XIX IMEKO World Congress
Fundamental and Applied Metrology
September 6–11, 2009, Lisbon, Portugal

MEASUREMENT AND CALIBRATION: CONSIDERATIONS BASED ON THE INTERNATIONAL VOCABULARY OF METROLOGY (VIM, 3RD ED.) AND RELATED STANDARDS

Roberto Buccianti[1], *Marco Cibien*[2], *Luca Mari*[3], *Bruno I. Rebaglia*[4]

[1] CEI – Comitato Elettrotecnico Italiano, Milano, Italy, r.buccianti@alice.it
[2] UNI – Italian Organization for Standardization, Milano, Italy, marco.cibien@uni.com
[3] Università Cattaneo – LIUC, Castellanza (VA), Italy, lmari@liuc.it
[4] ITIA – CNR, Milano, Italy, b.rebaglia@itia.cnr.it

Abstract − Following the publication of the 3rd edition of the *International vocabulary of metrology – Basic and general concepts and associated terms*, the paper gives a comprehensive analysis of specific issues concerning the calibration operations of a measuring instrument and the proper application of the many relevant concepts.

Keywords: measurement science, instrument calibration, uncertainty

1. INTRODUCTION

The recent publication of the third edition of the *International vocabulary of metrology – Basic and general concepts and associated terms* (VIM3 [1]), "intended to promote global harmonization of terminology used in metrology" {Scope} (the notation {…} is used as an internal reference to the referred document, and in particular to the VIM3 when not specified) has generated a new interest in identifying models of the measurement process and its properties that, at the same time, are based on the terminology and concepts set by the VIM and can be consistently interpreted in compliance with other relevant framework standards (such as the GUM [2], IEC 60359 [3], and ISO 5725 series [4]) as well as with particular guidance documents of specific application areas, such as the automotive field [5]. When introducing conceptual models and the related terminology for measurement, their consistency and applicability from the point of view of users, i.e., both those who perform measurements and those who exploit measurement results to support the decision making process, should be particularly taken into account. This paper focuses on the relations between measurement and calibration, making an attempt to answer the questions:

- what is the correct use of the information provided by calibration when implementing a measurement procedure?
- what are the relations between calibration and metrological confirmation? and between calibration data, instrumental uncertainty and measurement uncertainty?
- what is the proper interpretation of the term "accuracy" that sometimes is applied to address the metrological characteristic of a measuring instrument?

2. MEASUREMENT AND CALIBRATION

One of the most significant changes introduced by the VIM3, with respect to the second edition of the VIM (VIM2 [6]), lies in the definition of the concept of calibration.

Table 1. Definitions of "calibration".

VIM2 {6.11}	set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or values represented by a material measure or a reference material, and the corresponding values realized by standards
VIM3 {2.39}	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

The more comprehensive scope of the new definition underlines that the concept of calibration cannot be kept separated by the more fundamental concept of measurement. The VIM3 acknowledges that measurement is an experimental process performed by comparing quantities and aimed at obtaining information on a quantity {2.1, with Notes}, but does not make the structure of the process explicit. As a consequence, the VIM3 does not procedurally define measurement nor openly requires it to be performed by a measuring instrument (or, more generally, by a measuring system, which is a "set of one or more measuring instruments and often other devices, including any reagent and supply" {3.2}). However the usage of such a device "to generate measured quantity values" {3.2} can be considered the basic (if not the only) technique to carry out measurement(s). Furthermore, the assumptions that:

(i) the "quantity value provided by (...) a measuring system" {4.1} is an indication that "can be used to provide a corresponding measured quantity value" {2.10, Note 1}, even if in general it doesn't coincide directly with a measured quantity value, and that:

(ii) "a measurement result is generally expressed as a single measured quantity value and a measurement uncertainty" {2.9, Note 2}

entail that calibration – i.e., the operation whose definitive object is "to establish a relation for obtaining a measurement result from an indication" {2.39} – is mandatory for any measuring instrument and is a matter of interest to both the manufacturer and the user.

