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TEACHING GENERAL METROLOGY: WHY, WHAT, HOW?

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Abstract – Arguments are given in favour of teaching a course of General Metrology in technical universities, and some hints are formulated regarding the content of it. Several questions arise in connection with General Metrology, seen as a technical discipline, rather than a physical one. Is it useful to teach General Metrology as a separate course at a higher education level? If the answer is yes, what would be the best curriculum of such a course? When would it be most appropriate to teach the course, at the beginning or at the end of the series of basic technical disciplines? What are the main benefits such a course would bring to the general formation of the student of a technical university? The paper intends to present some aspects from our experience in this direction, after many years of teaching General Metrology at the University Politehnica of Bucharest, Romania, faculty of Electrotechnics.

Keywords: general metrology, measurement information, methods of measurement.

1. INTRODUCTION

Metrology is defined in the VIM [1] as “science of measurement”, and in the VML [2] as “field of knowledge concerned with measurement”. The latter document makes distinction between General Metrology, defined as “That part of metrology which deals with problems common to all metrological questions irrespective of the quantity measured”, and Applied Metrology, as “That part of metrology which deals with measurements made for specific applications”.

Usually, General Metrology includes topics like quantities, units of measurement, measurement errors and uncertainty, methods of measurement, measuring instruments, measurement standards, calibration of instruments, traceability, metrological infrastructures. Often, additional chapters such as industrial metrology, legal metrology, laboratory accreditation, a.o. are also considered.

Several questions arise in connection with General Metrology, seen as a technical discipline. Is it useful to teach General Metrology as a separate course at a higher education level? If the answer is yes, what would be the best curriculum of such a course? When would it be most appropriate to teach the course, at the beginning or at the end of the series of basic technical disciplines? What are the main benefits such a course would bring to the general formation of the student of a technical university?

This paper intends to present some aspects from our experience in this direction, after many years of teaching General Metrology at the University Politehnica of Bucharest, Romania, faculty of Electrotechnics [3].

The first reason for the General Metrology course to be taught as an independent technical discipline is its fundamental character. It is the best context to present the basic concepts of metrology, in a more adequate manner than it is commonly made in the courses of Physics. Also, it gives the student a new way of thinking when analyzing an engineering project, not only in terms of the quantities involved, but also considering the associated uncertainties. It provides a “cross section” through important aspects such as methods of measurement, structure of measuring instruments, measurement signals, sensors and transducers, output devices. A major concern of this general approach is the correct definition of the metrological properties of measuring instruments, applicable to all categories of instruments, irrespective of the nature of quantities involved. Basic knowledge about measurement standards, comparison of standards, calibration and traceability is also essential within a General Metrology course. Furthermore, a main component of the “metrological education” consists in features of a calibration laboratory, accreditation, role of metrology in quality assurance, metrological infrastructures.

More generally, students will experience to think in quantitative terms about every kind of engineering project, and learn to distinguish between what is essential and what is not, to correctly express various kinds of amounts, retaining the important components and neglecting the rest.

According to our experience, it would be better for students to attend the General Metrology course after they had already acquired some knowledge on measurements and instruments, e.g. after a "standard" course of electrical measurements (in case of the Electrotechnics faculty). In this way, they can easier accept the generalization of certain notions and will be satisfied discovering that many of the issues they had learned before were just particular cases of more general rules, properties or entities.

2. COMMENTS ON THE GENERAL METROLOGY COURSE

2.1. Structure of a General Metrology course

The following table summarizes the most important chapters of the General Metrology course (instead of numbers of hours, percents of total size are given):

Fundamental concepts	1 %	Measurement standards	6 %
Quantities and their measurement	5 %	Reference materials	4 %
Units of measurement	4 %	Calibration, traceability	7 %
Measurement errors	7 %	Calibration services, calibration laboratories	3 %
Measurement uncertainty	13 %	Laboratory accreditation	2 %
Measurement information	4 %	Legal metrology	8 %
Methods of measurement	4 %	Metrological infrastructures	4 %
Measuring instruments	13 %	International metrology organizations	2 %
Characteristics of measuring instruments	11 %	Metrology and quality assurance systems	2 %

2.2. *Theoretical aspects*

Basic concepts, general definitions, introduction of quantities, units, etc. are treated on an accessible level, compatible with the “engineering style” of the other courses. Quantities are defined based on set theory concepts, but in a less abstract manner than it is usually done in measurement theory textbooks. Clear distinction is made between additive and non-additive quantities (defined on the basis of conventional scales), with intuitive examples (temperature based on ITS, hardness, pH, etc.).

