Strategy 2018-2028

Consultative Committee for Length (CCL)

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1. Executive summary

This document has been prepared by the Consultative Committee for Length (CCL) Working Group on Strategy (WG-S) with the intended audience comprising mainly the CCL, NMI Directors, CGPM Delegates, the BIPM Director, and the CIPM. Additionally, it is made available as a public document on the BIPM web server in order that the end user community (industry, academia, regulatory bodies) may comment and provide feedback to the CCL and WG-S via any contact on the CCL web page (http://www.bipm.org/en/committees/cc/ccl/). The document was prepared initially in 2013 and is periodically updated.

The Strategy Document presents an overview of major challenges and demands for higher accuracy in micro and nanometrology, coordinate metrology, macroscale measurements and in-process metrology with direct traceability, as well as developments in optical frequency combs, angle measurement technology and stabilised lasers. A short description of interactions with the stakeholder community leads into the stakeholder and CCL view of future requirements (key metrology topic areas, the impact of new technologies and standardisation requirements).

The CCL has four Working Groups (one is a joint Working Group with the CCTF) and one Task Group. In the short-term, no further reorganization of CCL is anticipated.

Concise information on Calibration and Measurement Capabilities (CMCs) is given. The total number of CMCs was 1626 at the end of 2018. Only incremental increases are planned to total CMC numbers in the near future.

A discussion on the changing workload in support of the MRA (which comparisons are required, steps to minimise the workload, challenges encountered and issues for resolution, the effect of changing external requirements and new technologies) is presented. An outline work plan for the next ten years indicates anticipated meetings, timings of comparisons, and resource implications. Possible strategies that could reduce the cost of supporting the MRA are proposed for consideration. The document concludes with a list of completed and running comparisons and an online bibliography.

2. Scientific, economic and social challenges

Emerging areas of need where the CCL Working Groups and Discussion Groups have already identified issues that must be addressed are identified below.

1. Nanometrology

Nanometrology is a rapidly evolving field where disruptive step changes have already occurred and are likely to continue in the future. At present, several issues of clear importance to CCL are the following.

- The application of crystal-lattice based length standards, such as the use of atomically-defined step height standards for z-axis calibration in scanning probe instruments, the use of the silicon lattice for scale calibration in high resolution TEM, and x-ray interferometry for nanopositioning and the evaluation of displacement sensors. There is a growing need to reach consensus and develop practical guidelines for the use of such standards, as well as other alternative routes for realization of the SI metre in nanoscale dimensional metrology.

This is now a set of tasks within WG-Nano and has already resulted in the use of silicon lattice standards being included in the *Mise en Pratique* as secondary realisations of the metre.

- The challenge of methods divergence. The application-driven requirements on the uncertainty of dimensional nanometrology are such that methods divergence – for example between AFM, SEM, and optical metrology of linewidth – is becoming larger relative to individual method uncertainties, thus significantly complicating the interpretation of measurement results and of comparisons involving different techniques.
- The related challenge of hybrid metrology in which measurements using multiple techniques are combined to estimate a measurand – for example, NIST has explored the integration of AFM and optical measurements. Such an approach requires rigorous modelling and uncertainty analysis, but it can be advantageous by allowing different measurement principles to complement each other's limitations.
- Nanoparticles. There is an ever-growing number of definitions of nanoparticle size, many of these definitions are incompatible with each other and certification of nanoparticles is becoming an important issue. Future activities on nanoparticle size metrology may also involve other Consultative Committees.
- Need for new comparisons. Photomask metrology, silicon linewidth measurements, (in addition to nanoparticle size) are areas of significant need where new comparisons are underway or under development.

2. Coordinate Metrology

Coordinate measuring machines (CMM) or, more generally, coordinate measuring systems (CMS), are increasingly used in place of traditional measurement techniques. Issues currently under discussion include the following.

- Verification of performance of flexible measuring systems. Flexibility of the CMM is a great strength but makes it difficult to verify performance when the system may be used for a wide variety of tasks, including measurement of free-form surfaces, which are a considerable departure from traditional dimensional metrology gauges.
- Automated uncertainty analysis ("virtual CMM" or related techniques) can be expected to ease the problem of establishing uncertainty (needed for traceability) for arbitrary measurement tasks, but challenges remain in verifying uncertainty for more generalized measurements. So far only CMMs have benefited from such virtual machine approaches and other CMSs (e.g. laser trackers, laser scanners, X-ray CT) do not yet have such metrological approaches available to allow uncertainty estimation.
- Coordinate metrology is by nature very close to industrial needs. The same type or model of CMM can be easily found in NMIs' laboratories and in industry for actual inspection of parts. This proximity to the application encourages the NMIs to address industrial measurement problems too, e.g. finding viable measurement and evaluations procedures. A notable case is the evaluation of the uncertainty, as pointed out above. While techniques exist suitable for top level NMIs, only partial answers are available to users in industry for their routine activity. The full traceability chain is put at risk by the lack of proper uncertainty evaluation at the very last ring of the dimensional inspection of parts.

- Need for new comparisons. Testing based on a single measurement task is not sufficient to evaluate comprehensive performance of a CMM. Close coordination with standards organizations, specifically with the ISO/TC213/WG10, is needed to develop documentary standards to guide calibration and testing methods. New comparisons to verify CMM performance are currently under discussion.
- Integration of CMM-based CMCs in the KCDB is being debated since CMMs could be used to deliver CMCs that are also based on traditional (fixed-purpose) measuring instruments. Differentiation between the available options is discussed in a Guidance Document (CCL-GD-06).
- X-ray computed tomography (XCT) is a very fast-growing technology becoming more and more popular in industry. It revolutionises the way of making dimensional measurements, with unprecedented capability of measuring internal features. There are fundamental metrological issues still to be fully understood and resolved, mostly related to the complex physical phenomena that occur during the measurement. Further, the traceability for this technology depends also on the availability of proper standards, on which there is not general agreement yet. As for CMMs, also for CTs the evaluation of the uncertainty is far from well established. The increasing number of scientific publications on this topic reflects the attention given by the international community. The CCL encourages the NMIs to undertake further study on this promising subject.
- An increasing interest in large volume coordinate metrology (> 10 m^3) has been observed in recent years. Applications in aerospace, naval, civil and scientific areas are the main drivers. New technologies have been studied, including multilateration, FSI (frequency scanning interferometry) often in combination with multilateration techniques, and indoor GPS. A goal in this area is to achieve a fully traceable "metrology space", where space coordinates can be easily derived in a single reference frame all over a whole large building, such as a hangar or a factory shop floor. This and other approaches are seen as necessary enablers for "Industry 4.0" approaches to the next generation of fully automated factories and production facilities, as well as for bringing needed accuracy to robotics.

3. Optical Frequency Combs

Comb-based measurements have transformed the traceability path for realization of the unit of length via the vacuum wavelength of stabilized lasers. New guidelines for verification of comb-based measurements have been developed with consensus achieved at a 2012 meeting of WGFS and in following discussions. The new guidelines are now essentially finalized, ready for release. Potential widespread use of comb technology might require revisiting the issue of comb verification.

