Centro Nacional de Metrología

SIM Regional Supplementary Comparison

SIM.L-S6

Calibration of Gauge Blocks by Mechanical Comparison

Final Report

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1. Introduction

The Mutual Recognition Arrangement (MRA) of the *Conférence Internationale des Poids et Mesures* (*CIPM*) signed by the National Metrology Institutes (NMI) of different nations provides mutual recognition among the NMI of their national standards and their calibration services. A database has been set up by the *Bureau Interantional des Poids et Mesures* (*BIPM*) at its website where the Calibration and Measurement Capabilities (CMC) of each NMI are posted. To support the CMC claims of the NMI, the MRA requires, among other things, that they participate on a regular basis in Key Comparisons (KC) that test key measuring techniques. This would prove their technical competence, that they can provide this calibration service with the claimed uncertainty of the corresponding CMC and that they have metrological equivalence with the other signatory NMI that provide the same service.

The CIPM has therefore instructed the different CC (*Comité Consultatif*) to identify key techniques in order to define KC, as it is, for example, the calibration of Gauge Blocks (GB) by optical interferometry, identified as a key measuring technique by CCL (CC de *Longueurs*). Additionally, the CC as well as the regions may also identify other important comparisons called supplementary and identified with an S. The SIM region has identified the Calibration of GB by Mechanical Comparison as one if this comparisons. The *Centro Nacional de Metrología* (CENAM) was designated by SIM as pilot laboratory and CENAM has carried out this exercise under the name of SIM.L-S6:2007.

The calibration of GB by Mechanical Comparison is indeed a technique of paramount importance as it is at the highest level in the traceability chain of length for most countries of the American Continent. This comparison is meant to support the submitted CMC of these countries.

The measurand is the central length of the GB as defined in [1] and the circulated GB were used for two comparisons carried out in two stages:

- First stage, SIM.L- K1:2007, Calibration of GB by Optical Interferometry. Circulation from 2007-11-01 to 2010-04-25. The GB were also measured by Mechanical Comparison for those NMI also participating in SIM.L-S6:2007.
- Second stage, SIM.L-S6:2007, Calibration of GB by Mechanical Comparison. Circulation from 2010-03-02 to 2011-05-06 for the participants that measured only by Mechanical Comparison, this dates included two control measurements by interferometry.

In this second comparison there were 16 participants, 14 from the Americas, and 2 invited NMI from other regions. The circulation in the second stage had 10 participants. It should be noted that the circulation took relatively short time for the large number of participants thanks to the hand delivery from one NMI to the following one in nine out of the 10 steps so that customs clearance was simplified or avoided.

2. Participants

This comparison had 16 participants. **Table 1** shows the participating NMI and their corresponding contact person and information.

Contact	NMI	Information
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Tabla 1. List of participants in comparison SIM.L-S6:2007.

3. Circulation Schedule

As we mentioned, nine out of the ten participants in the second circulation stage delivered the artifacts by hand to the following participant which made the circulation time relatively short. Table 2 shows the circulation schedule for the two circulation stages. *LACOMET* retained 13 weeks the GB because of end-of-the-year holidays and internal administrative problems, they mentioned.

NMI	Dates		Reception of results
	Reception	Shipment	
Stage One Circulation			
NPLI	2008-03-02	2008-06-09	2009-08-07
CMI	2008-06-16	2008-08-05	2008-10-17
NIST	2009-04-20	2009-07-15	2010-03-02
INMETRO	2009-08-11	2009-09-08	2009-09-21
INTI	2009-11-13	2010-01-11	2010-01-11
Stage Two Circulation			
DICTUC	2010-04-29	2010-05-18	2010-06-15
LATU	2010-06-11	2010-07-06	2010-07-21
INDECOPI	2010-07-06	2010-07-30	2010-08-12
IBMETRO	2010-08-02	2010-08-18	2010-09-24
INEN	2010-08-18	2010-09-13	2011-05-16
SIC	2010-09-13	2010-10-13	2010-11-10
CENAMEP	2010-10-13	2010-11-09	2011-01-28
LACOMET	2010-11-09	2011-02-09	2011-04-01
TTBS	2011-02-14	2011-03-16	2011-04-13
BSJ	2011-03-16	2011-04-27	2011-06-09
CENAM (Pilot)	2011-04-28		2011-05-25

Tabla 2. SIM.L-S6:2007 dates of reception and shipment of artifacts and reception of results by the pilot laboratory.

4. Comparison Artifacts

A total of 14 grade K (according to [1]) rectangular GB were selected for the exercise. Seven steel GB and seven ceramics GB covering the range of short GB (from 0.5 mm to 100 mm). The specifications on the GB are shown in **tables 3** and **4**. The associated Coefficients of Thermal Expansion (CET) shown in the tables are those quoted by the manufacturer.

Nominal Length (mm)	Serial Number	Coefficient of Thermal Expansion (10^{-6} K^{-1})	Manufacturer
1.000 5	010223	10.9 ± 1	Mitutoyo
5	000482	10.9 ± 1	Mitutoyo
7	010764	10.9 ± 1	Mitutoyo
10	001329	10.9 ± 1	Mitutoyo
50	012254	10.9 ± 1	Mitutoyo
75	010630	10.9 ± 1	Mitutoyo
100	010850	10.9 ± 1	Mitutoyo

Table 3. Steel Gauge Blocks.

Nominal Length (mm)	**Serial Number**	**Coefficient of Thermal Expansion (10^{-6} K^{-1})**	**Manufacturer**
1.000 5	000288	9.3 ± 1	Mitutoyo
5	051836	9.3 ± 1	Mitutoyo
7	010323	9.3 ± 1	Mitutoyo
10	052351	9.3 ± 1	Mitutoyo
50	011002	9.3 ± 1	Mitutoyo
75	010370	9.3 ± 1	Mitutoyo
100	010773	9.3 ± 1	Mitutoyo

Table 4. Ceramics Gauge Blocks.

5. Measurement Protocol

Detailed instructions were included in the technical protocol. Participants were invited to perform the measurements according to their own calibration procedures, used to calibrate the GB of their customers.

The measurement was performed in all cases with a double probe GB comparator and in the vertical position as indicated in [1]. The method determines the difference in central length, l_c, of two GB of same nominal length set beside in the comparator platen as illustrated in **Figure 1**. The first GB is the laboratory's reference GB, calibrated by optical interferometry; and the test GB which is under circulation.

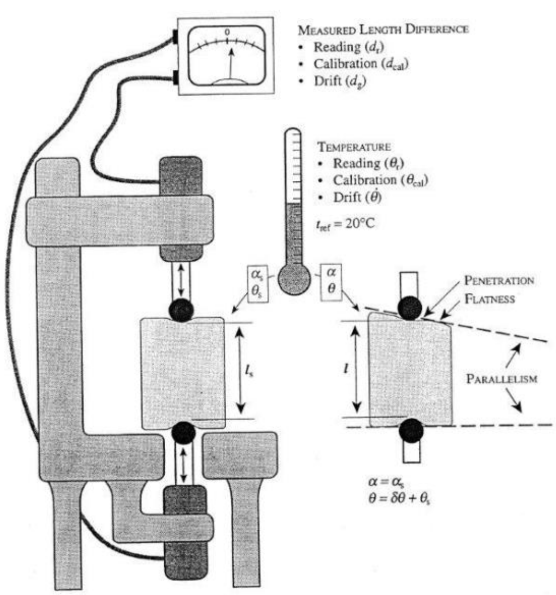


Figure 1. Illustration of the calibration method of GB by mechanical comparison showing the different variables of influence (taken from [9]).

6. Measuring Instruments

All participants measured with double probe electromechanical GB comparators with a resolution of 10 nm. Table 5 shows the makes, models and characteristics of the different instruments.

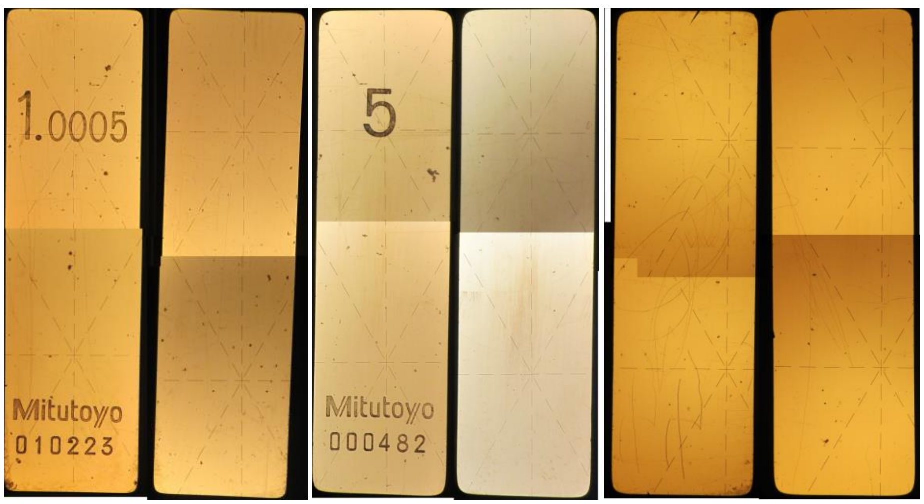
NMI	Manufacturer	Model	Measuring range mm	Traceability	Temperature variation range during measurements (°C)
CENAM	TESA	TESA-UPC	0 - 102	To SI standards of CENAM via GB calibrated by interferometry	19.32 – 19.60
NPLI	Mahr	Not indicated	0 – 175	Not indicated	19.5 – 20.5
CMI	TESA	TESA-UPC	0 – 100	To the Czech National Standard of Length (He-Ne/I2 633nm, He-Ne/I2 543.5nm, fs comb)	Not indicated
NIST	Mahr/Federal	130B-24	0 -102	NIST maintained Iodine-Stabilized Laser	20.08 – 20.17
INMETRO	TESA	TESA-UPC	0 - 102	To SI standards of INMETRO via GB calibrated by interferometry	20.0 – 20.5
INTI	Mahr	826E	0 - 175	To SI standards of INTI via GB calibrated by interferometry	20 ± 0.5
DICTUC	TESA	TESA-UPC	0 - 100	To SI standards of PTB via GB calibrated by interferometry	Steel 19.91 – 20.05 Ceramics 19.85 – 20.16
LATU	Mahr	826	0 - 100	Comparator to SI standards of PTB via GB calibrated by interferometry and to SI standards of CENAM via GB calibrated by interferometry	19.68 – 20.50
INDECOPI	Mahr	826 PC	0 – 175	To SI standards of CENAM via GB calibrated by interferometry	20.0 ± 0.5
IBMETRO	Steinmayer	EMP II	0 – 100	To SI standards of PTB via GB grade 0	19.95 – 20.15
INEN	Mahr	826	0 - 170	Not indicated, only mentioned that their GB are calibrated by interferometry	19 – 21
SIC	TESA	UPD	0 - 500	To SI standards of METAS via GB calibrated by interferometry	20 – 20.3
CENAMEP	Mitutoyo	GBCD-250	0 - 250	To SI standards of CENAM via GB calibrated by interferometry	20.3 – 20.6
LACOMET	TESA	TESA-UPC	0.5 - 100	To SI standards of PTB and CENAM via GB calibrated by interferometry	0.34
TTBS	TESA	TESA-UPC	0.5 - 100	To SI standards of METAS and NPL via GB calibrated by interferometry	0.018
JBS	Mahr-Federal	2247386	1 - 100	To SI standards of NIST	19.60 – 20.20

Table 5. GB comparators, measurement range, traceability and temperature variation of the participant laboratories.

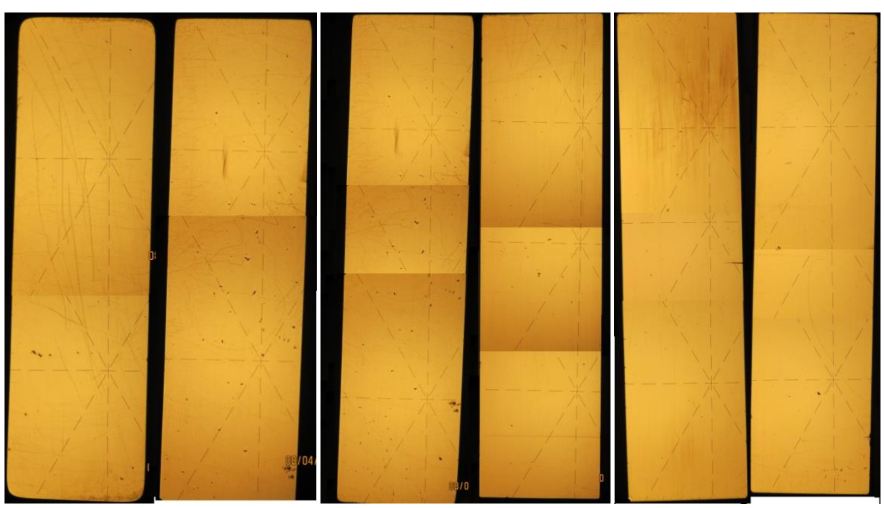
7. State and Behavior of Artifacts

7. 1 State of the Artifacts upon Reception

The participants were to inspect the state of the artifacts upon reception and inform the pilot according to the protocol. Although the selected GB were not brand new, they were in good conditions. They suffered some damage after the circulation, but the stability and the results obtained in the comparison prove the damages did not hamper or alter the measurements and the pilot laboratory was able to wring them all to a measurement platen without problems after circulation. **Figures 1** through **11** show the physical conditions of some of the steel GB upon reception at the pilot laboratory at the end of the exercise. The steel GB ended-up with quite a few scratches and specifically, the 5 mm GB, also presented rust spots.