The measurement consists of a sequence of operations with the purpose of obtaining experimentally a quantitative information concerning certain properties of an object or a system.

The information transmitted in a process of measurement is called measurement information.

Any measurement involves the object under measurement and the measuring instrument, as essential elements.

The object under measurement may be defined as a body, system or phenomenon, one property (attribute) of which is subjected to measurement.

In any measurement, an interaction takes place between the object and the instrument, the latter being influenced by the quantity to be measured, characteristic for the object. This interaction results in a transfer of information from the object to the instrument. However, the instrument-object interaction leads to undesired effects as well. Such an effect is the disturbance of the object caused by the measuring instrument. Another unwanted effect is that the instrument is influenced not only by the quantity to be measured, but also by other undesired quantities. Accordingly, the concept of «object under measurement» facilitates the explanation of notions such as «interaction error», «modeling error», «influence quantity», etc.

In its interaction with the object under measurement and the environment, the measuring instrument is influenced in general by several quantities. One of these quantities is the measurand (quantity to be measured) x, and the others are the influence quantities $q_1, q_2, \ldots q_n$. In the presence of all these quantities, the measuring instrument generates the output y given by the equation

$$y = f(x, q_1, q_2 \ldots q_n) \tag{1}$$

A small variation of the output, caused by slight changes of the measurand and the influence quantities, may be written as follows:

$$y = \frac{\partial f}{\partial x}\Delta x + \frac{\partial f}{\partial q_1}\Delta q_1 + \frac{\partial f}{\partial q_2}\Delta q_2 + \ldots + \frac{\partial f}{\partial q_n}\Delta q_n \tag{2}$$

The factor $\partial f / \partial x$ represents the useful sensitivity of the instrument, while the factors $\partial f / \partial q_i$ are the parasitic sensitivities of the instrument. The useful sensitivity should have a definite and stable value. The parasitic sensitivities are not required to have specific values, but must remain within permissible limits.

The measurand is one of the measurable quantities of the object under measurement (the conditions of measurability are separately discussed). The measuring instrument «selects» the desired measurand, among the quantities characteristic for the object. An ideal instrument responds only to the measurand, being insensitive to other quantities.

The influence quantities are quantities whose measurement is not desired, but exerting an effect upon the measuring instrument.

The influence quantities originate from the object under measurement or the environment.

2.3. *Units of measurement*

One of the important chapters of a general metrology course concerns the units of measurement. It is often seen as a mostly historical matter, left to be included in courses on physics. The worldwide use of at least two systems of units, the SI and the English (Imperial) systems, leads to the need of teaching both of them, in order the students to be familiar with the frequently employed units in the everyday life, in engineering and in computer technology. Cases where both systems are widely encountered – such as tubes and fittings, threads, gears, transportation, printing, computers – are much more easily handled by those being familiar with all the customary measurement units, able to "sense" their magnitude and to make quick conversions from ones to the others.

Obviously, this task would be much less difficult in the situation of a generalised SI system, such as it had been strongly hoped beginning with the sixties. Unfortunately, after more than four decades of "metrication" in the USA, the traditional English units are still used by almost everybody, except scientists. A significant example of what can happen when units belonging to different measurement systems are used, at the highest level of technology, is the Mars orbiter crash in September 1999, when the NASA engineers failed to make a conversion between pounds and newtons in sending the final data to the space vehicle reaching the vicinity of Mars, resulting in the destruction of the vehicle and finally a loss of $125 millions.

2.4. *On the measurement errors*

Errors of measurement are classified in general according to several criteria, such as mode of expression (absolute, relative, fiducial), occurrence in repeated measurements (systematic, random), time variation of the measurand (static, dynamic), conditions of measurement (intrinsic, complementary), etc.

A general classification of the errors of measurement according to the possible sources generating them is also important. Considering the main factors involved in a measurement, it is obvious that the errors of measurement can originate from:

- the measuring instrument,
- the object under measurement,
- the instrument-object interaction, and
- the environment.

Accordingly, one may speak of instrumental errors, modeling errors, interaction errors and environmental errors.

Instrumental error: error originating from the instrument used for the measurement.

