Asia-Pacific Metrology Programme

APMP Key Comparison

APMP.L-K1.1

Calibration of gauge blocks by interferometry

Final Report – Results

Contents

Appendices

A: Reporting Forms:

B: taken from Excel spread sheet

1. Introduction

It was decided to carry out a regional key comparison on gauge block measurements to follow up the previous comparison APMP.L-K1. The National Metrology Institute of Japan (NMIJ/AIST) acts as the pilot laboratory as APMP.L-K1.

The plan of APMP.L-K1.1 was announced at the meeting of The Asia Pacific Metrology Programme's Technical Committee for Length (APMP/TCL), which was held in Beijing in October 2004. The technical protocol and artefacts is modelled on that of APMP.L-K1.

A goal of dimensional metrology key comparisons is to compare routine calibration services offered by NMIs to clients. Uncertainty claims should match those listed in Appendix C of the Mutual Recognition Agreement (MRA) [BIPM, 1999]. To this end, participants in this comparison agree to use the same apparatus and methods as routinely applied to client artefacts.

The participant's replies have been collated into an Excel spreadsheet and are shown in Appendix B in an Excel workbook. These results are identified in the text with a B pre-fix.

2. Organization

2.1 Participants

APMP member laboratories were invited to join the comparison by the pilot laboratory. The service tested in this comparison is the measurement of central length of gauge blocks covering the range 0.5 mm to 100 mm to a standard uncertainty of less than approximately 50 nm.

2.2 Participants' details

INTERFEROMETRIC MEASUREMENTS		
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Table 1. Participant’s details at the start of the comparison

2.3 Comparison schedule

The comparison was carried out in a mixed form, circulation and star-type. Two circulation groups have been chosen with the pilot measuring before and after each group. Table B1 shows the original schedule and the actual schedule of participants.

2.4 Handling and transport

After the circulation, it was unable to measure the gauge block of 0.5 mm at the pilot laboratory because of damage. Four other gauge blocks have been damaged on one of the surfaces. It was able to wring the left surface of the gauge block of 1.1 mm in the last measurement at the pilot laboratory, however, the wringing quality was low because of the damage. The other artefacts showed some scratches, but were still in an acceptable condition for interferometric measurements.

3. Description of artefacts

The set contains 10 steel gauge blocks. The gauge blocks are of rectangular cross section, according to the international standard ISO 3650. The thermal expansion coefficient of the gauge block of 100 mm has been measured by the pilot laboratory. This value of the thermal expansion coefficient is applied to all gauge blocks.

Identification	Nominal length (mm)	Expansion coeff. (10^{-6} K^{-1})	Manufacturer
040792	0.5	10.6 ± 0.1	Mitutoyo
040330	1.01	10.6 ± 0.1	Mitutoyo
040163	1.1	10.6 ± 0.1	Mitutoyo
042650	6	10.6 ± 0.1	Mitutoyo
051520	7	10.6 ± 0.1	Mitutoyo
043000	8	10.6 ± 0.1	Mitutoyo
041583	15	10.6 ± 0.1	Mitutoyo
030770	80	10.6 ± 0.1	Mitutoyo
040779	90	10.6 ± 0.1	Mitutoyo
042033	100	10.6 ± 0.1	Mitutoyo

Table 2. Description of gauge blocks

4. Reported results

The Technical Protocol asked the participants to report the followings with the specified form:

A1: The central length measured in two orientations and the uncertainty for the average of these measurements , see Form A1 (Measurement results) .
A2: The observed condition of the measurement surfaces, see Form A2 (Inspection of the measurement surfaces)
A3: A description of the type of interferometer, the light sources, the method of fringe fraction determination, the method used for determination of refractive index of the air, the range of gauge block temperature during measurement and phase correction, see Form A3 (Description of the measurement instrument).
A4: The Uncertainty budget, see Form A4 (Uncertainty of measurement)

5. Analysis of the results

5.1 Discussion

The aim of this analysis is to find a key reference value which can be used to determine the deviations of the results of each laboratory. As APMP.L-K1, the weighted mean values are used as key reference values after excluding the measured value which corresponded to an absolute En number larger than one based on one-by-one procedure. Very similar key comparisons have been completed for Gauge blocks (CCL-K1, APMP.L-K1) and for Long Gauge blocks (CCL-K2, APMP.L-K2). The policy using a weighted mean as a key reference value has been agreed by all the participants of APMP.L-K1.1 before the Draft B becomes open to the public.
On the other hand, the values of CMS are also excluded from key reference values calculations because CMS reported their values with wrong phase corrections caused by mistakes in calculating the phase correction values. CMS explains that the correct phase correction values are 20 nm larger than those actually used in the reported values.

5.2 Weighting Factors and the Reference Value

Let the measured deviation from nominal size reported by each participant be x_i, where the number of laboratories is given by I. Since the gauge blocks have different lengths, thermal expansion coefficients, material properties *etc*, it is reasonable to expect that the data comes from separate populations (one per gauge block) and so analysis should be on a gauge-by-gauge basis.

Thus, for a particular gauge block:
Each laboratory reports a measured value, x_i, and its associated standard uncertainty $u(x_i)$.
The normalised weight, w_i, for the result x_i is given by:

$$w_i = C \cdot \frac{1}{[u(x_i)]^2} \tag{1}$$

where the normalising factor, C, is given by:

$$C = \frac{1}{\sum_{i=1}^{I} \left(\frac{1}{u(x_i)} \right)^2} \tag{2}$$

Then the weighted mean, $\bar{x}_w$, is given by:

$$\bar{x}_w = \sum_{i=1}^{I} w_i \cdot x_i \tag{3}$$

The simple mean uses a weighting factor of one and is given by:

$$\bar{x}_a = \sum_{i=1}^{I} \frac{x_i}{I} \tag{4}$$

Each participant, including the pilot, should only contribute once to any determination of a reference value. The comparison reference value $\bar{x}_{RV}$ can be set equal to the simple mean ($\bar{x}_a$ - Equation 4) or the weighted mean ($\bar{x}_w$ - Equation 3), and these options are discussed below.

5.3 Uncertainties

If the artefact uncertainty is ignored, the uncertainty of the reference value can be calculated as either the internal $u_{\text{int}}(\bar{x}_{RV})$ or external $u_{ext}(\bar{x}_{RV})$ standard deviation. The internal standard deviation is based on the estimated uncertainties $u(x_i)$ as reported by the participants:

$$u_{\text{int}}(\bar{x}) = \sqrt{\frac{1}{\sum_{i=1}^{I}\left(\frac{1}{u(x_i)}\right)^2}} = \sqrt{C} \tag{5}$$

The external standard deviation is the standard deviation of the spread of the residuals $x_i - \bar{x}_{RV}$, weighted by the uncertainties $u(x_i)$:

$$u_{ext}(\bar{x}\ ) = \sqrt{\frac{1}{(I-1)} \cdot \frac{\sum_{i=1}^{I} w_i (x_i - \bar{x}_{RV})^2}{\sum_{i=1}^{I} w_i}} \tag{6}$$

The residuals have an uncertainty which results from the measured value ($x_i \pm u(x_i)$) and the reference value ($\bar{x}_{RV} \pm u(\bar{x}_{RV})$) . The uncertainty of the reference value is taken to be the internal uncertainty and the uncertainty of the artefact $u_{art}(\bar{x}_{RV})$. The internal uncertainty can be viewed as setting a limit to the knowable accuracy of any artefact length, given the uncertainty of each measurement. The artefact uncertainty sets a limit on the stability of the artefact during the comparison. The pilot's measurements provide the best information on artefact changes, given that the same instrument and method were used each time. The uncertainty of the artefact is obtained by the standard deviation of measurements at the pilot laboratory.

The uncertainty for each participant's residual is therefore given by:

$$u(x_i - \bar{x}_{RV}) = \sqrt{[u(x_i)]^2 - [u_{\text{int}}(\bar{x}_w)]^2 + [u_{art}(\bar{x}_{pilot})]^2} \tag{7}$$

The internal uncertainty is subtracted from the participant's uncertainty because their result has already pulled the reference value in their direction (it has a negative correlation). This could be avoided by excluding them from the reference value they are compared with, but this approach is not used here.

5.4 Analysis using E$_n$ *values*

A check for statistical consistency of the results with their associated uncertainties can be made by calculating the E_n value for each laboratory, where E_n is defined as the ratio of the deviation from the weighted mean, divided by the uncertainty of this deviation, taken for a coverage factor of k=2:

$$E_n = \frac{x_i - \bar{x}_{RV}}{2 \cdot u(x_i - \bar{x}_{RV})} \tag{8}$$

E_n values should be less than 1, if the participant's result and uncertainty are consistent with the reference value. These values are shown in Table B12 and Fig B11

5.5 Stability of the artefacts

The pilot measured the artefact three times, that is before, middle of, and after the circulation. The uncertainty of the artefact is obtained by the standard deviation of the three measurements at the pilot laboratory.

Most of the artefacts show good stabilities, however, there are some gauges having rather large variation. Because the surfaces of some gauge blocks were deteriorated especially at the third measurement, the wringing quality might be rather poor. The pilot evaluated the value of phase correction by measuring an auxiliary gauge on a platen and a gauge block, and calculated their difference. Several auxiliary gauges and gauge blocks were used for the evaluation of the phase correction to average the effect of the surface damage, however the phase correction might be somewhat large.

The results and uncertainties of the first and third measurements at the pilot laboratory aren't used in calculations of the reference values. The results of the three measurements at the pilot laboratory have effects on the analysis using E_n values through the uncertainty of the artefacts.

5.6 Birge ratios tests

The statistical consistency of a comparison can also be investigated by the Birge ratio R_B, which compares the observed spread of the results with the spread expected from the individual reported uncertainties.

The application of least squares algorithms and the χ^2-test leads to the Birge ratio:

$$R_B = \frac{u_{ext}(\bar{x}_w)}{u_{int}(\bar{x}_w)} \tag{9}$$

The Birge ratio has an expectation value of $R_B = 1$, when considering standard uncertainties. For a coverage factor of $k = 2$, the expectation value is increased and the data in a comparison are consistent provided that

$$R_B < \sqrt{1+\sqrt{8/(I-1)}} \tag{10}$$

where I is the number of laboratories. For the case $I = 6$, a value of $R_B < 1.505$ indicates consistency.

Only one measurement from the pilot is used. The pilot's value NMIJ2 is used because this is towards the middle of the comparison.

The Birge ratios are shown in Table B15 and summarised below in Table 3.

