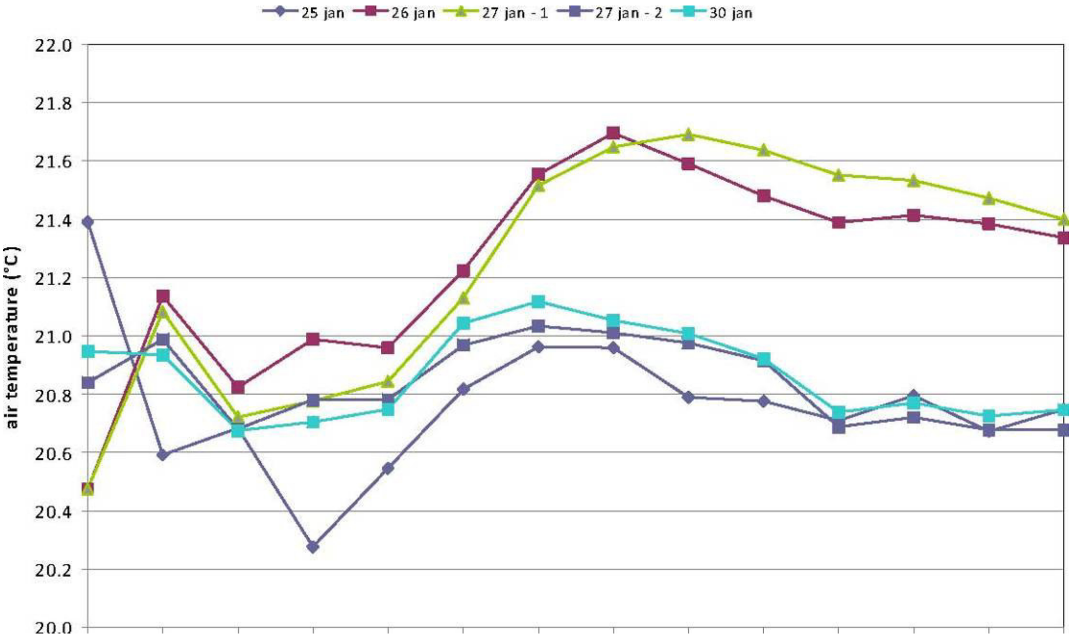


Fig. 8: each curve represents the temperature distribution along the rail during the measurements campaign

Carriage waving

Since the rail is not perfectly straight and the measurement laser is not coincident with the measurement beam, the Abbè error due to waving of the target must be considered. A quantitative measurement and a qualitative measurement were carried out. With an electronic level placed on the carriage, the straightness on the vertical plane has been mapped with a half meter resolution (the data are reported in fig 9). With a laser placed on the carriage the horizontal and vertical waving are qualitatively compared by looking at the movements of the light spot on a target fixed to the rail end. As a conclusion, the horizontal and vertical waving are comparable in magnitude and the peak to peak error is of the order of 300 arcseconds.

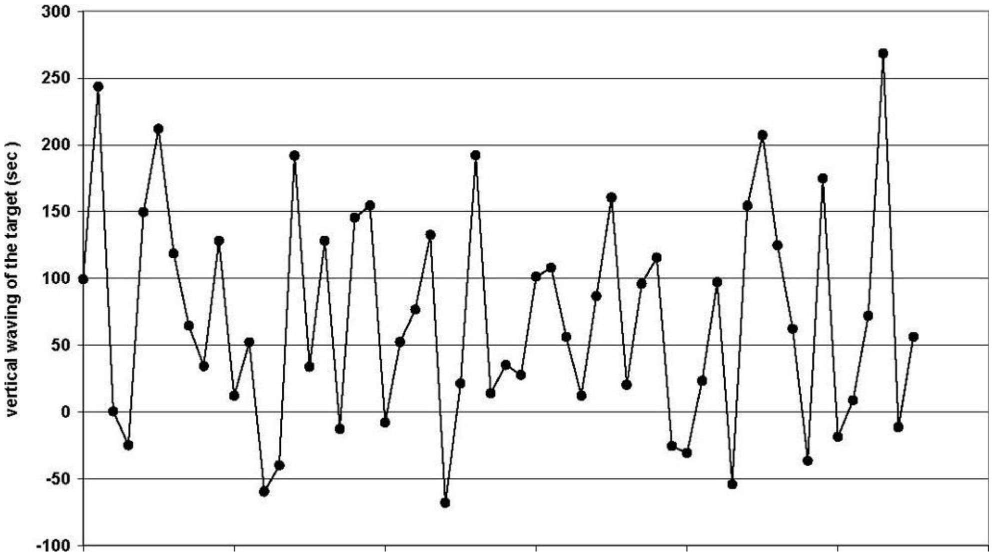


Fig. 9: vertical waving of the target measured by an electronic level placed on the carriage

Measurement procedure

The measurements were carried out according to the following procedure.

The target was set in the starting position with the procedure described above.

In sequence, the four EDMs are positioned on the base, the horizontal and vertical tilt are adjusted and the distance measurement is recorded. An additional fifth EDM (Bosh DLE 150 property of INRiM) was included in the measurement sequence. Each EDM is placed on the base and gently pushed against the reference wall in such a way that the measurement laser beam starting point is the same for all EDMs. Than the horizontal and vertical angles were adjusted in order to hit the central point of the target indicated with two black marks (see pictures 3 and 6) with “visual” alignment. The measurement button is then pressed several times (typically 5) and the average reading is recorded. Typical dispersion between readings is within few last digit units. In case the dispersion between readings is too large the anomaly is recorded.