3. ON THE INFORMATION PROVIDED BY CALIBRATION DIAGRAMS

A measuring instrument "may be an indicating measuring instrument" – which "provides an output signal [indication] carrying information about the value of the quantity being measured" – "or a material measure" – which "reproduces or supplies, in a permanent manner during its use, quantities of one or more given kinds, each with an assigned quantity value" {3.1, Note 2; 3.3 and 3.6}.

The basic (metrological) performance of any measuring instrument consists of its ability to establish and maintain a known relation among the indication(s) it provides (or the quantity(ies) it reproduces) and the corresponding quantity(ies) being measured, where the term "relation" includes both a numerical value and the associated uncertainty, that operatively is aimed at evaluating the risk for the value to be wrong. As stated, such a relation is found out by calibration, which therefore can be regarded as the main operation devoted to outline and describe the metrological performance of an instrument. It then follows that manufacturers, who obviously retain the key knowledge of each instrument and have a primary interest to attain and guarantee its performance, always provide all suitable information about the calibration process and its outcomes.

A common means manufacturers assume to formalize this information is a graphical representation, the "calibration diagram", which usually assumes the shape of a "strip of the plane defined by the axis of the indication and the axis of measurement result, that represents the relation between an indication and a set of measured quantity values." {4.30 Note 1} (see Fig. 1). Another means to deliver the same information is a simple statement about the "maximum permissible measurement error" {4.26}, which settles the extreme value(s) of the "measurement error" (i.e., the difference between the indication of the instrument and the quantity value supplied by a material measure having a negligible measurement uncertainty {2.16 Note 1, a)}), and may be expressed in the form of a constant or a function of the magnitude of the quantity being measured (this information is generally denoted with a MPE function (see Fig. 2).

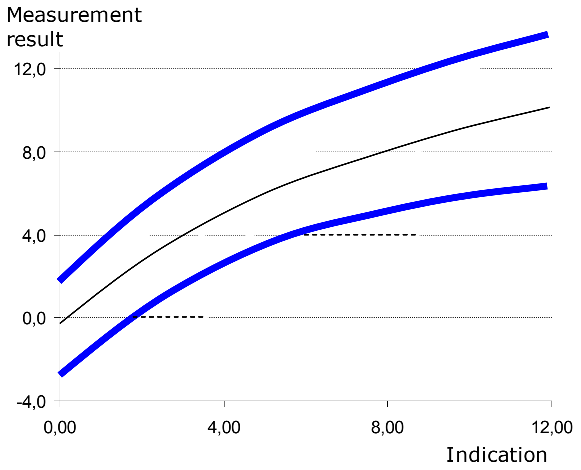

Fig. 1 – Example of a calibration diagram.

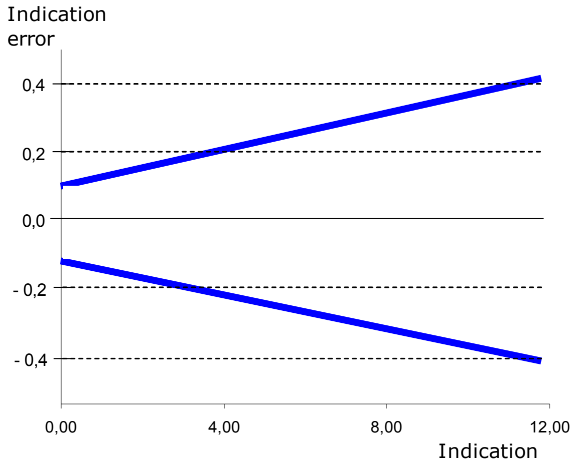

Fig.2 – Example of a MPE function.

Whatever means manufacturers choose, either a calibration diagram or a MPE function, this data fulfils both steps depicted in the VIM3 definition of calibration, since it makes available to the user of the instrument just what he needs in order to:

- interpret any indication in terms of the corresponding measured quantity value (step 1), and:
- attain additional information required to produce the related measurement result (step 2).

In particular, step 2 can be achieved since the user, when executing a given measurement task and developing the relevant uncertainty budget, derives a guaranteed value of the "instrumental measurement uncertainty" {4.26} from the width of the strip or the MPE range. For an unambiguous derivation, the manufacturer must clearly specify the underlying hypotheses to be assumed for the conversion error-to-uncertainty (i.e., shape of the distribution, coverage factor, etc.). Usually the manufacturer adds to calibration data a list of the main influence quantities that can significantly affect the behaviour of the measuring instrument, and specifies their relevant limiting values. The user shall recognize these limiting values as boundaries for the instrument operating conditions under which the relation established by the calibration deserves its validity. We claim that the manufacturer has two options to ascertain the limiting values, and that these options envisage two alternative strategies he may pursue to develop and represent the relation. Such two strategies can be described as follows.