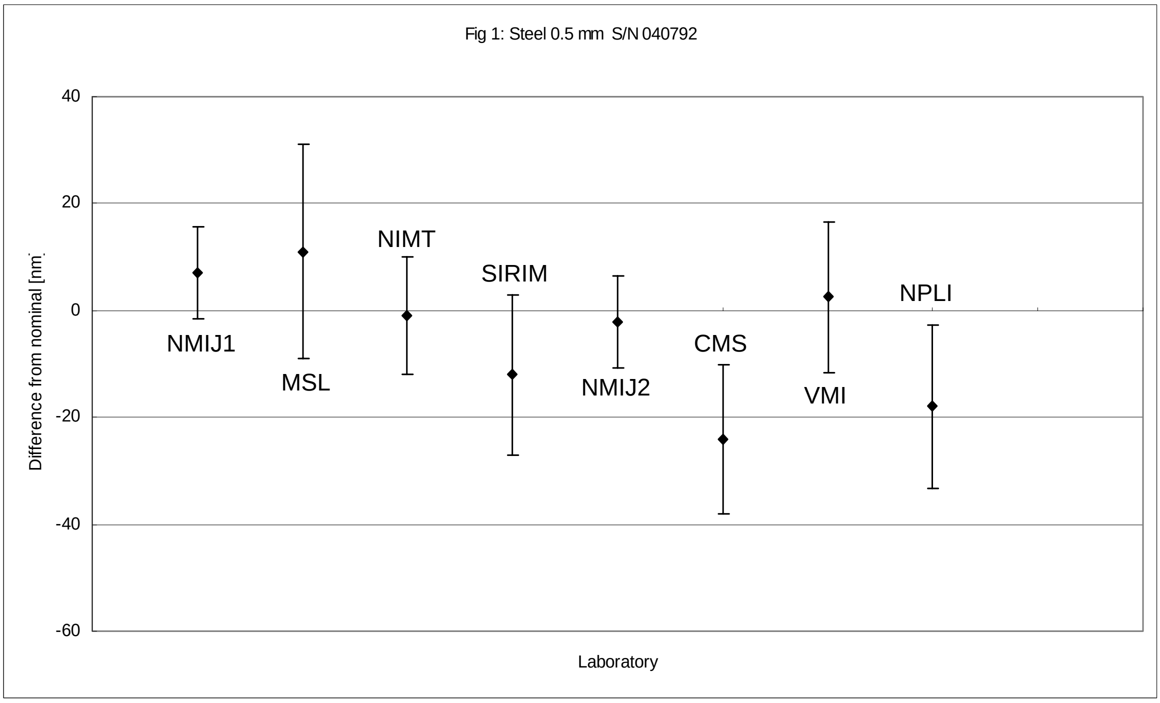
The Birge ratio should be less than 1.50 and this is roughly the case for all gauges.

Gauge Length [mm]	0.5	1.01	1.1	6	7	8	15	80	90	100
Birge ratios	0.63	0.93	1.43	1.17	1.19	0.64	0.68	0.69	1.05	0.77

Table 3. Birge ratios.

CRITICAL FIGURES FROM APPENDIX B

Figure 1 to 10: Measurement data from each participant with error bars corresponding to combined standard uncertainty.



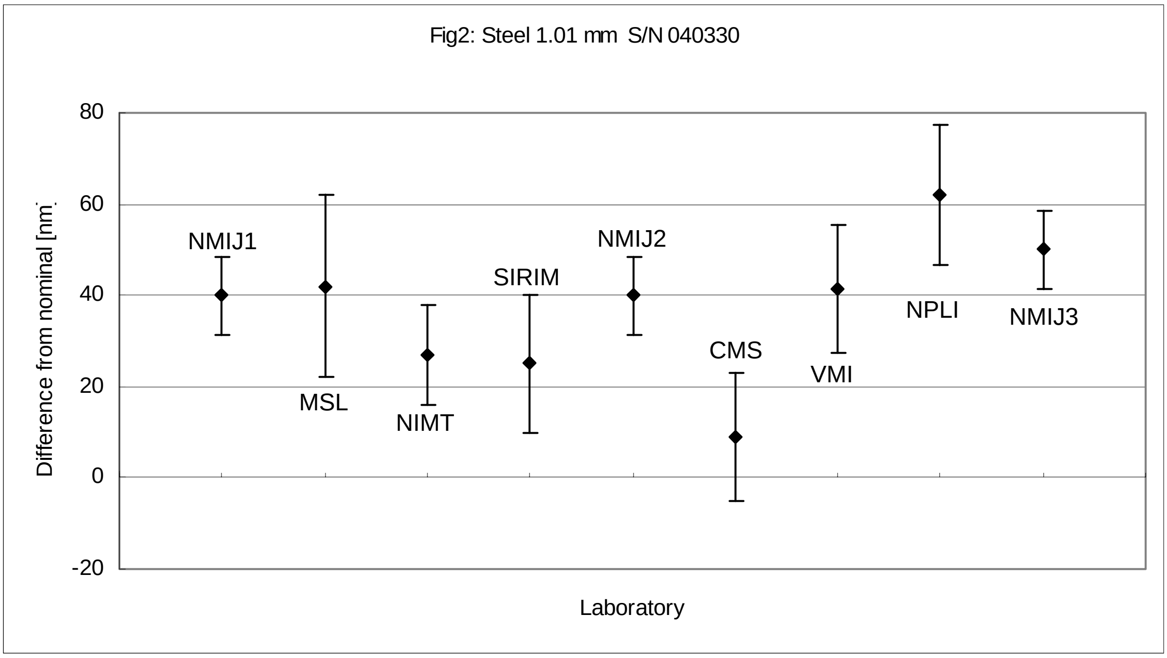


Fig. 1, 2

Fig3: Steel 1.1 mm S/N 040163

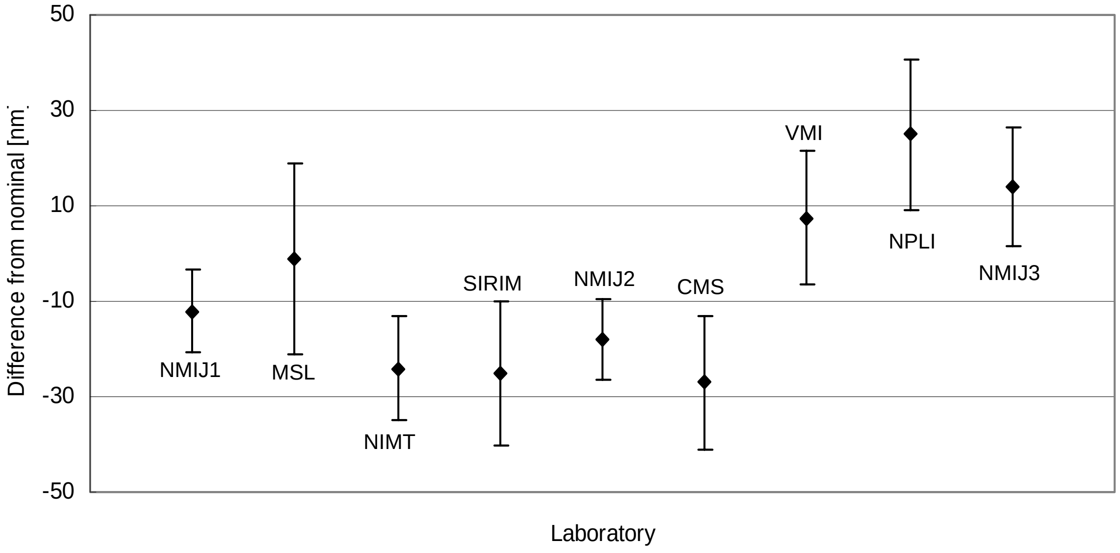


Fig4: Steel 6 mm S/N 042650

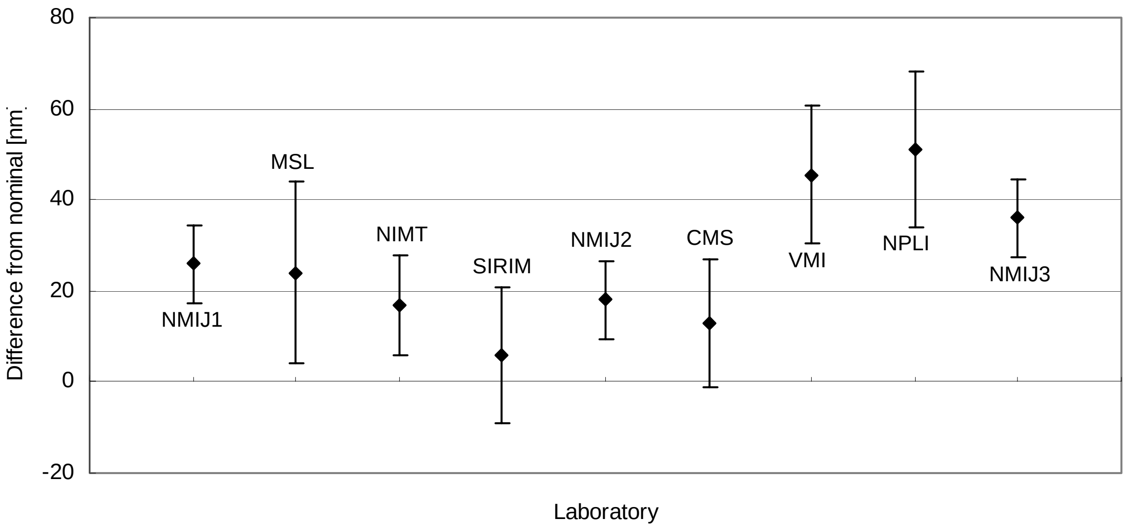


Fig. 3, 4

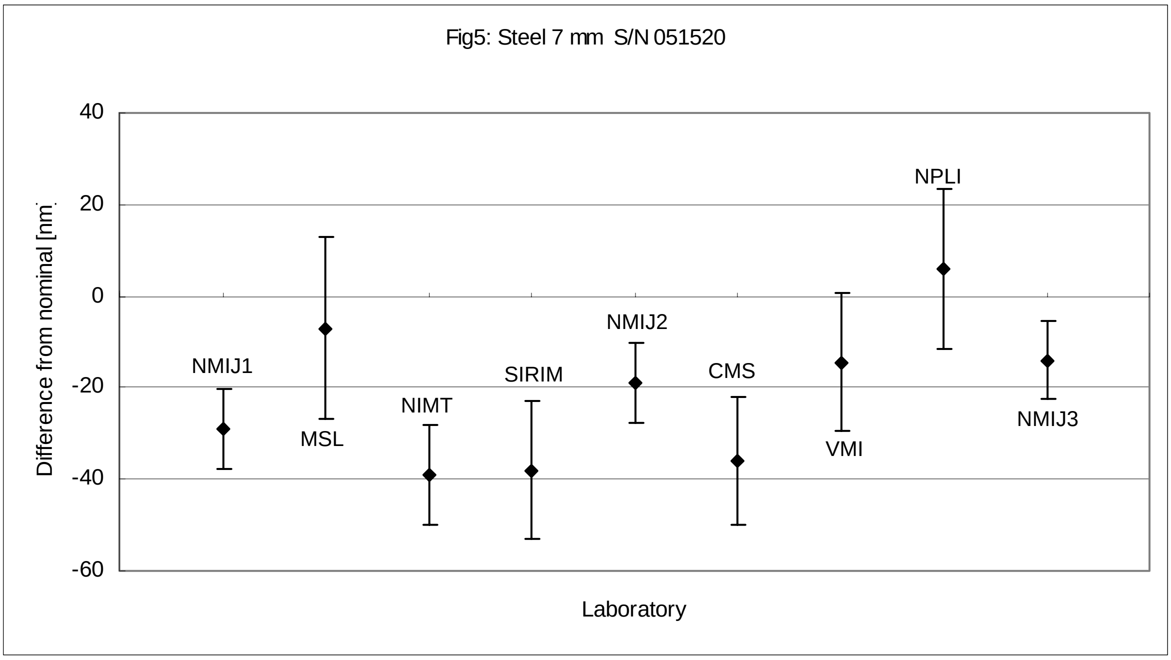


Fig5: Steel 7 mm S/N 051520
40
20
0
-20
-40
-60
Difference from nominal [nm]
NMIJ1
MSL
NIMT
SIRIM
NMIJ2
CMS
VMI
NPLI
NMIJ3
Laboratory

