EURAMET 725

CALIBRATION OF INDEX TABLES

Bilateral comparison

Final Report

Hugo Pirée, September 2013

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1 Introduction

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

The national metrology institute in Belgium (SMD) plans submitting a new entry in the Calibration and Measurement Capabilities (CMCs) declared by the NMIs in the CIPM Mutual Recognition Arrangement (MRA). This new entry will deal with angular measurements on index tables and polygons and will be supported by the results of this comparison.

Since the techniques applied by SMD for the calibration of index tables and of polygons are the same and considering that a comparison of index tables has not been organized in the recent past, the choice of comparing index tables was made.

When looking for a partner the following criteria were taken into account:
- the partner must have good results in recent comparisons of this type of measurements;
- the partner must have a CMC entry with a small uncertainty for this type of measurements;
- the partner has to be not to far from Belgium since transport of index tables is a rather delicate operation.

LNE in France participated successfully in the Euromet 371 comparison of polygons (same measuring technique as index tables), has a CMC entry for these types of measurements and is only some 350 km from SMD. LNE was contacted and very interested to participate.

The procedures outlined in the measuring instructions are principally intended to allow for a clear and unequivocal comparison of the measurement results and to complete the comparison in the time schedule provided for.

2 Organisation

2.1 Participants

Laboratory	Adress	Contact
SMD	Federal Public Service Economy, PME, Self Employed and Energy Division Quality and Safety National Standards SMD Koning Albert II laan 16 B-1000 Brussels Belgium	Hugo Pirée Tel: + 32 2 277 76 10 hugo.piree@economie.fgov.be

BNM-LNE	BNM-LNE Laboratoire National d'Essais 1, rue Gaston Boissier F-75015 Paris	Georges-Pierre Vailleau Tel: + 33 1 40 43 37 77 Fax: + 33 1 40 43 37 37 e-mail: georges.vailleau@lne.fr

2.2 Circulation

The initial planning was:

Laboratory	Country	Date
LNE	FR	April 2003 - October 2003
SMD	BE	December 2003 - June 2004

The measurements at LNE were performed from June to August 2003.

The measurements at SMD took much longer as planned because of:

- Problems with an autocollimator at SMD in 2004. Repair and recalibration was finalised in 2005;
- When starting the measurements at SMD in 2005, instabilities and too large errors (of more than 0,4") were observed on one of the Moore tables. These instabilities and errors were not present when the tables returned from LNE. The index table needed to be repaired. Moore reported that, during transport to Moore, the box was opened by customs, the Moore table unpacked, anti-oxidation protection taken off and the table detached from its fixings in the box. The table was then put back in the box without fixation and protection and forwarded to Moore. This caused further damage to the table.
- In 2006 the measurements at SMD could be restarted. A thorough investigation of unexpected differences between the 2 different methods applied by SMD caused a further delay;
- Index measurements were finalised at SMD in 2009;
- Measurements of the small angle divider were finalised at SMD in 2011.

3 Index tables

2 index tables are measured.

The first one is a Moore index table 1440 with serial number 287. This index table can be positioned over a full circle in steps of 15'. It has a mechanical lifting mechanism.

The second one is a Moore index table 1440 with serial number 271 and is equipped with a small angle divider with serial number SAD-164-1440-271. This index table can be positioned over a full circle in steps of 15'. It has a mechanical lifting mechanism. At each position, the generated angle can be adjusted over a range of 15' with the small angle divider. The small angle divider is based on a large micrometre screw with which the whole index table can be

rotated around it's axis on the small angle divider base plate. The resolution of the small angle divider is 0,1".

4 Measurement instructions

Before calibration, the index tables have to be inspected for damage. Cleaning of the table top surfaces could be necessary after unpacking.
Care should be taken for correct aligning of the index tables on the measuring equipment.
The points to be measured are from 0° to 360° every 15° (24 points in a circle), forwards and backwards.
If possible, measurements may be carried out in the zone 0° to 15° every 1° (15 points) and in the zone 0° to 5° every 15' (20 points).
If possible, measurements on the small angle divider may be carried out over the range of 0' to 15', every 50" (18 points).

4.1 Traceability

The measurements have to be traceable to the latest realisation of the metre as set out in the current “Mise en Pratique” or traceable to principle of the closed circle..

4.2 Measurand

For the index positions, the measurand is the deviation from the nominal total angle referred to 0°.

For the small angle divider, the measurand is the deviation from the nominal indication on the scale referred to 0’ on the scale.

4.3 Uncertainty

The uncertainty has to be estimated according to the ISO ‘Guide to the Expression of Uncertainty in Measurement’.

5 Instruments and measurement methods

5.1 LNE

5.1.1 Instruments

- Angular reference table developed by LNE
- Autocollimator Möller Wedel Elcomat HR
- Polygon

The measurements were performed in a temperature controlled laboratory at 20,0 °C ± 0,5 °C.

