Length—Evolution from Measurement Standard to a Fundamental Constant

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Introduction

The meter had its origin in August of 1793 when the Republican Government of France decreed the unit of length to be 10^{-7} of the earth's quadrant passing through Paris and that the unit be called the *meter*.[1] Five years later, the survey of the arc was completed and three platinum standards and several iron copies of the meter were made. Subsequent examination showed the length of the earth's quadrant had been wrongly surveyed, but instead of altering the length of the meter to maintain the 10^{-7} ratio, the meter was redefined as the distance between the two marks on a bar.

In 1875, the Treaty of the Meter established the General Conference on Weights Measures (Conférence Général des Poids et Mésures, CGPM) as a formal diplomatic organization responsible for the maintenance of an international system of units in harmony with the advances in science and industry. This organization uses the latest technical developments to improve the standards system through the choice of the definition, the method to experimentally realize the definition, and the means to transfer the standard to practical measurements. The international system of units (Système Intérnational d'Unités, SI) is constructed using seven base units for independent quantities and two supplementary units for angles and is a modern metric system.[2] Within the United States, the National Institute of Standards and Technology (NIST) has the responsibility for realizing the values of the SI units and disseminating them by means of calibrations to domestic users, as well as engaging in international research with other national laboratories and with the International Bureau of Weights and Measures (Bureau Intérnational des Poids et Mésures, BIPM).

Definition

The meter (m) is the Si unit of length and is defined as *the length of the path traveled by light in vacuum during the time interval of 1/299 792 458 of a second*.[3] This replaces the two previous definitions of the meter: the original adopted by CGPM in 1889 based on a platinum-iridium prototype bar, and a definition adopted in 1960 based on a krypton86 radiation from an electrical discharge lamp. In each case, the change in definition achieved not only an increase in accuracy, but also progress toward the goal of using fundamental physical quantities as standards, in particular, the quantum mechanical characteristics of atomic systems.

In 1889, there was one prototype meter, a bar made of a platinum iridium alloy with lines inscribed at each end; the distance between them defined the meter (see Figure 1). The length standard was disseminated to the national laboratories through the use of artifact meters, which were accurate (but not identical) replicas of the prototype meter. Each artifact meter was calibrated against the prototype for use as a national standard. A serious problem with a prototype standard results from the fact that there is no method to detect a change in its value due to aging or misuse. As a consequence, it is not possible to state the accuracy or stability of the prototype meter, although calibration uncertainties of the artifact meters can be assigned.

Figure 1. Historical Standard Platinum Iridium Meter Bar.

The development of the Michelson interferometer, which measures physical displacement in terms of optical wavelengths, and the realization that certain atoms and molecules have precisely defined and reproducible emission frequencies (and, thus, wavelengths) brought about the transition from a mechanical to an optical length standard. The krypton86 electrical discharge lamp was designed to produce the Doppler-broadened wavelength of the $2p_{10}$ $5d_5$ transition of the unperturbed atom. The two dominant wavelength shifts, one caused by the DC Stark effect and the other by the gas pressure in the discharge lamp, were opposite in sign and could be made equal in magnitude by the proper choice of operating conditions. Different krypton86 lamps reproduced the same wavelength to about 4 parts in 10^9, but had the disadvantage that the coherence length of its radiation was shorter than the meter, complicating the changeover from the older standard.

The ability to measure atomic wavelengths with higher accuracy and reproducibility has been further enhanced by the invention of the laser, along with techniques that permit the direct observation of the natural linewidth of atomic and molecular transitions without Doppler broadening. By using saturated absorption spectroscopy, which employs high-intensity counter-propagating laser beams, previously unresolved hyperfine transitions are measured to high accuracy.

Faced with the possibility that further advances in laser spectroscopy would lead to proposals for new length standards based on more precise atoms or molecules, a new concept for the length standard definition was developed. The second (which is equivalent to 9,129,631,770 oscillations of the ^{133}Cs atom) and the meter are independent base units. Traditionally, the speed of light was measured in terms of their ratio. By contrast, the present standard defines the meter in terms of the SI second and a defined (i.e., conventional) value for the speed of light in vacuum which fixes it to 299 792 458 m/s[1] exactly and the meter is determined experimentally. Since it is not based on a particular radiation, this definition opens the way to major improvements in the precision with which the meter can be realized using laser techniques without redefining the length standard.[4]

Realization

The BIPM stipulates that the meter can be realized by the following three methods. In these descriptions, c is the speed of light. The meter can be realized

By a direct measurement of the distance L that light travels in vacuum in the time interval t, using the relation $L = (c)(t)$;

By a direct measurement of the frequency f of radiation and calculating the wavelength L in vacuum λ using the relation $\lambda = c/f$;

By means of one or the radiations from a list provided by the BIPM whose frequency and vacuum wavelength can be used with a stated uncertainty.

