

Michelson and measurement

A boy who grew up in Western mining camps became the preeminent master of precision measurement by light waves, largely through his playful work with interferometers and his quest to know the 'innards' of his instruments.

Lloyd S. Swenson Jr

Measurement, as much as if not more than mathematics, is the essence of modern natural philosophy and artful invention. To measure is to begin to understand and to manipulate. Yet modern scientific instrumentation is so complex and so thoroughly prepackaged that it is difficult to know enough about what goes on inside the "black boxes" that we use to measure. Only a hundred years ago it was still possible for some people to at least appreciate and for a few to manipulate nearly every instrument in specialized usage. One such person in physical optics was Albert Abraham Michelson, a US naval officer who became a world-renowned experimenter and preeminent master of measurement by light waves largely through his playful work with interferometers and interferometry. Measurement was his mistress and muse, and by virtue of his quest to understand the "innards" of all his instruments, Michelson's name became practically synonymous with extremely precise measurement.

During the half-century from 1880 to 1930, Michelson perfected his skills as an optical scientist and gained the reputation of being one of the best experimental manipulators of optical apparatus in the world. He did this largely by designing and developing ever better, more precise and more accurate instruments and techniques for measuring extremely small and extremely large lengths, widths, angles

and distances. Central to his quest to understand visible nature was a device, eventually called the "interferometer," that he constantly worked at improving or adapting to novel uses. He did not create this device *de novo*, nor did he patent or market it after its principles of operation came to bear his name.

Yet Michelson's interferometer, first custom-made in Berlin in 1880 as a one-of-a-kind device by the scientific instrument makers Schmidt und Haensch, became a standard laboratory and "high tech" industrial tool by the time of the First World War. It had already been used in various permutations for a host of applications, as Michelson himself listed in 1902: measuring indices of refraction, thicknesses of soap films, coefficients of expansion and the gravitational constant; testing screws for uniformity of pitch; measuring light waves themselves; analyzing spectral lines; determining standards of length; testing the Zeeman effect; assisting astronomical measurements; and checking astronomical aberration.

These and other uses of Michelson's interferometer are far less famous than its supposedly central role in intellectual history as the primary instrument that "disproved" the existence of a luminiferous, or light-bearing, ether. This most celebrated story is often garbled, and many still think, mistakenly, that the Michelson-Morley experiment directly inspired young Albert Einstein to declare in 1905 that the electromagnetic ether was superfluous and to invent the first special, or

restricted, theory of relativity. (See the article by John Stachel on page 45.)

Spectacular as the interaction between experimental optics and electromagnetic theory building was, the mainline contributions of Michelson and his interferometric methods to classical optics far outstripped in both breadth and depth the indirect impact his work had on the scientific revolutions of the 20th century. Here it is important to emphasize that at the turn of the century invisible lights of all sorts were being extended or discovered—ultraviolet, infrareds, radio waves, x rays, emissions from radioactive materials and even microwaves. In all these discoveries interferometric methods sooner or later played a part. The electromagnetic spectrum of radiant energy transfer was being filled. On 10 December 1907 the Swedish Royal Academy of Sciences awarded Michelson its seventh Nobel Prize in Physics—the first ever to be given to an American in science. It was no accident and it was quite proper at the time that the citation read, "for his precision optical instruments and the spectroscopic and metrological investigations conducted therewith." Michelson had arrived as a world-renowned experimental physicist well before Max Planck and Einstein made theoretical physics a profession.

This article will attempt a cameo portrait of Michelson's life and work, trying to show historically how he conceived and designed an instrument that should rank with the telescope, microscope, barometer and thermom-



Albert Abraham Michelson (1852–1931) sketching himself while a cadet midshipman at the US Naval Academy in Annapolis, Maryland. Michelson was a member of the class of 1873. (Michelson Collection, Nimitz Library, US Naval Academy; courtesy of AIP Niels Bohr Library.)

eter in the pantheon of scientific tools. My focus is on Michelson's role in creating an apparatus, then a series of devices, through which to see and measure aspects of the cosmos never so well seen before. My purpose is to capture the essential features, somewhat exaggerated because of the need for economy, of Michelson's interferometry in words that epitomize his achievements.

Optics before Michelson

Michelson was born in Strzelno, Prussian Poland, on 19 December 1852, and was brought by his Jewish merchant parents to New York City late in 1855; from there the family traveled

onward via Panama to San Francisco in 1856. While the Civil War was raging back East, young Albert spent his boyhood days in California and Nevada mining camps and grew into a promising student. After President Lincoln's assassination Albert assumed the middle name of Abraham. From 1866 to 1869 he attended Boys' High School in San Francisco, where the principal, Theodore Bradley, took care to raise the promising boy into an accomplished youth with "great aptitude for scientific pursuits." After a summer spent back home in contests for an appointment to the US Naval Academy from the territory of Nevada, the ambitious young man boarded one

of the first West-to-East transcontinental railroad trains to plead his case in person at the White House. Amazingly, he succeeded in getting an over-quota appointment to the academy from President Ulysses S. Grant. Thus, Michelson became a midshipman, persevered and graduated from Annapolis in 1873, ninth in rank in a class of 29 but first in optics and second in other physical science subjects.

