PROGRESS IN METROLOGY AND PRECISION MEASUREMENT IN JAPAN

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1. Measurement Standards

Since having joined in Metric treaty in 1885, continued effort has been made to establish more accurate national measurement standards as well as to disseminate Metric System in Japan. As early as 1930's, the Meter bar was measured using the Fabry-Perot etalons with Cd lamp as the light source. The absolute measurement of Ampere was underteaken using the Rayleigh balance with the accuracy $1\sim2 \times 10^{-4}$ in 1939, and that of Ohm was undertaken using the mutual inductance method with the accuracy 2×10^{-5} in 1937 at the Electrotechnical Laboratory(ETL). ETL also joined the international comparison of the standard lamp for the photometric standard in 1940. The thermodynamical temperatures of the ice point, the silver point and the gold point had been measured at the Tokyo Institute of Technology in 1940's. The Central Inspection Institute of Weights and Measures(former name of the National Research Laboratory of Metrology(NRLM)) joined the international comparison of the Standard Platinum resistance thermometer in 1955. The absolute measurement of the gravitational acceleration was undertaken at NRLM in 1960's and the result was reported to the 1st International Conference on Precision Measurement and Fundamental Constants in 1970.

Researches and establishment of measurement standards of the highest accuracy have been carried out at the national laboratories, mainly NRLM and ETL. NRLM is responsible for the standards of length, mass, time/frequency and temperature and also the derived quantities, and ETL is responsible for the standards of electricity, photometry and radiation dosimetry. The Radio Research Laboratories(RRL) is responsible for emission of the standard wave.

1.1 Length standard and the relevant precision measurement

Stabilization of laser frequency has been studied at NRLM since 1960's, beginning from locking to the Lamb dip pattern then to the specific absorption line of molecule of CH_4 or I_2. Stability of the order of 10^{-12} has been attained[1),2)] and the wave length of He-Ne laser stabilized to I_2 absorption line was measured against the ^{86}Kr wavelength standard.[3)]
Measurement of the wavelength of CO_2 laser is under way using the technique of optical frequency multiplication and mixing.[4)]
Laser interferometers have been set up for calibration of the gauge

blocks and the line standards.[5] The latter was used for the international comparison of the line standards carried out in 1979. Two-wavelength interferometer is used for the measurement of length, and use of infrared region is advantageous. Two-wavelength

He-Ne and He-Xe infrared lasers have been set up at NRLM.[6]
Laser interferometry has been also applied to the measurement of earth strain.[7]

1.2 Mass Standard
A set of the standard weights used for the calibration are constituted dividing sequentially from the standard 1kg weight.
The weights used for routine calibration are made of stainless steel or brass, and the buoyancy correction is necessary when 1kg weight is calibrated against the national Prototype which is made of Pt-Ir alloy, since the density differs largely each other. A unique idea has been developed and implemented at NRLM which has enabled the accurate buoyancy correction without measuring the density of air. Buoyancy does not matter when the mass of two Prototypes are compared, but the adsorption of gases, specifically of water vapor, deteriorate the accuracy. It is quite difficult to measure the amount of gas adsorbed on the surface of the weight, and an elaborate method has been used to compare weights cancelling out the effect of adsorption.[8]

1.3 Time and frequency Standard
The Cs beam frequency standards has been established in NRLM in

order to realize SI second. The accuracy was estimated to be 5×10^{-13} but it may be improved more than twice since the elimination of distortion due to modulation has recently been confirmed by

introducing a computer in the servo loop.[9],[10]
The steep gradient of the magnetic field in the course of Cs beam may cause the uncertainty in determining the frequency of the conventional Cs beam type frequency standard, and the effect is under investigation at NRLM.
Routine reception of the Standard LORAN C time singnal emitted from Iwojima island has been continued at NRLM, RRL and Tokyo Astronomical Observatory(TAO), and the results have been routinely sent to BIH for the international comparison of time and frequency.

1.4 Standards of Electricity
Main emphasis is now put on so-called Josephson voltage standard as well as the resistance standard at ETL. The Josephson voltage standard is based on the Josephson effect which relates voltage V to frequency f as

$$V = \frac{h}{2e} f$$

where e and h are the elementary charge and the Planck constant, respectively.
The Josephson voltage obtained by a single junction is ordinarily less

than 10mV being inconvenient for practical use.
The multiple junction has been constructed at ETL to give Josephson voltage of 100mV, and the uncertainty has been evaluated to be 2.4×10^{-9} in the measurement of 1V.[11)]
The accuracy of the capacity standard was improved by the invention of the calculable capacitor, so-called cross capacitor. Using the horizontal cross capacitor specially designed at ETL, it was shown that the capacitance of 1pF standard capacitor was able to be measured with the accuracy of 0.22ppm.
The resistance of the standard resistors is accurately determined using CR bridge, and calibrating the capacitance of the capacitor in the arm by the cross capacitor. The accuracy of 3×10^{-7} has been maintained at ETL.

