Metrology: time for a new look at the physics of traceable measurement?

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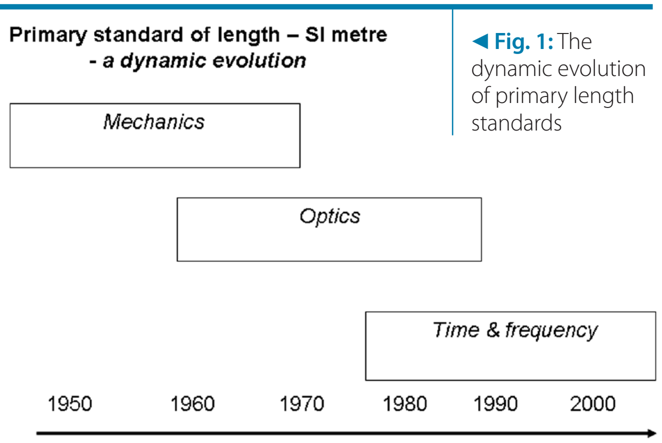
How do advances in physics contribute to the international system of measurement units, the SI, and to better measurements in all parts of society? Can collaboration between academic physicists and the national metrology institutes be more co-ordinated than today's occasionally ad hoc in order to better meet future demands for traceability?

The International System of Units referred to as the SI, covering the base units (metre, kilogram, second, kelvin, candela, ampere, mole) and the derived units, provides a basis for ensuring that reliable measurements give the same answer wherever they are made in modern society. This system is based on and, in turn, supports continual and long-term research in fundamental science and technology. There are many and distinguished examples where fundamental physics has contributed to the development of the SI and traceable measurements, involving several Nobel prizes in Physics.

There are ever increasing demands for traceable measurement – enabling reliable measurements that give the same answer wherever they are made - not only in traditional areas such as manufacturing and process industries but increasingly in wider areas:

- The emergence of new areas of science and technology such as nanotechnology and biotechnology
- The need to support traditional areas of physical metrology in which research is often becoming more complex
- Increased recognition of the value of Metrology in existing areas (clinical medicine, food safety, the environment etc)

In fact, demands are increasing so much that primary metrology, as provided by the national metrology institutes, is facing a dilemma of increasing consequence, since resources are limited. To solve this dilemma, European metrologists and others with a vested interest in traceable measurement are at present formulating plans for a new European-wide coordination of national metrology research programmes. In particular, a European ERA-NET programme iMERA [1], with the support of the European Commission, "*Implementing Metrology in the European research Area*", is at present laying the foundations of a co-ordinated approach to meet these metrology needs in Europe. The most recent plans for the EU's 7th framework programme in fact mentions metrology as one of only four proposed candidates for an Article 169 coordination action.



◀ **Fig. 1:** The dynamic evolution of primary length standards

The European metrology infrastructure is underpinned by the National Metrology Institutes (NMIs) in Europe. The NMIs provide the primary measurement capability to the calibration community and to industrial, regulatory and scientific customers. To ensure that this capability remains at the cutting edge many of the NMIs undertake significant research and development (R&D). This leading edge capability in turn provides the tools that enable world class R&D in wider fields.

Physics and the SI

Accurate measurement:
Is it the domain of the Engineer or the Physicist?

"The number of electrical measuring instruments recently devised is very great. The practical man is not satisfied with the delicate instruments of the physicist, whilst the latter, of course, cannot be satisfied with the results of the measuring instruments arranged by engineers and technical electricians, however satisfactory for industrial purposes" (*The Telegraphic Journal* 1884, quoted in [2])

Measurement accuracy is an elusive concept, often with different meanings for different people as illustrated by the above quote from over 120 years ago.

A good description may be found in recent international standardisation where accuracy is defined in terms of both precision (amount of scatter in repeated measurement data) and trueness (size of systematic error).

A broad generalisation would be to assign the task of achieving good precision to the measurement engineer, whereas it is the task of the physicist to provide best estimates of the true value of a physical quantity. Here "truth" refers not simply to a freedom from error, but to something rather more absolute, as we discuss below.

