Measurement comparisons: a tool to guarantee the Reliability of measurement systems and of high-tech industry

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Introduction

Measurement comparisons are the main tool to establish the measurements compatibility between different laboratories or different measurement methods. They are a mean to establish the equivalence of national standards maintained at the National Measurement Institutes (NMIs), the correctness of the measurement traceability transfer from NMIs to secondary calibration laboratories, of their accreditations, the competence of their operators and the suitability of their equipment. ILCs role is then of great importance as the NMIs and the secondary calibration laboratories lay at the top of a chain representing the measurement system of each modern industrialized country. Each step of this chain has to be under control to assure that final products (or product parts) are reliable and so that can eventually be assembled with other parts made in other countries. At international level, high accuracy key comparisons among NMIs serve to compare national standards while at national level, ILCs between NMIs and secondary calibration laboratories serve to verify the capabilities of those laboratories. In their turn, secondary laboratories calibrate the instrumentation of lower level and industrial laboratories. As these last ones support directly the industrial and manufacturing sectors, ILCs are the main tool to assure the reliability of measurement systems and thus represent a fundamental support for high-tech modern industry.

Key words: measurement comparison, inter-laboratory comparison, measurement compatibility, calibration, traceability, measurement traceability.

The context

A measurement comparison, or inter-laboratory comparison (ILC), serves to establish the compatibility among measurements. The definition of compatibility in [1] states that two measures of the same measurand are compatible if their difference is smaller than a chosen multiple of the uncertainty of that difference. Therefore, a compatibility test can be made to compare the measurement results made by means of the same measurement method, by means of different methods or by different laboratories, and even by different operators (intra-laboratory comparison). Another important concept is that of the *calibration* that, is an "*operation that, under specified* *conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication*" [1]. In every country, there is a national calibration system that usually is constituted by a National Metrology Institute (NMI), secondary calibration laboratories, many testing and industrial laboratories whose instrumentation have to be calibrated with traceability to national standards. The industrial laboratories often belongs to companies whose quality system is certified or in agreement with ISO 9000 Standards. A calibration traceability can be schematized through a chain starting from the national standards, normally maintained at the NMIs, till to the industrial and even domestic users. Except the last one, each step of this chain consists in the calibration of instruments, standards or devices belonging to a lower level subject (as a laboratory or a manufacturer) by an upper level subject (laboratory or NMI). Fig. 1 shows a traceability chain from the electrical DC Resistance and the DC Voltage national standards maintained at a NMI till to the users of electrical devices (as those in our houses and offices).