Figures 1, 2 and **3.** Aspect of the measuring faces of the 1.000 5, 5 and 7 mm Steel GB at the end of circulation.



Figures 4, 5 and **6.** Aspect of the measuring faces of the 10, 50 and 75 mm Steel GB at the end of circulation.

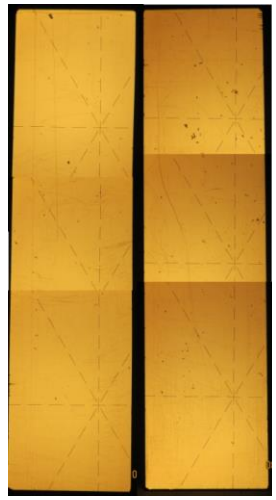


Figure 7. Aspect of the measuring faces of the 100 mm Steel GB at the end of circulation.

Four out of the seven ceramic GB suffered some damage on one of their measuring faces as shown in **Figures 8** to **11**, which consisted of burs or chipped edges. However, this condition did not hamper the wringing or caused any variation in length as it was proved by the control measurements performed at the end by the pilot laboratory by interferometry as well as by mechanical comparison.

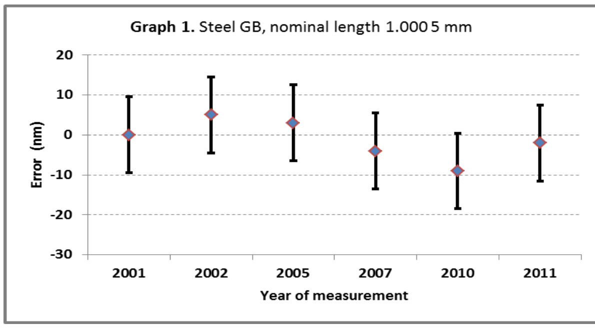
Figures 8, 9, 10 and **11.** Aspect of the measuring faces of the 10, 50, 75 and 100 mm Ceramic GB at the end of circulation.

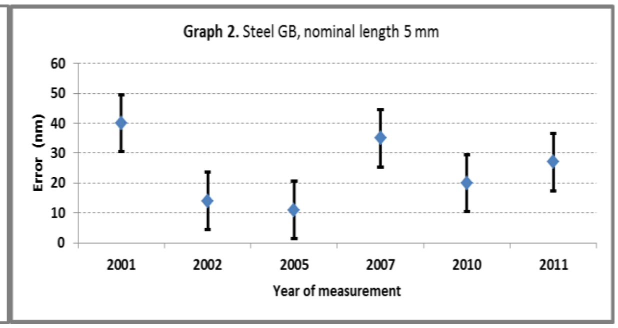
7. 2 Stability of the Standards

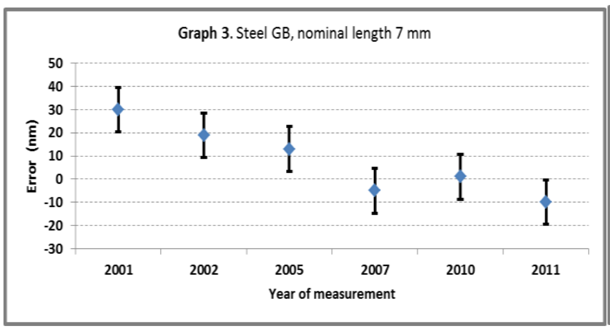
The GB were measured by interferometry several times by the pilot laboratory to verify their stability: when they were purchased (2002), two years before starting the comparison (Nov. 2005), before circulating them (Nov. 2007), after the round by interferometry (April 2010) and at the end of the circulation (May 2011). **Table 6** shows the deviations from nominal length determined at these different occasions for the steel GB, including the stated values on the certificates of the manufacturer. **Graphs 1** through **7** show these values for each GB.

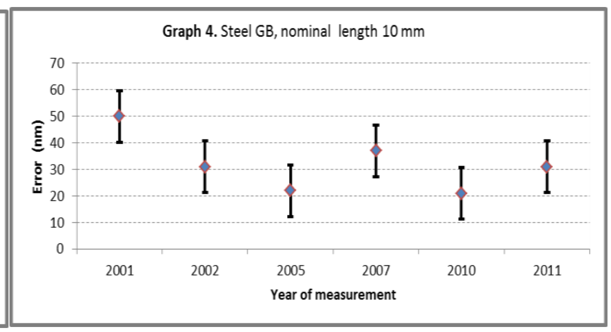
Serial Number	Nominal length (mm)	Deviation from nominal value (nm)					
		Manufacturer certificate 2001	**2002**	**2005**	**2007**	**2010**	**2011**
010223	1.000 5	0	5	3	-4	-9	-2
000482	5	40	14	11	35	20	27
010764	7	30	19	13	-5	1	-10
001329	10	50	31	22	37	21	31
012254	50	60	46	3	7	-3	8
010630	75	-50	-54	-104	-100	-107	-106
010850	100	20	18	-50	-51	-64	-50

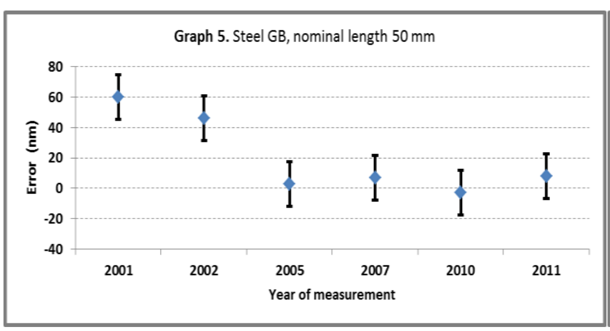
Table 6. Pilot Laboratory measured values of the steel GB at different occasions.

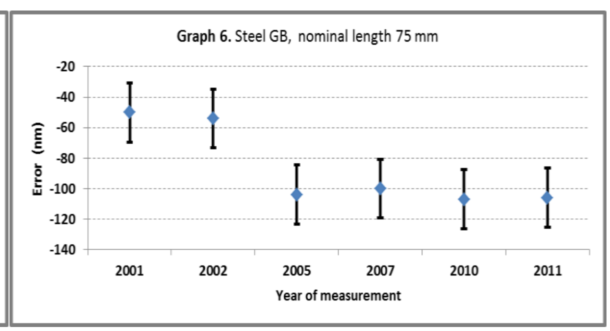


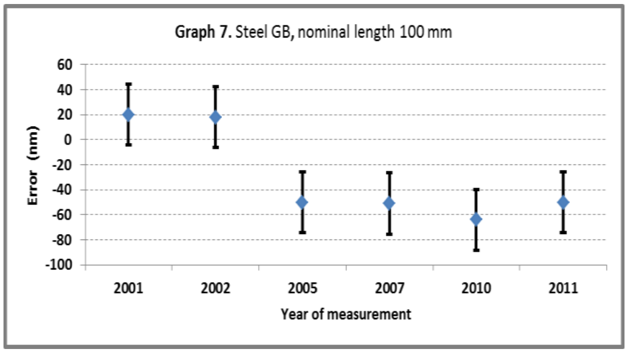










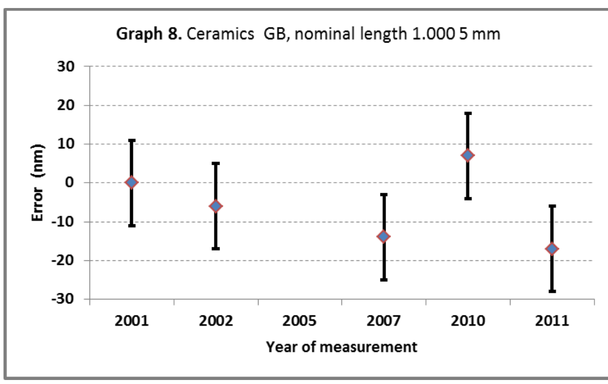


Graph 7. Steel GB, nominal length 100 mm

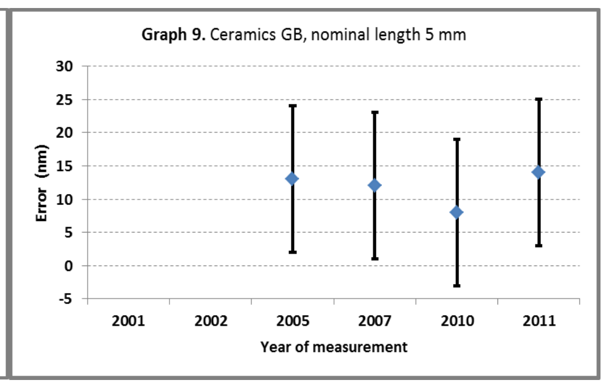
Table 7 shows the deviations from nominal length determined at these different occasions for the ceramics GB, including the stated values on the certificates of the manufacturer. **Graphs 8** through **14** show these values for each GB.

Serial Number	Nominal length (mm)	Deviation from nominal value (nm)					
		Manufacturer certificate 2001	2002	Manufacturer certificate 2005	2007	2010	2011
000288	1.0005	0	-6	----	-14	7	-17
051836	5	----	----	13	12	8	14
010323	7	50	46	----	57	48	35
052351	10	----	----	3	-13	-19	-29
011002	50	90	95	----	139	117	97
010370	75	100	110	----	118	124	123
010773	100	-60	-42	----	-34	-36	-41

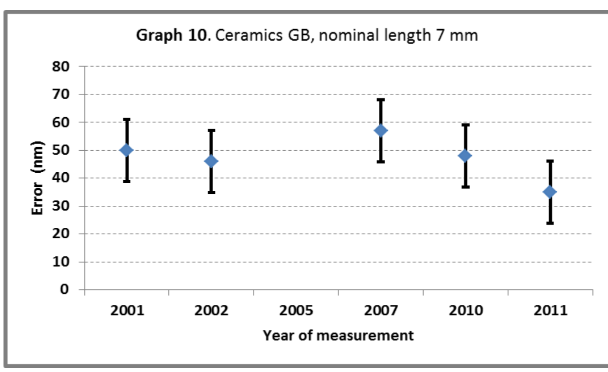
Table 7. Pilot Laboratory measured values of the ceramics *GB* in different occasions.