3.1. Strategy 1: reference conditions

According to this strategy, the stated limiting values for influence quantities define the so called “reference”, or “best performance”, conditions, the ones in which the instrumental uncertainty derived from the calibration data provided by the manufacturer is guaranteed. Typically the instrument is employed in measurements whose influence quantities are well within the boundaries of safe and good operation, but lie outside the reference conditions set by the manufacturer: this is the common situation met, e.g., by users of simple mechanical measuring instruments. Hence, when the user exploits the instrument in a given measurement process, the effects due to the actual variation of the influence quantities have to be kept into account in the measurement model he adopts to evaluate additional uncertainty contributions. This strategy is elegant, since it keeps the instrumental uncertainty and the measurement uncertainty separate, but its drawback is twofold: it forces the user to know analytically the measurement function, including the effects of influence quantities, and it requires the influence quantities to be measured.

3.2. Strategy 2: widened conditions

In this case [3 {6}] the limiting values for influence quantities are chosen by manufacturers aiming to identify all reasonably predictable conditions the user might face when he places the instrument in a given measurement process. As a consequence, the width of the calibration strip (or the MPE range) is widened, so to keep into account the effect of the possible variations of the influence quantities. This is the common situation met, e.g., by users of ordinary electrical measuring instruments. According to this strategy, the instrumental uncertainty derived from calibration data provided by the manufacturer represents a pragmatic preliminary approximation of the expected measurement uncertainty. The user can make use of this information directly in a specific measurement, so that there is no need to develop a detailed measurement model and a related uncertainty budget.

3.3. A comparison

The difference between these two strategies is critical: if a strategy 1 calibration data is misunderstood as a strategy 2, the effects of the actual influence quantities, as related to a specific measurement, are never taken into account and the corresponding instrument is erroneously granted a good metrological performance. If, vice versa, a strategy 2 calibration data is misunderstood as a strategy 1, the metrological performance of the corresponding instrument is considered erroneously poor and the effects of influence quantities are possibly taken into account twice when the instrument is employed in a specific measurement; this could yield the wrong consequence that measurement uncertainty looks too high for making useful decisions on measurement results. It is then clear that calibration data from instrument manufacturers should explicitly state the strategy according to which they have been generated, i.e., with influence quantities either in reference conditions or within a given wider range of variation.

3.4. On the use of the term “accuracy”

Occasionally manufacturers assume the terms “accuracy” or “accuracy level” to signify the metrological performance of an instrument, as documented by the calibration diagram or MPE function. In principle the concept of accuracy singles out a general property of a process; hence the claim of the accuracy level referred to a measuring instrument has to be interpreted as a complex assertion of the kind: every measurement process which employs the instrument and complies with the conditions stated by the relevant calibration data, with no further influence quantities of any type, produces results (i.e., measured quantity values with associated uncertainties) that never exceed the width of the corresponding calibration strip or MPE range. It is evident that such an assertion is quite theoretical when considering instruments with calibration data generated through a strategy 1, while it adequately fits those generated with a strategy 2.

4. CALIBRATION AND METROLOGICAL CONFIRMATION

The metrological confirmation of a measuring instrument is a procedure that must be considered when there is a need to be sure – or prove – that the instrument has or retains its basic metrological requirements related to a specific measuring task(s) [7 {3.5}]. It comprises:

- the assessment of the instrument performance, to be repeated periodically since the metrological performance of any instrument could decay with time and use, and:
- the comparison of the instrumental uncertainty with the tolerance (i.e., a target specification) associated to the quantity(ies) to be measured, which in turn is related to the uncertainty that can be accepted to keep the right decision based on the measurement result, with a given confidence; this operation is performed once for ever, for a specific measuring task, when deciding on the instrument to be used.

