SOME BASIC POINTS ABOUT METROLOGY

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in

Proceedings of the 1983 International School and Symposium on Precision Measurement and Gravity Experiment, Taipei, Republic of China, January 24 - February 2, 1983, ed. by W.-T. Ni (Published by National Tsing Hua University, Hsinchu, Taiwan, Republic of China, June, 1983)

OUTLINE

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I. Introduction

The development of mankind is closely related to his ability to measure. The advance of human society demands better ability to measure and more precise common standards; the achievements of metrology provide a needed foundation for society's advancements. This is even more clear in the modern industrial society. We must have strict common standards and effective calibration programs in order to obtain compatibility among various parts and products manufactured in different areas of the world. We must employ strict standards in order to achieve commutability among researchers of different laboratories. To maintain fareness in trading, we must have reasonable standards and suitable ability to measure.

Metrology is the science of measurement. Metro- comes from Greek word metron. Metron means measure. Since every scientific experiment has some quantity to measure. Therefore, in the general sense, metrology could include all experimental sciences. But this is not a good interpretation for a discipline of science. The major areas of metrology are measurements of general quantities, improvement of measurements and measurement systems. According to its aim and precision, metrology can be divided into

(i) Commercial (or Legal) Metrology
(ii) Industrial Metrology
(iii) Scientific Metrology.

Commercial metrology is the most widely used and usually involves legal matters. Scientific metrology looks for ever-increasing precisions and is the frontier of metrology. In this conference, we will be mainly concerned with scientific metrology and industrial metrology. Here I will talk about some basic points of metrology.[1]

II. Classification and Historical Perspective of Basic Standards

We begin by explaining two terminologies —— precision and accuracy. Precision is a measure of the repeatability of a measurement system. If a system has good repeatability, then the measurement results have "low scatter" and high precision. Suppose we have bought a 5½-digit digital multimeter, it would have 5½-digit repeatability, and hence, 5½-digit precision. But before a suitable calibration is made, the actual readings may have a systematic deviation and hence, not 5½-digit accuracy. Accuracy is a measure of closeness to the true value (in recognized units provided by common standards). After a good calibration, the multimeter would have a 5½-digit accuracy.

At an early age, people discovered that his ability to "just" measure was not enough. One has to compare one's measurements with those made by others. This requires common standards be adopted.

Standards can be classified into following three catagories:

(i) (Macroscopic) Natural objects —— parts of human body (finger, palm, span etc.), grains, silk threads, etc.

(ii) Artifacts —— pitch-pipes, the kilogram prototype, etc.

(iii) Properties of the (microscopic) structure of matter and fundamental physical laws —— for example, the second is defined to be 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 cesium-133 atom.

Natural objects are good for crude estimates. But since they vary from one object to another, they do not provide accurate standards. Historically Pharaoh Khufu was the first to decree a length standard called Royal Egyptian Cubit about 2900B.C. The standard was made of black granite and was supposed to be the length of Pharaoh's forearm and hand. The effectiveness of this standard can be seen from the building of the great Khufu Pyramid. No side of the pyramid's square base deviated from the mean side length (about 230 meters) by more than 5 parts in 10^4.

Since ancient times, Chinese use pitch standard to derive the standards for linear measure, capacity and weight in formulating metrological systems. Chien Han Shu (前漢書) (History of the Former Han Dynasty 206B.C. to 24A.D.) says: "The basis of the linear measure is the length of the Huang-chung pitch-pipe. Using grains of medium(-sized) black millet the length of Huang-chung is ninety fên, one fên being equal to the width of a grain of millet. Ten fên equal one tsun. Ten tsun equal one chih. .... The basis of the capacity measure is the capacity of the Huang-chung pitch-pipe. Using grains of medium(-sized) black millet twelve hundred(grains) fill its tube. The capacity is called ho. Ten ho equal one shen. Ten shen equal one tou...... The contents of one (Huang-chung) tube, i.e. twelve hundred (grains of) millet, weight twelve chu. Twice this weight is liang. Sixteen liang is one jin. ....."

漢書律歷志曰：「度者，本起黃鐘之長，以子穀秬黍中者，一黍之廣度之，九十分黃鐘之長，一為一分，十分為寸，十寸為尺，……量者，本起黃鐘之龠，以子穀秬黍中者，千有二百實其龠，合龠為合，十合為升，十升為斗，……權者，本起黃鐘之重，一龠容千二百黍，重十二銖，兩之為兩，十六兩為斤，三十斤為鈞，……。」

There are twelve lü (pitches) in the Chinese musical scale. Huang-chung is the lü with lowest pitch. So Huang-chung pitch tube is the longest and its length (ancient Huang-chung pitch tube) is 248.8mm. The lengthes of standard rules (chih) in different periods of China are listed in Table I.