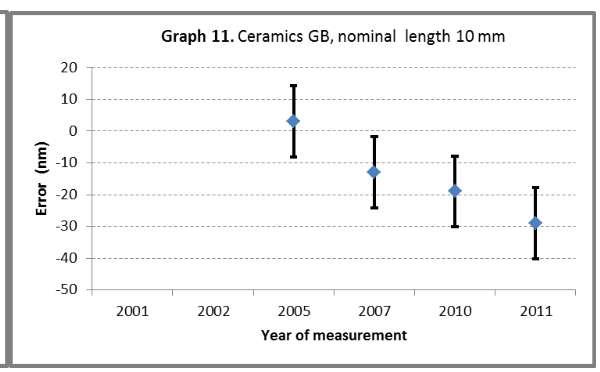
Graph 8. Ceramics GB, nominal length 1.000 5 mm



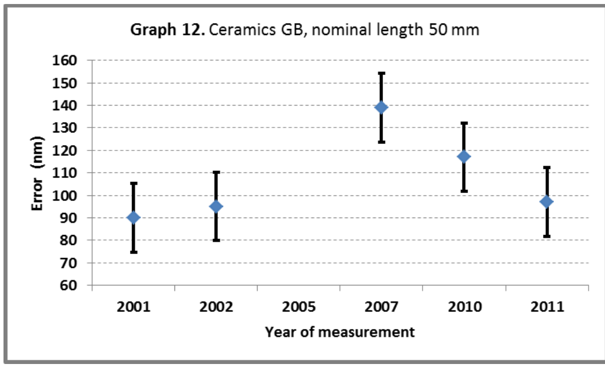
Graph 9. Ceramics GB, nominal length 5 mm

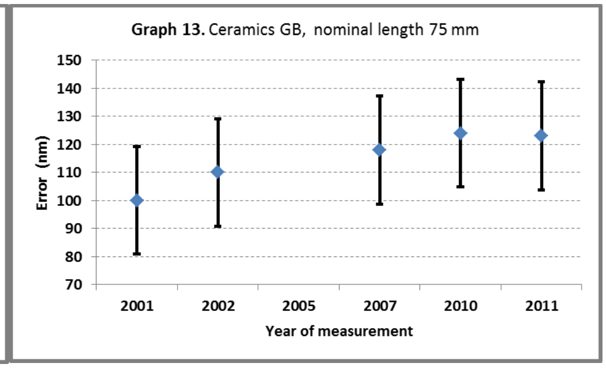


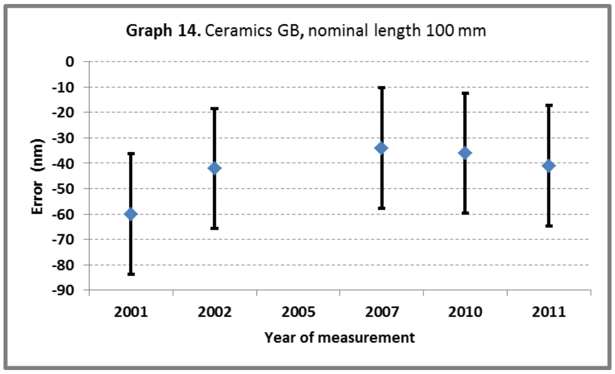
Graph 10. Ceramics GB, nominal length 7 mm



Graph 11. Ceramics GB, nominal length 10 mm







8. Measurement Results of Participants

All laboratories sent their results by e-mail. All information was received on the specified formats from appendices A, B, C, D and E of the Technical Protocol.

8.1 Measurement of the Central Length

Tables 8 and **9** and **graphs 16** through **22**, show the deviations of the central length with respect to nominal values and the claimed standard measurement uncertainties of each participant for the seven steel GB. Additionally, **graph 15** shows the claimed standard uncertainties of all participants.

Nominal Value mm	Deviation (e_{ij}) from nominal length for Steel GB nm							
	NPLI	CMI	NIST	INMETRO	INTI	LATU	DICTUC	INDECOPI
1.000 5	-20	20	-27	20	-12	-35	-15	20
5	10	60	27	62	-4	4	5	20
7	-40	20	2	21	-38	-12	-35	10
10	10	70	39	24	12	39	20	40
50	-30	80	15	11	-11	13	-10	0
75	60	-50	-107	-93	-127	-126	-110	-80
100	10	40	-67	-60	-66	-68	-60	10

Table 8A. Measurement results of the participants for the Steel GB.

Nominal Value mm	Deviation (e_{ij}) from nominal length for Steel GB nm							
	IBMETRO	INEN	SIC	CENAMEP	LACOMET	TTBS	BSJ	CENAM
1.000 5	-40	-10	-27	-13	22	30	Not reported	-2
5	0	10	-6	-3	46	70	11	23
7	-40	-30	-38	-13	27	20	-37	6
10	20	20	-7	31	66	20	15	24
50	-10	10	0	-10	36	200	-26	14
75	-130	-140	-127	-143	-83	-40	-295	-109
100	-70	40	-23	-112	-68	290	-47	-33

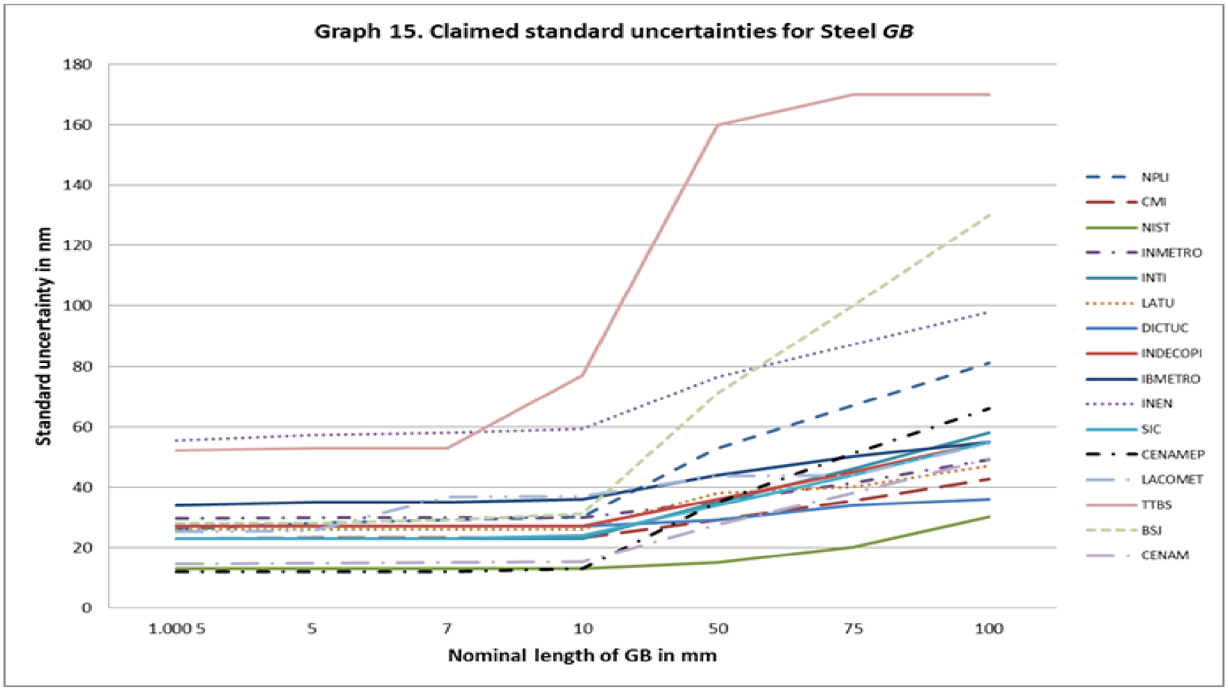
Table 8B. Measurement results of the participants for the Steel GB.

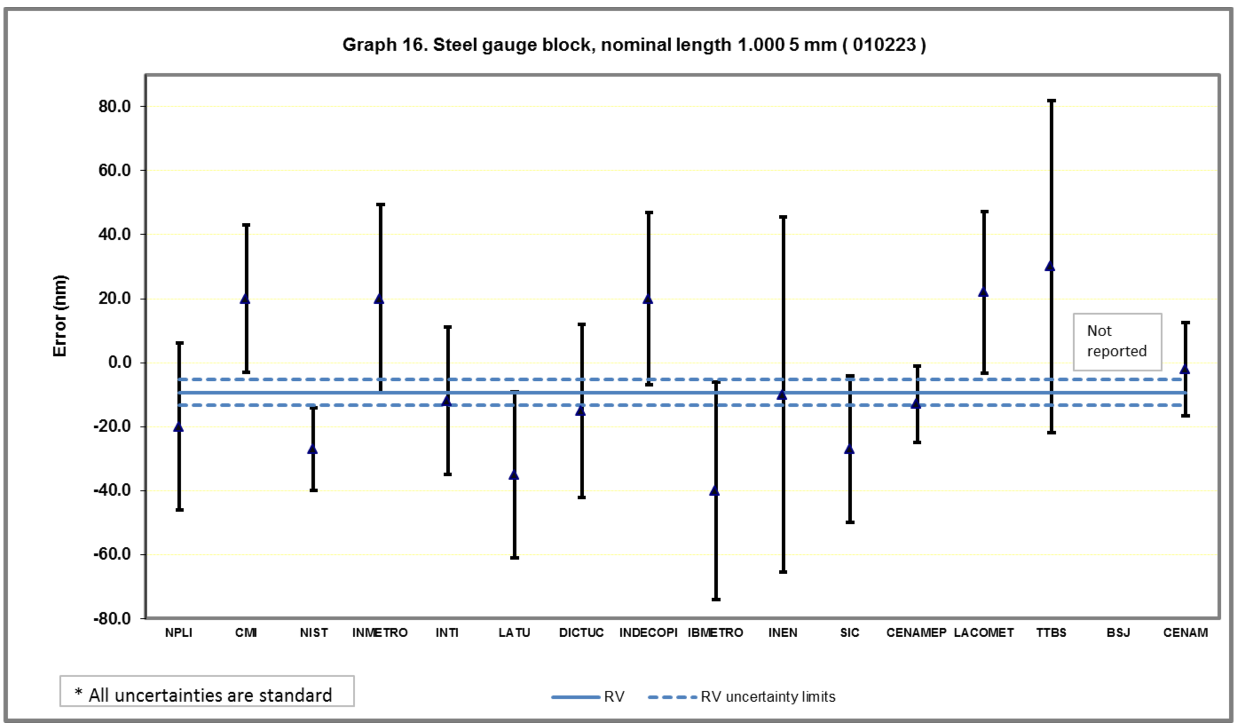
Nominal Value mm	Claimed standard uncertainties, $u(e_{ij})$, Steel GB nm							
	NPLI	CMI	NIST	INMETRO	INTI	LATU	DICTUC	INDECOPI
1.000 5	26	23	13	29.5	23.0	26.0	27	27
5	28	23.1	13	29.8	23.0	26.0	27	27
7	29	23.1	13	29.8	23.0	26.0	27	27
10	30	23.3	13	29.8	23.0	26.0	27	27
50	53	29.2	15	35.2	35.0	38.0	29	36
75	67	35.5	20	41.4	46.0	40.0	34	45
100	81	42.7	30	49.1	58.0	47.0	36	55

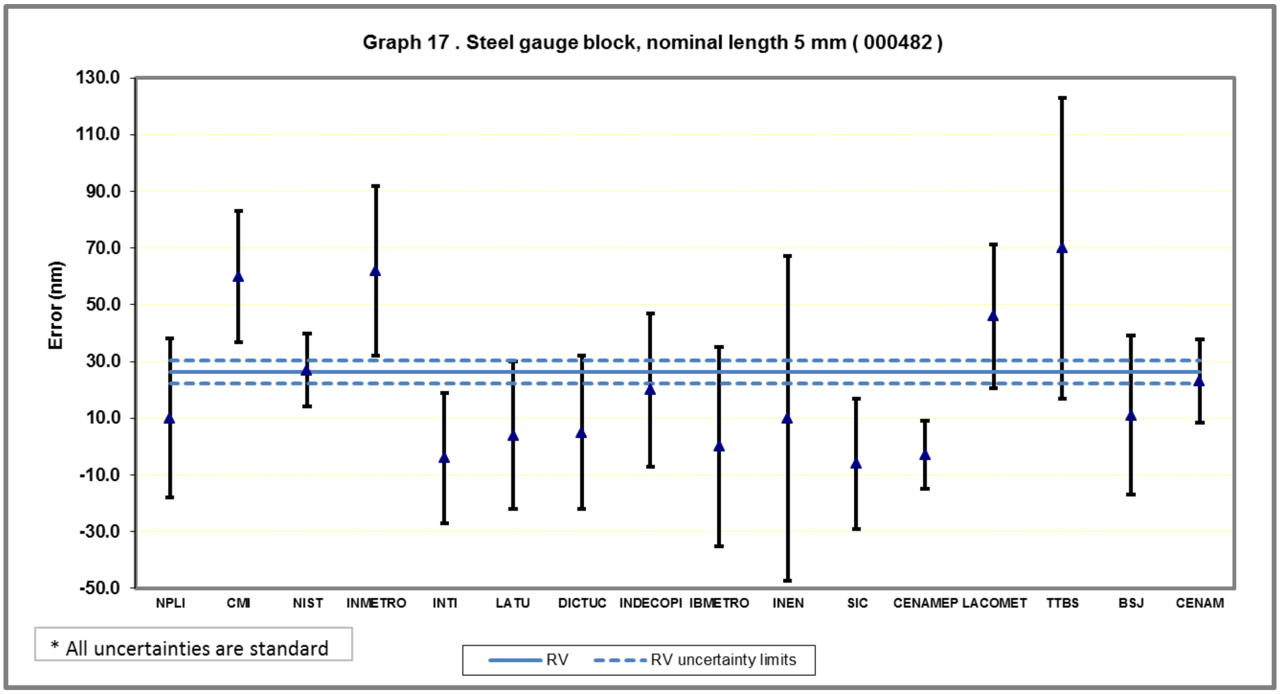
Table 9A. Claimed standard uncertainties of the participants for the Steel GB.

