Speed of Light From Direct Frequency and Wavelength Measurements

The National Bureau of Standards has had a long history of interest in the speed of light, and no doubt this interest contributed to the measurement described here [1]. As early as 1907, Rosa and Dorsey [2] determined the speed of light from the ratio of the capacitance of a condenser as measured in electrostatic and electromagnetic units. Over the ensuing years NBS developed still other methods to improve upon the accuracy of this important physical constant.

By the late 1960s, lasers stabilized in frequency to atomic and molecular resonances were becoming reliable research tools. These could be viewed as providing stable reference for either optical frequency or wavelength. This duality of frequency and length produced the obvious suggestion that a simultaneous measurement of frequency and length for the same laser transition would yield a very good measurement of the speed of light. In fact, a 1958 measurement of the speed of light by Froome [3] was done by determining the frequency and wavelength of a microwave source at 72 GHz. The frequency measurement was fairly straightforward, since frequency in the microwave and lower ranges can be readily measured with great accuracy. The speed-of-light measurement was limited primarily by the difficulty in measuring the very long wavelength (about 0.4 cm) of the 72 GHz radiation. Clearly, a better measurement would result if higher frequencies could be employed, where wavelengths could be more accurately measured. The measurement technology of that era was not up to the task. The wavelength of visible radiation could be measured fairly well, but no accurate methods for measuring visible frequencies were available. Whereas frequency could be measured quite well in the microwave to millimeter-wave region, wavelength measurements were problematic.

The measurement of the speed of light by the Boulder group involved the development of a new method. The approach taken was to synthesize signals at progressively higher and higher frequency using harmonic-generation-and-mixing (heterodyne) methods and to lock the frequency of a nearby oscillator or laser to the frequency of this synthesized signal [4]. Photodiodes, as well as metal-insulator-metal diodes, fabricated by adjusting a finely tipped tungsten wire against a naturally oxidized nickel plate, were used for harmonic generation and mixing. With this approach, a frequency-synthesis chain was constructed linking the microwave output of the cesium frequency standard to the optical region, so that the group could directly measure the frequency of a helium-neon laser stabilized against the 3.39 μm transition of methane. When the measurements were completed, the uncertainty limitation was found to be the asymmetry of the krypton line on which the definition of the meter was then based. The experiment thus showed that the realization of the meter could be substantially improved through redefinition.

This careful measurement resulted in a reduction of the uncertainty of the speed of light by a factor of nearly 100. The methods developed at NIST were replicated in a number of other laboratories, and the experiments were repeated and improved to the point where it was generally agreed that this technology could form the basis for a new definition of the meter. An important remaining task was the accurate measurement of still-higher (visible) frequencies which could then serve as more practical realizations of the proposed new definition. The Boulder group again took the lead and provided the first direct measurement of the frequency of the 633 nm line of the iodine-stabilized helium-neon laser [4], as well as a measurement of the frequency of the 576 nm line in iodine [5]. These measurements, and similar measurements made at other laboratories around the world, were the last ingredients needed to take up the redefinition of the meter.

The new definition of the meter, accepted by the 17th Conférence Générale des Poids et Mesures in 1983, was quite simple and elegant: "The metre is the length of the path traveled by light in vacuum during a time interval of 1/299 792 458 of a second." A consequence of this definition is that the speed of light is now a defined constant, not to be measured again. NBS had played a key role in pioneering measurement methods that resulted in this redefinition and in the optical frequency measurements that contributed to practical realizations of the definition. In subsequent years, measurement of other stabilized-laser systems added to the ways in which the meter could be realized. This way of defining the meter has proven to be particularly robust, since unlike a definition based on a standard such as the krypton lamp, length measurement can be continuously improved without resorting to a new definition.

Fig. 1. Winners of the Gold Medal from the Department of Commerce for their measurement of the speed-of-light. Shown left to right in front are Ken Evenson (project leader), Bruce Danielson and Gordon Day and in back left to right are Dick Barger, John Hall, Russ Petersen, and Joe Wells.

The measurement methods developed at NBS during this period also led to the development of high-resolution spectroscopic methods utilizing tunable frequency sources in the optical region [7,8]. These techniques produce results with at least 100 times smaller uncertainty than traditional spectroscopy involving wavelength measurement. The lower uncertainty has had impact in areas, such as radio astronomy and investigations of the upper atmosphere, where better determinations of spectral lines have facilitated studies of important molecules in space and in the stratosphere. Another notable result was the use of the methods to generate extensive tables of accurately measured spectral lines across the infrared spectrum [9]. These tables have contributed significantly to the reliability of laboratory spectroscopic measurements throughout this spectral region.

It is worth noting that management terminated the NBS work on frequency-synthesis chains shortly after completion of the work that led to the meter redefinition. Staff involved in this effort then redirected their efforts toward other programs. Ken Evenson, Russ Petersen, and Joe Wells initiated new work on high-resolution frequency-based spectroscopy using the mixing methods developed for the frequency-synthesis chain, while Bruce Danielson and Gordon Day eventually became involved in optical-fiber metrology and in other optical communication measurements. John Hall went on to develop high-performance laser systems within the Quantum Physics Division, a joint NIST-JILA enterprise, and Dick Barger left NBS to work at the University of Colorado. Russ Petersen died suddenly in 1983, just two months after the redefinition of the meter was made official, and Dick Barger died in 1998. Ken Evenson, Bruce Danielson, and Joe Wells have since retired from NIST.

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