Consultative Committee for Length – CCL

Working Group on Strategic Planning – WG-S

Strategy
Consultative Committee for Length

0. Document 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 (www.bipm.org/en/committees/cc/ccl/). The document was prepared initially in 2013 and is periodically updated.

This strategy document starts with a summary of the current status of the CCL and a description of its present structure and working groups, as was established following its reorganization in June 2009. 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.

The current status of the MRA implementation by CCL and the RMOs is summarised, first with information concerning comparisons. All 7 first round CCL Key Comparisons were completed during the time from 1999 to 2012. One CCL comparison (laser frequency/vacuum wavelength) is ongoing. One second round CCL Key Comparison is in progress and two others are planned to start in 2014-2015. Four pilot studies (later re-classified as CCL Supplementary Comparisons) and two BIPM Key Comparisons were also completed in the period up to 2012. 14 RMO Key Comparisons were completed in the period to 2012 as well as 33 RMO Supplementary Comparisons. 14 RMO Key Comparisons are in progress as well as 12 Supplementary Comparisons. A second round of RMO and Inter-RMO Comparisons is commencing. Repetition of comparison topics across the CCL and Inter-RMO comparisons is planned to be every 10 years.

Concise information on Calibration and Measurement Capabilities (CMCs) is given. The total number of CMCs was 1341 at the end of 2012 rising to 1453 in 2013. Only incremental increases are planned to total CMC numbers.

A summary of the role of the working groups is followed by 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). 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). 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. Finally the document concludes with a list of completed and running comparisons and an online bibliography.

1. General Information on the CCL

1.1 Administrative information

Date established:	This Committee dates back to 1952, when it was created as Consultative Committee for the Definition of the Meter, which in 1997 was renamed as Consultative Committee for Length.
President:	Massimo Inguscio, INRiM, since 5/2015 (previous President: Attilio Sacconi, ex-INRiM from 1/2008 to 4/2015)
No. of Members:	25 (+1 observer). 2 applicants for observer status presented in 2015.
No. of participants at last meeting:	2015 meeting had: 31 Delegates/Experts, 1 Guest, 3 BIPM Staff.
Previous Meeting:	2012 meeting had: 22 Members, 4 Guests, 5 BIPM Staff.
Periodicity of meetings:	2 to 3 years (2001, 2003, 2005, 2007, 2009, 2012, 2015, planned 2018).

1.2 Working Groups

This report is being prepared by the CCL strategy working group but generally covers the relevant activities of the CCL and all of its various working groups. The working groups have intertwined responsibilities that, taken together, include all of the issues that are addressed in this Strategy Document.

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: 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, this report mentions the work of the Task Group on KC linking, TG-L.

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

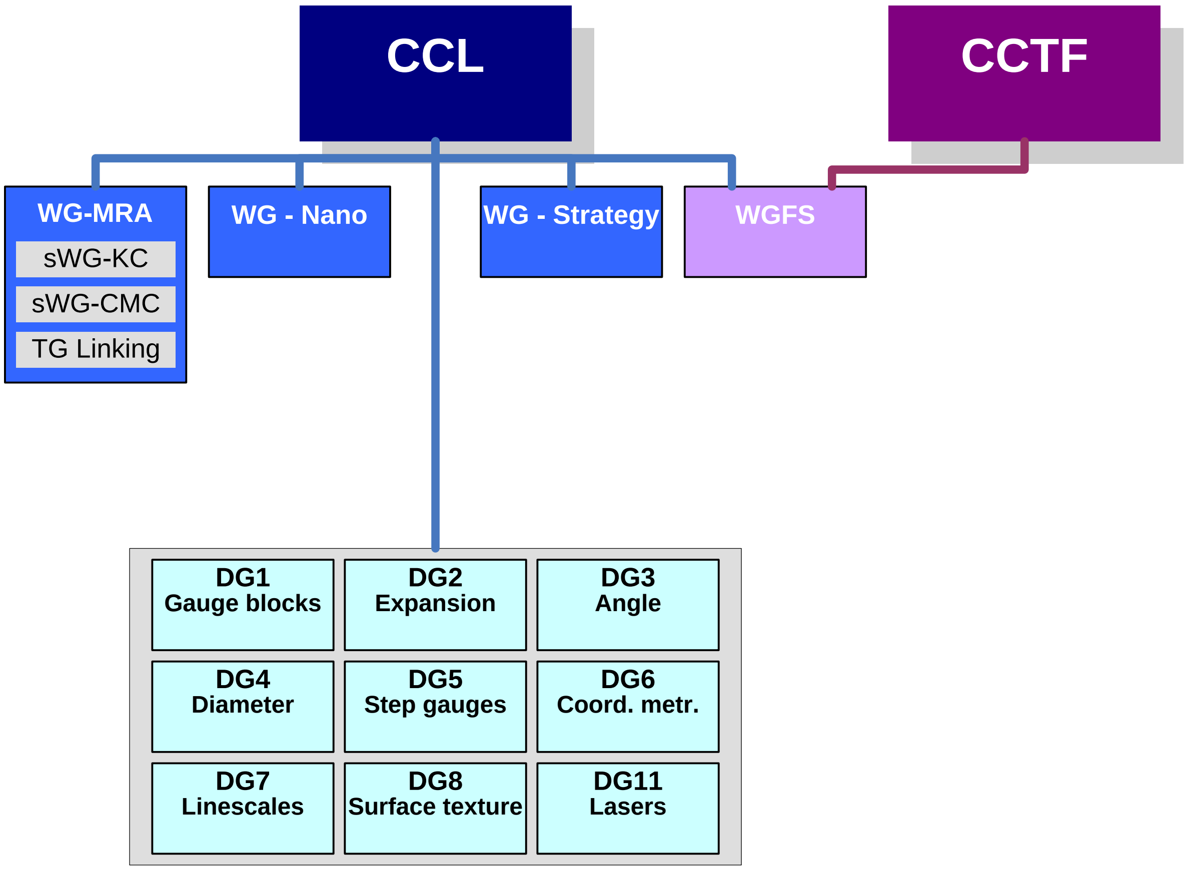

Figure 1 : CCL structure including Workings Groups and Discussion Groups

Although there are regions of overlapping responsibility of the working groups, in general WG-S is responsible for the planning activities of sections 5 and 6 of the document while much of the remaining document currently falls within the responsibilities of the WG-MRA and its subgroups. The terms of reference of the working groups are given in section 2.

Working Group on Strategic Planning (WG-S)

- Established: June 2009 (by 14th CCL)
- Chair: Massimo Inguscio (INRIM)
- No. of members: 16: 14 *ex officio* + 2 named
- Attending last meeting (Sept 2015): 10
- 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).

Working Group on the MRA (WG-MRA)

- Established: June 2009 (by 14th CCL)
- Chair: Andrew Lewis (NPL; 2013-)
- No. of members: 28: 26 ex officio + 2 named
- Attending last meeting (Sept 2015): 13 (+ 13 guests)
- Meeting frequency: yearly

- Comprises:
    - sub-Working Group on Key Comparisons (sWG-KC)
    - sub-Working Group on CMCs (sWG-CMC)
    - Task Group on KC Linking (TG-L)

WG area of responsibility

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.

Working Group on Dimensional Nanometrology (WG-N)

- Established: June 2009 (by 14th CCL)
- Chair: Ron Dixson (NIST), co-chair Harald Bosse (PTB)
- No. of members: 55
- Attending last meeting (Sept 2015): 22 (+ 4 guests)
- Meeting frequency: no fixed schedule but typically meets every 1 to 2 years

WG area of responsibility

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.

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

- Established: June 2009 (by 14th CCL)
- Chairs: Fritz Riehle (PTB) & Patrick Gill (NPL)
- No. of members: 8
- Attending last meeting: 6
- 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.

Task Group on Comparison Linking (TG-L)

- Established: June 2009 (by 14th CCL)
- Chairs: Rudolf Thalmann (METAS: 9/2015-); Harald Bosse (PTB; 2009-9/2015)
- 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.

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 terms and definitions related to their subject field.

