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Metrological Traceability at Different Measurement Levels

Oleh Velychko and Tetyana Gordiyenko

Abstract

The international agreements are the basis for establishing the global metrological traceability at different measurement levels. The concepts and concept relations around metrological traceability are presented. An important element of providing the metrological traceability is the evaluation of measurement uncertainty. The procedure of linking of key and supplementary comparison results is described. Linking of key and supplementary comparison results of the Regional Metrology Organization for some quantities according to the described procedure was presented. Results for all participants of presented key and supplementary comparisons are satisfactory for chi-square test and E_n number. The procedure of linking of key or supplementary comparison and national inter-laboratory comparison results is described. This procedure can be used for practical evaluation of specific inter-laboratory comparison results on a national level in different countries by means of laboratory results of the National Metrology Institute and Designated Institute. This procedure can contribute the mutual recognition of measurement and testing results by different countries. Linking of key comparison and inter-laboratory comparison results for some quantities according to the described procedure was presented. Results for all participants of presented key comparison and inter-laboratory comparison are satisfactory for chi-square test, E_n number, z scores and ζ scores.

Keywords: metrological traceability, measurement uncertainty, measurement standard, comparison, inter-laboratory comparison, National Metrology Institute, laboratory

1. Introduction

The Mutual Recognition Agreement (MRA) of the International Committee on Weights and Measures (CIPM) [1] and the MRA of the International Laboratory Accreditation Cooperation (ILAC) play an important role in overcoming technical barriers to international trade. CIPM MRA plays a key role in ensuring the international equivalence of national measurement standards of different countries. ILAC MRA plays a key role in ensuring international recognition of calibration results or test results in accredited calibration and testing laboratories. The main base of these agreements is special documents, guidelines, standards and recommendations [2].

National Metrology Institutes (NMIs) and Designated Institutes (DIs) play an important role in implementation of the CIPM MRA. They take an active part in organizing and conducting international comparisons of national standards.

Consultative Committees (CCs) of CIPM and the International Bureau of Weights and Measures (BIPM) carry out key comparisons (KCs) of national standards in different fields of measurements. KCs are also being carried out by Regional Metrology Organizations (RMOs), which are equivalent to CC KCs. Only RMO makes supplementary comparisons (SCs) for those measurements that are not covered by KC CC or RMO. Results of all comparisons of standards are published in a special database KC (KCDB) of BIPM [3].

For CC KC and RMO KC, the reference value (RV) of KC and degree of equivalence (DoE) of national standards with corresponding uncertainty are established [4, 5]. DoE derived from an RMO KC has the same status as that derived from a CC KC. RMO SC has the same status as RMO KC. RMOs have a procedure to carry out comparisons, but only the Euro-Asian Cooperation of National Metrological Institutions (COOMET) has guidelines on comparison data evaluation [6, 7].

According to results obtained by the NMI or DI (NMI/DI) in conducted comparisons, Calibration and Measurement Capabilities (CMCs) of NMI/DI are being prepared [8, 9]. The internationally recognized NMI CMCs are those that are published to the KCDB of BIPM. Metrological traceability [10] is important for industrial metrology, because it allows you to compare measurement accuracy in accordance with a standardized procedure for assessing measurement uncertainty [11].

ILAC publication [12] established the need to ensure a continuous calibration chain to international or national standards as the main element for establishing metrological traceability. Important roles for the implementation of this requirement are calibration laboratories (CLs).

Inter-laboratory comparisons (ILCs) are a form of experimental verification of accredited calibration and test laboratories. They must meet the requirements of international standards ISO/IEC 17025 [13] and ISO/IEC 17043 [14]. Their main goal is to determine the technical competence of accredited laboratories for specific activities. The purpose of the ILC is to establish the inter-laboratory differences of their participants. Successful laboratory results in ILC confirm technical competence for certain types of measurements or testing.

Establishment of measurement traceability at the highest metrological level is carried out in accordance with procedures through international comparisons of the national standards of NMI/DI. Establishment of metrological traceability at lower measurement level is carried out in accordance with the calibration procedures of working standards by both NMIs/DIs and accredited CLs.

For the highest level of the metrological traceability, it is advisable to develop a methodology for linking of results of RMO SC to RMO KC, and RMO SC to other RMO SC. For lower level of the metrological traceability, it is advisable to develop a methodology for linking of results of the national ILC to RMO KC or RMO SC. These methodologies can be used for practical assessment of results of specific RMO KC/SC as an extension of the technical basis of confirmation of NMI/DI CMC or specific ILC and at the national level in different countries using the comparison results and CMC NMIs/DIs.

2. Bases of metrological traceability

The concept of metrological traceability is important for industrial metrology and is associated with such basic metrological concepts as measurement result, calibration chain, and measurement uncertainty [10]. A partial concept diagram around metrological traceability is shown in **Figure 1**.

The concept diagram demonstrates associative relations of metrological traceability with metrological traceability chain, measurement result, measurement

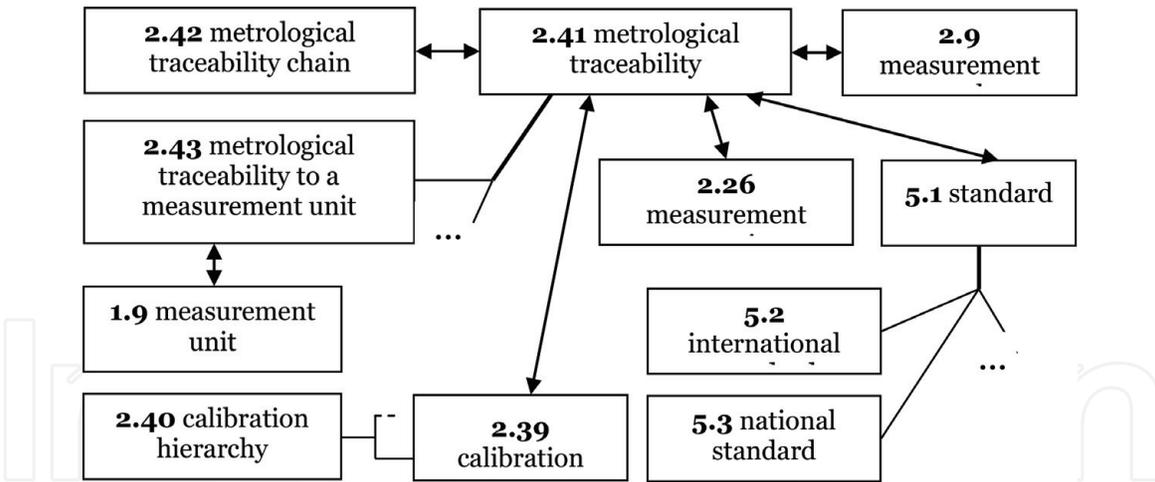


Figure 1.
 Partial concept diagram around metrological traceability.

uncertainty, standard, and calibration. Hierarchical generic relations of metrological traceability with a measurement unit and of standard with international standard and national standard are established. Hierarchical partitive relation of calibration hierarchy with calibration is also established.

At the modern stage of development of the industrial metrology, the role of NMIs/DIs and CLs increases significantly. This is due to the need to ensure mutual recognition of measurement results in different countries. Global metrological traceability at different measurement levels [15] is provided by the CIPM MRA and ILAC MRA. These agreements set out the basic requirements for ensuring mutual recognition of both measurements and testing.

The general scheme of global metrological traceability at different measurement levels is presented in **Figure 2**.