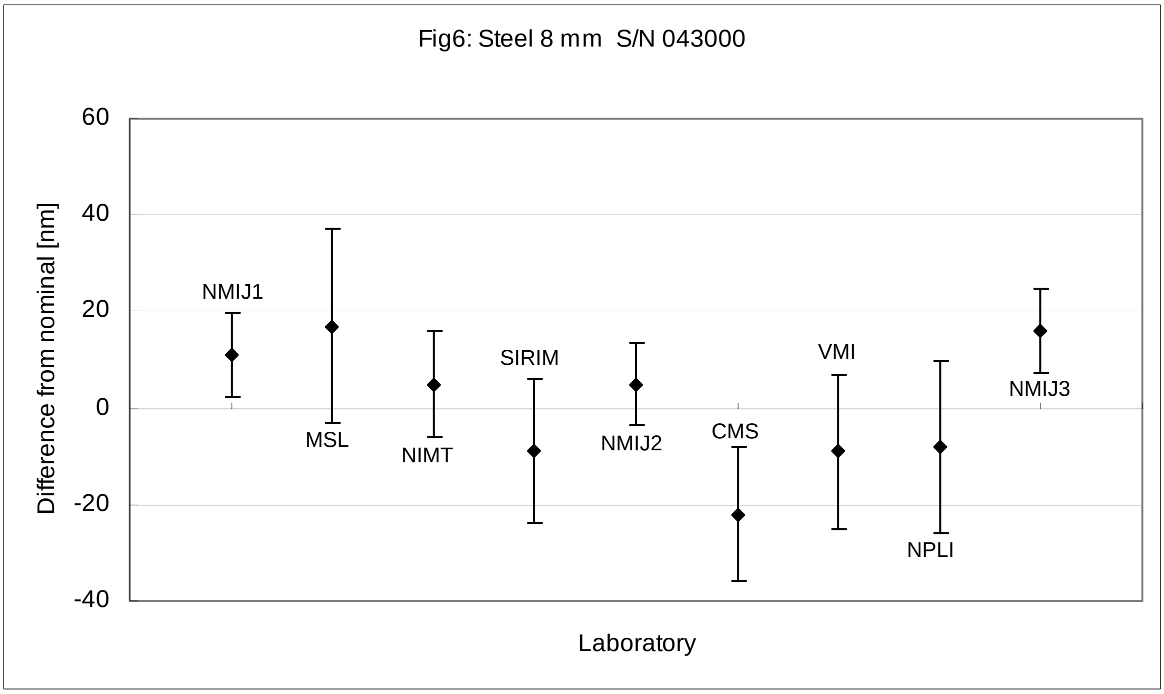


Fig6: Steel 8 mm S/N 043000
60
40
20
0
-20
-40
Difference from nominal [nm]
NMIJ1
MSL
NIMT
SIRIM
NMIJ2
CMS
VMI
NPLI
NMIJ3
Laboratory

Fig. 5, 6

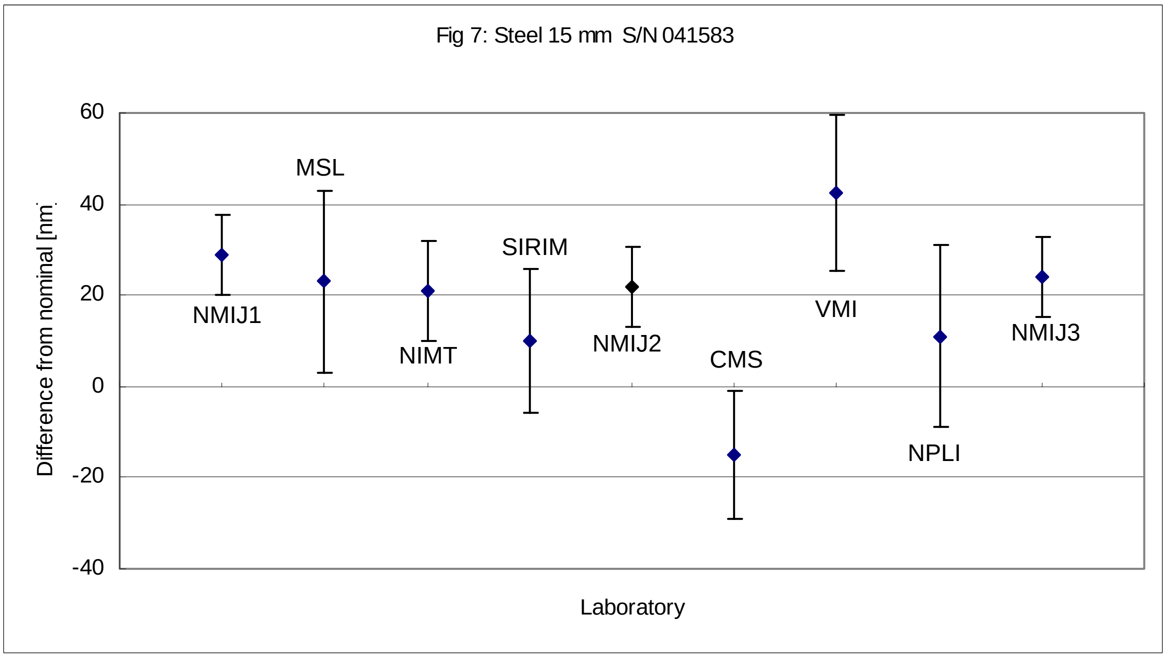


Fig 7: Steel 15 mm S/N 041583
Difference from nominal [nm]
60
40
20
0
-20
-40
Laboratory
NMIJ1
MSL
NIMT
SIRIM
NMIJ2
CMS
VMI
NPLI
NMIJ3

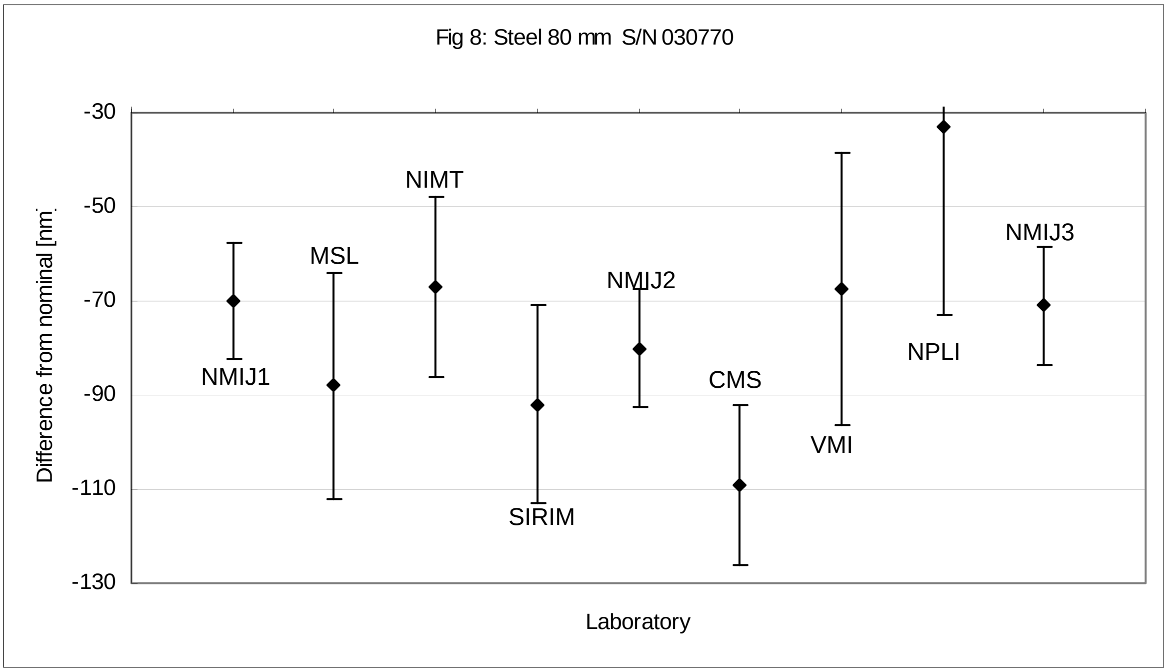


Fig 8: Steel 80 mm S/N 030770
Difference from nominal [nm]
-30
-50
-70
-90
-110
-130
Laboratory
NMIJ1
MSL
NIMT
SIRIM
NMIJ2
CMS
VMI
NPLI
NMIJ3

Fig. 7, 8

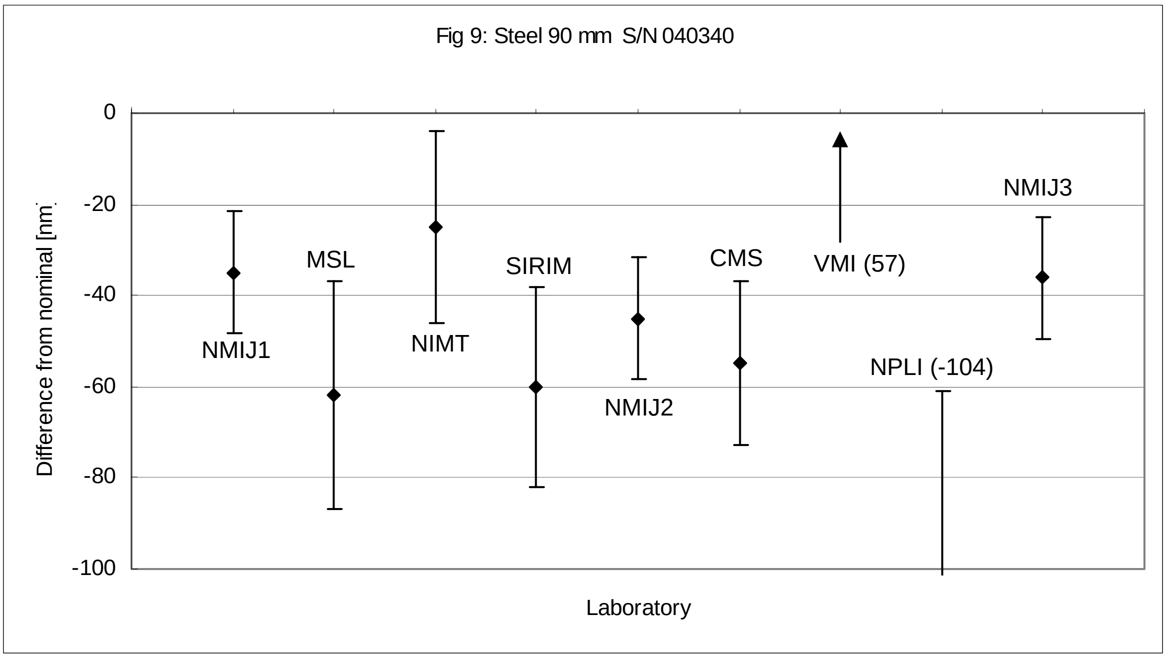


Fig 9: Steel 90 mm S/N 040340
0
-20
-40
-60
-80
-100
Difference from nominal [nm]
Laboratory
NMIJ1
MSL
NIMT
SIRIM
NMIJ2
CMS
VMI (57)
NPLI (-104)
NMIJ3