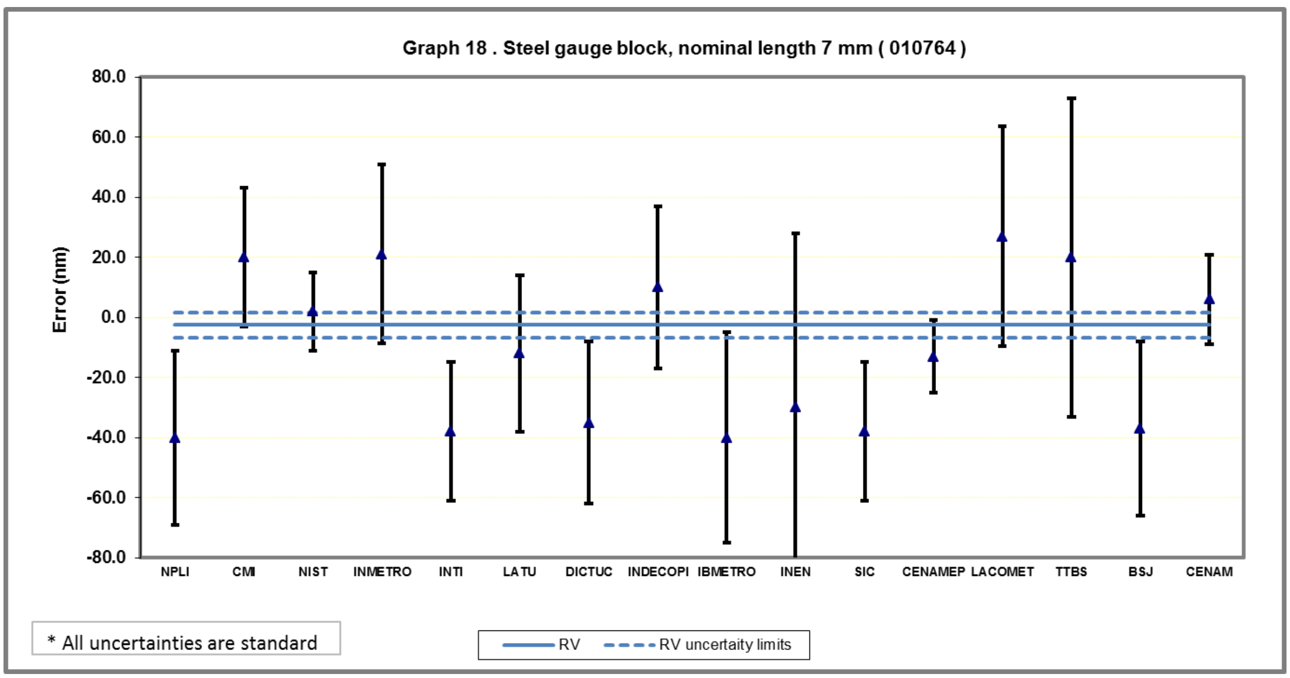
Nominal Value mm	Claimed standard uncertainties, $u(e_{ij})$, Steel GB nm							
	IBMETRO	INEN	SIC	CENAMEP	LACOMET	TTBS	BSJ	CENAM
1.000 5	34	55.4	23	12	25.3	52	Not reported	14.5
5	35	57.2	23	12	25.4	53	28	14.7
7	35	58	23	12	36.7	53	29	14.9
10	36	59.3	24	13	36.9	77	31	15.2
50	44	76.5	34	35	43.7	160	71	27.6
75	50	87.3	44	51	43.8	170	100	38.1
100	55	98	55	66	54.4	170	130	49.2

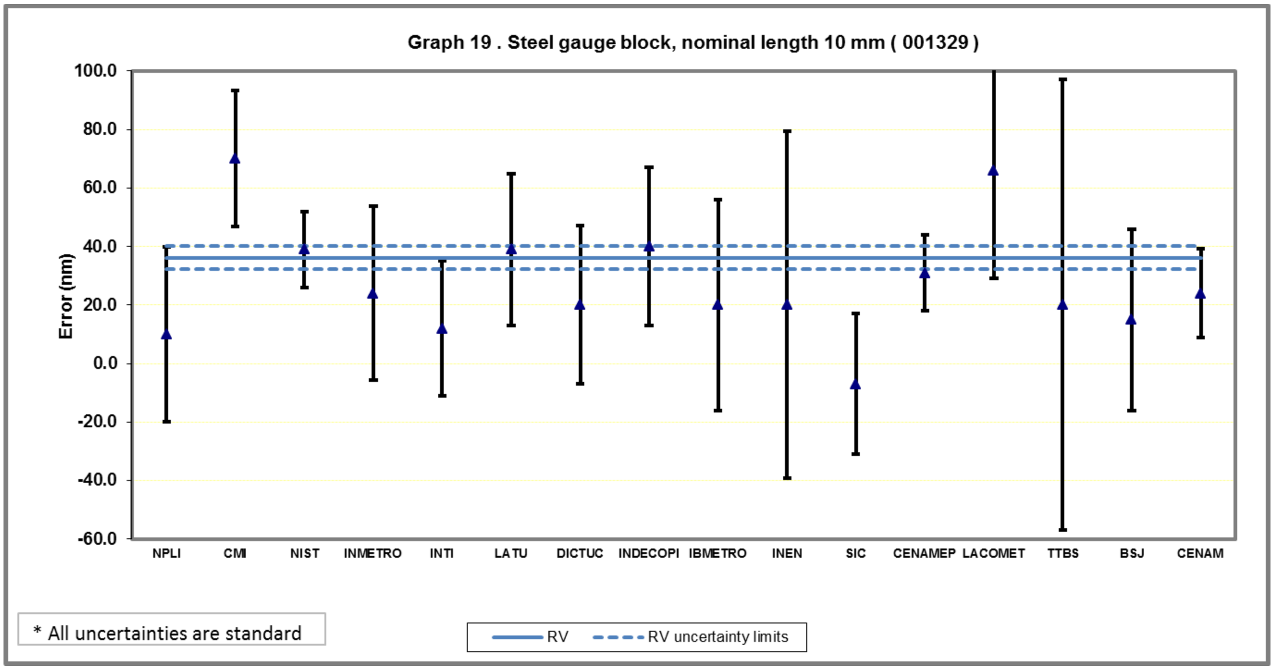
Table 9B. Claimed standard uncertainties of the participants for the Steel GB.

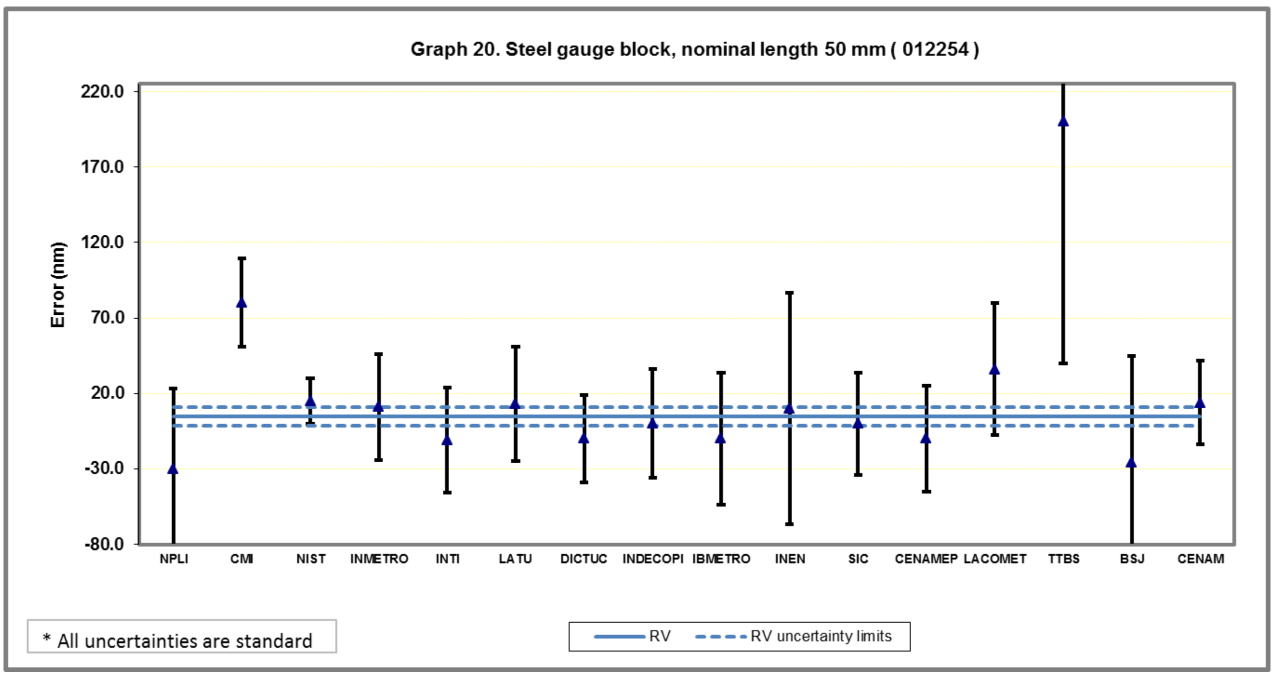

Graph 15. Claimed standard uncertainties for Steel GB
Standard uncertainty in nm
Nominal length of GB in mm
1.000 5
5
7
10
50
75
100
NPLI
CMI
NIST
INMETRO
INTI
LATU
DICTUC
INDECOPI
IBMETRO
INEN
SIC
CENAMEP
LACOMET
TTBS
BSJ
CENAM

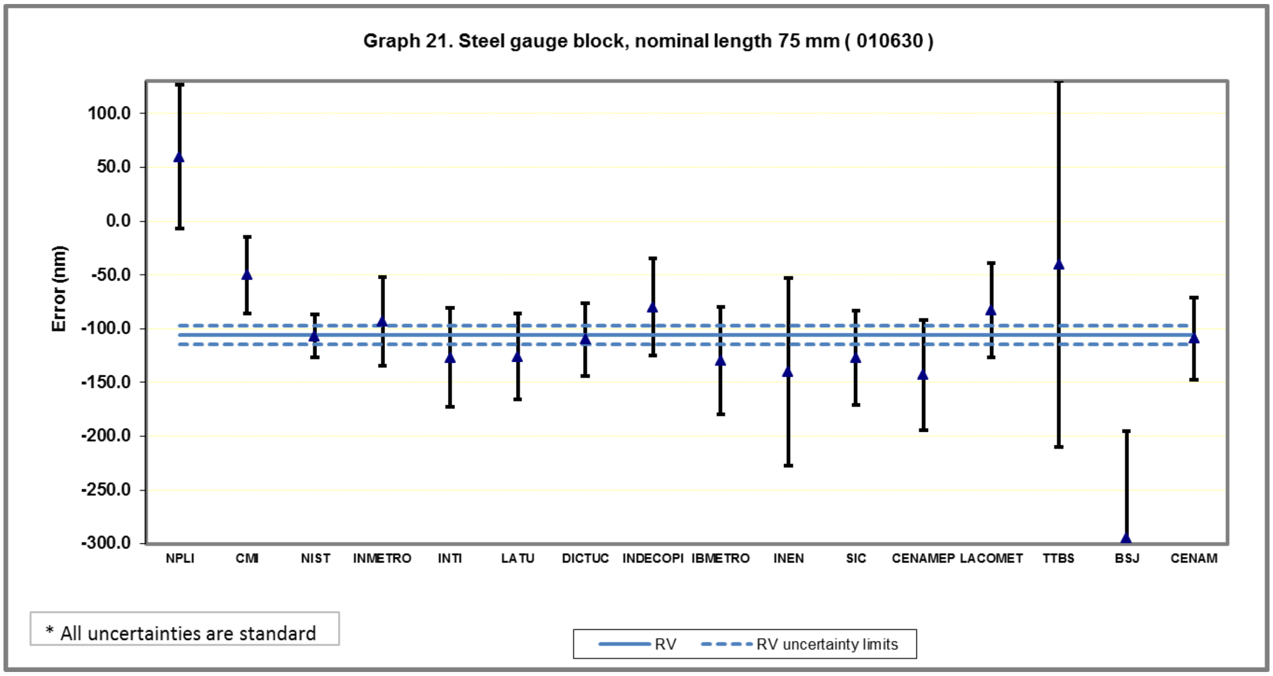

Graph 16. Steel gauge block, nominal length 1.000 5 mm (010223)
Error (nm)
NPLI
CMI
NIST
INMETRO
INTI
LATU
DICTUC
INDECOPI
IBMETRO
INEN
SIC
CENAMEP
LACOMET
TTBS
BSJ
CENAM
Not reported
* All uncertainties are standard
RV
RV uncertainty limits