5.1.2 Method

The index table is mounted on the angular reference table with its rotation axis in a vertical position.

A polygon is mounted on the index table, in front of the autocollimator. The autocollimator allows for the correspondence of the angles of the 2 systems.

A rotation corresponding to the step between 2 positions is generated clockwise with the reference system. The index table is then rotated anti-clockwise with the same nominal value.

The measured value is the deviation of the value indicated by the index table minus the conventionally true value of the reference table.

The origin of the measurements on the index table corresponds to the position where the 0 of the mobile part is in coincidence with the 0 situated nearby the handle on the fixed part.

The following measuring cycles have been realized:
- 3 cycles from 0° to 360° in steps of 15°,
- 2 cycles from 0’ to 15’ in increasing direction and in decreasing direction in steps of 50".

Note: At the end of the increasing part of a cycle, the small angle divider was turned further to the 950" position before going back to 900" and starting the decreasing part of the cycle.

Measuring the Moore 1 Table

5.2 SMD

5.2.1 Instruments

- 2 Autocollimator Taylor Hobson DA20
- 24 sided polygon and a flat mirror
- Laserinterferometer Agilent with angle optics

The measurements were performed in a temperature controlled laboratory at 20,0 °C ± 0,3 °C.

5.2.2 Method

For the 15° index steps 2 different methods were applied:

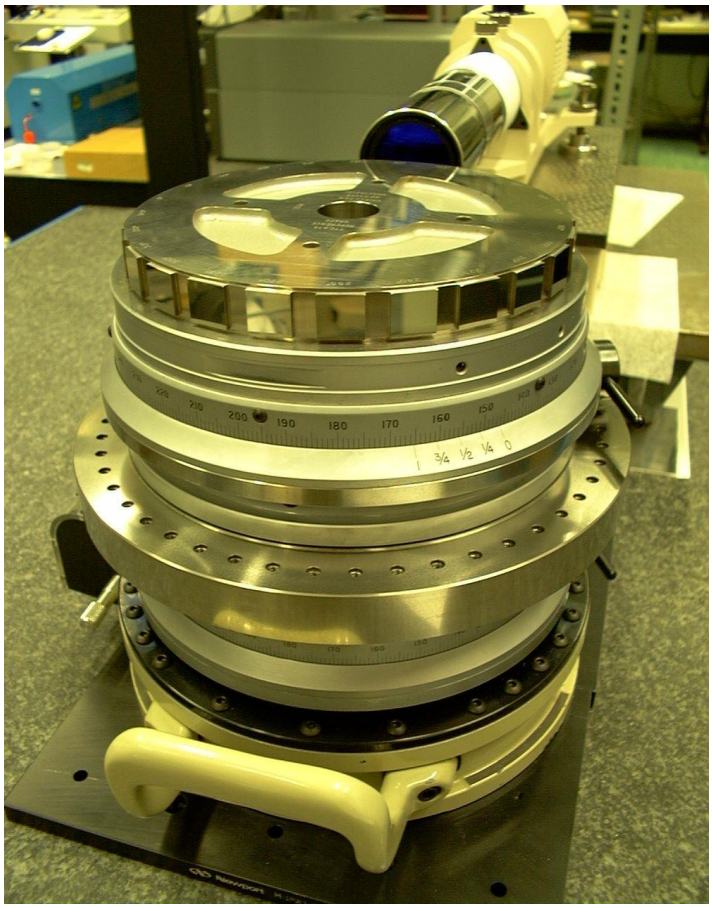
- 2 table stack with polygon /mirror fixed on top table and 1 autocollimator;
- 1 table with polygon / mirror fixed on table and 2 autocollimators.

The measurements were performed both in clockwise and counter clockwise directions.

In the 2 table method, all of the combinations of 15° steps were set on the index tables, resulting in a matrix set of 24 x 24 measurements of the polygon faces with the autocollimator. This allows an error separation matrix calculation to obtain the deviations from nominal of the 2 index tables and of the polygon. These 3 sets of results are each independent of the deviations of the 2 other elements in the stack.

In the 2 autocollimator method, the autocollimators were first positioned to read angles at 15° from each other. The mirror is fixed on the index table to be calibrated. The index table to be calibrated is mounted on the other index table. The autocollimators are set at 15° from each other. The mirror is in front of the 1st autocollimator (0° position). The 1st autocollimator value is recorded. Then the index table with the mirror is turned so that the mirror faces the 2nd autocollimator (15° position). The 2nd autocollimator value is recorded. Then the bottom table is turned 15° so that the mirror faces the 1st autocollimator with the index table to be calibrated in the 15° position. The 1st autocollimator value is recorded. The top index table is turned to 30° so that the mirror faces the 2nd autocollimator. The 2nd autocollimator value is recorded. This process is repeated until a full turn of the bottom index table.

For the small angle divider, the double reflector (angular reflector) of the angle optics of the laserinterferometer was mounted centrally on the index table top. The correction factor for the angle optics was obtained from values of the – 15°, 0° and + 15° positions of the index table as found with the 2 autocollimators method. During the determination of the correction factor, the true 0" position of the angle optics with respect to each other was calculated and adjusted. The laserinterferometer was zeroed at this position to minimise errors from the misalignment of the angle optics.
8 cycles from 0’ to 15’ (900") were realized in increasing direction and in decreasing direction in steps of 50". Before the start of the increasing part of a cycle, the small angle divider was turned to the – 300" (1 full turn of the micrometer screw) before going back to the starting point at 0°. After the end of the increasing part of a cycle, the small angle divider was turned further to the 1 200" position (1 full turn of the micrometer screw) before going back to 900" and starting the decreasing part of the cycle.



6 Stability

The results from LNE and SMD for the 2 index tables match quite well. So it can be concluded that the tables are stable and that the damage and repair did not have an effect on the 15° positioning precision.

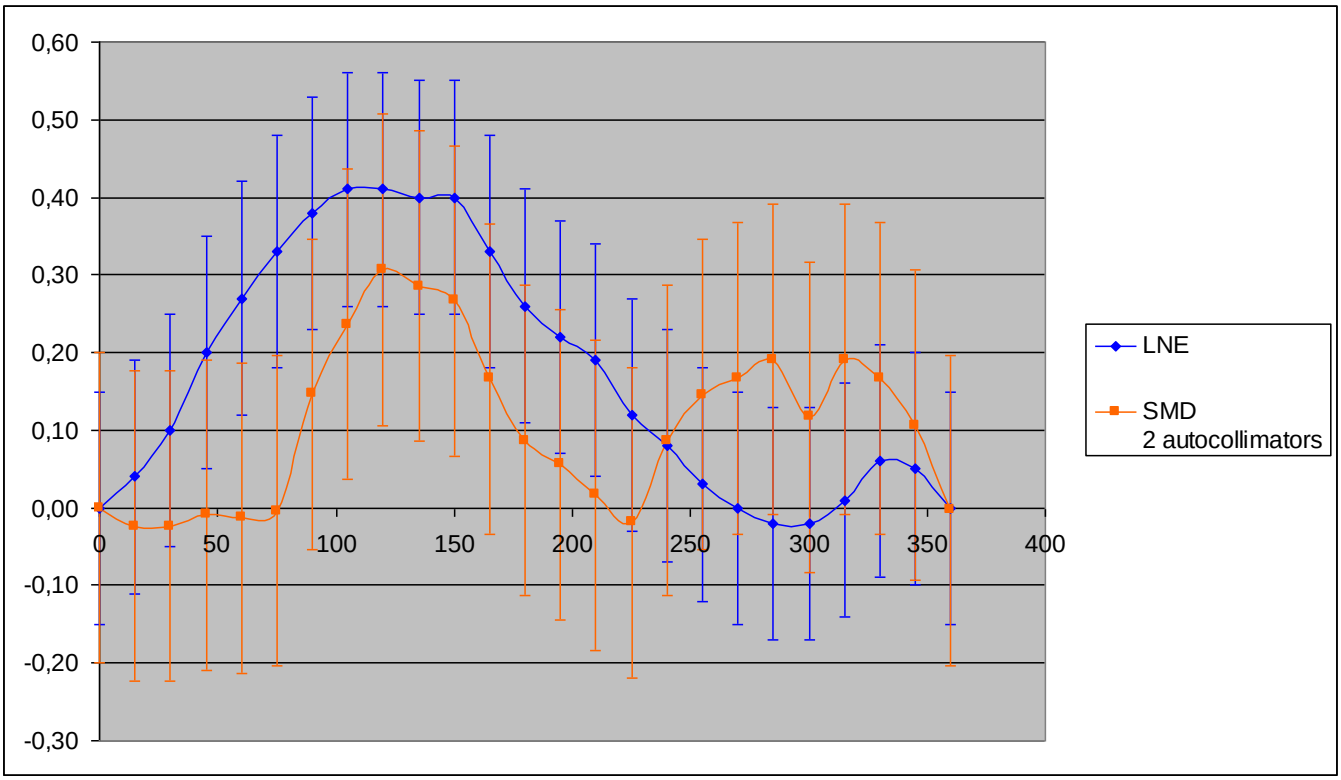
The results from LNE and SMD for the small angle divider do not match. The general profiles match, the range of the hysteresis matches, but the slope of the error graphs differ. It is not unambiguously clear if this is caused by instability or by measuring problems, but most probable is a change in the small angle divider (see discussion of the results).

7 Results

For SMD, only the results of the 2 autocollimator method are taken into account for this comparison. With the 2 table stack method, quite large differences, up to 0,5", were observed between the results of each table, depending of its position in the stack. When a table is in the top position, the results match quite well with the results from the 1 table 2 autocollimators method. When the index table is in the bottom position, differences and instabilities occur. Because of the principle of the error separation method, these instabilities in the bottom table have some influence on the results of the top table. Further investigations proved that the errors and the instability of the index tables depend on the load on top of the table.

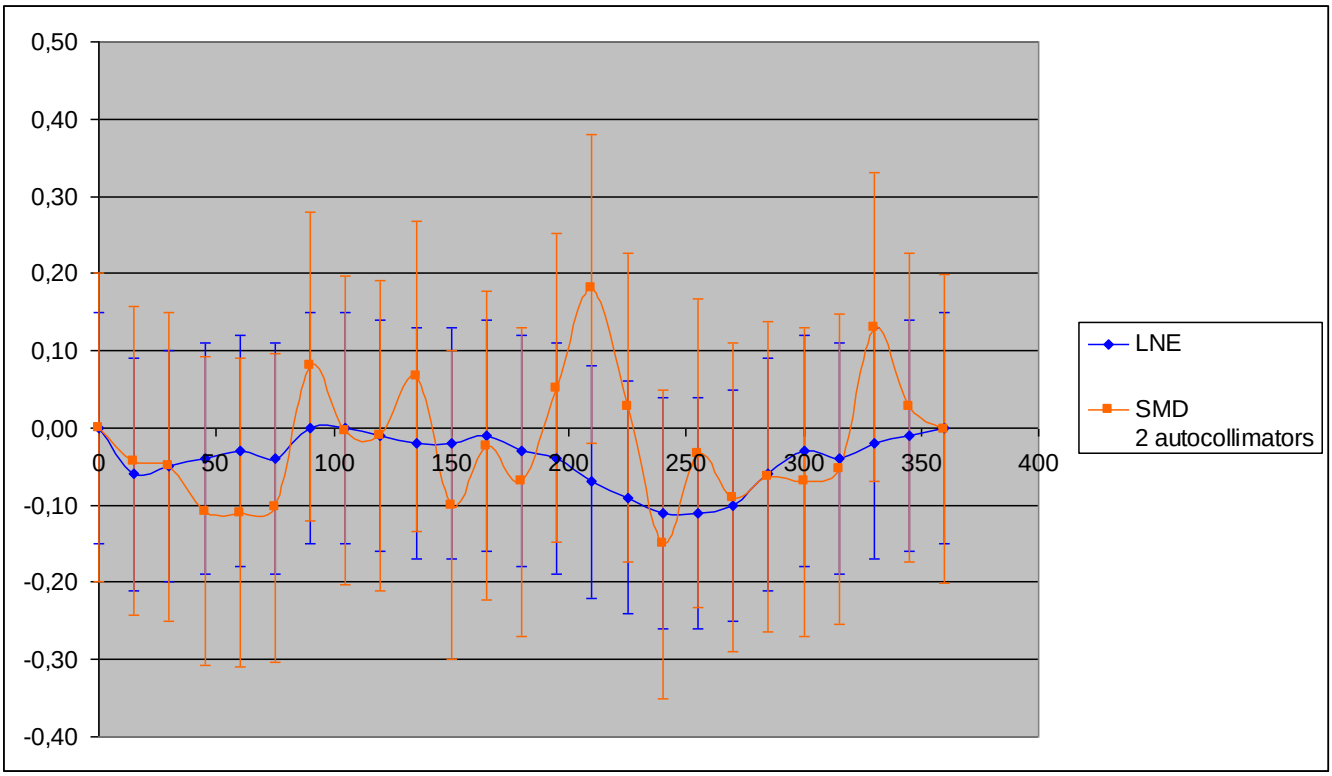
7.1 Index table Moore 1440 sn 271

	LNE		SMD		
Value set on MOORE 1 (271) *(degrees)*	Deviation *(")*	*U* *k = 2* (")	Deviation *(")*	*U* *k = 2* (")	*- 1 < en < 1*
0	0,00	0,15	0,00	0,20	0,00
15	0,04	0,15	-0,02	0,20	-0,26
30	0,10	0,15	-0,02	0,20	-0,49
45	0,20	0,15	-0,01	0,20	-0,84
60	0,27	0,15	-0,01	0,20	-1,13
75	0,33	0,15	0,00	0,20	-1,34
90	0,38	0,15	0,15	0,20	-0,93
105	0,41	0,15	0,24	0,20	-0,70
120	0,41	0,15	0,31	0,20	-0,41
135	0,40	0,15	0,29	0,20	-0,46
150	0,40	0,15	0,27	0,20	-0,53
165	0,33	0,15	0,17	0,20	-0,66
180	0,26	0,15	0,09	0,20	-0,69
