Consultative Committee for Length – CCL

Discussion Group on Gauge Blocks – DG1

14-15 June 2018

DG1 report to CCL, 2018

BIPM, Sèvres

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Discussions

The main topics of emails since the previous meeting of the CCL have been the organisations of the various international comparisons for MRA purposes. Additional discussion topics were raised in the period of preparing for the meetings of the CCL and its Working Groups and these are discussed below.

We wish former member Peter Franke from PTB best wishes for his retirement!

Discussion 1 – uncertainties for measurands other than central length

One topic raised by Tanfer Yandayan at the WG-MRA 2017 meeting in Espoo was:

> *DG1 to discuss recent supplementary comparison protocols and results for gauge block measurement by mechanical comparison which have included requests for measurements not only at the centre of the face, but also at the four nominated corner locations. In many cases the laboratories do not correctly calculate the (usually smaller) uncertainty of the measured variation in length. Only four laboratories currently have CMCs for variation in length. Some laboratories have the capability to measure flatness, variation in length and the fo and fu parameters, but not many customers request these.*

Comment from NPL: Tanfer raised this discussion issue as he had seen several comparison reports where laboratories had measured using the 5 point process but had simply multiplied the central length measurement uncertainty by 1.4142 to obtain the uncertainty of the variation in length. They had forgotten that there are correlated uncertainties between the maximum and minimum length measurements so the uncertainty should be somewhat different. We also noticed that the comparison reports did not really analyse the variation in length results and there were no conclusions made recording CMCs for variation in length.

Comment from KRISS: I agree that the measurement uncertainty for length difference of gauge block pairs, or variation in length should be smaller than that of central length due to correlation.

KRISS only measures variation in length of gauge blocks upon request from the customer, but there are seldom requests. And the f_o and f_u measurements are made only for the 11 block set used for calibrating gauge block comparators.

Previous comment from METAS: METAS does offer the f_o and f_u parameters on customer request, it's one of our standard services. Measured mostly by comparator (central length by interferometer, f_o and f_u by comparator). We believe that f_o and f_u measurements are validated by the calibration procedure of the comparator according to the EURAMET guide. On the GBI software we have implemented an evaluation of the 5 points giving equivalent results than those measured on a comparator. This was validated by comparison between both methods and shown to give an agreement well within the quoted uncertainty.

Previous comment from CEM: We measure f_o and f_u parameters only when calibrating sets of 11 gauges intended for the ulterior calibration of GB comparators. We follow a procedure based on the EURAMET Guide.

Previous comment from INMETRO: Our interferometry lab normally don´t give any flatness or f_o and f_u information for calibrated gauge blocks (only our automated interferometer directly gives such values). No customer yet has asked us to measure those values for the regular absolute interferometric calibrations. Nevertheless, a generic object presenting good parallelism between two of its flat faces can be easily measured with many current interferometers. Perhaps the current CMC definitions could be generalized to describe interferometric length measurements between two parallel faces of any object. Example: several years ago we got flatness information of all faces of a 12-sided optical polygon using the semi-automated GBI Mitutoyo interferometer.

In the similar ways as in CEM, INMETRO only provide f_o and f_u results in a regular basis along our differential calibration services, and for only one of the gauge-blocks of the set of pairs used to calibrate electromechanical comparators (as recommended by the EURAMET cg-2). There would be a good idea to think about inter-comparisons concerning differential measurements of gauge block pairs.

Discussion 2 – world's best CMC for gauge blocks – guidance?

In the 2015 DG1 report to CCL, I had entered the published CMCs into Excel and plotted them over the nominal length rage 0 mm to 100 mm. If we regard only those laboratories with the smallest CMC uncertainties (at or below the OIML 30 (1981) Order 1 requirement of 20 + 0.2 L nm), there seems to be a consensus on what may be regarded as the minimum uncertainty which can be achieved for gauge block calibration for customers. Re-plotting this again here with improved colours (and correcting some previous errors) gives the following.