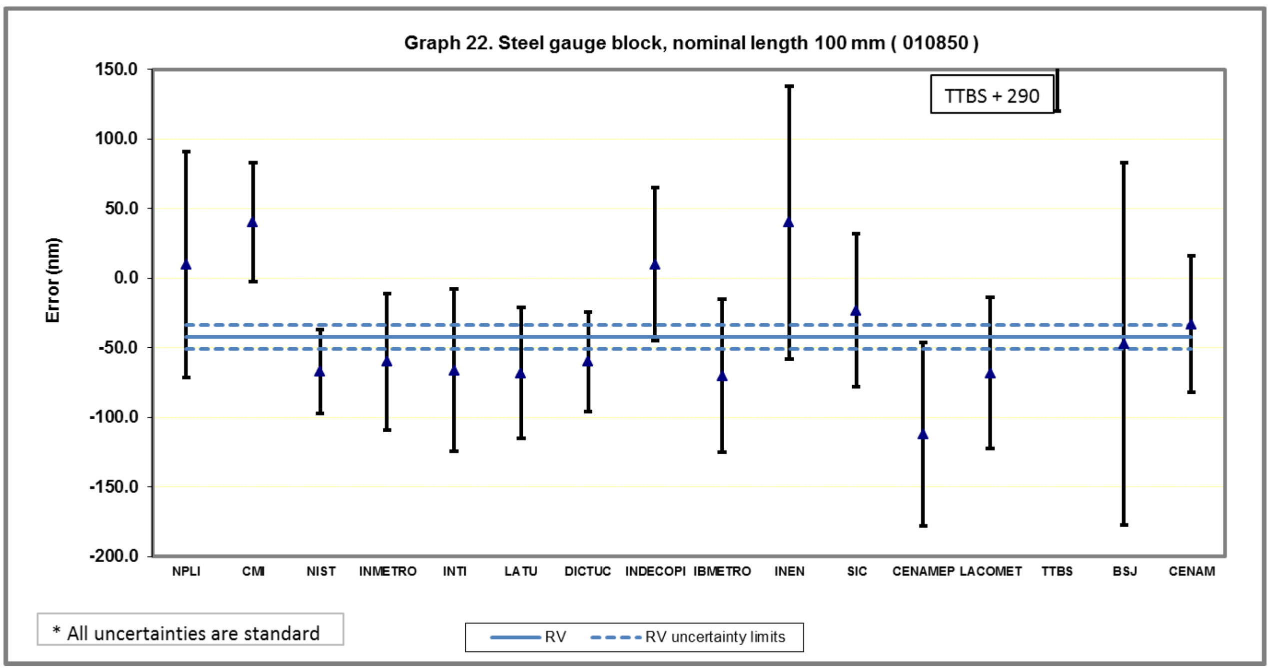

Graph 17 . Steel gauge block, nominal length 5 mm (000482)
Error (nm)
130.0
110.0
90.0
70.0
50.0
30.0
10.0
-10.0
-30.0
-50.0
NPLI
CMI
NIST
INMETRO
INTI
LATU
DICTUC
INDECOPI
IBMETRO
INEN
SIC
CENAMEP
LACOMET
TTBS
BSJ
CENAM
* All uncertainties are standard
RV
RV uncertainty limits


Graph 18 . Steel gauge block, nominal length 7 mm (010764)
Error (nm)
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
NPLI
CMI
NIST
INMETRO
INTI
LATU
DICTUC
INDECOPI
IBMETRO
INEN
SIC
CENAMEP
LACOMET
TTBS
BSJ
CENAM
* All uncertainties are standard
RV
RV uncertaity limits


Graph 19 . Steel gauge block, nominal length 10 mm (001329)
Error (nm)
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
NPLI
CMI
NIST
INMETRO
INTI
LATU
DICTUC
INDECOPI
IBMETRO
INEN
SIC
CENAMEP
LACOMET
TTBS
BSJ
CENAM
* All uncertainties are standard
RV
RV uncertainty limits


Graph 20. Steel gauge block, nominal length 50 mm (012254)
Error (nm)
220.0
170.0
120.0
70.0
20.0
-30.0
-80.0
NPLI
CMI
NIST
INMETRO
INTI
LATU
DICTUC
INDECOPI
IBMETRO
INEN
SIC
CENAMEP
LACOMET
TTBS
BSJ
CENAM
* All uncertainties are standard
RV
RV uncertainty limits





Tables 10 and **11** and **graphs 24** through **30**, show the deviations of the central length with respect to nominal values and their claimed standard measurement uncertainties of each participant for the seven ceramic GB. **Graph 23** shows the claimed standard uncertainties of the participants.

Nominal Value mm	Deviation (e_{ij}) from nominal length for Ceramics *GB* nm							
	NPLI	CMI	NIST	INMETRO	INTI	LATU	DICTUC	INDECOPI
1.000 5	-40	0	-27	-32	-9	-37	-17	-15
5	0	30	14	-14	10	-29	-17	-15
7	10	50	58	34	35	13	13	25
10	-80	0	-9	-24	-15	-18	-32	-25
50	20	140	116	97	89	103	65	55
75	40	150	148	89	122	111	101	135
100	-80	10	-5	-55	16	-53	-65	-15

Table 10A. Measurement results of the participants for Ceramics *GB*.

Nominal Value mm	Deviation (e_{ij}) from nominal length for Ceramics *GB* nm							
	IBMETRO	INEN	SIC	CENAMEP	LACOMET	TTBS	BSJ	CENAM
1.000 5	310	-10	-5	-12	-9	60	Not reported	-10
5	340	-20	-10	-1	-16	80	-36	-6
7	370	20	32	38	44	90	-18	65
10	320	-10	-40	-18	-15	Not reported	-68	-20
50	460	140	138	103	84	480	-16	100
75	480	170	155	164	102	480	-140	127
100	360	40	40	2	8	660	-195	-12

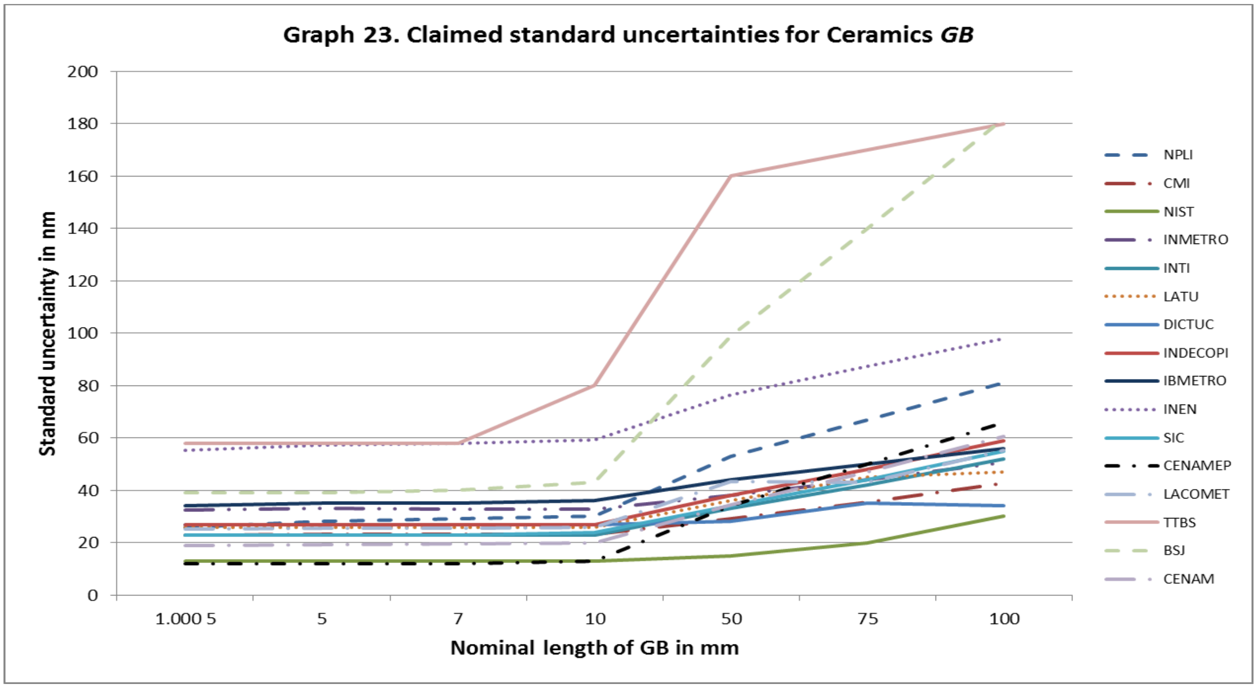
Table 10B. Measurement results of the participants for Ceramics *GB*.

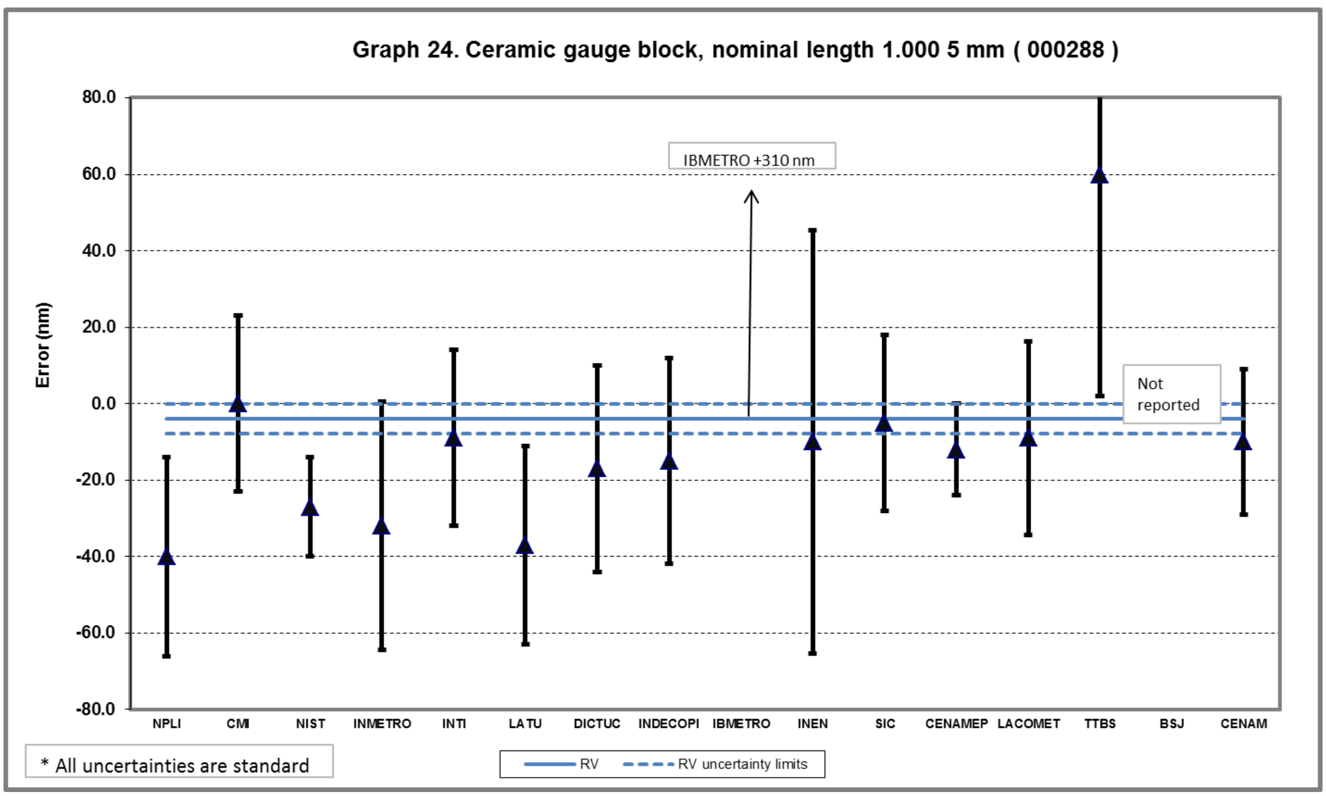
Nominal Value mm	Claimed standard uncertainties, $u(e_{ij})$, Ceramics *GB* nm							
	NPLI	CMI	NIST	INMETRO	INTI	LATU	DICTUC	INDECOPI
1.000 5	26	23	13	32.5	23	26	27	27
5	28	23.1	13	33.2	23	26	27	27
7	29	23.1	13	32.7	23	26	27	27
10	30	23.3	13	32.7	23	26	27	27
50	53	29.2	15	38.1	33	36	28	38
75	67	35.5	20	44	42	45	35	48
100	81	42.7	30	50.6	52	47	34	59