1.5 Temperature standards
Temperature standards are based on IPTS-68 which is going to be amended within 5 years. It is aimed at extending the temperature range where the standard platinum resistance thermometer(SPRT) is used as an interpolating instrument. Extensive study has been carried out at NRLM on the stability of SPRT for use at higher than the silver point, that is 961.93 $^{\circ}$C, and the results are expected to be taken into consideration at the amending IPTS-68.
It is known that the triple points are more accurately determined than the boiling points where precision measurement of pressure is needed. The triple point of In, 156.63 $^{\circ}$C, has been realized at NRLM for calibration of SPRT[12)], and that of oxygen, 54K, is now examined by a gas thermometer.[13)]
The monochromatic pyrometer using Si photodiode as the detector has been extensively investigated at NRLM for the industrial standard.[14)] It is expected to be used as the secondary standard instrument for the realization of IPTS-68 with the aid of the portable fixed point furnace for self-calibration.[15)]

2. Precision Measurement of the Physical Constants

Precision measurement of the fundamental physical constants is very important for the verification of the fundamental physical laws and also closely related with the establishment of measurement standards. Speed of light in vacuo has been accurately determined and it has led to the redefinition of the Meter. The uncertainty in the electrical unit is now limiting the accuracy of determining the value of the fundamental constants which involve measurement of the elctrical quantities. The mass standard in the metric system is the only standard defined by the artefact, and it can be redefined if the Avogadro constant is determined in the order of 10^{-9} which is still far from realization.

2.1 Rydberg constant

Rydberg constant is a constant appeared in the atomic spectral terms and expressed as

$$R = \frac{2\pi^2 e^4}{ch^3}\left(\frac{1}{1/m + 1/M}\right)$$

where c, e, h are the speed of light, the elementary charge and the Planck constant respecively, and m and M are the masses of the electron and the atomic nucleus. R for the infinite M, R_∞ , is also called the Rydberg constant and plays important role in the adjustment of the fundamental physical constants, since it can be determined very accurately with the aid of spectroscopy.

The Rydberg constant was determined at NRLM from the observation of the two-beam interferogram of H . The result was

$$R_H = 109\ 677.5855(85)\ \mathrm{cm}^{-1}$$

after the re-evalution.[16),17)]

2.2 Gyromagnetic ratio of proton

The angular precession frequency ω of the proton under magnetic field is given

$$\omega = \gamma_p B$$

where B is the magnetic flux density and γ p is a constant called the gyromagnetic ratio.

Two different techniques have been used for measuring γp. The more accurate method involves the free precession of protons in a small magnetic field of order of 0.001T which is obtained by passing a current known in terms of as-maintained electric units through a precision solenoid. The field is then calulated from the current and the accurately known dimensions of the solenoid. This method is called the low-field one.

The second method called the high-field one uses resonant absorbsion and is usually carried out in a coventional electromagnet at a field of order 0.5T.

The γ p has been determined at ETL with the low-field method and the revised system is under construction to obtain more accurate value than reported:

$$\gamma'_p = 2.6751630(85)\times10^8\ \mathrm{s}^{-1}\ \mathrm{T}^{-1}{}_{\mathrm{ETL}}$$

where γ'p denotes γp in H_2O.[18)]

The determination of γp with the high-field method is also under way at ETL. Both measurements are carried out in the non-magnetic laboratory recently completed in Tsukuba.

2.3 Quantized Hall Resistance

Motion of the electrons in MOS inversion layer is quantized at sufficiently low temperature when strong magnetic field is applied perpendicular to the surface. Then the ratio of the current passing in an oblong sample of MOSFET to the Hall voltage, the Hall conductivity, is quantized in units of e^2/h.

This phenomenon has been investigated theoretically by Ando et al[19] and von Klitzing has proposed an atomic resistance standards based on the effect.[20]

Precision measurement of the Hall resistance also provides a new method to determine the fine structure constant which is one of the important fundamental constants.

The quantized Hall resistance has been measured at ETL[21] and reported as

$$h/4e^2=6\ 453.1969(56)\ \Omega_{SI}$$

2.4 Density of Water

The density of water is an important physical constant as its value is used not only in density measurement but also in volume and pressure measurement. The absolute measurement of the density of water has been carried out at NRLM by the buoyancy method.[22]

A sinker of a known volume is immersed in water and buoyant force is measured by a hydrostatic balance, then the density of water ρ is given by

$$\rho = m_f/V$$

where m_f is the mass replacing the buoyancy on the sinker.

Spheres of transparent and opaque silica have been specially prepared and their volumes have been determined by measuring the diameters using the optical interferometer specially designed for the purpose.[23] A remote-controlled balance for weighing sinkers both in air and water was also equipped.

The thermal expansion coeffifients have also been measured by two different methods.[24] Final results will be obtained in near future.

2.5 Other physical constants

(a) Repeat distance of the lattice of Si

Precision measurement of the repeat distance of the lattice of Si leads to the determination of the Avogadro constant in ppm level. It is measured by combining X-ray and optical interferometer.

Its value has been determined both at NBS and PTB, and the results show statistically significant discrepancy. The measurement is under way at NRLM and a preliminary result is expected in near future.

(b) Magnetic flux quantum

Magnetic flux in a superconducting ring is quantized in units of h/2e, which is called the magnetic flux quantum and is denoted Φ_0. Precision measurement of Φ_0 is importance since it is closely related to the Jopephson voltage standard.

A new method to determine Φ_0 has been proposed aiming at obtaining the accuracy in subppm level.[25] A superconducting levitating system is composed of a superconducting floating body M and a superconducting coil. When the quasi-static state is realized by slowly flowing a current in the coil, the magnetic energy is substituted by the gravitational energy and Φ_0 can be determined by measuring the displacement of the floating body.

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