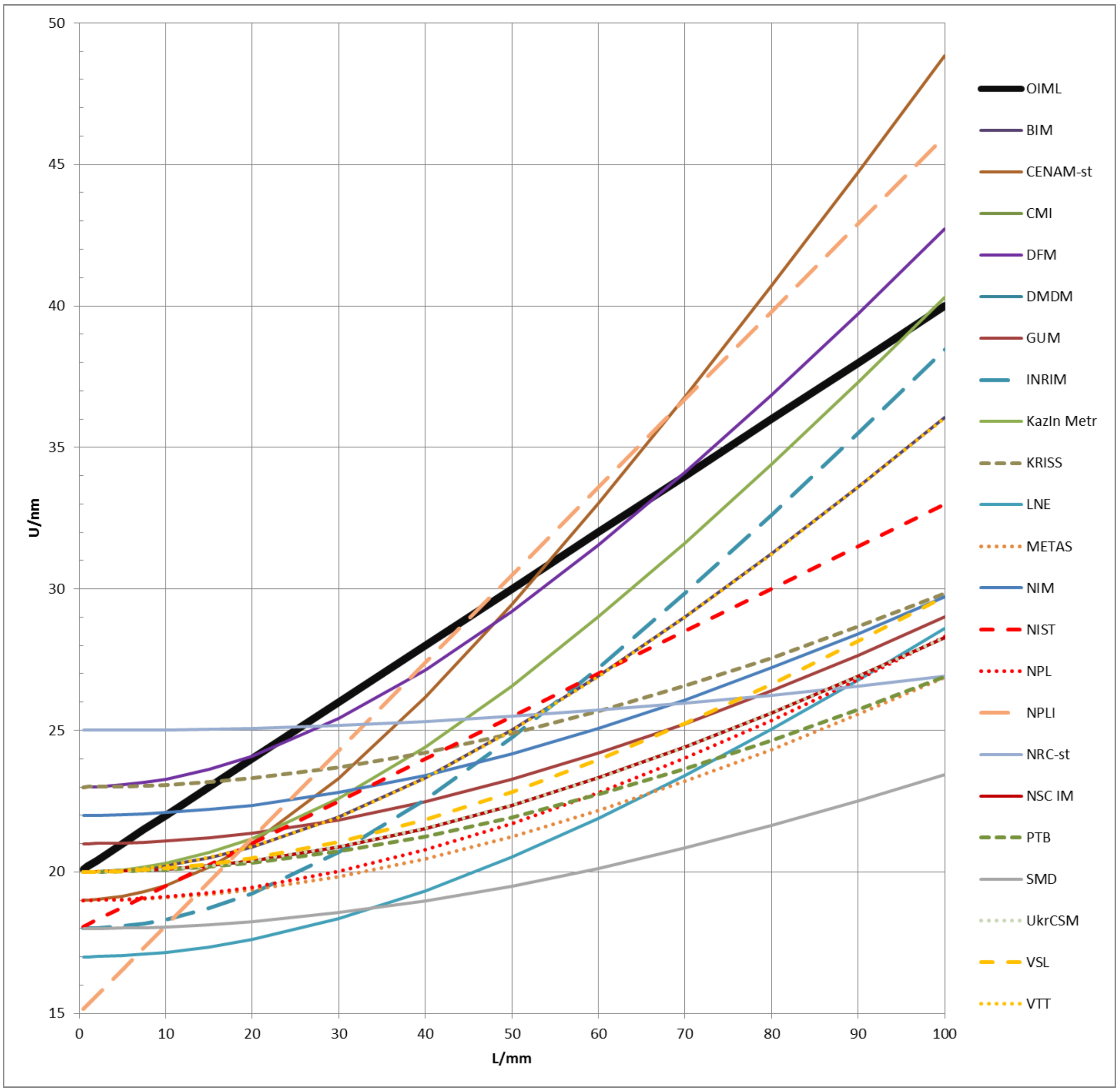

Figure 1 - CMC analysis: all NMIs offering CMCs which are close to Order 1 accuracy class of OIML 30 (1981).

During recent intra- and inter-RMO CMC reviews, there had been a small number of CMC claims for gauge block measurement by interferometry that had been submitted with uncertainties that were below the current state of the art (*i.e.* claiming smaller uncertainty than any other NMI). On more detailed examination, it was found that several uncertainty contributions that are commonly found in gauge block interferometer uncertainty budgets were missing or some critical input parameters had been given very low uncertainties. After adding in the missing terms and correcting those which were too optimistic, these new CMC claims matched very well with those existing CMCs in the KCDB that appear to define the state of the art.

There is obviously a varied range of expertise in gauge block measurement throughout the world – with some new laboratories starting up contrasted with well-established laboratories which have been calibrating gauge blocks for decades (perhaps almost a century…). Would it be worthwhile to establish, by way of some examples, what the community regards as exemplar uncertainty budgets for gauge block measurement by interferometry?

There are some documents already in the public domain (see for example the documents by NRC listed in the references list later in this report). These would remind people of all the different sources of uncertainty that they need to at least consider when preparing an uncertainty budget. It would also be possible to use this as an example of best practice – by having one or two example calculations, or some example tables which people can follow as examples of how to calculate uncertainties.

By way of example, the NPL uncertainty budget for the gauge block interferometer directly addresses the issue raised by Tanfer above, regarding correlated uncertainties which appear in the variation measurement. IN fact is does this because of the correlated uncertainties found in the phase correction (performed by the stack method).