Modeling error: error due to the replacement of the object under measurement by a more or less idealized model. In a process of measurement, the object under measurement is necessarily subjected to a mathematical and physical idealization. In this way, certain of its properties, characteristic quantities and imperfections are disregarded (examples: measurement of the diameter of a rod whose cross section is not exactly circular; measurement of the density of a nonhomogeneous substance; measurement of the RMS value of a nonsinusoidal AC voltage with an average-value voltmeter). When the measurand exhibits a time dependence, the results of repeated measurements show a dispersion, that may also be considered as a modeling error (the adopted model assumes a constant measurand).

Interaction error: error due to the disturbing effect exerted by the instrument on the object under measurement. The instrument-object interaction results in an energy exchange. The disturbance caused by this effect depends on the energy required by the instrument in a measurement, as compared to the available energy of the object under measurement. As a consequence, the measurand reaches a value which differs from that it had before the measurement (examples: deformation of the test object caused by a mechanical length measuring instrument; temperature change of a fluid caused by the immersion of a thermometer; power consumption of a voltmeter from the circuit in which the voltage is measured).

Environmental error: error due to factors external to the object under measurement and the measuring instrument (it is supposed that the external factors mentioned in the definition can act on both the object under measurement and the measuring instrument).

As far as systematic and random errors are concerned, it should be noted that most errors are variable in time, and their systematic or random character depends on the time interval considered.

2.5. *Measurement uncertainty*

This chapter is conceived in accordance with the actual internationally agreed upon procedures, which have found in the last ten years numerous applications, since the publication of the well known ISO Guide [4]. The main goal is (a) to provide complete information on the modality to arrive at the expression of the measurement uncertainty and (b) to give a sound foundation for the comparability of measurement results.

The evaluation and expression of the uncertainty in measurement is a dominant subject when discussing about General Metrology. It has a wide spectrum of applications, in technology, engineering, physical standards, reference materials, calibration, all kinds of measurements, quality control and management, legislation.

Relating to the measurement uncertainty, what is to be emphasized is that the crucial point is the *modeling* of the measurement. The remaining is a purely mathematical procedure, in accordance with the GUM "recipe", which can be performed even by a computer (there are already many computer softwares for this calculation!). Therefore, when teaching the chapter on measurement uncertainty, it is essential to add a large number of concrete examples, focussed on the correct formulation of the input/output relation typical for the given measurement, taking into account all relevant quantities.

2.6. *Measurement and information theory*

In a course of General Metrology, it is very useful – in our opinion – to highlight the relations between *information theory* and *measurement*. In particular, two issues can best illustrate these connections: (a) the informational approach to the measurement error, and (b) the informational / energetic behaviour of instruments that measure very low level quantities.

(a) Consider the case of an analogue measuring instrument having the read-out scale graduated in N divisions. If the entire scale corresponds to D units, and a division to d units (see figure 1, where $N = 100$), the number of possible significant readings is $N = D/d$. Assuming equal probabilities of the N values, the measurement information is

$$I = -\,\mathrm{lb}\ 1/N = \mathrm{lb}\ N = \mathrm{lb}\ D/d \qquad (3)$$

In general, if the accuracy class C of the instrument is introduced, this relation is equivalent to

$$I = \mathrm{lb}\ 100/2C \qquad (4)$$

This simple relation shows that the information delivered by a measuring instrument increases with its accuracy class.

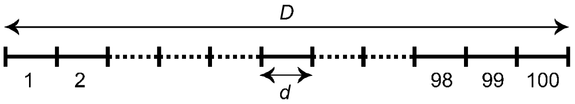

Figure 1. Scale of an analogue instrument

The information quantity obtained in general in a measurement can be calculated as a difference of two entropies:

$$I = -\int_{-\infty}^{\infty} p_o(x)\,\mathrm{lb}\, p_o(x)dx + \int_{-\infty}^{\infty} p(x)\,\mathrm{lb}\, p(x)dx \qquad (5)$$

where:

x value of the measurand;
$p_o(x)$ probability density before the measurement (corresponding to the “wide” curve in figure 2, characterized by σ_o)
$p(x)$ probability density after the measurement (corresponding to the “narrow” curve in figure 2, characterized by σ)

Introducing the normal (Gaussian) distribution functions

$$p_o(x) = \frac{1}{\sigma_o\sqrt{2\pi}}\exp\left(-\frac{(x-\overline{x})^2}{2\sigma_o^{\,2}}\right) \qquad (6)$$

$$p(x) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(x-\overline{x})^2}{2\sigma^2}\right) \qquad (7)$$

after calculating the integrals, the result is

$$I = \mathrm{lb}\frac{\sqrt{\sigma_o^2+\sigma^2}}{\sigma} \approx \mathrm{lb}\frac{\sigma_o}{\sigma} \qquad (8)$$

where σ_o is the standard deviation before the measurement, and σ is the standard deviation after the measurement. Obviously, σ is much lower than σ_o, which makes possible the simplification.