4. Angle measurement technology

Changes in technology and in industry practice are driving discussions of possible changes to the K3 (angle metrology) key comparison; the last several decades have seen increasing use of encoder technology for angle measurement whereas historically important artefacts such as angle blocks have almost entirely disappeared. However, verification of encoders is critically dependent on alignment of parts during calibration such that the limiting factor becomes the alignment, and this is often pre-set by the manufacturer. Therefore, artefact uncertainties would likely dominate such a comparison, which may not test the true capabilities of the NMI participants. The comparison EURAMET.L-K3.2009, ended in 2016, was the first ever on high-resolution electronic autocollimators. Apart from the conventional MRA outcomes, data from this KC made it possible to discover the previously neglected effect of the air pressure (and then of the local altitude) on the autocollimator's angle response. This is a good example of how a KC can contribute to science in addition to delivering outcomes targeted at the MRA.

5. Length service classification scheme (DimVIM)

The DimVIM may need expansion to suitably describe measurement tasks for different materials and measuring instruments, and to accurately reflect the range of measurement capabilities of flexible measurement systems such as coordinate measuring machines. The new entry "Standards of 1D point-to-point dimensions", introduced in 2018, is an example of a "flexible" CMC. The challenge of defining the exact boundaries of such flexibility has been resolved in this case with the specific guidance document CCL-GD-06. This is intended to make the CMC approval process consistent over different RMOs and over time, and to clarify which calibrations fall under such CMC and which are traditional CMC categories.

6. Technology development

There are many other areas where dimensional measurement technology is developing rapidly but where potential impact of these trends on CCL is still unclear and has not yet been actively discussed. Changing technology should be monitored closely to determine how CCL might address emerging needs such as described below.

Trends in micro- and nanometrology

- There is a drive toward numerous enhancements of the measurement capabilities of Scanning Probe Microscopes, with goals of improving resolution, lateral scanning range, scanning speed, intelligent probing and control systems, sampling strategies, and multisensory integration. Needs in biotechnology, advanced materials, genetics and ultra-precision engineering are foreseen.
- Three-dimensional capability for both micro- and nano- measurements is slowly improving, including 3D probing and scanning for micro-CMMs. There is a need for true 3D metrology and for accessing true 3D features including deep micro-bores, sidewalls, undercuts, etc.
- All aspects of traceability at the micro- and nano- level are subject to increasing demands. New nano- standards and procedures are needed to fill gaps in traceability chains. Better models are needed for uncertainty estimation, along with new international comparisons to verify these methods. Advances in optical interferometry are beginning to contribute to traceable calibration at the sub-nanometer level with improved accuracy. Unmet traceability needs are particularly pronounced for emerging measurement technologies such as scatterometry or focused ion beam and helium ion microscopy.
- New strategies for characterization of structured surfaces are coming into use, including scatterometry, diffractometry, and spectroscopic ellipsometry over regions of interest less than 500 nm and stylus and optical instruments with sub-nanometer vertical resolution at larger scales.

- Improved cleaning technology is surprisingly critical for micro- and nano- measurements. Cleaning is particularly challenging for three dimensional, high-aspect ratio structures in the micro-scale, such as micro-holes.
- New trends in advanced manufacturing may ultimately require incorporation of metrology into the process. In some cases, such as directed self-assembly at the micro- and nano-scale, it could mean development of entirely new approaches to dimensional metrology.

Trends in coordinate metrology

- A proliferation of new technologies for coordinate measurement, each with its unique set of errors, includes X-ray computed tomography (XCT), articulating arm coordinate measuring machines (AACMM), laser trackers, laser tracers (measuring only range to target), frequency scanning interferometry (FSI), optical scanners, and indoor-GPS (based on rotating infra-red beam generators).
- Digital manufacturing is driving demand for vastly higher point coordinate data density (data collection rates doubling roughly every 18 months). Scanning CMM probes, CT scanners, structured light systems, or similar techniques produce massive data sets where interpretation of the data presents new challenges (as well as data storage and data transmission). A related trend (mentioned previously) is the increasing prevalence of free-form surfaces which are difficult to measure due to the need to refer to geometric reference standards (planes, spheres) with large differences from freeform surfaces.
- A separate digital manufacturing issue is the need for traceability of the measurand result and also the associated metadata linked to the result. Data mining approaches require accuracy and traceability of all data in order to make valid decisions about production processes.
- Viable techniques for evaluating the uncertainty in coordinate measurements are urgently needed in industry. The most popular use of CMSs is for part inspection in manufacturing. Its paradigm is the verification of conformance to specifications, for which the uncertainty has an essential role (see JCGM 106 and more specifically ISO 14253-1).
- Advanced manufacturing methods such as 3D printing may ultimately require a new paradigm that incorporates metrology into the manufacturing process. This could mean integration of traditional tools such as displacement interferometers into the 3D printing manufacturing systems.

Trends in macroscale measurements

- GNSS (Global Navigation Satellite System), complemented by new technologies for absolute distance measurement, is increasingly impacting macro-scale measurement. Applications in land surveying, natural disaster detection, large structure stability monitoring require length references that are long term stable, with high accuracy.
- Refractive index measurement in non-uniform environments presents an important challenge for both macroscale and mid-scale manufacture due to the effect on laser wavelength-based length scales and refraction causing beam bending effects.
- Multi-frequency/multi-colour techniques (frequency combs or multiple laser sources) — for both refractive index measurement and for absolute interferometry — are a departure from

current metrology practice based almost exclusively on a single laser wavelength (633 nm helium neon laser).

- On-line tools are needed for rapid and large area (>100 cm^2) assessment (>20 m/min) of thickness, structure, composition, activity and defect detection during processing.

In-process metrology with direct traceability

- Realising the SI units much closer to their point of use will potentially provide intrinsically traceable metrology instruments allowing substantially shorter traceability chains and reduced calibration requirement.
- Optical frequency comb technology can provide direct traceability of the optical frequencies used in interferometers or other instruments, where the link to the SI second might potentially be delivered to the shop floor via satellite (GNSS), fiber, or chip-scale atomic clock. Improved reliability and ease of use of combs will enable integration into measurement systems, creating possibilities for new measurement techniques with direct traceability.
- EU's "Factory of the Future" envisages metrology embedded in the manufacturing system; machine tools with embedded metrology can be used as in-situ, in-process metrology devices that calibrate themselves with traceability to the SI.

7. Demand for higher accuracy

An ever-increasing demand for higher accuracy has been an ongoing theme of all aspects of dimensional metrology, beginning with the industrial revolution and now unabated in the age of information and synthetic biology. Emerging needs include a number of applications spanning a variety of length scales, such as particle accelerators (~10^3 m), aerospace (~10^2 m), pressure standards (10^{-1} m), fuel injectors (10^{-4} m), and nano- technologies (~10^{-9} m) - where nano-technology includes measurements of feature size, form, and/or location for semiconductor & nanoelectronics, nanoparticles, nano-structured surfaces, and nano-biological systems, e.g. DNA molecules.

