Report on Bilateral Line-Scale Comparison

SIM.L-K7.2016

Final Report

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1. FOREWORD

Since the line scale used in this comparison was planned to be used in the next EURAMET line scale comparison (originally planned as EURAMET.L-K7.2019), the CCL WG-MRA (Meeting No 10, 17 –18 October 2019) decided that the KCRV of this comparison would be held secret until publication of the Draft B of the EURAMET.L-K7.2019. Therefore, the initial version of Draft B did not contain the results of measurements and the KCRVs contained only the uncertainty budgets and the degrees of equivalence. With the action A.13 of the CCL WG-MRA (Meeting No 13, 8–10 November 2022) it was decided to submit the full report including KCRVs, for review and publication. This document supports the measurement capabilities of both the laboratories.

2. INTRODUCTION

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

2.2 Two National Metrology Institutes take part in this bilateral comparison, registered as SIM.L-K7.2016, INRIM (Italy) and INTI (Argentina). The aim is to give metrological equivalence to the measurement of line scales at INTI.

2.3 INRIM is acting as the pilot laboratory and in this function is responsible for providing the travelling standard, the evaluation of the measurement results and the final report.

2.4 The comparison will be accomplished in accordance with the BIPM CIPM MRA-G-11 “Guidelines for Planning, Organizing, Conducting and Reporting” for Key, Supplementary and Pilot Comparisons.

2.5 The Technical Protocol was prepared following the layout principles of the documents for previous comparisons. The allowance to use parts of this prior work wherever possible is gratefully acknowledged.

2.6 The comparison was registered in the BIPM KCDB; the artefact circulation started in October 2017 and was completed in May 2019.

3. MEASUREMENT ARTEFACT

3.1 List of participant laboratory and their contact persons.

Laboratory	**Contact person, Laboratory**	**Phone, email**
INRIM	Roberto Bellotti INRIM – Istituto Nazionale di Ricerca Metrologica Strada delle Cacce 91 10135 Torino, Italy	Tel : + 39 011 3919 967 r.bellotti@inrim.it
INTI	Bruno R. Gastaldi INTI- Instituto Nacional De Tecnología Industrial Avenida Vélez Sarfield 1561 5000, Córdoba, Argentina	Tel: +54 – 0351 – 4604137 gastaldi@inti.gob.ar

3.2 Comparison time

Laboratory	RMO	Measurement time
INTI	SIM	March - April 2018
INRIM	EURAMET	May 2019

4. MEASUREMENT ARTEFACT

The scale is made of a glass ceramic Zerodur, manufactured by Heidenhain, and provided by INRIM, Next are indicated the characteristics of the scale as reported in Figure 1

S/N: 13475807

Total length of main graduation: 280 mm

Length of line structure: 1 mm (main graduation)

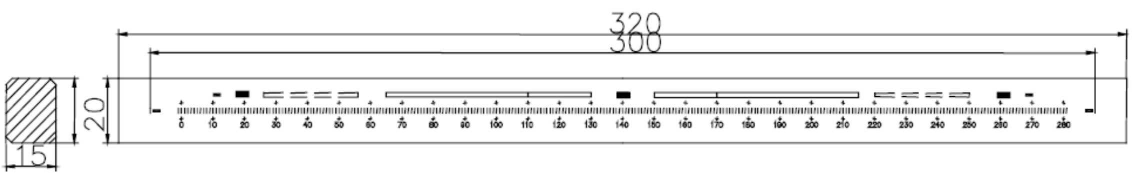
Width of line structure: 4 μm (main graduation)

Zerodur:

Thermal expansion coefficient: α = [1.826 – 0.229 (t-20)]$\cdot$10 $^{-8}$ K^{-1} , U_α = 6$\cdot$10 $^{-10}$ K^{-1}

Length compressibility: dL_p = -5.76$\cdot$10^{-10} hPa^{-1} U_{dLp} = 0.08$\cdot$10^{-10} hPa^{-1}

Overall dimension: 320 mm x 20 mm x 15 mm



Main graduation: 280 mm length, 1 mm pitch, CD 4 µm, 1 mm line length

Figure 1 – Line scale characteristics

5. HANDLING THE ARTEFACT

5.1 General Handling

Open the box carefully and only in a clean environment. Use clean room gloves in order to handle the scale and never touch the surface of the scale. It is not allowed to use any type of glue or wax for fixing the scale. When not in use, place the scale back into its container to avoid dust or dirt deposits.

