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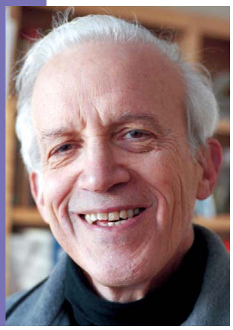

Master Michelson's measurement

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Albert A. Michelson, master in the US Navy, measured the speed of light in 1879 with a precision ten times better than the best value from Europe. He had little schooling in physics and no research experience: This was the work of a prodigy. In the following three years, he invented the Michelson interferometer and carried out his first ether drift experiment. He went on to lay the foundations for high-precision measurements and natural physical standards. Michelson's report on his speed-of-light measurement, which has been preserved in his own handwriting, describes exactly how he executed his wizardry.[1] Physicists, particularly experimental physicists, who read the document will recognize Michelson's instinct for key issues, his frustrations in making things work, and his struggles to achieve honest results.

Michelson's background was hardly auspicious for a physicist. In 1856, when Albert was four years old, his father, a peddler, fled with his family from Poland to California. They settled in Murphy's Camp, a lawless gold-rush town that was a good place for a boy to learn how to fight but not how to read and write. When Albert reached the age of 14, he was sent to San Francisco, where he worked his way through high school. His scientific precociousness inspired the principal to provide him with room and board, plus a job helping in the physics classes.

The US Naval Academy at Annapolis, Maryland, was one of the few institutions where a penniless boy could learn science. On finishing high school in 1869, Albert applied to his state representative for entrance but was passed over. Undeterred, he crossed the country and personally persuaded the president, Ulysses S. Grant, to admit him.

Michelson acquitted himself well at Annapolis, particularly after settling a debt of honor by pummeling his challenger in the boxing ring. According to his daughter's biography, Michelson did not shine in seamanship but did shine in optics.[2] He studied physics from a widely used textbook by Adolphe Ganot. The text is crammed with elaborate illustrations of machines, but it has little discussion of physical principles and generally avoids math. How Michelson developed the mindset of a skilled physicist from a curriculum based on Ganot is a puzzle. He graduated in 1873 and went to sea for two years on an obligatory voyage. Physics had to be deferred.

On returning to the US, Michelson was assigned to Annapolis as an instructor in physics and chemistry. The commander asked him to look into Léon Foucault's measurement of the speed of light. Michelson was instantly hooked. Foucault claimed an accuracy of half a percent. Michelson decided that he could do much better. In the fall of 1877, he sketched an experimental plan, and within two years he demonstrated that he could, indeed, do much better. His report on the measurement is essentially a treatise on pushing the frontiers of precision in an age of iron and steam.

In Foucault's method, light from a slit reflects from a rapidly revolving mirror, travels to a distant mirror where it is reflected back to the revolving mirror, and is brought to a focus. The image from the reflected beam is displaced from its initial position due to the rotation of the mirror while the light traverses the apparatus. Finding the speed of light requires measuring the path length, the rate of rotation of the mirror, and the displacement of the image. Michelson set out to measure each of these to 1 or 2 parts in 10 000.

Michelson reasoned that the precision of Foucault's measurement was limited by uncertainty in measuring how far the slit image was deflected, so the obvious way to improve the accuracy was to increase the deflection. Increasing the deflection required increasing the length of the baseline. Foucault used a path length of about 66 feet; Michelson called for a base length close to 2000 feet. With a mirror spinning at 256 rotations per second, the image displacement would be 133 mm, about 20 times larger than Foucault's.

