BE-BI

Concepts and Glossary for the Specification of the Beam Instrumentation

J-J. Gras [BE-BI]

Summary

This document describes a measurement chain at the conceptual level and present the technical glossary that will be used to specify as precisely as possible its components and requirements.

This is a BE-BI internal publication.

Table of Content

1. Introduction

The specification of the measuring devices implies a precise description of their requirements. Experience has shown when talking about dynamic ranges, precision,… that well-known terms are used with different meanings and that there are several synonyms for the same concepts. This is probably a sign that the definitions of some concepts has to be sharpened. Starting from common sense and using available documents from Cern [1] and ISO [2,3], we attempt in this note to clarify the issues and propose a glossary with hopefully un-ambiguous definitions of the terminology.

We first introduce the concepts and definitions. The key words (printed in bold) are then gathered in a glossary for a quick access. A clear glossary being a tool rather than a goal, there is no attempt at universality or completeness. This document discusses the minimum set of concepts and terminology found so far useful and shall be expanded whenever required.

2. The Measurement Chain

We describe in Figure 1 a typical beam measurement chain.

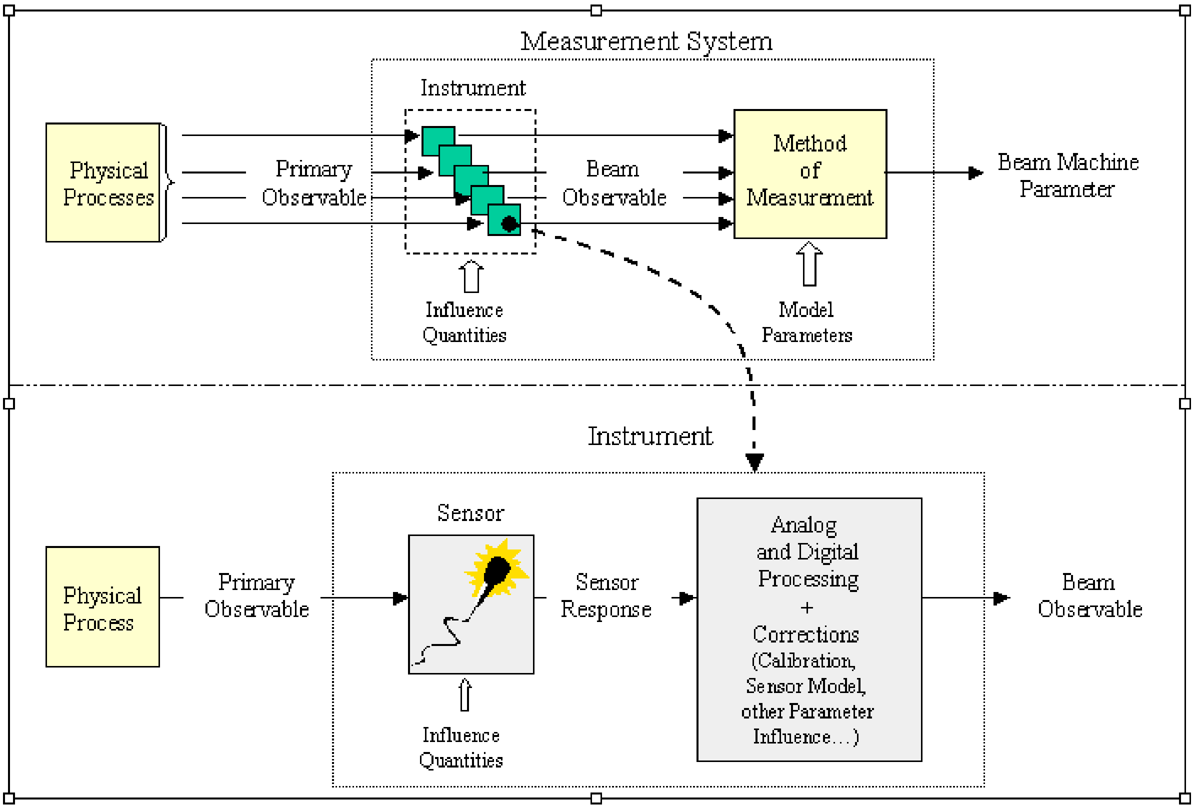

Figure 1: Measurement chain description

2.1. Observables and Parameters

The physical process is the beam dynamics in the accelerator electro-magnetic field. It is accessible through quantities referred as **primary observables** (i.e. electromagnetic coupling, synchrotron radiation, optical transition radiation…). The **instrument** converts the primary observables into **beam observables** such as the beam position, the transverse and longitudinal distributions, the beam current and the losses. They can be different from the **beam** and **machine parameters** which are derived from them (the beams ignore the theory of beam dynamics and its parameterisation). Examples of parameters are the betatron tunes and chromaticity, the Twiss parameters, the anharmonicity, the field multipoles…

