

Consultative Committee for Length (CCL)

President: Dr Ismael Castelazo

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1. Executive summary

The CCL is concerned with matters related to the definition and realization of the metre, practical length and angle measurement, and coordinate metrology. The CCL also provides advice to the CIPM (International Committee for Weights and Measures) in the field of length metrology. In addition, the CCL is responsible for implementation of length - related aspects of the Mutual Recognition Arrangement (MRA), through which National Metrology Institutes (NMIs) recognize each other's measurements.

The CCL maintains a portfolio of Key Comparisons (KCs) that have been optimized to cover the full range of possible CMCs. To achieve this scope the CCL Working Group on the CIPM MRA (CCL-WG-MRA) has worked on an extensive set of guidance documents, comparison protocols and report templates that are freely-accessible. The CCL Working Group on Dimensional Nanometrology (CCL-WG-N) has been proactive in comparisons that are intended to support this area, with several KCs having been performed and others that are ongoing.

Length has a significant impact on most human activities today; the CCL maintains a watching brief to ensure that the needs of society, research and industry are satisfied, by forming links with relevant bodies and user communities.

The future direction for the CCL concerns new areas such as 3D dimensional nanometrology, support for industry's move to non-contact surface scanning (healthcare and energy sectors), extending 3D metrology traceability to larger ranges (aerospace, precision civil engineering), compensating for thermal and refractive index effects at different scales, and issues of traceability at the nanometre and sub-nanometre scales (advanced science). A move towards metrology embedded in the manufacturing process represents a paradigm shift away from the traditional role of the calibration laboratory. These, and other new needs, will extend the workload of the CCL and its members over the coming years.

2. Scope of the CC

Present activities of the CCL concern practical length and angle measurement (from one dimension to three dimensions, from sub-nanometre to tens or hundreds of metres) and future optical frequency standards (for metre realizations).

This scope may be considered to include related issues such as nano-scale surface science, thermal properties of artefacts and instruments, refractive index compensation for optical beam propagation, laser physics, optics, instrumentation, interferometry, mechanical design, and mathematical software/data processing and advanced modelling. As such, there is some overlap between the work of the CCL and eleven of the fifteen Technical Work Areas of VAMAS (Versailles Project on Advanced Materials and Standards) and closer interactions with VAMAS are foreseen.

3. Strategy

To provide the highest level of efficiency, the CCL is supported by four Working Groups (WGs): the Working Group on Strategic Planning (CCL-WG-S) oversees the revision of the CCL strategy and associated documents on a regular basis; it collects and makes available information giving evidence for the continuing importance of metrology in length. The Working Group on Dimensional Nanometrology (CCL-WG-N) is seeking to harmonize traceability

routes, terminology and reference standards for users in the area of nano-science. The Working Group on the CIPM MRA (CCL-WG-MRA): ensures the coordination of CCL and regional metrology organization (RMO) key and supplementary comparisons; maintains links with the RMOs, seeking to ensure the involvement of member laboratories of the CCL in major comparisons in the field of length, thereby providing the means for assuring world-wide traceability and equivalence of length measurements at the highest levels of accuracy; and facilitates the inter-regional CMC review process. Through the joint CCL-CCTF Frequency Standards Working Group (WGFS), the CCL coordinates work on new realizations of the metre as optical frequency standards.

The CCL has also set up a number of technical Discussion Groups, with membership beyond that of the CCL, where experts discuss new standards, recent scientific advances, and highlights of ongoing research activities within and across the regions, in order to maximize benefits and support cooperative research.

In 2018, the CCL reviewed its strategy to assure consideration of the present and future needs in length metrology. The findings of the strategy document were condensed into two overall requirements for the future strategy:

- to anticipate future needs for instrumentation, standardization and traceability in emerging areas of science and industry, encompassing a wide variety of length scales under a range of measurement conditions; and
- to maintain maximum efficiency of the CIPM MRA processes thereby reducing costs to metrology institutes in all the regions, whilst supporting mutual recognition.

3.1 Future science objectives

Dimensional metrology, traceable to the SI metre, underpins all world-wide manufacturing, assembly and construction from nanometre scales (nano-science), through macro-scales (automotive industry, healthcare, precision engineering), to decametre (and larger) scales (aerospace industry, ship-building, surveying). Organizations that undertake significant international trade are especially sensitive to traceability, particularly when multinational sourcing of components and assemblies is prevalent. Although classical dimensional metrology is a mature and well established field, and the forthcoming SI revision has minimal impact on the CCL, demands from external customers as well as the Grand Challenges (for example quality of life, energy needs, health, and environment) are setting the research agenda for CCL members.