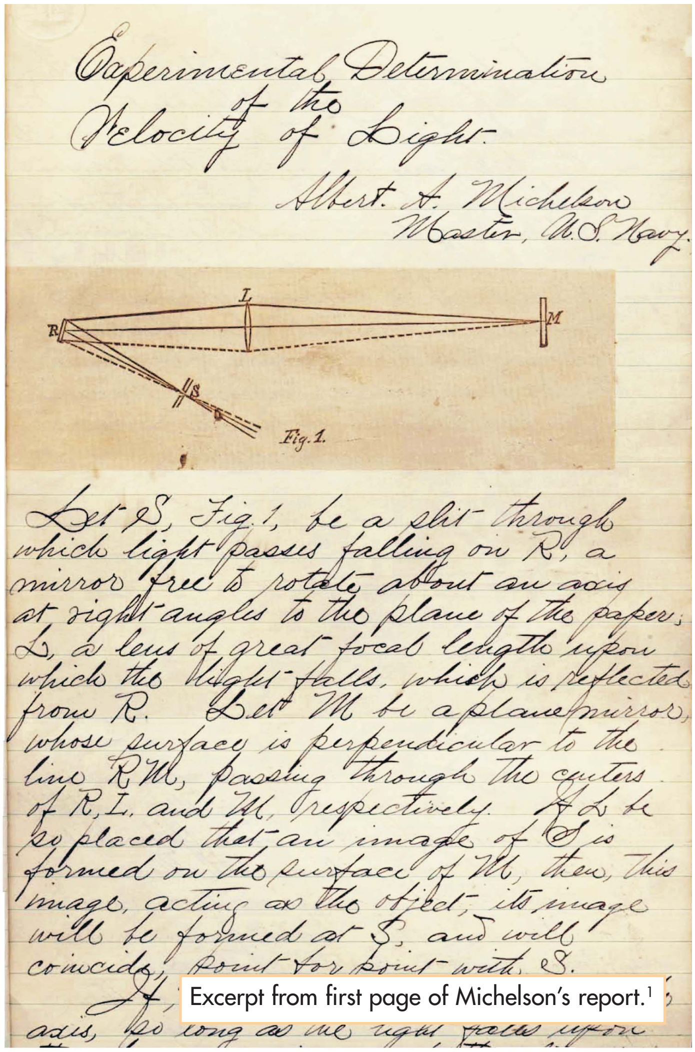
Living without electronics

If you have an experimental knack, you might find it interesting to figure out how Michelson could make a mirror rotate at 256 rotations per second and measure its rate to 1 part in 10 000 without benefit of electric motors or electronics, though I doubt that many 21st-century physicists could replicate Michelson's 19th-century achievement. It will not be of much help for you to learn that Michelson did this with compressed air, tuning forks, and mirrors. The techniques were essentially all known, but Michelson applied them with unprecedented virtuosity.

Michelson powered the rotating mirror with a turbine that was supplied by air from a compressor driven by a steam engine and controlled by a homemade bellows-like pressure regulator. The turbine caused endless mechanical problems and required laborious tinkering. He eventually found an acoustical criterion for success: "When the adjustment is perfect, the apparatus revolves without giving any sound."

Michelson monitored the rotation rate by watching the pulses of light from the slit using a small mirror at the tip of a tuning fork. The tuning fork operated continuously, driven electromagnetically by a coil and an interrupter. He synchronized the pulse rate with the tuning fork by adjusting the turbine's speed until the slit's image was stationary. The tuning fork was frequently calibrated against a standard tuning fork that was kept in an isolated, temperature-controlled chamber. Michelson had a good ear; by counting beats for 60 seconds, he could measure the difference in their frequencies to an accuracy of 0.01 or 0.02 beats per second.

To calibrate his standard tuning fork, Michelson used a now-antique device called a chronoscope. A tiny


Experimental Determination of the Velocity of Light.

Albert A. Michelson
Master, U.S. Navy.

Let S, Fig. 1, be a slit through which light passes falling on R, a mirror free to rotate about an axis at right angles to the plane of the paper; L, a lens of great focal length upon which the light falls, which is reflected from R. Let M be a plane mirror, whose surface is perpendicular to the line RM, passing through the centers of R, L, and M, respectively. If L be so placed that an image of S is formed on the surface of M, then, this image, acting as the object, its image will be formed at S, and will coincide, point for point with S.

If, … axis, so long as the light falls upon …

Excerpt from first page of Michelson's report.[1]

needle attached to the tuning fork left a fine wiggly line in lampblack on a slowly rotating drum. A spark triggered by a pendulum or chronometer (he used both) made a mark every second. Counting the wiggles between the marks gave the frequency. Finally, the chronometer was calibrated against Earth's rotation by timing the transits of stars at the US Naval Observatory. He noted that over the period of a week the chronometer ran fast by 1.34 seconds per day.