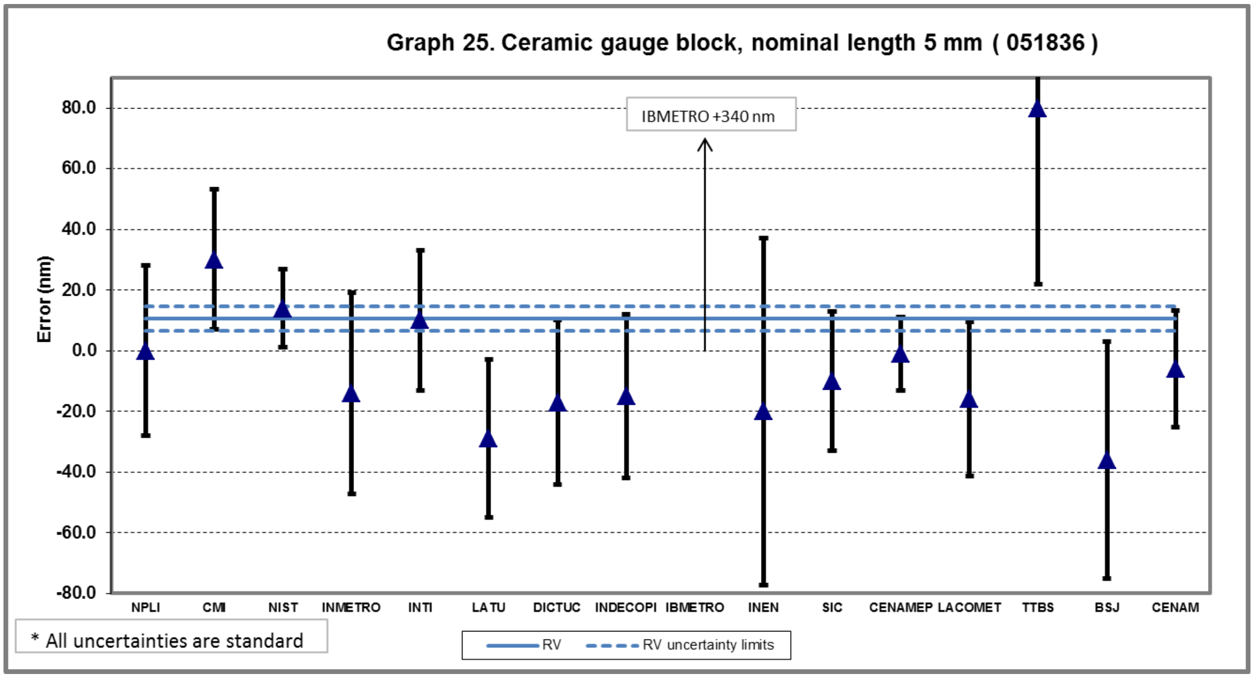
Table 11A. Claimed standard uncertainties of the participants for Ceramics *GB*.

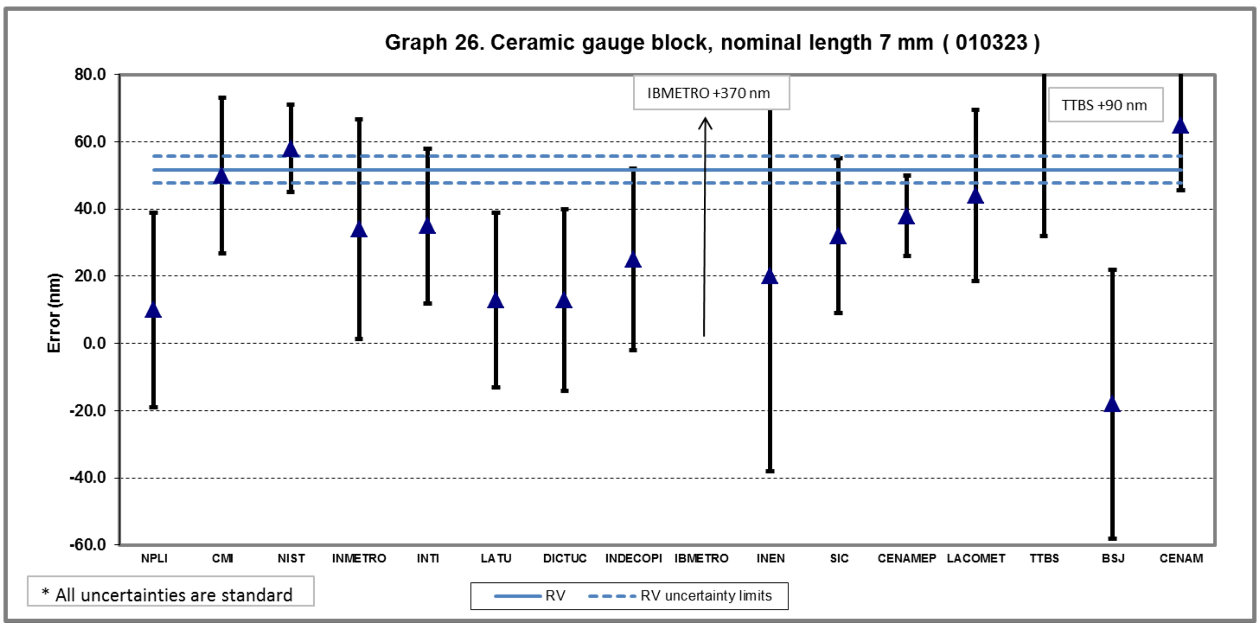
Nominal Value mm	Claimed standard uncertainties, $u(e_{ij})$, Ceramics *GB* nm							
	IBMETRO	INEN	SIC	CENAMEP	LACOMET	TTBS	BSJ	CENAM
1.000 5	34	55.4	23	12	25.3	58	Not reported	19.0
5	35	57.2	23	12	25.4	58	39	19.2
7	35	58	23	12	25.5	58	40	19.4
10	36	59.3	24	13	25.7	Not reported	43	19.9
50	44	76.5	34	34	43.5	160	99	34.5
75	50	87.3	44	50	43	170	140	47.1
100	56	98	55	66	55.3	180	182	60.6

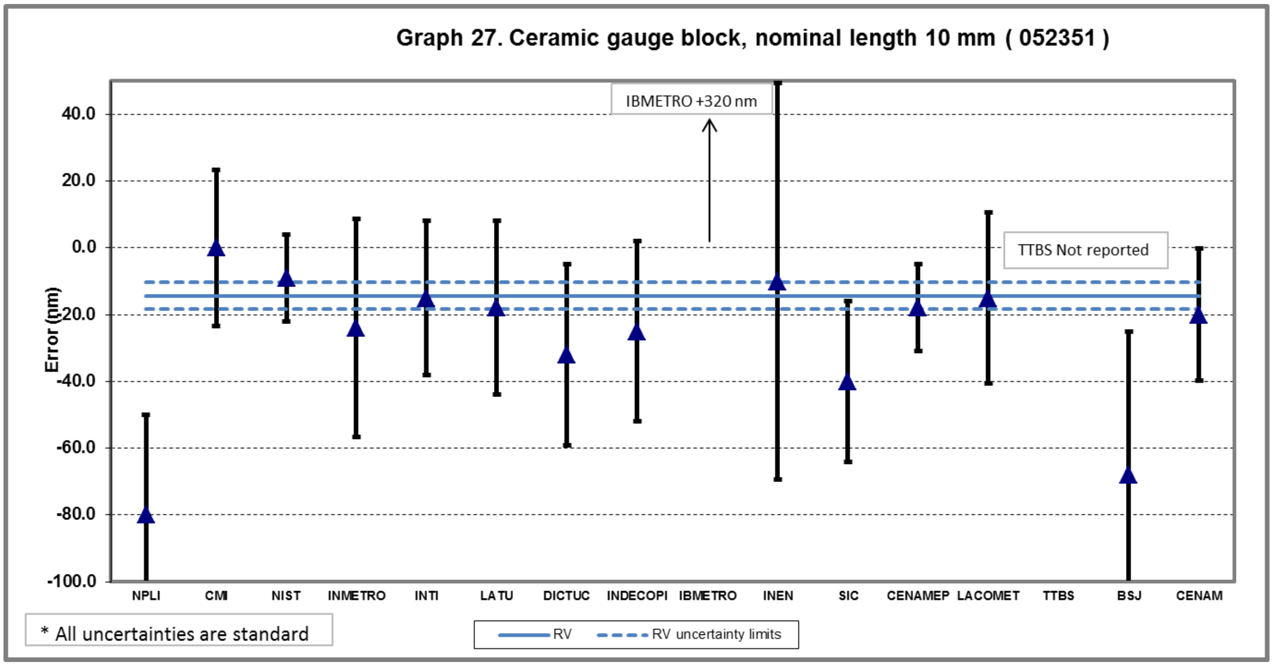
Table 11B. Claimed standard uncertainties of the participants for Ceramics GB.

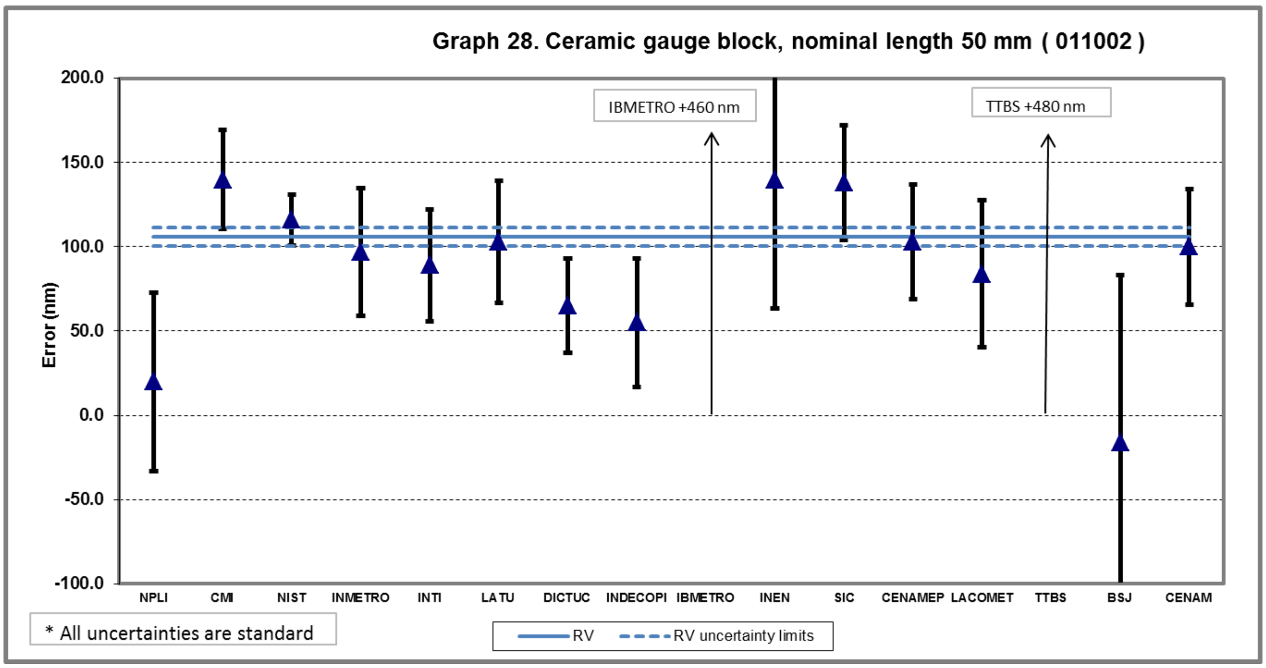

Graph 23. Claimed standard uncertainties for Ceramics GB
Standard uncertainty in nm
Nominal length of GB in mm
0
20
40
60
80
100
120
140
160
180
200
1.000 5
5
7
10
50
75
100
NPLI
CMI
NIST
INMETRO
INTI
LATU
DICTUC
INDECOPI
IBMETRO
INEN
SIC
CENAMEP
LACOMET
TTBS
BSJ
CENAM

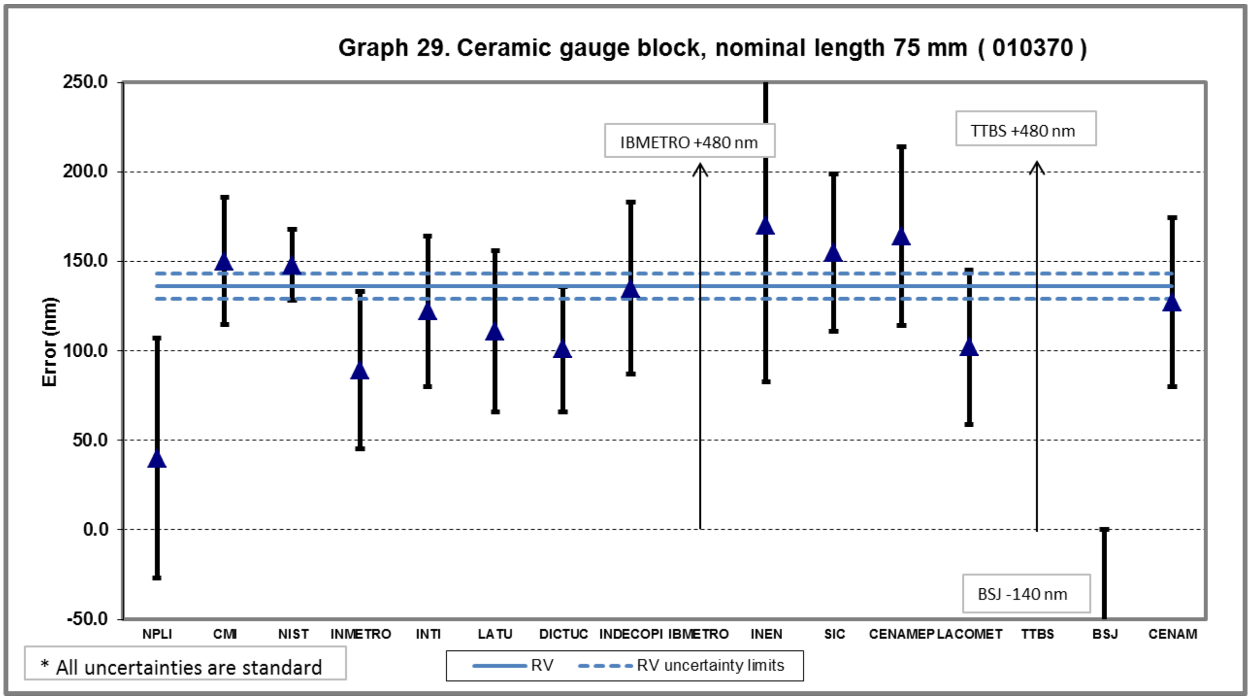

Graph 24. Ceramic gauge block, nominal length 1.000 5 mm (000288)
Error (nm)
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
IBMETRO +310 nm
Not reported
NPLI
CMI
NIST
INMETRO
INTI
LATU
DICTUC
INDECOPI
IBMETRO
INEN
SIC
CENAMEP
LACOMET
TTBS
BSJ
CENAM
* All uncertainties are standard
RV
RV uncertainty limits

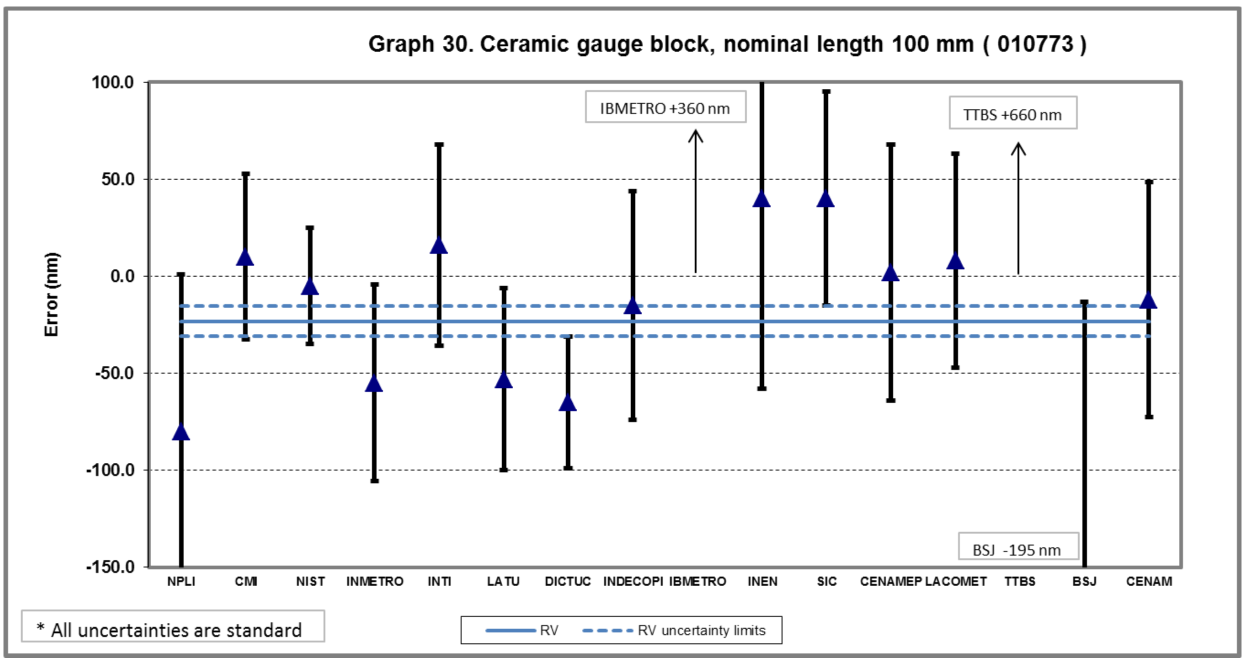

Graph 25. Ceramic gauge block, nominal length 5 mm (051836)
Error (nm)
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
IBMETRO +340 nm
NPLI
CMI
NIST
INMETRO
INTI
LATU
DICTUC
INDECOPI
IBMETRO
INEN
SIC
CENAMEP
LACOMET
TTBS
BSJ
CENAM
* All uncertainties are standard
RV
RV uncertainty limits


Graph 26. Ceramic gauge block, nominal length 7 mm (010323)
Error (nm)
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
IBMETRO +370 nm
TTBS +90 nm
NPLI
CMI
NIST
INMETRO
INTI
LATU
DICTUC
INDECOPI
IBMETRO
INEN
SIC
CENAMEP
LACOMET
TTBS
BSJ
CENAM
* All uncertainties are standard
RV
RV uncertainty limits


Graph 27. Ceramic gauge block, nominal length 10 mm (052351)
IBMETRO +320 nm
TTBS Not reported
Error (nm)
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
-100.0
NPLI
CMI
NIST
INMETRO
INTI
LATU
DICTUC
INDECOPI
IBMETRO
INEN
SIC
CENAMEP
LACOMET
TTBS
BSJ
CENAM
* All uncertainties are standard
RV
RV uncertainty limits


Graph 28. Ceramic gauge block, nominal length 50 mm (011002)
IBMETRO +460 nm
TTBS +480 nm
Error (nm)
200.0
150.0
100.0
50.0
0.0
-50.0
-100.0
NPLI
CMI
NIST
INMETRO
INTI
LATU
DICTUC
INDECOPI
IBMETRO
INEN
SIC
CENAMEP
LACOMET
TTBS
BSJ
CENAM
* All uncertainties are standard
RV
RV uncertainty limits


Graph 29. Ceramic gauge block, nominal length 75 mm (010370)
Error (nm)
250.0
200.0
150.0
100.0
50.0
0.0
-50.0
IBMETRO +480 nm
TTBS +480 nm
BSJ -140 nm
NPLI
CMI
NIST
INMETRO
INTI
LATU
DICTUC
INDECOPI
IBMETRO
INEN
SIC
CENAMEP
LACOMET
TTBS
BSJ
CENAM
* All uncertainties are standard
RV
RV uncertainty limits


Graph 30. Ceramic gauge block, nominal length 100 mm (010773)
Error (nm)
100.0
50.0
0.0
-50.0
-100.0
-150.0
IBMETRO +360 nm
TTBS +660 nm
BSJ -195 nm
NPLI
CMI
NIST
INMETRO
INTI
LATU
DICTUC
INDECOPI
IBMETRO
INEN
SIC
CENAMEP
LACOMET
TTBS
BSJ
CENAM
* All uncertainties are standard
RV
RV uncertainty limits

9. Reference Value (RV) and equations to determine the performance of participants

All usual parameters of the central tendency were calculated: the median, the simple mean and the inverse-variance weighted mean. All of these values appear in **Annex A**. However, the Supplementary Comparison Reference Values were obtained from the Regional Key Comparison SIM.L-K1:2007, as the artifacts were the same. These RV were calculated as the simple mean for all consistent results of the interferometric comparison [2].

The Reference Values, $\bar{e}_j$ and their Expanded Uncertainties, $U(\bar{e}_j)$ for the different *GB* j of both materials are shown in **Table 13**.

Supplementary Comparison Reference Values (RV)				
Nominal Length mm	**Steel**		**Ceramics**	
	Ref. Value, $\bar{e}_j$	$U(\bar{e}_j)$	***Ref. Value,*** $\bar{e}_j$	$U(\bar{e}_j)$
1.005	-9.3	8.2	-3.9	7.8
5	26.4	8.3	10.6	7.9
7	-2.6	8.3	51.7	7.9
10	36.2	7.8	-14.3	8.1
50	4.9	12.5	105.9	11.3
75	-105.6	17.0	136.2	13.9
100	-42.0	17.1	-23.1	15.6

Table 13. Reference values (simple mean of largest sub-set of consistent results of SIM.L-K1:2007 comparison) as deviations from Nominal Value and corresponding Expanded Uncertainty for both steel and ceramic *GB*. All values in nanometers.

For each laboratory, i, which measures each gauge block, j, let the measured deviation from nominal length be denoted by d_{ij} and calculated as,

$$d_{ij} = e_{ij} - \bar{e}_j \qquad (1)$$

Statistical consistency of the results with their associated uncertainties can be verified by calculating the normalized error E_n.

$$E_n = \frac{|d_{ij}|}{\sqrt{U^2(e_{ij})+U^2(\bar{e}_j)}} \qquad (2)$$

If E_n is greater than 1 it is considered that the result is inconsistent.

10. Participants Results of the Comparison

The reported measurement results were analyzed by simple statistical means to allow identification of any significant bias. **Tables 14** and **15** show the differences of the results of the participants with respect to the **RV** of each GB j, d_{ij}, and the corresponding Normalized Error, E_n calculated from equation **(2)**. Note that the uncertainties in this equation are expanded uncertainties.

NMI (i→)	NPLI		CMI		NIST		INMETRO		INTI		LATU	
Nominal Length (j↓)	d_{ij}	E_n	d_{ij}	E_n	d_{ij}	E_n	d_{ij}	E_n	d_{ij}	E_n	d_{ij}	E_n
1.000 5	-10.7	0.20	29.3	0.63	-17.7	0.65	29.3	0.49	-2.7	0.06	-25.7	0.49
5	-16.4	0.29	33.6	0.72	0.6	0.02	35.6	0.59	-30.4	0.65	-22.4	0.43
7	-37.4	0.64	22.6	0.48	4.6	0.17	23.6	0.39	-35.4	0.76	-9.4	0.18
10	-26.2	0.43	33.8	0.72	2.8	0.10	-12.2	0.20	-24.2	0.52	2.8	0.05
50	-34.9	0.33	75.1	1.26	10.1	0.31	6.1	0.09	-15.9	0.22	8.1	0.11
75	165.6	1.23	55.6	0.76	-1.4	0.03	12.6	0.15	-21.4	0.23	-20.4	0.25
100	52	0.32	82	0.94	-25	0.40	-18	0.18	-24	0.20	-26	0.27

Table 14A. Deviation from reference value for each GB, d_{ij} (nanometers) and Normalized Error, E_n, of the **Steel GB** for the first six participants.

NMI (i→)	DICTUC		INDECOPI		IBMETRO		INEN		SIC		CENAMEP	
Nominal Length (j↓)	d_{ij}	E_n	d_{ij}	E_n	d_{ij}	E_n	d_{ij}	E_n	d_{ij}	E_n	d_{ij}	E_n
1.000 5	-5.7	0.10	29.3	0.54	-30.7	0.45	-0.7	0.01	-17.7	0.38	-3.7	0.15
5	-21.4	0.39	-6.4	0.12	-26.4	0.37	-16.4	0.14	-32.4	0.69	-29.4	1.16
7	-32.4	0.59	12.6	0.23	-37.4	0.53	-27.4	0.24	-35.4	0.76	-10.4	0.41
10	-16.2	0.30	3.8	0.07	-16.2	0.22	-16.2	0.14	-43.2	0.89	-5.2	0.19
50	-14.9	0.25	-4.9	0.07	-14.9	0.17	5.1	0.03	-4.9	0.07	-14.9	0.21
75	-4.4	0.06	25.6	0.28	-24.4	0.24	-34.4	0.20	-21.4	0.24	-37.4	0.36
100	-18	0.24	52	0.47	-28	0.25	82	0.42	19	0.17	-70	0.53

Table 14B. Deviation from reference value for each GB, d_{ij} (nanometers) and Normalized Error, E_n, of the **Steel GB** for the next six participants.