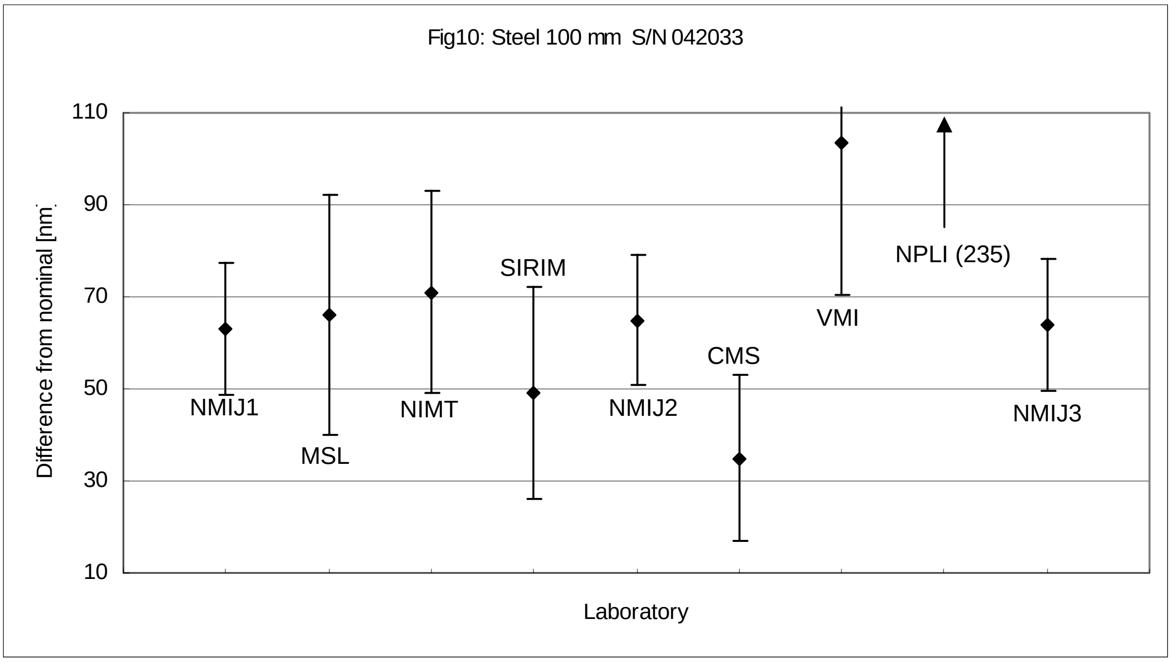


Fig10: Steel 100 mm S/N 042033
110
90
70
50
30
10
Difference from nominal [nm]
Laboratory
NMIJ1
MSL
NIMT
SIRIM
NMIJ2
CMS
VMI
NPLI (235)
NMIJ3

Fig. 9, 10

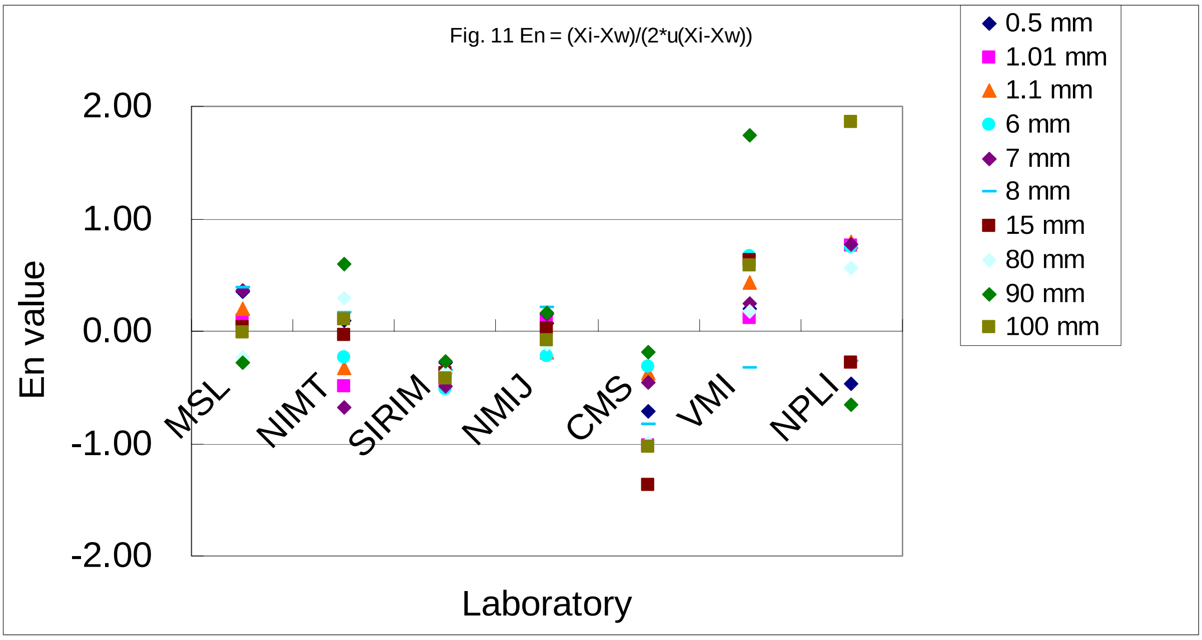


Figure 11: En values

Appendix A Reporting Forms

A1

Measurement results:

Steel gauge blocks:

Id. no.	nom. length	central length (**deviation** from nominal length)			uncert. (1s)	eff. deg. of freedom
	L (mm)	Δl left (µm)	Δl right (µm)	Δl (µm)	u_c (nm)	n_{eff}
040792	0.5					
040330	1.01					
040163	1.1					
042650	6					
051520	7					
043000	8					
041583	15					
030770	80					
040779	90					
042033	100					

A2

Inspection of the measurement surfaces, steel gauge blocks

0.5 mm

left right

1.01 mm

left right

1.1 mm

left right

6 mm

left right

7 mm

left right

8 mm

left right

15 mm

left right

80 mm

left right

90 mm

left right

100 mm

left right

A3

Description of the measurement instrument

Make and Type of interferometer..

....

....

....

....

....

Light sources / Wave lengths used:...

....

....

....

....

Method of fringe fraction determination:..

....

....

....

....

Method used for determination of refractive index of the air:...

....

....

....

....

Range of gauge block temperature during measurements:...

....

....

....

Phase correction:

gauge block material	material of reference flats	phase correction applied (give range, if applicable)
steel		

A4

Uncertainty of measurement

x_i	$u(x_i)$	n_i	$c_i = \partial l/\partial x_i$	$u_i(l)$ / nm

Combined standard uncertainty: $u_c(l) =$

A5

Telefax Telefax Telefax Telefax Telefax

To: **Akiko Hirai**
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Japan
Fax: +81-29-861-4080
e-mail: a-hirai@aist.go.jp

From: (participating laboratory)

We confirm having received the standards of the *follow-up comparison of APMP. L-K1 on gauge block measurement* on ....(date).

After visual inspection

no damage has been noticed.

the following damage(s) must be reported:
....
....
....
....

Date: Signature:

....

Table 1

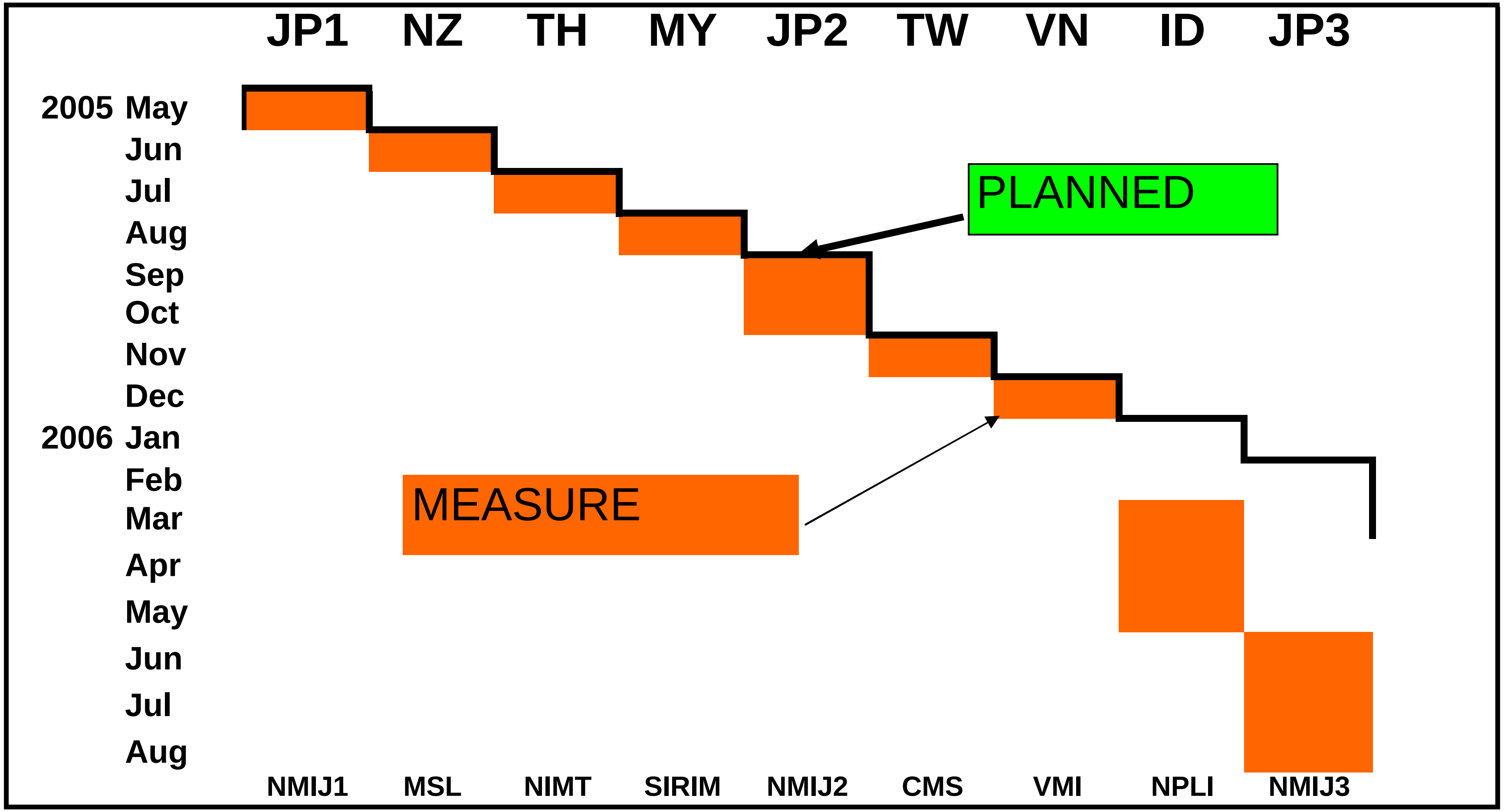

JP1
NZ
TH
MY
JP2
TW
VN
ID
JP3
2005 May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2006 Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
PLANNED
MEASURE
NMIJ1
MSL
NIMT
SIRIM
NMIJ2
CMS
VMI
NPLI
NMIJ3

Table 2 Steel 0.5mm S/N 040792

							Non-weighted		Weighted				Institute number for xref
	Economy	Laboratory	Δl_{left}(um)	Δl_{right}(um)	Δl (um)	u_c(nm)	x_i-x_{ref}	$(x_i-x_{ref})^2$	$u^{-2}(x_i)$	$u^{-2}(x_i)*x_i$	wi after convergence	wi(xi-xref)^2	I
2	New Zealan	MSL	0.0140	0.0090	0.0110	20.0	14.250	203.063	0.003	0.028	0.066	13.373	6
3	Thailand	NIMT	-0.0010	-0.0010	-0.0010	11.0	2.250	5.063	0.008	-0.008	0.217	1.116	
4	Malaysia	SIRIM	-0.0120	-0.0110	-0.0120	15.0	-8.750	76.563	0.004	-0.053	0.117	8.910	Consistent RB
5	Japan	NMIJ2	-0.0020	-0.0030	-0.0020	8.6	1.250	1.563	0.014	-0.027	0.355	0.570	1.505
6	Taiwan	CMS	-0.0160	-0.0320	-0.0240	14.0	-20.750	430.563	0.005	-0.122	0.134	57.644	O
7	Vietnam	VMI	0.0090	-0.0040	0.0025	14.0	5.750	33.063	0.005	0.013	0.134	4.459	
8	India	NPLI	-0.0190	-0.0160	-0.0180	15.4	-14.750	217.563	0.004	-0.076	0.111	24.057	
1	Japan	NMIJ1	0.0110	0.0020	0.0070	8.6	10.250	105.063	0.014	0.095	0.355	37.455	
9	Japan	NMIJ3	-	-	-	-	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	