195	0,22	0,15	0,06	0,20	-0,66
210	0,19	0,15	0,02	0,20	-0,69
225	0,12	0,15	-0,02	0,20	-0,56
240	0,08	0,15	0,09	0,20	0,03
255	0,03	0,15	0,15	0,20	0,46
270	0,00	0,15	0,17	0,20	0,67
285	-0,02	0,15	0,19	0,20	0,84
300	-0,02	0,15	0,12	0,20	0,55
315	0,01	0,15	0,19	0,20	0,72
330	0,06	0,15	0,17	0,20	0,43
345	0,05	0,15	0,11	0,20	0,22
360	0,00	0,15	0,00	0,20	-0,01



7.2 Index table Moore 1440 sn 287

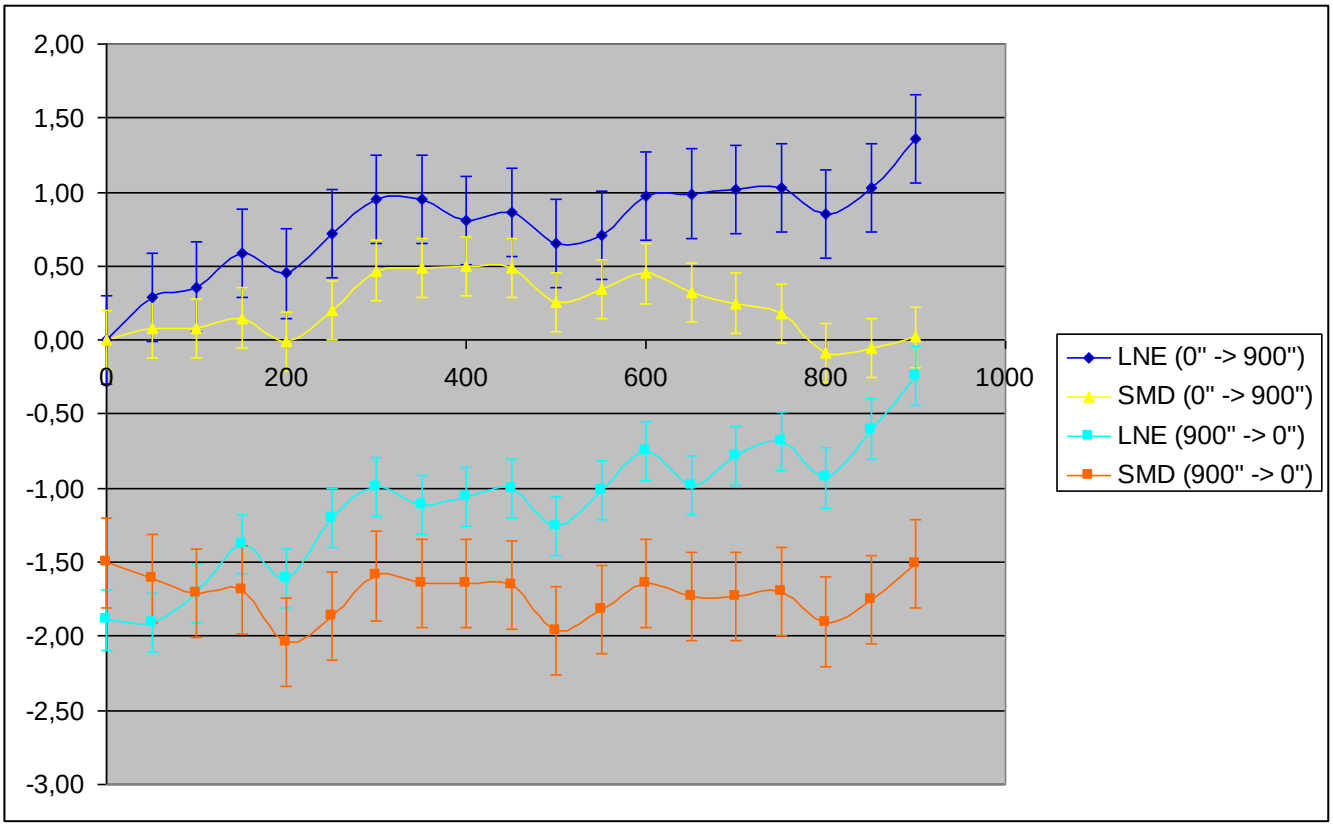
	LNE		SMD		
Value set on MOORE 1 (271) *(degrees)*	Deviation *(")*	*U* *k* = 2 (")	Deviation *(")*	*U* *k* = 2 (")	*- 1 < en < 1*
0	0,00	0,15	0,00	0,20	0,00
15	-0,06	0,15	-0,04	0,20	0,07
30	-0,05	0,15	-0,05	0,20	0,00
45	-0,04	0,15	-0,11	0,20	-0,27
60	-0,03	0,15	-0,11	0,20	-0,32
75	-0,04	0,15	-0,10	0,20	-0,25
90	0,00	0,15	0,08	0,20	0,32
105	0,00	0,15	0,00	0,20	-0,01
120	-0,01	0,15	-0,01	0,20	0,00
135	-0,02	0,15	0,07	0,20	0,35
150	-0,02	0,15	-0,10	0,20	-0,32
165	-0,01	0,15	-0,02	0,20	-0,05
180	-0,03	0,15	-0,07	0,20	-0,16
195	-0,04	0,15	0,05	0,20	0,37
210	-0,07	0,15	0,18	0,20	1,00
225	-0,09	0,15	0,03	0,20	0,47
240	-0,11	0,15	-0,15	0,20	-0,16
255	-0,11	0,15	-0,03	0,20	0,31
270	-0,10	0,15	-0,09	0,20	0,04
285	-0,06	0,15	-0,06	0,20	-0,01
300	-0,03	0,15	-0,07	0,20	-0,16
315	-0,04	0,15	-0,05	0,20	-0,05
330	-0,02	0,15	0,13	0,20	0,60
345	-0,01	0,15	0,03	0,20	0,15
360	0,00	0,15	0,00	0,20	-0,01