1. Continue to improve and develop access to realizations of the metre

New traceability routes to the metre are to be investigated at the nanometre and sub-nanometre scales (where wavelengths of optical frequency standards are ‘too big’) in addition to ongoing research on realizations of the metre via updates to the list of frequencies. These will provide improved accuracy and traceability to dimensional nanometrology enabling reduced dependence on ‘vertical’ processes in the nano-industry.

The CCL-WG-N has explored new routes for traceability of length measurements at the nanometre and sub nanometre scale. At the 2016 meeting of the CCL-WG-N it became clear that the lattice parameter of silicon had the potential of a new traceability route, for TEM, AFM and displacement metrology. At the 2018 meeting at BIPM, cases for the three routes to traceability for length metrology via silicon lattice parameter quoted in CODATA were presented. For displacement generation and measurement, x-ray interferometry can be used. A series of silicon samples comprising stacked rings of atomically flat regions separated vertically by a distance corresponding to the silicon d_{111} lattice spacing (0.314 nm) have been produced and can be used

as step-height standards for AFM or optical interference microscopes. For TEM, direct counting of atoms in a silicon pillar is possible. These proposals were put forward to the CCL and will be incorporated into the revised *Mise en Pratique* as secondary realizations of the metre.

2. Provide CCL support for new topic areas

The CCL-WG-N has been proactive in this area with the work on the silicon lattice parameter essential for the semiconductor industry. Other anticipated end-user benefits include improvements to biological compatibility of nano-scale devices (medicine). A series of pilot studies have been successfully concluded and renamed as CCL supplementary comparisons. Further pilot studies are planned (semiconductor standards) as well as ongoing advice and input to ISO standardization:

- Nano 6: measurement silicon lines, completed in 2017
- Nano 1: a photomask comparison, the technical protocol is being prepared by PTB and the comparison is likely to start in 2019
- Nanoparticles comparison completed, comparison piloted by CMS/ITRI and NMIJ involving seven measurement methods on five samples (nano gold, nano silver, 3× polystyrene latex)
- EURAMET 1239 measurement of surface roughness by AFM: delayed but about to start.
- EURAMET 1242 measurement of areal roughness parameters: completed in 2018,
- High precision flatness over 300 mm: currently being discussed.

Discussion Group 6 on coordinate metrology tackled the issues of CMCs based on popular flexible machines such as coordinate measuring machines (CMMs) and the preference of industry for non-contact optical-based measurement *in situ* (lack of traceability, decreased accuracy relative to contacting techniques, but faster and hence preferred by users). This topic will benefit users in energy production (connectors used in oil and gas pipelines, gears used in wind turbines, plasma containment panels in fusion reactors) as well as health (validation of X-ray Computed Tomography, advanced prosthetics).

Long-range metrology/geodesy is an established research area for many NMIs but a relatively new topic for some. However, this metrology area is gaining importance (for example aerospace, geodetics and surveying, GPS location verification, civil engineering, large science projects such as the large Hadron Collider (LHC) successor, large optical telescopes). Initial beneficiaries are companies that manufacture large products (for example aircraft, civil nuclear) where metrology-enhanced automation and *in situ* metrology will reduce manufacturing cycle times and reduce costs on long lead-time, expensive components.

3.2. Future CIPM MRA objectives

To minimize the cost of setting up the CIPM MRA processes within the CCL and to pre-empt ongoing support issues, the majority of the CCL's work in recent years has been concerned with efficient implementation of the CIPM MRA. In particular the CCL has implemented, via the CCL-WG-MRA, several strategies to minimize the workload of CCL member laboratories associated with the CIPM MRA, whilst providing sufficient evidence to support CMCs. Since the outset, the CCL has foreseen the time and resource impact the CIPM MRA would have on its members and has strived to minimize the disruption and costs of the initial implementation and ongoing support for the CIPM MRA. This ongoing work targets three issues; minimizing the workload for comparison pilots; minimizing the portfolio of Key Comparisons; and reducing the burden on CCL member laboratories. The CCL maximized the breadth of support for CMCs by

comparison evidence by undertaking a comparison review based on a skills matrix and giving clear guidance to accreditation bodies on the minimum necessary set of comparisons, thus reducing the number of comparisons and increasing confidence in their support for CMCs. The CCL-WG-MRA has also prepared an extensive set of guidance documents, comparison protocols and report templates, which can be used by pilots of key and supplementary comparisons. These freely-accessible documents are in addition to the publicly accessible copies of almost all CCL and RMO comparison protocol documents. The benefits have been to: spread the workload; reduce staff time per comparison; speed up the comparison process; and obtain clear validation of CMCs from comparison results.