I can also comment that some uncertainty budgets reviewed recently have different input values compared with one another but the overall output value, the combing uncertainty, is close to other uncertainty budgets. Does this represent some fundamental limit to the measurement of gauge blocks by interferometry, or are people adjusting their input numbers to achieve combined uncertainties that are similar to accepted CMC claims.

Comment from KRISS:

(1) I agree that an example of uncertainty budget will be helpful especially for newcomers to this society.

(2) Gauge blocks having nearly zero thermal expansion coefficient are commercially available these days, and CMC for these blocks will be much smaller than those for usual materials. Thus, the material of gauge block might need to be considered when we talk about “world’s best CMC” of gauge blocks.

Comment from METAS:

The paper J E Decker and J R Pekelsky, Metrologia 34, 6 (1997) (Ref. 112 in this report) is sufficient. Another useful source might be the final report of CCL-K1 (Ref. 321 in this report), where all major uncertainty components of all participating laboratories are compared.

Discussion 3 – MRA – auxiliary influence quantities & accredited laboratories

Tanfer at UME raises an issue regarding the use of accredited laboratories to calibrate the sensors used in gauge block interferometers. In the document Traceability in the CIPM MRA, there is note 3:

> *Note 3: For auxiliary influence quantities, not part of the main traceability path to the SI for a particular measurand and with uncertainties that can be shown to make only a minor contribution to the total combined uncertainty of the CMC, an NMI or other DI is free to use measurement services provided by laboratories accredited by a signatory to the ILAC Arrangement.*
>
> [red is my highlight]

This is in contrast to the main influence quantities, for which the document states:

> *A National Metrology Institute (NMI) or other Designated Institute (DI) publishing Calibration and Measurement Capabilities (CMCs) in the BIPM Key Comparison Database (KCDB) has two choices for establishing its traceability route to the SI: 1. via a primary realization or representation of the unit of measurement concerned, in which case traceability must be declared to its own demonstrable realization of the SI; 2. via another NMI or DI having relevant CMCs with appropriate uncertainty published in the KCDB or through calibration and measurement services offered by the BIPM, in which case traceability must be declared through the laboratory providing the service.*

According to these two statements, only minor contributing influence quantities may be traceable through calibrations at accredited laboratories – all other influence quantities which require traceability to the SI must be via an NMI/DI with CMCs or via a primary SI unit realisation or services offered by the BIPM. Tanfer points out that in most GBI uncertainty budgets, it is not the SI metre realisation that is the largest influence quantity, but usually the temperature measurement (or perhaps the air pressure measurement). So this is a reminder that for a CMC involving a GBI, the lab should be having their temperature sensors calibrated by an NMI/DI and not by an accredited laboratory.

Given that this is probably the case for many other dimensional uncertainty budgets, do we need to make NMIs/DIs more aware of this CIPM guidance?

Discussion 4 – laser tubes for use in interferometry lasers

From METAS:

There is one point which came up very recently at METAS and which is certainly of general interest for DG1 members: green He-Ne lasers. The tube of our green TESA laser broke and we wanted to replace it, but unfortunately Melles Griot don't produce them any longer, and it seems to be very difficult to find another supplier of green He-Ne laser tubes, sufficiently short to have 3 modes within the gain curve and allowing to apply the two mode stabilization technique. So information within your report on who can provide He-Ne laser tubes other than 633 nm and suitable for length interferometry would be very helpful.

Comment from NPL:

I agree. NPL works closely with Hexagon Metrology in Telford UK (formerly TESA) and we are aware of the lack of possible suppliers for the green He-Ne tubes (previously supplied by Melles Griot). This is becoming a problem for Hexagon who still manufacture the red, green and yellow lasers – they need tubes for new lasers and for re-tubing old lasers.

Comment from METAS:

[METAS has been in contact with Lasos who have stated that 'Probably in 3. quarter of this year we are able to develop some more customer specific types.' This was in response to a METAS request looking for green He-Ne tubes.]

I think a common initiative of some NMIs and also industry like Hexagon would be a good idea. Shall we try to gather other interested institutes, through DG1 for example?

Discussion 5 – key comparison topics run as supplementary comparisons

A comparison numbering problem has been noticed in comparison GULFMET.L-S2 which is a comparison being run in the newest RMO that joined the CIPM MRA recently. Previously, GULFMET, under co-piloting of TUBITAK UME, set up comparison GULFMET.L-S1 concerning gauge block measurement by comparison. Two labs from other regions were added to the loop (Turkey and Malaysia) to provide extra participants (thus giving added redundancy in case of problems and providing good links to outside the region). GULFMET.L-S1 is progressing well and now includes a new NMI from EURAMET (Albania) that received training during EURAMET project 1237 in conducting international comparisons.