International comparisons of national standards of NMIs/DIs are carried out as part of activities of the CIPM consultative committees (CCs) and technical committees of six RMOs. Results of these comparisons are technical basis for the preparation of NMI/DI CMC for publication in KCDB of BIPM. Accredited CLs and testing laboratories participate at the national level in the ILCs as part of activities of

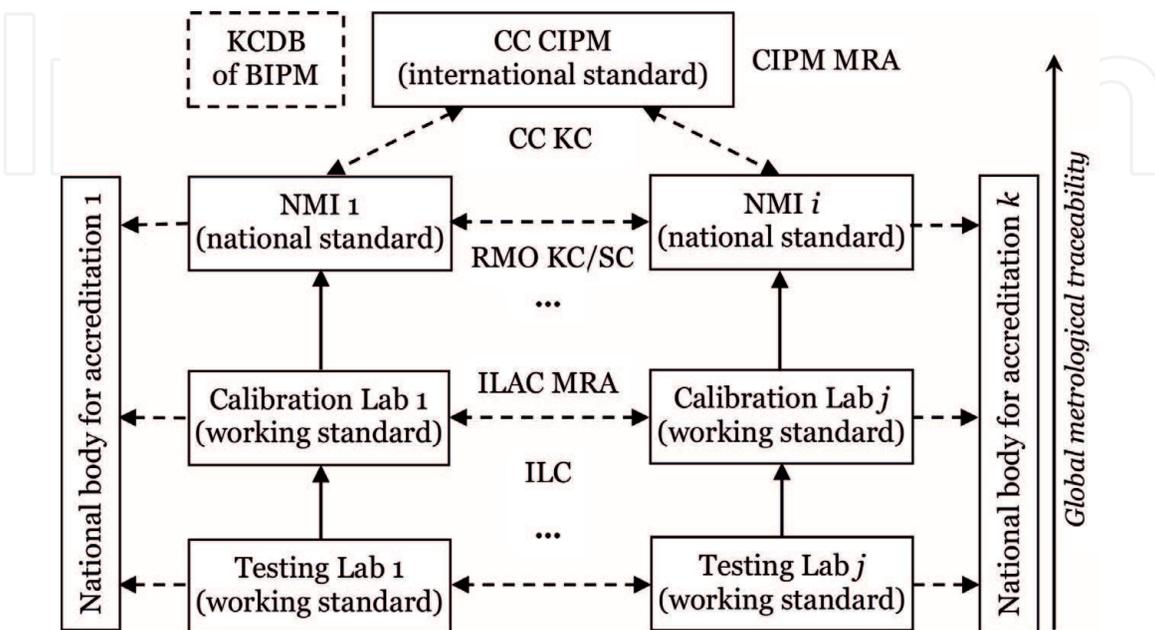


Figure 2.
 The general scheme of global metrological traceability at different measurement levels.

national accreditation bodies. The calibration hierarchy is provided by calibration of the working standards and MIs: CLs—for testing laboratories; NMIs/DIs—for CLs.

3. The data evaluation of standard comparisons

The diagram of concept relations for standard comparisons is shown in **Figure 3**. Besides to KCs and SCs, pilot comparisons are also carried out, which all these comparisons can be bilateral. The organization of CC KCs and RMO KCs/SCs is the responsibility of pilot laboratory (PL) whose functions are performed by one of the selected NMI/DI [4, 6, 7]. The main responsibilities of PL include development of technical protocol of comparison, selection, and research of traveling standard, and the development of draft comparison reports. Coordination of the entire work of the PL as part of comparison is carried out by the contact person of PL.

The organizational scheme of standard comparisons is shown in **Figure 4**. NMI 1 is PL and is responsible for organizing the delivery of traveling standard to NMI participants. This scheme can be circular or radial. In the second case, it is better to provide research of drift of the traveling standard. The most commonly used is a mixed comparison scheme: after several NMI/DI participants of comparison, a traveling standard returns to PL for research of their drift.

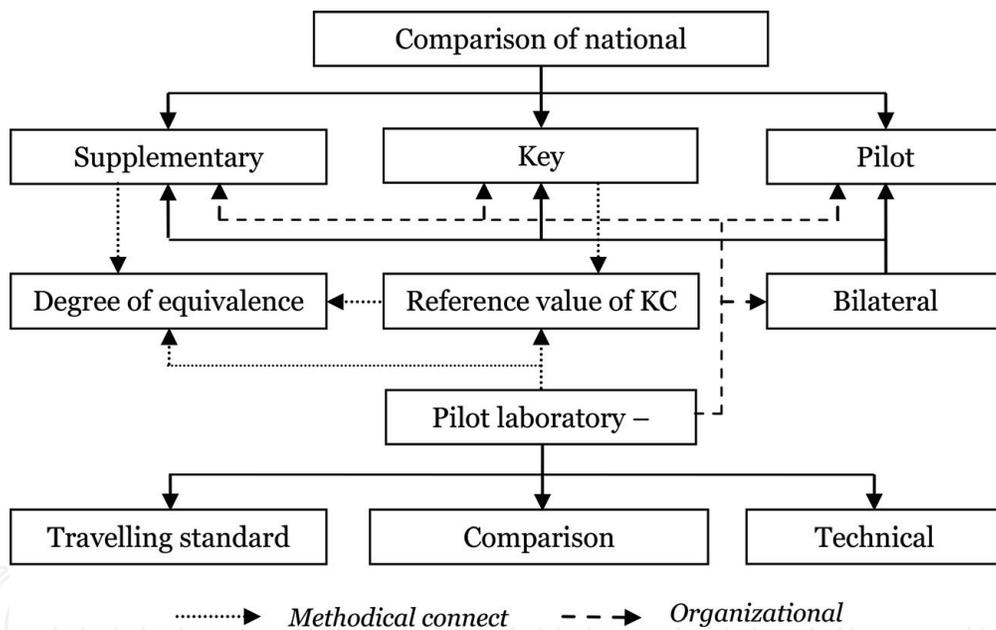


Figure 3.
The diagram of concept relations for standard comparisons.

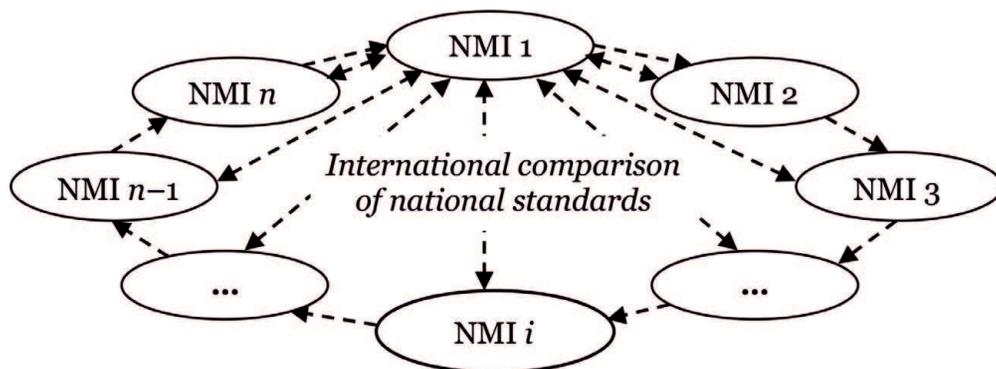


Figure 4.
The organizational scheme for standard comparisons.

RMO organizes KC with a number of joint NMI/DI participants with CC KC. This is necessary in order to link the results of the RMO KC with the results of the CC KC. For this purpose, equivalent technical protocols of both comparisons are used. The procedures for evaluating the data obtained at RMO KC are necessary to establish the DoE of national standards of NMI participants. PL calculates the KC RV and DoE for all NMI participants when preparing draft of comparison reports. The procedures used for evaluating RMO SC data are the same as for RMO KC. SC RMO complements KC CC or RM KC and is not second level comparison. RMO SC results are also published in KCDB of BIPM [16, 17].