8. Stabilised lasers for dimensional metrology

Discussion group DG1 has identified a problem related to the availability of certain type of He-Ne laser tubes which are used to provide secondary wavelengths for many interferometer systems. Recent mergers and re-structuring of laser tube suppliers has seen the availability of these tubes decline to the point where none are currently available. Whilst these particular lasers are not the primary traceability route to the SI metre, they are listed in the *Mise en Pratique* of the definition of the metre and are still demanded at the NMIs/DIs.

Furthermore, the vision of "Factory of the Future" and the idea of realising the SI length unit on the shop-floor in industry or high level accredited laboratories, may require stabilized lasers of higher output power (more cost effective for multiple beams from single laser) and ruggedness. Only recently have higher powered diode lasers become available with wavelengths close to those offered by traditional stabilised He-Ne and Nd:YAG lasers – however further developments in frequency stabilisation and vibration immunity are needed.

3. Vision and mission

Vision

To be universally recognized as the world focus for length metrology.

Mission

To work with the NMIs of the BIPM Member States, the RMOs and strategic partners to promote global compatibility of length and angle measurements, through promoting traceability to the SI metre and associated derived units for length quantities.

4. Strategy

Strategic Objectives

1. Promote global uniformity of length measurements
2. Establish international equivalence of NMI calibration and measurement capabilities
3. Support the development of length measurement science and technology

Key initiatives

1. Support the activities of the CIPM MRA
2. Develop the *Mise en Pratique* to include secondary realisations of the metre
3. Develop guidance and activities to support confidence in emerging areas in length metrology

5. Activities to support the strategy

5.1. Progressing metrology science

5.1.1. Major changes in needs, technologies or areas of interest and the effect on the activities of the CCL

Several technological developments had a direct effect on the activities of the CCL and its working groups. The first was the advent of frequency combs, which profoundly affected the traceability chain connecting vacuum wavelength of lasers to the definition of the second, and changed the emphasis of the CCL Working Group on the *Mise en Pratique* (MePWG) from metre definition and realisation to joint metre/second realisations linked by the speed of light. A result was that the CCL joined with the CCTF to create the Frequency Standards Working Group (WGFS). This re-organization served as one impetus for the broader reorganization of CCL's WGDM into WG-MRA and WG-S. The frequency comb also led to the end of key comparison BIPM.L-K10 which was first replaced with BIPM.L-K11 and then with CCL-K11. This final change was accompanied by the closing of the Length section at BIPM.

Concurrently, the increasing significance of nanotechnology was instrumental in the formation of the nanometrology discussion group (DG-7) as a separate working group

(WG-N) with the same status as the WG-S and WG-MRA. The WG-N continues the work of the previous nanometrology discussion group: organizing nanometrology pilot studies and supplementary comparisons that address emerging needs in this field; raising the profile of nanometrology (CCL was the first CC with a working group on nanometrology); and serving as a CCL nanometrology contact point for relationships with other CCs and organizations outside CCL.

Another technology development influencing CCL work is the increasing accuracy of Coordinate Measuring Machines (CMMs) and their increased use for measurements at the accuracy level of NMIs. This was one driving force behind the decision to cancel the 'ball plate & hole plate' K6 key comparison and look for a new range of artefacts more related to real-world measurement, and to open wider the subject field for DG6. For example, several NMIs offer services for freeform or complex shapes and will require CMCs in this area with underpinning comparison evidence. Coordinate metrology has rapidly evolved from a CMM-based discipline into a wider one with a variety of instruments. This suggested the introduction of the more general term Coordinate Measuring System (CMS), which includes the CMMs. Important areas where CCL's attention might be required are the (dimensional) Computed Tomography (CT) and the coordinate metrology of large volumes (several cubic metres). These issues and other ongoing technological developments are discussed further in the next section.

5.1.2. NMI research activities

CCL encourages the NMIs to undertake research that addresses the challenges highlighted earlier in this document and expect that the CCL will play an active role in resolving the outstanding issues. Apart from the technical discussions in the various CCL Discussion Groups, there is no overall coordination of the NMIs' research work, somewhat due to the varied needs of the different economies. The only inter-NMI coordination of research efforts that occurs is within EURAMET, under the EMPIR programme which is now setting European Metrology Networks, which have specific NMI research coordination tasks to perform (in their area of influence).

5.2. Improving stakeholder involvement

There are stakeholders concerned with the work of CCL at several levels. At the highest level, any NMI who is a member of the MRA is a stakeholder with considerable interest in the process, and already provides input directly through their CCL representatives and via CIPM or CGPM.

Beyond the NMIs, important stakeholders include the RMOs, certification bodies, standards organizations, calibration laboratories, equipment manufacturers, military, and government legislative or regulatory bodies involved with new laws and directives. The ultimate beneficiaries are the industries that rely on the organizations listed above, and consumers served by these industries. For length metrology, some major industrial stakeholders include automotive, aerospace, and semiconductor manufacture, but an exhaustive list would touch on every aspect of manufacturing, engineering, and science (e.g. geodetic measurement for particle accelerators, interferometry for satellite missions, alignment of RF antennas, waveguide and aperture calibration for communications and radiometry, vibration isolation platforms, robot metrology for healthcare, transport, etc.)

When appropriate, stakeholders beyond the NMIs can provide feedback through their NMI; NMIs are generally sensitive to stakeholders who describe un-met measurement needs or have problems with the existing measurement infrastructure. The NMIs gather feedback through direct contact with individuals in industry, participation in standards organizations, or through workshops and conferences. In some cases, stakeholders sit on program formulation committees or advisory boards that guide NMI research activities. Although stakeholders are not normally allowed to participate in CCL meetings, this would be possible under existing CIPM rules, if required. However, the anticipated route for stakeholder involvement is via input to the NMIs' programmes or coordinated research actions such as the European Metrology Research Programme, EMRP (now complete) and its successor European Metrology Programme on Innovation and Research, EMPIR (in progress).

5.2.1. Coordination with Standards Organizations

The CCL can most effectively carry out future work by maintaining close ties to standards organizations, because we are mutual stakeholders with a strong interest in the work of the other organization. In fact, there has long been an informal but significant relationship in this regard; for many years CCL laboratories and CCL committee members have played a leading role in national, international, and industry-based standards organizations, a notable example being ISO/TC213 and the development of the GPS (Geometrical Product Specification) system of ISO standards. The recent bi-lateral decision of establishing a formal liaison between CCL and the ISO/TC213 is a notable example of mutual involvement of stakeholders. Looking toward future work, as CCL starts to promote new length standards based on the new silicon lattice realisation of the metre (section 5.1), the impact will be magnified when standards organizations take up our recommendations. Similarly, we will benefit from close cooperation with standards groups as we explore new ideas about verification of CMM performance for non-task-specific measurements. In Europe, parts of the EMPIR Programme are specifically dedicated to coordinating and performing pre-normative work at the NMIs.