The carriage was then moved in the next position (about 5 m) and the measurement sequence was repeated for the 5 EDMs. The operation is repeated up to 25 m. The 25 m measurement is than repeated again as well as all the points till the first one, so that each point is measured twice each set. Since the carriage movement is “open loop” the positioning of the carriage was not exactly in the nominal 5 m intervals. For each positioning the incremental displacement is measured by the interferometer in the Doppler mode. Finally, the measured values were averaged in order to give a single value for each nominal position.

At the end of the measurement set, when the carriage is at the 30 cm position again, the sum of the interferometric measurements should be very close to zero. The residual value is compared with the difference between the first and the final measurements of the mechanical probe. The difference must be within the uncertainty of the Doppler technique, otherwise some error occurred in the measurement set that must be repeated.

At the end of the session, 10 complete sets of measurements recorded from the 20th to the 30th of January 2012 have been considered for this report.

Additional remarks

Effect of laser pointing

During a preliminary set of measurements we noticed a strong and unexpected dependence of the measurement result on the position of the laser spot on the target. Indeed, since no particular instructions were given about the relative position of the laser spot on target position (except to exclude the central joint between the two halves) we decided to work relatively close to the right side of the target -closer to the interferometer beam- in order to reduce the Abbè error. We noticed very large errors at large distances in particular of the Leica DISTO D3a (see figure 10).

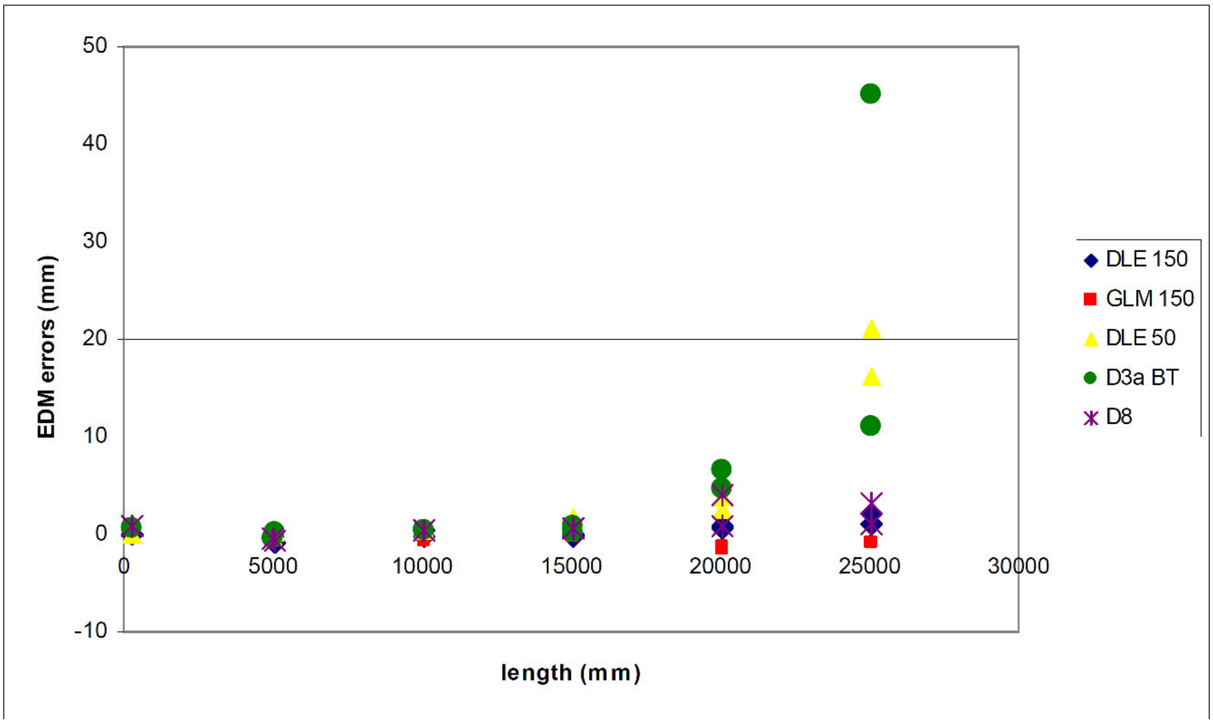


Fig. 10: errors of each EDM In a preliminary set of measurements

We also noticed that this error was strongly dependent on the position of the spot on the target. For this reason we carried out a set of measurements at the maximum length in different positions of the target, from one edge to the other, according to figure 11. The results are reported in table V.