In metrology, these quantities subject to measurements (observable and parameters) are also called **measurands**.

An important characteristic of an observable is its **dynamic range,** defining the set of all possible values it may take. These values are **true values**, inaccessible in practice. The concept is however useful in calculations.

2.2. Measurement System

The **measurement system** is the logical block that allows the measurement of a beam/machine parameter from the true values of primary observables. It includes the measuring devices and the algorithms necessary to convert the measured values of the primary observables into the wanted beam/machine parameter. Its capability is limited by the uncontrolled part of the **influence quantities** (like surrounding temperature, ground instabilities, EMC...) and by the model imperfections.

An important issue is its **sensitivity,** defined as the change in the measured beam/machine parameter divided by the corresponding change of the true values of the primary observables.

2.3. Instrument

The measurement of the beam observables involves a physical process, e.g. photon counting by diodes or electro-magnetic coupling for the BPM electrodes. This measuring device or **instrument** is composed of:

- a **sensor** that will translate the primary observable into electrical signals,
- the analog and digital processing,
- the **correction** algorithm.

Important parameters of the instrument are

- its **sensitivity**, defined as the change of the beam observable divided by the corresponding change of the primary observable,
- its **dynamic range**, defined as the range of values of the beam observable which can be measured with a given **precision** goal,
- its precision, discussed in section 3.

Note that the concept of sensitivity is `distributive' in a measurement system while the concept of dynamic range is different for observables and **measurement devices**.

The ideal transfer function of a measurement device is linear with a slope equal to the sensitivity of the measurement devices. **Correction** may be made inside the instrument to take into account known systematic deviations arising from the physics of the process involved or from the **influence quantities**. The latter summarize the possible influence of the environment of the instrument. Their range of values defines the **conditions** under which a measurement can be performed.

2.4. Response

The evaluation of a beam observable is often called the **response** of the instrument. The response is the true value of the observable augmented by a measurement error.

2.5. Measurement Method

The **measurement method** is an algorithm. It requires in general several beam observables and a model of the accelerator or of the beam to compute beam/machine parameters. A simple example is the measurement of the dispersion: it requires the measurement of two orbits, two RF frequencies, the beam energy, the knowledge of the momentum compaction and an assumption on the linearity of the dynamics over the measured momentum range. The knowledge of the measurement method is required to calculate the propagation of the measurement errors, estimate the model errors to finally estimate the precision of the measurement of the beam/machine parameters.

3. The Precision of Measurements and Measuring Devices

When reporting the result of a measurement, some indication on its **precision** is necessary to assess its reliability. Precision is a general concept to characterise the quality of an instrument or of a measurement. This word includes different notions which are now detailed.

3.1. Errors versus Uncertainties

When measuring a quantity, the measurement device adds an error to the true value of the measurand. The equation of the measured value of the measurand is therefore

Response = True Value + Error

Although the true value and error are unknown, this expression is useful to study the propagation of errors throughout the measurement methods when the parameters measured do not depend straightforwardly on the observables.

The true value of the errors being unknown, an estimate of their statistical distribution is somehow made. The most relevant parameter of this distribution is called the **uncertainty**. In most cases the uncertainty is either the standard deviation of the error distribution or a domain which contains the estimated value of the measurand (or the error) at a given level of confidence:

True Value of the Measurand ∈ Measured Value ± Uncertainty

under given **Conditions**

3.2. Confidence Levels and Error Distributions

3.2.1. Confidence Levels

A confidence interval is a interval estimate of a parameter and is used to indicate the reliability of an estimate. It is an observed interval (i.e it is calculated from the observations), in principle different from sample to sample, that frequently includes the parameter of interest, if the experiment is repeated. How frequently the observed interval contains the parameter is determined by the **Confidence Level**.