C (after convergence)	26.282	sum(wi)	1.000	RB
uint(x)	5.127	sum(wi(xi-xr	52.484	0.632
uart(xpilot)	6.364	uext(x)	3.240	

Non-weighted mean [nm]

x_a -3.2500

$u(x_a)$ 4.2303

1st

Weighted mean [nm]

x_w -3.2664

$u(x_w)$ 5.1266

		x_i-x_{RV}	$U(x_i-x_{RV})$	En	O: good
New Zealan	MSL	14.266	40.705	0.350	O
Thailand	NIMT	2.266	23.257	0.097	O
Malaysia	SIRIM	-8.734	30.933	-0.282	O
Japan	NMIJ2	1.266	18.781	0.067	O
Taiwan	CMS	-20.734	28.998	-0.715	O
Vietnam	VMI	5.766	28.998	0.199	O
India	NPLI	-14.734	31.710	-0.465	O
Japan	NMIJ1	10.266	18.781	0.547	O
Japan	NMIJ3	#VALUE!	#VALUE!	#VALUE!	#VALUE!

Yellow cells are not used to calculate the weighted mean.

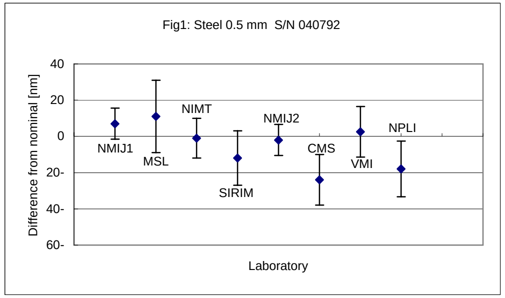


Table 3 Steel 1.01mm S/N 040330

							Non-weighted		Weighted				Institute number for xref
	Economy	Laboratory	Δl_{left}(um)	$\Delta l_{\mathrm{right}}$(um)	Δl (um)	u_c(nm)	x_i-x_{ref}	$(x_i-x_{ref})^2$	$u^{-2}(x_i)$	$u^{-2}(x_i)*x_i$	wi after convergence	wi(xi-xref)^2	I
2	New Zealan	MSL	0.0370	0.0480	0.0420	20.0	2.417	5.840	0.003	0.105	0.066	0.970	6
3	Thailand	NIMT	0.0070	0.0460	0.0270	11.0	-12.583	158.340	0.008	0.223	0.218	27.095	
4	Malaysia	SIRIM	0.0240	0.0250	0.0250	15.0	-14.583	212.674	0.004	0.111	0.117	20.261	Consistent RB
5	Japan	NMIJ2	0.0390	0.0400	0.0400	8.6	0.417	0.174	0.014	0.541	0.356	1.204	1.505
6	Taiwan	CMS	0.0230	-0.0060	0.0090	14.0	-30.583	935.340	0.005	0.046	0.134	114.189	O
7	Vietnam	VMI	0.0350	0.0480	0.0415	14.0	1.917	3.674	0.005	0.212	0.134	1.497	
8	India	NPLI	0.0590	0.0650	0.0620	15.5	22.417	502.507	0.004	0.258	0.110	62.259	
1	Japan	NMIJ1	0.0410	0.0400	0.0400	8.6	0.417	0.174	0.014	0.541	0.356	1.204	
9	Japan	NMIJ3	0.0570	0.0440	0.0500	8.6	10.417	108.507	0.014	0.676	0.356	49.881	
								C（after cor	26.320		sum(wi)	1.000	RB
								uint(x)	5.130		sum(wi(xi-xr	113.286	0.928
								uart(xpilot)	5.774		uext(x)	4.760	

Non-weighted mean [nm]

x_a 39.5833

$u(x_a)$ 5.4259

1st

Weighted mean [nm]

x_w 38.1608

$u(x_w)$ 5.1303

		x_i-x_{RV}	$U(x_i-x_{RV})$	En	O: good
New Zealan	MSL	3.839	40.349	0.095	O
Thailand	NIMT	-11.161	22.629	-0.493	O
Malaysia	SIRIM	-13.161	30.464	-0.432	O
Japan	NMIJ2	1.839	17.997	0.102	O
Taiwan	CMS	-29.161	28.497	-1.023	X
Vietnam	VMI	3.339	28.497	0.117	O
India	NPLI	23.839	31.449	0.758	O
Japan	NMIJ1	1.839	17.997	0.102	O
Japan	NMIJ3	11.839	17.997	0.658	O

Yellow cells are not used to calculate the weighted mean.

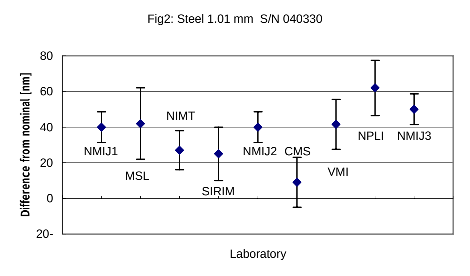


Table 4 Steel 1.1mm S/N 040163

							Non-weighted		Weighted				Institute number for xref
	Economy	Laboratory	Δl_{left}(um)	Δl_{right}(um)	Δl (um)	u_c(nm)	x_i-x_{ref}	$(x_i-x_{ref})^2$	$u^{-2}(x_i)$	$u^{-2}(x_i)*x_i$	wi after convergence	wi(xi-xref)^2	I
2	New Zealan	MSL	-0.0070	0.0050	-0.0010	20.0	4.917	24.174	0.003	-0.003	0.066	6.559	6
3	Thailand	NIMT	-0.0160	-0.0310	-0.0240	11.0	-18.083	327.007	0.008	-0.198	0.218	37.033	
4	Malaysia	SIRIM	-0.0220	-0.0270	-0.0250	15.0	-19.083	364.174	0.004	-0.111	0.117	23.090	Consistent RB
5	Japan	NMIJ2	-0.0240	-0.0120	-0.0180	8.6	-12.083	146.007	0.014	-0.243	0.357	17.636	1.505
6	Taiwan	CMS	-0.0100	-0.0440	-0.0270	14.0	-21.083	444.507	0.005	-0.138	0.135	34.601	O
7	Vietnam	VMI	0.0080	0.0070	0.0075	14.0	13.417	180.007	0.005	0.038	0.135	45.938	
8	India	NPLI	0.0200	0.0300	0.0250	15.7	30.917	955.840	0.004	0.101	0.107	138.540	
1	Japan	NMIJ1	-0.0140	-0.0110	-0.0120	8.6	-6.083	37.007	0.014	-0.162	0.357	0.379	
9	Japan	NMIJ3	-	0.0140	0.0140	12.5	19.917	396.674	0.006	0.090	0.169	105.320	

C（after cor	26.393	sum(wi)	1.000	RB	
uint(x)	5.137	sum(wi(xi-xr	268.795	1.427	
uart(xpilot)	17.010	uext(x)	7.332		

Non-weighted mean [nm]

x_a -5.9167

$u(x_a)$ 8.1593

1st

Weighted mean [nm]

x_w -10.9701

$u(x_w)$ 5.1374

		x_i-x_{RV}	$U(x_i-x_{RV})$	En	O: good
New Zealan	MSL	9.970	51.495	0.194	O
Thailand	NIMT	-13.030	39.189	-0.332	O
Malaysia	SIRIM	-14.030	44.179	-0.318	O
Japan	NMIJ2	-7.030	36.710	-0.191	O
Taiwan	CMS	-16.030	42.846	-0.374	O
Vietnam	VMI	18.470	42.846	0.431	O
India	NPLI	35.970	45.141	0.797	O
Japan	NMIJ1	-1.030	36.710	-0.028	O
Japan	NMIJ3	24.970	40.948	0.610	O

Yellow cells are not used to calculate the weighted mean.

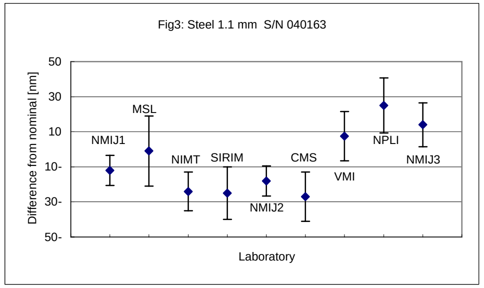


Fig3: Steel 1.1 mm S/N 040163

Table 5 Steel 6 mm S/N 042650

							Non-weighted		Weighted				Institute number for xref
	Economy	Laboratory	Δl_{left}(um)	Δl_{right}(um)	Δl (um)	u_c(nm)	x_i-x_{ref}	$(x_i-x_{ref})^2$	$u^{-2}(x_i)$	$u^{-2}(x_i)*x_i$	wi after convergence	wi(xi-xref)^2	I
2	New Zealan	MSL	0.0210	0.0260	0.0240	20.0	-2.917	8.507	0.003	0.060	0.068	0.049	6
3	Thailand	NIMT	0.0190	0.0150	0.0170	11.0	-9.917	98.340	0.008	0.140	0.226	8.543	
4	Malaysia	SIRIM	0.0050	0.0070	0.0060	15.0	-20.917	437.507	0.004	0.027	0.121	35.724	Consistent RB
5	Japan	NMIJ2	0.0140	0.0220	0.0180	8.6	-8.917	79.507	0.014	0.243	0.369	9.802	1.505
6	Taiwan	CMS	0.0180	0.0080	0.0130	14.0	-13.917	193.674	0.005	0.066	0.139	14.365	O
7	Vietnam	VMI	0.0490	0.0420	0.0455	15.0	18.583	345.340	0.004	0.202	0.121	60.665	
8	India	NPLI	0.0380	0.0640	0.0510	17.1	24.083	580.007	0.003	0.174	0.093	72.482	
1	Japan	NMIJ1	0.0240	0.0270	0.0260	8.6	-0.917	0.840	0.014	0.352	0.369	3.000	
9	Japan	NMIJ3	0.0470	0.0250	0.0360	8.6	9.083	82.507	0.014	0.487	0.369	61.004	
								C（after cor	27.327		sum(wi)	1.000	RB
								uint(x)	5.228		sum(wi(xi-xr	187.266	1.171
								uart(xpilot)	9.018		uext(x)	6.120	

Non-weighted mean [nm]

x_a	26.9167
$u(x_a)$	7.1861

1st

Weighted mean [nm]

x_w	23.1506
$u(x_w)$	5.2275

		x_i-x_{RV}	$U(x_i-x_{RV})$	En	O: good
New Zealan	MSL	0.849	42.615	0.020	O
Thailand	NIMT	-6.151	26.458	-0.232	O
Malaysia	SIRIM	-17.151	33.407	-0.513	O
Japan	NMIJ2	-5.151	22.624	-0.228	O
Taiwan	CMS	-10.151	31.623	-0.321	O
Vietnam	VMI	22.349	33.407	0.669	O
India	NPLI	27.849	37.225	0.748	O
Japan	NMIJ1	2.849	22.624	0.126	O
Japan	NMIJ3	12.849	22.624	0.568	O

Yellow cells are not used to calculate the weighted mean.

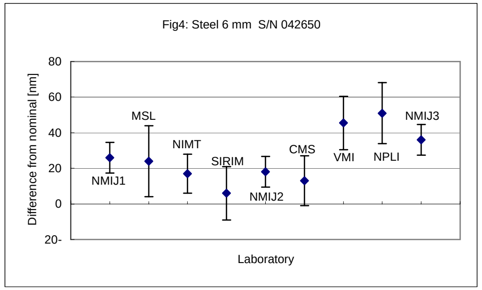


Table 6 Steel 7 mm S/N 051520

							Non-weighted		Weighted				Institute number for xref
	Economy	Laboratory	Δl_{left}(um)	Δl_{right}(um)	Δl (um)	u_c(nm)	x_i-x_{ref}	$(x_i-x_{ref})^2$	$u^{-2}(x_i)$	$u^{-2}(x_i)*x_i$	wi after convergence	wi(xi-xref)^2	I
2	New Zealan	MSL	-0.0100	-0.0030	-0.0070	20.0	11.583	134.174	0.003	-0.018	0.069	15.859	6
3	Thailand	NIMT	-0.0390	-0.0380	-0.0390	11.0	-20.417	416.840	0.008	-0.322	0.227	63.856	
4	Malaysia	SIRIM	-0.0360	-0.0400	-0.0380	15.0	-19.417	377.007	0.004	-0.169	0.122	30.371	Consistent RB
5	Japan	NMIJ2	-0.0300	-0.0080	-0.0190	8.6	-0.417	0.174	0.014	-0.257	0.371	3.824	1.505
6	Taiwan	CMS	-0.0110	-0.0610	-0.0360	14.0	-17.417	303.340	0.005	-0.184	0.140	26.591	O
7	Vietnam	VMI	-0.0090	-0.0200	-0.0145	15.0	4.083	16.674	0.004	-0.064	0.122	7.246	
8	India	NPLI	-0.0080	0.0190	0.0060	17.4	24.583	604.340	0.003	0.020	0.091	72.068	
1	Japan	NMIJ1	-0.0250	-0.0340	-0.0290	8.6	-10.417	108.507	0.014	-0.392	0.371	17.080	
9	Japan	NMIJ3	-0.0040	-0.0240	-0.0140	8.6	4.583	21.007	0.014	-0.189	0.371	24.996	

	C（after cor	27.414		sum(wi)	1.000	RB
Non-weighted mean [nm]	uint(x)	5.236		sum(wi(xi-xre	193.224	1.187
x_a -18.5833	uart(xpilot)	7.638		uext(x)	6.216	
$u(x_a)$ 7.1861						

1st

Weighted mean [nm]

x_w -22.2119

$u(x_w)$ 5.2359

		x_i-x_{RV}	$U(x_i$-$x_{RV})$	En	O: good
New Zealan	MSL	15.212	41.517	0.366	O
Thailand	NIMT	-16.788	24.651	-0.681	O
Malaysia	SIRIM	-15.788	31.995	-0.493	O
Japan	NMIJ2	3.212	20.482	0.157	O
Taiwan	CMS	-13.788	30.128	-0.458	O
Vietnam	VMI	7.712	31.995	0.241	O
India	NPLI	28.212	36.534	0.772	O
Japan	NMIJ1	-6.788	20.482	-0.331	O
Japan	NMIJ3	8.212	20.482	0.401	O

Yellow cells are not used to calculate the weighted mean.

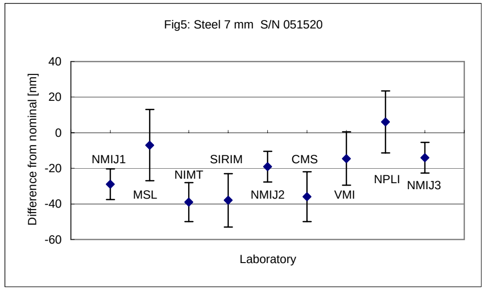


Fig5: Steel 7 mm S/N 051520

Table 7 Steel 8 mm S/N 043000

							Non-weighted		Weighted				Institute number for xref
	Economy	Laboratory	Δl_{left}(um)	Δl_{right}(um)	Δl (um)	u_c(nm)	x_i-x_{ref}	$(x_i-x_{ref})^2$	$u^{-2}(x_i)$	$u^{-2}(x_i)*x_i$	wi after convergence	wi(xi-xref)^2	I
2	New Zealan	MSL	0.0140	0.0210	0.0170	20.0	16.833	283.361	0.003	0.043	0.070	16.946	6
3	Thailand	NIMT	0.0120	-0.0030	0.0050	11.0	4.833	23.361	0.008	0.041	0.231	2.963	
4	Malaysia	SIRIM	-0.0070	-0.0110	-0.0090	15.0	-9.167	84.028	0.004	-0.040	0.124	13.459	Consistent RB
5	Japan	NMIJ2	-0.0040	0.0140	0.0050	8.6	4.833	23.361	0.014	0.068	0.377	4.847	1.505
6	Taiwan	CMS	-0.0100	-0.0330	-0.0220	14.0	-22.167	491.361	0.005	-0.112	0.142	78.082	O
7	Vietnam	VMI	0.0080	-0.0260	-0.0090	16.0	-9.167	84.028	0.004	-0.035	0.109	11.829	
8	India	NPLI	-0.0040	-0.0120	-0.0080	17.7	-8.167	66.694	0.003	-0.026	0.089	7.899	
1	Japan	NMIJ1	0.0050	0.0160	0.0110	8.6	10.833	117.361	0.014	0.149	0.377	34.663	
9	Japan	NMIJ3	0.0130	0.0190	0.0160	8.6	15.833	250.694	0.014	0.216	0.377	80.266	
								C（after cor	27.911		sum(wi)	1.000	RB
								uint(x)	5.283		sum(wi(xi-xr	57.943	0.644
								uart(xpilot)	5.508		uext(x)	3.404	

Non-weighted mean [nm]

x_a	0.1667
$u(x_a)$	4.3391

1st

Weighted mean [nm]

x_w	1.4161
$u(x_w)$	5.2831

Economy	Laboratory	x_i-x_{RV}	$U(x_i$-$x_{RV})$	En	O: good
New Zealan	MSL	15.584	40.121	0.388	O
Thailand	NIMT	3.584	22.219	0.161	O
Malaysia	SIRIM	-10.416	30.161	-0.345	O
Japan	NMIJ2	3.584	17.479	0.205	O
Taiwan	CMS	-23.416	28.172	-0.831	O
Vietnam	VMI	-10.416	32.151	-0.324	O
India	NPLI	-9.416	35.537	-0.265	O
Japan	NMIJ1	9.584	17.479	0.548	O
Japan	NMIJ3	14.584	17.479	0.834	O

Yellow cells are not used to calculate the weighted mean.

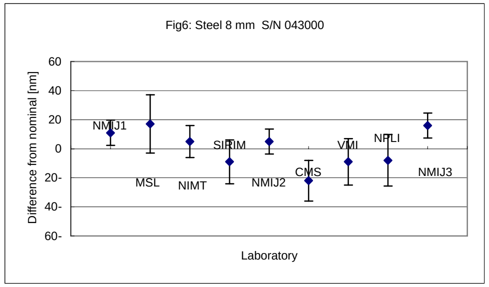
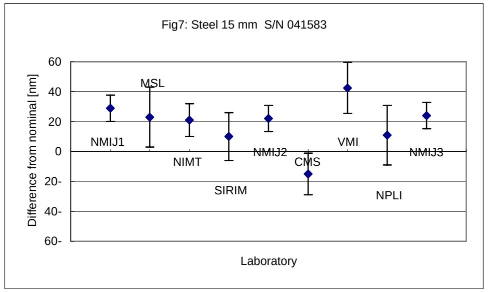


Table 8 Steel 15 mm S/N 041583

							Non-weighted		Weighted				Institute number for xref
	Economy	Laboratory	Δl_{left}(um)	Δl_{right}(um)	Δl (um)	u_c(nm)	x_i-x_{ref}	$(x_i-x_{ref})^2$	$u^{-2}(x_i)$	$u^{-2}(x_i)*x_i$	wi after convergence	wi(xi-xref)^2	I
2	New Zealan	MSL	0.0270	0.0190	0.0230	20.0	1.417	2.007	0.003	0.058	0.074	0.122	6
3	Thailand	NIMT	0.0280	0.0140	0.0210	11.0	-0.583	0.340	0.008	0.174	0.246	0.127	
4	Malaysia	SIRIM	0.0120	0.0080	0.0100	16.0	-11.583	134.174	0.004	0.039	0.116	15.977	Consistent RB
5	Japan	NMIJ2	0.0210	0.0230	0.0220	8.8	0.417	0.174	0.013	0.284	0.385	0.031	1.505
6	Taiwan	CMS	-0.0180	-0.0110	-0.0150	14.0	-36.583	1338.340	0.005	-0.077	0.152	204.903	O
7	Vietnam	VMI	0.0480	0.0370	0.0425	17.0	20.917	437.507	0.003	0.147	0.103	44.520	
8	India	NPLI	0.0070	0.0140	0.0110	19.9	-10.583	112.007	0.003	0.028	0.075	8.641	
1	Japan	NMIJ1	0.0300	0.0280	0.0290	8.8	7.417	55.007	0.013	0.374	0.385	20.401	
9	Japan	NMIJ3	0.0240	-	0.0240	8.8	2.417	5.840	0.013	0.310	0.385	2.004	
								C（after cor	29.789		sum(wi)	1.000	RB
								uint(x)	5.458		sum(wi(xi-xr	69.417	0.683
								uart(xpilot)	3.606		uext(x)	3.726	



Non-weighted mean [nm]

x_a	21.5833
$u(x_a)$	4.7826

1st
Weighted mean [nm]

x_w	21.7175
$u(x_w)$	5.4579

		x_i-x_{RV}	$U(x_i$-$x_{RV})$	En	O: good
New Zealan	MSL	1.282	39.152	0.033	O
Thailand	NIMT	-0.718	20.417	-0.035	O
Malaysia	SIRIM	-11.718	30.933	-0.379	O
Japan	NMIJ2	0.282	15.576	0.018	O
Taiwan	CMS	-36.718	26.774	-1.371	X
Vietnam	VMI	20.782	32.998	0.630	O
India	NPLI	-10.718	38.947	-0.275	O
Japan	NMIJ1	7.282	15.576	0.468	O
Japan	NMIJ3	2.282	15.576	0.147	O

Yellow cells are not used to calculate the weighted mean.