4. Activities and achievements since the last meeting of the CGPM

4.1. Main activities

Since the previous General Conference, the CCL has met twice (3-year cycle) and its working groups have each met three or four times. The Discussion Groups have continued to be active and reported to the CCL meetings outside of the normal meeting schedule; topics included not only comparison planning but recent technical advances, contributions to standards and ideas for potential collaborative research.

In terms of the CIPM MRA, the recommendations made by the CCL-WG-MRA revision were analysed and the following actions were made. The CCL-WG-MRA has prepared an extensive set of guidance documents and reporting templates for use by future comparison pilots in order to reduce the workload and cost, thereby attracting new offers to pilot comparisons. Within EURAMET, several non-CCL members have started to use these templates and documents and at least one new key comparison pilot has come forward. The CCL-WG-MRA anticipated the recommendation of the CIPM *ad hoc* Working Group on Governance; regional Technical Committee Chairs have been *ex officio* members since the CCL-WG-MRA was formed.

The CCL WG-MRA sWG-CMC: Sub-group on CMCs and the DimVIM (sWG-CMC) has refreshed of the ‘DimVIM’ (CMC categorization list) and taken over responsibility for its maintenance. The list is used outside the NMI community by regulators and other service portals as it presents harmonized terminology for dimensional metrology in 14 languages (English, Chinese, Czech, Finnish, French, German, Greek, Italian, Japanese, Korean, Portuguese, Spanish, Thai and Turkish).

Length CMCs are currently registered in the KCDB as numerical equations, but this format is usually not used in publications or in accreditation bodies, so the CMCs are not compliant with the approach used by accreditors. The CCL proposal to move to quantity equations that will become technically feasible in the forthcoming KCDB 2.0 was approved by the CIPM. The workload required to make the change will mainly be the responsibility of the NMIs with equation-based CMCs; these are mostly in length (~850), mass (~400) and some in chemistry.

The CCL is working on the preparation of the new *Mise en Pratique* document for the metre, using the standard template and the information shown on the BIPM website for the three existing methods of realizing the metre, together with two documents prepared previously within the WG-MRA. The Si lattice is included in the document as a secondary representation of the metre, as suggested by the WG-N.

Considering that NMIs are encouraged to keep the number of CMCs to the minimum necessary and that duplication should be avoided, a flexible CMC “Standards of 1D point-to-point dimensions” has been approved by the CCL. The basic idea is that the same equipment may be

used for calibrating different standards with similar uncertainty, a typical example being a coordinate-measuring machine (CMM) used to calibrate standards whose measurands lay on a single straight line. Since the CCL Length Service Classification (DimVIM) is organized by standards, and the use of the abovementioned equipment would require duplicated CMCs, guidance document CCL-GD-6 was developed to prevent confusion due to the coexistence of conventional and flexible CMCs.

In the period since the 25th meeting of the CGPM (2014), several CCL members have been involved in two conferences: MacroScale (www.macroscale.org) and NanoScale (www.nanoscale.de). In addition, the list of optical frequency standards used for the realization of the definition of the metre and the secondary representations of the second has been updated by the WGFS and adopted by the CIPM after approval by the CCTF.

(see document <https://www.bipm.org/utis/en/pdf/CIPM/CIPM2015-II-EN.pdf> - Appendix 2).

Staff from CCL member laboratories and members of CCL Working Groups participate in national and international standardization committees. The majority of participations are via the ISO GPS (Geometrical Product Specification) matrix of standards. Key international committees with CCL representation include: ISO TC 213 (Dimensional and geometrical product specifications and verification), ISO TC 60 (Gears), ISO TC 1 (Screw threads), ISO TC 201 (SC9) (AFM probe calibration), ISO TC 202 (Microbeam analysis), ISO TC 229 (Nanotechnology), IEC TC 113 (Nanotechnology) and API SC7 (Gauging resources for gauges used in the oil and gas industries).

4.2. Challenges and difficulties

An ongoing challenge is to extend the SI to smaller scales and larger scales whilst continuing to support existing capabilities. The CCL has already prioritized the nano-scale regime by setting up the WG-N.