1.3 Key comparisons, supplementary comparisons, 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 laser frequency/vacuum wavelength comparison (CCL-K11) has started. Comparison CCL-K6 is suspended pending a decision on a different style of artefact. 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. The topic of thermal expansion is being considered by Discussion Group 2, for possible inclusion in the future comparison portfolio. Cycle 2 of the key comparisons started in 2011.

Number of KCs organized (from 1999 up to and including 2012)

BIPM comparisons: 2

- BIPM.L-K10 (Stabilized laser frequency/vacuum wavelength)
- BIPM.L-K11 (Stabilized laser frequency/vacuum wavelength)

CCL comparisons: 8

- CCL-K1 (short gauge blocks)
- CCL-K2 (long gauge blocks)
- CCL-K3 (angle)
- CCL-K4 (diameter)
- CCL-K5 (step gauge)
- CCL-K6 (ball plate)
- CCL-K1.2011 (short & long gauge blocks)
- CCL-K11 (laser frequency/vacuum wavelength)

RMO key comparisons: 35 (various – topics K1-K6 and K11 as per CCL, plus new topics for round two: K7-linescales & K8-surface texture).

RMO supplementary comparisons: 57 (various topics of regional importance).

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

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

1.4 CMCs

Number of CMCs published in KCDB supported by CC body activities:
up to and including 2012: 1341
rising in 2015 to: 1520

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

2. Terms of Reference

In overview, present activities of CCL concern matters related to the definition and realization of the metre, practical length and angle measurement, coordinate metrology and advice to the CIPM in the field of length metrology.

Terms of Reference for the CCL Working Groups are given below. The Terms of Reference can also be found on the BIPM web site, which also includes ToR for sWG-KC, sWG-CMC, and TG-L.

2.1 WG-S 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.

2.2 WG-MRA 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.

2.3 WG-N 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.

2.4 WGFS 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.

3. Baseline (up to and including 2012)

3.1 Support of comparisons and CMCs

The comparisons and CMCs supported by the CCL and its working groups were given above in Section 1.

It is clear that there is not a direct one-to-one mapping between comparison topics and CMCs – 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).

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.

3.2 Important achievements/outcomes

Many of the activities of the CCL and its working groups over the period 1999-2012 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 100 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 13 languages and has served as a template for other CCs, accreditation bodies, and other organizations (WGDM, sWG-CMC)**

   CCL was one of the first CCs to develop a categorisation scheme (DimVIM) for the CMCs. The original list has now been translated by dimensional experts into 13 languages, ensuring harmonisation 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 harmonising 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 have to 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 harmonising the service categories was extended to harmonisation of the CMC template files with the result that Length CMCs were amongst the first to enter the KCDB. The guidance document 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 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.

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.

9. **Linking concepts, including Workshop on comparison linking (TG-L)**

   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, flatness, pre-existing damage, thermal properties, and measurand definitions. Some properties lead to systematic bias in results which some participants are unable to determine, however they are covered by conservative elements in the uncertainty budget. Comparing the results on a 10 mm steel gauge block measured in EURAMET with those of a 1 mm ceramic gauge block measured in APMP 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 by a purely numerical means unless further analysis is performed. TG-L has been examining ways of linking comparisons on disparate artefacts. A workshop was held in 2007 to discuss various ways of linking comparisons.

10. **KC log files to assist in tracking the status of ongoing comparisons.**

    Although the KCDB manager is required to be kept informed of comparison progress, sWG-KC and WG-MRA periodically require detailed information in the exact status of comparisons in order to prepare reports and documents for meetings. A log file template has been developed which records detailed information about the progress of each comparison and provides links to the comparison guidance document at each stage.

11. **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.

12. **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 will allow 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.

3.3 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 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 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.

Another technology development influencing CCL work is the increasing accuracy of **coordinate measuring machines** (CMMs) and their increased use for measurements at the 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. This issue and other ongoing technological developments are discussed further in Section 5, Future Scan.

3.4 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**

   Some questions relating to linking a set of CCL and RMO comparisons with different artefact standards conducted at different times are not yet resolved in a satisfactory way.