3.2.2. Rectangular Distribution

If a quantity is specified by fabrication tolerances, the distribution of errors should be assumed to be constant within the domain allowed by the tolerances. Let x be the quantity and Δx the tolerance, the standard deviation is given by:

$$\sigma_x = \Delta x / \sqrt{3}$$

3.2.3. Gaussian Distribution

If a quantity is known by measurements or if the sources of uncertainties are numerous, the Gaussian distribution is generally a good approximation.

The confidence levels associated to various tolerances expressed as a function of the standard deviation are given in table 1:

Tolerance	Confidence Level
±1 σ	68.3%
±1.5 σ	86.6%
±2 σ	**95.5%**
±2.5 σ	98.8%
±3 σ	99.7%

Table 1

3.2.4. Combinations of Errors

In most cases, the errors are not correlated (or their correlation is not known). Taking into account their assumed distributions, the tolerances are converted into standard-deviations. The latter are summed quadratically and converted back to tolerances, assuming that the final distribution is gaussian.

If the errors are correlated, the standard deviations will be summed.

Under normal circumstances, we choose a confidence level of 95.5%, i.e. a tolerance at 2 σ. In certain cases, a 3 σ tolerance may have to be used.

3.3. Uncertainties versus Accuracy

While the uncertainty is a statistical quantity qualifying the precision of a class of measurements, the **accuracy** qualifies the demand on precision for the same measurements. The concepts are close but the point of view differs:

- If, for a single class of measurements, the uncertainty equals the accuracy, the precision of the measurement exactly matches the requirement.

- If there are several possible classes of measurements which may be carried out with a given instrument, their requirements on accuracy may differ. When the uncertainty of the measurement is equal or lower than the tightest requirement on accuracy, the precision of the instrument is deemed satisfactory.

Uncertainty ≤ Accuracy

within given **Conditions**

3.4. Resolution

Another important precision concept is the **resolution**. The resolution is the smallest increment that can be induced or discerned by the measurement device within given conditions. The resolution usually arises from systematic (e.g. diffraction limit, quantification error) and noise effects (see section 4.2).

3.5. Repeatability versus Reproducibility

We discussed so far the precision of isolated measurements or of classes of measurements assumed to have been carried out at the same time. We describe here the time dependence of the precision, often called **stability**:

- The **repeatability** expresses the closeness of the agreement between the results of successive measurements of the same measurand carried out under the same **repeatability conditions**, i.e.:
    - the same measurement procedure
    - the same measuring instrument, under the same conditions (same influence quantity values…)
    - repetition over a `short' period of time
- The **reproducibility** expresses the closeness of the agreement between the results of successive measurements of the same measurand carried out under conditions which may have change in the meantime.

The systematic part of the reproducibility error is generally called the **drift**.

3.6. Reliability, Availability and Safety Integrity Levels

...Chapter in Work...

Several terms can be used to express the robustness of a system:

- **Reliability** is the ability of a system to perform and maintain its functions in routine circumstances, as well as hostile or unexpected circumstances. This is a quite subjective definition.
- **Availability** is the proportion of time a system is in a functioning condition. This term can be quantified and is more relevant for specifications

The following terms are more or less equivalent:

- **MTBF** = mean time between failure
- **MTTR** = mean time to recovery

Since **Availability= MTBF/(MTBF+MTTR)**

The requirements in terms of reliability of a system depend on its **Criticality**. **Criticality** can be defined as the degree of being of the highest importance. In our context, it is often based on the importance of the damage consequences of a system failure in terms of human safety, machine down time and/or repair cost.

In this contaxt, **Safety Integrity Levels** (SIL) may be used whenever necessary to specify a target level of risk reduction for critical systems.

To achieve a given **SIL**, the device must meet targets for the maximum probability of dangerous failure (see following table). The concept of 'dangerous failure' must be rigorously defined for the system in question, normally in the form of requirement constraints.