GULFMET does not yet have any Member or Observer of CCL and this has triggered recent discussions on what comparisons can be organized in that region. The MRA documents allow any member of an RMO to participate in that RMO's key comparisons and so it is possible for GULFMET to organize their own K1 comparison topic as a key comparison. Tanfer prepared some slides and gave information on this matter during the GULFMET meeting (April 2017) to all TCs of GULFMET. GULFMET have at least one NMI which is capable of also making measurements by interferometry and so a second comparison has now been organized in this topic, which is a bilateral with UME (Turkey) and this was registered as GULFMET.L-S2 (December 2017). However the CCL sWG-KC chair has noted that the topic of this comparison is gauge block measurement by interferometry.

Comment by sWG-KC chair:

I think we should discuss changing the numbering of this comparison to be GULFMET.L-K1, because gauge block measurement by interferometry is a Key Comparison topic. The Key Comparison topics were carefully chosen to test the main skills required in dimensional metrology. As such it is necessary to ensure that the comparison is repeated every 10 years and this is not normally the case for supplementary comparisons. Also it is desirable to minimize the number of comparisons and by making this into a Key Comparison topic, the sWG-KC will be aware of the participants and can try to ensure that the GULFMET laboratories can be included in the next cycle of the K1 topic, so that they do not need to run their own bilateral (or multi-lateral comparison).

It is probably worth reminding people of the relevant document Guidelines for Key Comparisons, where it states:

> *6.2 Participation in key comparisons organized by an RMO is open to all RMO members and to other institutes that meet the rules of the regional organization (including institutes invited from outside the region) and that have technical competence appropriate to the particular comparison.*

Discussion 6 – High precision measurement of long gauge blocks by mechanical probing: Are mechanical measurements with low uncertainties better fit for the industry?

Tanfer states that one practical approach to calibrate particularly long gauge blocks with low uncertainties is precise mechanical probing / comparison considering the conditions of the measurement faces of the long gauge blocks.

TUBITAK UME calibrate long gauge blocks by mechanical comparison with uncertainties of Q[56, 0.4 *L*] nm, *L* in mm (CMC entry) (uncertainty range is 75 nm to 400 nm for gauge length 125 mm to 1000 mm). This is a regular service given to industry and other NMIs. The service is much favoured by CMM users and agencies of CMM manufacturers that perform CMM calibration, verification and maintenance. This service was first evaluated during comparison EURAMET.L-K2 (2003-2006) which discovered that the uncertainty value is over estimated. With improved calibration of temperature sensors and current environmental control it is possible to achieve uncertainties of Q[47, 0.16 *L*] nm, *L* in mm (uncertainty range is 51 nm to 167 nm for gauge length 125 mm to 1000 mm). This was tested in comparison EURAMET.L-K1.2011 (2011-2015) with a good success. For this service, TUBITAK UME enjoys using "special 1 m Gauge Block Comparator" delivered by PTB during the cooperation project in 1990s.

In Figure 2 (overleaf) we present uncertainty values of the countries given in CMC list for long gauge blocks and length bars. We also added there the new uncertainty value of UME as "UME_EURAMET.L-K1" in addition to UME_CMC. In Figure 3, we only show the services that give uncertainty values less than 0.5 µm (favorable value particularly by CMM users and maintenance/verification providers).

Tanfer raises the comment that there are several possible systems for high precision long gauge block calibration by mechanical contact (e.g. the instruments at UME and PTB, the NPL Length Bar Machine (with a similar device used at NMC A*STAR), the proposed NPL 1D machine shown on a poster presentation at MacroScale 2017). There are also some other systems at NMIs that have not participated in a comparison because the K2 comparison topic (which is currently halted) concerned measurement by interferometry (although at least one participant made some contact-based measurements). Tanfer mentions some of the benefits of mechanical contact-based measurements include the avoidance of wringing problems or double phase corrections required in double ended (non-wrung) interferometer systems. He is concerned that there may soon be a requirement to conduct a K2 key comparison on high precision long gauge block measurements, allowing both interferometers and high precision mechanical comparators (lower accuracy services can always claim CMCs if there is some internal quality system and a link to some other service which has taken part in a comparison).

He asks if CC should consider a new round of K2 comparisons. We could, for example, operate the comparison as two loops: loop 1 for low uncertainties (U < 0.5 µm) and loop 2 (U > 0.5 µm), with lengths between 125 mm and 1000 mm.

What are the thoughts on this?