The implementation of the metrological confirmation of a measuring instrument requires the user to perform a specific calibration activity under his own responsibility. Commonly he entrusts a portion of the first step of this calibration to a dedicated laboratory, maybe external to his organisation. This early operation is aimed at establishing the relation between a (generally small) number of quantity values provided by material measures and the corresponding indications of the instrument under test. The influence quantities acting on the instrument in such operation must comply with whatever limiting value may be fixed by the instrument manufacturer. The user obtains from the calibration laboratory a report / certificate, where the observed indication errors are listed together with relevant uncertainties. To complete the first step of calibration, the reported information has to be worked up to define the relation between the input quantities to be measured and the corresponding indications, as well as the instrumental uncertainty, both relatively to the entire measuring interval {4.7} of the instrument. How to accomplish this duty is up to the user, who can use the certificate issued by the calibration laboratory in two basic different ways, as follows.

4.1. Verification

If the user has chosen the instrument reckoning that its instrumental uncertainty, as derived from manufacturer calibration data, fulfils all requirements related to his measuring task(s), then he can use the contents of the certificate solely to notice if all the reported indication errors (with associated uncertainties) lie inside the calibration strip or MPE range stated by the manufacturer. In this case the certificate confirms the validity of the initial manufacturer calibration and legitimates all previous judgements concerning the adequacy of the instrument performance in the measuring task under consideration. Hence the user is allowed to go on with employing the instrument without any correction and adopting the instrumental uncertainty derived from that initial calibration. Otherwise he has to take on some suitable corrective action.

This type of exploitation of the certificate issued by the dedicated laboratory is usually denoted as “calibration verification”.

4.2. Adjustment

It may happen that the instrumental uncertainty derived from manufacturer calibration data does not comply with the user measurement task(s). While a straightforward solution would be to choose another instrument guaranteeing better performance, technological or economical reasons might preclude this option. In this case, the user shall investigate if the instrumental uncertainty derived from the calibration provided by the manufacturer can be reduced. This can be regarded as a feasible objective for instruments having both a strategy 1 or – even more – a strategy 2 calibration data, provided that their repeatabilities have proven to be adequate. In many cases, mainly for simple measuring instruments, manufacturer calibration data refers to the whole family of instruments identified with a given model and is guaranteed when such instruments operate within the asserted limits for the influence quantities. But the certificate issued by the calibration laboratory gives the user a kernel of information which refers specifically to his own instrument, whose behaviour – under the specific operating conditions implemented in the laboratory when executing the comparisons – is an individual within a collection of possible behaviours, all compliant with the general performance that manufacturer guarantees for every instrument of the same model. Hence the user can build for this instrument an individual calibration diagram, or MPE function, consistently with the definition in the VIM3. He shall implement the following operations:

a) interpolating the discrete set of indication errors reported in the certificate, to create a continuous one-to-one correspondence between indications and measured quantity values, extended to the working interval of interest, which for the individual instrument might be a subset of the interval of indications foreseen for the model;

b) evaluating the uncertainty contribution coming from the interpolation algorithms, which has to be combined with the uncertainty associated with the indication errors, as specified in the certificate, to obtain an individual instrumental uncertainty having reference conditions corresponding to those recalled in the certificate issued by the laboratory.

Accordingly, the user has created, under his complete responsibility, a sort of “new” instrument, where each indication must be corrected according to the previously defined one-to-one correspondence (operation a)). For the metrological confirmation of this new instrument, related to a specific measuring task, the previously defined individual instrumental uncertainty (operation b)) must be considered.

This type of exploitation of the certificate issued by the dedicated laboratory can be denoted as “calibration adjustment”, since it requires the instrument indications to be corrected according to calibration data.

5. CONCLUSIONS

The proper definition of the metrological performance of each measuring instrument is a basic requirement to produce measurement results which the user can adequately employ for making right decisions. In this concern calibration holds a major role. Calibration data provided by the manufacturer supply the user with basic information useful to understand the metrological performance of a given instrument and to compare it with the requirements of any specific measuring task. The user can implement further specific calibration operations when he needs to verify and document that the instrument in use retains its metrological performance or when he tries to improve the rated metrological performance, using the corresponding calibration data to correct the instrument indications and to define specific operating conditions.

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