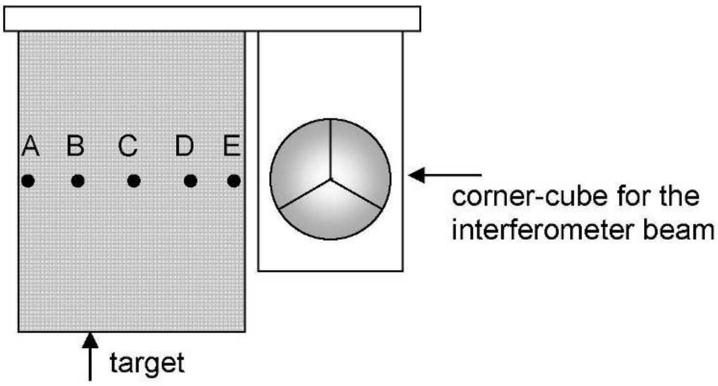


Fig. 11: positions of the laser spot on the target to study the dependence of the EDM errors on the laser spot position (front view)

EDM	A	B	C	D	E
Leica D3a	-4	+1	0	+24	+43
	/	+2	0	+42	+40
	-1	/	0	/	+38
Leica D8	0	0	0	2	+7
	/	/	0	+12	+23

table V: deviations (in mm) from the length measured at point C, aiming the laser spot at different positions of the target (notations as in figure 11)

We tried to find an explanation to this effect in the shape of the laser spot: if the spot was particularly defocused or had high diffraction, some of the energy could fall out of the target and affect the measurement result. In fact the images of the spots (shown in fig. 12) do not support this hypothesis. Finally we decided to use the center of the (half) target for the comparison.

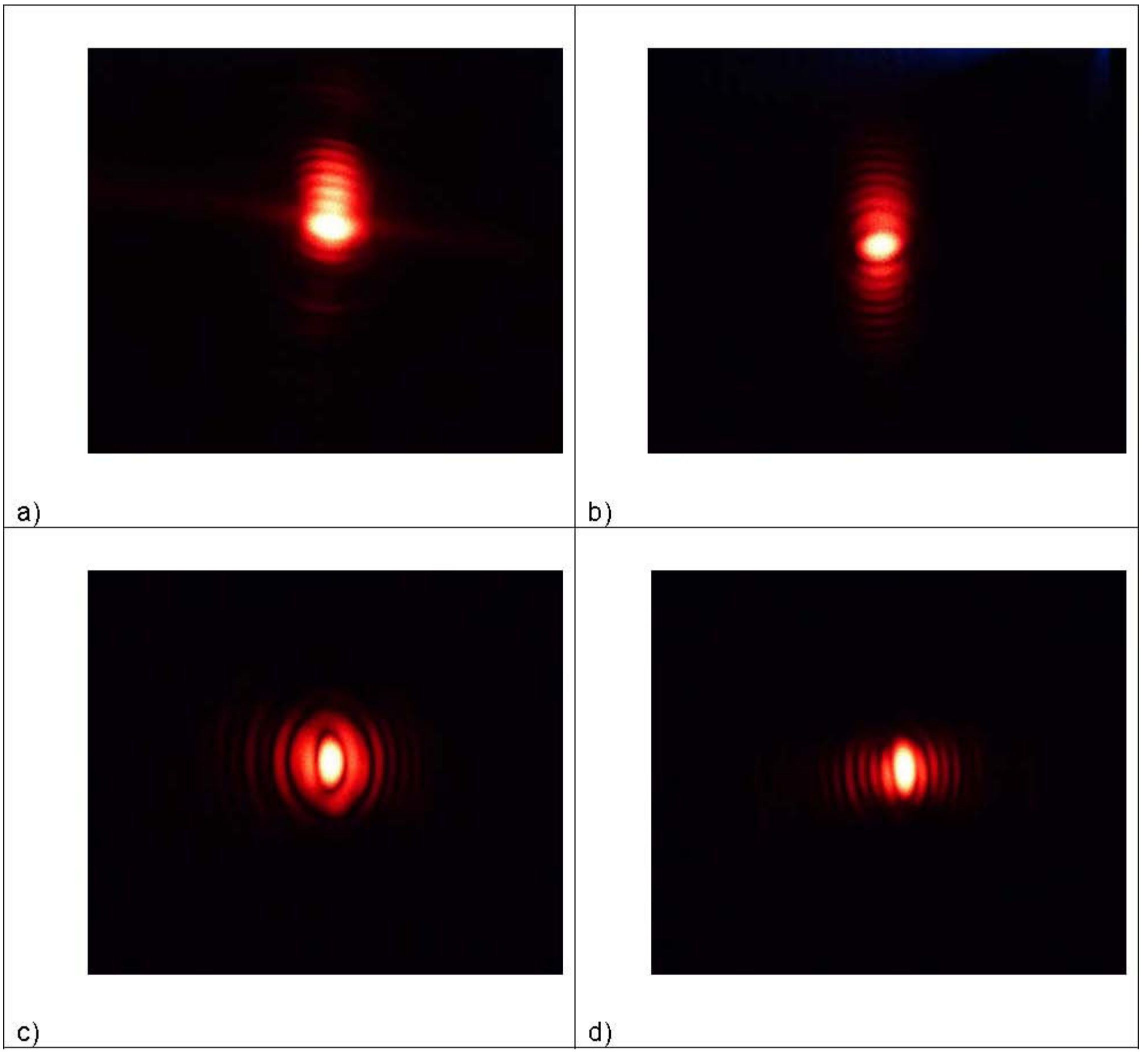


Fig. 12: Laser spot of different EDMs at 25 m: a) Bosch GLM 150, b) Bosch DLE 50, c) Leica DISTO D3a, d) Leica DISTO D8

Changing the target

In order to investigate the influence of the target on the measurements, a cardboard foil (400 x 400) mm was fixed to the target mounting and a complete set of measurements was performed. The results, reported in figure 13 and 14, do not show any evidence of a possible dependency of the EDM measurement on the target kind.

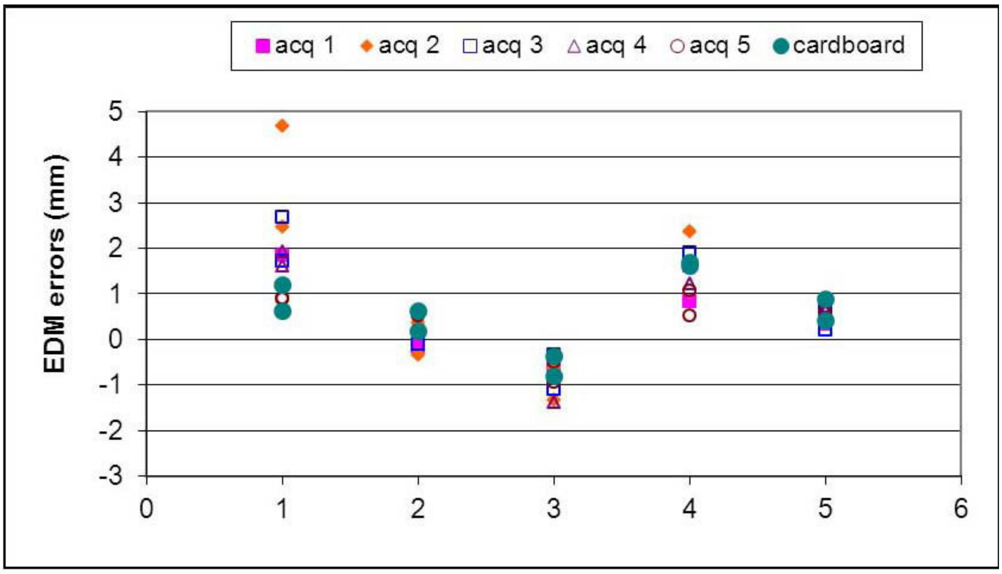


Fig. 13: EDM errors at 20 m (1=DISTO D3a, 2= DLE 150, 3 = GLM 150, 4= DLE 50, 5 = DISTO D8)

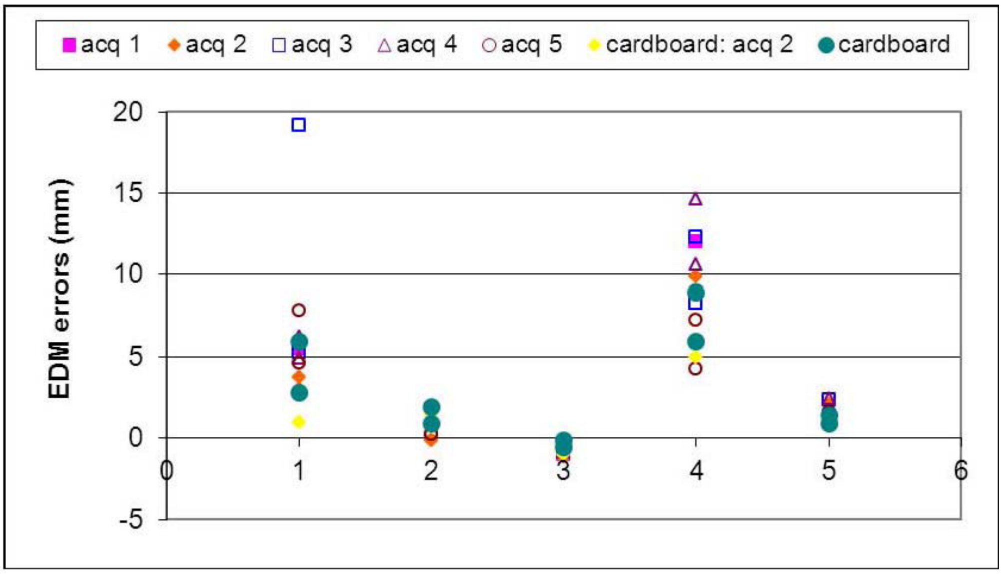


Fig. 14: EDM errors at 25 m (1=DISTO D3a, 2= DLE 150, 3 = GLM 150, 4= DLE 50, 5 = DISTO D8)

Measurement at 50 m

Although we are not able to perform traceable length measurements beyond 28 m, we wanted to get a sense of EDMs behaviour at longer distances. So a target (represented by a rack side wall) was placed at approximately 50 m: one after the other, the EDM's were positioned on the base and pointed towards the target. The measurements were repeated, then the target was replaced by the target used for the comparison and a third set of measurements were performed. To our great surprise, all the EDM's were in good agreement (within 2 or 3 mm for each set of measurement), even those which showed errors of the order of five to ten millimeters at 25 m, namely BOSCH DLE 50 and LEICA DISTO D3a. Therefore each set of measurements was averaged and the deviations from the mean value are reported in figure 15.

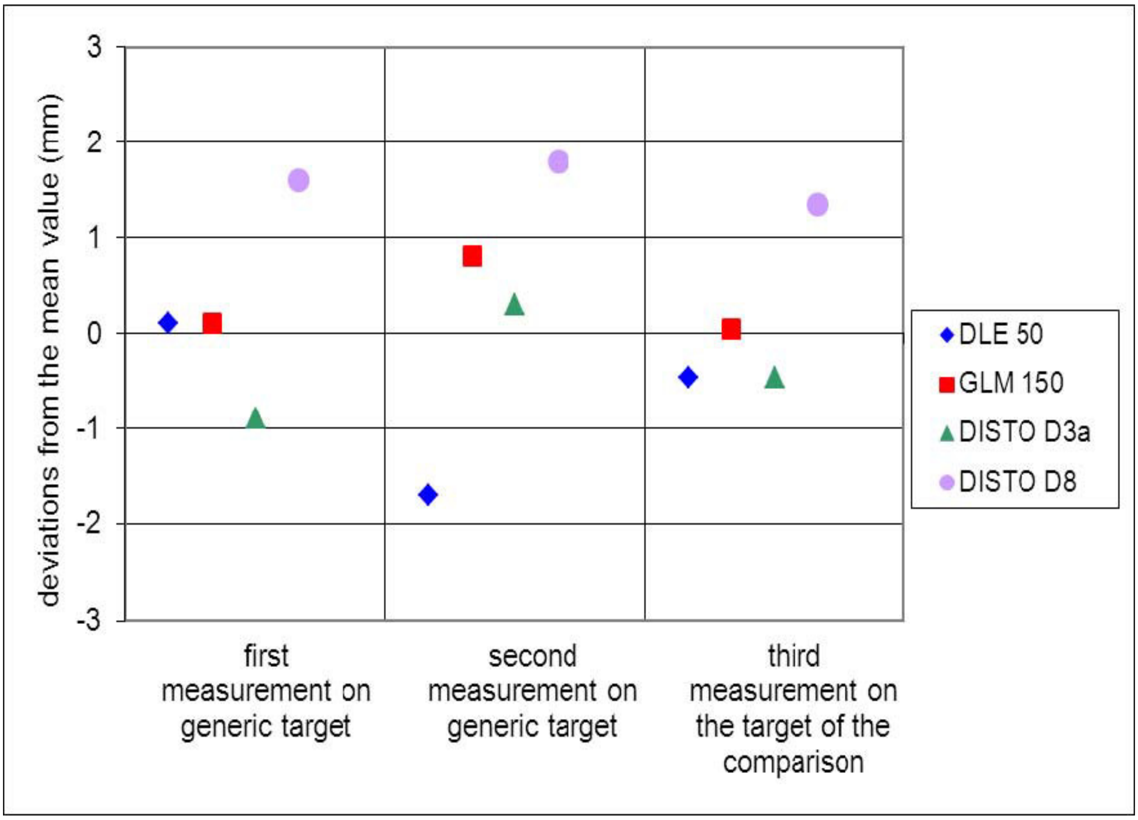


Fig. 15: Deviations from average value of the measurements At 50 m.

A1.9. CEM, Spain

Short description of the measurement bench

To make the measurements of EDMs we have used a reference line made of adjustable supports fixed on a wall of the laboratory. Each support is nominally separated five metres from the previous one; so we can generate reference lengths up to fifty metres with a pitch of five metres. The supports are designed to accommodate both targets and handheld EDMs. Distances between supports were measured by using a total station traced to national standards. The relative angles of the bases have been measured and corrected.