Table I. The lengthes of official chih in different periods of China (After reference 3)

Dynasties and Periods		The length of one chih in millimeters
Huangdih, Yu(虞), Hsia	(2697B.C. to 1766B.C.)	248.8 mm
Shang (Yin)	(1766B.C. to 1122B.C.)	311.0 mm
Chou	(1122B.C. to 225B.C.)	199.1 mm
Chin, Han	(350B.C. to 8A.D.)	276.5 mm
Hsin, Hou Han	(9A.D. to 220A.D.)	230.4 mm
Hou Han	(After 81 A.D.)	237.5 mm
Wei, Jihn	(220A.D. to 273A.D.)	241.2 mm
Jihn	(274A.D. to 316A.D.)	230.4 mm
Eastern Jihn	(317A.D. to 430A.D.)	244.5 mm
Northern and Southern Dynasties		Many different length standards
Sui	(581A.D. to 606A.D.)	295.1 mm
Sui	(607A.D. to 618A.D.)	235.5 mm
Tang, Wu Tai	(618A.D. to 960A.D.)	311.0 mm
Sung, Yuan	(960A.D. to 1368A.D.)	307.2 mm
Ming	(1368A.D. to 1644A.D.)	311.0 mm
Ching	(1644A.D. to 1911A.D.)	320.0 mm
Republic	(1912A.D. to now)	METRE

In the western world during the medieval age, the metrological standards were in great chaos. During the French evolution, the French Academy constructed a new system of units. The unit of length is called meter, from the Greek word metron, meaning measure. The meter was equivalent to one ten-millionth of a quadrant of the earth's meridian. The gram is defined to be the weight of 1 cm^3 of water at its highest density.

In 1875, seventeen nations met in an International Conference on Weights and Measures, and on May 20th of the same year signed the "Treaty of the Meter". Committees were appointed to construct the permanent standards that would be technically superior to those made during the French revolution. The treaty also provided for an International Bureau of Weights and Measures to be established on neutral ground in Sèvres, France. This laid the foundation for an international system of units.

Any artifact may wear and change slowly during the course of time. The development of science makes us realizing the high uniformity and invariance of the fundamental physical laws. Hence the fundamental physical constants and the microscopic properties of matter determined by these fundamental physical laws become the most natural and most precise sources of standards. At present in the International System of Units, the only base unit based on an artifact is the kilogram (Table II). The kilogram protatype is stable to 10^{-8}. At present, the accuracy of measuring Avogadro number N_A is about 1 ppm. If we can measure Avogadro number and count atoms in a specified mass to an accuracy better than 10^{-8}, then the kilogram can be defined as the mass of $(1/12)\mathrm{x}1000N_A$ C^{12}-atoms. At that time all units can be derived from the fundamental physical constants and the microscopic properties of matter.

III. The International System of Units[4]

The name Système International d'Unités (International System of Units), with the abbreviation SI, was adopted by the 11th Conférence Générale des Poids et Mesures in 1960.

This system includes three classes of units:

- base units,
- supplementary units,
- derived units,

which together form the coherent system of SI units.

A. Base units

The International System of Units is founded on the seven base units listed and defined in Table II.

B. Supplementary units

The Conférence Générale des Poids et Mesures has not classified certain units of the International System under either base units or derived units.

These units, radian (rad) and steradian (sr), are called "supplementary units" and may be regarded either as base units or as derived units.

Table II. SI base units

From The International System of Units, Natl. Bur. Stand. (U.S.) Spec. Publ. 330 (1977), and subsequent action by the 16th General Conference on Weights and Measures (1979).

Name	Symbol	Definition
meter	m	"The meter is the length equal to 1 650 763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the krypton-86 atom."
kilogram	kg	"The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram [a cylinder of platinum-iridium]."
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 cesium-133 atom."
ampere	A	"The ampere is the constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per meter of length."
kelvin	K	"The kelvin is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water." The "degree Celsius" is defined by the equation $t = T - T_0$, where T is the thermodynamic temperature in kelvins and $T_0 = 273.15$K.
mole	mol	"The mole is the amount substance of system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12."
candela	cd	"The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian."

The radian is the plane angle between two radii of a circle which cut off on the circumference an arc equal in length to the radius.

The steradian is the solid angle which, having its vertex in the centre of a sphere, cuts off an area of the surface of the sphere equal to that of a square with sides of length equal to the radius of the sphere.

C. Derived units

Derived units are expressed algebraically in terms of base units and/or supplementary units. Their symbols are obtained by means of the mathematical signs of multiplication and division; for example, the SI unit for velocity is metre per second (m/s) and the SI unit for angular velocity is radian per second (rad/s).

For some of the derived SI units, special names and symbols exist; those approved by the Conférence Générale des Poids et Mesures are listed in Table III.

It may sometimes be advantageous to express derived units in terms of other derived units having special names; for example, the SI unit for electric dipole moment is usually expressed as C·m instead of A·s·m.

Table III. SI derived units

Quantity	Name of derived SI unit	Symbol	Expressed in terms of base or supplementary SI units or in terms of other derived SI units
frequency	hertz	Hz	$1\ \mathrm{Hz} = 1\ \mathrm{s}^{-1}$
force	newton	N	$1\ \mathrm{N} = 1\ \mathrm{kg \cdot m/s^2}$
pressure, stress	pascal	Pa	$1\ \mathrm{Pa} = 1\ \mathrm{N/m^2}$
energy, work, quantity of heat	joule	J	1 J = 1 N·m
power	watt	W	1 W = 1 J/s
electric charge, quantity of electricity	coulomb	C	1 C = 1 A·s
electric potential, potential difference, tension, electromotive force	volt	V	1 V = 1 J/C
electric capacitance	farad	F	1 F = 1 C/V
electric resistance	ohm	Ω	1 Ω = 1 V/A
electric conductance	siemens	S	$1\ \mathrm{S} = 1\ \Omega^{-1}$
flux of magnetic induction, magnetic flux	weber	Wb	1 Wb = 1 V·s

magnetic flux density, magnetic induction	tesla	T	1 T = 1 Wb/m^2
inductance	henry	H	1 H = 1 Wb/A
luminous flux	lumen	lm	1 lm = 1 cd·sr
illuminance	lux	lx	1 lx = 1 lm/m^2
absorbed dose	gray	Gy	J/kg
activity	bequerel	Bq	s^{-1}
dose equivalent	sievert	Sv	J/kg

D. Multiples of SI units

The prefixes given in Table IV (SI prefixes) are used to form names and symbols of multiples (decimal multiples and sub-multiples) of the SI units.

Table IV. SI prefixes

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{18}	exa	E	10^{-1}	deci	d
10^{15}	peta	P	10^{-2}	centi	c
10^{12}	tera	T	10^{-3}	milli	m
10^{9}	giga	G	10^{-6}	micro	μ
10^{6}	mega	M	10^{-9}	nano	n
10^{3}	kilo	k	10^{-12}	pico	p
10^{2}	hecto	h	10^{-15}	femto	f
10^{1}	deka	da	10^{-18}	atto	a

The symbol of a prefix is considered to be combined with the unit symbol* to which it is directly attached, forming with it the symbol for a new unit which can be provided with a positive or negative exponent and which can be combined with other unit symbols to form symbols for compound units.

* In this case, the term "unit symbol" means only a symbol for a base unit, a derived unit with a special name or a supplementary unit; see, however, the note about the base unit kilogram.

Examples

$1\ cm^3 = (10^{-2}m)^3 = 10^{-6}m^3$

$1\ \mu s^{-1} = (10^{-6}s)^{-1} = 10^6 s^{-1}$

$1\ mm^2/s = (10^{-3}m)^2/s = 10^{-6}m^2/s$

Compound prefixes should not be used; for example, write nm (nanometre) instead of mμm.

NOTE - Because the name of the base unit, kilogram, for mass contains the name of the SI prefix "kilo", the names of the decimal multiples and sub-multiples of the unit of mass are formed by adding the prefixes to the word "gram"; for example, milligram (mg) instead of microkilogram (μkg).

IV. Systems of Units and Selections of Basic Quantities

In the course of development of systems of units, there are two basic categories: absolute system of units and gravitational systems of units. Any system of units that is defined in terms of mass, length, and time is called an absolute system of units (Example: SI units). Engineers are more interested in force, and its measurement, than in mass. If one use weight as a measure of force to replace the unit of mass, then one has a gravitational system of units. Weight and mass are related by

$$f = mg,$$

where g is the gravitational acceleration. Since g varies with places and time. To define mass, one has to define a standard g first.

The number and choice of basic quantities are not fixed. They depend on practical needs and precisions that can be obtained for different quantities and fundamental constants. For example, the precise measurements of frequency and light velocity can make length a derived quantity; the precise measurements of average particle kinetic energy and Boltzmann constant can make temperature ($E = kT$) a derived quantity; the precise measurement of Avogadro number can make amount of substance a derived quantity. According to the definitions of ampere and candela in Table II, current and luminous intensity can already be regarded as derived quantities. If all these spell out, we are left with only two basic quantities —— mass and time. From the precise measurements of Planck constant $\hbar$ and the gravitational constant G, we can define fundamental length, fundamental time and fundamental mass as follows:

$$\text{Planck length} = (\hbar G/c^3)^{\frac{1}{2}} = 1.616 \times 10^{-35}\text{m},$$

$$\text{Planck time} = (\hbar G/c^5)^{\frac{1}{2}} = 5.391 \times 10^{-44}\text{sec},$$

$$\text{Planck mass} = (\hbar c/G)^{\frac{1}{2}} = 2.177 \times 10^{-8}\text{kg}.$$

If this is done, then all quantities are derived —— derivable from fundamental physical laws and their constansts. But this is still unpractical. For $\hbar$ is only measured to 5 ppm while G to 70 ppm; the mass, length, time standards in Table II have far better absolute accuracies.

On the other hand, before we know that heat and work are equivalent or before the joule equivalent of heat is measured, heat is also a basic quantity. Moreover, if we can measure area on a curved surface directly and more precisely, then area can also be considered as a basic quantity.

In the definitions of seven SI base units, the definitions of ampere, mole and candela involve one or more other base units. The absolute accuracies achievable today for time, length, mass and temperature standards are as follows:

Time (Cesium atom) : 10^{-13}-10^{-14}

Length (Krypton atom) : 3×10^{-9}

Mass (Artifact) : 10^{-8}

Temperature (Triple point of water) : 10^{-6}.

Before 1972, the accuracy of the measurement of speed of light is slightly better than 1 ppm. In 1973 scientists at the National Bureau of Standards in Boulder, Colorado, reported[5,6] separate measurements of the wavelength and frequency for a helium-neon laser stabilized to an absorption line in methane and obtained through the fundamental relation $c=\lambda\nu$ the speed of light

$$c = 299\,792\,457.4 \pm 1.1 \text{ m/sec} \quad (0.004 \text{ ppm}).$$

Now although the precision of the speed of light can be measured to $3\text{x}10^{-11}$, its accuracy can not be improved, because the limit of the absolute accuracy of length standard. To improve it, we have to redefine the unit of length. There are two ways: (i) use the wavelength of a stable laser source; (ii) use the formula $\lambda = c/\nu$ to define length unit in terms of time standard and the speed of light. Because of the unity of spacetime in relativity theory, the second way is more appealing and satisfactory. The 1983 Conférence Générale des Poids et Mesures may redefine the meter as "the length of the path traveled by light in a vacuum during a time interval of 1/299 792 458 of a second".[7] With this definition of length, the speed of light is

$$c = 299\,792\,458 \text{ m/sec.}$$

In actual practice, there are many situations in which the distance is measured by light travel time already, e.g., lunar laser ranging and radiometric observations of the solar system. Moreover we can say that I am 5.8 ns high, the wire is 0.3 ns long or this crystal is 3 ps thick.

V. Uniformity and Invariance of Physical Laws and Microscopic Properties of Matter.

Natural objects like hands, grains vary in size. Would microscopic structures of matter, fundamental physical laws and their constants vary with objects, space and time as precisions ever increased? This is a very important question. During the last couple of decades, the improvements on the accuracy of frequency measurements and standards are rather successful. Under appropriate environment control, 10^{-14} stability over 100 sec can be achieved for hydrogen maser clock. But hydrogen maser clock can vary at 10^{-13} level due to temperature change, pressure change or stress change. Other precision measurements are similar. The microscopic structures of matter change slightly due to environment factors. But in a laboratory, the environmental factor can be controled (as to the gravitational effects, see next section). At the present, there is no evidence for any variations of the microscopic structures of matter under same environment. Astrophysical observations tell us that the structures of matter and fundamental physical laws billion years ago and billion light-years away are the same as in the laboratories on earth. For example, Tubbs and Wolfe[8] show that the coincidence of redshifts deduced from 21 cm and resonance transitions in absorbing gas detected in front of four quasi-stellar objects results in stringent limits on the variation of the product of three physical constants both in space and in time. They find that $\alpha^2 g_p(m/M)$ is spatially uniform, to a few parts in 10^4, throughout the observable universe, where α is the fine structure constant, g_p is the gyromagnetic ratio of the proton and (m/M) is the ratio of electron-to-proton masses. This uniformity holds subsequent to an epoch corresponding to less than 5% of the current age of the universe t_0 (about 10^{10} years). Moreover, time variations in $\alpha^2 g_p m/M$ are excluded to the same accuracy subsequent to an epoch corresponding to $\gtrsim 0.20\ t_0$. Let $k = \alpha^2 g_p m/M$, then we have