Absolute accuracy and physics

The "delicate" instruments of the physicist, referred to in 1884, were not only used merely to make precise measurements (such as of the small electric currents in earlier telegraphy). The physicists' instruments also provided above all an "absolute" accuracy, in other words a "trueness", by which electrical quantities could be derived from the units of length, mass and time, the fundamental "base" units of the Metric system at that time. The universality and trueness of the latter were based on the ultimate physical reference of the era, namely the size and period of rotation of the Earth in true revolutionary universality "A tous temps: A tous peuples". It took many years and was not until the electron was discovered at the turn of the century before direct electrical measurements, with the voltmeter and ammeter, became to be raised in dignity and gain recognition as part of fundamental physics [3].

The same holds today in metrology: it is important to make precise measurements, in terms of low scatter or small uncertainty, as may be achieved by engineering a better measurement instrument. But perhaps arguably the main realm of the physicist in metrology is to provide for measurements which are traceable to absolute measures (ultimately, the universal fundamental constants). This enables the results of measurement to be related, not only of a particular quantity made by different people at different times and places (so important for trade and industry) but also to express dif-

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Needs Ressources	Science/strategic	Manufacturing	Trade	Nano-technology	Regulation	Food
Mass		X		X		X
Lenght		X				
Time	X				X	
Electricity				X		
Amount of substance			X			

▲ **Fig. 2:** Matching needs and resources in metrological traceability

ferent – apparently unrelated – quantities to each other in a more global sense. This latter universality of fundamental metrology relies on our understanding of the structure of the universe – spanning the realms of cosmology to elementary particle physics [4].

Examples of the Physics behind the SI

The symbiotic development of metrology and physics can be well illustrated by the development of the SI definition of the unit of length – the metre.

At the end of the 19th century, Michelson in pioneering work at the BIPM performed optical interferometric length measurement, linked the optical wavelength of an atomic discharge lamp to the metre as realised at that time with prototype bars. These bars were a practical realisation of the standard of length based on the circumference of the Earth since the days of the French Revolution. Building in part on Michelson's early research, during the first half of the 20th century, the wavelength of discharge lamps (such as krypton) provided a suitable definition of the metre of the Metric System. With the advent of the laser in the late 1950's (Nobel prize in Physics 1964 [5]), optical interferometric length measurement advanced where the increased coherence of laser light compared with conventional light sources enabled measurement over greater distances and with better accuracy. At the same time this coherence was also exploited in controlling the absolute wavelength of the novel lasers which became a de facto length standard when actively stabilised to a stable spectral reference, such as an atomic or molecular resonance, based on advances in laser spectroscopy (Nobel prize in Physics 1981 [6]). By the time it was judged appropriate to re-define the metre of the SI, the field had advanced sufficiently that the new definition of the metre is now expressed in terms of the distance travelled by light in a certain time interval [7]. This definition implies a fixed value of the speed of light and reflects the higher accuracy of time/frequency measurement compared with interferometric length measurement and, most recently with the technique of optical frequency comb which enables the comparison of optical and microwave frequencies with essentially unlimited accuracy (Nobel prize in Physics 2005 [8]) way beyond the limits set in optical interferometry.

Much of the research lying behind this example of the dynamic evolution of the SI metre, and similar developments for the other measurement quantities (Table 1), has been performed not only at the national metrology institutes but also at many of the leading university and research institutes. Fundamental metrology has benefited from scientific "spin-off", in some cases in an *ad hoc* manner, in others, in symbiosis, with the development of fundamental physics and applied technological research.

Future challenges for accurate and efficient measurement

As a link between fundamental science and the needs of society, metrological traceability forms an essential technological infrastructure for modern society [9].

The continual increase in demand for accurate and efficient measurement in science, technology and international trade lead to the need to develop improved measurement standards and techniques. These developments need to be carried out well in advance of their application in science and industry, and can only take place on the basis of a solid foundation of long-term metrological research closely linked to advances in science

Particular challenges in the development of metrological traceability which can be met by intensified research are [10]:

A. Implementation of measurement systems
- Extended measurement areas and measurement quality
- Extended scales (pico, (10^{-12}) to tera (10^{12}))
- On-line, dynamic measurements
- Several simultaneous parameters

B. Development of measurement systems
- Sensor development
- Fundamental science (nanophysics, microwave photonics, surface chemistry, etc)
- Networking of measurement sensors

