Consultative Committee for Length: Current Status and Strategy

1. Introduction

This document provides a brief description of the activities of the Consultative Committee for Length (CCL) and its strategic vision for meeting future measurement challenges. This is a modified and condensed version of a more detailed description and strategy document, "Strategy 2013-2023, Consultative Committee for Length" (CCL/WGS/SD-L) [1]. The current document is intended for a broader audience than was the original document, which was primarily directed toward individuals who are intimately involved with international metrology organizations, but the original document [1] can be usefully consulted by anyone who might have unanswered questions after reading this abbreviated version.

Figure 1. The metre, originally defined by a length marked on a bar such as shown in the background, is currently defined via the speed of light and realized via the wavelength and frequency of lasers, as illustrated by the laser beam in the foreground.

The CCL is concerned with matters related to the definition and realization of the metre, practical length and angle measurement, and coordinate metrology. The CCL also provides advice to the CIPM (International Committee for Weights and Measures) in the field of length metrology. In addition, CCL is responsible for implementation of length-related aspects of the Mutual Recognition Arrangement (MRA), through which National Metrology Institutes (NMIs) recognize each other's measurements. This document discusses two broad aspects of CCL activity. The first topic is activities associated with the MRA. The second topic is future trends in metrology— how technological developments will impact length measurement and the work of the CCL.

2. CCL and the MRA

The technical basis of mutual recognition is provided by measurement intercomparisons through which NMIs directly demonstrate their ability to carry out measurements similar to what they perform for customers. CCL has established a set of "key comparisons" for this purpose. One of the comparisons, CCL-K11, involves measurement of laser frequency, which underlies all other length measurements because laser frequency (which determines laser wavelength in vacuum) provides a fundamental method for realisation of the definition of the metre (as recommended by CCL in the *mise en pratique*). All other key comparisons require measuring artefact standards that are commonly used in industry, including end standards (gage blocks and length bars, CCL-K1), angle standards (optical polygons and other angle artefacts, CCL-K3), diameter standards (rings, plugs, and spheres, CCL-K4), coordinate measuring machine artefacts (step gages, CCL-K5, and formerly ball plates, CCL-K6), line scales (CCL-K7), and surface texture standards (step height and roughness standards, CCL-K8).

It is neither practical nor desirable to test every possible measurement capability of the NMIs. The key comparisons represent a limited portfolio of measurements that test the principal techniques underlying length measurements and are required of a competent dimensional metrology laboratory. Different comparisons test different techniques, but an individual key comparison tests more than one specific skill and underpins more than one CMC (Calibration and Measurement Capability) listed in Appendix C of the MRA. 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. For example, good performance in the CCL-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.

Figure 2 shows the relation between the key comparisons and the principal techniques. Although the comparison titles refer to artefacts, rather than techniques, the different types of artefacts require different measuring techniques and skills.

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.

The extent to which one comparison provides evidence of competence in another measurement is a matter of judgment and requires development of consensus. Always the question is asked, "How far does the light shine?" The goal of the key comparisons is to provide a minimal suite of comparisons that illuminates all of the 1500 length-related CMCs listed in Appendix C of the MRA. This cannot always be achieved; when the key comparisons cannot provide full confidence in a CMC, supplementary comparisons are carried out as needed, usually under the auspices of the Regional Metrology Organizations (RMOs) or occasionally of CCL. There have been 62 supplementary comparisons covering 32 topics. Key comparisons are repeated at regular intervals, but this is not true for the supplementary comparisons. Other CMCs without direct comparison evidence to support them have to be accepted based on quality system assurance and other evidence.

The list of key and supplementary comparisons is not static. CCL supports Pilot Studies to determine if new comparisons are desirable and practical. This is particularly important in developing fields such as nanometrology, where five pilot studies have been upgraded to supplementary comparisons and one to a key comparison. Future changes in the key comparisons are anticipated in angle measurement and coordinate metrology, driven by changing technology and measurement practice. This is discussed further in the following section.

3. Future Trends and Challenges (2016-2026)

A broad overview of coming measurement challenges for industry and science has been well summarized in the EURAMET Science and Technology Roadmaps for Metrology [2] and the Strategic Research Agenda for Metrology [3]. Among these anticipated developments, some are already active areas of discussion within CCL, 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.

3.1 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.

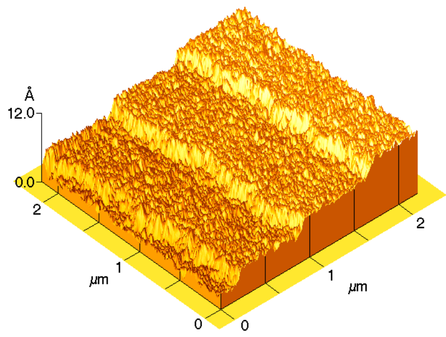

Figure 3. Single-atom steps on a silicon (111) lattice.

- 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 Transmission Electron Microscopy (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 Atomic Force Microscopy (AFM), Scanning Electron Microscopy (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 (National Institute of Standards and Technology) 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.

3.2 Coordinate Metrology

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

Figure 4. Step gages, ring gages, plugs, and long end standards being measured on a CMM. The flexibility of a CMM might eventually enable a shift away from some of the traditional artefact standards and the key comparison portfolio will evolve accordingly.

- 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 into the current MRA framework is being debated since CMMs could be used to deliver CMCs which are also based on traditional (fixed-purpose) measuring instruments and are tested by different key comparisons. Differentiation between the available options may be required.

3.3 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 (joint Working Group on Frequency Standards of the CCL and CCTF) 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. Should the cost of comb systems reduce significantly and their robustness increase, the possibility of using them to measure absolute distance as well as refractive index may see them used in more applications, leading to further need for guidance and even CMCs.

3.4 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. Other research such as under the EURAMET SIB58 Angle Project [4] into interferometric angle metrology and devices based on laser gyros or inertial systems may play a larger part in future precision angle metrology.

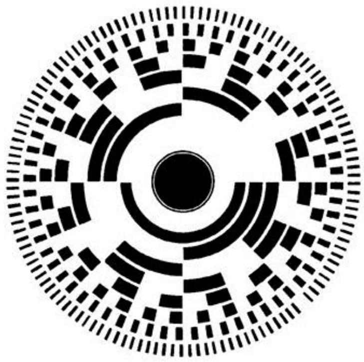

Figure 5. Angle encoders are playing an increasing role in angle metrology.

3.5 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. Presently the DimVIM is structured around specific artefacts rather than measurement tasks. This was appropriate when a specialized measuring apparatus was used for each artefact, but makes less sense for CMM-based measurements. For a CMM, it makes little difference if a measured linear dimension is the diameter of a ring gauge or the distance between two opposing faces of a step gauge. It may be practical to define a DimVIM measurement category not by the name of the artefact but by the basic operation—measuring a linear dimension between gauge points on opposing surfaces—which could cover a variety of artefacts with a single DimVIM entry and a single CMC.

3.6 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. At the micro/nano level, suitable standards for areal surface texture are not available and much needed.

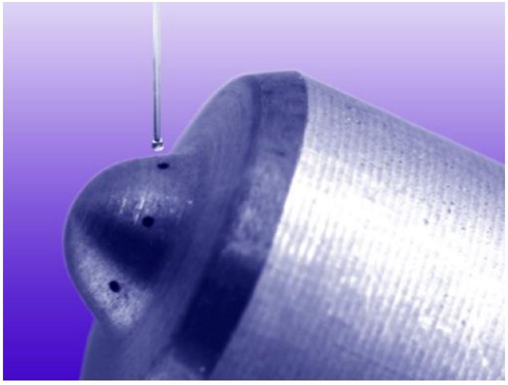

Figure 6. Micro-probe measures 130 µm diameter holes in an advanced fuel injector.

- 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 measurement 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 in many application areas. These surfaces are difficult to characterise using platonic models and generally require measurement of a point cloud and manually-guided analysis to remove outliers and relate points to features on the surface.

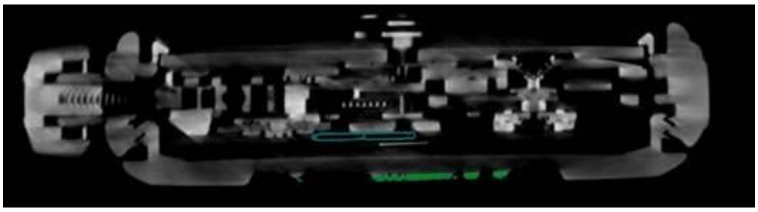

Figure 7. X-ray CT allows measurements of hidden features with high data density, as in this cross-sectional image of a watch.

