Using Time to Measure Length

The meter is the length of the path traveled by light in a vacuum during a time interval of 1/299,792,458 of a second—proposed redefinition of the meter.

It is currently possible to measure time from the frequency of transitions in atomic clocks much more accurately than it is to measure distance from the wavelength of optical radiation. Hence, the proposal by the Consultative Committee for the Definition of the Meter (CCDM) opens the way to a much improved determination of the meter. Recently, researchers at the National Bureau of Standards (NBS) in Boulder, Colorado, reported new measurements of the frequencies of two transitions in molecular iodine in the visible region of the electromagnetic spectrum. Either of these frequencies in conjunction with the proposed new definition would provide a realization of the meter that is more than ten times as accurate as the current standard, which is based on the wavelength of light emitted by a krypton-86 atom.

The interesting feature of the proposed definition, which is quite likely to be adopted this October during the 1983 General Conference on Weights and Measures in Paris, is that it does away with the krypton meter standard and replaces it with a time standard. Whenever anyone wanted to replicate the meter to a particular accuracy, an atomic clock of the appropriate accuracy would be the reference. The connection between time and distance in the new definition of the meter is the speed of light, which would no longer be a quantity to be measured but would have a fixed value defined as 299,792,458 meters per second. The connection is by means of the relation $\lambda\upsilon = c$, where λ is the wavelength and υ is the frequency of the light (*Science*, 25 February, p. 913). Some metrologists have wondered if it would be possible to replace the seven base standards (time, distance, mass, temperature, current, voltage, and resistance) with a single base standard—time. The redefinition of the meter is the first step in this process.

In principle, the most accurate meter could then be determined from the best atomic clock, cesium-133, which is accurate to about 8 parts in 10^{14}. The present meter standard is accurate to about 4 parts in 10^9. In practice, the improvement by a factor of 50,000 is not yet realizable. The second is defined by a microwave (9.192 631 770 GHz) transition in cesium-133 with a wavelength of about 3.3 centimeters. Length metrology is most conveniently done with optical devices such as interferometers whose interference fringes can be accurately measured. Interferometers of the required accuracy for 3-centimeter radiation would be transcontinental in size. Laboratory scale equipment must therefore be based on visible light.

This is where the NBS work comes in. The group headed by Kenneth Evenson has measured the frequencies of two visible wavelength transitions in molecular iodine to an accuracy of 1.6 parts in 10^{10}, which is about 1000 times better than previous determinations. Moreover, the realization of the new definition of the meter based on either of these frequencies would be a considerable improvement on the present krypton standard. In other words, the new frequency measurements, as well as similar ones under way in other laboratories around the world, provide the first practical way to implement the proposed new meter.

Measuring frequencies in the visible is far from straightforward because the electronic devices that work so well for microwaves cannot respond fast enough to measure frequencies counted in the hundreds of terahertz (THz). The now time-honored approach to this problem is to construct a chain of frequency sources of progressively higher frequencies, starting with the cesium atomic clock at the bottom and working up. By accurately comparing the frequency of each source in the chain to the one below it and to the one above it, metrologists can reach the top of the chain. Until the recent NBS reports, the most accurate frequency measurements of this type ended in the infrared.

In the NBS experiments, the entire frequency source chain from the cesium atomic clock to the visible is quite lengthy. The interesting part of the chain in one experiment begins with a frequency-stabilized carbon dioxide gas laser emitting radiation at about 26 THz (11.5 micrometers wavelength) and ends with a frequency-stabilized tunable dye laser that emits in the visible. The carbon dioxide laser frequency is fixed by a molecular transition within the carbon dioxide itself. The dye laser frequency is fixed by a visible (520-THz) transition within molecular iodine. The iodine gas is in a cell outside the laser optical cavity. In between on the chain are two infrared lasers (a helium-neon gas laser at 250 THz and a solid-state color center laser at 130 THz) whose frequencies are each fixed with respect to the laser just above them in the chain. For a given pair of lasers, nonlinear lithium niobate crystal doubles the frequency of the lower frequency light. By a process called frequency mixing a germanium diode generates a signal having a frequency equal to the difference $\upsilon_{high} - 2\upsilon_{low}$. The signal from the diode feeds back to control the lower frequency laser in the pair.

The final value for the frequency of the molecular iodine transition is determined at the carbon dioxide end of this segment of the chain. A metal-insulator-metal diode accepts the radiation from the color center laser and the carbon dioxide laser (as well as a second carbon dioxide laser of a slightly different frequency). Diodes of this type can simultaneously generate multiples of the input frequencies and do frequency mixing. In this case the frequency of the output signal is $\upsilon_{color\ center} - 3\upsilon_{CO_2} - 2\upsilon_{CO_2'}$. It is this frequency that is actually measured and from which the visible frequency is calculated.

Details of the upper part of the chain in the second experiment are quite different from those of the first. However, the top of the chain was a helium-neon gas laser that was frequency-stabilized to another molecular iodine transition near 473 THz.

Evenson told *Science* that several other groups around the world have similar efforts under way. Metrologists at the National Physical Laboratory in the United Kingdom hope to have a measurement of the 473-THz radiation by this fall. Researchers at the National Research Council of Canada are in the midst of a 520-THz determination. And investigators in the U.S.S.R., Japan, West Germany, France, and Italy have efforts under way to make these or related measurements.—**ARTHUR L. ROBINSON**