PFD (Probability of Failure on Demand) and RRF (Risk Reduction Factor) of continuous operation for different SILs as defined in IEC EN 61508 are as follows:

SIL	**PFD**	**PFD (power)**	**RRF**
1	0.00001-0.000001	10^{-5} - 10^{-6}	100,000-1,000,000
2	0.000001-0.0000001	10^{-6} - 10^{-7}	1,000,000-10,000,000
3	0.0000001-0.00000001	10^{-7} - 10^{-8}	10,000,000-100,000,000
4	0.00000001-0.000000001	10^{-8} - 10^{-9}	100,000,000-1,000,000,000

n.b.: The robustness of an acquisition chain is just as poor as its weakest link. In the context of beam instrumentation specifications, any SIL requirement will be only considered by the beam instrumentation group for the part that falls under its responsibility. Hazards of the surrounding general services (main power, GMT, control system...) used by the instrument will not be taken into account and must be identified and analysed separatly to get the full system picture.

...Chapter in Work...

4. Nature and Break-down of the Errors or Uncertainties

With the understanding that the errors are true values while the **uncertainties** are parameters of the error distributions, it is not necessary anymore to distinguish them when considering their natures. We therefore stick to the usual vocabulary.

4.1. Systematic and Random Errors

In the absence of any **noise** and under strictly nominal conditions, a measurement may be perturbed by **systematic errors** not [fully] corrected in the instrument or introduced by some limitations of the measurement method. **Random errors** are caused by the noise in the instrument or by random fluctuations of the influence quantities.

It should be noted that this separation is not absolute and depends on the exact definition of the instrument. An offset of a BPM is a systematic error when measuring the beam position. When considering the BPM system as a whole, the BPM offsets are mostly a random error with some possibly small systematic component.

4.2. Break-down of the Errors

Qualifying the precision of a measurement by its uncertainty may often not convey sufficient information. For instance, an uncorrected offset will have no effect on a differential measurement between two consecutive acquisitions. The uncertainty due to a random noise may be reduced by averaging. The non-linearity may induce a fake signal in an interesting frequency band.

In this chapter, we define in addition to the previous glossary a few terms to specify the different types of **Errors/Uncertainties** encountered so far (not exhaustive).
Practically, any of the following error component whose value is less than the resolution of the instrument is deemed negligible.

4.2.1. Noise

The **noise** is the range of the random error contribution to the measurement within given conditions. By random, we mean unpredictable (like noise collected by cables…) or unpredicted (like error coming from influence quantities fluctuations that we could but don't measure…).

4.2.2. Offset

The **offset** is a constant contribution to the evaluation independent of the measurement point within given conditions. This definition implies that the **offset** can be corrected to a certain extend by calibration techniques. In the case of the BPM's for instance, the global offset is given by the mechanical alignment error and the electronic offset. A basic property for an offset is that it disappears during relative measurements.

4.2.3. Scaling Factor

The **scaling factor** introduces a linear error equal to the measurand value multiplied by the scaling factor error over the whole dynamic range.

4.2.4. Linear Coupling Factors

The evaluation of the measurand may be perturbed by an error linear in other quantities that the measurand itself: the influence quantities. For instance, a **roll** of a BPM introduces a dependence of the horizontal beam position on the vertical one.

4.2.5. Non Linearity

The **non linearity** is the error due to the higher-order dependence of the measurement on the measurand and on the influence quantities. It is defined by its maximum in specified dynamic ranges for the measurand and the other relevant quantities. Whenever possible, the type of the non-linearity is specified, e.g. a dominant third harmonic…

4.2.6. Trend

The **trend** represents the contribution to the correction or uncertainty due to the evolution of an influence quantity.

5. Glossary

Most of the following definitions of general metrological terms are taken from [1, 2]. We give in *Italic* the French equivalent of the word defined. The use of parentheses around certain words means that these terms can be omitted if this is unlikely to cause confusion. We also added a few definition for our own purpose, i.e. the BI functional and technical specifications.

Accuracy (of measurement) ~ *Exactitude (de mesure)* [1,2]

Closeness of the agreement between the result of a measurement and the value of the measured quantity.

> It is a qualitative concept used to specify requirements or tolerances.
>
> The term precision should not be used for 'accuracy'.
>
> The term Accuracy should not be used for relative precision from shot to shot. Repeatability and Reproducibility should be used instead.

Conditions ~ *Conditions* [2]

Description of the environment for a set of measures. It consists of ranges of the measured and influence quantities, time… where the given properties of the measurement are valid. Every entity not specified in these conditions is supposed to have no significant effect on the measure.