(i) limit on temperal variation of k : $|\dot{k}/k| < 10^{-13}/\mathrm{yr}$,
(ii) limit on spatial variation of k : $|k'/k| < 10^{-13}/\ell.\mathrm{y}.$

That a quantity as complex as g_p, which depends on all the details of strong interaction physics, is uniform throughout most of spacetime, even in causally disjoint regions, suggests that all physical laws are globally invariant to a high precision.

Laboratory, geological and space observations also give constraints on the temperal and spatial variations of fundamental constants. At present, the best constraints on the temporal variations of the fundamental interaction constants come from Shlyakhter[9] analysis of the natural Oklo reactor over geological time scale:

(i) fine structure constant $\alpha = e^2/\hbar c$: $|\dot{\alpha}/\alpha| \lesssim 10^{-17}/\mathrm{yr}$
(ii) weak interaction constant $\beta = g_f m^2 c/\hbar^3$: $|\dot{\beta}/\beta| < 10^{-12}/\mathrm{yr}$
(iii) strong interaction constant $g_s{}^2$: $|\dot{g}_s/g_s| < 10^{-18}/\mathrm{yr}$.

Recent radiometric observations of the planets give a constraint of $2 \times 10^{-10}\mathrm{yr}^{-1}$ for $|\dot{G}/G|$.[10,11]

VI. Einstein Equivalence Principle and Its Empirical Tests

In the last section, we mentioned that all environmental factors except gravity can be controlled in a laboratory experiments. Gravity is universal, long-ranged and additive. Therefore it can not be controlled entirely. But, just because this universality, there is equivalence. In 1907, Einstein[12] proposed the complete physical equivalence of a homogeneous gravitational field to a uniformly accelerated reference system and derived clock and energy redshifts in a gravitational field from this equivalence. When applied to a spacetime region where inhomogeneities of the gravitational field can be neglected, this equivalence dictates the behavior of matter in gravitational field. The postulate of this equivalence is called the Einstein Equivalence Principle (EEP). EEP is an important cornerstone of Einstein's General Theory of Relativity. EEP survives all precision tests to date.[13] The uniformity of physical laws analyzed in the last section also gives support to EEP.

According to EEP, in a local laboratory experiment where the inhomogeneities of the gravitational field can be neglected, we can use accelerated reference frame in special relativity to treat it. Therefore, if we give the apparatus an appropriate acceleration (or let it in a free-fall status), the experiment would be independent of where and when it is done. To the present achievable accuracy, acceleration effects in the earth-bound laboratories can usually be neglected. In some experiments, e.g. those done near the gas-liquid critical point,[14] where the acceleration (gravity) effects can not be neglected, we only need to take the special relativistic acceleration into account.[15] According to EEP, the measurements done in a standards laboratory of a space station outside of solar system would agree with those on earth. EEP quarantees the establishment of universal standards and their implementations.

On the other hand, further tests of EEP demand more precise standards and progress in metrology. The test of gravitational redshift derived from EEP is such an example: In 1976, Vessot et al[16] used an atomic hydrogen maser clock in a space probe to test and confirm the metric gravitational redshift to an accuracy of 1.4×10^{-4}. The space probe attained an altitude of 10,000 km above the earth's surface. This experiment improved by two orders of magnitude as compared to the earlier ones.[17] Routine results of standards laboratories and their comparisons could also be considered as tests of EEP. Thus we see the close relationships between EEP and advanced metrology.

VII. Quantum Metrology

In modern society, electromagnetic measurements are indispensible. The developments of Josephson voltage standard, quantum flux measurement and quantized Hall resistance increase the precisions of many electromagnetic measurements. The precise measurements of time and length use quantum transitions of atomic systems. All these belong to the realm of quantum metrology. In next decade, we will see even more prevailing development of quantum metrology.

VIII. Concluding Remarks

Metrology is the basis for precision industry and precision measurement. As society develops, we demand ever precise industry. As physics develops we look for new frontiers. These new frontiers can be found in higher energy accelerators, astrophysical situations and precise measurements of minute effects. The weight of precision measurement in physics will grow steadily. Thus, we see the increasing importance of metrology.

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