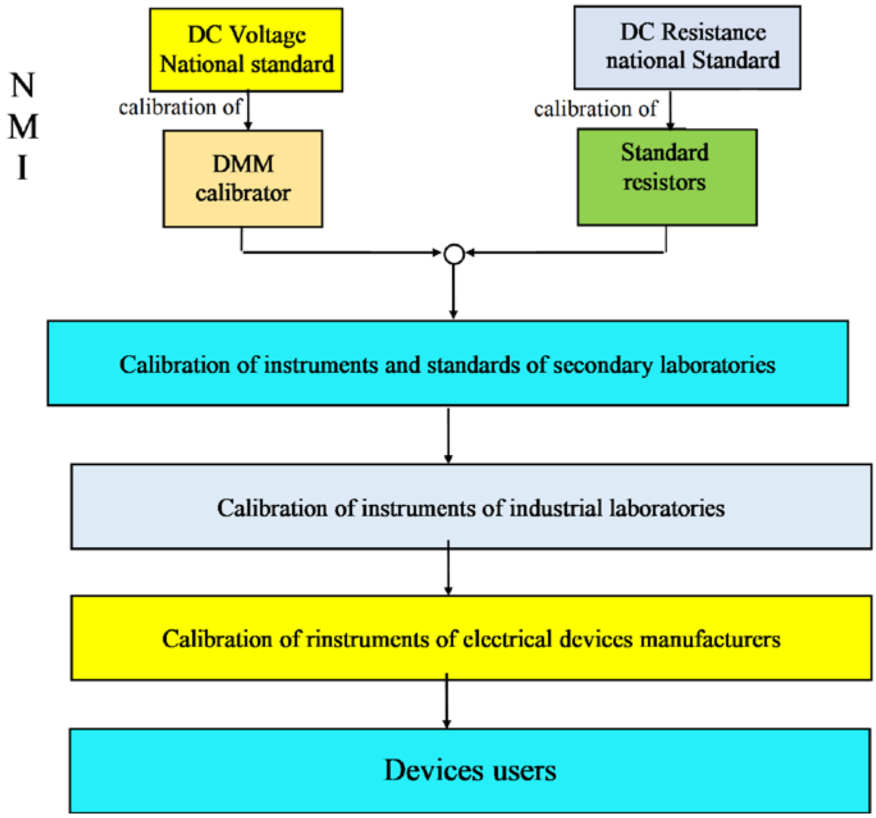

Fig. 1. Traceability chain from electrical national standards till to the users of electrical devices as domestic appliances.

Similar chains are available in the majority of the industrialized countries. The activities of each step of this chain have to be under control. The measurement capabilities of the NMIs and of the secondary calibration laboratories have to be verified also by means of ILCs at international or national level. By means of the ILCs, the measurements of any laboratory are compared with reference values and therefore the ILCs are a useful mean to verify the laboratories competence. As a large number of NMIs are now signatory of the MRA[1], they participate to international key comparisons organized by the CIPM (*Comité international des poids et mesures*, International Committee for Weights and Measures). In their turn, secondary calibration laboratories, usually accredited by national accreditation services, obtain, maintain, or improve their accreditation also through the successful participation to ILCs.

Preliminary operations of the ILCs

Before the execution of the ILCs, technical protocols have to be sent to the participant laboratories. These protocols, besides the measurement instructions, have to contain issues for the management and shipping of the travelling standards or instruments. These have to be transported in suitable packages with impact-resistant materials. The shipping have to be carried out by personnel of the laboratories by car or by means of reliable couriers. In the protocols, forms to report to the ILC provider eventual damages to the travelling devices at the reception and malfunctions during the measurements, have to be added. The measurement points on which the ILCs have to be carried out are agreed in the CIPM Committees (for key comparisons) or established according to the laboratories accreditation schedules (for ILCs with secondary laboratories) to check the most significant points for each relevant physical measurement quantity and range.

Evaluation of the results and typologies of ILCs

The results of the ILCs are generally evaluated by means of the normalized error E_n defined as:

$$E_n = \frac{m_L - m_{ref}}{\mathrm{U}(m_l - m_{ref})} \qquad (1)$$

where m_L is the value measured by a laboratory, m_{ref} is the reference value and $U(m_L - m_{ref})$ is the uncertainty of the difference of the two measurement values [2]. The compatibility condition is satisfied when $|E_n| \leq 1$ in an established number of measurement points. Fig. 2 shows two examples of compatibility checks and, in particular, it shows the results of the same measurement made by two

[1] The CIPM Mutual Recognition Arrangement (CIPM MRA) is the framework through which National Metrology Institutes demonstrate the international equivalence of their measurement standards and the calibration and measurement certificates they issue. The outcomes of the Arrangement are the internationally recognized (peer-reviewed and approved) Calibration and Measurement Capabilities (CMCs) of the participating institutes.

laboratories and between two different methods. Each measure is associated with a measurement uncertainty. The overlapping of the uncertainty bars is an evidence of the compatibility of the measurements.

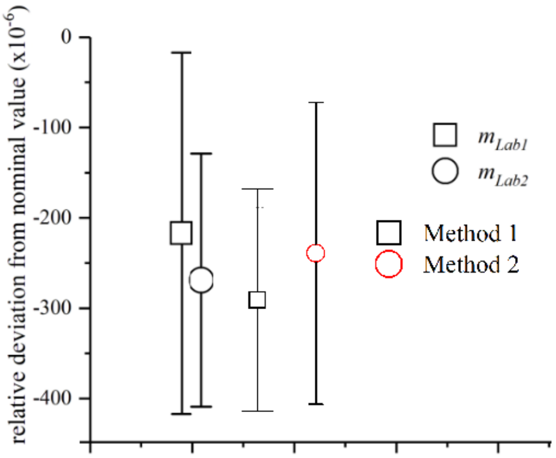

Fig. 2. Measurement results between two laboratories and between two measurement methods. The uncertainty bars correspond to expanded uncertainties at a 95 % confidence level.