Correction ~ *Correction* [1,2]

Value added algebraically to the primary result of a measurement to compensate for systematic error.

> The correction is equal to the negative of the estimated systematic error.

Correction Factor ~ *Facteur de Correction* [1,2]

Numerical factor by which the primary result of a measurement is multiplied to compensate for systematic error.

Dead Band ~ *Zone Morte* [2]

Maximum interval through which a measurand may be changed in both directions without producing a change in response of a measure.

Drift ~ *Dérive* [2]

Slow change of a metrological characteristic of a measuring instrument corresponding to the systematic effects of the reproducibility error.

Dynamic Range ~ *Gamme Dynamique*

We differentiated two types of dynamic ranges depending on the context:

- For an observable, the dynamic range is the set of all possible values it may take
- For an instrument, the dynamic range is defined as the range of values of the beam observable which can be measured with a given precision.

Error (of measurement) ~ *Erreur* [1,2]

Result of the measurement minus the true value of the measured quantity.
Two different types of errors are defined:

Random Error ~ *Erreur Aléatoire* [1,2]

Result of a measurement minus the mean that would result from an infinite number of measurements of the same observable carried out under repeatability conditions.

> Random error is the contribution of the random effects to the error of the measurement.
>
> Random error is equal to error minus systematic error.

Systematic Error ~ *Erreur Systématique* [1,2]

Mean that would result from an infinite number of measurements of the same Measurand carried out under repeatability conditions minus a true value of the Measurand.

> Systematic error is the contribution of the systematic effects to the error of the measurement.
>
> Systematic error is equal to error minus random error.
>
> Like the value of the measurement, systematic error cannot be exactly evaluated.

Influence Quantity ~ *Grandeur d'Influence* [1,2]

Quantity that is not the measurand but that affects the result of the measurement (like the bunch current for orbit measurements, surrounding temperature, ground instabilities, EMC...).

Instrument ~ *Instrument*

The instrument is the measurement device that transforms the primary observable (the electromagnetic coupling for instance) into an evaluation of the beam observable (the beam position in this case). It may consist of a sensor, an analogue and digital treatment and a correction algorithm.

Linear Coupling Factors ~ *Facteurs de Couplage Linéaire*

The evaluation of the measurand may be perturbed by an error linear in other quantities that the measurand itself: the influence quantities. For instance, a roll of a BPM introduces a dependence of the horizontal beam position on the vertical one. The linear coupling factors introduce a systematic error equal to the influence quantity value multiplied by the corresponding linear coupling factor.

Measurand ~ *Mesurande* [1,2]

Particular quantity subject to measurement. In our context, the measurand of a sensor is the primary observable, the measurand of an instrument is the beam observable, the measurand of a measurement system is the beam/machine parameter.

Measurement ~ *Mesurage* [1,2]

Set of operations having the object of determining a value of a quantity.

Measurement Device ~ *Moyen de Mesure*

A measurement device is a generic term. It can be one of the three following items:

- A sensor
- An instrument
- A measurement system

Measurement Method ~ *Méthode de Mesure*

The measurement method is the algorithm that compute the requested beam/machine parameters from the evaluation of several beam observables and the knowledge of a model of the accelerator or the beam.

Measurement System ~ *Système de Mesure*

The measurement system is the measurement device that transforms a set of primary observable into an evaluation of a beam or machine Parameter. It consists of several instruments feeding a measurement algorithm.

Noise ~ *Bruit*

Range of the random error contribution to the measurement within given conditions.
By random, we mean unpredictable (like noise collected by cables…) or unpredicted (like error coming from influence quantities fluctuations that we could but don't measure…).

Non Linearity ~ *Non Linéarité*

The non linearity is the error due to the higher-order dependence of the measurement on the measurand and on the influence quantities. It is defined by its maximum in specified dynamic ranges for the measurand and the other relevant quantities. Whenever possible, the type of the non-linearity is specified, e.g. a dominant third harmonic,…

Observable ~ *Observable*

Quantity being used as an input to evaluate an other quantity. In our context, we differentiated two types of observables:

Primary Observable

The primary observable is the input of the instrument, and thus of the sensor, like for instance the electromagnetic coupling, the synchrotron radiation...

Beam Observable

The beam observable is the output of the instrument, like for instance the beam position, and will be used as the input for the beam/machine parameter evaluation algorithm.

