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Fundamental metrology/Métrologie fondamentale

Measurement and society

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Abstract

In modern society, metrology is a hidden infrastructure, that affects most human activities. Several domains in which measurements, and therefore metrology, play a crucial role are presented and illustrated with examples: manufacturing industries, navigation, telecommunications, medicine, environment, and scientific research. The BIPM and the national metrology institutes are at the top of traceability chains, which guarantee that all measurements are performed in conformity with the International System of Units (SI) and are therefore comparable. Finally, some indications of the economic benefits of metrology are given. ***To cite this article: T.J. Quinn, J. Kovalevsky, C. R. Physique 5 (2004).***

Résumé

Mesures et société. Dans la société moderne, la métrologie est une infrastructure cachée qui affecte la plupart des activités humaines. On présente plusieurs domaines dans lesquels la mesure et la métrologie jouent un rôle crucial : industries manufacturières, navigation, télécommunications, médecine, environnement, recherche scientifique. Le BIPM et les laboratoires nationaux de métrologie sont au sommet des chaînes de traçabilité qui garantissent que toutes les mesures sont effectuées en conformité avec le Système international d'unités (SI). Enfin, on donne quelques indications sur les bénéfices économiques de la métrologie. ***Pour citer cet article : T.J. Quinn, J. Kovalevsky, C. R. Physique 5 (2004).***

Keywords: metrology; International System of Units

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1. Introduction

In modern society there exists a vast, often invisible, infrastructure of services, supplies, transport and communication networks. Their existence is usually taken for granted, but their presence and smooth operation are essential for everyday life. Part of this hidden infrastructure is metrology, the science of measurement.

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National and international trade is increasingly governed by agreements signed between pairs of trading nations or, more commonly these days, between trading blocks of nations. Included in these trade agreements we now find a requirement for mutual recognition of measurements and tests. This is to avoid double testing, in both exporting and importing countries, causing time delays and possibly putrefied and refused products, and is designed principally to eliminate what are called technical barriers to trade, as well as eliminating the additional costs of double testing. The need for mutual recognition of measurement and test is having a considerable influence on the way that international metrology is carried out. In October 1999 the directors of the national metrology institutes of thirty-eight industrialised countries signed a Mutual Recognition Arrangement (MRA) for national measurement standards and for calibration certificates issued by national metrology institutes [1]. It allows any signatory country to accept as valid a calibration certificate issued by the national metrology institute of another signatory country, as if it was issued by its own. This MRA was drawn up by the International Committee for Weights and Measures under the Metre Convention and it will have far-reaching consequences. Since 1999 a number of other countries and economies have signed and there are now (April 2004) forty-four Member States, thirteen Associate States and Economies and two intergovernmental organisations making a total of fifty-nine signatories to the CIPM MRA.

This agreement goes much further than the informal recognition that existed among the major national metrology institutes up to now. It is one of the consequences of the globalisation of trade and society, and will form the technical basis for other wider agreements now required by governments.

The economic success and safe use of most manufactured products is critically dependent on how well they are made, a requirement in which measurement plays a key role. Telecommunications, transport and navigation are highly dependent on the most accurate frequency and time services. Human health and safety depend on reliable measurements in medical diagnosis and therapy. Food and agriculture are closely regulated in terms of the use of pesticides and food additives, and it is essential to have reliable means of measuring their presence in the human food chain. Protection of the environment and large-scale studies related to global climate change depend critically on accurate measurements, often extending over long periods of time. These require accurate and stable measurement standards that are the same all over the world. Physical theory, upon which all of our high technology activities are based, is reliable only to the extent that predictions from theory can be tested and verified quantitatively. This calls for measurements of the highest accuracy.