5.2 Cleaning

Cleaning the scale with soft tissues or similar should be avoided. If it is necessary to clean the scale before the measurement clean air or other clean gas (preferable to very low pressure) can be used.

5.3 Temperature measurement of the artifact

For the measurement of the artefact, it is not allowed to fix the temperature sensors to the artefact using any type of glue, wax or clamping fixture. It is recommended to measure the temperature in the mounting fixtures.

5.4 Storage

Use original transportation container to avoid dust deposits. Always try to keep the artefact under good measuring room conditions, i.e. within the room, where it gets calibrated.

5.5 Stability

INRIM has measured the line scale in 2015 and 2019, only the data measured in 2019 are used in this bilateral comparison. By comparing the data of 2015 and 2019 by means of the compatibility index E_n, as defined in equation [5], no significant drift has been estimated.

6. MEASURAND

The measurand is the deviation from the nominal distance between the center line position of the reference line [position 0] and the center line position of the measured line. The measurement is carried out in the central section of the lines with a measuring window of 50-100 μm.

7. RESULTS

The results reported by the participants are plotted in the graph in Figure 2. Values of the deviation from nominal length and measurement uncertainties are given Table 1 and Table 2.

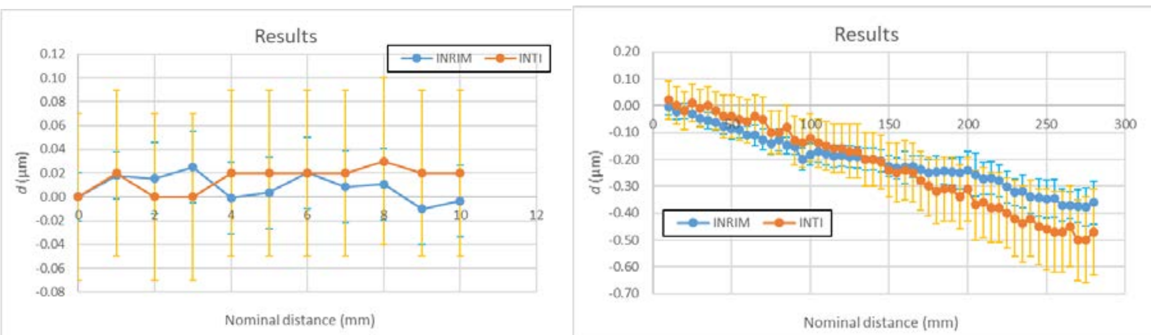


Figure 2 – Comparison between INRIM and INTI results. On the left, results for nominal distance 0 mm – 10 mm with a pitch of 1 mm. On the right, results for 0 mm – 280 mm with a pitch of 5 mm. Error bars corresponds to the standard uncertainty (k = 1).

Results and uncertainties reported by participants: distance 0 mm - 10 mm every 1 mm.

Nominal distance (mm)	*d* (μm) INRIM	*u* (μm) INRIM	*d* (μm) INTI	*u* (μm) INTI
0	0.00	0.02	0.00	0.07
1	0.02	0.02	0.02	0.07
2	0.02	0.03	0.00	0.07
3	0.03	0.03	0.00	0.07
4	0.00	0.03	0.02	0.07
5	0.00	0.03	0.02	0.07
6	0.02	0.03	0.02	0.07
7	0.01	0.03	0.02	0.07
8	0.01	0.03	0.03	0.07

9	-0.01	0.03	0.02	0.07
10	0.00	0.03	0.02	0.07

Table 1 – Results as reported by INRIM and INTI for nominal distances 0 mm – 10 mm with a pitch of 1 mm.

Results and uncertainties reported by participants: distance 0 mm - 280 mm every 5 mm.

