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# The Speed of Light

## A Metrologist's Historical Perspective

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*In the last 375 years, metrologists have progressed from Galileo and his candle flame to current methods of laser measurement techniques. By analyzing this historical perspective, we realize that even the greatest scientists of history have had to deal with problems that the modern metrologist copes with on a day-to-day basis.*

The velocity of electromagnetic radiation, more commonly known as the speed of light, is a fundamental physical constant (at least as defined by current knowledge). A fundamental physical constant is a physical quantity that comes very close to being a natural unit of science. Other natural units of measurement include the elementary charge, electron mass, Planck's constant, the Avogadro constant and the proton mass. Although fundamental constants are not defined as SI units (French abbreviation for international system of units), physicists are defining an increasingly close relationship between the fundamental constants and SI units. As an example, for the SI measurement of length, the fundamental constants of the velocity of light, the Rydberg constant, and the lattice spacing of silicon are used.

As a metrologist, it is interesting to examine the historical development of some of these fundamental constants or SI units. By reviewing the original experiments and noting the measurement error associated with the experiment, we gain an appreciation of the increase in precision each scientist brought to determining the velocity of light. The measurement of the velocity of light was the first fundamental physical constant to be quantified, and has had many improvements in its accuracy of measurement. The table following lists some of the advances in the measurement of the velocity of light.

In 1600, about the time that America was being colonized, Galileo was the first to attempt to measure the velocity of light with his famous lantern experiment. Galileo set up two lanterns with shutters on two hills, he operated one lantern, and his assistant operated the other. Galileo used the shutter to shut off the light from his lantern, and when his assistant saw the light go out, he was to close the shutter over his lantern. Galileo attempted to measure the time interval between the closing of the shutters, but found that the light would extinguish faster than they could react to measure. Through this experiment

Galileo concluded that light was extremely fast, but could not quantify it.

Roemer, however, succeeded in producing the first finite value for the velocity of light after his study of the systematic variation of the apparent period of Jupiter's first moon around its parent planet. This was the first scientifically determined velocity of light at  $2.14 \times 10^8$  m/s; it deviates 30% from today's value. Considering the available tools and information in 1676, achieving this measurement was quite a feat. The major source of error in his experiment was from inadequate knowledge of the radius of the orbit of Earth.

Bradley confirmed that light did in fact have a finite, measurable velocity in 1729. His experiment involved the apparent change in position of the stars as a result of the motion of the Earth about the Sun. Bradley improved the accuracy of the measurement tenfold, measuring the velocity of light at  $3.08 \times 10^8$  m/s.

In 1849, Fizeau made his toothed wheel (720 teeth) measurement between two hills near Paris which were about 8.6 km apart. This provided the first terrestrial confirmation of the finitude of the velocity of light. Although his measurement of  $3.14 \times 10^8$  m/s was less accurate than the experiment of Bradley, the invention of the toothed wheel measurement system paved the way for Michelson's rotating mirror experiments.

The "quantum leap" in light measurement was made in 1879 by Michelson. He established a phenomenally more accurate measurement of  $2.99798 \times 10^8$  m/s. This was approximately 600 more times more accurate than the previous experiments of Fizeau and Bradley. Michelson employed a rotating mirror, incorporated with a mile long evacuated pipe in order to remove the effects of refraction of air. The total distance traveled by the light was over 70 km. It is important to note that of the scientists we are discussing, Michelson was the first to produce an estimate of uncertainty of measurement. Michelson won

the Nobel Prize for Physics in 1907 for his optical precision instruments and metrological investigations carried out with their aid.

The development of pulsed microwave instruments during World War II led to the measurement of the velocity of microwave radiation using an evacuated cavity resonator by Essen and Gordon-Smith. The implementation of microwave technology decreased the uncertainty of measurement for the velocity of light to approximately 1/20 of its previous value.

In 1958, Froome increased the accuracy of microwave velocity measurement even further by employing a 1.25 cm wavelength Michelson interferometer. It is important to note that, before the use of interferometers, scientists had great difficulty in making accurate length measurements. In fact, many measurements were subsequently corrected after recalibration of the length standards based on interferometric measurement techniques.

The last three experiments listed in the table below, that of Evenson, Blaney, and Woods, were all performed using either helium-neon or carbon dioxide lasers. In general, their technique was to frequency

modulate the laser at a microwave frequency (approximately 5 GHz), thereby producing sidebands. These sidebands were used with a piezo-electrically adjusted Fabry-Perot interferometer. The wavelength measurement from the interferometer, and the frequency measurement of the sidebands produced a measurement of the velocity of light. It was largely from these three experiments that the present internationally agreed upon value for the velocity of light was decided.

In 1958, the International Scientific Radio Union and the International Union for Geodesy and Geophysics reviewed all available results and recommend that the international use for the value of the velocity of light in vacuum be set at  $2.9979245 \times 10^8$  m/s. This lasted until the adoption of the value of  $2.997924580 \times 10^8$  m/s by the Consultative Committee for the Definition of the Meter in 1972. This is still the internationally agreed upon value for the velocity of light in vacuum.

Although the definition of the speed of light has remained unchanged for 24 years, it is by no means permanently set at this value. Changes to the velocity of light and other fundamental physical constants

will be re-measured and redefined in the future as our understanding of the universe is refined further.

All scientists have to understand and be able to calculate measurement uncertainty and be cognizant of the fact that scientists sometimes unknowingly introduce error into their experiment via calibration error of their test equipment. As professional metrologists, it is important to have a good working knowledge of fundamental constants such as the velocity of light and to understand how they were developed. In the last 375 years, metrologists have progressed from Galileo and his candle flame to current methods of laser measurement techniques. By analyzing this historical perspective, we realize that even the greatest scientists of history had to deal with problems that the modern metrologist copes with on a day-to-day basis.

#### References

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2. B.W. Petley, *The Fundamental Physical Constants and the Frontier of Measurement*, Adam Hilger, 1988.

*Jeff Gust is a metrology engineer for GTE Electronic Repair Services. GTE ERS is composed of six service centers located nationwide and is one of the largest fourth-party depot and support organizations in the United States. A single source provider, the company offers a broad range of repair and support services to manufacturers, local exchange, and long distance carriers, and major end-users.*

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The Speed of Light: Some Selected Measurements

Date	Scientist	Country	Method	Speed (10 <sup>8</sup> m/s)	Uncertainty (m/s)
1600	Galileo	Italy	Lanterns and shutters	"Fast"	?
1676	Roemer	France	Moons of Jupiter	2.14	?
1729	Bradley	England	Aberration of light	3.08	?
1849	Fizeau	France	Toothed wheel	3.14	?
1879	Michelson	United States	Rotating mirror	2.99910	75,000
1879	Michelson	United States	Rotating mirror	2.99798	22,000
1950	Essen	England	Microwave cavity	2.997925	1,000
1958	Froome	England	Microwave interferometer	2.997925	100
1972	Evenson et al.	United States	Laser method	2997924574	1.1
1974	Blaney et al.	England	Laser method	2.997924590	0.6
1976	Woods et al.	England	Laser method	2.997924588	0.2
1983	Internationally adopted value			2.99792458	Exact