RMO KC and RMO SC data evaluation usually includes determining the following characteristics: determining the RV comparison with the corresponding uncertainty, the DoE with corresponding uncertainties for each NMI/DI participant, and a pair DoE of i -th NMI/DI participant and j -th NMI/DI participant with corresponding uncertainties [6, 7]. RMO KC data evaluation includes the definition of such additional characteristics: converted KC data with corresponding uncertainties and DoE with corresponding uncertainties for each NMI/DI participant, except for linking NMI/DI.

The RMO KC/SC RV X_{RV} is calculated as the mean of NMI/DI participant results from RMO KC/SC data are given by

$$X_{RV} = \frac{\sum_{i=1}^n x_{NMIi}}{\sum_{i=1}^n 1} \quad (1)$$

with the combined standard uncertainty

$$u^2(X_{RV}) = 1 / \sum_{i=1}^n \frac{1}{u^2(x_{NMIi})}, \quad (2)$$

where x_{NMIi} is the result for i -th NMI/DI participant in RMO KC/SC; $u(x_{NMIi})$ is corresponding standard uncertainty for i -th NMI/DI participant in RMO KC/SC; $i = 1, 2, \dots, n$, n is the total number of NMI/DI participants of RMO KC/SC.

The DoE of i -th NMI/DI participant D_{NMIi} and corresponding combined standard uncertainty $u(D_{NMIi})$ are estimated as

$$D_{NMIi} = x_{NMIi} - X_{RV}, \quad (3)$$

$$u^2(D_{NMIi}) = u^2(x_{NMIi}) + u^2(X_{RV}). \quad (4)$$

Pairs of DoE of i -th NMI/DI participant and j -th NMI/DI participant D_{NMIij} of RMO KC/SC and corresponding combined standard uncertainty $u(D_{NMIij})$ are estimated as

$$D_{NMIij} = x_{NMIi} - x_{NMIj}, \quad (5)$$

$$u^2(D_{NMIij}) = u^2(x_{NMIi}) + u^2(x_{NMIj}). \quad (6)$$

On the basis of the measurement results of RMO KC/SC and corresponding combined standard uncertainties claimed by NMI/DI participants of RMO KC/SC, the chi-square test value is calculated [7].

$$\chi^2 = \sum_{i=1}^n \frac{D_{NMIi}^2}{u^2(x_{NMIi})}. \quad (7)$$

If the calculated chi-criterion value does not exceed the chi-square test critical value with the coverage level of 0.95 and freedom degrees of $n - 1$

$$\chi^2 < \chi_{0.95}^2(n - 1), \quad (8)$$

then data can be acknowledged as consistent. This is the objective confirmation of declared uncertainties.

The NMI/DI participants of RMO KC/SC that provides maximum E_n number are determined [7].

$$\max_i E_n = \frac{|D_{NMIi}|}{2\sqrt{u^2(x_{NMIi}) - u^2(X_{RV})}}. \quad (9)$$

Then the data of NMI/DI participants with the largest value of E_n number are temporarily excluded from consideration, and the procedure for checking of consistency of the comparison data is repeated. Sequential data exclusion is repeated until the condition (8) is fulfilled.

The State Enterprise “Ukrmetrteststandard” (UMTS) was PL of several COOMET KCs and SCs in the field of electricity and magnetism (EM) in 2005–2018. UMTS as PL prepared and agreed with all NMI/DI participants draft reports on comparison COOMET.EM-K4, COOMET.EM-K5, COOMET.EM-K6.a, COOMET.EM-S2, COOMET.EM-S4, COOMET.EM-S13, COOMET.EM-S14, which comparison results are published in the KCDB of BIPM.

COOMET.EM-K4 comparison of national standards of a nominal capacitance of 10 pF at frequencies of 1000 and 1593 Hz was organized UMTS and carried out in 2005–2009. KV of COOMET.EM-K4 is $X_{KV} = -0.13 \mu\text{F}/\text{F}$ at a frequency of 1000 Hz, and corresponding combined standard uncertainty is $u(X_{KV}) = 0.22 \mu\text{F}/\text{F}$ ($k = 2$ for coverage level of 0.95). DoE for NMI/DI participants of COOMET.EM-K4 comparison for a nominal capacitance of 10 pF at a frequency of 1000 Hz [18] is shown in **Figure 5**.

Results of COOMET.EM-K4 comparison for a nominal capacitance of 10 pF at a frequency of 1000 Hz were checked for the fulfillment of the chi-square test. The obtained value of the chi-square test for all NMI/DI participants can be considered consistent, since the condition of expression (8) is satisfactory ($\chi^2 = 0.68 < \chi_{0.95}^2(n - 1) = 1.15$). The same results of COOMET.EM-K4

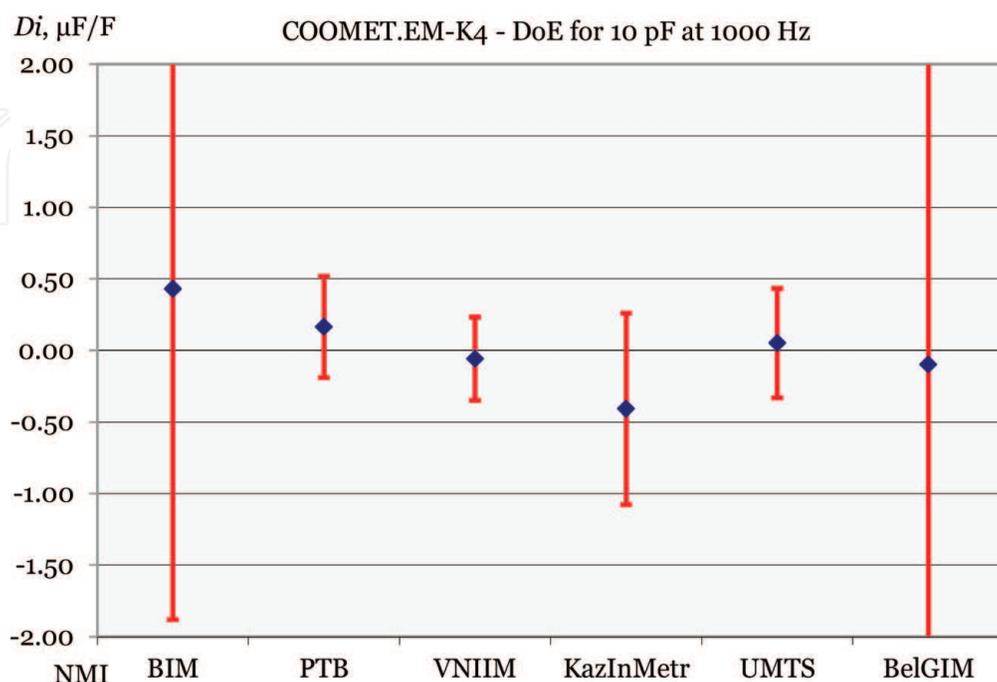


Figure 5.
DoE for NMI/DI participants of COOMET.EM-K4 comparison.

comparisons for all NMI/DI participants were checked for E_n number using Eq. (9). The resulting E_n number values for all NMI/DI participants do not exceed the value 1.0.

Results for the NMI/DI participants of COOMET.EM-K4 comparison are shown in **Table 1** for a nominal capacitance of 10 pF at a frequency of 1000 Hz.

COOMET.EM-K6.a comparison of AC voltage of 3 V at frequency of 20 kHz at frequencies of 1, 20, 100, and 1 MHz was organized UMTS and carried out in 2013–2014. KV of COOMET.EM-K6.a of AC/DC voltage transfer of AC voltage of 3 V at frequency of 20 kHz is $X_{KV} = -2.0 \mu\text{V/V}$, and corresponding combined standard uncertainty is $u(X_{KV}) = 1.9 \mu\text{V/V}$ ($k = 2$ for coverage level of 0.95). DoE for NMI/DI participants of COOMET.EM-K6.a comparison for AC voltage of 3 V at frequency of 20 kHz [19] is shown in **Figure 6**.

Results of COOMET.EM-K6.a comparison of AC/DC voltage transfer of AC voltage of 3 V at a frequency of 20 kHz were checked for the fulfillment of the chi-criterion. The obtained value of the chi-square test for all NMI/DI participants can be considered consistent, since the condition of expression (8) is satisfied ($\chi^2 = 0.64 < \chi_{0.95}^2(n - 1) = 0.71$ without INM data). The same results of COOMET.EM-K6.a comparisons for all NMI/DI participants were checked for E_n number using Eq. (9). The resulting E_n number values for all NMI/DI participants do not exceed the value 1.0.

Results for the NMI/DI participants of COOMET.EM-K6.a comparison are shown in **Table 2** for AC/DC voltage transfer of AC voltage of 3 V at a frequency of 20 kHz.

CMC [8] has three unambiguous characteristics: measurand, measurement range, and measurement uncertainty (generally given at a confidence level of 0.95).

NMI	BIM	PTB	VNIIM	KazInMetr	UMTS	BelGIM
$D_{NMI}, \mu\text{F/F}$	0.43	0.16	-0.06	-0.41	0.05	-0.10
$u(D_{NMI}), \mu\text{F/F}$	1.16	0.18	0.15	0.33	0.19	1.09
E_n	0.19	0.46	0.20	0.61	0.13	0.05

Table 1.
 Results for NMI/DI participants of COOMET.EM-K4 comparison.

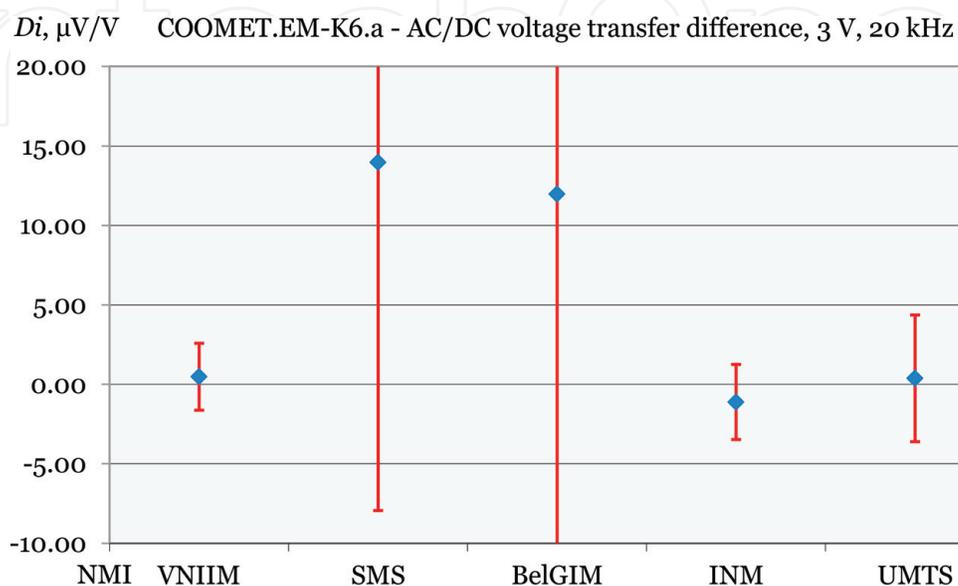


Figure 6.
 DoE for NMI/DI participants of COOMET.EM-K6.a comparison.

NMI	VNIIM	SMS	BelGIM	INM	UMTS
$D_{NMI}, \mu V/V$	0.48	13.98	11.98	-1.12	0.38
$u(D_{NMI}), \mu V/V$	1.05	10.96	14.47	1.19	2.00
E_n	0.23	0.64	0.41	0.47	0.10

Table 2.

Results for NMI/DI participants of COOMET.EM-K6.a comparison.

They also contain a description of the used method or used measuring system, values of influence parameters, and any other relevant information. Normally for CMC, there are four ways in which a complete statement of uncertainty may be expressed: measurement range, equation, fixed measurand, and a matrix of measurement uncertainties.

CMC must be consistent with information from some or all of the following sources: results of KC and SC, knowledge of technical activities by other NMIs/DIs, including publications, other available knowledge and experience, etc. Results of RMO KCs/SCs are the ideal supporting evidence, but they can be used for fixed measurand only.

Methodologies for estimating the measurement uncertainty in a wide range of capacitance from 10 pF to 10 nF at frequencies of 1000 Hz and 1592 Hz and of inductance from 10 μ H to 10 Hz at 1000 Hz are described in [20, 21], respectively. In these methodologies, requirements of both GUM [11] and regional recommendation [22] are used.

4. Linking procedures for international comparisons

Only CC KC results have a KC RV. Through joint NMI/DI participants, RMO KC must be linked to corresponding CC KC. The complete results of the linked RMO KC are presented in exactly the same form as the corresponding CC KC in KCDB of BIPM [4].

DoE of i -th NMI/DI participant of RMO KC is estimated as

$$d_{NMIi} = D_{NMIi} + \Delta, \quad (10)$$

where D_{NMIi} is result for NMI/DI participant from RMO KC only; d_{NMIi} is result for i -th NMI/DI participant which is linked to CC KC.

The correction factor for i -th linking NMI/DI is estimated as

$$\Delta_{iLink} = d_{iLink} - D_{iLink} \quad (11)$$

where d_{iLink} is result for i -th linking NMI/DI from CC KC; D_{iLink} is result for i -th linking NMI/DI from RMO KC.

The total correction factor Δ is then calculated as the weighted mean of the correction factor for linking NMI/DI participants, that is:

$$\Delta = \sum_{iLink}^k w_{iLink} \Delta_{iLink}, \quad (12)$$

$$w_{iLink} = \frac{s^2(\Delta)}{s^2(\Delta_{iLink})}, \quad (13)$$

$$s^2(\Delta) = 1 / \sum_{iLink}^k \frac{1}{s^2(\Delta_{iLink})}. \quad (14)$$

The standard uncertainty $s(\Delta_{iLink})$ associated with Δ_{iLink} is calculated by the root-sum-square of the transfer standard uncertainty in CC KC: u_T is transfer standard uncertainty in RMO KC; $u(p_i)$ is standard uncertainty associated with the imperfect reproducibility of results of NMI_{iLink} in time period spanning two measurements; r_{iLink} is uncertainty associated with the imperfect reproducibility of measurement results of NMI_{iLink} in time period spanning its two measurements in CC KC and RMO KC; $i = 1, 2, \dots, k$, k is total number of linking NMIs/DIs.

Table 3 lists the quantity values used in calculation linking total correction factor Δ and corresponding standard deviation $s(\Delta)$ for CCEM-K4 and COOMET.-EM-K4 comparisons for nominal capacitance 10 pF at a frequency of 1592 Hz [18].

The combined standard uncertainty is calculated as:

$$u^2(d_{NMIi}) = u^2(D_{NMIi}) + u^2(\Delta) = u^2(D_{NMIi}) + s^2(\Delta) + u^2(X_{RV}), \quad (15)$$

where $u(X_{RV})$ is combined standard uncertainty in CC KC RV.

The expanded uncertainty is $U(d_{NMIi}) = ku(d_{NMIi})$ which is chosen $k = 2$ for a coverage level of 0.95.

An example of linking of EUROMET.EM-K4, APMP.EM-K4.1, and COOMET.-EM-K4 results to the CCEM-K4 results for nominal capacitance of 10 pF at frequency 1592 Hz [18, 23, 24] is shown in **Figure 7**. When linking results of those comparisons, the presented linking procedure was used.

Results of EUROMET.EM-S26 comparison have been linked to EUROMET.EM-S20 comparison (two RMO SCs for an inductance of 100 mH at frequency

Linking NMI	d_{iLink}	D_{iLink}	Δ_{iLink}	u_T	$u(p_i)$	r_{iLink}	$s(\Delta_{iLink})$	w_{iLink}	Δ	$s(\Delta)$
VNIIM	-0.12	-0.10	-0.02	0.02	0.08	0.07	0.16	0.49	0.11	0.11
PTB	-0.00	-0.17	0.17	0.02	0.08	0.07	0.15	0.51		

Table 3.
 CCEM-K4 and COOMET.EM-K4 data for linking NMIs, $\mu F/F$.

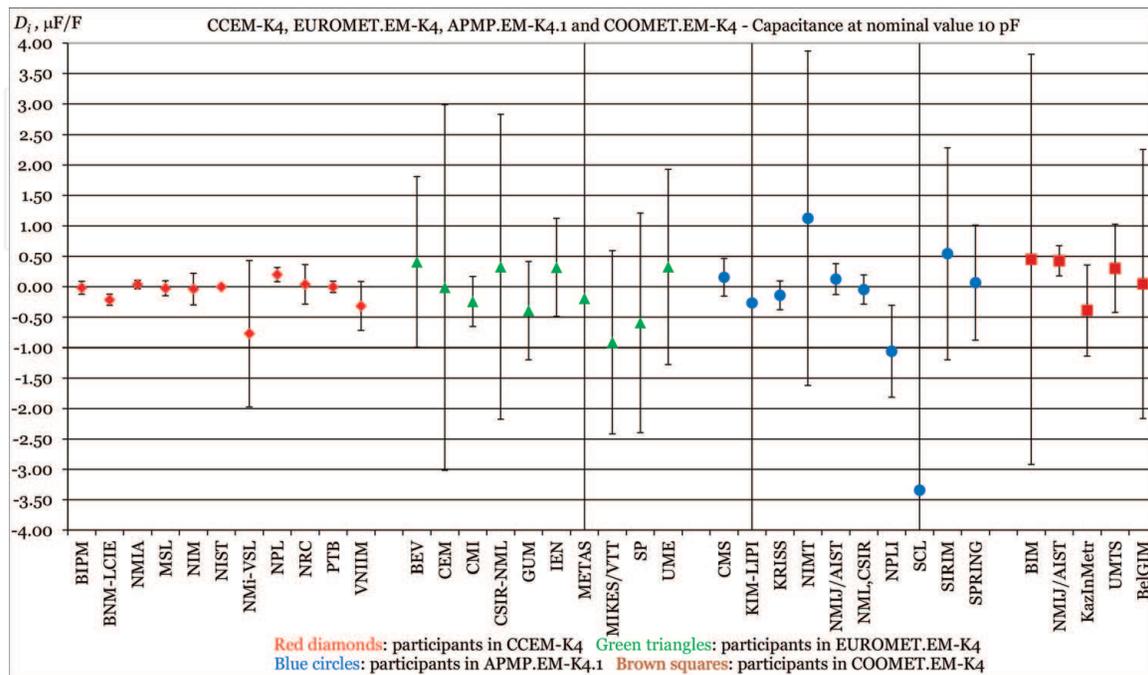


Figure 7.
 Corrected DoE for participants of CCEM-K4, EUROMET.EM-K4, APMP.EM-K4.1, and COOMET.EM-K4 comparisons.

1000 Hz) with used special linking procedure [25] which is similar to the described linking procedure. Results of COOMET.EM-S2 comparison have been linked to EURAMET.EM-K5.1 comparison for electrical power [26]; results of COOMET.EM-S1 comparison have been linked to COOMET.EM-K6.a comparison of AC/DC voltage transfer difference [27] (RMO SC to RMO KC for similar values of physical quantities). When linking results of those comparisons, the described linking procedure was used.

Table 4 lists data for calculated total correction factors Δ and corresponding combined standard uncertainties $u(\Delta)$ for linking of COOMET.EM-S1 comparison results to COOMET.EM-K6.a comparison results for AC voltage of 3 V at frequencies of 1 kHz, 20 kHz, and 100 kHz [19], where X_{K6aKV} is COOMET.EM-K6.a RV; $u(X_{K6aKV})$ is combined standard uncertainty of COOMET.EM-K6.a RV.

Linked results of COOMET.EM-S1 (mark *) and COOMET.EM-K6.a comparison of AC/DC voltage transfer difference of AC voltage of 3 V at frequencies of 1, 20, and 100 kHz [27] are shown in **Figure 8**. When linking results of those comparisons, the presented linking procedure was used.

For consistency verification of results of COOMET.EM-K6.a and COOMET.EM-S1 comparisons, the value of chi-square test was calculated. The obtained value of chi-square test for all participants can be considered consistent: $\chi^2 = 0.58 < \chi_{0.95}^2(n - 1) = 0.71$ (without VNIIM result) at frequency 1 kHz; $\chi^2 = 0.46 < \chi_{0.95}^2(n - 1) = 0.71$ at frequency 20 kHz; and $\chi^2 = 0.49 < \chi_{0.95}^2(n - 1) = 0.71$ (without VNIIM result) at frequency 100 kHz.

The maximum E_n number and declared uncertainties for DoE of NMI/DI participants of COOMET.EM-K6.a and COOMET.EM-S1 comparisons are judged as

Frequency	X_{K6aKV}	$u(X_{K6aKV})$	Δ	$u(\Delta)$
1 kHz	0.30	0.85	-0.60	1.15
20 kHz	-2.00	0.95	1.70	1.30
100 kHz	-6.80	1.70	5.60	1.85

Table 4.

Data for linking of COOMET.EM-S1 comparison results to COOMET.EM-K6.a comparison results, $\mu V/V$.

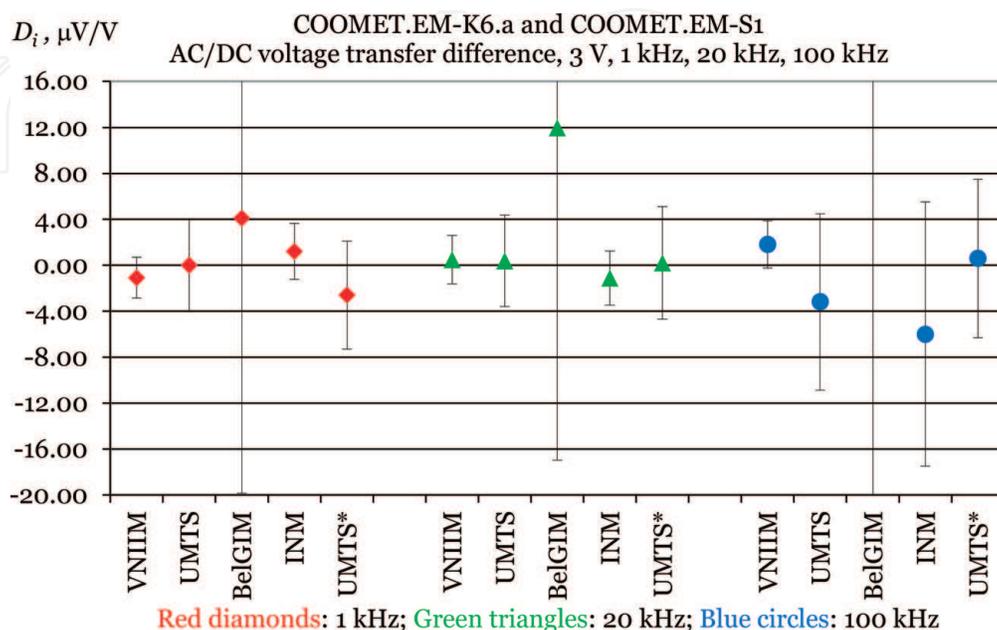


Figure 8.

Corrected DoE for participants of COOMET.EM-K6.a and COOMET.EM-S1 comparisons.

NMI	VNIM	UMTS	BelGIM	INM	UMTS*
1 kHz					
$D_{NMI}, \mu\text{V/V}$	-1.10	0.00	4.10	1.20	-2.60
$u(D_{NMI}), \mu\text{V/V}$	0.90	2.02	11.97	1.22	2.35
E_n	0.28	0.00	0.17	0.28	0.44
20 kHz					
$D_{NMI}, \mu\text{V/V}$	0.48	0.38	11.98	-1.12	0.20
$u(D_{NMI}), \mu\text{V/V}$	1.06	2.00	14.47	1.19	2.45
E_n	0.11	0.07	0.41	0.26	0.03
100 kHz					
$D_{NMI}, \mu\text{V/V}$	1.81	-3.19	25.80	-5.99	0.60
$u(D_{NMI}), \mu\text{V/V}$	1.03	3.84	69.50	5.75	3.45
E_n	0.28	0.32	0.19	0.46	0.06

Table 5.
 Results for NMI/DI participants of COOMET.EM-K6.a and COOMET.EM-S1.

confirmed by Eqs. (8) and (9) accordingly. Results for NMI/DI participants of COOMET.EM-K6.a and COOMET.EM-S1 comparisons are satisfactory (Table 5).

5. The data evaluation of national inter-laboratory comparisons

A number of studies are devoted to urgent questions of the data evaluation of ILC: the use of different methods for inconsistent data evaluation of ILC discussed in [28], suggested approaches to verifying the reliability of measurement results for CL participations of ILC [29], the application of z score test for performance evaluation of CLs recommended instead of E_n number since this number is not applicable due to the difficulty in determining the assigned value (AV) [30], algorithms for conducting ILC and obtaining precision data for CMC evaluation of laboratories are considered in [31–33], etc.

The general scheme of ILC is shown in Figure 9. Lab 1 is reference laboratories (RLs) of ILC. This scheme can be either circular or radial. Most often, a mixed

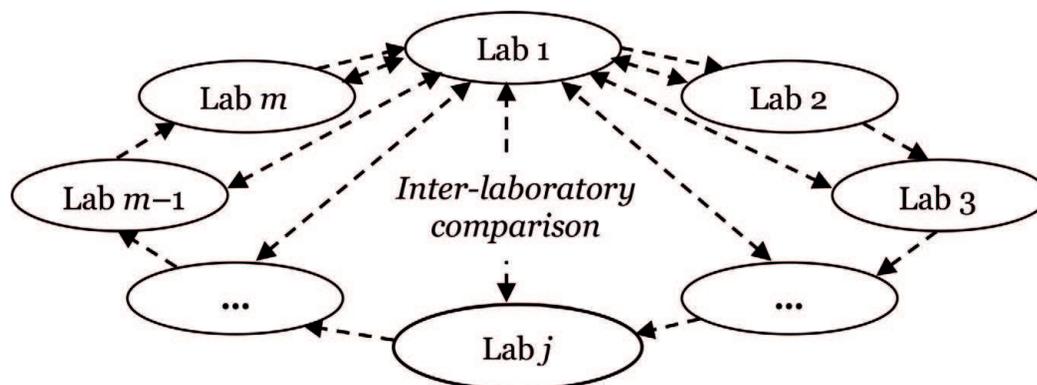


Figure 9.
 The organizational scheme for ILCs.

scheme of ILCs is used: after several Lab participants, the traveling standard is returned to RL for research of its drift.

ILCs based on fundamental requirements: the repeatability and instability of traveling standard. Main steps common to nearly all ILCs are: the determination of AV, the calculation of performance statistics, the evaluation of performance, and the preliminary determination of ILC traveling standard stability [14].

The RL processes the data received from CL participants according to results of ILC for CL. Verification of ILC data is required for consistency. In the case of uncoordinated data, an analysis is conducted for the purpose of rejecting these data or for further harmonization by correction of the applied indicators. To verify the consistency of data, comparative analyses of the relevant criteria for performance statistics are carried out and the most effective for use in processing of the data is selected [14, 34].

There are various procedures available for the establishment of AV. These procedures involve the use of, in particular AVs—as determined by analysis, the measurement or standard comparison, traceable to a national or an international standard. The general algorithm for data evaluation of ILC is described in [35]. This algorithm allows RL to take into account all the reporting features of ILC.

The laboratory difference D_{labj} for j -th CL participant of ILC is calculated using Equation [14, 35, 36].

$$D_{labj} = x_{labj} - X_{AV}, \quad (16)$$

where x_{labj} is the measured value for i -th CL; X_{AV} is AV which is determined by RL. The percent laboratory difference $D_{\%labj}$ for ILC is calculated using equation

$$D_{\%labj} = [D_{labj}/X_{AV}] \cdot 100. \quad (17)$$

The criteria for performance evaluation will be established after taking into account whether methods for evaluating the performance characteristics consider the main features, namely: the statistical determination of indicators, i.e. when the criteria must be suitable for each indicator; the compliance with the purpose, given criteria that take into account, for example, technical specifications for characteristics of method and recognized level of participant studies, etc. [14].

The most often to check consistency of ILC data that uses E_n number which is calculated using equation

$$E_n = D_{labj} / \sqrt{U^2(x_{labj}) - U^2(X_{AV})}, \quad (18)$$

where $U(x_{labj})$ is the expanded uncertainty of a participant's result; $U(X_{AV})$ is the expanded uncertainty of RL's AV.

For an E_n number:

$|E_n| \leq 1.0$ indicates satisfactory performance;

$|E_n| > 1.0$ indicates unsatisfactory performance.

For checking consistency of ILC data, a z scores is also used, which is calculated by the equation

$$z = D_{labj} / \sigma, \quad (19)$$

where σ is the standard deviation for qualification assessment.

The value of σ can be calculated based on [14]: estimates from a statistical model (main model) or results of a precision experiment, estimates from previous ILC rounds or assumptions based on experience, results of participating laboratories,

that is, normal or robust standard deviation, based on the results of ILC participating laboratories, etc.

For checking consistency of the ILC data, a ζ scores is used, which is calculated by the equation

$$\zeta = D_{labj} / \sqrt{u^2(x_{labj}) - u^2(X_{AV})} \quad (20)$$

where $u(x_{labj})$ is the combined standard uncertainty associated with result of the laboratory participating in the ILC; $u(X_{AV})$ is the combined standard uncertainty of ILC AV.

For a z scores and a ζ scores:

$|z| \leq 2.0$ and $|\zeta| \leq 2.0$ indicate a satisfactory performance characteristic and do not require adjustment or response measures;

$2.0 < |z| < 3.0$ and $2.0 < |\zeta| < 3.0$ indicate a dubious performance characteristic and require precautionary measures;

$|z| \geq 3.0$ and $|\zeta| \geq 3.0$ indicate an unsatisfactory performance characteristic and require adjustment or response measures.

Obvious blunders, such as those with incorrect units, decimal point errors, and results for a different ILC item will be removed from the data set and treated separately. These results will not be subject to outlier tests or robust statistical methods. If results are removed as outliers, they will be removed only for calculation of summary statistics. These results should still be evaluated within ILC scheme and be given the appropriate performance evaluation [35].

The value of expanded uncertainty $U(X_{AV})$ is estimated as

$$U(X_{AV}) = 2 \cdot \sqrt{u^2(x_{ref}) + u^2(x_{stab})}, \quad (21)$$

where $u(x_{ref})$ is the standard uncertainty obtained by calibrating traveling standard with a RL; $u(x_{stab})$ is the standard uncertainty from the instability of traveling standard during ILC period.

The value of standard uncertainty $u(x_{stab})$ is estimated as

$$u(x_{stab}) = \Delta X_{\max} / \sqrt{3}, \quad (22)$$

where ΔX_{\max} is the maximum change in nominal value of traveling standard during ILC period.

Linking the correspondingly expanded uncertainties of AV U_{AV} when RL of ILC are NMIs, accredited by CLs or accredited RLs that are not NMIs or accredited by CLs, is as follows [36]:

$$U_{AV \text{ NMI}} < U_{AV \text{ CL}} < U_{AV \text{ RL}}, \quad (23)$$

that is, the most accurate ILCs are those that are performed by NMIs.

The value of the expanded uncertainty $U_{AV \text{ NMI}}$ for a case where the NMI is RL can be derived from results of corresponding international comparisons of national standards in which the NMI participated. The value of the expanded uncertainty $U_{AV \text{ CL}}$ for a case where CL is RL can be derived from corresponding calibration certificates for working standards issued by the NMI using CL in ILC. The value of the expanded uncertainty $U_{AV \text{ RL}}$ for a case where an RL is an accredited provider can be obtained from corresponding calibration certificates for working standards issued by accredited CLs that use RLs in ILC.

An example of the laboratory difference D_{lab} of lab participants for national ILC of AC/DC voltage transfer difference of AC voltage of 3 V at a frequency of 20 kHz

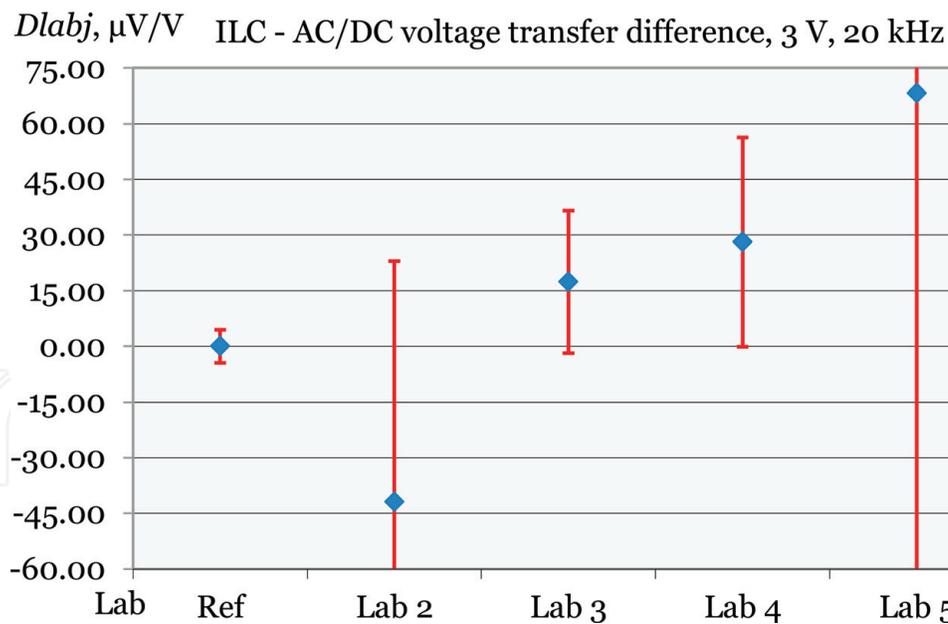


Figure 10.
Results of national ILC for AC/DC voltage transfer difference.

Lab	Ref	Lab 2	Lab 3	Lab 4	Lab 5
D_{lab} , $\mu\text{V}/\text{V}$	0.00	-42.00	17.40	28.10	68.20
$u(D_{lab})$, $\mu\text{V}/\text{V}$	2.25	32.50	9.60	14.10	1570.00
E_n	0.00	0.65	0.91	0.99	0.02
z	0.00	1.04	0.43	0.70	1.69
ζ	0.00	0.32	0.45	0.50	0.01

Table 6.
Results for all lab participants of ILC.

with respect to the AV with expanded uncertainty $U(D_{lab})$ [37] is shown in **Figure 10**.

For verification of consistency of the ILC results, the value of chi-square test was calculated. The obtained value of chi-square test for lab participants can be considered consistent: $\chi^2 = 2.52 < \chi_{0.95}^2(n-1) = 2.73$ (without Lab3 and Lab 4 results). Results for lab participants of ILC are satisfactory (**Table 6**).

6. Linking procedures for international comparisons and national inter-laboratory comparisons

ILCs for CLs are carried out in different countries. To ensure the mutual recognition of calibration results, it is advisable to establish the relationship between these ILCs. To do this, NMI/DI results of international standard comparisons can be used. In this case, the DoE of NMI/DI standards and their uncertainty may be taken into account. Thus, it is possible to establish the metrological traceability of CL standards to corresponding national standards.

The organizational scheme of linking of international standard comparison and national ILC is shown in **Figure 11**. The Lab 1 is RL for ILC which is also i -th NMI for RMO KC/SC.

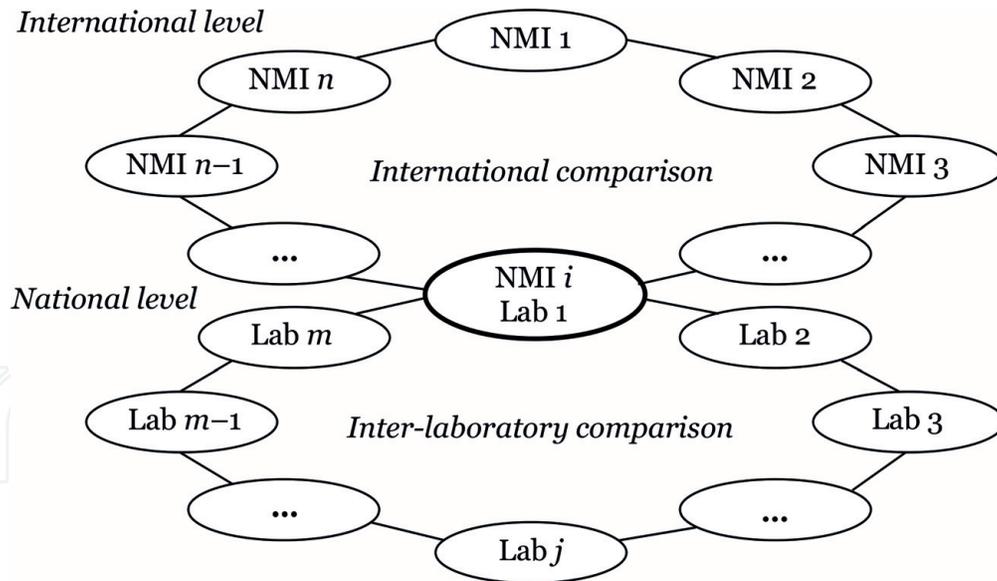


Figure 11.
 The organizational scheme for linking of RMO KC/SC and national ILC.

In [38], the proposed procedure links RMO KC/SC and ILC results for CL. This procedure can be used for practical estimation of specific ILC results on a national level in different countries by means of NMIs/DIs results from RMO KC/SC.

The result of i -th NMI in some specific RMO KC/SC can be determined for linking in a specific ILC. Results of ILC will be expressed in relation to specific RMO KC/SC RV through linking laboratory—RL. For this purpose, the laboratory difference of ILC D_{labj} will be corrected by a correction factor d_{lab} , which is determined from the results of participant Lab 1 (RL) in RMO KC/SC and ILC (Lab 1 – NMI i):

$$d_{lab} = D_{NMIi} - D_{lab1} \quad (24)$$

with the combined standard uncertainty:

$$u^2(d_{lab}) = [u^2(D_{NMIi}) + u^2(D_{lab1})]/2. \quad (25)$$

The corrected DoE for j -th lab participant in ILC with respect to linking to RMO KC/SC RV is estimated as

$$D'_{labj} = D_{labj} + d_{lab} \quad (26)$$

with the combined standard uncertainty:

$$u^2(D'_{labj}) = u^2(D_{labj}) + u^2(d_{lab}) \quad (27)$$

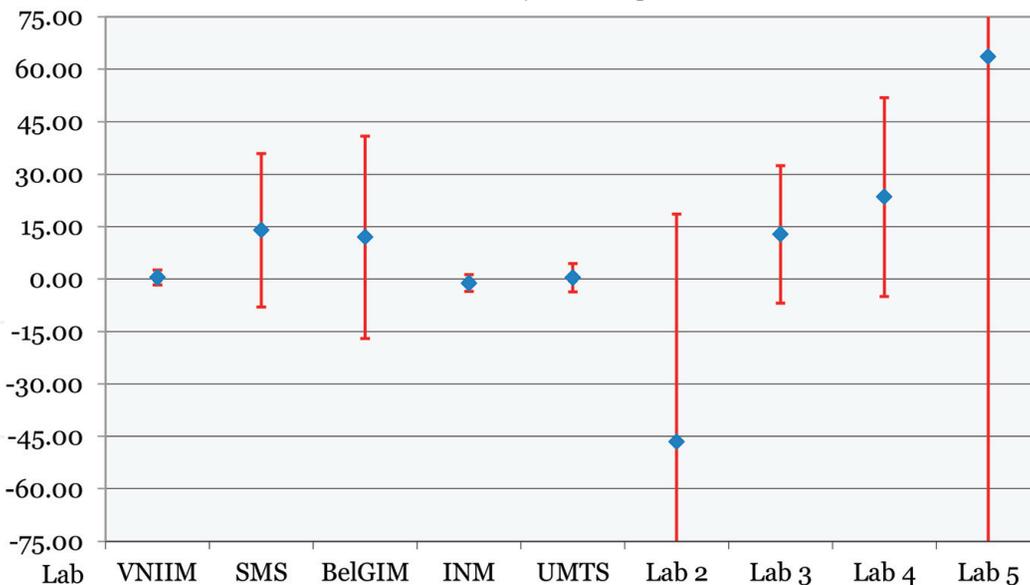
The values of E_n number is determined by the equation

$$E_{nlabj} = |D'_{labj}|/U(D'_{labj}) \leq 1.0. \quad (28)$$

The values of z scores is determined by the equation

$$z_{labj} = |D'_{labj}|/\sigma_{lab} < 2.0, \quad (29)$$

where σ_{lab} is the standard deviation, based on the results of ILC participating laboratories.

D_{labj} , $\mu\text{V}/\text{V}$ COOMET.EM-K6a - ILC for AC/DC voltage transfer difference, 20 kHz**Figure 12.**

The corrected laboratory difference for lab participants of national ILC for AC/DC voltage transfer standards with respect to linking to COOMET.EM-K6.a.

NMI-Lab	VNIIM	SMS	BelGIM	INM	UMTS	Lab 2	Lab 3	Lab 4	Lab 5
D'_{lab} , $\mu\text{V}/\text{V}$	0.50	14.00	12.00	-1.10	0.40	-46.60	12.80	23.50	63.60
$u(D'_{lab})$, $\mu\text{V}/\text{V}$	1.05	10.95	14.45	1.20	2.00	32.50	9.85	14.20	157.00
E_n	0.23	0.64	0.41	0.47	0.10	0.72	0.65	0.83	0.20
z	0.02	0.49	0.42	0.04	0.01	1.62	0.45	0.82	2.22
ζ	0.11	0.32	0.21	0.24	0.05	0.36	0.33	0.41	0.10

Table 7.

Results for all NMI/DI and lab participants.

The values of ζ scores is determined by the equation

$$\zeta_{labj} = |D'_{labj}|/u(D'_{labj}) < 2.0. \quad (30)$$

An example of the corrected laboratory difference D'_{lab} of lab participants for national ILC of AC/DC voltage transfer difference of AC voltage of 3 V at a frequency of 20 kHz with respect to linking to COOMET.EM-K6.a with expanded uncertainty [38] is shown in **Figure 12**. When linking results of those comparisons, the presented linking procedure was used.

For verification of consistency of COOMET.EM-K6.a and ILC results, the value of chi-square test was calculated. The obtained value of chi-square test for lab participants can be considered consistent: $\chi^2 = 0.71 < \chi_{0.95}^2(n-1) = 0.42$. Results for all NMI/DI and lab participants are satisfactory (**Table 7**).

7. Conclusions

CIPM MRA and ILAC MRA are the basis for establishing the global metrological traceability and play an important role in overcoming technical barriers to international trade. The calibration hierarchy and measurement uncertainty evaluation are

important elements of providing metrological traceability. The general scheme of the global metrological traceability at different measurement levels is presented. NMIs/DIs and accredited CLs play an important role in establishing those traceability.

The organizational scheme for standard comparisons and RMO KC and RMO SC data evaluation procedure is presented. Results of data evaluation for COOMET.-EM-K4 and COOMET.EM-K6.a comparisons are indicated. Results of those comparisons were checked for the fulfillment of the chi-square test. The obtained values of the chi-square test for NMI/DI participants are satisfactory. Results for all NMI/DI participants of those comparisons for E_n number are also satisfactory.

The procedure of linking of RMO KC and RMO SC results is presented. Linking of COOMET.EM-S1 and COOMET.EM-K6.a comparison results of AC/DC voltage transfer difference at different frequencies is presented. The value of chi-criterion for linked comparison results was calculated. The obtained value of chi-square test for NMI/DI participants of those comparisons is satisfactory. Results for all NMI/DI participants of those comparisons for E_n number (from 0.03 to 0.46) are also satisfactory.

Results of linking of COOMET.EM-S1 and COOMET.EM-K6.a comparison results can also be used as the technical basis of confirming CMC NMIs/DIs. Such work can be done by PL of RMO KC or RMO SC, as well as by NMI/DI experts. The NMIs/DIs also must implement a full assessment of the uncertainty budget and the metrological traceability for validation of their CMCs in a wide range of used quantities.

The organizational scheme for ILs and ILC data evaluation procedure is presented. Results of data evaluation for ILC of AC/DC voltage transfer difference are indicated. Results of this comparison were checked for the fulfillment of the chi-square test. The obtained value of the chi-square test for laboratory participants is satisfactory. Results for all laboratory participants of this comparison for E_n number are also satisfactory.

The organizational scheme of linking of international standard comparison and national ILC is indicated. The procedure of linking of RMO KC or RMO SC and national ILC results is presented. This procedure can be used for practical estimation of results specific ILC on a national level by means of the results from NMI/DI laboratories. Linking of COOMET.EM-K6.a comparison and national ILC of AC/DC voltage transfer difference results was presented. The value of chi-square test was calculated and the obtained value of chi-square test for all participants can be considered consistent. Results for all participants of comparisons are satisfactory for E_n number (from 0.10 to 0.83), z scores (from 0.01 to 2.22), and ζ scores (from 0.05 to 0.41).

Results of this linking can be used also for different metrological areas as technical basis of confirming CMC accredited laboratories. Such work can be done by RL of the ILC, as well as by metrological experts. The RL of the ILC can also implement a full assessment of the uncertainty budget and the metrological traceability for validation of their CMCs in a wide range of used quantities.

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