7.3 Small angle divider on Index table Moore 1440 sn 287

	LNE (0" -> 900")		SMD (0" -> 900")		
Value on vernier (")	Average deviation of the small angle divider ascending values (")	*U* *k* = 2 (")	Average deviation of the small angle divider ascending values (")	*U* *k* = 2 (")	*- 1 < en < 1*
0	0,00	0,2	0,00	0,3	0,00
50	0,29	0,2	0,08	0,3	-0,59
100	0,36	0,2	0,08	0,3	-0,78
150	0,59	0,2	0,15	0,3	-1,22
200	0,45	0,2	-0,01	0,3	-1,28
250	0,72	0,2	0,20	0,3	-1,45
300	0,95	0,2	0,47	0,3	-1,33
350	0,95	0,2	0,48	0,3	-1,29
400	0,81	0,2	0,50	0,3	-0,86
450	0,86	0,2	0,49	0,3	-1,03
500	0,65	0,2	0,26	0,3	-1,10
550	0,71	0,2	0,34	0,3	-1,02
600	0,97	0,2	0,45	0,3	-1,44
650	0,99	0,2	0,32	0,3	-1,86
700	1,02	0,2	0,25	0,3	-2,14
750	1,03	0,2	0,18	0,3	-2,35
800	0,85	0,2	-0,08	0,3	-2,59
850	1,03	0,2	-0,06	0,3	-3,01
900	1,36	0,2	0,02	0,3	-3,72

	LNE (900" -> 0")		SMD (900" -> 0")		
Value on vernier (")	Average deviation of the small angle divider decending values (")	*U* *k* = 2 (")	Average deviation of the small angle divider decending values (")	*U* *k* = 2 (")	*- 1 < en < 1*
900	-0,24	0,2	-1,51	0,3	-3,52
850	-0,6	0,2	-1,75	0,3	-3,19
800	-0,93	0,2	-1,90	0,3	-2,70
750	-0,68	0,2	-1,70	0,3	-2,83
700	-0,78	0,2	-1,73	0,3	-2,63
650	-0,98	0,2	-1,73	0,3	-2,08
600	-0,75	0,2	-1,64	0,3	-2,48
550	-1,01	0,2	-1,82	0,3	-2,25
500	-1,26	0,2	-1,96	0,3	-1,94
450	-1	0,2	-1,66	0,3	-1,82
400	-1,06	0,2	-1,64	0,3	-1,62
350	-1,11	0,2	-1,64	0,3	-1,47
300	-0,99	0,2	-1,59	0,3	-1,67
250	-1,2	0,2	-1,86	0,3	-1,83
200	-1,61	0,2	-2,04	0,3	-1,20
150	-1,38	0,2	-1,69	0,3	-0,86
100	-1,71	0,2	-1,71	0,3	0,01
50	-1,91	0,2	-1,61	0,3	0,84
0	-1,89	0,2	-1,50	0,3	1,07