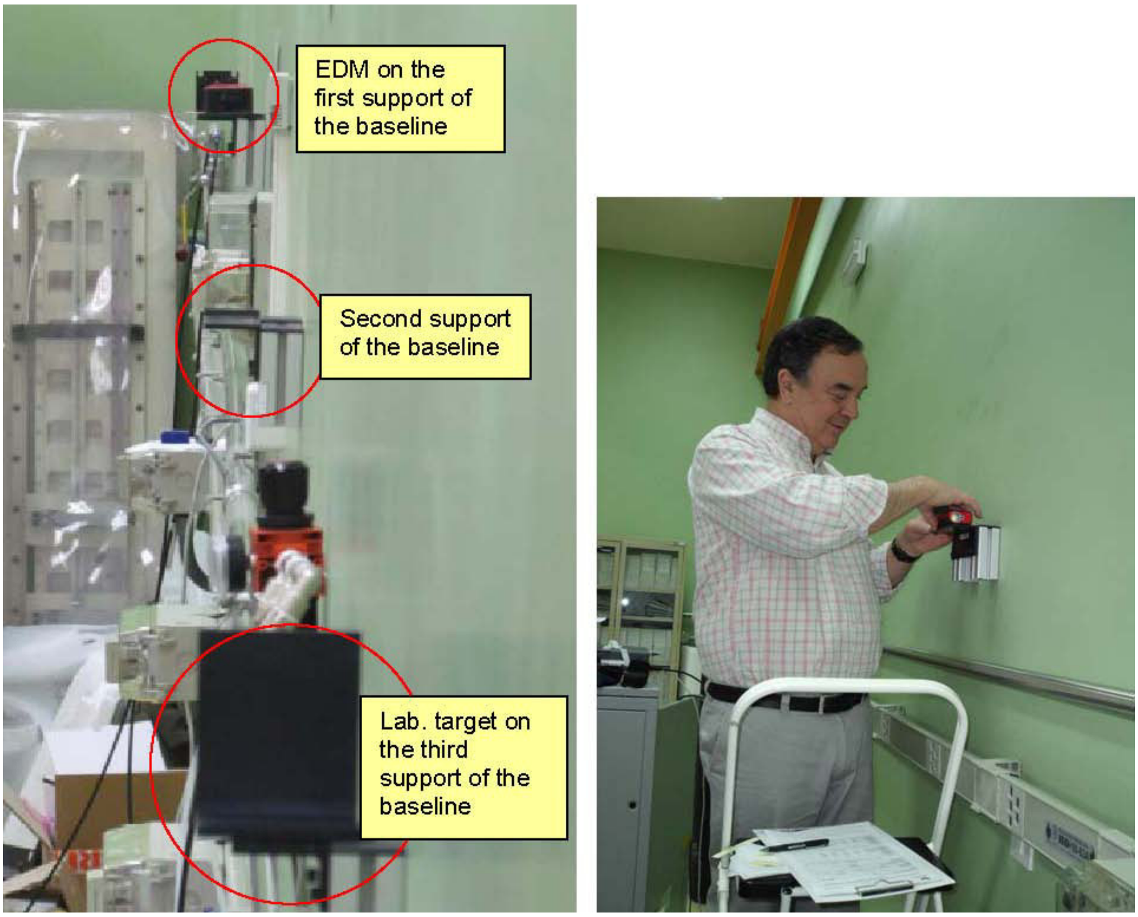


Fig. 1 - View of three consecutive supports of the 50 m baseline (left). Lab. technician situating an EDM on the first support of the baseline (right)

Length measurement instrument

The baseline was calibrated by using a total station Leica TDA5005 with spherical reflector, the calibration uncertainty being 0,2 mm for k = 2.

The target is provided by the comparison. The quality of the target was judged as not good due to geometrical constructive errors and the lack of rigidity and stability. We measured the flatness of the target surface, the distance edge-surface and the angle between them by using a 3D coordinate measuring machine. The results of flatness and angle were included in the uncertainty budget and the distance EDM-target was corrected for each EDM, due to each beam impinged on a different point of the target.

We were not able to measure the distance 0 to 0,3 m because the baseline pitch is 5 meters and although we are able to measure shorter values in a different facility, the target was not appropriate for our bench.

Fig. 2 - View of an EDM on the first support of the baseline (left). A closer look showing the support adjustments and the origin plate (right)

Fig. 3 - View of the comparison target on one of the supports of the baseline (left). A closer look showing the target edge against the support rigid reference (right)

Measurement method

The measurements were carried out by comparison against the known values of the calibrated baseline (metallic references on supports).

Environmental conditions were maintained within the following limits:

- Temperature: 20 ºC ± 0,5 ºC,
- Humidity: 45 % ± 10 %.

Each laser distance measuring instrument was placed at the first support of the base and aligned so that the laser beam was perpendicular to the target, as indicated by the comparison protocol.

For each measurement we took the average of thirty measurements. It permitted us to evaluate the repeatability of the instrument.

A1.10. BEV, Austria

Short description of the measurement bench

Fig. 1
Carriage of tape bench. View from the laser interferometer side. Retroreflector mounted on the vertical plate, the EDM target is mounted on the backside.

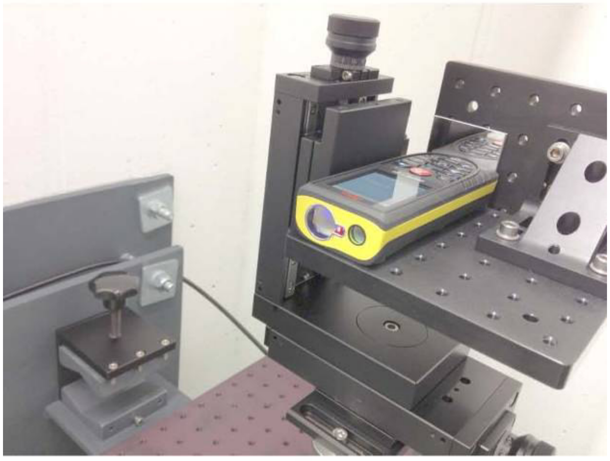


Fig. 2
Support for the DUT. Adjustable with 2 translational and 2 rotational degrees of freedom, respectively

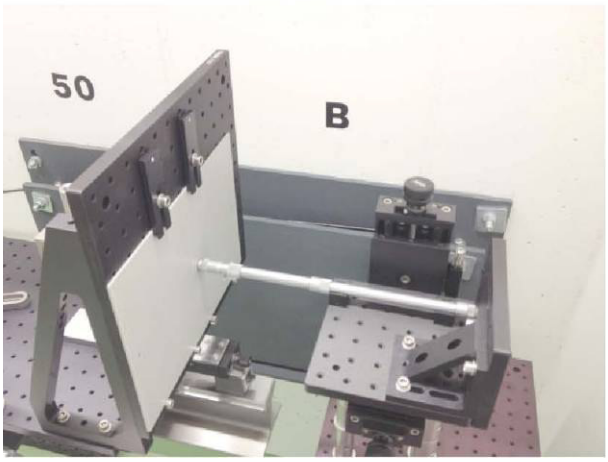


Fig. 3
Setting of the 300 mm starting position. Note the rough-and-ready mounted target plate.

Fig. 4
Laser interferometer side of the bench. The DUT is 50 m away on the other side.