Michelson embedded a detail in his report that triggered a wave of nostalgia for me and probably resonates with the experience of most scientists. The detail was a date, 4 July 1879. Few pages were dated, and no other date was written as boldly. Clearly, the date carried a message. On the Fourth of July, Naval officers at Annapolis could be expected to be on parade or joining in the general celebration. Michelson wanted to tell the world that he chose, instead, to work in the laboratory. The reason for my particular nostalgia was that early in my graduate student career, on another Fourth of July, in 1956, I was working at a drafting table in the Lyman Laboratory at Harvard University, drawing plans for an atomic beam apparatus. Sounds of music and the explosions of fireworks drifted from the Cambridge Common. I clearly recall thinking along the lines, "The public is enjoying itself, but I am a physicist and I have more important things to do." In writing the date, Michelson undoubtedly had a similar thought. Apparently, I was not the only young physicist who indulged in self-dramatization!

Hands-on physics

The remaining tasks for Michelson, measuring the baseline with a steel tape and the slit image displacement with a micrometer, employed a length standard that he enigmatically described as "Wurdemanne's copy of the standard yard." He later sent the measuring tape to Stevens Institute and the micrometer to Harvard Observatory, where his calibrations were duly confirmed.

Michelson's report is full of details: coping with nonlinearities in the micrometer screw; supporting the measuring tape on blocks so that its droop would compensate for its stretching due to the tension; correcting for temperature variations, the refractive index of the atmosphere, and the like. His narrative is filled with tactile details: Before starting a set of measurements, he stoked the boiler for the steam engine that powered the turbine's air compressor; to adjust the turbine speed he tugged on a cord that ran to the far corner of his experimental shack; prior to each use of the chronoscope, he had to slowly turn its drum over a flame to coat it with soot; in the morning he evidently set out in the dark because the atmosphere became unstable an hour after sunrise.

The result of Michelson's measurement as listed with the data is that the speed of light is 299 940 ± 50 km/s. However, in his narrative, Michelson states emphatically that his measurement is correct "to within one two-thousandth part," which corresponds to an uncertainty of 150 km/s. His result actually differs by 148 km/s from the modern value, 299 792.458 km/s.

In addition to his technical skills, Michelson displayed considerable political skill in obtaining access to a site within the Naval Academy with an unobstructed view of 2000 feet, borrowing equipment far and wide, and winning the support of Simon Newcomb, the leading US astronomer and head of the US Naval Observatory, who became his mentor. Michelson completed his measurement in less than two years, a remarkable achievement considering that he started with neither equipment nor a laboratory.

Michelson's measurement made him a celebrity. The *New York Times* carried an article and his hometown newspaper made him a local hero. However, his scientific success did not make him a hero to the US Navy, which had him scheduled for sea duty. With a little help from Newcomb, Michelson obtained a leave of absence, and in the fall of 1880, he sailed for Europe to study physics and mathematics seriously.

Once in Europe, Michelson's dreams of studying math and physics got sidetracked. Instead of attending lectures, during an 18-month sojourn, he invented the interferometer that carries his name and searched without success for a sign of Earth's motion through the ether. After his great achievement in measuring the speed of light, failure to detect the ether was a blow. He confirmed the failure definitively five years later when he repeated the experiment with Edward Morley. Although the Michelson–Morley experiment is a landmark in physics, it gave Michelson no pleasure. His passion for measuring the speed of light, however, never ceased. On the day that he died, 9 May 1931, he was dictating notes on a new measurement.

I thank Charles Holbrow for helpful comments.

References

1. A. A. Michelson, *Experimental Determination of the Velocity of Light*, Lund Press, Minneapolis, MN [circa 1964]. An augmented article is available at http://www.gutenberg.org/files/11753/11753-h/11753-h.htm.
2. D. M. Livingston, *The Master of Light, A Biography of Albert A. Michelson*, Scribner, New York (1973). ■