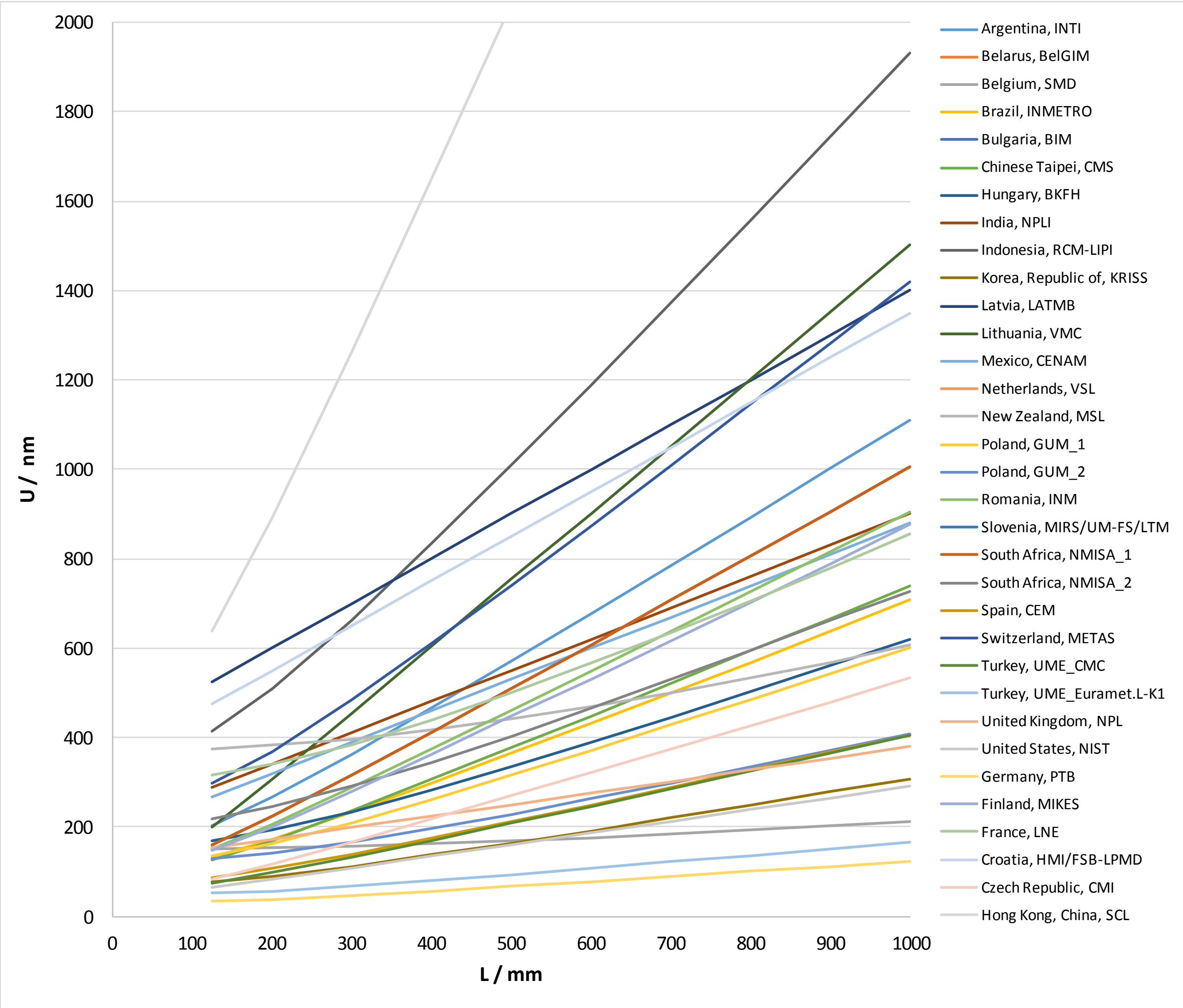

Figure 2 - CMC analysis: all NMIs offering CMCs for Long Gauge block and length bar calibration.