Measurement procedure

1. The EDM is positioned with the help of a 4-axis positioning stage so that its laser beam is coaxial with the measurement direction of the laser interferometer (in head on configuration).
2. The EDM is removed from its support. The bench carriage is positioned so that the distance of the target plate from the EDM back support is 300 mm. A length bar with spherical faces is used for this adjustment. The laser interferometer is preset to 300 mm and the EDM is put back on its support.
3. At each position 10 consecutive measurements are taken (repeatability) and the carriage is moved to the next position. The carriage is manually moved under control of the laser interferometer until it is within ±30 µm at the correct position. (Exception: for the DLE 150 the target is not positioned at 10 m but at 10 m – 1 mm to make use of the higher resolution). The indicated (not the nominal) distance of the laser interferometer is recorded for the determination of the deviation.
4. After reaching the 50 m position all points are measured in reverse order (bidirectional). Immediately after the last measurement the EDM is removed and the indication using the 300 mm length bar is checked (thus noting a possible drift of the setup)
5. Each instrument was measured 4 times according to this procedure on different days (reproducibility of bench and instrument).

Length measurement instrument

Agilent laser interferometer with long range option. The bench was completed short time before performing these measurement. So the characterisation was not complete and the respective measurement uncertainty of the laser interferometer is estimated rather high. But anyway its contribution to the overall uncertainty can nearly be neglected.

Additional remarks

The uncertainty originating from the DUT is the dominating uncertainty contribution. Specifically the resolution of the two Bosch instruments (1 mm) and the repeatability are the largest contributions. For the DLA 50 the pooled standard deviation of a reading at 50 m is larger than 2 mm. Moreover the length dependence is not a simple function.

All of the instruments show a significant deviation of the laser beam from the normal of the back (reference) face of the instrument. The measured angles reach from 0,4° (D3a) to 1,1° (DLE 50). This leads, depending on the outer dimensions of the instruments, to a constant uncertainty contribution of 0,2 mm in our setup. It must be noted that the reference faces are not well defined in most of the instruments.

The reproducibility is quite different for the four instruments, so only part of it originates from the setup. For CMC claims we will use the standard uncertainty value of the most reproducible instrument (D3a) which amounts to 0,13 mm. For an ideal instrument with a resolution of 0,1 mm and perfect repeatability we would thus have a constant expanded uncertainty of 0,53 mm up to 50 m.

A1.11. JV, Norway

Short description of measurement bench

EDM under calibration and the reference system are aligned along a 50 m measurement bench with rails to carry the linear movement of a target plate for the EDM and a corner cube reflector for the reference system. The distance between parallel axis of EDM and axis of the reference system is 130 mm. Abbe error due to angle errors for the movement is smaller than 0.1 mm and is corrected for at each measurement point. At long lengths, an aperture is used approximately midway between the target plate and the EDM to avoid interfering stray light to the EDM.

Alignment procedure:

1) Alignment of reference system to the movement of the carriage (rails).
2) Alignment of the EDM to the movement of the carriage (rails).
3) Alignment of a plane mirror at the position of the target plate using back-reflection to the EDM output (normal incident of light on the mirror)
4) Take out the EDM, and align the zero reference plate at the back of the EDM to the plane mirror.
5) The mirror is replaced by the target plate, and the target plate is aligned to the zero reference plate.
6) Zero setting of the reference measurement system when target plate is at zero distance to the reference plate at the back of the EDM.
7) Put the EDM back in position and realign it to the movement of the carriage (rails).
8) Zero setting of the EDM to the reference plate.

Image 1)

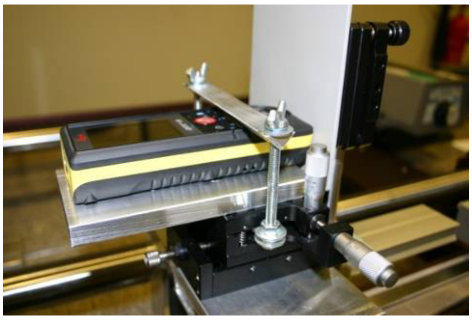


Image 2)

Image 3)

Image 4)

Image 1) Items 5) – 6) in alignment procedure.

Fixture for HP linear interferometer is seen bottom right. Part of Wyler instrument is seen to the left, blue colour.

Image 2) Items 7) and 8) in alignment procedure.

Micrometer screws for angle alignment in two directions and linear translation for zero setting of the EDM. Push button on the EDM is positioned at the tilting point of the angle adjustment table to maximize stability during measurement. HP 5519 A laser head is seen to the right.

Image 3) Ready to measure at selected distances from zero point, the reference plate.

Image 4) EDM spot size at 50 m.

Length measurement instrument

- Hewlett Packard Dynamic Calibrator 5519 A (max range 80 m).
- Pressure, air temperature, humidity: Vaisala.

- Digital high resolution angle measurement: Wyler.

I used our own target plate, which is of the same type as enclosed in the artefact suitcase, article number 766560 from Leica, but with reduced size: width x hight = 90 x 137 mm.

The zero reference plate is of similar type and size.

Before measurements, batteries of EDMs were switched to new batteries. Old batteries are switched back after calibration.

For L > 5 m, an aperture of similar size as the target plate is used approximately midway between the EDM and the target plate.