A new style of inter-RMO comparison, which is similar to a ‘virtual CCL comparison’, but with a reduced planning and participation workload (especially for CCL members), has been developed and presented to the CIPM. The second cycle of key comparisons is now being planned as a mixture of ‘classical’ and ‘inter-RMO’ styles. Linking of comparison results from one comparison to another, especially when the artefact sizes and properties are different across the comparisons, is proving difficult and it is not clear if end users of the CIPM MRA actually need this to be performed when making judgements regarding CMCs. Also, some dimensional comparisons generate large sets of data and representing the results in the BIPM key comparison database (KCDB), especially in graphical format, is difficult. A linescale comparison (on a reduced set of measurands) generated 960 results for a single artefact. Calculation of over 921,000 pairwise degrees of equivalence is not practical or useful. Better metrics are needed to summarize large comparison datasets, to allow meaningful comparison of CMC claims and to display them in the KCDB.

Industrial use of CMMs is increasing, despite unclear traceability routes and issues regarding CMCs for these services - this is a topic under active debate in the Discussion Group on coordinate metrology. CMMs are used extensively throughout industry and can measure a large selection of items, many of which are also used in key comparisons. A way has been found to express CMCs based on the use of these machines that does not conflict with existing CMCs in the KCDB, enabling wider applicability of the CIPM MRA. Similarly, there is a need for traceability in software used in dimensional metrology and some CCL members are seeking CMC categories in this field to satisfy customer requirements. However, undertaking this within

the scope of the CIPM MRA is a challenge, possibly requiring inter-disciplinary discussions with other Consultative Committees.

5. Outlook in the short and long term

In the short term, work in the Discussion Groups will continue towards the next cycle of key comparisons. Further development of standards in nanometrology and instigation of further pilot studies, potentially in cross-discipline topics (for example nanoparticles are not simply a dimensional topic) will be a topic on the agenda of future WG-N meetings. Initiation of activities at some CCL member laboratories into X-ray Computed Tomography (XCT) as a dimensional metrology tool will trigger new studies that could lead to new CMCs and the necessary support for them. Coordinated assistance for NMIs in explaining the new SI definitions to end users may be required. Development of some services in long-range metrology will occur and some member laboratories and the CCL will need to address the needs for verification of these services. There will also be a challenge of maintaining momentum on the CIPM MRA as the CCL moves into the second cycle of key comparisons, whilst new techniques and research will demand reallocation of resources. For several member laboratories, the issue of reinstating CMCs in areas where there is no longer a CCL key comparison (where a comparison topic has been abrogated) will need to be addressed.

In the longer term, it is likely that there will be a replacement of some classical services and a change of the Discussion Groups' emphasis; this will be coupled to the challenge of setting up a new range of topics for key comparisons and new rounds of CMC submission in future topics (for example XCT services). There will be a requirement for more support for *in situ* services for customers (calibrations outside laboratory environments) and the ensuing traceability issues.

Annex: CC Data

CCL set up in 1997	(CCDM from 1952-1997)
President: I. Castelazo	Executive secretary: G. Panfilo
Membership:	24 members and four observers + BIPM Director (<i>ex officio</i>)
List of CCL members and observers:	http://www.bipm.org/en/committees/cc/ccl/members-cc.html
Meetings since the 24th CGPM meeting:	23-24 September 2015 / 14-15 June 2018
Full reports of the CCL meetings:	http://www.bipm.org/en/committees/cc/ccl/publications-cc.html
Four Working Groups:	http://www.bipm.org/en/committees/cc/ccl/working_groups.html
Strategic Planning (CCL-WG-S)	
Dimensional Nanometrology (CCL-WG-N)	
CCL-CCTF Frequency Standards (WGFS)	
CIPM MRA (CCL-WG-MRA)	
	Sub-group on key comparisons (sWG-KC)
	Sub-group on CMCs and the DimVIM (sWG-CMC)
	Task Group on KC linking (TG-L)
Nine Discussion Groups	https://www.bipm.org/en/committees/cc/ccl/#discussion-groups

CCL Comparison activity	Completed	In progress	Planned [period]
CCL key comparisons (and supplementary comparisons)	7 key 4 supplementary	2 key	5 [2015-2019]
BIPM comparisons	2	0	0
CC pilot studies	0	0	1 [2017]
CMCs	1071 CMCs in 51 service categories registered in the KCDB		