Nominal distance (mm)	***d* (µm) INRIM**	***u* (µm) INRIM**	***d* (µm) INTI**	***u* (µm) INTI**
10	0.00	0.03	0.02	0.07
15	-0.02	0.03	0.00	0.07
20	-0.02	0.03	-0.02	0.07
25	-0.03	0.03	0.01	0.07
30	-0.05	0.03	-0.01	0.07
35	-0.06	0.03	0.00	0.07
40	-0.06	0.03	-0.02	0.07
45	-0.08	0.03	-0.04	0.08
50	-0.09	0.04	-0.04	0.08
55	-0.09	0.03	-0.05	0.08
60	-0.11	0.03	-0.06	0.08
65	-0.11	0.04	-0.04	0.08
70	-0.13	0.04	-0.05	0.08
75	-0.14	0.04	-0.10	0.08
80	-0.13	0.04	-0.10	0.08
85	-0.15	0.03	-0.08	0.08
90	-0.15	0.03	-0.13	0.09
95	-0.20	0.04	-0.14	0.09
100	-0.18	0.04	-0.12	0.09
105	-0.17	0.04	-0.14	0.09
110	-0.18	0.04	-0.15	0.09
115	-0.19	0.04	-0.16	0.09
120	-0.19	0.04	-0.16	0.09
125	-0.19	0.04	-0.17	0.10
130	-0.19	0.04	-0.17	0.10
135	-0.20	0.04	-0.20	0.10
140	-0.20	0.04	-0.20	0.10
145	-0.21	0.04	-0.21	0.10
150	-0.22	0.04	-0.24	0.10
155	-0.23	0.04	-0.25	0.11
160	-0.23	0.06	-0.24	0.11
165	-0.23	0.04	-0.25	0.11
170	-0.24	0.05	-0.28	0.11
175	-0.25	0.05	-0.30	0.11
180	-0.25	0.06	-0.32	0.12

185	-0.24	0.05	-0.31	0.12
190	-0.25	0.05	-0.31	0.12
195	-0.25	0.06	-0.34	0.12
200	-0.24	0.07	-0.31	0.12
205	-0.26	0.08	-0.37	0.13
210	-0.27	0.06	-0.36	0.13
215	-0.27	0.06	-0.38	0.13
220	-0.28	0.06	-0.38	0.13
225	-0.30	0.06	-0.40	0.13
230	-0.32	0.05	-0.42	0.14
235	-0.32	0.06	-0.44	0.14
240	-0.34	0.06	-0.42	0.14
245	-0.34	0.07	-0.45	0.14
250	-0.35	0.07	-0.46	0.15
255	-0.35	0.07	-0.47	0.15
260	-0.37	0.06	-0.47	0.15
265	-0.37	0.05	-0.45	0.15
270	-0.37	0.06	-0.50	0.15
275	-0.38	0.07	-0.50	0.16
280	-0.36	0.08	-0.47	0.16

Table 2 – Results as reported by INRIM and INTI for nominal distances 0 mm – 280 mm with a pitch of 5 mm

8. MEASUREMENT UNCERTAINTY

The uncertainty of measurement shall be estimated according to the ISO Guide to the Expression of Uncertainty in Measurement (GUM) and the complete uncertainty budget must be reported.

Uncertainty budget of INTI

		u(xi)	unity	dist	Degrees of freedom	ci=df/dxi	unity	constant ui(y)/nm	funtion of L ui(y)/y	example for 280 mm [nm]
Detection	Resolution	0,005	pixel	R	infinite	4,07E+02	nm/pixel	1,17E+00		1,17
	Detection repetibility	17,00	nm	R	infinite	1,00E+00		9,81E+00		9,81
	Parallelism between line edges	9,00	nm	R	infinite	1,00E+00		5,20E+00		5,20
	Parallelism between lines	9,00	nm	R	infinite	1,00E+00		5,20E+00		5,20
	Point determination error in the linear regression	17,00	nm	R	infinite	1,00E+00		9,81E+00		9,81
	Linear regression error	29,00	nm	R	infinite	1,00E+00		1,67E+01		16,74
	Sistem detection error	100,00	nm	R	infinite	1,00E+00		5,77E+01		57,74
	Nonlinearity of edge detection system	0,000	nm	R	infinite	1,00E+00		0,00E+00		0,00
	Detection statistics	35,00	nm	R	infinite	1,00E+00		7,00E+00		7,00
										63
Interferometer	Wavelength accuracy	0,1	nm/mm	R	infinite	1,00E+00			5,77E-02	16,17
	Wavelength stability	0,02	nm/mm	R	infinite	1,00E+00			1,15E-02	3,23
	Wavelength stability per hour	0,002	nm/mm	R	infinite	1,00E+00			1,15E-03	0,32
	Electronics error	10,00	nm	R	infinite	1,00E+00		5,77E+00		5,77
	Opctics nonlinearity	5	nm	R	infinite	1,00E+00		2,89E+00		2,89
	Ambient pressure	0,07	mmHg	N	50	4,00E-01	nm/mmHg/mm		2,80E-02	7,84
	Ambient temperature	0,021	°C	N	50	1,00E+00	nm/°C/mm		2,10E-02	5,88
	Ambient humidity	2,5	%	R	infinite	1,25E-02	nm/mm/%		3,13E-02	8,75
	Thermal gradient of optical components	0,1	°C	R	infinite	5,00E+02	nm/°C	2,89E+01		28,87
	Death path	0,5	mm	R	infinite	1,00E+00	nm/mm		2,05E-01	57,37
	Alignment error	0,05	nm/mm	R	infinite	1,00E+00			2,89E-02	8,08
	Resolution	5	nm	R	infinite	1,00E+00		2,89E+00		2,89
										68
Scale and mounting	Scale thermal gradient	0,045	°C	R	infinite	1,15E+01	nm/mm/°C		2,99E-01	83,66
	Temperature variation during the measurement	0	°C	R	infinite	1,15E+01	nm/mm/°C		0,00E+00	0,00
	Uncertainty of the temperature sensors	0,0235	°C	N	50	1,15E+01	nm/mm/°C		2,70E-01	75,67
	Uncertainty of the coeffcient of thermal expansion	1,15	nm/mm/°C	R	infinite	2,60E-01	°C		1,73E-01	48,34
	Misalignment around Z axis	50	nm/mm	R	infinite	5,00E-05			1,44E-03	0,40
	Misalignment around Y axis	50	nm/mm	R	infinite	5,00E-05			1,44E-03	0,40
										123
uA	Statistical uncertainty	16,82	nm	N	4,00	1,00	nm	16,82	0,10	45,12
							uc^2	5076,86	0,25	
	Effective degrees of freedom							905,69		**160,29**
	Coverage factor							2,01		
					Constant		a=	143,03		
					function of L		b=	1,01		

