Consultative Committee for Length (CCL)

1. **Executive summary**

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.

Through the joint CCL-CCTF Frequency Standards Working Group (WGFS), the CCL coordinates work on new realizations of the metre as optical frequency standards, and through its Dimensional Nanometrology Working Group it is seeking to harmonize traceability routes, terminology and reference standards for the users of nano-science. The CCL has also implemented a set 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.

Classical dimensional measurement services are now in place in the majority of national metrology institutes (NMIs) and are backed by Calibration and Measurement Capabilities (CMCs) with validated key and supplementary comparison evidence. 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 work of the CCL in recent years has concerned efficient implementation of the CIPM MRA. In particular the CCL has implemented, via its Working Group on the CIPM MRA (WG-MRA) several strategies to minimize the workload of CCL member laboratories associated with the CIPM MRA, whilst providing sufficient evidence to support CMCs. These strategies include a new style of inter-regional comparison, extensive guidance documents and reporting templates for comparison pilots, two reviews of the key comparison portfolio, two workshops on comparisons (analysis and linking), and regular meetings of the CC Working Groups.

However, the future direction for the CCL concerns new areas and represents a potential paradigm shift. New areas include: 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 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 CCL**

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), future optical frequency standards (for metre realizations) and advice to the CIPM in the field of length metrology. 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 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

The CCL Strategy document (http://www.bipm.org/utils/en/pdf/CCL-strategy-document.pdf) notes the recent restructuring of the CCL and distils 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

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 (e.g. 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 scale (where wavelengths of optical frequency standards are ‘too big’) in addition to ongoing research on realizations of the metre via updates to the Mise en Pratique/Joint Frequency list. These will provide improved accuracy e.g. for GNSS users and traceability to dimensional nanometrology enabling reduced dependence on ‘vertical’ processes in the nano-industry.

2. Provide CCL support for new topic areas

In nanometrology, the CCL has set up a Working Group on Dimensional Nanometrology (WG-N) which has met three times to date (the previous Nanometrology Discussion Group was established in the late 1990s). A series of pilot studies has 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. The WG-N has drafted a paper on traceability routes for size metrology of nano-scaled features for the semiconductor industry making use of the Si single crystal lattice. Other anticipated end-user benefits include improvements to biological compatibility of nano-scale devices (medicine).

Discussion Group 6 on coordinate metrology is beginning to tackle the issues of CMCs based on popular flexible machines such as Coordinate Measuring Machines 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 has beneficiaries in energy production (connectors used in oil and gas pipes, 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. Few CMCs have been submitted so far and only one supplementary comparison has been carried out (EURAMET.L-S20). However, this metrology area is gaining in importance (e.g. aerospace, geodetics and surveying, GPS location verification, civil engineering, large science projects such as the LHC successor,
large optical telescopes). Initial beneficiaries are companies that manufacture large products (e.g., 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. Better compatibility and part/assembly accuracy will lead to a reduction in fuel burn in automotive and aviation applications (more efficient energy use, lower emissions); better GNSS accuracy will allow better navigation (denser traffic, autonomous vehicles) and improved accuracy for large particle accelerator projects will enable new science.

3.2. Future CIPM MRA objectives

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:

1. Minimizing workload for comparison pilots
   The WG-MRA has 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 successes 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. An additional benefit has been more time available in CCL meetings for non-MRA related discussions.

2. Minimizing the portfolio of Key Comparisons
   The CCL maximized the breadth of support of CMCs by comparison evidence by undertaking a comparison review based on a skills matrix (see CCL Strategy document, §3.1, p8) 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 key comparison portfolio of the CCL is one of the smallest amongst the Consultative Committees (nine topics), yet supports a moderately large set of CMCs (~1500).

3. Reducing the burden on CCL member laboratories
   The CCL instigated and coordinated the use of inter-regional key comparisons, organized and run as Regional Metrology Organization (RMO) comparisons rather than CCL comparisons, and coordinated inter-RMO participation in them. Freedom to choose this style, as well as regular interlinked CCL and RMO comparisons, reduced the number of times the CCL member laboratories were required to act as linking laboratories. Secondary benefits included closer harmony across the regions – smaller (non CCL) laboratories had closer contact with those in other regions and a wider pool of potential pilots for the comparisons.

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

4.1. Main activities

Coordination activities of the CCL and its Working Groups

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

The WG-MRA has coordinated and reviewed results from a number of comparisons and pilot studies as summarized in the Annex. 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 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 WG-MRA was formed.