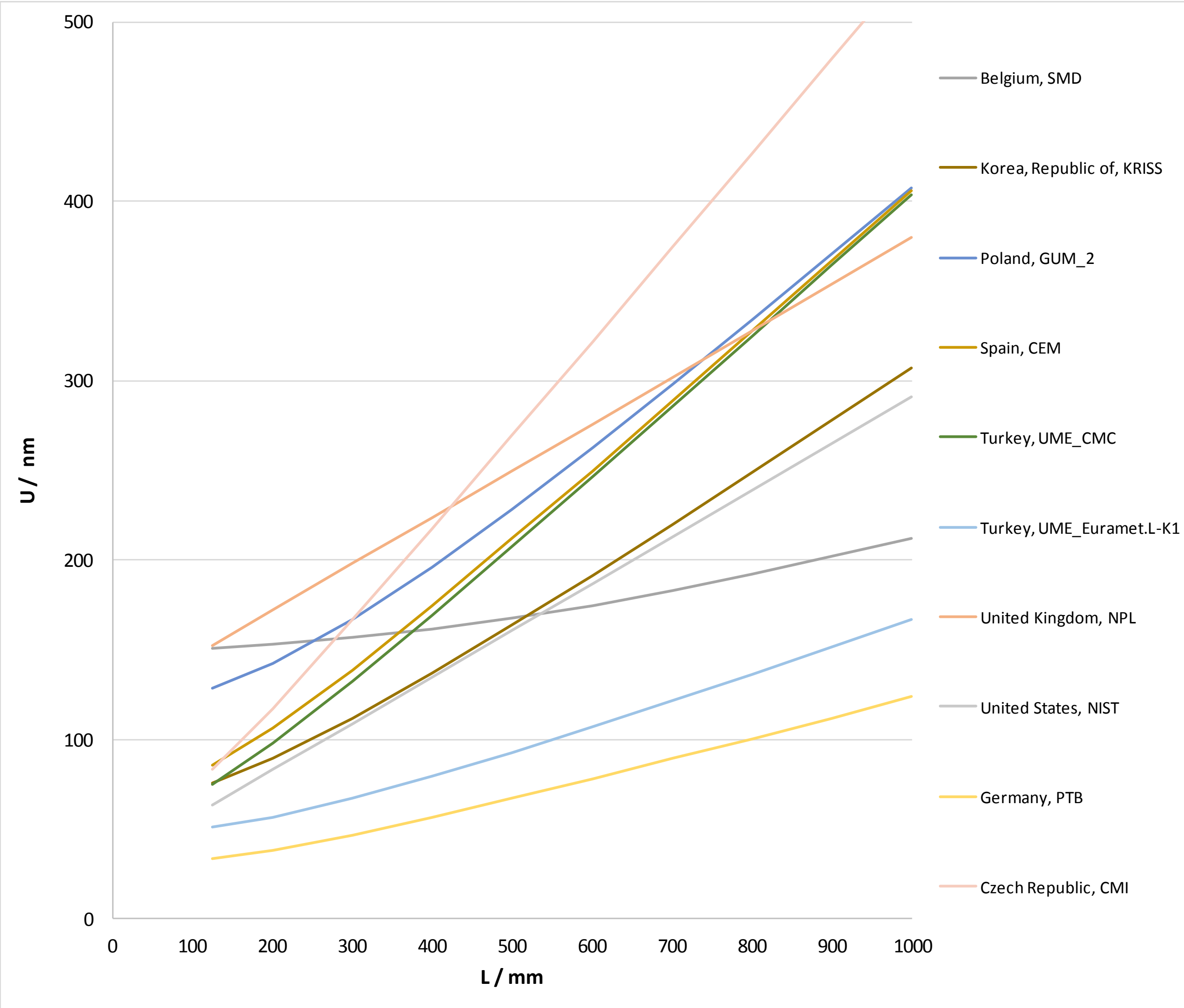

Figure 3 - CMC analysis: NMIs offering CMCs for Long Gauge block and length bar calibration with uncertainty value less than 0.5 µm (favorable value particularly by CMM users and maintenance/verification providers).

Discussion 7 – Air temperature measurements in gauge block (and other dimensional) metrology

Andrew Lewis from NPL reminds people about a recent paper by NPL colleagues which will shortly be added to the References list for DG1:

'Air temperature sensors: dependence of radiative errors on sensor diameter in precision metrology and meteorology', de Podesta *et al.* 2018 *Metrologia* **55** 229-244. DOI: 10.1088/1681-7575/aaaa52

Abstract of this Open Access paper:

> In both meteorological and metrological applications, it is well known that air temperature sensors are susceptible to radiative errors. However, it is not widely known that the radiative error measured by an air temperature sensor in flowing air depends upon the sensor diameter, with smaller sensors reporting values closer to true air temperature. This is not a transient effect related to sensor heat capacity, but a fluid-dynamical effect arising from heat and mass flow in cylindrical geometries. This result has been known historically and is in meteorology text books. However, its significance does not appear to be widely appreciated and, as a consequence, air temperature can be—and probably is being—widely mis-estimated.
>
> In this paper, we first review prior descriptions of the 'sensor size' effect from the metrological and meteorological literature. We develop a heat transfer model to describe the process for cylindrical sensors, and evaluate the predicted temperature error for a range of sensor sizes and air speeds. We compare these predictions with published predictions and measurements. We report measurements demonstrating this effect in two laboratories at NPL in which the air flow and temperature are exceptionally closely controlled. The results are consistent with the heat-transfer model, and show that **the air temperature error is proportional to the square root of the sensor diameter and that, even under good laboratory conditions, it can exceed 0.1 °C for a 6 mm diameter sensor.**
>
> We then consider the implications of this result. In metrological applications, errors of the order of 0.1 °C are significant, representing limiting uncertainties in dimensional and mass measurements. In meteorological applications, radiative errors can easily be much larger. But in both cases, an understanding of the diameter dependence allows assessment and correction of the radiative error using a multi-sensor technique.

