Chapter 1: Generalities on Metrology

Introduction

What is the purpose of metrology?

Metrology, in the etymological sense of the term, translates to the Science of Measurement and its Applications.

Metrology traditionally deals with the determination of characteristics (called quantities) which can be fundamental, such as length, mass, time, etc., or derived from fundamental quantities, such as area, speed, etc. However, in common testing domains, there are numerous characteristics that only have an indirect relationship with these quantities. This is the case, for example, with hardness, viscosity, etc., which can pose problems in interpretation.

Measuring a physical quantity involves assigning it a quantitative value by taking as a reference a quantity of the same nature called a unit. In the common language of "metrologists," one often hears: to measure is to compare!

The results of measurements are used to make decisions:

- Acceptance of a product (measurement of characteristics, performance, conformity to a requirement);
- Adjustment of a measuring instrument, validation of a process;
- Adjustment of a parameter within the framework of controlling a manufacturing process;
- Validation of a hypothesis;
- Environmental protection;
- Definition of the safety conditions of a product or system;
- ...

All these decisions contribute to the quality of products or services: the quality of a measurement result can be *quantified* thanks to its uncertainty.

N.B.: Without uncertainty, measurement results can no longer be compared:

- either with each other (cross-testing);
- or relative to reference values specified in a standard or specification (product conformity).

Measurement of a physical quantity

First, let's define what is meant by **physical quantity**:

A physical quantity X is a discernible property characterizing an object, a system, or a physical state.

Two physical quantities are of the same kind (or of the same nature) when they can be compared. A quantity is measurable when one can define its equality with a quantity of the same nature and when their sum (or ratio) with a quantity of the same nature makes sense. If a quantity is measurable, one can then assign an objective numerical value to this quantity by counting how many times a quantity of the same kind, taken as a reference, to which the numerical value **1 (one)** is conventionally assigned and called a unit, is contained in the considered quantity.

The result is then written in the form:

$$X = \{X\} \cdot [X]$$

where X is the name of the physical quantity, $[X]$ represents the unit, and $\{X\}$ is the numerical value of the quantity expressed in the chosen unit.

N.B.: Every physical quantity is invariant, meaning it does not depend on the unit in which it is expressed. For example:

- Length of the ruler: 30.48 *cm*;
- " 0.3048 *m*;
- " 12 *inches*;
- " 1.646×10^{-4} *nautical miles*.

We note that the numerical value depends on the chosen unit. Consequently, it must always be specified.

A bit of vocabulary

In official vocabulary, the operation commonly called measurement is called **measuring**. Similarly, the physical quantity subjected to the measuring operation is called the **measurand**. Beware of false friends; the operation of **calibration** must be distinguished from that called **adjustment**.

N.B.: The term *precision* should not be used, but rather the term *uncertainty*.

It is important to differentiate the **repeatability** of measurement results, which is the closeness of agreement between successive results of the same measurand obtained under the same conditions of measurement, from **reproducibility**, where measurements are performed by varying the conditions of measurement.

The main parameters ensuring conditions of measurement for repeatability and reproducibility are recalled:

Repeatability:

- Same method;
- Same item (sample);

- Same laboratory;
- Same operator;
- Same equipment;
- Same ...

Furthermore, successive tests must be carried out over a short duration relative to the dynamics of the physical phenomena involved in a test.

Reproducibility:

- Same method;
- Same items;
- Different laboratory;
- Different operator;
- Different equipment;
- – ...

Types of Metrology

Metrology is divided into three categories comprising different levels of complexity and accuracy:

- Scientific metrology (also called **fundamental** or **laboratory** metrology) deals with the organization and development of measurement standards and their maintenance (at the highest level).

  Fundamental metrology has no international definition, but it indicates the highest level of accuracy for a given field. Fundamental metrology, therefore, must be considered the highest branch of scientific metrology.

- Industrial metrology aims to ensure the proper functioning of measuring instruments used in industry, as in production and testing processes.

- Legal metrology is concerned with measurements that influence the transparency of economic transactions, health, and safety. In other words, it is a set of rules imposed by the State concerning the system of units, the production, or the use of measuring instruments.