NMI (i→)	LACOMET		TTBS		BSJ		CENAM	
Nominal Length (j↓)	d_{ij}	E_n	d_{ij}	E_n	d_{ij}	E_n	d_{ij}	E_n
1.000 5	31.3	0.61	39.3	0.38	Not reported	Not reported	7.3	0.24
5	19.6	0.38	43.6	0.41	-15.4	0.27	-3.4	0.11
7	29.6	0.40	22.6	0.21	-34.4	0.59	8.6	0.28
10	29.8	0.40	-16.2	0.11	-21.2	0.34	-12.2	0.39
50	31.1	0.35	195.1	0.61	-30.9	0.22	9.1	0.16
75	22.6	0.25	65.6	0.19	-189.4	0.94	-3.4	0.04
100	-26	0.24	332	0.98	-5	0.02	9	0.09

Table 14C. Deviation from reference value for each GB, d_{ij} (nanometers) and Normalized Error, E_n, of the **Steel GB** for the last four participants.

NMI (i→)	NPLI		CMI		NIST		INMETRO		INTI		LATU	
Nominal Length (j↓)	d_{ij}	E_n	d_{ij}	E_n	d_{ij}	E_n E_n	d_{ij}	E_n	d_{ij}	E_n	d_{ij}	E_n
1.000 5	-36.1	0.69	3.9	0.08	-23.1	0.85	-28.1	0.43	-5.1	0.11	-33.1	0.63
5	-10.6	0.19	19.4	0.41	3.4	0.13	-24.6	0.37	-0.6	0.01	-39.6	0.75
7	-41.7	0.71	-1.7	0.04	6.3	0.23	-17.7	0.27	-16.7	0.36	-38.7	0.74
10	-65.7	1.09	14.3	0.30	5.3	0.19	-9.7	0.15	-0.7	0.01	-3.7	0.07
50	-85.9	0.81	34.1	0.57	10.1	0.32	-8.9	0.12	-16.9	0.25	-2.9	0.04
75	-96.2	0.71	13.8	0.19	11.8	0.28	-47.2	0.53	-14.2	0.17	-25.2	0.28
100	-56.9	0.35	33.1	0.38	18.1	0.29	-31.9	0.31	39.1	0.37	-29.9	0.31

Table 15A. Deviation from reference value for each GB, d_{ij} (nanometers) and Normalized Error, E_n, of the **Ceramics GB** for the first six participants.

NMI (i→)	DICTUC		INDECOPI		IBMETRO		INEN		SIC		CENAMEP	
Nominal Length (j↓)	d_{ij}	E_n	d_{ij}	E_n	d_{ij}	E_n	d_{ij}	E_n	d_{ij}	E_n	d_{ij}	E_n
1.000 5	-13.1	0.24	-11.1	0.20	313.9	4.59	-6.1	0.05	-1.1	0.02	-8.1	0.32
5	-27.6	0.51	-25.6	0.47	329.4	4.68	-30.6	0.27	-20.6	0.44	-11.6	0.46
7	-38.7	0.71	-26.7	0.49	318.3	4.52	-31.7	0.27	-19.7	0.42	-13.7	0.54
10	-17.7	0.32	-10.7	0.20	334.3	4.61	4.3	0.04	-25.7	0.53	-3.7	0.14
50	-40.9	0.72	-50.9	0.66	354.1	3.99	34.1	0.22	32.1	0.47	-2.9	0.04
75	-35.2	0.49	-1.2	0.01	343.8	3.41	33.8	0.19	18.8	0.21	27.8	0.28
100	-41.9	0.60	8.1	0.07	383.1	3.39	63.1	0.32	63.1	0.57	25.1	0.19

Table 15B. Deviation from reference value for each GB, d_{ij} (nanometers) and Normalized Error, E_n, of the **Ceramics GB** for the next six participants.

NMI (i→)	LACOMET		TTBS		BSJ		CENAM	
Nominal Length (j↓)	d_{ij}	E_n	d_{ij}	E_n	d_{ij}	E_n	d_{ij}	E_n
1.000 5	-5.1	0.10	63.9	0.55	Not reported	Not reported	-6.1	0.16
5	-26.6	0.52	69.4	0.60	-46.6	0.59	-16.6	0.42
7	-7.7	0.15	38.3	0.33	-69.7	0.87	13.3	0.34
10	-0.7	0.01	Not reported	Not reported	-53.7	0.62	-5.7	0.14
50	-21.9	0.25	374.1	1.17	-121.9	0.61	-5.9	0.08
75	-34.2	0.39	343.8	1.01	-276.2	0.99	-9.2	0.10
100	31.1	0.28	683.1	1.90	-171.9	0.47	11.1	0.09

Table 15C. Deviation from reference value for each GB, d_{ij} (nanometers) and Normalized Error, E_n, of the **Ceramics GB** for the last four participants.

Table 16 shows the Root Mean Square (RMS) values of the deviations of the participants, δ_{RMS}, with respect to the RV. It gives a general idea of the deviations of each participant with respect to RV. It is determined as:

$$\delta_{RMS} = \sqrt{\frac{\sum_{i=1}^{n}(e_{ij} - \bar{e}_j)^2}{n}} \quad \textbf{(3)}$$

Where:

e_{ij} – Deviation from nominal of laboratory i on GB j,

$\bar{e}_j$ – RV of GB j,

n – Number of GB

NMI	δ_{RMS} (nm)	
	Steel GB	Ceramics GB
NPLI	69.5	62.5
CMI	52.2	20.9
NIST	12.4	13.0
INMETRO	21.9	27.1
INTI	24.1	18.2
LATU	18.6	28.6
DICTUC	18.4	32.5
INDECOPI	25.2	24.7
IBMETRO	26.5	340.3
INEN	36.3	34.4
SIC	27.6	31.3
CENAMEP	32.8	16.1
LACOMET	27.5	22.1
TTBS	149.7	350.0
BSJ	80.8	147.5
CENAM	8.1	10.5

Table 16. RMS Values of the deviations with respect to the RV, δ_{RMS}, of the participants.

In this case, as the RV is determined external to the comparison, it is not possible calculate Birge ratio.

11. Discussion and Conclusions

11.1 Discussion

- The comparison was linked to a previous interferometric comparison that measured the same artifacts. This was an advantage as the RV were obtained from the interferometric stage providing low uncertainty RV for the Mechanical Compariosn exercise. Not only were the RV obtained by a metrological superior technique, but it was the result of the measurement of several participants that measured by this technique.
- In the second stage of circulation which included only those NMI that measured exclusively by mechanical comparison (10 laboratories), the timing of circulation (from 2010-04-15 to 2011-04-28) was short thanks to the hand-delivery of the artifacts to the following participant. We would like to thank the participants for having taken this trouble and we suggest adopting this transport option whenever possible as it reduces the time of circulation and the risk of damage to the artifacts during transport.

- There was also some time saving during circulation in the first stage, as the NMI that participated in both exercises received the artifacts only once and measured by both techniques during the same period.
- Declared standard uncertainties among participants spread over a 6 fold range, going from 10 nm to 60 nm for the shortest GB and from 25 nm to 180 nm for the 100 mm GB.
- A few participants had the same traceability source because their master GB were calibrated at a same laboratory. However, we consider the influence of these correlations minimal and they were not taken in account in the present analysis.

11.2 Conclusions

- From Section 7 we observe that there were no appreciable changes on the measurements performed by the pilot laboratory of the ensemble of the GB of both materials over the last five years. Even though some drift may be appreciated on the steel GB during their first years of their history, the values shown prove they reached stability since 2005 approximately. Therefore, it can be assumed that the artifacts behaved adequately during the comparison exercise and that the exercise was valid.
- It may not be asserted that there was more consistency in one material or another and results were similar for both materials.
- From the comparison of the simple mean and weighted mean presented in Appendix A with the RV for all GB, we observe that both means are always pretty close to the RV. We do not identify either any systematic effect between the Interferometric mean or RV and the mechanical comparison mean.
- Once Expanded Uncertainties are considered, the performance of most of the participants for the steel GB was good, even though three results had normalized errors greater than one: NPLI on the 75 mm, CMI on the 50 mm and CENAMEP on the 5 mm; and BSJ did not present results for the 1.000 5 mm GB.
- IBMETRO presented inconsistent results for the ceramic GB. As they obtained consistent results for the steel GB, we presumed their “raw” measurements of the Ceramic GB were probably good, but that they applied a wrong correction for comparing GB of two different materials. In effect, they informed us after circulation of DRAFT A, they made such a mistake and they are already amending the miscalculation in the procedures of their Quality Management System.
- Also for the ceramic GB TTBS obtained inconsistent results for the three longer ones; and TTBS and BSJ did not present results for two nominal values.
- For the rest of the participants their results are judged satisfactory which proves their technical competence.

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Annex A Calculation of Alternate Statistical Parameters.

Steel gauge blocks / Nominal length, mm							
Statistical estimator	**1.000 5[1]**	**5**	**7**	**10**	**50[2]**	**75[3]**	**100[4]**
Reference Value, RV	**-9.3**	**26.4**	**-12.5**	**36.2**	**4.9**	**-105.6**	**-42.0**
Standard uncertainty	**4.1**	**4.2**	**4.2**	**3.9**	**6.3**	**8.5**	**8.6**
Simple arithmetic mean	-5.9	20.9	-11.1	27.7	0.1	-104.6	-50.3
Standard uncertainty	7.7	7.6	7.8	8.7	11.7	17.1	17.6
Birge Ratio	0.77	0.83	0.83	0.57	0.40	0.50	0.54
Weighted mean	-10.2	16.9	-8.8	29.7	5.4	-104.9	-54.9
Standard uncertainty	5.5	5.4	5.5	5.7	8.6	10.5	13.8
Birge Ratio	0.87	0.97	0.94	0.76	0.44	0.62	0.56
Median	-11.0	10.5	-12.5	22.0	0.0	-109.5	-60.0
Observed chi-squared	10.7	17.3	14.6	10.1	2.6	5.0	4.6
Degrees of freedom	14	15	15	15	13	13	12
$Pr\{\chi^2(v) > \chi^2_{obs}\}$	0.71	0.30	0.94	0.82	1.00	0.976	0.97
Reduced chi-squared	0.76	1.16	0.97	0.67	0.20	0.38	0.39

[1] BSJ not considered in the statistical parameter calculations as they did not measure.
[2]. CMI and TTBS were eliminated from the statistical parameter calculations.
[3]. NPLI and BSJ were eliminated from the statistical parameter calculations.
[4] CMI, INEN and TTBS were eliminated from the statistical parameter calculations.

Ceramics gauge blocks / Nominal length, mm							
Statistical estimator	**1.000 5[5]**	**5[6]**	**7[6]**	**10[7]**	**50[8]**	**75[9]**	**100[8]**
Reference Value, RV	**-3.9**	**10.6**	**51.7**	**-14.3**	**105.9**	**136.2**	**-23.1**
Standard uncertainty	**3.9**	**4.0**	**4.0**	**4.1**	**5.7**	**7.0**	**7.8**
Simple arithmetic mean	-11.6	-2.0	33.9	-26.7	96.2	131.2	-13.0
Standard uncertainty	8.2	8.2	8.2	8.0	11.2	13.7	16.3
Birge Ratio	0.78	0.89	0.82	0.75	0.87	0.56	0.66
Weighted mean	-16.1	-0.5	39.8	-20.6	102.8	132.4	-17.5
Standard uncertainty	5.8	5.7	5.7	5.9	8.6	11.1	13.6
Birge Ratio	0.64	0.79	0.86	0.77	0.91	0.62	0.73
Median	-11.0	-10.0	34.0	-19.0	100.0	131.0	-5.0
Observed chi-squared	9.8	12.5	14.7	8.9	10.1	4.4	6.6
Degrees of freedom	13	14	14	13	12	11	12
$Pr\{\chi^2(v) > \chi^2_{obs}\}$	0.71	0.57	0.40	0.78	0.61	0.96	0.88
Reduced chi-squared	0.75	0.89	1.05	0.69	0.84	0.40	0.55

[5] IBMETRO and BSJ were not considered for the statistical parameter calculations.
[6] IBMETRO was not considered for the statistical parameter calculations.
[7] IBMETRO and TTBS not considered for the statistical parameter calculations.
[8] IBMETRO, TTBS and BSJ not considered for the statistical parameter calculations.
[9] NPLI, IBMETRO, TTBS and BSJ were eliminated from the statistical parameter calculations.