Some key points from the paper:

- "The radiative error for an air temperature sensor in flowing air depends upon the sensor diameter and air speed, with smaller sensors and higher air speeds yielding values closer to true air temperature. This is not a transient effect related to the sensor heat capacity, but a fluid-dynamical effect arising from heat and mass flow in cylindrical geometries in the steady state."
- "Without auxiliary measurements, there is no simple way to detect whether or not a temperature sensor is being affected by a radiative load. The low heat capacity of the air makes air temperature sensors especially susceptible to radiative errors, particularly in slow moving air. As a consequence, almost every air temperature measurement made—even in well-controlled environments— is subject to radiative errors of unknown magnitude."
- "An air flow of ~0.11 m s^{-1} is insufficient to effectively cool objects larger than a fraction of a millimetre in diameter. Large objects within the room are radiatively coupled to the lights, walls, ceiling and floor much more strongly than they are thermally coupled to the air."
- "The true air temperature (which determines the refractive index of the air) is likely to be lower than the air temperature indicated by any contact thermometer. However, 'thin and shiny' thermometers, *i.e.* those with a low emissivity surface, are likely to give a better estimate than 'thick and dark' thermometers. Even in these well-controlled environments, errors exceeding 0.1 °C are possible."
- "Additionally, strategies such as enclosing a laser beam within a tube to reduce the effects of air turbulence, can potentially introduce systematic errors if the air temperature is not measured within the tube. Similarly,

> the 'radiation shielding' recommended in [another paper] could easily produce additional errors since the shield may create an unrepresentative micro-climate within it."

In the paper, 'Laboratory 1' was in fact the Gauge Block Interferometer laboratory at NPL. In this laboratory we have observed diurnal changes of the temperature reported inside the gauge block interferometer when the controlling sensor was suspended in the middle of the room. We suspect that this was due to changes in radiative load from the walls, some of which are coupled to the outside of the building through glass corridors. When the outside air temperature dropped the temperature in the gauge block interferometer increased and *vice versa*. We think that this was due to the sensor in the laboratory sensing the decreased radiative load and compensating by warming the air. We obtained more stable temperatures by mounting the air conditioning sensor inside the gauge area of the gauge block interferometer (with suitable adjustment to PID loop parameters to slow the effect of transients such as the operator's hands wringing gauges inside the instrument).

In the older NPL building (dating from ~1910) the NPL-designed air temperature control system used sensors which were part shielded inside small plastic canisters to avoid radiative effects.

So one must be careful to consider the effects of radiative head load on air temperature sensors used in dimensional metrology, especially when trying to (1) stabilize an object temperature at 20 °C by using conditioned air, and (2) make accurate air temperature measurement for use in refractive index compensation.

The paper gives some possible approaches to minimize this problem.

Comparison activities

At the moment, one region is running a gauge block comparison, two regions are planning a comparison and the current CCL comparison is nearly concluded. That completes cycle 2 of the K1 (gauge blocks) topic.

- CCL-K1.2011 - reporting
- GULFMET.L-S2 – running (actually K1 topic)
- AFRIMETS.L-K1 – planning
- APMP.L-K1.2018 - planning

Cooperation projects

EURAMET project 1237

EURAMET project 1237 ‘Calibration of Short Gauge Blocks by Mechanical Comparison’ started on 1 August 2012 under collaboration type of ‘consultancy’. The aim of this project is to prepare the West Balkan Countries for inter-comparison measurements and identify the problems that may occur when such countries participate in MRA comparisons. It was an exercise with 2 days preparatory workshop at the initialisation stage and was piloted by UME. The comparison exercise started after the workshop as planned but there were several delays due to lack of the equipment of the participants, movement of the laboratories, change of the staff *etc*. Such problems were overcome by helping these new NMIs through exchange of several mails even performing second short workshop for their new staff in UME. Despite these difficulties, the project was completed by following the guides for MRA comparisons and the final report is ready.

Various solutions were applied to solve the problems and NMIs were practically trained for further comparisons. The problems and outcomes are summarised below.

Problems:

- Delays.
- Equipment and standards (lack of equipment).
- Staff (lack of staff and staff lost).
- Laboratory conditions.
- Movement of Lab to new premises.
- Delivery of the items (ATA CARNET and Custom problems).
- Bad treatment of standards/failure of comparison (prevented by workshop in EURAMET 1237).
- Filling of the forms and preparation of the report by NMIs (improved by workshop).

Outcomes:

- NMIs are now aware of the importance of the custom issues and has started cooperation with their departments doing custom clearance in advance.
- NMIs understand the procedure for correction of their results during stages of draft A and B: which kind of corrections, how to show the mistakes to the pilots with proofs.
- Improvements for their process and precise determination of their uncertainty budgets.
- One trainee NMI has CMC on GB now.
- Two NMIs have participated in another MRA comparison (GULFMET.L-S1) successfully fulfilling the main aim of the project.

  Interim information was provided about the results of some countries in order to encourage them to participate in the MRA comparison. This worked very well and one country participated in MRA comparison (EURAMET project 1254). This NMI now has registered CMC on Gauge Blocks.

BIPM – TUBITAK UME Project Placements

The staff of the TUBITAK UME Dimensional Laboratory enjoyed taking part in the cooperation between TUBITAK UME and the BIPM's Capacity Building and Knowledge Transfer Programme on a training programme named "BIPM – TUBITAK UME Project Placements". A visiting scientist from the Zambia Bureau of Standards, Ms. Natasha Sichone, studied the calibration of short gauge blocks for a period of five weeks as a selected participant in the programme. With the knowledge gained from the training, it is expected that the Zambia Bureau of Standards will successfully take part in a comparison and then declare CMCs for short gauge blocks in the near future.

Other notes

<u>News from NPL</u>

Recently (May 2018) NPL has re-run the course on *Gauge Block Measurement by Interferometry*. We will be running the course again only on demand – are there any people in DG1 who would like this training (the course is theory and practical, over 2 days, and takes a maximum of 6 trainees).

National and International Specification standards

Some items of note regarding current specification standards such as items for consideration by working groups for any updated versions.

<u>ISO 3650 (1998) errata/omissions (left standing from the 2015 report)</u>

NPL previous comments:

(1) Page 1 makes explicit reference to ISO 14253-1:1998 on decision rules for conformance or non-conformance with specifications. One issue with this is with regards to the flatness tolerances for grade K gauge blocks. It is difficult to achieve low uncertainty in the flatness measurement, especially when using a comparator and this places excessive demands on the manufacture of grade K gauges in order that an NMI can certify them as compliant if one applies the default rules from ISO 14253 (reduction of the tolerance zone by the measurement uncertainty). This is explicitly stated at section 7.1.

(2) There is no actual text which defines the f_o and f_u parameters – they are effectively only defined in Figure 3 on page 3.

(3) Definition of the Unit of length on page 4 will need updating after the new SI is operational.

(4) Would it be useful opt give the equations for vertical compression and horizontal bending for section 5.4?

(5) The definition of deviation from flatness (section 3.5, figure 2) explicitly refers to all points of the measuring face and does not exclude the regions where there may be engraving (on short gauges). Thus, gauges with engraved measuring faces should automatically fail this tolerance. For phase stepping systems where the entire face can be measured, there should be information on excluding a certain zone around the engravings

VTT-MIKES previous comments:

(6) ISO/TC 213 should consider how the progress with double ended gauge block interferometers would benefit gauge block users and if it is necessary or beneficial to the community to reformulate the ISO 3650 to match with new methods.

A*STAR-NMC previous response:

Agreed and it will be useful for point (4) to be specified. Our colleague from accreditation body is puzzled why gauge block calibration can go without flatness measurement. It may be good for this to be further elaborated.

Andrew Lewis, NPL
DG1 moderator

4 June 2018

Comprehensive list of papers relating to DG1

It seems worthwhile to include in this report and to keep regularly updated a fully comprehensive list of all papers in the field of gauge block, length bar and long gauge block measurement and closely-related topics. [NB this is extracted from references database software – please inform me of any corrections to existing entries. For any new entries please send me a link to the article, DOI is best, so that I can enter into the database].

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3. Abdel-Maaboud, N. F. Automated Contactless Gauge Block Interferometer. *J. Phys. Sci.* **28,** 87–98 (2017).
4. Abirami, A., Nagarani, G. & Siddhuraju, P. Phase-measuring algorithm to suppress inner reflection of transparent parallel plate in wavelength tuning Fizeau interferometer. *Precis. Eng.* **48,** 1–10 (2014).
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9. Aiming, G. E., Chen, L., Chen, J. & Zhu, R. Research on Processing Technique for Interference Pattern with Step Using Phase-shift interferometry. *Proc. SPIE* **4231,** 371–374 (2000).
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