Method 1 follows directly from the definition, but cannot achieve the accuracy possible with the other two, and so is not used for practical purposes.

Method 2 measures laser frequencies in terms of the cesium clock. A complicated series of measurements is required because of the large difference between the microwave clock (9 GHz) and visible frequencies (500 THz), and because different regions of the electromagnetic spectrum require different measurement technologies. The general technique is to detect the beat frequency generated by focusing two or more laser beams, for example, the harmonic of one oscillator or laser and the fundamental of another, on nonlinear detector diodes, and adding or subtracting microwaves, to reduce the frequency of the beat signal so that it is within range of the counter. In the microwave region, commercial diodes are used. In the infrared region, specially constructed metal-insulator-metal diodes are used because of their ability to rectify signals at optical frequencies. In the visible region, parametric up-conversion is used to convert infrared radiation into visible light that is compared to a visible stabilized laser using a photo diode.[5] The accuracy of the chain of frequency measurements from the cesium clock to the red helium-neon line (633 nm) is about 7.2 parts in 10^{12} and has an advantage over interferometry because corrections do not have to made for diffraction effects, reflective phase shifts, or the index of refraction.

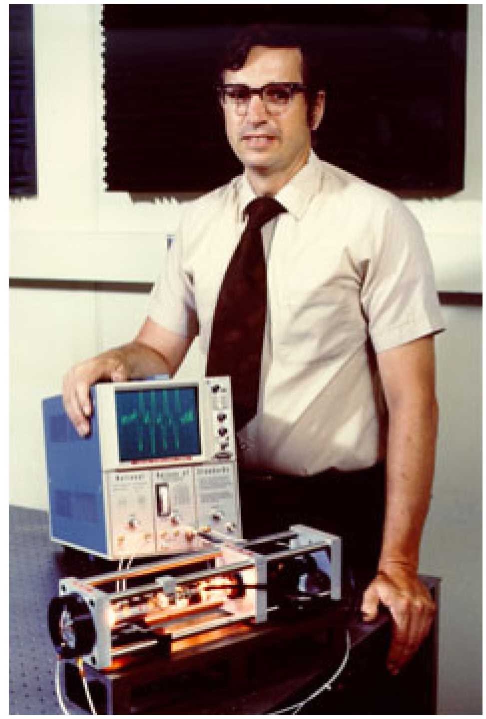

Figure 2. Iodine Stabilized HeNe Laser.

Method 3 establishes practical length standards by using the frequencies of certain stabilized lasers whose performance has been carefully measured using Method 2 and calculating the wavelengths. In this way, a laboratory standard of known frequency can be constructed using the specifications and operating conditions provided by the BIPM. These descriptions also indicate the error associated with this method of realization. For length metrology, the iodine stabilized HeNe laser operating at 633 nm is the most common because it is convenient to operate, accurate to 2.5 parts in 10^{11}, and is used to calibrate commercial displacement measuring interferometer systems (see Figure 2).

Transfer

The ability to transfer the length standard to practical measurements is influenced by the index of refraction (n) of the beam path of the measuring instrument since the wavelength of the HeNe laser (633 nm) is air is smaller than its vacuum wavelength by 2.7 parts in 10^4 for standard atmospheric conditions. If the system is in a vacuum, the frequency of the length standard stipulated by the BIPM is used to calibrate the working laser and no further adjustments need to be made. If the system is not in a vacuum, an additional wavelength adjustment must be made for the index of refraction of the measurement environment. This can be done by a direct measurement of n or it can be calculated using an empirically derived formula whose input variables are temperature, barometric pressure, relative humidity, and CO2content.[6] The accuracy of the calculation using the empirical formula is about 1 part in 10^7 when state-of-the-art technology is used for measuring the four input variables, so the index of refraction adjustment results in a reduction in accuracy by a factor of 500 compared to the accuracy in vacuum.[7]

Summary

The modern length standard has evolved over a period of 200 years which has brought it to a point where it can be continually improved without the necessity of changing its definition. We may suspect that the developers of the first length standard were as unprepared to predict present day developments as we are to predict the advances that will be made in the next century. Such developments will, no doubt, cause great excitement for those who make precision measurements.

References

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