Table 9 Steel 80 mm S/N 030770

							Non-weighted		Weighted				Institute number for xref
	Economy	Laboratory	Δl_{left}(um)	Δl_{right}(um)	Δl (um)	u_c(nm)	x_i-x_{ref}	$(x_i-x_{ref})^2$	$u^{-2}(x_i)$	$u^{-2}(x_i)*x_i$	wi after convergence	wi(xi-xref)^2	I
2	New Zealan	MSL	-0.0950	-0.0810	-0.0880	24.0	-16.750	280.563	0.002	-0.153	0.116	13.045	6
3	Thailand	NIMT	-0.0650	-0.0680	-0.0670	19.0	4.250	18.063	0.003	-0.186	0.185	19.944	
4	Malaysia	SIRIM	-0.0930	-0.0900	-0.0920	21.0	-20.750	430.563	0.002	-0.209	0.151	32.303	Consistent RB
5	Japan	NMIJ2	-0.0810	-0.0790	-0.0800	12.5	-8.750	76.563	0.006	-0.512	0.427	2.914	1.505
6	Taiwan	CMS	-0.1010	-0.1180	-0.1090	17.0	-37.750	1425.063	0.003	-0.377	0.231	230.712	O
7	Vietnam	VMI	-0.0710	-0.0640	-0.0675	29.0	3.750	14.063	0.001	-0.080	0.079	7.757	
8	India	NPLI	-0.0320	-0.0340	-0.0330	40.0	38.250	1463.063	0.001	-0.021	0.042	82.162	
1	Japan	NMIJ1	-0.0710	-0.0700	-0.0700	12.5	1.250	1.563	0.006	-0.448	0.427	23.307	
9	Japan	NMIJ3	-0.0650	-0.0780	-0.0710	12.5	0.250	0.063	0.006	-0.454	0.427	17.424	
								C（after cor	66.721		sum(wi)	1.000	RB
								uint(x)	8.168		sum(wi(xi-xr	158.124	0.688
								uart(xpilot)	5.508		uext(x)	5.624	

Non-weighted mean [nm]

x_a -71.2500

$u(x_a)$ 8.7233

1st

Weighted mean [nm]

x_w -77.3879

$u(x_w)$ 8.1683

		x_i-x_{RV}	$U(x_i-x_{RV})$	En	O: good
New Zealan	MSL	-10.612	46.459	-0.228	O
Thailand	NIMT	10.388	36.034	0.288	O
Malaysia	SIRIM	-14.612	40.230	-0.363	O
Japan	NMIJ2	-2.612	21.896	-0.119	O
Taiwan	CMS	-31.612	31.788	-0.994	O
Vietnam	VMI	9.888	56.731	0.174	O
India	NPLI	44.388	79.085	0.561	O
Japan	NMIJ1	7.388	21.896	0.337	O
Japan	NMIJ3	6.388	21.896	0.292	O

Yellow cells are not used to calculate the weighted mean.

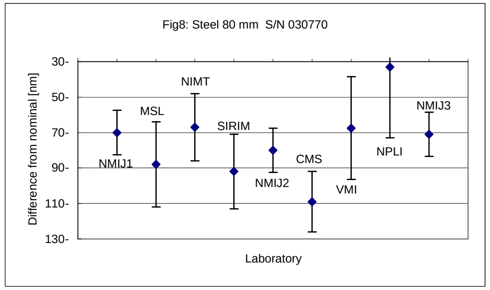


Table 10 Steel 90 mm S/N 040340

							Non-weighted		Weighted				Institute number for xref
	Economy	Laboratory	Δl_{left}(um)	Δl_{right}(um)	Δl (um)	u_c(nm)	x_i-x_{ref}	$(x_i$-$x_{ref})^2$	$u^{-2}(x_i)$	$u^{-2}(x_i)*x_i$	wi after convergence	wi(xi-xref)^2	I
2	New Zealand	MSL	-0.0630	-0.0610	-0.0620	25.0	-2.800	7.840	0.002	-0.099	0.133	62.365	5
3	Thailand	NIMT	-0.0250	-0.0250	-0.0250	21.0	34.200	1169.640	0.002	-0.057	0.188	44.289	
4	Malaysia	SIRIM	-0.0640	-0.0570	-0.0600	22.0	-0.800	0.640	0.002	-0.124	0.172	66.350	Consistent RB
5	Japan	NMIJ2	-0.0450	-0.0450	-0.0450	13.4	14.200	201.640	0.006	-0.251	0.463	10.062	1.554
6	Taiwan	CMS	-0.0240	-0.0860	-0.0550	18.0	4.200	17.640	0.003	-0.170	0.256	55.120	O
7	Vietnam	VMI	0.0510	0.0620	0.0565	31.0	115.700	13386.490	0.001	0.059	0.086	810.360	
8	India	NPLI	-0.0960	-0.1110	-0.1040	43.1	-44.800	2007.040	0.001	-0.056	0.045	181.204	
1	Japan	NMIJ1	-0.0350	-0.0360	-0.0350	13.4	24.200	585.640	0.006	-0.195	0.463	13.167	
9	Japan	NMIJ3	-0.0360	-	-0.0360	13.4	23.200	538.240	0.006	-0.200	0.463	8.694	
								C（after con	83.048		sum(wi)	1.000	RB
Non-weighted mean [nm]								uint(x)	9.113		sum(wi(xi-xre	364.271	1.047
x_a	-59.2000							uart(xpilot)	5.508		uext(x)	9.543	
$u(x_a)$	13.0131												

1st							2nd (VMI excluded)			
Weighted mean [nm]										
x_w	-40.3357						x_w	-48.7041		
$u(x_w)$	8.7431						$u(x_w)$	9.1131		
			x_i-x_{RV}	$U(x_i$-$x_{RV})$	En	O: good	x_i-x_{RV}	$U(x_i$-$x_{RV})$	En	O: good
	New Zealand	MSL	-21.664	48.120	-0.450	O	-13.296	47.845	-0.278	O
	Thailand	NIMT	15.336	39.744	0.386	O	23.704	39.410	0.601	O
	Malaysia	SIRIM	-19.664	41.852	-0.470	O	-11.296	41.535	-0.272	O
	Japan	NMIJ2	-4.664	23.104	-0.202	O	3.704	22.525	0.164	O
	Taiwan	CMS	-14.664	33.340	-0.440	O	-6.296	32.941	-0.191	O
	Vietnam	VMI	96.836	60.494	1.601	X	105.204	60.276	1.745	X
	India	NPLI	-63.664	85.123	-0.748	O	-55.296	84.968	-0.651	O
	Japan	NMIJ1	5.336	23.104	0.231	O	13.704	22.525	0.608	O
	Japan	NMIJ3	4.336	23.104	0.188	O	12.704	22.525	0.564	O

Yellow cells are not used to calculate the weighted mean
Red cells have absolute En over one.

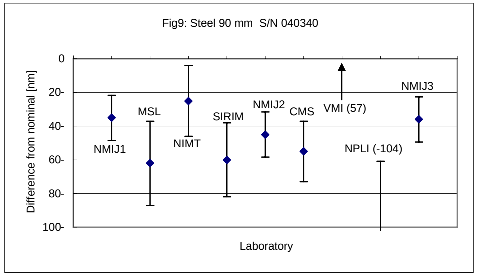


Table 11 Steel 100 mm S/N 042033

							Non-weighted		Weighted				Institute number for xref
	Economy	Laboratory	Δl_{left}(um)	Δl_{right}(um)	Δl (um)	u_c(nm)	x_i-x_{ref}	$(x_i$-$x_{ref})^2$	$u^{-2}(x_i)$	$u^{-2}(x_i)$*x_i	wi after convergence	wi(xi-xref)^2	I
2	New Zealan	MSL	0.0880	0.0440	0.0660	26.0	-4.900	24.010	0.001	0.098	0.132	7.245	5
3	Thailand	NIMT	0.0710	-	0.0710	22.0	0.100	0.010	0.002	0.147	0.184	1.077	
4	Malaysia	SIRIM	0.0460	0.0530	0.0490	23.0	-21.900	479.610	0.002	0.093	0.168	100.261	Consistent RB
5	Japan	NMIJ2	0.0720	0.0580	0.0650	14.3	-5.900	34.810	0.005	0.318	0.435	30.839	1.554
6	Taiwan	CMS	0.0460	0.0230	0.0350	18.0	-35.900	1288.810	0.003	0.108	0.274	405.187	O
7	Vietnam	VMI	0.1150	0.0920	0.1035	33.0	32.600	1062.760	0.001	0.095	0.082	73.888	
8	India	NPLI	0.2670	0.2020	0.2350	46.2	164.100	26928.810	0.000	0.110	0.042	1087.819	
1	Japan	NMIJ1	0.0620	0.0640	0.0630	14.3	-7.900	62.410	0.005	0.308	0.435	47.227	
9	Japan	NMIJ3	-	0.0640	0.0640	14.3	-6.900	47.610	0.005	0.313	0.435	38.598	
								C（after conv	88.934		sum(wi)	1.000	RB
Non-weighted mean [nm]								uint(x)	9.430		sum(wi(xi-xr	213.309	0.774
x_a	70.9000							uart(xpilot)	1.000		uext(x)	7.303	
$u(x_a)$	8.9476												

1st						2nd (NPLI excluded)			
Weighted mean [nm]									
x_w	73.4207					x_w	66.6883		
$u(x_w)$	9.2400					$u(x_w)$	9.4305		
		x_i-x_{RV}	$U(x_i$-$x_{RV})$	En	O: good	x_i-x_{RV}	$U(x_i$-$x_{RV})$	En	O: good
New Zealan	MSL/IR	-7.421	48.647	-0.153	O	-0.688	48.500	-0.014	O
Thailand	NIMT	-2.421	39.981	-0.061	O	4.312	39.803	0.108	O
Malaysia	SIRIM	-24.421	42.172	-0.579	O	-17.688	42.003	-0.421	O
Japan	NMIJ2	-8.421	21.919	-0.384	O	-1.688	21.592	-0.078	O
Taiwan	CMS	-38.421	30.960	-1.241	X	-31.688	30.729	-1.031	X
Vietnam	VMI	30.079	63.392	0.474	O	36.812	63.279	0.582	O
India	NPLI	161.579	90.555	1.784	X	168.312	90.477	1.860	X
Japan	NMIJ1	-10.421	21.919	-0.475	O	-3.688	21.592	-0.171	O
Japan	NMIJ3	-9.421	21.919	-0.430	O	-2.688	21.592	-0.125	O

Yellow cells are not used to calculate the weighted mean.
Red cells have absolute En over one.

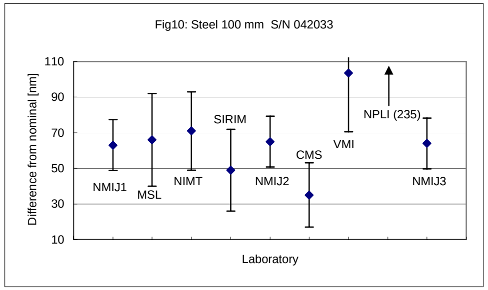


Fig10: Steel 100 mm S/N 042033

Table 12 Summary and En number

Xi-Xref 2*u(Xi-Xref)

(a) 1st (All institutes except CMS are used for Reference values)

Nominal Length [mm]	0.5	1.01	1.1	6	7	8	15	80	90	100
MSL	14 ± 41	4 ± 40	10 ± 51	1 ± 43	15 ± 42	16 ± 40	1 ± 39	-11 ± 46	-22 ± 48	-7 ± 49
NIMT	2 ± 23	-11 ± 23	-13 ± 39	-6 ± 26	-17 ± 25	4 ± 22	-1 ± 20	10 ± 36	15 ± 40	-2 ± 40
SIRIM	-9 ± 31	-13 ± 30	-14 ± 44	-17 ± 33	-16 ± 32	-10 ± 30	-12 ± 31	-15 ± 40	-20 ± 42	-24 ± 42
NMIJ	1 ± 19	2 ± 18	-7 ± 37	-5 ± 23	3 ± 20	4 ± 17	0 ± 16	-3 ± 22	-5 ± 23	-8 ± 22
CMS	-21 ± 29	-29 ± 28	-16 ± 43	-10 ± 32	-14 ± 30	-23 ± 28	-37 ± 27	-32 ± 32	-15 ± 33	-38 ± 31
VMI	6 ± 29	3 ± 28	18 ± 43	22 ± 33	8 ± 32	-10 ± 32	21 ± 33	10 ± 57	97 ± 60	30 ± 63
NPLI	-15 ± 32	24 ± 31	36 ± 45	28 ± 37	28 ± 37	-9 ± 36	-11 ± 39	44 ± 79	-64 ± 85	162 ± 91