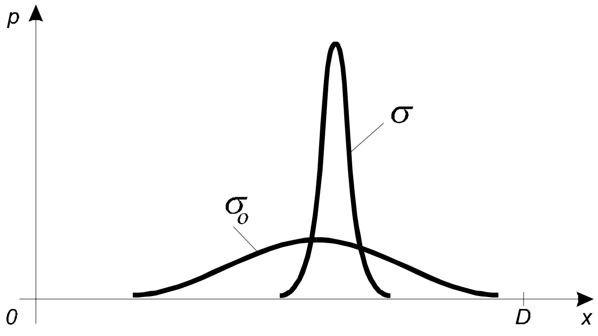

Figure 2. Distribution curve before and after measurement

Therefore, in terms of information theory, a measurement can be regarded as a process by which the distribution law of the measurand becomes narrower (more concentrated) and possibly with its maximum shifted. The quantity of information gained in a measurement can be expressed as $\mathrm{lb}(\sigma_0/\sigma)$, where lb is the symbol of the binary logarithm, σ_0 is the standard deviation before the measurement, and σ is the standard deviation after the measurement. This relation is of major importance in the informational theory of measurement, giving a quantitative measure of the information conveyed in a measurement process. There are many interesting examples in metrology where the application of this formula reveals the informational character of certain operations or processes. We give here only one: the well known “uncertainty ratio” σ_1/σ_2 between the standard deviation σ_1 of the reference standard and the standard deviation σ_2 of the instrument to be calibrated may readily be expressed in terms of the information quantity transferred by calibration from the reference standard to the calibrated instrument.

Even more interesting is to compare the measurement error corresponding to the rectangular distribution (with limits ±Δ) with the error resulting in the assumption of other distribution laws, the comparison criterion being the equality of the information quantities. It can be shown that for normal distribution the quantity Δ, called *entropic error*, is $\Delta = \sqrt{\pi e/2}\,\sigma = 2,07\,\sigma$ and for other distributions $\Delta = t\sigma$, where t, for most distribution laws encountered in practice, takes values between 1,73 and 2,07. The entropic error Δ may be considered as an error limit of a measurement process. There is a surprising similarity of this approach to the results of the classical theory of errors and uncertainty.

(b) It is known that in any measuring system a thermal fluctuation effect (thermal noise) is present, whose power related to the input is given by the Nyquist formula

$$P_n = 4\,k\,T\,\Delta f \qquad (9)$$

where: $k = 1{,}38 \cdot 10^{-23}$ J/K the Boltzmann constant
T absolute temperature
Δf frequency spectrum of the thermal noise

The duration of a measurement t_m is closely related to the value of Δf. In the informational theory of measurements, the following relation is given:

$$t_m = 0{,}25\,\pi\,e / \Delta f \approx 2{,}13 / \Delta f \qquad (10)$$

On the other hand, the product of the noise power P_n and the measurement duration t_m gives the energy W_n of the noise that accompanies the measurement. Assuming room temperature ($T = 293$ K):

$$W_n = \pi\,e\,k\,T = 3{,}5 \cdot 10^{-20}\ \text{J} \qquad (11)$$

This noise energy outstandingly illustrates the existing relation between information and energy in measurements. *It can be regarded as the minimum energy required for obtaining an information of 1 bit.* Indeed, since any measurement is associated with a thermal noise whose energy in given by (11), the presence or the absence of a signal – equivalent to an information of 1 bit – can be detected only if its energy (the “useful” energy) is comparable to W_n (since otherwise the signal will be “buried” in the noise and will not be noticeable).

In informational terms, a measuring instrument or a measurement process may be characterized from this point of view by the information / energy ratio, or the *informational / energetic efficiency*, expressed in bit / joule. It represents the ratio between the information quantity obtained and the energy quantity spent in a measurement. From the above considerations, the informational / energetic efficiency has a natural limit, approx. equal to $3 \cdot 10^{19}$ bit/J. Practical values for common categories of instruments range from $10^{15}\ldots10^{19}$ bit/J for electrometers to $10^{14}\ldots10^{18}$ bit/J for high-speed oscilloscopes and high-sensitivity galvanometers and $10^{4}\ldots10^{8}$ bit/J for usual moving-coil instruments.