2,00
1,50
1,00
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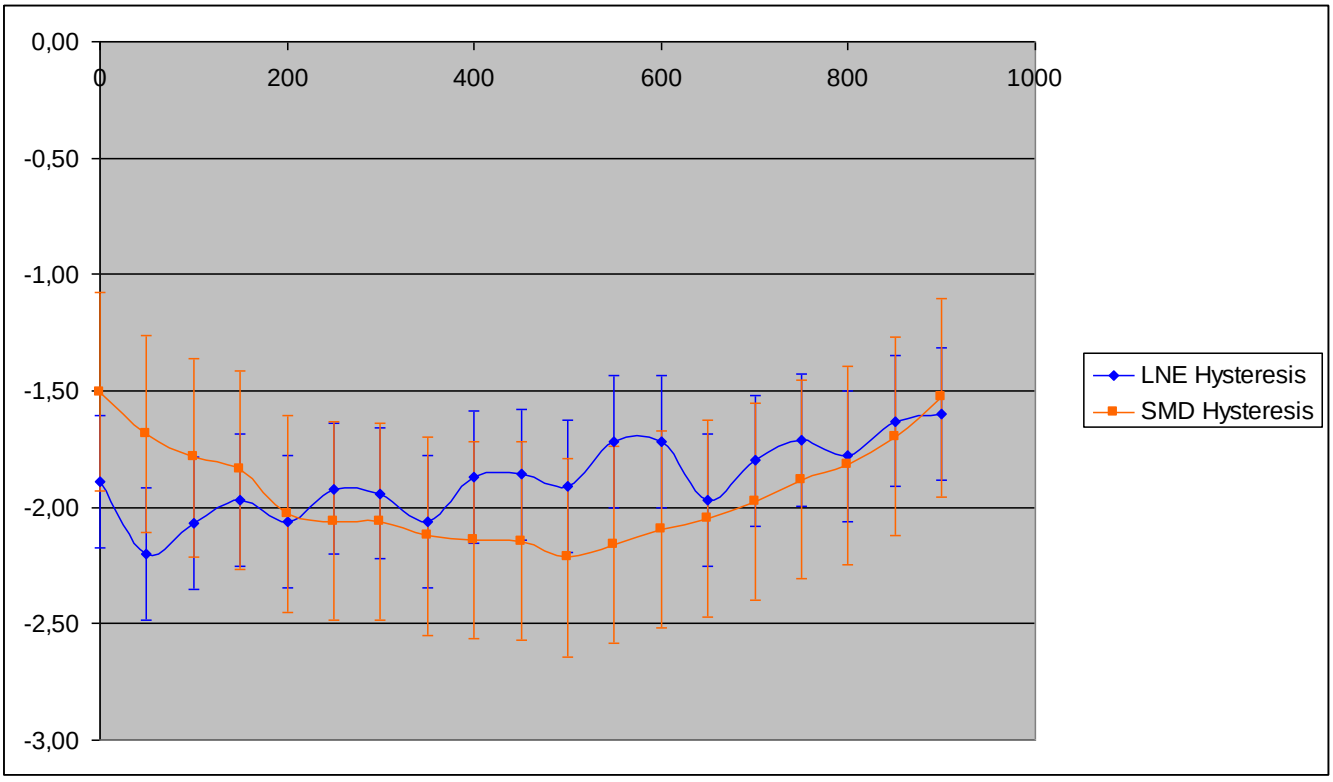
0,00
-0,50
-1,00
-1,50
-2,00
-2,50
-3,00
0
200
400
600
800
1000
LNE (0" -> 900")
SMD (0" -> 900")
LNE (900" -> 0")
SMD (900" -> 0")


0,00
-0,50
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-1,50
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-2,50
-3,00
0
200
400
600
800
1000
LNE Hysteresis
SMD Hysteresis

7.4 Discussion of results

The calibration results for the index positions are in good agreement. Out of 48 results, only 2 have an e_n value slightly above 1. The reason why these 2 e_n value are slightly above 1 could not be determined. When taking into account the smoothness of the error graphs one can suppose that the origin of the differences is in the SMD results. When comparing the results for the Moore 1440 sn 271 table there is however a strange “flip over” in the graphical representation for angles from SMD between 215° and 360 °, compared to the rather smooth graph from LNE. Taken into account the uncertainties these values are acceptable, but a further investigation at SMD could be useful.

For the small angle divider most of the e_n values are > 1 and go up to about 3 at the end of the measuring range. At the end of the measuring range, the values found by SMD are 1,34" smaller the those from LNE for the increasing values. At the same position the difference for the descending values is 1,27". This comes from a difference in slope between the results from LNE and SMD. When not taken into account the linearity difference, he general shape of the error graphs and the hysteresis between the 2 measuring directions match well (all e_n <1).