Scientific and Industrial Metrology

Metrology, measurement, and testing activities are sets of values that ensure the quality of industrial activities. This includes needs in terms of traceability, which become as important as the measurement itself.

Field of Activity

Scientific metrology can be divided into 9 technical fields of activity: mass, electricity, length, time and frequency, thermometry, ionizing radiation and radioactivity, photometry and radiometry, acoustics, and amount of substance.

Table 1: Domains, sub-domains and main measurement standards

Domains	**Sub-domains**	**Main Measurement Standards**
Mass and related quantities	Mass Measurement	Mass standards, balances, mass comparators.
	Force and Pressure	Load cell, deadweight tester, force, torque converters, oil/water lubricated piston-cylinder pressure balance, force testing machine.
	Volume and Density	Aerometers, glassware laboratory, vibration densimeter, capillary viscometers, rotational viscometers.
	Viscosity	Viscometric scale.
Electricity and Magnetism	Electricity – Direct Current	Cryogenic DC current comparators, Josephson effect and quantum Hall effect, Zener diode reference, potentiometric methods, comparison bridge.
	Electricity – Alternating Current	DC/AC converters, capacitance standards, air capacitors, inductance standards, compensators, wattmeters.
	Electricity – High Frequency	Thermal converters, calorimeters, bolometers.
	High Current and High Voltage	Current and voltage transformers, high voltage reference sources.
Length	Wavelength and Interferometry	Stabilized lasers, interferometry, interferometric measurement systems, interferometric comparisons, optical frequency generator.
	Dimensional Metrology	Gauge blocks, line standards, step gauges, rings, dial comparators, plugs, gauges, comparators, microscopes, optical flat, coordinate measuring machine, laser micrometer scanner, depth gauges.
	Angle Measurement	Auto-collimators, angle plates, angle gauges, polygons, levels.
	Form	Straightness, flatness, parallelism, squareness, circularity, cylindrical standards.
	Surface Quality	Step height and groove standards, circularity standard, circularity measuring equipment.

Time and Frequency	Time Measurement	Cesium atomic clock, time interval equipment.
	Frequency	Atomic clocks and fountains, quartz oscillators, lasers, electronic counters and synthesizers, (geodetic length measurement tools).
Thermometry	Temperature Measurement by Contact	Gas thermometers, ITS-90 fixed points, resistance thermometers, thermocouples.
	Temperature Measurement without Contact	High temperature black bodies, cryogenic radiometers, pyrometers, silicon photodiodes.
	Hygrometry	Dew point mirror or electronic hygrometers, dual pressure/temperature humidity generator.
Ionizing Radiation and Radioactivity	Absorbed Dose – Industrial Products	Calorimeters, high dose calibrated cavities, bichromate dosimeters.
	Absorbed Dose – Medical Products	Calorimeters, ionization chambers.
	Radiation Protection	Ionization chambers, reference beams/fields/radiations, proportional and other counters, tissue equivalent proportional counter, Bonner sphere neutron spectrometer.
	Radioactivity	Well-type ionization chambers, certified radioactive sources, gamma and alpha spectrometry, 4 detectors.
Photometry and Radiometry	Optical Radiometry	Cryogenic radiometer, detectors, stabilized lasers as reference source, reference fibers.
	Photometry	Visible detectors, Si photodiodes, detector quantum efficiency.
	Colorimetry	Spectrophotometer.
	Optical Fibers	Reference fibers.
Flow Measurement	Gas Flow (Volume)	Bell provers, rotary gas meters, gas turbine meters, sonic nozzle transfer standards.
	Water Flow (Volume, Mass and Energy)	Volume standards, Coriolis flowmeter, level gauge, inductive flowmeter, ultrasonic flowmeter.
	Liquid Flow other than water	
	Anemometry	Anemometers.

Measurement Standards

A measurement standard is a realized definition of a given quantity, with a determined value and an associated measurement uncertainty, used as a reference.