C. Measurement knowledge transfer
- Industrial metrology training
- Industrial measurement needs and applications
- University measurement education
- Mobility of national metrologists

The spectacular development of novel sensors, based on many principles such as nanotechnology and MEMS, optoelectronics, etc, can be regarded as the modern day equivalent of the instrument makers of Victorian times. Sensors lead to better quality, economy and efficiency by:

- playing a decisive role in modern process industry and manufacturing industry for automatic measurement and process control
- integration in many modern products for measurement, monitoring and control throughout the whole product lifecycle
- use as an interface between information networks and "reality" for the exchange of information signals in an extended IT-society [10]

The emphasis in much sensor development is on precision – obtaining measurements, perhaps in harsh environments, of a variety of quantities. These are perhaps not only individual physical quantities, but also "new" quantities – like smell – which do not easily fit into fundamental physics but are nevertheless essential.

Another multidisciplinary aspect of metrology is illustrated in Fig. 2. Such a matrix emphasises that metrological traceability in one sector—say the food industry—may place demands not only on obvious 'chemical' quantities such as the amount of substance, but also at the same time on traditional physical quantities such as mass or electrical quantities. Similarly, the development of measurement science in relation to one particular quantity may also have bearing on the corresponding development of metrological traceability of another quantity. There are indeed many similarities between metrology in chemistry and physics and this facilitates in the widest sense comparison of the measurement of different quantities [5].

Planning the European Metrology Research Area with the help of the Physicist

Considering the development to date of the SI, which has gone hand in hand with the progress of physics, it is natural to contemplate the ways physicists may collaborate with metrologists in the future and suggests a more co-ordinated approach as one way of solving the dilemma facing international metrology.

Physics and Metrology in the European Research Area

The European Commission in planning its vision of the European Research Area as one of the main elements of the current 6th framework programme of research in the European Union [11], has sought European added value, where:

- 'critical mass' of a particular research project (financial and human resources) exceeds means of single country
- complementary national skills are combined, particularly in interdisciplinary situations
- Cross-border nature of problems (e.g. environment, etc)

In physics, as in metrology, some experiments in research demand truly international facilities – such as CERN. In most cases, however, fundamental metrology research can still be performed on a "table top". Examples of current European projects:

- **JAWS –** development of a new Josephson Arbitrary Waveform Synthesizer (JAWS) for calibrations of low frequency, low voltage signals of arbitrary waveforms and their root-mean-square values (AC/DC standards) [12]
- **Watt balance –** under the co-ordination of the French NMI with the aim of replacing the present definition of the SI kilogram, and where amongst others Sweden contributes with its competence in nanometric surface analysis [13]
- **Optical frequency comb –** a new project inspired within the CCL network, and aimed at developing an optical waveform synthesiser with applications in microwave photonics, arbitrary waveform synthesis in electrical metrology as well as a possible future re-definition of the SI second through linking microwave and optical frequency metrology [14].

"Federated excellence" – ensuring the multi-disciplinarity of metrology

Metrology is multi-disciplinary in essence. In formation, metrology draws on potentially all realms of physics: In application, metrology enables measurements of potentially all quantities to be related to one another in a true and absolute sense – that is the key of metrology.

In planning for a European metrology research area, it is natural therefore to arrange for research environments where as many measurement quantities are maintained and developed in synergy. It may not be necessary to have primary metrological facilities in all areas, but secondary metrology in house in one measurement quantity leads to improved primary metrology in another measurement quantity.

We have also seen how, in the dynamic development of the SI, the physical emphasis behind each measurement unit evolves

▼ **Table 1:** Some of the SI units [7] and related physics research

Measurement unit	Definition	Realisation/reproduction	Related physics research	Research organisation
second, *s*	The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom.	Primary frequency standards that produce electromagnetic oscillations at a frequency whose relationship to the transition frequency of the atom of caesium 133. Uncertainty of 2 parts in 10^{15}	Atomic precision spectroscopy (Nobel Prize 1989) Laser cooling of atoms (Nobel Prize 1997)	Ramsey, Dehmelt, Paul (Harvard, Univ. Washington, Univ. Bonn) Chu, Cohen-Tannoudji, Phillips (Stanford, ENS, NIST)
ampere, *A*	The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2 x 10^{-7} newton per metre of length.	Volt and the ohm based upon the Josephson and quantum-Hall effects stability better than a few parts in 10^7. Conventional values for the Josephson constant K_J and the von Klitzing constant R_K.	(BCS) Theory of superconductivity (Nobel Prize 1972) Tunnelling phenomena in solids (Nobel Prize 1973) Quantised Hall effect (Nobel Prize 1985)	Bardeen, Cooper, Schrieffer (Harvard, Princeton) Esaki, Giaever, Josephson (Univ. Cambridge) von Klitzing (Univ. Würzburg)
metre, *m*	The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second.	Frequency-stabilised lasers locked to atomic or molecular resonances.	Laser spectroscopy (Noble Prize 1981) Optical frequency comb (Nobel Prize 2005)	Bloembergen, Schawlow (Univ. Toronto, Bell Labs); Hänsch (Max-Planck Institute for Quantum Optics, Garching); Hall (JILA, Boulder)

from one physical discipline to another – from mechanics, through optics to time & frequency, for the SI metre for instance (Fig. 1). It would therefore be a mistake to give sole rights of maintaining a certain primary physical quantity to just one institute that happens today to have the right competence – tomorrow, physics may lead to a completely new realm.

Arenas for cooperation in Physics and Metrology

Primary metrological research is not, and in the future will not necessarily be, only the reserve of the larger European countries. As long as an individual (even a small) country feels it needs and can afford to perform fundamental physics research on its own terms (albeit often in international collaboration), then it should also be allowed to choose to maintain national metrology competence in its own way. Referring countries to the services of the national metrology institutes of other (usually larger) countries can be a poor substitute to maintaining their own competence in metrology, both for domestic knowledge transfer and international cooperation in accurate measurement, as has been expressed in responses to a recent survey of European stakeholders in Metrology [15].

Metrology benefits from as many independent realisations as possible of a particular measurement – the "more the merrier" - in the identification and elimination of systematic errors. Note that this covers not only several laboratories each using the same realisation, but also independent realisations where completely different roots to a measurement quantity are compared and contrasted. Metrological redundancy is not a luxury but rather a necessity for the future development of accurate measurement.

Examples of existing arenas for collaboration between physicists and metrologists include the CGPM (Conférence Générale des Poids et Mesures) and its various consultative committees; CODATA's working group on Fundamental Constants; and the International Union of Pure and Applied Physics Commission 2: SUNAMCO "Standards, units and nomenclature, atomic masses and fundamental constants" which has a mandate:

"To promote the exchange of information and views among the members of the international scientific community in the general field of Fundamental Constants including:

- physical measurements;
- pure and applied metrology;
- nomenclature and symbols for physical quantities and units;
- encouragement of work contributing towards improved recommended values of atomic masses and fundamental physical constants and facilitation of their universal adoption."

Perhaps one of the more essential ingredients in improving innovation is the efficient transfer of measurement knowledge, where metrologists act as intermediaries between advances in measurement science and the innovative company [16]. Alongside traditional training courses, there should be increasing attention paid to the educational and knowledge transfer opportunities in collaborations between universities and national metrology institutes.

The ERA-NET iMERA [1] has in fact several tasks addressing stakeholder interaction and knowledge transfer (KT). This gives ample opportunity for spreading awareness and obtaining feedback, and encouraging active participation, from various societal groups not immediately in the measurement research sphere. An initial task has been to organise a European workshop at the end of 2005 which has identified opportunities for the practitioners to improve national KT activities (Task 1.4 in project iMERA [1]).

Conclusion

In meeting challenges to the future of fundamental metrology, it is clear that cooperation between physicists – both pure and applied - and metrologists should be strengthened. ■

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Erratum - Europhysics news 36/6 - page 206

In the Andrea Rapisarda and Alessandro Pluchino article about "Nonextensive thermodynamics and glassy behaviour", the conclusion has been truncated. You should have read:
Summarizing the HMF model and its generalization, the a-XY model, provide a perfect benchmark for studying complex dynamics in Hamiltonian long-range systems. It is true that several questions remain still open and need to be further studied with more detail in the future. However the actual state of the art favours the application of Tsallis thermostatistics to explain most of the anomalies observed in the QSS regime. The latter seems to have also very interestings links to glassy dynamics.