Offset ~ *Piédestal*

Constant contribution to the evaluation independent of the measurement point within given conditions. This definition implies that the offset can be corrected to a certain extend by calibration techniques. In the case of the BPM's for instance, the global offset is given by the mechanical alignment error and the electronic offset. A basic property for an offset is that it disappears during relative measurements.

Parameter ~ *Paramètre*

Quantity derived from one or several beam observables through a given procedure or set of calculations (like the lifetime, the tune, the machine optic…).
We differentiated beam parameters (like lifetime, tune…) and machine parameters (Optic…).

Precision ~ *Précision*

General concept to characterise the quality of an instrument. This word includes different notions (like accuracy or resolution) and should only be used in this view. We will for instance speak of document describing in details the accuracy and resolution as a document describing the precision of the instrument.
Precision should not be used for accuracy or resolution.

Quantity ~ *Grandeur* [1,2]

Attribute of a phenomenon, body or substance that may be distinguished qualitatively and determined quantitatively.

Repeatability (of results of measurements) ~ *Répétabilité* [1,2]

Closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement.

These conditions are called repeatability conditions. They include:

- The same measurement procedure
- The same measuring instrument, under the same conditions (same influence quantity values…)
- Repetition over a short period of time

Repeatability may be expressed quantitatively in terms of the dispersion characteristics of the results. In some cases, reproducibility can be more relevant than absolute accuracy.

Reproducibility (of results of measurements) ~ *Reproducibilité* [1,2]

Closeness of the agreement between the results of successive measurements of the same measurand carried out under conditions which may have change in the meantime.

Reproducibility may be expressed quantitatively in terms of the dispersion characteristics of the results. In some cases, reproducibility can be more relevant than absolute accuracy.

Resolution ~ *Résolution* [1,2]

Smallest increment of the measurand that can be induced or discerned by the system within given conditions.

Response ~ *Réponse* [2]

Depending on the context:

- Output signal of a sensor.

Or

- Result of a measurement.

Roll ~ *Roulis*

Tilt angle along the longitudinal axe.
For instance, a small rotation of a BPM of Roll gradients will induce a correction of Roll*y in the x measurement.

Scaling Factor ~ *Facteur d'Echelle*

The scaling factor introduces a systematic error equal to the measurand true value multiplied by the scaling factor.

Sensitivity ~ *Sensibilité* [2]

- The sensitivity of a sensor will be the change in the response of the sensor divided by the corresponding change in the primary observable.
- The sensitivity of an instrument will be the change in the evaluation of a beam observable divided by the corresponding change in the primary observable.
- The sensitivity of an measurement system with respect to a given primary/beam observable will be the change in the evaluation of a beam/machine parameter divided by the corresponding change in the primary/beam observable.

Sensor ~ *Capteur* [2]

Element of a measuring instrument or measuring chain that is directly affected by the measurand. The sensor is the measurement device that transforms the primary observable (which is functionally related to the beam observable to measure) into usable electrical signals.

Stability ~ *Stabilité*

General concept to characterise the behaviour in time of an instrument. This word includes the following two different notions: the repeatability and the reproducibility. Stability should only be used in this view.

Trend ~ *Tendance*

Contribution to the correction or uncertainty due to the evolution of an influence quantity.

Uncertainty (of measurement) ~ *Incertitude* [1,2]

Parameter, associated with the result of a measurement, that characterises the dispersion of the values that could reasonably be attributed to the measurand.

> This parameter could be, for example, a standard deviation (or a given multiple of it), or the half-width of an interval having a stated level of confidence.

Conventional Value (of a quantity) ~ *Valeur Conventionnelle* [1,2]

Value attributed to a particular quantity and accepted, sometime by convention, as having an uncertainty appropriate for a given purpose (like the wave length of a laser used for test…).

6. Acknowledgements

We would like to express here our gratitude to F. Bordry (SL-PO) who introduced us to the standart documents mentioned in the references and to the members of the SL-BI Specification and Technical Committees for their valuable comments.

7. References

[1] LHC Dynamic Effects Working group

[2] "Guide to the Expression of Uncertainty in Measurement", BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML.

[3] "International Vocabulary of Basic and General Terms in Metrology", BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML.