Consultative Committee for Length – CCL

WORKING GROUP ON MRA – WG-MRA

F. Meli, 13 November 2020

Guidance Document GD-2

Version 2.1

Comparison scheme applied in dimensional metrology

Document history

V1.0 This document was originally prepared for the WGDM meeting in 2009 by R. Thalmann

V2.0 Updated by R. Thalmann including linking issues for WG-MRA March 2020

V2.1 Updated external links and minor amendments by F. Meli, Nov. 2020

1. Introduction

The motivation to propose an alternative to the hierarchical scheme of CCL and RMO key comparisons is to overcome problems related to dimensional metrology comparisons and to improve the efficiency in the process to achieve mutual equivalence of calibration and measurement services delivered by NMIs. The described scheme has been introduced by WGDM some years ago, approved by CCL and was applied several times in key comparisons. It was, however, questioned by the CIPM, whether the rules of the MRA were fulfilled. The purpose of the present document is to get acceptance and to show, that CCL-RMO key comparisons can be conducted in such a way, that they are equivalent to the classical scheme of CCL and RMO key comparisons.

2. The characteristics of dimensional metrology comparisons

The issues related to dimensional metrology key comparisons as discussed below are certainly not unique and do - at least partly - also apply to other metrology fields. Therefore, the concept developed in the following chapter might find its application beyond the field of dimensional metrology.

- **Key comparison to support CMCs**
  All dimensional metrology KCs do not compare national standards, but test the principal techniques and the competence of participating laboratories, and thus provide the supporting evidence for their CMCs. The measurement uncertainties are several orders of magnitude larger than the uncertainty of the realisation of the metre. They compare measurement instruments and methods with the help of often multiple artefacts.
- **Artefact properties leading to systematic uncorrected errors**
  The artefacts used in different comparisons (CC or RMO) have different properties, have limited and usually unpredictable stability and not all NMIs can fully correct for artefact-based systematic errors. Therefore, a strict numerical linking by transferring a KCRV with its associated uncertainty from a primary to a secondary comparison is in most cases not appropriate.
- **Artefact stability**
  Star circulation schemes which are sometimes used to overcome the stability problem, exacerbate the damage of the artefacts and the cost for the pilot NMI, given the usually large number of participating laboratories.
- **Artefact cost**
  The artefacts are costly and they often get damaged during the comparisons. It therefore gets more and more difficult to find a pilot laboratory volunteering to donate such artefacts for a period of about three years.
- **Measurement capabilities**
  Due to the large differences in the level of claimed uncertainty and the large number of interested participating laboratories both, regionally and worldwide, it became necessary to run comparisons at different levels of uncertainties. Although CCL members are generally considered to be the most competent laboratories, this is not necessarily the case for all quantities and service categories.

- **Number of laboratories and equal status**
  CCL as well as EURAMET and APMP key comparisons usually attract a large number of laboratories. CCL has recognized that it would not be possible to allow all interested CCL members to participate in CCL comparisons. Instead it was stressed that RMO key comparisons can have equal status, which is not possible with a hierarchical numerical linking, where the KCRV together with its associated uncertainty is transferred from the CCL comparison to the RMO comparison. The propagation of the reference value uncertainty from CCL to RMO comparisons compromises the quality of the RMO comparison and thus tends to force highly qualified labs to participate at the CCL level, which leads to too many participants.

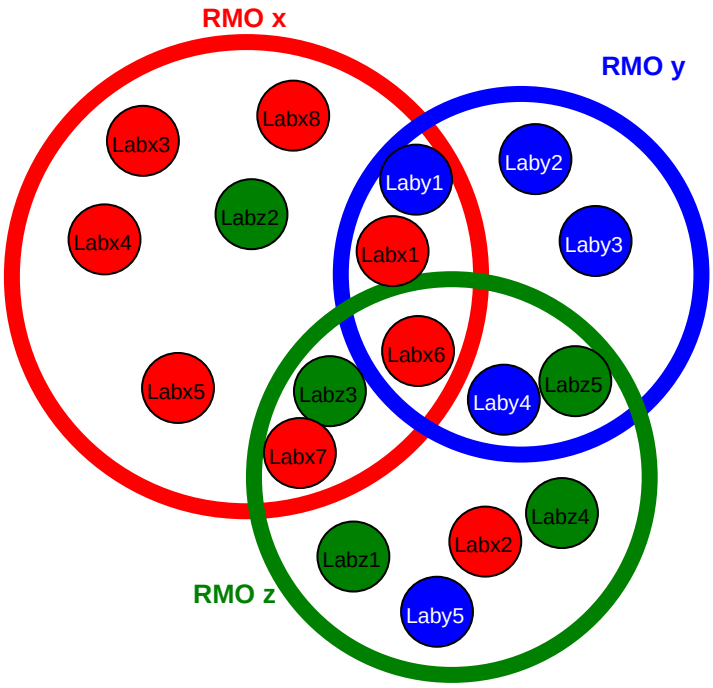
3. CCL-RMO key comparisons

3.1 The CCL-RMO key comparison scheme

As a practical, efficient solution to the problems described above, CCL has discussed and agreed to a new scheme of comparisons: CCL-RMO key comparisons follow the idea of several comparisons mutually linked together, without the necessity of a top-level comparison delivering a KCRV.

CCL-RMO comparisons are carried out in the following way (see graphical scheme):

- The key comparisons are organized by the RMOs, with participation across the regions, addressing the specific needs of the participating laboratories in terms of artefact choice and target uncertainty level.
- It is assured that common participation of at least **two competent laboratories** for any two comparisons provide a proper linking of the entire comparison scheme.
- The coordination of the regional KCs is carried out by the responsible working group of CCL, assuring that they are adequately distributed in time, be repeated at a frequency required for supporting the CMC claims, and that they can be linked.
- The classical scheme of CCL and RMO key comparisons can be considered a special case of the more general CCL-RMO scheme.
- By taking the subset of those laboratories having participated in more than one comparison for providing the link between the comparisons, a “virtual comparison” may be formed equivalent to the CCL key comparison in the classical scheme.



The proposed CCL-RMO comparison scheme offers the following advantages:

- It guarantees equal status of CCL and RMO comparisons.

- It provides more flexibility in grouping laboratories of different regions in order to achieve comparisons of similar size and to run comparisons with adequate artefacts at different levels of uncertainty. For example, two regional comparisons may be run at the same time with the same protocol, but at different levels of uncertainty, as it was done e.g. in EUROMET.L-K4.2005.
- It allows for an optimized and possibly reduced number of comparisons, and consequently requires lower expenses for purchasing suitable artefacts, less pilot laboratories and reduced workload for CCL members.
- The scheme with comparisons not restricted to individual RMOs but with inter-RMO participation gives more flexibility and more frequent opportunities for any laboratory to join a comparison when needed to support its CMCs.

3.2 Equivalence to classical scheme

In terms of linking laboratories within and across regions by calculation of their respective degrees of equivalence (DOE), the classical (hierarchical) and the CCL-RMO comparison scheme can be regarded to be equivalent. The linking of the comparisons is guaranteed by common participation of selected laboratories. It has to be noted, that the classical scheme with a CC comparison and numerically linked RMO comparisons is by far idealized in most cases: the linking is not simultaneous, but the time delay between the different comparisons is often very long, sometimes comparable to the repetition frequency of the KCs.

The concept of an overall key comparison reference value KCRV, however, must be abandoned in the CCL-RMO comparison scheme. In artefact based comparisons, where the principal measurement techniques related to the CMCs are tested and compared, the reference values are just best available values of specific, usually imperfect and non-stable artefacts, of different size and quality, but not values of national standards for the quantity of length. Hence, CCL-RMO comparisons provide degrees of equivalence for the declared CMCs with respect to comparison reference values, and through consistency of the different comparisons, they ensure that any laboratories worldwide being consistent with the comparison reference value are comparable.

CCL shall define quantities and realisations of the length units, where a KCRV is needed to ensure the equivalence of national standards, and for which key comparisons the CCL-RMO comparison scheme may be applied to ensure the equivalence of CMCs (see sect. 3.3).