It is estimated that between 3 and 6% of the Gross Domestic Product (GDP) in an advanced industrial economy is accounted for by measurement and measurement-related operations. About half of all manufactured products are individual items such as aircraft, motor vehicles and computers, together with their component parts. For most of these products their performance and perceived quality, and hence their commercial success, are determined by how well they are made – sometimes in quite unexpected ways. An example of how quality and commercial success can be linked to manufacturing precision appeared in the early 1980s and was related to the relative ease with which the doors of Japanese cars could then be opened compared with their US competitors. To open the doors of Japanese cars needed a force only one third of that required for US cars, a difference whose origin lay in the tolerance of 1 mm on doors and door assemblies specified for Japanese cars compared with the 2 mm set for US cars. Ease in opening of the door appears to be an important factor in the customer's perceived quality of the whole product and is directly related to precision of manufacture: the economic consequences for the US motor industry of this difference in perception of quality were dire. At a much higher technological level, the commercial success of CD and DVD home entertainment systems depends on extreme precision in the manufacturing some of the key components, such as the lenses that focus the laser beam that reads or writes the micrometer-sized pits on the disks.

One might think that, for the purposes of international trade, high-level metrology needs to be carried out by the most technologically advanced nations. While there is some truth in this, there are pressing needs for a sound metrological base in all countries including those in development and those in transition. An important aspect of international trade in these latter countries is related to the need to be able to demonstrate that their exported food products meet strict sanitary and phyto-sanitary requirements in the importing countries. A costly example of the absence of such capability was the refusal of the European Union to allow the importation of Lake Victoria fish because of doubts as to its level of pollution. The Countries concerned, Kenya, Tanzania, and Uganda lost some 100 million euros during the two-year ban which was lifted only after an adequate metrology, testing and quality assurance infrastructure had been put in place on site to test fish before export. A metrology capability is also necessary to verify that imported products meet the required specification. This is not only to avoid costly failures, but also in order to be able to provide the protection of the health and safety of the people of these countries from what might otherwise be second-rate goods refused by countries with the proper means to verify conformity to standards. The establishment of high-technology manufacturing facilities in any country normally calls for a basic infrastructure that includes metrology and this is important for all countries. The absence of such a technological infrastructure is certainly an impediment to inward investment.

2. Measurement in manufacturing industries

Engineering tolerances, i.e. the amount by which dimensions are permitted to depart from specification, have fallen in practically all industrial production by a factor of three every ten years since 1960. The result is that production engineers in the large-scale manufacture of automotive and electronic products are now required to work at tolerances previously attempted only in fine, small-scale work. For example, the pistons of car engines now under development are made to a tolerance of about 7 micrometres, roughly that used for the components of mechanical wristwatches.

There are two reasons for this improvement of precision in manufacturing industries over the past thirty years. The first is that in traditional mechanical engineering, improvements in performance and reliability have only been possible through improved precision in manufacture. For example, much of the improvement in car fuel efficiency over the past twenty-five years has been due to improved manufacturing tolerances – the pieces fit together much better than in the past. This is also shown by the disappearance of what used to be known as 'running in' when the driver of a new car had to maintain low speeds for the first few hundred or a thousand kilometres and there had to be frequent oil changes to remove the particles produced during this running in process. The second is that many of the new technologies, often based upon the practical applications of recent discoveries in physics, simply do not work at all unless high-precision manufacturing is available. Examples of some of these are the electro-optic industries using lasers and fibre-optics, the manufacture of large-scale, integrated circuits and the commercial production of videodisks.

The industrial applications of 10 volt Josephson systems highlights some of the unexpected advantages to be gained by having a measurement capability two orders of magnitude in advance of apparent needs. Some major manufacturers of digital multimeters installed systems which provide measurements on the production line with an accuracy at least one hundred times better than the final specification of the instruments. In doing this they found two important advantages, which justified the expense and effort. First, deviations from mean production specifications were noticed well before they became significant, so corrections could be applied, with the result that 100% of the production is well within specification. Second, final calibrations for linearity and accuracy could be made quickly and efficiently, and no significant error arose from the calibration equipment. The systems thus improved the efficiency of production and the quality of the final product.

Most industrial products are manufactured using a certain number of components, which are often produced by different subcontractors, some of which may be abroad. It is essential that the constituents fit perfectly one to another. In some cases, for instance aircraft or satellite manufacturing, there are hundreds of them. The interfaces are defined by engineering specifications, with exact values and their tolerances. This implies that all the companies have identical measurement capabilities. The role of the world-wide metrological network set up by the BIPM and based on the SI (see [2]) is crucial. This seems evident, but history shows that this is not always the case. In 1999, NASA launched a Mars Polar Lander, which crashed on arrival to the planet. It was shown that the units used by the subcontractor in its software to control the landing were feet and pounds, instead of the metre and the kilogram used by NASA in its software. This is of course a special case, but smaller measurement misfits may be just as devastating.

3. Measurement in navigation and communications

The difference in longitude between any two places on the surface of the Earth is proportional to the difference between the local times at the two places. This was known to Hipparcus in the 2nd century BC, but it was not until the middle of the 18th century AD, when sufficiently accurate sea-going clocks were made by John Harrison, that it became possible to make a useful estimate of longitude in this way. Harrison accomplished the remarkable feat of building, in the period from 1730 to 1760, clocks and watches which neither gained nor lost more than about four minutes on a voyage from London to the West Indies (about 77° West of Greenwich). This transformed sea navigation.

Accurate timekeeping remains the key to precise navigation but the clocks used are now atomic ones and the method is quite different from that understood by Hipparcus. In 1989, Norman Ramsay received the Nobel Prize for physics for his key contribution to the development of atomic clocks, which are now the time-keepers of today's most precise navigation system the GPS (Global Positioning System). The Nobel Prize in 1997 was awarded to Chu, Cohen-Tannoudji and Phillips for their work on the production and manipulation of cold atoms leading to a new generation of cold-atom clocks already more than an order of magnitude more accurate than the classic caesium beam standards [3]. This will rapidly lead to even more accurate navigation.

GPS is another example of how improvements in accuracy of measurement can suddenly lead to completely new industries of enormous magnitude and potential. GPS was originally designed as a purely military global positioning system and was fitted with special coding (Selective Availability, SA) so that users outside the US military had a precision more than ten times worse in positioning. It was soon found, however, that the number of civil users of GPS was growing much more rapidly than expected. By 1992, the sales of GPS hardware reached 120 million dollars and the new industry based on GPS, which produces digital maps and associated navigation systems, had sales approaching 2 billion dollars. By the year 2000 all of this had increased ten times and the civil use of GPS had become so important that on 1 May 2000 the SA was definitively switched off and civil users had the same high accuracy of positioning as the US military. It is now clear that such systems cannot be restricted to military use. Before such satellite navigation systems can be accepted for civil aviation use, however, it is necessary that there be back-up systems in place. A European system, Galileo, is being planned and there already exists the Russian system GLONASS available for civil use.

The technology of accurate time dissemination and the maintenance of national time scales to within a few microseconds worldwide are of considerable commercial importance in its own right. Calls are constantly being made to increase the rate of data flow in networks and other telecommunications systems. In these, one limitation to the speed of operation of such systems is jitter in the basic frequency of interconnected parts of the system. When national networks are connected, it is a basic requirement that their time and frequency systems fit together without significant drift or jitter. This is the most demanding industrial requirement for frequency standards.

4. Measurements in medical diagnosis and therapy

The impact of measurement on trade, commerce, the manufacture of high-technology products and fundamental physics touches us all, but it is usually indirect. Metrology has a much more direct influence on our lives, however, when it involves medical diagnosis or therapy or when we consume food and drink whose purity and freedom from contamination with heavy metals or pesticide residues rely on measurements. The accuracy required in these measurements is much less than that in many of the examples given earlier in this article. Nevertheless, the reliability of these measurements related to human health and safety must be beyond reproach, because errors can kill. The economic impact of measurements related to medical diagnosis and treatment is very large. Most industrialised states spend some 10% of their GDP on health. In the USA it is closer to 15%. Studies have shown that as much as 10 to 15% of the costs of medical care are in measurements and tests, most of it related to diagnosis. This represents a very large amount of money and governments are now realising that more must be done to improve the reliability of such measurements and tests. The European Union's recent *In Vitro Diagnostic* Directive will have far-reaching consequences in this area because it requires that all medical instrumentation used and imported into the EU must have a calibration traceable to appropriate standards. This is not the case at the moment.

In medical therapy, permissible errors must not be much greater than the smallest physiological effect that can be detected, usually a few percent. Without considerable care, however, errors very much larger than this can occur. Without the efforts that are already made to assure accuracies of a few percent in radiotherapy, for example, overdoses or underdoses of a factor of ten would be common. This is because the routine production of well-characterised ionising radiations is difficult: the radiations themselves are invisible and no immediate physical or biological effects are discernible either to the operator or to the patient. Of a great concern is the fact, that in the case of absorbed doses of ionising radiations for therapeutic objectives, the ideal accuracy is hardly reached even in the best metrological laboratories, whereas a slight overdose may burn tissues and a slight underdose is ineffective [4]. In this domain, increased efforts in research are particularly important.

Similar difficulties exist in ensuring accurate and reliable measurements of the presence of heavy metals or pesticide residues in food and water. In fractional terms, the accuracies required are even lower than in medical diagnosis or therapy, but the measurements are difficult to make and an accuracy of even 50% may be hard to obtain because the total quantity involved is so very small. Nevertheless, properly evaluated accuracies are essential to monitor long-term changes in the quality of our food and in the environment. Without a firmly evaluated accuracy there is no way of knowing whether apparently reproducible results are constant in time. To the question, "Is the amount of lead in our drinking water smaller than it was ten years ago?" it is not clear that a reliable answer can be given.

5. Global climate studies

Global climate studies have been under way for many years in an attempt to find out first whether there is clear evidence of climate change and second whether human activities are influencing the climate. There is now a broad consensus that the climate is changing and that the emissions of the so-called greenhouse gases must be having some effect. The Kyoto Agreement on limiting emissions of these gases is slowly starting to be implemented and it is becoming clear that there will be important measurement issues that will have to be faced. The trading of emission quotas, as foreseen in the Kyoto agreement will, as in any other trading activity, require agreement of the trading parties to the measurements of the quantity of emissions traded.

There is now considerable activity in the national metrology institutes to prepare for this. In a more general sense, climate studies are based on the combination of data from a wide range of disciplines such as oceanography, solar physics, atmospheric physics, vulcanology and so on. It is first necessary that the data and measurements in all these areas be made using instruments all calibrated in the same units. It is also evident that in any long-term programme to observe small changes in critical climate parameters, the measurements made at the beginning of the study must be compatible with those made at the end, i.e., the measurement standards used to calibrate them must have long term stability. An example of such a requirement for long-term stability of standards is in the measurement of changes in the amount of ozone in the upper atmosphere. The aim of these studies is to find out the rate at which the amount of ozone is changing over decades. The measurements are delicate and great efforts have to be made to ensure that measurements are properly linked to standards with a known uncertainty. The consequence of these requirements is that all instruments used in climate studies, in all disciplines, must be calibrated in SI units with a carefully evaluated uncertainty since these are the only units that we can be sure are not drifting with time. The Metre Convention and the BIPM are in place to guarantee the reliability in time of the standards to which measurements are referred. This is done in particular by linking them to fundamental and atomic constants.

6. Accuracy rather than simply reproducibility or precision

In all of what has so far been said, the term ‘accuracy’ has been used without really defining it or justifying its need. Another word often used is ‘precision’ meaning in some way the spread of the measurement results. The argument is sometimes advanced that so-called ‘absolute accuracy’ is hardly ever needed and that in practical applications the requirements are only for reproducibility, i.e. the same measurement of the same quantity always giving the same result, and for worldwide uniformity or precision that allows small changes to be seen. What is not understood in these sorts of arguments is that it is only by means of accurate measurements, which are measurements that provide a close representation of nature, that the apparently simple requirement for long-term reproducibility can be met. Accurate measurements are those made in terms of units firmly linked to fundamental physics so that they are: (a) repeatable in the long term; and (b) consistent with measurements made in other areas of science and technology. They are thus much more than merely reproducible or uniform. Measurement standards based upon material artefacts cannot provide the assurance of long-term stability and, indeed, the principal weakness of the SI in this respect is our inability to establish the long-term stability of the kilogram with respect to atomic or fundamental physical constants. The precision with which measurements are made depends on the methods and procedures applied. The accuracy and the precision must be matched. It serves no useful purpose if the precision is not sufficient even if the accuracy is good.

The role of the so-called fundamental physical constants is important both in physics and metrology. The values of these constants in SI units are obtained either directly from experiments or indirectly by calculation using one of the many relations that exist between the constants. The universal nature of these constants allows relationships to be found between them that span wide areas of science and are susceptible to experimental test in diverse ways. To obtain satisfactory agreement between the measured values of these constants using methods based upon quite different physical principles is one of the most important experimental tests of the consistency of physical theory and is an important activity in metrology. An example is provided by electric units [5]. Confidence in the predictions of such theories underpins all of today’s advanced technology, but this confidence exists only because the predictions are tested with the utmost rigour by experiment.

7. National and international measurement standards and traceability of measurements

The establishment of accurate and practical measurement standards linked to fundamental constants, having also the range and diversity required for the whole of modern science and technology, is a major undertaking. It is the role of the national metrology institute to establish the national standards and to disseminate them to national users by means of calibrations. It is also the role of the national metrology institute to carry out the necessary international comparisons to demonstrate international equivalence of the national standards. Measurement standards are rarely static; with the exception of the kilogram, practically all the other basic units of the SI have been transformed in recent years to take advantage of discoveries in physics [2]. The different domains of measurement science, for example length, time and electricity are much more closely linked than in the past since all are now intimately linked through a common dependence on quantum and solid-state physics.

Many of the important measurement activities already mentioned involve metrology in chemistry. Chemistry is a very vast field, which, in addition to many industrial applications (plastics, oil-derived products, dyes, textiles, etc.) is the major technique in the fields of environment, pollution, laboratory medicine, food safety, pharmaceutics, forensics, etc. For each application, the metrological approaches are specific [6]. For some years the national metrology institutes have been working to put in place the same sort of measurement infrastructure for chemistry as has existed for more than a century for physics and engineering. The rapidly developing field of biotechnology will also require measurement standards and these are also being considered.

In some domains, such as in voltage or laser wavelength standards, it is now common for industrial users to have direct access to atomic or quantum-based standards of the highest accuracy. For the most demanding users, the former hierarchical system of standards is thus disappearing, to be replaced by a system of comparisons, which merely verify that these independent commercial primary standards are operating correctly. The role of the national laboratory is therefore to provide the means of making these comparisons and to ensure that its own standards are closely linked with those of other countries, either directly or through the BIPM.

Traceability of measurement results means that a given result is obtained in terms of measurement units that are linked by an unbroken chain of calibrations or comparisons to national measurement standards – generally in practical terms – to SI units, although this is often not yet possible for measurements on biological activity. At each link of the chain the uncertainty of the calibration or comparison must be evaluated. In this way a proper uncertainty of the final measurement in terms of SI units can be given. It is only if the uncertainty has been properly calculated that it is possible to estimate the reliability of a measurement and decide whether or not it is suitable for the application in hand. The traceability chain may be long, with many intervening calibrations through a complex hierarchy of standards or it may be short with just one calibration from the national metrology institute.

Any comparison or calibration is bound to introduce some measurement error. This adds up to the uncertainty of the reference. As a result, the uncertainty increases while the traceability chain reaches the user. The loss of accuracy can be of one, sometimes two orders of magnitude. For this reason, the national metrology institutes must maintain their standards to the best possible level, significantly higher that the actual needs of the users. In many cases, however, notably in chemistry and ionising radiation measurements, this is a challenge that is not yet possible to meet.

Traceability across national boundaries requires that appropriate international comparisons have been made to link national standards in different countries. The CIPM MRA is designed to put in place a worldwide network to provide the technical basis for worldwide comparability of measurement results. It consists of a set of so-called 'key comparisons' chosen to test the principal techniques in each field, plus a scheme to evaluate the uncertainties if calibrations are offered by national metrology institutes. The evaluation is made by experts drawn from regional metrology organisations and is based on a wide range of criteria including the results of key comparisons. So far, some five hundred key comparisons have been started and more than one hundred completed. Some sixteen thousand individual measurement and calibration capabilities of NMIs have been approved and placed on the BIPM key comparison database on the BIPM website. The CIPM MRA has been signed by the Directors of the national metrology institutes of all the industrialised nations of the world and an increasing number of developing states as well. Also some intergovernmental organisations having metrological activities have signed the CIPM MRA. Full details of the CIPM MRA can be found on the BIPM website (http://www.bipm.org) together with detailed descriptions of the Metre Convention, the BIPM and the text of the CIPM MRA.

8. What are the economic benefits of metrology?

What is the cost of maintaining the world's measurement system and does it provide good value for money? An indication of the amounts spent by the industrialised nations of the world on the provision of measurement standards and calibration services is given by the following figures. In the USA and Japan about 40 parts per million of GDP (equivalent to nearly 300 million dollars for the US) is spent annually on these services; fractions of GDP spent in the larger European countries are similar. In some of the rapidly developing countries as much as 100 parts per million of GDP is being spent on establishing a measurement infrastructure. The annual cost of the BIPM, about 10 million US dollars, represents on average for the contributing member states of the Metre Convention about 1% of what they spend nationally on metrology. In any particular country, the government can use figures of this sort as a guide but it is clear that in any particular case the government has to balance the conflicting demands from all areas such as health, education, defence, etc.

The principal source of funding for metrology in all developed industrialised countries is central government. The management of the measurement system is sometimes in private hands but the base funding is always governmental. For the developing countries and those in transition, metrology is now considered an essential part of the technological infrastructure and therefore they finance for establishing a metrology service is available through the funding agencies.

In recent years considerable efforts have been made to quantify the benefits from metrology. Studies have been made at the NIST, in the UK, in Canada and in the European Commission. All show that government spending on the metrological infrastructure of a country gives a high rate of return, i.e., the financial benefits far outweigh the costs. In addition, improved metrology in healthcare, for example, brings considerable benefits to human health in addition to the direct savings from a reduction in repeat measurements. It is not possible to give here a summary of these studies but the reader is referred to the original texts most of which are referenced and summarised in the Report "*Evolving Needs for Metrology in Trade, Industry and Society and the Role of the BIPM*" on the BIPM website, www.BIPM.org.

9. Conclusions

In summary, the need for accurate measurement standards linked to fundamental and atomic constants is the following:

- metrology is an essential part of the infrastructure of today's world and provides a high rate of return on investment;

– national and international trade increasingly require demonstrated conformity to written standards and specifications with mutual recognition of measurement and test results, i.e., worldwide traceability of measurement results to the SI;
– the economic success of most manufacturing industries is critically dependent on how well products are made, a requirement in which measurement plays a key role;
– navigation, telecommunications, now becoming an increasingly important part of today's world, require the most accurate time and frequency standards;
– human health and safety depend on reliable measurements in diagnosis and medical treatment, and in the production and trade in food and food products;
– the protection of the environment from the short-term and long-term destructive effects of industrial activity can only be assured on the basis of accurate and reliable measurements;
– global climate studies depend on reliable and consistent data from many disciplines over long periods of time and this can only be assured on the basis of measurement standards linked to fundamental and atomic constants;
– physical theory, upon which all of this rests, is reliable only to the extent that its predictions can be verified quantitatively and this calls for measurements of the highest accuracy.

The way in which the measurement infrastructure is organised and how it is financed are, of course, matters for individual governments to decide. What is sure, however, is that an advanced industrial economy must have access to measurement standards: the government and industry must have access to advice on measurement matters; there must be experts qualified to represent national interests on international bodies concerned with measurement; and, finally, there must exist the research base in measurement science without which none of this is possible.

All of this is assured through the activities of the national metrology institutes working together with the BIPM under the Metre Convention. The Convention has, and continues to provide the formal framework in which worldwide activities in metrology are coordinated and the SI is maintained to provide the essential measurement system for today's society.

One hundred years ago, far-sighted men clearly understood the link between the economic success of manufacturing industry and access to accurate measurement standards, and the need for research to allow these standards to advance. Since then, the accuracies required, and the range of applications requiring accurate measurement, have increased almost beyond recognition, but the basic arguments for a national measurement infrastructure remain today exactly as set out by such eminent scientists as Siemens, Galton, Rayleigh, Maxwell and Kelvin.

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