The ILCs can be bilateral or multilateral. A bilateral ILC involves only two laboratories as two NMIs or a reference laboratory and a laboratory whose capabilities have to be verified. This is the case for example of a NMI (or a ILCs provider) and a secondary calibration laboratory. A multilateral ILC involves a group of laboratories as a group of NMIs or a reference laboratory and a group of secondary laboratories. Fig. 3 shows the result of a multilateral ILC for the electrical Resistance involving the National Institute of Metrological Research (INRIM, the Italian NMI) and secondary accredited laboratories regarding the calibration of a low value resistor [3]. As in the majority of the multilateral ILCs, the reference laboratory (INRIM in this case) made a measurement before initiating the circulation of the resistor, other two measurements during the circulation and another at the end of the circulation. This is due to the need to verify the stability or drift of the travelling items and in case to interpolate the measurement values made by the reference laboratory at the corresponding dates of the measurements of the participants as shown with the plot line of Fig. 3. When the participant laboratories are many and belonging to different countries as in key comparisons, the “pilot laboratory” (normally the laboratory that makes available the circulating standards) could carry out the measurement several times (circulation with petal scheme).

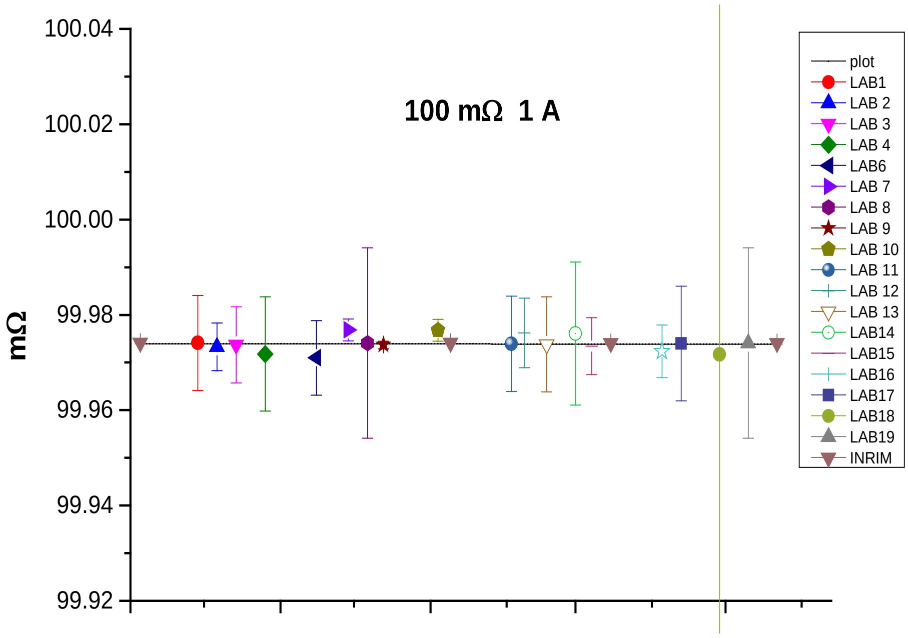

Fig. 3. Results of a multilateral ILC between INRIM and Italian accredited secondary laboratories for DC Resistance on a 100 mΩ resistor at a measuring current of 1 A [3].

The key comparisons are made to establish the compatibility of the national standards maintained at the NMIs. For this kind of ILC the reference value (key comparison reference value, KCRV) is obtained from the measurements and uncertainties of all the participating laboratories. Rules to evaluate the results of these ILCs are given by in [4] and applied for example in the comparison [5]. Cox in [4] states that there are two possible estimators for the reference value: the weighted mean or the more robust median to choose alternatively according to the respect of some conditions. Fig. 4 reported in [5], shows the results of a 100 TΩ standard resistor at 1000 V in the Supplementary Comparison EURAMET.EM-S32 "*Comparison of resistance standards at 1 TΩ and 100 TΩ*. The x-axis reports the participant NMIs while the y-axis reports the compatibility index (DoE, i.e degree of equivalence) of each NMI with respect the KRCV. Some NMIs resulted not compatible in this measurement as both their values and uncertainty bars do not intercept the black horizontal line representing the KCRV.