2.7. Classification of the methods of measurement

The basic idea in the classification of *methods of measurement* is that a measurement is, without exception, a comparison. The presence of a reference quantity is essential in any measurement (although not always obvious).

The measurement can be performed by *simultaneous comparison* or by *successive comparison.*

In the simultaneous comparison, the measurand (quantity to be measured) is directly compared to a reference quantity of the same kind.

In the successive comparison, the reference (comparison) quantity does not participate in every measurement: it is used for the initial calibration (or graduation) and, if necessary, the periodic recalibration of the measuring instrument, which stores in its “memory” the calibration information. This information once received from the standard is transmitted by the measuring instrument every time a measurement is made. Consequently, in a simultaneous comparison the information is transferred at the same time from the standard and from the object under measurement, through the comparing instrument, to the observer (or other recipient of the measured data), whereas in the successive comparison this information is transferred in two stages, from the standard to the measuring instrument (at calibration) and then from the object under measurement to the measuring instrument and the observer (at every measurement).

In the simultaneous comparison, the measurand can be compared either to a reference quantity of equal (or nearly equal) value, or to a reference quantity of different value. The two kinds of measurement may be called “1:1 comparison” and respectively “1:*n* comparison”.

The 1:1 comparison is either a direct comparison, when the measurand is directly compared to the reference quantity, or an indirect comparison, when the measurement employs an intermediate device (comparator).

The direct 1:1 comparison can be performed by a differential method or a null method.

The indirect 1:1 comparison requires an intermediate comparator (comparing instrument). The main variants of the indirect 1:1 comparison are the method of simple comparison, the method of substitution and the method of transposition; the last two methods avoid the errors arising from the comparator, by a double measurement.

The 1:*n* comparison, where the measurand is compared to a reference quantity of different value, has two possible implementations: by superposition and by ratio techniques.

The method of successive comparison is typical of direct indicating instruments, in which one or more conversions of the signal carrying the measurement information take place. The examination of two simple examples will reveal some interesting features of the successive comparison: (a) the moving-coil ammeter and (b) the voltage/time conversion digital multimeter. In both cases, a simultaneous comparison occurs, between two intermediate quantities, one determined by the measurand and the other determining the output quantity [active and restoring torques for (a), intermediate and ramp voltages for (b)].

Figure 1 illustrates in a schematic way this classification.

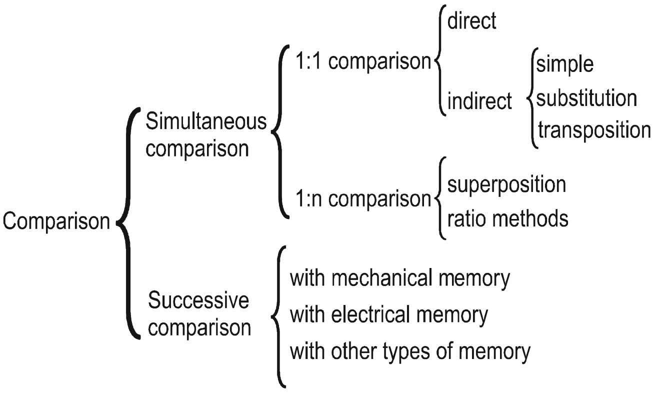

Figure 3. A general classification of the methods of measurement

2.8. Measuring instruments

Important points related to the measuring instruments are: general classifications, structure, measurement signals, measurement converters (transducers), measurement systems, metrological features and parameters.

The most common models of instrument structures are: series connection, feedback connection, two-input (multiplying or dividing) devices. In series connected structures, successive conversions take place, specific for each category of instrument (e.g. in an electronic strain measuring instrument, typically six such conversions may be identified, but there are cases where more than ten successive conversions occur). Converters may be classified in input, intermediary and output converters; analog / analog, analog / digital, digital / analog and digital / digital converters; dimensional or non-dimensional converters; "computing" converters.

Concerning the measuring systems, it is important to distinguish between systems composed of interchangeable or non-interchangeable elements, that is essential for their metrological characterization.

A special attention is given to the expression of performance characteristics of measuring instruments, first of all the error limits specifications. In this respect a lot of confusions are being produced, and therefore systematic and thorough explanations are required.