Example: The meter is defined as the length of the path travelled by light in vacuum during a time interval of 1/299,792,458 of a second. The meter is realized at the primary level in terms of the wavelength of a helium-neon laser stabilized on iodine. At lower

Acoustics, Ultrasound and Vibrations	Acoustic Measurements in Gases	Standard microphones, pistonphones, condenser microphone, sound calibrator.
	Accelerometry	Accelerometers, force transducer, vibration generator, laser interferometry.
	Acoustic Measurements in Liquids	Hydrophones.
	Ultrasound	Ultrasonic power measurement, radiation force balance.
Amount of Substance	Environmental Chemistry	Certified reference materials, mass spectrometers, chromatographs.
	Materials Chemistry	Material purity, certified reference materials.
	Nutritional Chemistry Biochemistry Microbiology	Certified reference materials.
	pH Measurement	Certified reference materials, standard electrodes.

levels, material measures such as gauge blocks are used, and traceability is ensured using optical interferometry to determine the length of the gauge blocks in reference to the laser wavelength.

The different levels of measurement standards are shown in Figure 2.1. The fields of activity, sub-fields, and important measurement standards are presented in Table 2.1.

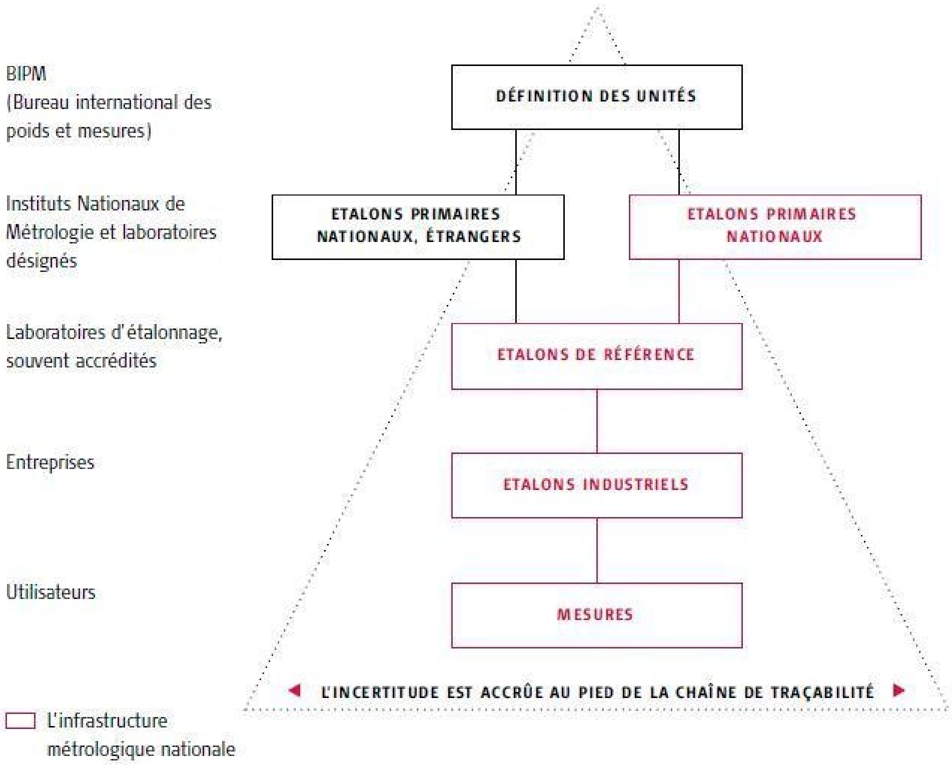

Figure 1: The traceability chain

Certified Reference Materials (CRMs)

A Certified Reference Material is a reference material characterized by a metrologically valid procedure for one or more specified properties, accompanied by a certificate that provides the value of the specified property, its associated uncertainty, and a statement of metrological traceability. Each certified value is associated with an uncertainty at a determined confidence level.

Certified reference materials are generally prepared in batches. The values of the properties are determined within specified uncertainty limits by measurements on representative samples of the entire batch.

Traceability

A traceability chain is "an unbroken chain of comparisons, all having stated uncertainties" (see Figure 1.1). This ensures that a *measurement result, or the value of a standard, is linked to references at the highest levels, the highest level being the primary standard.*

An end user must obtain traceability to the highest-level international standards either directly via a national metrology institute or through a secondary laboratory or calibration service.

Calibration

Calibration is a set of operations that establish, under specified conditions, the relationship between the values of quantities indicated by a measuring instrument or measuring system, or the values represented by a material measure or a reference material, and the corresponding values realized by standards.

A basic tool that ensures the traceability of a measurement is the calibration of a measuring instrument or a reference material. Calibration determines the characteristic performance of an instrument or a reference material. This is achieved by means of a direct comparison to a measurement standard or a certified reference material. A calibration certificate is issued and, in most cases, a label is affixed to the instrument.

Three major reasons for having an instrument calibrated:

1. To ensure that the instrument's reading is consistent with other instruments.
2. To determine the accuracy of the instrument's reading.
3. To establish the reliability of the instrument, i.e., that it can be trusted.

The result of a calibration can be recorded in a document called a **calibration certificate** or **calibration report**.

Legal Metrology

Legal metrology is the third category of metrology. The main objective of legal metrology is to ensure citizens correct measurement results during:

- Official and commercial transactions;
- Work, health, and safety contexts.

The government takes responsibility for ensuring the credibility of such measurements. Legally controlled instruments must guarantee correct measurement results:

- Under working conditions;
- For the entire period of use;
- Within the given permissible errors.

Therefore, worldwide, legislation issues requirements for measuring instruments and methods of measurement and testing, including pre-packaged products.

Metrological Vocabulary, Definitions

All definitions in this section are taken from the guide 'International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM)'.

Metrology

"Science of measurement and its applications".

Reference Material

"Material, sufficiently homogeneous and stable with reference to specified properties, which has been established to be fit for its intended use in measurement or in examination of nominal properties".

N.B.: Reference materials with or without assigned values can be used for measurement precision control, whereas only those with assigned values can be used for calibration or measurement trueness control.

Quantity

"Property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a reference".

N.B.: The reference can be a measurement unit, a measurement procedure, a reference material, or a combination of them.

Quantity Value

"Number and reference together expressing magnitude of a quantity".

N.B.: Depending on the type of reference, the quantity value is:

- Either the product of a number and a measurement unit;

  Example: Length of a given rod: 5.34 m or 534 cm.

  It is important to note that the unit is generally omitted for dimensionless quantities. **Example:** Mass fraction of cadmium in a given specimen of copper: 3 g/kg or 3×10^{-9};

- Or a number and the reference to a measurement procedure;

  Example: Rockwell C hardness of a given specimen: 43.5 HRC

- Or a number and a reference material.

  Example: Arbitrary substance concentration of lutropin in a given specimen of human blood plasma using the WHO international standard 80/552: 5.0 IU/l, where "IU" stands for "International Unit of WHO".

Numerical Quantity Value

“Number in the expression of a quantity value, other than any number serving as the reference”.

Measurement Standard

“Realization of the definition of a given quantity, with a determined quantity value and associated measurement uncertainty, used as a reference”.

In most cases, a standard is created from a reference material to obtain a given quantity, with a determined value and associated measurement uncertainty, used as a reference.

Working Standard

“Measurement standard that is used routinely to calibrate or verify measuring instruments or measuring systems”. A working standard used for verification is also designated as a “**verification standard**” or “**control standard**”.

N.B.: In the case where a measurement procedure is calibrated with a working standard, if one then wants to perform a verification of this procedure, another working standard must be used, which can then be called a “verification standard” or “control standard”.

Measurand

“Quantity intended to be measured”.

N.B.: The complete specification of the measurand requires three elements: the quantity, the constituent, and the system.

Example: Determination of the **molar concentration** of **lactose** in **milk**.

Measurement

“Process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity”.

Measurement Method

“Generic description of the logical organization of the operations implemented in a measurement”. Measurement methods can be qualified in several ways: direct measurement method, indirect measurement method, absolute measurement method, relative measurement method, direct comparison method, null method, etc.

Measurement Principle

"Phenomenon serving as a basis of a measurement".

Example: Thermoelectric effect applied to the measurement of temperature.

Measurement Procedure

"Detailed description of a measurement according to one or more measurement principles and to a given measurement method, based on a measurement model and including any calculation aimed at obtaining a measurement result".

Measurement Model

"Mathematical relation among all the quantities involved in a measurement".

Measured Quantity Value

"Quantity value representing a measurement result".

N.B.: For a measurement involving repeated indications, each can be used to provide a corresponding measured quantity value. This set of individual measured quantity values can then be used to calculate a resulting measured quantity value, such as an average or a median, generally with an associated measurement uncertainty that decreases.

When a measured quantity value is given, the measurement uncertainty is generally not associated, nor the necessary information concerning the measurement. A measured quantity value should therefore not be confused with a measurement result.

Measurement Result (Result of Measurement)

"Set of quantity values being attributed to a measurand together with any other available relevant information".

N.B.: A measurement result is generally expressed by a single measured quantity value and a measurement uncertainty.

International Metrology Institutions

The Metre Convention

The **Metre Convention** is the international treaty signed on May 20, 1875, in Paris (France) by seventeen states with the aim of establishing a global authority in the field of metrology. It thus succeeded the *International Commission of the metre* set up in 1870.

To this end, three structures were created. The Convention thus delegates to the **General Conference on Weights and Measures (CGPM)**, the **International Committee for Weights and Measures (CIPM)**, and the **International Bureau of Weights and Measures (BIPM)** the authority to act in the field of metrology, ensuring harmonization of the definitions of the different units of physical quantities. These works finally led to the creation of the **International System of Units (SI)**.

General Conference on Weights and Measures (CGPM)

The CGPM meets at least once every 6 years upon convocation by the French Ministry of Foreign Affairs. The current frequency is 4 years. It is a diplomatic conference that brings together the delegates of the 55 Member States of the Metre Convention and the 34 associates of the CGPM (as of 01/08/2011).

During each general conference, members base their decisions on the report(s) of the International Committee for Weights and Measures (CIPM) detailing the work accomplished. They then take appropriate measures for the extension and/or improvement of the International System of Units (SI), as well as general provisions and recommendations concerning metrology. Administrative decisions concerning the operation of the BIPM are also discussed.

In summary, the CGPM's mission is:

- To elect the members of the CIPM;
- To discuss and decide on the necessary measures to ensure the extension and improvement of the implementation of the International System of Units, the SI;
- To sanction the results of new fundamental metrological determinations and to adopt various scientific resolutions of international scope;
- To adopt important decisions concerning the operation and development of the BIPM.

International Committee for Weights and Measures (CIPM)

The CIPM meets annually. It is composed of 18 personalities, scientists and metrologists of different nationalities, elected in a personal capacity by the CGPM.

The CIPM's mission is:

- To prepare proposals and recommendations to be submitted to the CGPM;
- To supervise and direct the work of the BIPM;
- To prepare an annual report on the financial and administrative situation of the BIPM.

Given the growing number of Member States and the scientific and technical work developed by National Metrology Institutes, the CIPM has created, since 1927, a series of Consultative Committees to enable it to study more thoroughly scientific and technical progress that can have a strong influence on metrology.

The Consultative Committees (CCs) are composed of experts and world specialists working in National Metrology Institutes. The number of members is limited; therefore, not all Member States of the Metre Convention are represented in each CC. The chairmanship of a Committee is held by a member of the CIPM.

The CCs' mission is:

- To study scientific and technical work and progress, and their consequences in metrology;
- To prepare recommendations that will be discussed by the CIPM and then presented to the CGPM;

- To organize international comparisons of measurement standards and analyze their results;
- To issue recommendations on the work that the BIPM could carry out.

International Bureau of Weights and Measures (BIPM)

The BIPM, located at the "Pavillon de Breteuil" in Sèvres (Paris), is a scientific metrology laboratory whose essential mission is to ensure the uniformity of measurements (both physical and chemical) worldwide. The Director of the BIPM is appointed by the CGPM. The BIPM conducts fundamental research aimed at improving reference standards in collaboration with National Metrology Institutes (NMIs), participates in and organizes international comparisons, and maintains the reference standards under its responsibility.

The only quantity still represented by a material standard is mass. The BIPM maintains the international prototype of the kilogram, K, to which the NMIs must compare. This comparison is performed very rarely so as not to alter the characteristics of the international prototype. Only three comparisons have been made to date.

International Organization of Legal Metrology (OIML)

The OIML is an intergovernmental organization established on October 12, 1955; its objective is to promote the standardization of legal metrology. In 2015, it had 60 Member States (including Algeria) and 68 Corresponding Members.

The mission of the OIML is to enable economies to set up effective, mutually compatible, and internationally recognized legal metrology infrastructures, in all areas for which governments are responsible, such as those that facilitate trade, establish mutual trust, and harmonize levels of consumer protection worldwide.

The OIML aims to:

- Develop model regulations, standards, and related documents intended for use by legal metrology authorities and industry;
- Provide mutual recognition systems that reduce trade barriers and costs in a global market;
- Represent the interests of the legal metrology world within international organizations and forums concerned with metrology, standardization, testing, certification, and accreditation;
- Promote and facilitate the exchange of knowledge and skills within the global legal metrology community;
- In cooperation with other metrology bodies, raise awareness of the contribution that a solid legal metrology infrastructure can make to modern economies.

In addition to these institutions, we can mention: Africa Metrology System (AFRIMETS) and the Maghreb Metrology Network (MAGMET).

National Metrology Institutions

History of Algerian Metrology

- Before 1962: Service des Poids et Mesures (Weights and Measures Service)
- From 1962 to 1980: Service des instruments de Mesure (Measuring Instruments Service) (attached to the Directorates of Industry and Energy).
- From 1980 to 1986: Sous-direction des instruments de mesure de wilaya (Wilaya Measuring Instruments Sub-directorate)
- In 1986: Creation of the Office National de Métrologie Légale (ONML) (National Office of Legal Metrology)
- In 2002: Conseil National de Métrologie (National Metrology Council) created by executive decree No. 02-220 of June 20, 2002.

National Office of Legal Metrology (ONML)

ONML is a Public Administrative Establishment (EPA), under the Ministry of Industry and Mines, endowed with financial autonomy and created in 1986 by Decree No. 86-250 of September 30, 1986.

Missions of the ONML

- To participate in safeguarding public guarantee and protecting the national economy in terms of national and international commercial exchanges;
- To carry out studies and tests of new models of measuring instruments with a view to their approval;
- To carry out initial and periodic verification of measuring instruments used in commerce and industry;
- To carry out surveillance to ensure that measuring instruments comply with legal requirements;
- To develop technical regulations;
- To acquire and maintain national standards;
- To develop and promote metrology.

Regulation and Legislation

Law 90-18 relating to the National Legal Metrology System establishes the general rules contributing to the protection of the citizen and the national economy.

The national legal metrology system uses the International System of Units (SI). It comprises the following seven base units:

1. The metre, unit of length;

2. The kilogram, unit of mass;
3. The second, unit of time;
4. The ampere, unit of electric current;
5. The kelvin, unit of thermodynamic temperature;
6. The candela, unit of luminous intensity;
7. The mole, unit of amount of substance.

Implementation of the National Legal Metrology System

The national legal metrology system has the following missions:

- Approval of models of measuring instruments;
- Initial verification of new measuring instruments;
- Periodic verification;
- Initial verification of repaired measuring instruments;
- Surveillance.

These missions aim to define the conformity control of instruments intended to measure quantities. Conformity control includes:

- The study and testing of new models of measuring instruments with a view to their approval;
- The initial verification of new or readjusted measuring instruments, to ascertain that new instruments conform to an approved model and that readjusted instruments meet regulatory requirements;
- The periodic verification of measuring instruments, aimed at ensuring that these instruments have undergone initial verification and to prescribe the readjustment or decommissioning of those that do not meet regulatory conditions;
- Surveillance to ensure that measuring instruments in service comply with legal requirements, that they are in regular working order, and that they are used correctly and fairly.

Verification marks are affixed to controlled measuring instruments. These marks are characterized as follows:

- Initial verification mark: Star inscribed in a circle.
- Periodic verification mark: One of the letters of the national language alphabet.
- Rejection mark: Asterisk in a circle.
- Any holder of a measuring instrument not bearing the conformity verification mark is punishable by the penalties provided for in Articles 451 and 452 of the Penal Code.