Table 3 – Uncertainty budget of INTI

Giving $U_{95\%}$ = Q[144 nm, 1.01E-06 *L*]

Uncertainty budget of INRIM

In the following table the uncertainty budget of INRIM is shown for the case *L* = 280 mm only. The uncertainties of the other values of *L* are lower since the repeatability contribution is lower. The values are the ones reported in Table 1 and 2 in section 7.

name and symbol x_i	$u(x_i)$	$u(x_i)/x_i$	unit	distr.	ν_i	$c_i = \partial dL/\partial x_i$	u_i /nm	$u_i(L)$ / L
repeatability	78		nm	N	15	1	78	
Interferometer readings	28		nm	R	71	0.58	16	
		$3.7\cdot10^{-8}$		N	104	1		$3.7\cdot10^{-8}$
Probe readings	8		nm	R	50	0.58	4	
uncertainty of the coefficient of thermal expansion (α) of scale	$5.0\cdot10^{-9}$		K^{-1}	R	50	$0.58\cdot(t_s - 20)$		$3.0\cdot10^{-10}$
difference of the scale temperature from the reference temperature during measurement	100		mK	R	15	$0.58\cdot3\cdot10^{-8}$ K^{-1}		$1.7\cdot10^{-9}$

uncertainty of the coefficient of compressibility (*k*) of the scale material	$1 \cdot 10^{-12}$		Pa^{-1}	R	50	$0.58 \cdot (101325 - P)$		$5.8 \cdot 10^{-11}$
variations of air pressure during measurement	100		Pa	R	15	$0.58 \cdot 5.8 \cdot 10^{-12}\ Pa^{-1}$		$3.3 \cdot 10^{-10}$
geometrical effects	24		nm	R	18	0.58	14	
		$1.2 \cdot 10^{-7}$		R	130	0.58		$7.0 \cdot 10^{-8}$

Combined standard uncertainty: u_c = 84 nm (*L*=280 mm)

Effective degree of freedom: ν_{eff} = 20

Expanded uncertainty: U_{95} = 175 nm (*L*=280 mm)

Table 4 – Uncertainty budget of INRIM for the case L = 280 mm

9. ANALYSIS

9.1 Calculation of KCRV

The Key Comparison Reference Value KCRV is calculated as the weighted mean of the results of INRIM and INTI. Considering that each laboratory reports a measured value x_i and an associated standard uncertainty $u(x_i)$, the weighted mean is calculated in general as

$$\bar{x}_w = \frac{\sum_i u(x_i)^{-2} x_i}{\sum_i u(x_i)^{-2}} \qquad [1]$$

And in the particular case of two measurements the KCRV is simply given by

$$\bar{x}_w = \frac{\frac{x_1}{[u(x_1)]^2} + \frac{x_2}{[u(x_2)]^2}}{\frac{1}{[u(x_1)]^2} + \frac{1}{[u(x_2)]^2}} \qquad [2]$$