The behaviour of measuring instruments in the practical conditions of use is also particularly important for those involved in designing, implementing and exploiting measurement and control systems. In this context, the following aspects can be emphasized:

- The instrument-object interaction: the influence of the instruments upon the object under measurement, characterized by a parameter called *transparency* (or *finesse*); stability to overcharge; the instrument-object interconnecting.
- The instrument-environment interaction: influence of the atmosphere, surrounding fields (gravitational, electromagnetic, ionizing radiations, etc.), neighbouring objects and bodies, electrical supply, other instruments and accessories. Reference, rated and transportation (shelf) conditions have to be normalized. Sometimes the instrument itself may have an influence upon the environment. In a broad sense, the parameter "time" can

also be considered here, as an influencing factor (short-term and long-term drifts, ageing, etc.).

- The instrument-operator interaction (of foremost importance for the users): read-out devices and displays (analogue, digital, graphic), inscriptions and symbols, other means of information, controls, etc. A special mention is made of the accompanying documentation, which has to be considered as part of the instrument.

2.9. Measurement standards

The basic idea is that no measurements are possible at all without measurement standards. Such standards are needed at any level of a measurement system. Students have to be given pertinent information about the role of measurement standards, their derivation, comparison, calibration, traceability.

Standards are classified according to their destination, in: definition, conservation and transfer standards; according to their structure, in individual, series or group standards; according to their rank and role, in primary, secondary, reference and working standards. A particular role in the modern metrology is played by the so-called intrinsic standards, based on reproducible physical phenomena, not needing comparison to other standards.

Other subjects to be treated in this part of the General Metrology course: determination and recording of long time unstability of standards; interlaboratory comparisons of standards; dissemination of the units of measurement; the optimal recalibration periods; construction, utilities and environmental requirements for calibration laboratories.

2.10. Calibration and verification

Calibration of standards and/or instruments may be accomplished in different ways: directly (without an intermediary comparator) or through a comparator; by comparison with one or more different standards; by calibrating the individual components, and not the system as a whole; in special cases, by self-calibration, etc. In all cases, it is essential that the method of calibration assure the traceability to internationally recognized standards.

Distinction has to be made between calibration and verification. Generally, it is thought that calibration applies to the "non-regulated" area, whereas verification is specific to the "regulated" area. Another difference is that calibration is valid only for the moment of its accomplishment (it is a "photograph" of the calibrated item), but verification refers to a time interval until the next verification, guaranteeing the compliance with the requirements during this entire period. Nowadays, especially in connection with the quality assurance systems, the tendency is to extend the applicability of verification to all kinds of instruments, based on the definition of ISO Guide 25 (Verification: confirmation by examination and provision of evidence that specified requirements have been met).

2.11. Quality management

In a calibration laboratory, it is essential to implement an adequate quality management system, according to the general guidelines contained in ISO 9001:2000 series, and in conformance with the specific requirements of ISO 17025. Accreditation of the laboratory by a third party is required, to objectivate and make more credible its entire operation.

Therefore, it is important in a General Metrology course to outline the principles on which these documents rely, and to underline especially those aspects directly related to the metrological conditions.

The calibration laboratory has to document its policies, systems, programmes, procedures and instructions at a level which can assure the quality of the calibration results. The content of all documents used in this context should be transmitted to the laboratory personnel, understood and implemented. The major document, that represents a "radiography" of the organisation, is the Quality Manual, a basic requirement of the ISO 17025 standard.

3. CONCLUSION

We have been trying to bring up arguments in favour of introducing a course of General Metrology in technical universities. From the starting point, General Metrology is seen as a technical discipline, rather than a physical one. The illustrative examples given in the paper suggest certain new ways of teaching General Metrology, maintaining it among the "horizontal" type of engineering courses, essential for the technical education of a graduate student.

The paper is a result of our experience in this direction, after many years of teaching General Metrology at the University Politehnica of Bucharest, Romania, faculty of Electrotechnics.

REFERENCES

[1] International Vocabulary of Basic and General Terms in Metrology, ISO, 1993

[2] Vocabulary of Legal Metrology, OIML, 1978

[3] A. Millea, “General Metrology”, *Editura Tehnica,* Bucharest, 1985 (in Romanian)

[4] Guide to the Expression of Uncertainty in Measurement, First edition, ISO, Genève, 1993

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