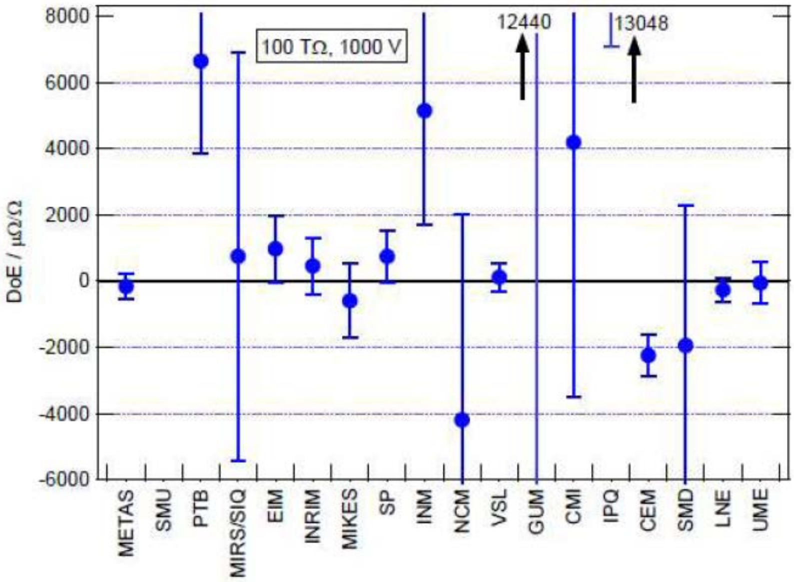

Fig. 4. View of the compatibility index (degree of equivalence DoE) in the Euramet.EM-S32 key Comparison at 100 TΩ, 1000 V [5].

At national level, normally an ILC takes place between a NMI (or a ILCs provider technically adequate and operating according to [6]) and secondary calibration laboratories. In this case the reference value is usually obtained from the measurements of only the NMI or of the reference measurements provider [3, 7–10]. The reference measurement can be written as:

$$m_{ref} \pm U_{ref} \qquad (2)$$

while the measurements of participant laboratories can be written as:

$$m_1 \pm U_1, m_2 \pm U_{2,\ldots\ldots,}m_n \pm U_n \qquad (3)$$

Correlations between the measurements of the reference laboratory and of the participants could arise when these last send their reference standards to the same reference laboratory for calibration. The E_n defined in (1), in the case of a national multilateral ILC for the nth participant laboratory is given by:

$$E_n = \frac{m_n - m_{ref}}{U(m_{ref-m_n})} \qquad (4)$$

In $U(m_n - m_{ref})$, the correlation due to the common uncertainty component both in U_n and U_{ref} due to the relevant national standard is evaluated according to [10]. It suggests that the correlation factor between m_n and m_{ref} is the ratio between the square of the type B component of the uncertainty of the the national standard and the product of U_n and U_{ref}. Normally, taking into account the correlation, leads to a decrease of the uncertainty making more reliable the ILC.

Reports of the ILCs

Rules to prepare ILCs reports are given in [6]. They shall include mainly:

- Names and contacts of the provider (or pilot) and of the participant laboratories;
- The description and characteristics of the travelling instruments or standards;
- Circulation scheme and shipping modalities;
- Events that influenced circulation and the travelling standards;
- Dates and certificates/reports number issued by participants and by the reference laboratory;
- Reference measurements;
- Modalities of the evaluation of the results;
- Results with E_n values;
- Conclusions;
- Confidentiality terms.

Benefits from ILCs for secondary calibration laboratories

The technical surveillance of secondary laboratories based on a regime of regular successful participation to ILCs is a guarantee of:

- Competence of the operators;
- Suitability of the instrumentation, laboratory and equipment;
- Correctness of technical procedures;
- Correctness of the evaluation of the uncertainties.

Worldwide ILCs

Fig 5 shows the worldwide organization of key comparisons carried out by the Consultative Committees (CC) of the CIPM, by the BIPM[2] and by the Regional Metrology Organizations ( ).

[2] The Bureau international des poids et mesures the intergovernmental organization through which Member States act together on matters related to measurement science and measurement standards.