The uncertainty of the weighted mean is calculated as

$$u(\bar{x}_w) = \sqrt{\frac{1}{\frac{1}{[u(x_1)]^2} + \frac{1}{[u(x_2)]^2}}} \qquad [3]$$

After having calculated the KCRV, as in equation [1], the deviation of each laboratory from the KCRV is represented by the difference $d = x_i - \bar{x}_w$. The uncertainty associated with the difference *d* is obtained by considering the propagation of uncertainty and the correlation existing between x_i and $\bar{x}_w$, giving

$$u(d) = u(x_i - \bar{x}_w) = \sqrt{[u(x_i)]^2 - [u(\bar{x}_w)]^2} \quad [4]$$

Statistical consistency between the results of the NMIs (x_i, $U(x_i)$) and the KCRV ((x_w), $U(x_w)$) is obtained with the calculation of the compatibility index E_n, where U is the expanded uncertainty, obtained from the standard uncertainty by multiplying by a suitable value of k to obtain a 95 % confidence level.

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

In the following table the results with the KCRV and the calculated E_n values are shown.

Nominal distance (mm)	$\bar{x}_w$ (µm)	$u(\bar{x}_w)$ (µm)	$\|E_n\|$ INRIM	$\|E_n\|$ INTI
0	0.00	0.02	0.00	0.00
1	0.02	0.02	0.01	0.01
2	0.01	0.03	0.10	0.10
3	0.02	0.03	0.16	0.16
4	0.00	0.03	0.14	0.14
5	0.01	0.03	0.11	0.11
6	0.02	0.03	0.00	0.00
7	0.01	0.03	0.08	0.08
8	0.01	0.03	0.13	0.13
9	-0.01	0.03	0.20	0.20
10	0.00	0.03	0.15	0.15

Table 5 – KCRV, associated standard uncertainty and E_n

Nominal distance (mm)	$\bar{x}_w$ (µm)	$u(\bar{x}_w)$ (µm)	$\|E_n\|$ INRIM	$\|E_n\|$ INTI
10	0.00	0.03	0.15	0.15
15	-0.02	0.03	0.14	0.14
20	-0.02	0.03	0.00	0.00
25	-0.02	0.03	0.27	0.27
30	-0.04	0.03	0.25	0.25
35	-0.05	0.03	0.36	0.36
40	-0.06	0.03	0.27	0.27
45	-0.07	0.03	0.22	0.22
50	-0.08	0.04	0.26	0.26
55	-0.09	0.03	0.24	0.24
60	-0.10	0.03	0.28	0.28
65	-0.10	0.04	0.40	0.40
70	-0.11	0.04	0.43	0.43

75	-0.13	0.04	0.24	0.24
80	-0.12	0.04	0.15	0.15
85	-0.14	0.03	0.40	0.40
90	-0.15	0.03	0.12	0.12
95	-0.19	0.04	0.31	0.31
100	-0.17	0.04	0.31	0.31
105	-0.17	0.04	0.16	0.16
110	-0.18	0.04	0.15	0.15
115	-0.18	0.04	0.14	0.14
120	-0.18	0.04	0.13	0.13
125	-0.19	0.04	0.10	0.10
130	-0.19	0.04	0.10	0.10
135	-0.20	0.04	0.00	0.00
140	-0.20	0.04	0.01	0.01
145	-0.21	0.04	0.02	0.02
150	-0.23	0.04	0.07	0.07
155	-0.23	0.04	0.07	0.07
160	-0.23	0.05	0.04	0.04
165	-0.23	0.04	0.10	0.10
170	-0.25	0.05	0.17	0.17
175	-0.26	0.05	0.21	0.21
180	-0.26	0.05	0.27	0.27
185	-0.25	0.05	0.26	0.26
190	-0.26	0.05	0.25	0.25
195	-0.27	0.05	0.33	0.33
200	-0.26	0.06	0.25	0.25
205	-0.29	0.07	0.37	0.37
210	-0.29	0.05	0.31	0.31
215	-0.29	0.05	0.39	0.39
220	-0.30	0.05	0.35	0.35
225	-0.32	0.05	0.34	0.34
230	-0.33	0.05	0.33	0.33
235	-0.34	0.06	0.40	0.40
240	-0.35	0.06	0.26	0.26
245	-0.36	0.06	0.34	0.34
250	-0.37	0.06	0.33	0.33
255	-0.37	0.06	0.37	0.37
260	-0.39	0.06	0.31	0.31
265	-0.38	0.05	0.25	0.25
270	-0.39	0.06	0.39	0.39
275	-0.40	0.06	0.35	0.35
280	-0.38	0.07	0.31	0.31