Actions by SMD after receiving the results from LNE:

- First, the correction factor for the SMD angle optics was rechecked but showed no problem. The correction factor of the angle optics was determined at - 15°, 0° and + 15° of index table sn 271. These positions showed no evident problem with the index position measurements. After application of the correction factor in the software, the - 15°, - 10°, - 5°, 0°, 5°, 10° and + 15° positions on the index table were checked and the laserinterferometer showed no error of more than 0,05".
- At the same time the angle φ_0 between the angle interferometer optic and the angle retroreflector was minimised to < 10", resulting in a possible measuring error at the end of the measuring range of the small angle divider of less than $5 \cdot 10^{-8}$".
- Then the start position for the small angle divider and the angular laserinterferometer is at 0° on the index table and 0" on the small angle divider. At the 900" position on the small angle divider, the index table was turned back over 1 index step from 0" to - 900" so that the angular reflector was again in the start position with the small angle divider in the 900" position. The laserinterferometer showed a difference of less than 0,15" with respect to the start position.
- Finally the measurements on the small angle divider were repeated. The new results confirmed the original results.

So it may be concluded that there is no reason why the results from SMD should be wrong.

Since the measurements at LNE were performed with the same angular reference table as used for the measurements of the index steps, and since the results for the index steps show no problem one can reasonably conclude that there should be no problem with the results from LNE for the small angle divider.

Taken into account these facts it seems that the difference could most probably come from a drift or change in the small angle divider.

The difference in linearity between the measurements at LNE and the measurements at SMD corresponds to a difference in the micrometre screw’s axial displacement of the small angle divider of 0,9 µm over a total range of 0,63 mm or to a difference of 0,2 mm in the distance from the index table rotation point to the micrometer screw axis, or a combination of those. Possible causes could be:

- Wear in the micrometer screw because the measurements were made with an interval of 8 years;
- In this 8 years interval, the micrometer screw was dismounted from the small angle divider unit for maintenance and cleaning;
- Other not yet detected problem in the index table.

One of these causes or a combination of those probably explains the difference between the results from LNE and SMD for the small angle divider.

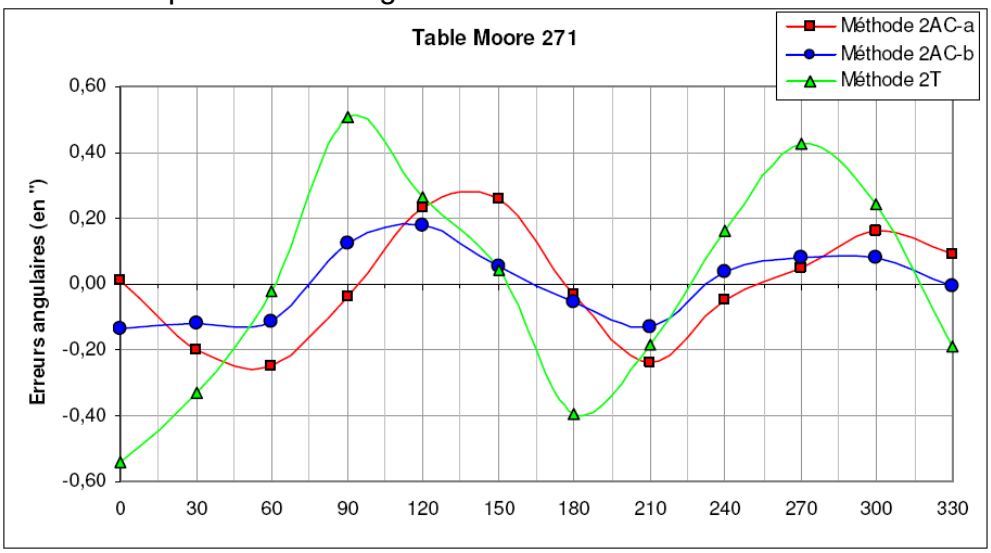
8 Conclusions

This comparison was organised for the support of a CMC entry from SMD for the calibration of indexing tables and polygons. The results for the indexing positions show no problem for the Moore 1440 sn 287 indexing table. For the other index table, 2 out of 24 results have $1 < |e_n| < 1{,}5$. Before applying for a CMC entry SMD will:

- Revise its uncertainty budget to check if there was no underestimation of a contribution;
- Repeat the measurements of the index positions.
- Limit the CMC entry to the 2 autocollimator method.

The differences between SDM and LNE for the small angle divider are most probably caused by some change in the small angle divider. Because SMD wants to have a good support for a possible CMC entry for those types of measurements and because SMD will participate in the EURAMET.L-K3a comparison of autocollimators (measurements planned in 2012), SMD will wait for applying for a CMC entry for small angles until confirmation is obtained of good results in EURAMET.L-K3a.

The effect of load on the deviations of an indexing tabled showed up during this comparison. As an example the following values were obtained:



The red and blue graph are results with minimum load on the indexing table top. The green graph are results with a load on the table top, equal to the mass of the table itself. Further investigations will be made.