4. **Artefact instability**

   Artefact stability and damage during shipment continue to be significant problems for many comparisons.

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.

See also the section "Future Scan" regarding coming challenges.

3.5 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.

4. Stakeholders

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, *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) and its successor EMPIR.

5. Future Scan (10 years)

A broad overview of coming measurement challenges for industry and science has been well summarized in the EURAMET TC-L 2012 Roadmaps and in the EMRP Programme Outline. Among these anticipated developments, some are already active areas of discussion within CCL and the Working Groups, while for others the impact on future directions of the CCL is not yet clear.

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

5.1 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 or the use of the silicon lattice for scale calibration in high resolution TEM. 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.
- 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.
- Need for new comparisons. Photomask metrology, silicon linewidth measurements, and nanoparticle size are areas of significant need where new comparisons are underway or under development.

5.2 Coordinate Metrology

Coordinate measuring machines or, more generally, coordinate measuring systems, 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.
- 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 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 which are also based on traditional (fixed-purpose) measuring instruments. Differentiation between the available options may be required.

5.3 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.

5.4 Angle measurement technology

Changes in technology and in industry practice are driving discussions of possible changes to the K3 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.

5.5 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.

5.6 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.
- 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 3-D metrology and for accessing true 3-D 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.

Trends in coordinate metrology

- A proliferation of new technologies for coordinate measurement, each with its unique set of errors, includes X-ray computed tomography (CT), articulating arms, laser trackers, laser scanners, and indoor-GPS.
- 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. A related trend (mentioned previously) is the increasing prevalence of free-form surfaces.

Trends in macroscale measurements

- GNSS (Global Navigation Satellite System), complimented by new technologies for absolute distance measurement, is increasingly impacting macro-scale measurement.
- Refractive index measurement in non-uniform environments presents an important challenge for both macroscale and mid-scale manufacture.
- 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.

5.7 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.

5.8 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 and the development of the GPS (Geometrical Product Specification) matrix of ISO standards. Looking toward future work, if CCL promotes new length standards based on the silicon lattice (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.

6. Rationale for various activities (2013-2023)

6.1 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 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 section 5 will require new comparisons to support new measurement technologies. There are not yet 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).

6.2 NMI research activities

We encourage the NMIs to undertake research that addresses the challenges of section 5, 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. The only inter-NMI coordination of research efforts that occurs is within EURAMET, under the EMRP/EMPIR.

6.3 BIPM Program

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 Metrology Summer School, 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.

Traceability to the metre

Before the closure of the BIPM length section, the BIPM had considerable skills and experience in laser stabilization and provided a free service for verification of *Mise en Pratique* lasers via the BIPM key comparisons. Since the length section closure, the 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 service for free. 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.

6.4 CCL Structure and utilization of resources

The CCL was restructured recently (2009) to improve efficiency of the MRA process and is unlikely to require significant restructuring in the short to medium term.

The CCL has strengthened the role of CCL DGs by requiring them to report directly to the CCL. The pool of available experts for DG membership is larger than that of just the CCL members, so the CCL can draw on greater resources for this aspect of its future planning and technical discussion. By removing the MRA processes to a smaller WG (compared with WGDM) more time is available in CCL meetings for technical discussions, especially those involving the DGs.

In the future, CCL may see consolidation or interaction between DG1 (gauge blocks), DG4 (diameter), DG5 (step gauges) and DG6 (coordinate metrology) as CMMs become more prevalent at offering services in 1D. CCL is unlikely to see complete abandonment of early DGs until CMMs can routinely offer similar uncertainty levels to bespoke interferometry systems (*e.g.* considerably better than 100 nm for 1 m length bars, better than 20 nm for short gauge blocks).

6.5 CCL and WG future meetings

The CCL and WG meetings now generally operate on a 3-yearly cycle, based around the CCL meeting. In years of a CCL meeting, the WGs meet at the BIPM just prior to the CCL meeting. In non-CCL years, the WGs tend to meet at locations offered by hosting RMOs. There are also two dimensional metrology conference series organised by CCL members: Nanoscale and Macroscale. WG-MRA so far plans to meet just after the Macroscale meeting in the same venue.

2012	CCL year	CCL, WG-S, WG-MRA, and WG-N meetings at BIPM
2013	RMO year	WG-MRA, WG-S and WG-N hosted by Taiwan, APMP; Nanoscale conference France;
2014	RMO year	Macroscale conference, WG-MRA (& possibly WG-S), hosted by BEV, EURAMET
2015	CCL year	CCL, WG-S and WG-MRA meetings at BIPM
2016	RMO year	Offers to host from NL and ZA
2017	RMO year	Macroscale conference, WG-MRA (& WG-S) possibly hosted by MIKES/VTT EURAMET
2018	CCL year	CCL, WG-S and WG-MRA meetings at BIPM

6.6 MRA optimization

CCL has already implemented several optimisations of the MRA process as detailed earlier in this document including: guidance documents and templates for pilots; a mixture of comparison styles (CCL, RMO, CCL-RMO) to optimise participation; KC portfolio explicitly limited to testing key techniques not all services; use of node/regional laboratories for some comparisons as well as multiple loops with different artefacts.

One issue which may offer a potential for optimization is that of whether or not a numerical link between comparisons is actually required by end users of the MRA. CCL may consider referring the issue of KC linking to the BIPM Director’s Group on Uncertainty and it would welcome, as part of the forthcoming review of the efficiency of the MRA, the opinions and feedbacks of end users’ comments on this question of comparison linking. At the moment, few CCL comparisons have any linking and a reduction in comparison workload could be obtained by explicit removal of the requirement to link comparisons.

There are certain subjects, such as characterisation of nanoparticles, where the processes see a split horizon between different groups at several NMIs and this reduces efficiency of the coordination process. CCL would welcome closer interaction within the NMIs to ensure inter-group discussion of comparison processes.

Significant further optimization of MRA processes or reduction in the cost of supporting the MRA would require radical changes to the way the MRA is operated within CCL. The following suggestions (particularly those with a question mark) are not intended to be conclusions but are intended to serve as a provocative basis for continuing discussions. No decisions will be made until after the CIPM's MRA efficiency review is concluded.

Significant reduction in comparison frequency?

The simplest method to substantially reduce the work load would be to not phase out comparisons entirely but increase repeat frequency to 15 years or more (instead of 10) at least for CCL key comparisons if not for all types of comparisons. See section 7.3 for further discussion.

A single key comparison in CCL?

The MRA may be interpreted as calling for key comparisons of techniques which realise national measurement standards. For length, CCL-K11 is the only comparison that truly tests national measurement standards. It could be advantageous to run only CCL-K11 as a traditional CCL comparison, while other existing KCs are run as inter-regional RMO key comparisons as described in section 3.

Impact of Coordinate Measuring Machines (CMMs) on comparison topics

A topic of current discussion is whether it is possible that a fairly simple test of proficiency for CMM measurements could qualify the machine for a wide variety of measurements. Some CCL member NMIs calibrate diameter standards such as ring gauges using CMMs and then might not need to take part in a separate diameter (K4) key comparison or step gauge (K5) comparison. This increased optimistic view of 'how far the light shines' could be extended to offer alternative ways of supporting CMC claims rather than direct participation in all key comparison topics. There are technical limitations to this approach, and at present it is difficult to foresee the elimination of more fundamental comparison topics such as gauge blocks. But as a general principle, we may expect that technological advances could eventually enable a shift away from some of the traditional artefact standards and the key comparison portfolio will evolve accordingly.

Increased shining of the light: supplementary comparisons

CCL (more precisely, the RMOs with CCL consultation) has undertaken a number of supplementary comparisons partly because they were in topics which were of keen interest at the time and partly because it seemed that the light of the key comparison topics did not shine far enough to support the greater majority of CMC entries. These comparisons have been useful but do not necessarily set a precedent requiring a continuation of this level of comparison activity.

6.7 Future definition and realizations of the metre

The 2012 CCL meeting discussed the proposed text for the forthcoming revision of the SI and was of the opinion that it was not fully happy with the wording (in particular that proposed for the next definition of the metre) but the reasons behind it are understood. CCL takes note of the proposed new definitions.

In terms of realisation of the metre, CCL foresees continuing progress in the field of optical frequency standards and expects that the joint working group of CCL and CCTF will continue to propose new additions to the joint list of frequencies with increasingly smaller uncertainties. Separately, there are discussions within WG-N on alternative routes to realizing the metre in a format that is more easily suited to the needs of dimensional nanometrology, since sub-division of optical wavelengths of the order of 0.5 µm to sub nanometre fractions (or approaching pm dimensions) is non-trivial. Silicon lattice standards may provide a more readily accessible traceability route.

7. Required Key comparisons and pilot studies 2013-2023 with indicative repeat frequency

7.1 Proposed Dates

Planning of future comparisons is primarily the responsibility of WG-MRA. Likely dates of future comparisons are shown in the table on the page following Section 9. Essentially, the anticipated 10 year repeat cycle of comparisons is as follows.

2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
K1					K4,K5	K3,*K6*	K7	K8		K1		

7.2 How far the light shines

As described previously, there are 7 key comparisons which test the principal techniques of length metrology: K1 (gauge blocks), K3 (angle standards), K4 (cylindrical diameter), K5 (step gauge), K7 (line scales), K8 (surface texture), and K11 (laser wavelength).

It is the stated intention of CCL to not support every CMC with direct comparison evidence, contrary to requests received from some accreditation bodies. The DimVIM currently lists over 100 service categories and whilst several categories could be combined into a single comparison topic, this would still lead to an unmanageable number of comparisons (somewhere in the region of 30 topics) requiring an average participation in three topics per year to maintain the 10 year periodicity. Even if some topics were classified as supplementary, the comparison burden would be unacceptable.

7.3 Impact of lengthening the repeat frequency or stopping the comparison

As was discussed in Section 3, several comparisons have been terminated or reformulated, such as K2 (long gauge blocks) absorbed into K1 (gauge blocks), K6 (ball plates) expected to be replaced with a new CMM comparison, and the replacement of BIPM.L-K10 (lasers) with CCL-K11. There are no plans for elimination of other key comparisons; the existing set of comparisons was formulated as a minimal set needed to test basic measurement techniques (as described above).

Lengthening the time between comparisons would in principle have little adverse effect, if the quality system is working properly. It is more problematic in cases where there are changes in staff or equipment. If the same operator and same equipment are used on the same artefacts, there is little lost if we lengthen the periodicity. However, lengthening the repeat frequency might make it more difficult for laboratories beginning new services or upgrading services supported by these comparisons, who do not want to wait a long period of time before introducing new CMCs. To some extent this problem is ameliorated by the possibility of bilateral comparisons, but widespread bilateral comparisons are inefficient relative to a multilateral comparison, and may leave some issues unresolved. It is probably necessary for a case-by-case examination of the needed frequency of KCs by WG-MRA, rather than an overall statement that a 10-year repeat frequency is suitable for all key comparisons.

Cancellation of a key comparison topic causes certain issues with support for CMC claims. As an example, when the K6 topic was closed, some NMIs which had poor performance in the last K6 comparison were left with no planned future comparisons with which to reinstate their greyed-out CMCs. Enthusiasm for assisting with a bilateral follow-up comparison was limited. Alternative methods are being examined to allow reinstatement of the affected CMCs. This highlights the issue of adding a topic to the comparison portfolio – it requires mandatory participation and if the topic is then removed, CMCs can be affected.

8. Resource implications for laboratories for piloting comparisons

It is estimated that piloting a well-established comparison requires at least 20 days work, including selection/procurement of artefacts, pre-circulation verification of artefact stability, several stability measurements mid-circulation (assuming that these measurements can be performed quickly), possibly replacing damaged artefacts, preparation of the protocol and several iterations of draft A and draft B reports, and possibly exploring new analysis methods. For a pilot study, the time estimates would increase, and it may be difficult to disentangle which part of the effort should be assigned to the comparison or assigned to a basic research effort.

Significant resources are also required to simply participate in a comparison, even if not a pilot. The minimum resource expenditure is essentially the cost or equivalent time investment for a standard calibration of the set of comparison artefacts, with some additional effort required to deal with customs and provide information to the pilot in an appropriate format. Additional work is also required when normal measurement procedures have to be modified to accord with the protocol. It is clear from this that the majority of CCL key comparisons are those centred around existing measurement services rather than testing equivalency of national standards at the NMI level. They thus take less time than comparisons in other CCs which are much closer to the SI realizations.

One comparison that requires notably more effort than a normal calibration is K11 (laser vacuum wavelength), which typically requires two days of travel plus several days of measurement, whereas a typical customer laser calibration might require less than 8 hours of work.

For other types of comparisons, the time required to participate should more closely approach the time for a routine calibration, at least in principle. In practice, the time commitment might significantly exceed that of a customer calibration because pressure for a good result in a key comparison is usually much higher than for a routine calibration; some laboratories may therefore carry out multiple measurements and checks beyond the typical calibration procedure. For purposes of estimating the effort of comparisons as presented above, any such additional effort has been budgeted toward maintenance of the measurement system, but it is nevertheless possible that the actual cost of participating in a key comparison will significantly exceed the cost of a routine calibration.

It should also be noted that the longest time period in many comparisons is that required for reporting – the effect is small on the actual budget required (since it is a small amount of time, but spread over a long duration), but does require the budget used by the participants to be made available over an extended time period (sometimes up to 6 years to start, complete and report on a comparison). The effect is most acutely felt by the pilot.

Resource implications for new pilots may be slightly greater than experienced pilots as they 'learn the process'. Also, comparisons in new topic areas will require more resource for: artefact characterisation, measurand definition and protocol preparation, analysis, reporting and discussion.

In 2015, two pilots reported on their records of piloting their respective comparisons. A large dual-loop gauge block comparison with regional participation amassed 2600 hours of work at the pilot institute. This comparison required significant effort to be used in the numerical linking process, to take into account artefact drift and correlations. A smaller inter-regional comparison in surface texture, organised as a follow on comparison immediately after a similar one in the same region, amassed 200 hours of work for the pilot.

9. Summary table of comparisons, dates, required resources and the laboratories already having institutional agreement to pilot particular comparisons

A summary of CCL comparisons is given at the end of this document. The future comparisons listed in the second part of the table (and in CCL-WG/MRA-GD-4) are tentative suggestions from WG-S that have only recently been approved by WG-MRA but not yet by CCL. It must be emphasized that the table could be misleading if it were misinterpreted as providing a complete picture of the resources consumed in support of the MRA, because it does not include the many regional comparisons, for which the total effort exceeds that of the CCL comparisons. (For a better picture of the full effort, see the historical record in CCL-WG/MRA-GD-4).

Also, as stated in section 8, in some cases the cost of participating in a comparison might significantly exceed the estimate based on the analysis of section 8.

10. Document Revision Schedule

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

KEY COMPARISON TABLES

Metrology Area	CCL	Colour codes:	KC Completed / KC In Progress / KC Planned
Date updated	2012 Dec 3		

Table 1 Completed Comparisons and comparisons under way

Sub Area	Reference No.	Description	Pilot (Coordinating) Laboratory / Number of praticipants	Start date	Status	Comments	Horizon for repeating (or not) with timeline	How far does the light shine? (DimVIM service category)	Estimate of resouces in person months (PM) for piloting and particpating (per particpant) if known
	CCL								
Gauge blocks	CCL-K1	Gauge blocks by interferometry	METAS/15	1998	Completed		<10 years	2.2.1	1.2 (pilot)+ 0.13 (per lab)
Gauge blocks	CCL-K2	Long gauge blocks by interferometry	NPL/13	1999	Completed	now part of CCL-K1		2.2.2 , 2.2.3	1.2 (pilot)+ 0.1 (per lab)
Angle	CCL-K3	12-sided polygon and 4 angle blocks	NMISA/14	2000	Completed		<10 years	3.1.1 , 3.1.2 , 3.1.3 , 3.4.1	1.2 (pilot)+ 0.1 (per lab)
Diameter	CCL-K4.a	Internal diameter standards	NIST/11	2000	Completed		<10 years	2.4.2	1.2 (pilot)+ 0.1 (per lab)
Diameter	CCL-K4.b	Externel diameter standards	NIST/11	2000	Completed		<10 years	2.4.1	1.2 (pilot)+ 0.1 (per lab)
Step gauge	CCL-K5	1-D coordinate measuring machine artefacts	PTB/13	1999	Completed		<10 years	2.2.4 , 2.2.5	1.2 (pilot)+ 0.1 (per lab)
Ball plate	CCL-K6	2-D coordinate measuring machine artefacts	CENAM/12	2000	Completed		Stopped	5.4.1 , 5.4.2	1.2 (pilot)+ 0.1 (per lab)
Line scale	CCL-S3	Nanometrology: line scale standards	PTB/13	2000	Completed	later CCL-K7	<10 years	2.3.1 , 2.3.2 , 2.3.7 , 2.3.8 , 2.3.9	1.5 (pilot)+ 0.5 (per lab)
Optical frequency	BIPM.L-K10	Comparison of optical frequency and wavelength standards	BIPM/45	1988	Completed		Stopped	1.1.1	1.2 (pilot)+ 0.1 (per lab)
Optical frequency	BIPM.L-K11	Comparison of optical frequency and wavelength standards	BIPM/34	2004	Completed		Stopped	1.1.1 , 1.1.2	1.2 (pilot)+ 0.1 (per lab)
Gauge blocks	CCL-K1.2011	Short and long gauge blocks by interferometry	CENAM/NRC//17	2011	In progress			2.2.1, 2.2.2	1.0 (pilot)+ 0.13 (per lab)
Optical frequency	CCL-K11	Comparison of optical frequency and wavelength standards	BEV/MIKES/NMIJ/NPL/NRC/25	2008	Ongoing		<10 years	1.1.1 , 1.1.2	1.0 (pilot)+ 0.25 (per lab)

Table 2 Planned comparisons including ongoing BIPM comparisons

Sub Area	Reference No.	Description	Pilot (Coordinating) Laboratory	Expected Start date	Estimate of resouces in person months (PM) for piloting and particpating (per particpant)	Rational for Key Comparison	Interested /agreed/ expressed by:	How far does the light shine?	Special aspects related to logistics
Gauge blocks	CCL-K1	Short and long gauge blocks by interferometry		2011, 2021	1.0 (pilot)+0.13 (per lab)	periodic repetition		2.2.1, 2.2.2	
Angle	CCL-K3	12-sided polygon and 4 angle blocks		2017	1.0 (pilot)+0.1 (per lab)	periodic repetition		3.1.1 , 3.1.2 , 3.1.3 , 3.4.1	
Diameter	CCL-K4	Diameter standards		2014	1.0 (pilot)+0.1 (per lab)	periodic repetition		2.4.2	
Step gauge	CCL-K5	1-D coordinate measuring machine artefacts		2016	1.0 (pilot)+0.1 (per lab)	periodic repetition		2.2.4 , 2.2.5	
Line scale	CCL-k7	Nanometrology: line scale standards		2018	1.0 (pilot)+0.2 (per lab)	previously CCL-S3		2.3.1 , 2.3.2 , 2.3.3, 2.3.7 , 2.3.8 , 2.3.9	
Surface Texture	CCL-K8	Roughness and step height standards		2019	1.0 (pilot)+0.1 (per lab)	principal technique		5.1.1, 5.1.4, 5.1.6	
Optical frequency	CCL-K11	Ongoing comparison of optical frequency and wavelength standards	BEV/MIKES/NMIJ/NPL/NRC	2008	1.0 (pilot)+0.25 (per lab)	periodic repetition	BEV	1.1.1 , 1.1.2, 2.1.1	
New CMM ?	CCL-K?	New CMM comparison, To Be Determined		2017	TBD	replaces K6		TBD	

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 15th meeting (19 – 20 September 2012) to the International Committee for Weights and Measures. http://www.bipm.org/utils/common/pdf/CCL15.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