CCL-K11 (MeP stabilized lasers) is a priori the fundamental comparison for the national standards of length. The definition of the key comparison reference value and the comparison scheme are described in a separate document [1] and follow a scheme similar to the CCL-RMO comparisons, involving regional nodes. The problem of linking these nodes still has to be addressed.

3.3 Linking comparisons by statistical consistency

The CCL WG-MRA has set up a task group on linking TG-L, whose term of reference is to "*work out appropriate ways of linking dimensional metrology key comparisons and* ***to support the DG moderators and KC pilots in linking the KCs****"*. The TG-L has developed, proposed and also applied different methods for linking the results of different comparisons. The application of these methods depends on the scheme of the comparisons, which are introduced earlier in this document and can be summarized as follows:

A. Classical, hierarchical scheme, which requires to choose one comparison as a primary to link the results of other (secondary) comparisons to the first one. This is typically the case for CIPM key comparisons considered to be "primary" and RMO key comparisons considered to be "secondary".

B. The comparisons to be linked are treated equally. This is typically the case for the CCL-RMO scheme, where RMO key comparisons are run in parallel with common participants of other RMOs. Also included in this scheme is the case, where within a comparison two loops are run in parallel and need to be linked.

The linking methods identified so far by CCL and considered to be sufficient for CIPM MRA length comparisons are:

1. Numerical linking: Propagating the key comparison reference value KCRV and its uncertainty from a higher level comparison (e.g. CIPM comparison) to a lower level comparison (e.g. RMO compar-

ison) through the results of laboratories having participated at both levels [2]. This requires a hierarchical comparison scheme A and measurands, which do not too much depend on artefact properties, ideally primary realisations of units and national standards.

2. Visual linking: The results are typically represented on a common graph of both comparisons to be linked, showing deviations from the key comparison reference value KCRV and their uncertainty, where the KCRV is determined in each comparison. The comparisons are considered to be linked, when the results of laboratories having participated in both comparisons are consistent with the respective KCRV. It is commonly accepted to have typically two or three common participants. This method may be applied to both comparison schemes A and B, however, in case of scheme A the CIPM and the RMO comparisons are considered on an equal basis in terms of the KCRV. Comparisons K1 and K8 were linked by this method [3, 4].

3. Distributed linking: The results of two simultaneous comparisons or two parallel loops of one comparison are linked by calculating for each comparison a separate reference value, influenced by the results of common participants in both comparisons, i.e. the KCRV in comparison (b) depends on the results of a common participant obtained in comparison (a) and vice versa [5]. This method is only applicable for comparisons schemes B and has been successfully applied in several CCL comparisons [6, 7].

4. References

[1] *Technical protocol for the CCL-K11 key comparison of optical frequency/wavelength standards*, https://www.bipm.org/kcdb/comparison?id=978 → CCL-K11 Technical Protocol

[2] Jennifer E Decker, A G Steele and R J Douglas, *Measurement science and the linking of CIPM and regional key comparisons*, Metrologia 45 (2008) 223–232

[3] *CCL Key comparison K8, Surface roughness standards, Ongoing report on linking the comparisons*, https://www.bipm.org/utils/common/pdf/CC/CCL/CCL-K8-linking-report.pdf

[4] *CCL Key comparison K1, Gauge blocks measured by interferometry, Ongoing report on linking the comparisons*

[5] Michael Krystek and Harald Bosse, *A Bayesian approach to the linking of key comparisons*, http://arxiv.org/abs/1501.07134

[6] Final Report EURAMET.L-K7.2006

[7] Final Report EURAMET.L-K4.2005

In summary:

- The concept of a KCRV which is transferred from a high level comparison to a lower level comparison is abandoned in those cases, where a KCRV would not represent a realisation of a unit, but is artefact dependent, and does thus not compare national standards.
- The concept of hierarchical CC and RMO comparisons is abandoned for some KC topics; instead, CCL-RMO key comparisons are carried out, linking in an ideal way the NMIs on a worldwide scale and providing equivalence and consistency of CMCs.
- Linking between comparisons can be made by rigorous statistical consistency tests or visually on a common graph, showing that common participant's results were consistent in both comparisons. Calculation of DoE is still done.