Trends in large scale measurements

- GNSS (Global Navigation Satellite System) and new technologies for absolute distance measurement are increasingly impacting outdoor and indoor macro-scale measurement.
- Factory-wide metrology networks providing location and orientation information for robotic systems will be needed for autonomous 'Industry 4.0' operations.
- 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 (>20m/min) of thickness, structure, composition, activity and defect detection during processing.
- Large science infrastructure (LHC replacement, large optical telescopes, beam therapy suites) require metrology at tens of micrometres level for ranges from 10 m up to hundreds of metres.

Figure 8. Measurements up to 40 m with high precision are crucial to assembly in aerospace manufacturing.

In-process metrology with direct traceability

- Realizing 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 through e.g. gas cell frequency standards.

Figure 9. In-situ metrology of a turbine.

3.7 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. Applications in plasmonics are now starting to look for dimensional control at sub-nanometer levels.

Finally, another driver pushing higher accuracy in dimensional measurements is problems of fundamental metrology, such as establishing accurate standards of derived units (pressure, flow, capacitance, irradiance, etc.) or measuring fundamental physical constants (Planck constant, Boltzmann constant, universal gravitational constant), as illustrated in Figure 10. Mass measurement (watt balance, used to measure the Planck constant or, in the new SI, to realise the mass unit—Fig 10f), capacitance standards (calculable capacitor—Fig 10c), or the silicon sphere (for determination of the Avogadro constant—Fig 10a) all benefit from optical interferometry at the sub-nanometer level to measure linear dimensions or displacements. It can be equally important to know dimensional form; the cylindricity of the electrode in the calculable capacitor (10c), or of the piston and cylinder of a piston gauge pressure standard (10b), must be maintained at state-of-art tolerances (tens of nanometers) and the geometry must be mapped by a state-of-art CMM. CMM measurements of geometry are also critical to an acoustic resonator for determination of the Boltzmann constant (10e) and even for the balance wheel at the top of the watt balance (10f). A recent measurement of the universal gravitational constant (10d) is simply built around a CMM to provide careful measurements of the positions of the source masses.