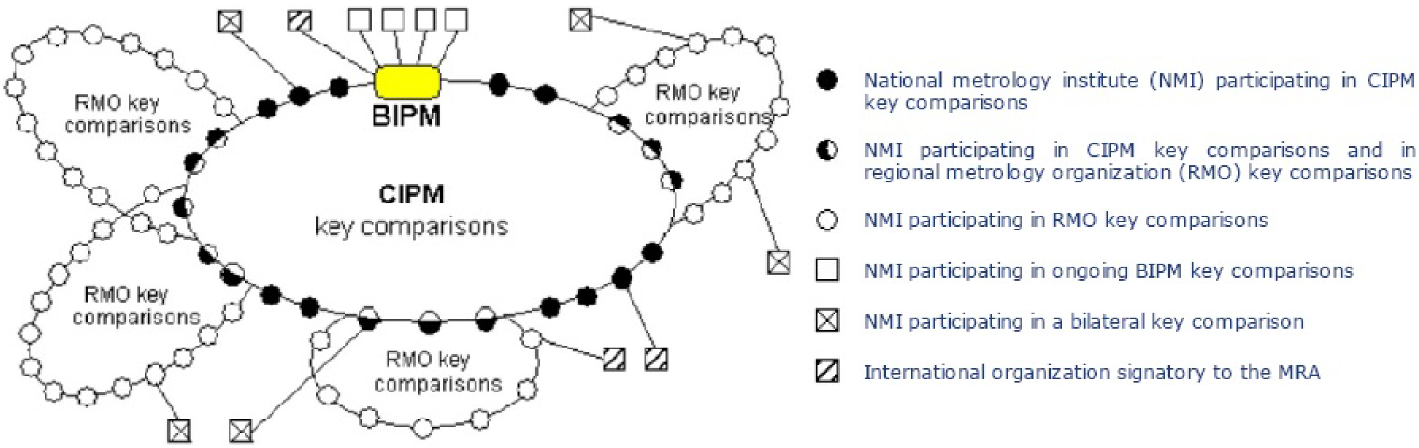

Fig. 5. Worldwide organization of key comparisons.

The key comparisons are of two types:

- CIPM key comparisons carried out by NMIs with the highest level of competence. Highly reliable reference values for the involved quantities are obtained from these comparisons;
- RMO key comparisons carried out at the level of RMOs.

A NMI that participates successfully to a CIPM key comparison delivers the reference value if it participates also to a corresponding RMO key comparison. In fact, the RMOs organize key comparisons with corresponding protocols to those of the CIPM key comparisons. Other high-level comparisons involve the BIPM and external laboratories. This system allows checking the compatibility around all the world. Secondary laboratories accredited by national accreditation services signatory of the EA MLA[3], besides to participate to ILCs with their NMIs or ILCs providers, can participate also to international ILCs organized by the EA[4].

Conclusions

The measurement comparisons are an effective mean to assess the technical and measurement capabilities of every subject acting in the field of calibration and measurement. They are a tool to verify:

– The equivalence of the national standards maintained at the NMIs (by means of key comparisons) and, as consequence, the equivalence of their calibration certificates;

[3] The EA Multilateral Agreement (EA MLA) is a signed agreement between the EA Full Members whereby the signatories recognise and accept the equivalence of the accreditation systems operated by the signing members, and also the reliability of the conformity assessment results provided by conformity assessment bodies accredited by the signing members.
[4] The European co-operation for Accreditation or EA is an association of national accreditation bodies in Europe that are officially recognised by their national Governments to assess and verify—against international standards—organisations that carry out evaluation services such as certification, verification, inspection, testing and calibration (also known as conformity assessment services).

– The reliability of the traceability transfer from NMIs to secondary calibration laboratories through the periodical calibration of their reference standards and the correctness of their accreditation. As consequence, ILCs contribute to establish the worldwide equivalence of the calibration certificates issued by the secondary laboratories.

The equivalence of calibration certificates means that the calibrations of the instrumentation of the secondary laboratories and of lower level and industrial laboratories (Fig. 1) are equivalent and compatible. As industrial laboratories belong or support directly the industrial and manufacturing sectors, this equivalence is a guarantee for the production systems allowing also joint development by more countries. Ultimately, the ILCs are the main tool to guarantee the reliability of worldwide measurements and therefore they are a strategic support for high-tech industry in today-global market and a benefit for final users.

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