5.3. Promoting global comparability

5.3.1. Support of comparisons and CMCs

Selection of key comparison topics

The guiding philosophy behind the selection of the key comparisons was to establish a suite of comparisons that test the basic techniques and skills underlying NMI measurements. In principle, any CMC can be related back to one of these techniques, by arguing that the basic technique was tested in some key comparison. When the relationship of the new CMC to the key comparison is tenuous, a regional supplementary comparison might be needed to bolster the claims. But the MRA was never intended to require comparisons of every possible measurement; if the relationship is reasonably direct, we may rely on the quality system to assure confidence in the new CMC.

It may be anticipated that the trends described in sections 2 and 5 will require new comparisons to support new measurement technologies. There are not yet any concrete proposals for any new key comparisons, although there are anticipated needs, including some which are now being addressed by pilot studies in nanometrology. Comparisons will only be considered when the metrology uses techniques which are not already tested by existing comparisons, or when existing techniques have to be augmented to operate at considerably different ranges or environments (e.g. interferometry in a shop-floor situation over tens of metres).

The CMCs in length are organised in a hierarchical categorisation scheme known as the 'DimVIM'. The majority are in the sub-classification of dimensional metrology, the remainder concerning laser frequencies (for realization of the metre).

It is clear that there is not a direct one-to-one mapping between comparison topics and CMCs – instead the comparison topics are chosen to test the key techniques of dimensional and laser frequency metrology. Although the comparison titles refer to artefacts, rather than techniques, the different types of artefacts require different measuring techniques and skills. The following skills and techniques are tested by the dimensional comparisons (based on WGDM discussions from 2001, with subsequent updates such as the decision to add CCL-K7 and CCL-K8 to the comparison portfolio).

Principal Techniques	CCL-K1	CCL-K2	CCL-K3		CCL-K4	CCL-K5		CCL-K6	CCL-K7	CCL-K8
	gauge block	length bar	poly	gau.	diameter	ball	step	2D CMM	linescale	surf tex.
Realizing the Metre definition										
Interferometry	2	2			2	2		2	2	1
Wavelengths in air	2	2			2	2		2	2	1
Gauge Issues										
Temperature of Gauge	1	2			2	2		2	2	1
Mounting & Aligning	1	2	2		2	2		2	2	1
Wavefront Probing										
Reflection Phase Effects	2	1								
Wringing	2	1								
Mechanical Probing										
Stylus contacting at surface, 1-D					2	1	2	1		2
Bi-directional probing for size					2		2			
Probing for 3-D center coordinates						2		2		
Image Probing										
Sensing Line Centres									2	
Angle Metrology										
Measuring small angles (autocoll.)			1	2						
Large Angle Gen: Circle Dividers			2	1				1		
Small Angle Gen: SineBar, CircDiv.				2						
Formal mathematical processing of data sets										
ISO parameter extraction										2
Form Metrology										
Flatness										1
Roundness					1					
Thread, Gear Profile										
3-D Surface										1

Figure 2: Relation of principal techniques to key comparisons. An entry of 2 in the table indicates that the key comparison topic provides a strong test of the technique. An entry of 1 indicates that the technique has some relation to the key comparison but is not a major consideration.

The number of CMCs in length published in the KCDB increased from 1341 in 2012 to 1626 in 2018. It is expected that CMCs in length will have only a marginal increase in the near future.

5.3.2. Important achievements/outcomes

Many of the activities of the CCL and its working groups over the period 1999-2018 have focused on delivering the workload of the CIPM MRA in the most efficient, yet scientifically rigorous way. It is worthwhile to summarise these outputs and achievements here in case that other Consultative Committees may benefit from the work of CCL.

1. **Identification of the Key Comparisons based on the concept of "How far the light shines" and the Principal Techniques in Dimensional Metrology (WGDM, sWG-KC)**

Rather than a series of comparisons based on different dimensional ranges, different quantities and different measuring instruments, the comparison portfolio is based on testing the principal techniques required of a competent dimensional metrology laboratory, with different comparisons testing different techniques. Where possible, a range of different sized artefacts and materials is included in each comparison, e.g. in the K1 comparison, gauges typically range from 1 mm to 1000 mm and are in two or more materials.

Ability of a participant to do well in one comparison is taken as evidence of competence in all services based on similar techniques, backed by a fully operational quality system. Thus, good performance in the K1 comparison can support all gauge block services of the participant including those based on mechanical contact rather than interferometry; internal comparison audits ensure the traceability between K1 interferometry equipment and other services.

2. **DimVIM, the CCL Length Services Classification scheme, which has been translated into 14 languages and has served as a template for other CCs, accreditation bodies, and other organizations (WGDM, sWG-CMC)**

CCL was the first CC to develop a categorization scheme (DimVIM) for the CMCs (in 1999). The original list has now been translated by dimensional experts into 14 languages, ensuring harmonization of terms and CMCs across the regions. External agencies are now using the DimVIM for similar activities. The multi-language DimVIM is made freely available from the BIPM web server.

Cross-CC discussions have already taken place with regards to harmonizing categories which overlap CC fields of expertise, e.g. thermal expansion of reference material (CCT) vs. thermal expansion of dimensional artefacts (CCL).

3. **Concept of CCL-RMO comparisons (interlinked RMOs in same comparison) (WGDM)**

The interlinked RMO comparisons improve the efficiency of the process where there are insufficient numbers of laboratories offering a service to make the classical scheme (of CCL and multiple RMO comparisons) worthwhile. It reduces the burden of the CCL laboratories which are often used as linking laboratories which must take part in multiple comparisons. Interlinking of inter-regional RMO comparisons can be performed through a 'virtual CCL comparison' when CCL members take part within the RMO comparisons, thus allowing for comparison of performance across the regions.

4. **Guidance documents on formatting of CMCs (WGDM, sWG-CMC)**

WGDM's efforts in harmonizing the service categories was extended to harmonization of the CMC template files with the result that Length CMCs were amongst the first to enter the KCDB. The guidance document on CMCs was updated in 2015 to form the basis of a new WG-MRA guidance document (CCL-WG/MRA-GD-5).

5. **Methods of key comparison analysis, including hosting a workshop (WGDM)**

As the first key comparisons were being completed several methods for analysis of the results emerged from different communities. CCL via its WGDM organized a workshop (13-14 September 2005) on analysis of key comparisons, held at the BIPM. Participations included papers and presentations by members of the BIPM Director's Group on uncertainties.

6. **Comparison protocols that have served as a model for subsequent comparisons (WGDM) and have evolved into accepted templates** (CCL-WG/MRA-GD-3.1) **for future comparisons.**

To reduce the burden on future pilots, all comparison protocol documents from CCL key comparisons are made available from the KCDB and previous pilots offer them to future pilots to use. The protocols from the earlier comparisons were adapted and edited for use in later comparisons. The principal items across the portfolio have been edited into a template comparison protocol, which is made available (from the CCL website) for use by future pilots of comparisons.

7. **Detailed guidance document** (CCL-WG/MRA-GD-1) **on conducting comparisons and evaluating impact on CMCs (WGDM, sWG-KC)**

Keeping track of the various CIPM, JCRB and CCL rules and guidance on performing comparisons and evaluating the impact of the results on CMCs is important; a summary document of all decisions of CCL, CIPM and JCRB that relate to comparisons and CMCs has been prepared, including a flow chart of the process and detailed instructions at every stage, demarking the tasks and responsibilities of the WG-MRA and its two sub groups on CMCs and KCs.

8. **Template document for preparing key comparison final reports** (CCL-WG/MRA-GD-3.2, CCL- WG/MRA-GD-3.3) **and guidance on preparing reports** (CCL-WG/MRA-GD-3) **(sWG-KC)**

Further assistance was given to comparison pilots, by condensing the outputs of the workshop on comparison analysis, recent CIPM decisions, and experience of previous pilots, by preparing guidance and template documents for key comparison report writing. These are made freely available in the BIPM web site. The documents include spreadsheets for analyzing comparison results.

9. Linking concepts

Dimensional metrology comparisons are artefact based, and due to possible damage to artefacts caused by the accelerated use experienced during a comparison, they are unsuitable for large circulations. Thus, different artefacts are used in the CCL comparisons, with variations in: materials, nominal sizes, quality, hardness, form errors, pre-existing damage, or thermal properties. Some properties lead to systematic bias in results which some participants are unable to determine, however they should be covered by the uncertainty budget. Comparing the results of an artefact value in one comparison with the value of a different artefact in another comparison is not straightforward. Equivalency of participants has to be judged on a comparison by comparison basis and linking of one comparison to another cannot be accomplished by purely numerical means unless further analysis is performed. TG-L has been addressing this issue and a workshop was held in 2007 to discuss various ways of linking comparisons. Three well established methods are now available which can be chosen to link comparison on a case by case basis. A full linking exercise for one key comparison topic (K8, surface texture) has been accomplished, serving as a template for linking further comparisons, planned for the near future.

The Task Group on linking has issued guidance on linking of comparisons and has provided a list of comparisons which may now be linked using one of the available methods. The Task Group works with the pilots of comparisons to help perform the linking.

10. Detailed review of all comparison final reports.

At its meeting in 2013, WG-MRA instigated a procedure for improving the quality of MRA comparison final reports by requiring the chair of sWG-KC to allocate at least two persons from the WG-MRA to perform a detailed review of all future key and supplementary comparison final reports before they are approved for entry into the KCDB.

11. Instigation of the procedures for inclusion of 'flexible scope' CMCs.

The 2015 WG-MRA meeting proposed and CCL (2015) accepted the concept of allowing generic one- dimensional length CMCs (e.g. for services offered using a CMM) to be included in the KCDB Appendix C. This allows an increase in the number of services offered to customers, which are covered by the CIPM MRA but without any significant increase in CMC numbers. A flexible-scope CMC however may raise an issue on its exact boundaries, i.e. how flexible it can be. The DG6 discussed this issue thoroughly and the outcomes are captured in the document CCL-GD-06 (approved by CCL in 2018).

5.3.3. Major challenges and difficulties encountered and issues that require resolution

1. Extent of the comparison portfolio

It is challenging to strike the appropriate balance in deciding how much comparison activity is required. There is a great need for an efficient, small set of comparisons that is not unnecessarily burdensome, but CMCs for specialized measurements may be only tangentially supported by this set of comparisons. Always there is a question, "How far does the light shine?”

2. Difficulty recruiting pilots

As the comparisons become routine with little recognition for the work, it is more difficult to recruit pilot laboratories. This is further complicated by the fact that piloting and participating in comparisons consumes significant resources for which it is sometimes difficult to get institutional support, even for the purchase of needed artefacts.

3. Linking issues

Questions relating to linking a set of CCL and/or RMO comparisons conducted at different times over a longer period are yet to be addressed in a satisfactory way, but the Task Group on Linking has issued guidance on how best to link at this time.

4. Artefact instability

Artefact stability and damage during shipment continue to be significant problems for many comparisons. The damage occurs despite best handling efforts and comes partly from the fact that a 2-year comparison sees handling and measurement of the artefacts once every month – far more frequent than a typical triennial calibration usually experienced by artefacts.

5. Artefact circulation

Customs and shipping problems contribute to the challenge of keeping comparisons on schedule.

6. Corrective actions on CMCs

Even with considerable effort, there has been imperfect follow-up on needed corrective action following problematic measurement results. However recent initiatives set in place in 2015 and followed at the subsequent WG-MRA meetings in 2016-2018 have managed to address all the corrective actions identified in Executive Reports in a coherent and constructive manner. This does, however, require vigilance and extra effort within the RMO TC-L communities, particularly by the TC-L chair persons.

5.3.4. Information on repeat frequencies of any comparisons to date

Detailed information on repeat frequencies is maintained by the sub working group on key comparisons (sWG- KC), and is given in the Key Comparison Planning Spreadsheet (CCL-WG/MRA-GD-4). The original intent was to repeat comparisons every 7 years, but in many cases the interval has stretched to 10 years, which has been established by the CCL (2012) as the maximum interval for key comparisons and maximum interval at which an NMI must repeat a comparison.

In some cases, the comparison has been restructured: the K2 comparison of long end standards was absorbed into the gage block comparison K1, and BIPM.L-K10 has been subsumed by CCL-K11. The K6 comparison has been terminated but is expected to be replaced by a CMM comparison of some kind. Two new key comparison topics have been added—K7 (line scales) and K8 (surface texture). However, the portfolio of comparison topics is not expected to see significant growth.

5.4. Work program of the BIPM laboratories

At the present time, there is no length program at BIPM, and consequently there are few suggestions for the program. Educational efforts, such as the BIPM Capacity Building and Knowledge Transfer (CBKT) Programme, have proven useful in the past and should be continued.

However, recent discussions in WG-S and WG-MRA have brought to light some issues, which may require eventual resolution or involvement by the BIPM, such as variation in CMC and KC planning and reviewing activities in different regions.

Traceability to the metre

Since the BIPM length section closure, the laser key comparison activity (which is essentially a 'free calibration service') has been operated by several node laboratories of the CCL-K11 comparison, all currently offering this service for free. Thus, the cost of the verification service, previously funded from the BIPM budget, is now funded directly by the NMIs. Instead of a single facility, 5 node laboratories with essentially duplicate facilities make the service available. As NMI research activities evolve, it remains to be seen whether the node laboratories will continue to offer this free service. Verification of traceability to the metre may then only be available on a commercial paid-for basis.

Loss of centralized expertise (absorption cells, etc.)

For many years the centralized expertise at BIPM allowed it to act as a clearing house for useful information relating to the SI metre, and the loss of this resource may have an adverse impact on some CCL member states. For example, information is emerging about a worldwide reduction in the availability of iodine cells suitable for metre realization lasers. This niche activity was previously provided by the BIPM until closure of the length section. Many CCL laboratories now use femtosecond combs as their traceability route and the demand from them for iodine cells has declined. However, smaller economies which do not have recourse to the levels of accuracy provided by comb systems still rely on iodine-stabilised lasers for their metre realization. Lack of qualified iodine cells may become a barrier to these and future economies achieving SI traceability for length metrology.

Annex

1. General information

Name: Consultative Committee for Length

Date established: 1952

CC President: Ismael Castelazo

CC Executive Secretary: Gianna Panfilo

Number of CC Members: 24

Periodicity between Meetings and date of last/next Meeting:
The CCL meets every three years. The last meeting was held in June 2018. The next meeting is scheduled for 2021.

Terms of Reference

- to progress the state-of-the-art by providing a global forum for NMIs to exchange information about the state-of-the art and best practices in length metrology,
- to define new possibilities for length metrology to have impact on global measurement challenges by facilitating dialogue between the NMIs and new and established stakeholders, and
- to demonstrate and improve the global comparability of length measurements. Particularly by working with the RMOs in the context of the CIPM MRA to
  - plan, execute and monitor KCs, and to
  - support the process of CMC review.

Working Groups:

Much of the early work toward implementation of the MRA was carried out by the Working Group on Dimensional Metrology (WGDM). WGDM was set up by CCL in 1992 together with the Working Group on the *Mise en Pratique*, MePWG, for the practical realization of the metre. Up to 2008, MEPWG maintained the list of recommended radiations for realization of the meter and oversaw BIPM laser frequency comparisons. WGDM, under the leadership of Jim Pekelsky (NRC; 1992 - 2002), Nick Brown (NMIA; 2002 - 2006), and Rudolf Thalmann (METAS; 2006 - 2009), was charged with developing the detailed organizational infrastructure needed to provide a technical underpinning of the MRA, via organising and executing the first round of dimensional key comparisons, establishing procedures for the preparation and review of CMCs, and fostering close cooperation between CCL , the regional metrology organizations, and the NMIs.

In 2009 there was a restructuring of the CCL working groups with the formation of new groups that replaced the WGDM and the MePWG, i.e., the CCL Working Group on Strategic Planning (WG-

S), the CCL Working Group on the CIPM MRA (WG-MRA) with sub-working groups sWG-KC on key comparisons and sWG-CMC on CMCs, and the CCL Working Group on Dimensional Nanometrology (WG-N). In addition, there is a joint CCL-CCTF Working Group on Frequency Standards (WGFS), which among other duties is developing guidance on verification of optical frequency combs, a subject that impacts the calibration of lasers for use in dimensional metrology. Finally, the CCL includes a Task Group on KC linking, TG-L, whose activities are described below.

The reorganization of the CCL resulted in the loss of opportunities to exchange technical information not related to the MRA, which occurred before at the WGDM. In order to provide an alternative forum, the CCL established "Discussion Groups" organized around the technical areas covered by the key comparisons.

Discussion Groups are charged to advise the CCL on matters relating to their respective subject field; to produce a working document on principal uncertainty components in the subject field; and to harmonize the related terms and definitions.

These groups operate for the most part by electronic communication and are open to all interested members of the length community. They report directly to the CCL in CCL-meeting-years or to the WG-MRA in other years.

The current structure of the CCL, its working groups and other entities is shown below in figure 1.

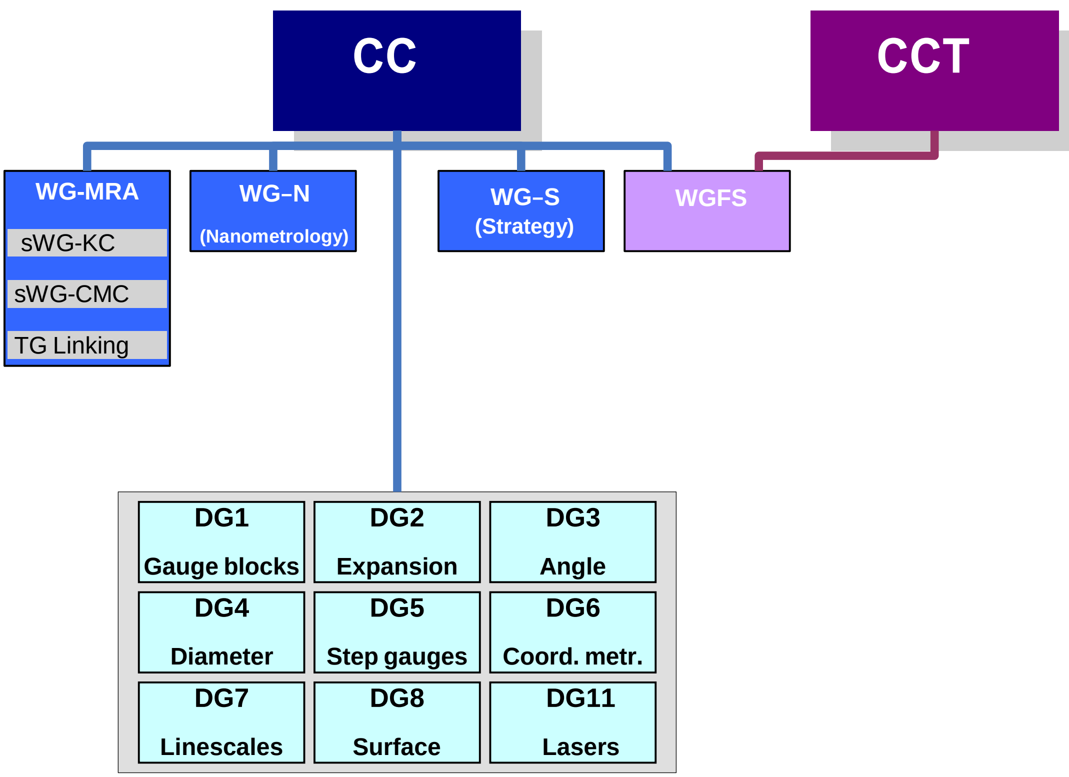

Figure 1. CCL structure

Working Group on Strategic Planning (WG-S)

- Established: June 2009 (by 14th CCL)
- Chair: Ismael Castelazo (CENAM)
- No. of members: 16: 14 *ex officio* + 2 named
- Attending last meeting (June 2018): 20
- Meeting frequency: usually every 1 to 2 years

<u>WG area of responsibility</u>

WG-S, chaired by the CCL President, is charged with developing the long-term strategy for CCL. Membership was chosen by CCL in 2009 (chairs of other WGs and RMO representatives).

Terms of Reference:

- To collect and make available information giving evidence for the continuing importance of metrology in Length;
- to collect and make freely available information from the Member NMIs of the CCL regarding long-term research and development activities in order to encourage collaboration and coordination;
- to propose long-term plans for future activities of the CCL over the next ten to fifteen years and review and update these plans on a regular basis;
- to collaborate with the CCTF to continue to establish and support optical frequency sources that are needed for dimensional metrology interferometers.

Working Group on the MRA (WG-MRA)

- Established: June 2009 (by 14th CCL)
- Chair: Alessandro Balsamo (INRIM; 2018-)
- No. of members: 29: 27 ex officio + 2 named
- Attending last meeting (June 2018): 20 (+ 20 guests)
- Meeting frequency: yearly
- Comprises:
  - sub-Working Group on Key Comparisons (sWG-KC) – Chair Andrew Lewis (NPL; 2009-)
  - sub-Working Group on CMCs (sWG-CMC) – Chair Jose Carlos de Oliveira (INMETRO; 2009-)
  - Task Group on KC Linking (TG-L) – Chair Rudolf Thalmann (METAS; 2015-)

<u>WG area of responsibility</u>

WG-MRA was created by CCL in 2009 as a relatively small group to take over all MRA workload from the WGDM, whilst leaving the previous WGDM technical discussions to the CCL Discussion Groups. Membership of WG-MRA is mostly ex-officio positions based on the membership of its two sub-Working Group: essentially it comprises RMO representatives, comparison pilots, Discussion Group moderators and members of the Task Group on Linking. Guests at the meeting are common, especially in non-CCL years, when the WG-MRA encourages hosting of the meeting by different RMOs in order to increase inter-RMO cooperation – guests from the hosting NMI and those nearby often attend.

Terms of Reference:

- To maintain links with the regional metrology organizations, 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;
- to make recommendations to the CCL on the needs and priorities for additional international comparisons in length under the auspices of the CCL;
- to ensure the coordination of CCL and RMO key and supplementary comparisons;
- to approve the Length key comparison protocols and reports;
- to facilitate the inter-regional CMC Review Process, by:
    a) establishing and maintaining lists of service categories, and where necessary rules for the preparation of CMC entries;
    b) agreeing on detailed technical review criteria;
    c) coordinating and where possible conducting inter-regional reviews of CMCs submitted by RMOs for posting in Appendix C of the CIPM MRA;
    d) providing guidance on the range of CMCs supported by particular key and supplementary comparisons;
    e) identifying areas where additional key and supplementary comparisons are needed;
    f) monitoring the review of existing CMCs in the context of new results of key and supplementary comparisons;
- to report to the CCL.

Sub Working group on CMCs and the DimVim (sWG-CMC)

Chair: José Carlos Valente de Oliveira (INMETRO; 2009-)
No. of members: 7

Task description:

- to establish and maintain lists of service categories (DimVIM) and, where necessary, rules for the preparation of CMC entries (DimVIM Guide);
- to agree on detailed technical review criteria;
- to coordinate and, where possible, conduct inter-regional reviews of CMCs submitted by RMOs for posting in Appendix C of the CIPM MRA;
- to provide guidance on the range of CMCs supported by particular key comparisons;
- to identify areas where additional key and supplementary comparisons are needed; and
- to monitor the review of existing CMCs in the context of new results of key and supplementary comparisons.

Sub working group on key comparisons (sWG-KC)

Chair: Andrew Lewis (NPL; 2009-)
No. of members: 20

Task description:

- to coordinate, supervise and support the administrative process of the pilot laboratories in conducting key comparisons;

- to examine all relevant documents for each key comparison, starting with the protocol and ending with the Draft B report;
- to advise the pilot laboratory in preparing the text of the entry to Appendix B of the CIPM MRA as required, including the calculation of degrees of equivalence and linking, and to prepare a recommendation on these subjects for approval by the CCL;
- to prepare guidance documents on identifying significant deviations for use by the pilot laboratories; and
- to advise the pilot laboratory in preparing a comparison status document, and to prepare a recommendation for this summary for the CCL.

Working Group on Dimensional Nanometrology (WG-N)

- Established: June 2009 (by 14th CCL)
- Chair: Andrew Yacoot (NPL; 2018-)
- No. of members: 49
- Attending last meeting (June 2018): 23 (+ 5 guests)
- Meeting frequency: no fixed schedule but typically meets every 1 to 2 years

<u>WG area of responsibility</u>

WG-N was created in 2009 from the former Discussion Group 7 (DG7) on dimensional nanometrology. The membership is open to experts from NMIs/DIs in the field of nanometrology and the WG meets at convenient opportunities to discuss the evolving needs of the nanometrology community. WG-N and the previous DG7 have organised several pilot studies in dimensional nanometrology.

Terms of reference:

- To serve as a forum in which NMI experts in dimensional nanometrology can share their experiences, discuss standardization needs and identify developing trends and traceability needs in dimensional nanometrology;
- to promote and rationalise the research into dimensional nanometrology, looking for improving calibration and measurement services within NMIs, so offering new accurate and traceable services as demanded by R&D Institutions, Industry and other Stakeholders;
- to coordinate (in cooperation with WG-MRA) the completion of previously agreed-upon pilot studies, supplementary, and key comparisons in dimensional nanometrology;
- to serve as a discussion and development forum for new comparison proposals in dimensional nanometrology and to make recommendations to the CCL when new comparisons are needed;
- to serve as a CCL nanometrology contact point for relationships with other CCs and organizations outside CCL.

Working Group on Frequency Standards (WGFS) – joint with CCTF

- Established: June 2009 (by 14th CCL)
- Chairs: Sebastien Bize (OBSP; for CCTF; 2018-) & Michael Matus (BEV; for CCL; 2018-)
- No. of members: 17
- Attending last meeting: 17
- Meeting frequency: no fixed schedule

WG area of responsibility

The WGFS took over the role of the former MePWG, but added liaison with CCTF due to the overlap between frequency standards being used as realisations of the definition of the metre as well as secondary representations of the second.

Terms of reference:

- To make recommendations to the CCL for radiations to be used for the realization of the definition of the metre and to make recommendations to the CCTF for radiations to be used as secondary representations of the second;
- to maintain together with the BIPM the list of recommended frequency standard values and wavelength values for applications including the practical realization of the definition of the metre and secondary representations of the second;
- to take responsibility for key comparisons of standard frequencies such as CCL-K11;
- to respond to future needs of both the CCL and CCTF concerning standard frequencies relevant to the respective communities.

Task Group on Comparison Linking (TG-L)

- Established: June 2009 (by 14th CCL)
- Chair: Rudolf Thalmann (METAS; 2015-)
- No. of members: 11: 3 ex officio + 8 named
- Attending last meeting: N/A
- Meeting frequency: no fixed schedule – works mostly by correspondence

TG area of responsibility

The TG-L is charged with developing methods to link the dimensional key comparisons (CCL, RMO, Inter-RMO). This is particularly important as most comparisons use artefacts of different materials, types and nominal sizes and numerical linking across the regions and CCL is non-trivial.

Task description:

- Work out appropriate ways of linking dimensional metrology key comparisons;
- Support the DG moderators and KC pilots in linking the KCs.