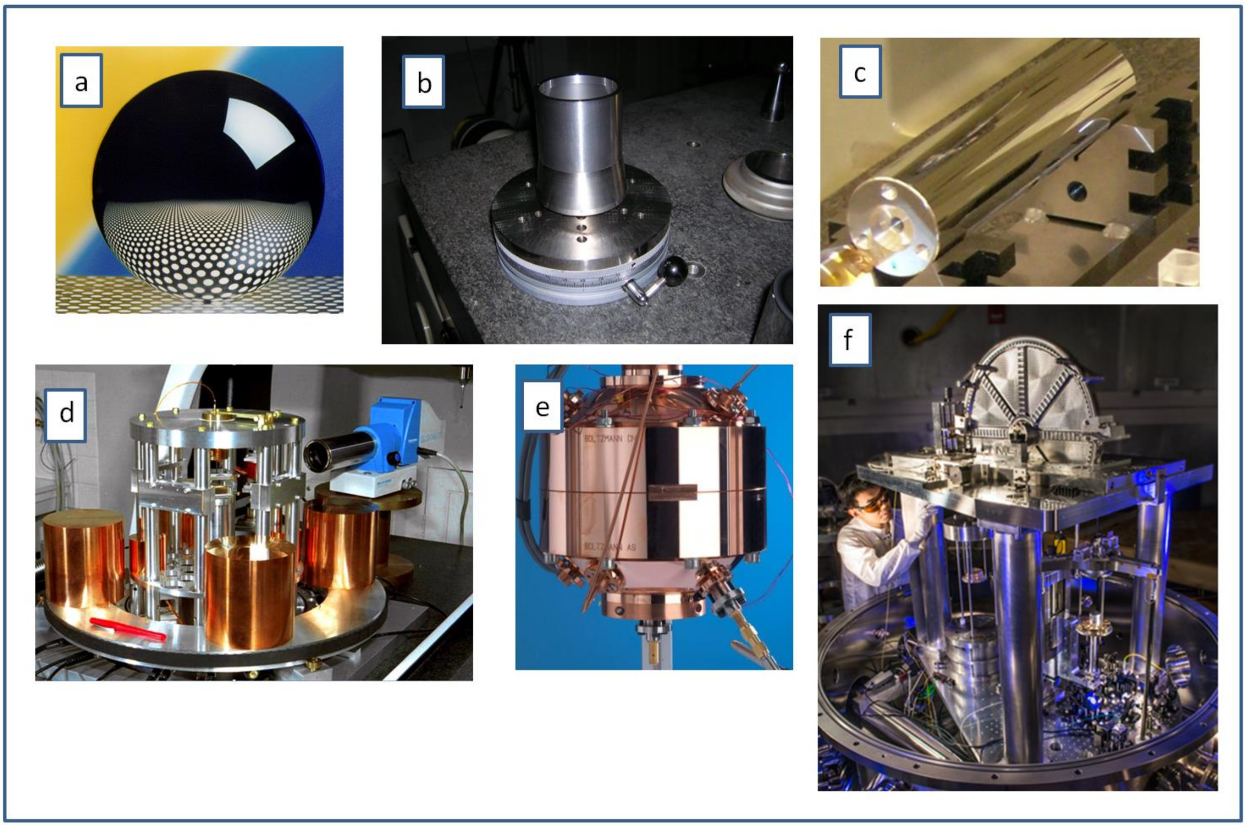

Figure 10. Ultra-precise dimensional measurements impact other fields of fundamental metrology and the measurement of physical constants. See the preceding text for a full description. (10a) shows a silicon sphere, part of the Avogadro project, which required precision diameter and form measurement. The pictured piston pressure standard (10b) and the electrode for the calculable capacitor (10c) are being measured (diameter and form) on a CMM, and the apparatus for the universal gravitational constant (10d) is sitting on a CMM that provides critical in-situ metrology. At the back of 10d is an autocollimator for precise angle measurement—another aspect of dimensional metrology that is necessary to this experiment. The Boltzmann resonator in (10e) was manufactured using diamond turning with in situ interferometry and later CMM measurement, for form and ellipticity.

A recent (2015) dramatic example of length measurement for scientific application is the detection of gravitational waves by the LIGO observatories. The detected strain amplitude was 1×10^{-21}, corresponding to a change in the length of the 4 km LIGO interferometer by one billionth (10^{-9}) of an atomic diameter.

3.8 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 3.1), 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.

4. Concluding Remarks

Although this document treats the CCL as a single entity, in reality most of the activity has been done in various working groups that share these tasks, and in discussion groups that address specific measurement tasks. The structure of these groups, their terms of reference and leadership, and their accomplishments are detailed in reference [1]. The references below also include links to additional documents that were developed by the working groups [5-11]. These documents include guidance documents for conducting comparisons and evaluating impact on CMCs, templates for comparison protocols and reports, explanations of policy, linking concepts, and the DIM VIM classification scheme developed by CCL which has also served as the template for other Consultative Committees and for standardization groups.

The CCL has evolved in response to changes in the structure of international metrology (the advent of the MRA) and in response to technological advances such as frequency combs. It may be anticipated that the trends described in Section 3 will require additional changes in the future, including new comparisons to support new measurement technologies and possibly a broader definition of CMCs that mesh with the continuing trend away from fixed gauges and towards more flexible measurement systems.

One basic task of the CCL will continue to be advising the CIPM. Other stakeholders in our work include NMI signatories to the MRA, the Regional Metrology Organizations, certification bodies, standards organizations, calibration laboratories, equipment manufacturers, and government legislative or regulatory bodies involved with new laws and directives. The ultimate beneficiaries are the industries that rely on these organizations, 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.).

5. References to Supporting Web Documents

1. Strategy 2013-2023, Consultative Committee for Length (CCL/WGS/SD-L)
http://www.bipm.org/utils/en/pdf/CCL-strategy-document.pdf

2. EURAMET Science and Technology Roadmaps for Metrology
https://www.euramet.org/Media/docs/Publications/roadmaps/EURAMET_Science_and_Technology_Roadmaps_for_Metrology.pdf

3. Strategic Research Agenda for Metrology in Europe, Version 1.0 (03/2016)
http://www.euramet.org/sra

4. European Metrology Research Project "Angle Metrology"
http://anglemetrology.com/

5. 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

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

7. 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

8. 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

9. 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

10. 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

11. 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

6. Photo and Picture Acknowledgements

Figures 1, 9, and 10e: Courtesy of National Physical Laboratory (NPL)
Figures 3,4, 6, 10b,10c, 10f: Courtesy of National Institute of Standards and Technology (NIST)
Figure 5: "Encoder Disk with dark and transparent segments", by electro-labs.com, is licensed under CC BY-NC-SA 4.0
Figure 8: Courtesy of Airbus
Figure 10a: Courtesy of Physikalisch-Technische Bundesanstalt (PTB)
Figure 10d: Courtesy of International Bureau of Weights and Measures (BIPM)