Table 6 – KCRV, associated standard uncertainty and E_n

9.2 Calculation of the Degrees of Equivalence

The Degree of Equivalence, DoE, for a laboratory is calculated simply by the difference $d = x_i - \bar{x}_w$.
The expanded uncertainty is calculated as in equation [4] as

$$U(d) = U(x_i - \bar{x}_w) = \sqrt{[U(x_i)]^2 - [U(\bar{x}_w)]^2} \quad [6]$$

	INRIM		INTI	
Nominal distance (mm)	$d = x_i - \bar{x}_w$ (µm)	$U(x_i - \bar{x}_w)$ (µm)	$d = x_i - \bar{x}_w$ (µm)	$U(x_i - \bar{x}_w)$ (µm)
0	0.00	0.01	0.00	0.13
1	0.00	0.01	0.00	0.13
2	0.00	0.02	-0.01	0.13
3	0.00	0.02	-0.02	0.13
4	0.00	0.02	0.02	0.13
5	0.00	0.02	0.01	0.13
6	0.00	0.02	0.00	0.13
7	0.00	0.02	0.01	0.13
8	0.00	0.02	0.02	0.13
9	0.00	0.02	0.03	0.13
10	0.00	0.02	0.02	0.13
15	0.00	0.02	0.02	0.13
20	0.00	0.02	0.00	0.13
25	-0.01	0.02	0.03	0.13
30	-0.01	0.02	0.03	0.13
35	-0.01	0.02	0.05	0.13
40	-0.01	0.02	0.04	0.13
45	0.00	0.02	0.03	0.15
50	-0.01	0.04	0.04	0.14
55	0.00	0.02	0.04	0.15
60	-0.01	0.02	0.04	0.15
65	-0.01	0.04	0.06	0.14
70	-0.02	0.04	0.06	0.14
75	-0.01	0.04	0.03	0.14
80	-0.01	0.04	0.02	0.14
85	-0.01	0.02	0.06	0.15
90	0.00	0.02	0.02	0.17
95	-0.01	0.03	0.05	0.16
100	-0.01	0.03	0.05	0.16
105	-0.01	0.03	0.03	0.16
110	0.00	0.03	0.03	0.16
115	0.00	0.03	0.02	0.16
120	0.00	0.03	0.02	0.16
125	0.00	0.03	0.02	0.19
130	0.00	0.03	0.02	0.19
135	0.00	0.03	0.00	0.19

140	0.00	0.03	0.00	0.19
145	0.00	0.03	0.00	0.19
150	0.00	0.03	-0.01	0.19
155	0.00	0.03	-0.02	0.21
160	0.00	0.06	-0.01	0.19
165	0.00	0.03	-0.02	0.21
170	0.01	0.04	-0.03	0.20
175	0.01	0.04	-0.04	0.20
180	0.01	0.05	-0.06	0.21
185	0.01	0.04	-0.06	0.22
190	0.01	0.04	-0.05	0.22
195	0.02	0.05	-0.07	0.21
200	0.02	0.07	-0.05	0.21
205	0.03	0.08	-0.08	0.22
210	0.02	0.05	-0.07	0.24
215	0.02	0.05	-0.09	0.24
220	0.02	0.05	-0.08	0.24
225	0.02	0.05	-0.08	0.24
230	0.01	0.03	-0.09	0.26
235	0.02	0.05	-0.10	0.26
240	0.01	0.05	-0.07	0.26
245	0.02	0.06	-0.09	0.25
250	0.02	0.06	-0.09	0.27
255	0.02	0.06	-0.10	0.27
260	0.01	0.04	-0.08	0.28
265	0.01	0.03	-0.07	0.28
270	0.02	0.04	-0.11	0.28
275	0.02	0.06	-0.10	0.29
280	0.02	0.07	-0.09	0.29

Table 7 – Degree of Equivalence and associated expanded uncertainty

9.3 Discussion of the results

Considering the results in Table 5 and 6, since the E_n values are smaller than 1, the reported measurement results of INRIM and INTI are considered as consistent and the comparison is considered as successful.