CCL Discussion Groups (DG1-DG8, DG11)

- Established: June 2009 (by 14th CCL)
- Open membership
- One moderator per DG
- Discuss recent research, events, ideas for comparisons
- Report directly to CCL during CCL meetings or to WG-MRA in non-CCL years, as required
- Topics:
  - DG1 – Gauge blocks (short & long)
  - DG2 – Thermal expansion (of dimensional artefacts)
  - DG3 – Angle
  - DG4 – Diameter
  - DG5 – 1D CMM (Coordinate Measuring Machines) artefacts (step gauges)
  - DG6 – Coordinate metrology
  - DG7 – Linescales
  - DG8 – Surface texture
  - DG11 – Stabilised lasers

DG area of responsibility (example)

To advise the CCL on matters relating to the DG's subject field; to produce a working document on principal uncertainty components in the subject field; and to harmonize the related terms and definitions.

2. List of key and supplementary comparisons and pilot studies

The first round of CCL Key Comparisons concerned 6 topics in dimensional metrology (CCL-K1 to CCL-K6) together with 2 laser frequency/vacuum wavelength comparisons organised by the BIPM (BIPM.L-K10 and BIPM.L-K11). These comparisons have all been completed. A new ongoing laser frequency/vacuum wavelength comparison (CCL-K11) has started. Comparison CCL-K6 was typically based on ball and hole plates and was suspended in view of the cost of such artefacts, not fully justified by the wide spread of these CMC's. Comparisons CCL-K1 and CCL-K2 have now been merged into a new CCL-K1 topic, and two new topics (K7 linescales and K8 surface texture) have been added to the portfolio. Cycle 2 of the key comparisons started in 2011. The topic of thermal expansion is being considered by Discussion Group 2, for possible inclusion in the future comparison portfolio.

Number of KCs organized (from 1993 up to and including 2018)

Comparison	Description	Pilot (Coordinating) Laboratory	Start date	Status
BIPM.L-K10	Frequencies of helium-neon lasers at wavelength 633 nm	BIPM	1993	Completed
BIPM.L-K11	Primary wavelength standards	BIPM	2004	Completed
CCL-K1	Short gauge blocks	METAS	1998	Completed
CCL-LK2	Long gauge blocks	NPL	1999	Completed
CCL-K3	Angle	NMISA	2000	Completed
CCL-K4	Diameter	NIST	2000	Completed
CCL-K5	Step gauge	PTB	1999	Completed
CCL-K6	Ball plates	CENAM	2000	Completed
CCL-K11	Laser frequency / vacuum wavelength	BEV/MIKES/ NPL/NMIJ/NRC		Ongoing
CCL-K1.2011	Short and long gauge blocks	CENAM/NRC	2011	In progress
CCL-K4.2015	Calibration of diameter standards	NIST	2015	In progress

RMO key comparisons: 39 (various –K1-K6 and K11 as per CCL, plus new topics for round two: K7-linescales & K8-surface texture). Two RMO key comparisons are in the planning stage.

- K1 (short gauge blocks) – 9 comparisons plus 2 in planning
- K2 (long gauge blocks) – 2 comparisons
- K3 (angle) – 7 comparisons
- K4 (diameter) – 5 comparisons
- K5 (step gauges) – 5 comparisons
- K6 (ball plate) – 3 comparisons
- K7 (linescales) – 5 comparisons
- K8 (surface texture) – 3 comparisons (since designation as Key topic)

RMO supplementary comparisons: 61 (various topics of regional importance, some comparisons abandoned since 2015).

Number of CC Pilot studies organized (from 1999 up to and including 2012)

Six, with four of those completed being subsequently re-classified as CCL SCs (all in the Nano area).

3. Summary of work accomplished

- Eight key comparisons completed, one ongoing and two in progress.
- Strategy document and *Mise en Pratique.*
- Ten guidance documents for comparisons and CMC entries.
- DimVim – Classification of services in length.
- 1626 CMCs reviewed and published in the KCDB.

4. Document revision schedule

- 1 year for exceptions
- 2 years updating of all lists
- 4 years major revision, with extension of period covered by rolling programme.

Document	Type of revision	Date of revision
CCL Strategy 2018-2028	4-year major revision	November 2018

5. Bibliography of Supporting Web Documents

1. BIPM CCL Members
   http://www.bipm.org/en/committees/cc/ccl/members_cc.html

2. Consultative Committee for Length (CCL), Report of the 17th meeting (14-15 June 2018) to the International Committee for Weights and Measures
   https://www.bipm.org/utils/common/pdf/CC/CCL/CCL17.pdf

3. Comparison scheme applied in dimensional metrology (CCL-WG/MRA-GD-2)
   http://www.bipm.org/wg/CCL/CCL-WG/Allowed/General_CCL-WG_docs/CCL-WG-MRA-GD-2.pdf

4. CCL Length Services Classification 'DimVim'
   http://www.bipm.org/utils/common/pdf/DimVIM/dim-vim- en.pdf.

5. Technical Protocol Template (CCL-WG/MRA-GD-3.1)
   http://www.bipm.org/wg/CCL/CCL- WG/Allowed/General_CCL-WG_docs/CCL-WG-MRA-GD-3.1-KC-technical-protocol-template.doc

6. Guidance Document GD-1: Running of MRA comparisons in length metrology and monitoring their impact on CMCs (CCL/WG-MRA/GD-1)
   http://www.bipm.org/wg/CCL/CCL-WG/Allowed/General_CCL-WG_docs/CCL-WG- MRA-GD-1-v6.pdf

7. Template for Reports of Comparisons
   http://www.bipm.org/wg/CCL/CCL-WG/Allowed/General_CCL-WG_docs/CCL-WG-MRA-GD-3.2-KC-report-template.doc

8. Guide to preparation of Key Comparison Reports in Dimensional Metrology v1.3 and guidance on preparing reports (CCL-WG/MRA-GD-3)
   http://www.bipm.org/wg/AllowedDocuments.jsp?wg=CCL-WG

9. European Metrology Research Programme (EMRP)
http://www.euramet.org/index.php?id=emrp

10. The European Metrology Programme for Innovation and Research (EMPIR)
http://www.euramet.org/index.php?id=research_empir

11. EURAMET Science and Technology Roadmaps for Metrology
http://www.euramet.org/index.php?id=roadmaps

12. European Metrology Research Programme Outline 2008
http://www.euramet.org/index.php?eID=tx_nawsecuredl&u=0&g=0&t=1420205929&hash=ddd7b07f58dd6c96eb1ef422a66b2147434240c7&file=uploads/media/EMRP-outline2008_05.pdf

13. Key Comparison Planning Spreadsheet, Current version (02/2014) is "CCL-WG-MRA-GD4-KC-Planning.xls" http:/www.bipm.org/wg/CCL/CCL-WG/Allowed/General_CCL-WG_docs/CCL-WG-MRA-GD4-KC-Planning.xls