Additional remarks

Reports on EDM indicated values at each measurement point is the average value of n = 5 repetitions. A linear model of the standard deviation for the repeatability of the EDM readings at different lengths is estimated using m = 20 repetitions at least 5 positions along the scale. An estimate of the length dependent repeatability is made for each instrument.

The expanded uncertainty, U(95%), is rounded up to the limiting resolution of 1 mm in the interval 10 m to 40 m for Bosch GLM 150.

After the calibration, we also estimated the angle error of the optical axis of the EDM to its back plane (back reference of EDM):
Bosch DLE 50: 26 mrad up, measured at 50 m.
Bosch GLM 150: 8 mrad to the left, measured at 50 m.
Leica DISTO D3a: 3.7 mrad down, measured at 20 m.
Leica DISTO D8: 2 mrad to the left and 4 mrad down (4.5 mrad total), measured at 20 m.

The distance between parallel walls will be measured too large if the back plane is assumed to be normal to the optical axis of the EDM by $\Delta L/L = (1/\cos\alpha - 1)$.
Bosch DLE 50: $\Delta L/L$ = 340 ppm (ΔL = 17 mm at L = 50 m).
Bosch GLM 150: $\Delta L/L$ = 32 ppm (ΔL = 1.6 mm at L = 50 m).
Leica DISTO D3a: $\Delta L/L$ = 7 ppm (ΔL = 0.34 mm at L = 50 m).
Leica DISTO D8: $\Delta L/L$ = 10 ppm (ΔL = 0.5 mm at L = 50 m).

A1.12. METAS, Switzerland

Short description of measurement bench (photo recommended)

50 m bench with laser interferometer (see photo, detailed description in: Michel Degoumois, *Un Long laboratoire de mesure*, OFMETinfo Vol.5, No 2, 1998).

Length measurement instrument

HP 5529 B laser interferometer, range 80 m.

A1.13. GUM, Poland

Short description of measurement bench

The 50 m bench is situated in the corridor laboratory located in the basement and has its own air conditioning system with air temperature 20 ± 1 °C and humidity 50 ± 10 % RH . The measuring carriage is carried microscope with CCD camera and the optics associated with the interferometer. The carriage is driven using belt-transmission and electrical engine with remote – controlled variable speed drive.

The EDM was placed on the fixed adjustable plate on the other end than laser interferometer. The target plate of the EDM was placed on the measuring carriage. For each EDM 3 series of measurement were done. Before the each measurement EDM was repositioned and aligned again.

Length measurement instrument

1. Laser interferometer HP 5529A with long-range option laser head HP 5519A
2. Ambient measurement system, number and location of sensors:
   - 20 air temperature sensors type YSI with KEITHLEY multimeter; they are placed very close to axis of the laser beam,
   - air pressure and humidity are measured with Vaisala barometer and thermohigrometer,
   - CO_2 content was measured with analyzer made by Intelli Charge, type SPN 4462.

Appendix 2: Corrections of reports

13.1 CEM, Spain

CEM reported two errors in their report:

1) Bosch GLM 150, EDM error for 35 m should be -0.8 mm instead of the indicated 0.8 mm;
2) Leica DISTO D8, EDM error for 35 m should be -0.19 mm instead of the indicated 0.19 mm.

Proposed corrections have been included in Tables 2 and 4 of the Final Report.

13.2 AS Metrosert, Estonia

AS Metrosert reported mixed up of all results for Bosch DLE 50 and Bosch GLM 150. The results and uncertainties sent for DLE 50 was results for GLM 150 and vice versa.

Proposed corrections have been included in Tables 1 and 2 of the Final Report.

13.3 INRIM, Italy

Among the data reported from INRIM, some anomalies were found in the measurements of BOSCH DLE 50 and LEICA DISTO D3a at distances of 20 and 25 m.

After preliminary discussion on Draft A, it was understood that those anomalies could be explained as a sensitivity of said instruments to the laser light that, once diffused by the target, is reflected by surfaces parallel to the measurement axis and detected together with the wanted signal. The superimposition of the two signals can cause a “pulling” effect leading to an overestimation of the distance, being the reflected path always longer than the direct one. Indeed, in the INRIM’s set-up, the target was mounted pretty close to the flat rail used for the carriage movement, being likely responsible for unwanted reflections that disturbed the measurements.

Since the errors reported in INRIM’s measurements can be ascribed to a defect of BOSCH DLE 50 and LEICA DISTO D3a and/or to a lack of description of the working conditions of said instruments, INRIM asked to eliminate its measurement points at 20 and 25 m of said instruments from the comparison.

Proposed corrections have been included in Tables 1 and 3 of the Final Report.

13.4 JV, Norway

Justervesenet has changed the procedure and introduced two apertures instead of only one aperture (iris) which was positioned at half distance between EDM and target. The reason is that the reference beam also has an aperture and it is positioned right below the beam from the EDM (130 mm distance between axes). Some diffusively reflected stray light from the EDM target might enter the aperture for the reference beam, reflect at the measurement table and reach the detector of the EDM. In our calibration set-up, we have only seen problems at $L > 30$ m. We will position the first aperture at ca 5 m from the EDM, and then the second aperture at ca 25 m. This combination of two apertures will effectively eliminate interference of stray light from the measurement table to the EDM detector for all lengths up to 50 m.

Justervesenet also increases the uncertainty component regarding repeatability / reproducibility so that the expanded uncertainty increases from 1.4 mm to 1.5 mm.