Xi-Xref 2*u(Xi-Xref)

(b) After convergence

Nominal Length [mm]	0.5	1.01	1.1	6	7	8	15	80	90	100
MSL	14 ± 41	4 ± 40	10 ± 51	1 ± 43	15 ± 42	16 ± 40	1 ± 39	-11 ± 46	-13 ± 48	-1 ± 49
NIMT	2 ± 23	-11 ± 23	-13 ± 39	-6 ± 26	-17 ± 25	4 ± 22	-1 ± 20	10 ± 36	24 ± 39	4 ± 40
SIRIM	-9 ± 31	-13 ± 30	-14 ± 44	-17 ± 33	-16 ± 32	-10 ± 30	-12 ± 31	-15 ± 40	-11 ± 42	-18 ± 42
NMIJ	1 ± 19	2 ± 18	-7 ± 37	-5 ± 23	3 ± 20	4 ± 17	0 ± 16	-3 ± 22	4 ± 23	-2 ± 22
CMS	-21 ± 29	-29 ± 28	-16 ± 43	-10 ± 32	-14 ± 30	-23 ± 28	-37 ± 27	-32 ± 32	-6 ± 33	-32 ± 31
VMI	6 ± 29	3 ± 28	18 ± 43	22 ± 33	8 ± 32	-10 ± 32	21 ± 33	10 ± 57	105 ± 60	37 ± 63
NPLI	-15 ± 32	24 ± 31	36 ± 45	28 ± 37	28 ± 37	-9 ± 36	-11 ± 39	44 ± 79	-55 ± 85	168 ± 90

(c) En number after convergence

Nominal Length [mm]	0.5	1.01	1.1	6	7	8	15	80	90	100
MSL	**0.35**	**0.10**	**0.19**	**0.02**	**0.37**	**0.39**	**0.03**	**-0.23**	**-0.28**	**-0.01**
NIMT	**0.10**	**-0.49**	**-0.33**	**-0.23**	**-0.68**	**0.16**	**-0.04**	**0.29**	**0.60**	**0.11**
SIRIM	**-0.28**	**-0.43**	**-0.32**	**-0.51**	**-0.49**	**-0.35**	**-0.38**	**-0.36**	**-0.27**	**-0.42**
NMIJ	**0.07**	**0.10**	**-0.19**	**-0.23**	**0.16**	**0.21**	**0.02**	**-0.12**	**0.16**	**-0.08**
CMS	**-0.72**	**-1.02**	**-0.37**	**-0.32**	**-0.46**	**-0.83**	**-1.37**	**-0.99**	**-0.19**	**-1.03**
VMI	**0.20**	**0.12**	**0.43**	**0.67**	**0.24**	**-0.32**	**0.63**	**0.17**	**1.75**	**0.58**
NPLI	**-0.46**	**0.76**	**0.80**	**0.75**	**0.77**	**-0.26**	**-0.28**	**0.56**	**-0.65**	**1.86**

Red cells mean absolute En over one.

CMS's values are excluded from key reference values calculation because CMS reported their values with wrong phase corrections.

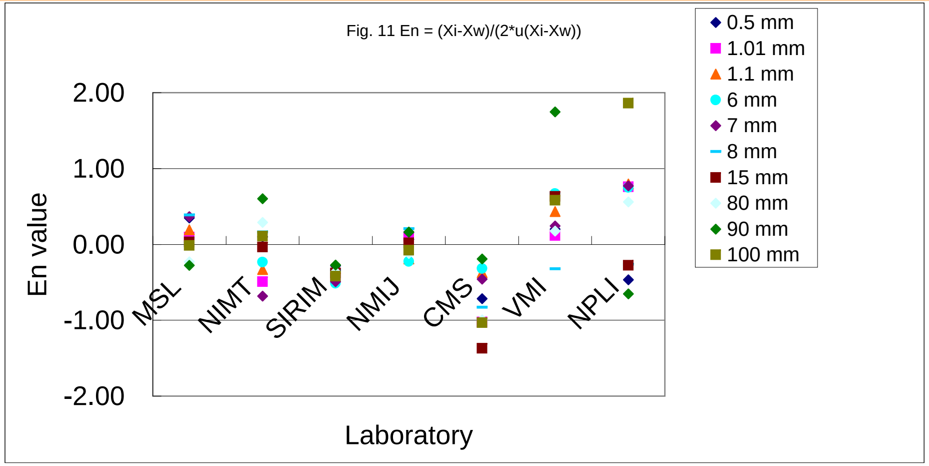


Fig. 11 En = (Xi-Xw)/(2*u(Xi-Xw))

Table 13 Measurement instruments and conditions reported by the participating laboratories

Laboratory	Make and Type of interferometer	Light sources / Wavelengths used	Method of fringe fraction determination	Method used for determination of refractive index of the air	Range of gauge block temperature during measurements	Material of reference flats	Phase correction applied for steel
MSL	NPL Hilger Type TN 190.2 gauge block interferometer. This is a Fizeau type interferometer and has been modified to include a fibre optic feed for the laser light, a video camera to observe the fringe pattern, and motors to select the wavelength and gauge block. All this is done under computer control [1].	HP5500C Zeeman stabilised helium-neon laser, wavelength in vacuum = 632.991417 nm. Mercury-198 lamp, green line, wavelength in vacuum = 546.22705 nm Note: The Mercury lamp green line is only used to determine the fringe order. The gauge length is calculated from the fringe fraction obtained from the laser source.	The fringe fraction is determined by computer analysis of a fringe image acquired by a video camera. The fringe pattern is modelled by two sets of parallel lines, separately fitted by a least squares method to the gauge block and to the platen areas of the image. The fringe fraction along the centre line of the gauge block is then calculated from the line positions and interpolated to the centre of the gauge block [2].	Calibrated sensors measure air temperature, pressure and humidity before and after ezch fringe measurement. The revised Edlen equations given in [3] are used to calculate the refractive index of the air.	The gauge temperature was in the range 20.00 C to 20.16 C for all measurements.	steel	-10.2 nm
NIMT	Mitutoyo, Twyman-Green interferometer	Stabilized He-Ne laser / Wavelength used 632.990940 nm	Computerized phase difference angle determination with "8-point Average 4-slit" method	Modified Edlen equation	20+-0.3 C	Quartz	42 nm
SIRIM	NPL-TESA gauge block interferometer based on Twyman-Green Interferometer	Two frequency-stabilised He-Ne lasers with wavelengths 633 nm and 543 nm were used.	The gauge blocks were calibrated by interferometric measurement using the exact-fraction method. Interference fringes were observed using a CCD camera linked to a PC. After stabilisation, a series of measurement consisting of not less than three length determinations was carried out. Corrections due to tempoerature, humidity and atmospheric pressure were calculated automatically.	The refractive index of air was calculated using the Edlen formula. Data from air temperature probe, pressure transducer and dew point meter were input to the computer automatically.	Air temperature range: 19.871 C to 20.153 C Gauge block temp: 19.902 C to 20.194 C	Tungsten Carbide	-6 nm
NMIJ	NRLM-Tsugami GB interferometer based on Twyman-Green's interferometer	Zeeman stabilized 633 nm He-Ne laser, Iodine stabilized frequency-doubled Nd:YAG laser 532 nm, Rubidium stabilized 782 nm diode laser	The fringe ftaction is determined by computer analysis of a fringe image acquired by a CCD camera.	The refractive index of the air is determined by using Ciddor's equation (Applied Optics, Vol.35, No.9, pp.1566-1573 (1996). The environmental data of air temperature, air pressure, dew point and CO2 content in the equipment were measured.	19.98 C to 20.03 C	steel	9.7 nm
CMS	Brown and Sharpe GBI300 Twyman-Green type gauge block interferometer	Stabilized He-Ne laser: 633 nm and 543 nm	Phase stepping method	Edlen's equation	(20.0+-0.1) C	steel	-57 nm
VMI	1. Gauge blocks are measured by the TESA upd gauge blocks comparator with uncertainty U = (0.07 + 0.5L) mm; [L]:m within half wavelength l = 633 nm. 2. Gauge blocks are wrung to a steel platen and viewed with an inteferometer-Michelson type. Measurements are made of the path difference between the top of the gauge block and the platen in wavelength. The fringe position are determined by the length of gauge block and the wavelength of the light.	He-Ne stabilized laser sources wavelength 633 nm	The fringe fraction of gauge block are measured by CCD camera and seizaed by frame grabber of image processor.	The refractive index of air, n, is determined by the Edlens's equation by using the measured values of air temperature, pressure, relative humidity.	The temperature of gauge blocks is within 0.5 C of 20.0 C. The temperature of gauge block is measured three times, at the start, half way through the measurement and at the end, using two thermometers. The temperature change during the measurement is less than 0.02 C.	steel	11 nm
NPLI	Hilger Watt gauge block interferometer, TN 180 302/52714, Fizeau Type	Monochromatic radiation of Cd114 isotopic lamp	Eye estimation	Modified Edlen equation	Stabilized at 20.20 C - 20.60 C and maximum variation of temperature from the stabilized values is < 0.02 C	Tungsten Carbide	25 nm

[1] E.F.Howick and C.M. Sutton, Improvements to a 1960's Hilger gauge block interferometer, in Recent Developments in Optical Gauge Block Metrology, SPIE Proceedings 3477 (1998).

[2] E.F. Howick, L.R. Watkins and S.M. Tan, Automation of a 1960's Hilger gauge block interferometer, Metrologia 40, 139 (2003).

[3] R. Muijlwijk, Update of the Edlen Formulae for the Refractive Index of Air, Metrologia 25, 189 (1988)

Table 14 Summary of measurement uncertainty

Standard uncertainty u(L) = [a, b*L] = SQRT(a^2+(b*L)^2)

Coeff.	a	b	Length (m)	0.0005	0.00101	0.0011	0.006	0.007	0.008	0.015	0.08	0.09	0.1
MSL	0.02	0.17		0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.024	0.025	0.026
NIMT	0.011	0.19		0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.019	0.020	0.022
SIRIM	0.015	0.171		0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.020	0.021	0.023
NMIJ	0.0086	0.114		0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.013	0.013	0.014
CMS	0.014	0.12		0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.017	0.018	0.018
VMI	0.014	0.189		0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.021	0.022	0.024
NPLI	0.015	0.31		0.015	0.015	0.015	0.017	0.017	0.017	0.020	0.040	0.043	0.046

The pilot's comments:
For the MRA we show u(L) and this is what we hope to demonstrate in the Key Comparison. Unfortunately the Technical Protocol did not specifically ask participants to state their uncertainty this way, although many did. I have attempted to extract the a and b coefficients from the informatiuon supplied and this is shown in the table. Please check your values and let me know if you want a change.

This table shows the calculated uncertainties by the formulae with [a, b*L] format, which is equal to SQRT(a^2+(b*L)^2).

Blue cells mean some difference between the formulae and the uncertainty reported with the central lengths.

Light blue cells mean slight difference between the formulae and the uncertainty reported with the central lengths.

NPLI represent the formulae with a+b*L format.

Table 15 Birge ratio

Gauge Length [mm]	0.5	1.01	1.1	6	7	8	15	80	90	100
Birge Ratio	0.63	0.93	1.43	1.17	1.19	0.64	0.68	0.69	1.05	0.77
consistent RB less than	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.55	1.55