The sub-working group on CMCs (sWG-CMC) has carried out a refresh 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 13 languages (English, Chinese, Czech, Finnish, French, German, Greek, Italian, Japanese, Korean, Portuguese, Spanish and Turkish). Discussions have started on possible new CMC categories in the area of Coordinate Measuring Machine metrology of master artefacts and specific tasks. This is a new development because, until now, all CMC entries have been for calibration of items (i.e. to a defined standard) – new CMCs are foreseen that are the second letter of ‘CMC’, namely measurement capabilities – custom items without a specification standard e.g. bespoke parts. This could see a significant increase in CMC scopes for member laboratories opening the way for further recognition of services for customers.

Conferences

In the period since the last General Conference, the CCL has been associated with two MacroScale (www.macroscale.org) conferences:

- **MacroScale 2011** hosted by METAS in Bern, Switzerland, in October 2011. Inter-RMO participation, with 25 presentations, 18 of which were subsequently published in a special issue of *Measurement Science and Technology* (http://iopscience.iop.org/0957-0233/23/9).
- **MacroScale 2014** hosted by BEV in Vienna, Austria, in October 2014. As of early September 2014 there were 31 presentations and 34 posters in the conference programme. Papers are expected to be published in *Measurement Science and Technology*.

Also, the NanoScale conferences (www.nanoscale.de) are organized through a cooperation amongst CCL member laboratories (PTB, LNE, METAS), especially those active in the WG-N.

Updates to the frequency list by CCL-CCTF Frequency Standards Working Group (WGFS)

Since the last CGPM meeting there has been continuing work on updating the list of optical frequency standards suitable for use as metre realizations. Updates, approved by CIPM, include the following unperturbed transitions:

- $3s^2 \, ^1S_0 - 3s^3p \, ^3P_0$ of the $^{27}$Al$^+$ ion;
- $5d^{10}6s^2 \, ^2S_{1/2} - 5d^96s^2 \, ^2D_{5/2}$ of the $^{199}$Hg$^+$ ion;
- $6s^2 \, ^1S_0 - 6s6p \, ^3P_0$ of the $^{199}$Hg neutral atom;
- $6s^2 \, ^2S_{1/2} - 4f^{13}6s^2 \, ^2F_{7/2}$ of the $^{171}$Yb$^+$ ion;
- $6s^2 \, ^2S_{1/2} - 4f^2 \, ^2D_{5/2}$ of the $^{88}$Sr$^+$ ion;
- $4s^2 \, ^2S_{1/2} - 3d^2 \, ^2D_{5/2}$ of the $^{40}$Ca$^+$ ion;
- $1S - 2S$ of the $^1$H neutral atom;
- $5s^2 \, ^1S_0 - 5s5p \, ^3P_0$ of the $^{87}$Sr neutral atom;
- $6s^2 \, ^1S_0 - 6s6p \, ^3P_0$ of the $^{171}$Yb neutral atom; and
- ground-state hyperfine transition of $^{87}$Rb.
Standardization activities

Staff of CCL member laboratories and members of CCL Working Groups participate in national and international standardization committees. The majority of participation is via the ISO GPS (Geometrical Product Specification) matrix of standards. (GPS standards provide an international language of symbols for expressing tolerances in technical drawing. This makes it possible for a drawing of a component that has been developed in one country to be sent to another country, where the drawing can be understood and the component manufactured, without the designer and supplier having any common language except GPS).

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
- 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.

The new style of inter-RMO comparisons has been thoroughly explained to the CIPM. These comparisons are similar to a ‘virtual CCL comparison’, but with a reduced planning and participation workload (especially for CCL members). Now that this is clear, the second cycle of key comparisons is 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 recent 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 simply not practical or useful. Better metrics are needed to summarize large comparison datasets and to allow meaningful comparison with CMC claims and display in the KCDB.

Industrial use of Coordinate Measuring Machines (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. Ways need to be 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 discussion with other Consultative Committees.
5. **Outlook in the short and long term**

**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 (e.g. nanoparticles is not just 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 eventually leading to new CMCs and the necessary support for them. (Issues include: accuracy, verification, machine calibration/error mapping, comparability, material artefacts, and safety). Coordinated assistance for national metrology institutes (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.

**Longer term**

In the longer term, it is likely that there will be a replacement of some classical services and change of 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 (e.g. 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.

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**Annex: CC Data**

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<th>(CCDM from 1952-1997)</th>
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<td>President: A. Sacconi</td>
<td>Executive secretary: L. Robertsson</td>
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<td><strong>Membership:</strong></td>
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