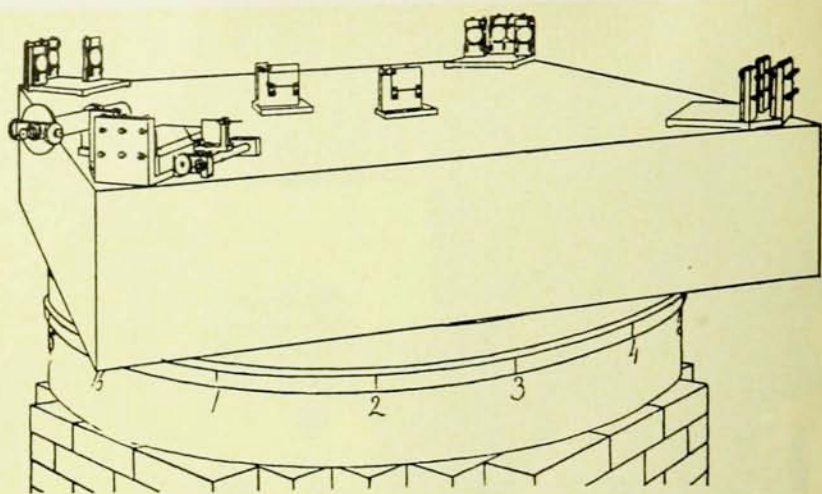
After a furlough and then two years at sea under sail and with auxiliary steam, Ensign Michelson was assigned instructional duties in physics and chemistry back at the Naval Academy. There, under the direction of Commander William T. Sampson, Michel-

son began his career in optics with a lecture demonstration in which he tried to determine the velocity of light using a rotating mirror, Foucault's method. Meanwhile, he had married well—Sampson's wife's niece, Margaret Heminway—and his first son had been born. During the academic year 1877–78 Michelson studied the published accounts of the acknowledged French leaders in optical research. Soon he found several ways to improve upon their efforts. His frontier boyhood, his schooling in San Francisco, his Naval Academy training and his maritime experiences were beginning to pay dividends.

At mid-century the lingering Newtonian-Huyghensian controversy over the ultimate nature of light had seemingly been settled in favor of the undulatory, vibratory, wave or ether theory rather than the corpuscular, ballistic, particle or emission theory. The contest appeared dramatically resolved by overwhelming experimental evidence before Michelson got involved. There were many reasons for this, not least of them the fascinating cooperation, then competition, between Armand Hippolyte Louis Fizeau and Jean Bernard Léon Foucault to be first to measure the velocity of light, then to prove that its velocity in water is less than in air—which result would and did favor waves over particles.

Thomas Young in London and Augustin Jean Fresnel in Paris had done much to advance the wave theory of light through studies of interference and transverse wave motion, respectively. Jean Baptiste Joseph Fourier and Dominique-François-Jean Arago likewise had been influential in clarifying conduction, radiant heat and polarization phenomena. Josef Fraunhofer, by developing spectroscopy in the 1820s; Michael Faraday, by developing the basic ideas of electromagnetic field theory in the 1840s; and Charles Wheatstone, by developing experimental acoustics, optics and electrical measuring devices in the 1850s, also helped set the stage. When James Clerk Maxwell's grand synthesis of light, electricity and magnetism finally appeared in treatise form in 1873, it failed to gain immediate and widespread acceptance, although the next 15 years of experimental work proved its majestic significance.

Most of these scientific heroes in Michelson's chosen field were dead by the time he appeared to take up their challenges. He admired the combined genius of Wheatstone, Arago, Foucault and Fizeau above all. They were the kind of experimenters that he most trusted. Another generation of leaders in his profession, only a few years older



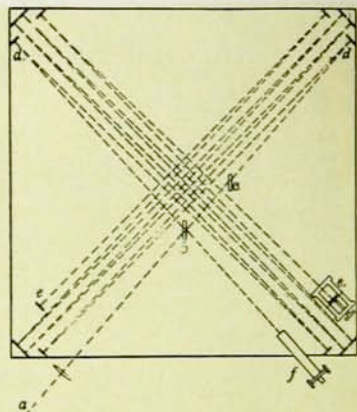
than Michelson, were impressed by his potential. Simon Newcomb, for example, the Canadian-American professor of mathematics and astronomy at the US Naval Observatory, and Hermann von Helmholtz, the German physician turned physiologist and physicist, were both solicitous and encouraging mentors for young Michelson. Maxwell had just died, but William Thomson (later Lord Kelvin) and Lord Rayleigh were lively supporters of Michelson's plans for the uses of light-wave measurements.

During his 1880–82 postgraduate studies in Europe, Michelson met experts who were most helpful because their work was more specifically spectroscopic. In Berlin he met Gustav R. Kirchhoff and Hermann Karl Vogel; in Heidelberg, Robert W. Bunsen and Georg H. Quincke; and in Paris, Jules C. Jamin, Eleuthère-Elie-Nicolas Mascart, M. Alfred Cornu, Alfred Potier and Gabriel Lippmann, who would win the next Nobel Prize for Physics after Michelson's. Hendrik A. Lorentz in Leiden became Michelson's chief friendly critic.

Developing the interferometer

Having found several relatively cheap and facile ways to improve on Foucault's revolving mirror for the determination of the velocity of light, Michelson confided to his patron Newcomb a plan for answering Maxwell's despair over ever finding a way to measure second-order effects—effects on the order of 1 in 100 000 000, for example, the square of the ratio of the velocity v of the Earth in its orbit to the velocity V of light. (Only later was the upper case symbol V for the velocity of light replaced by the lower case c .)

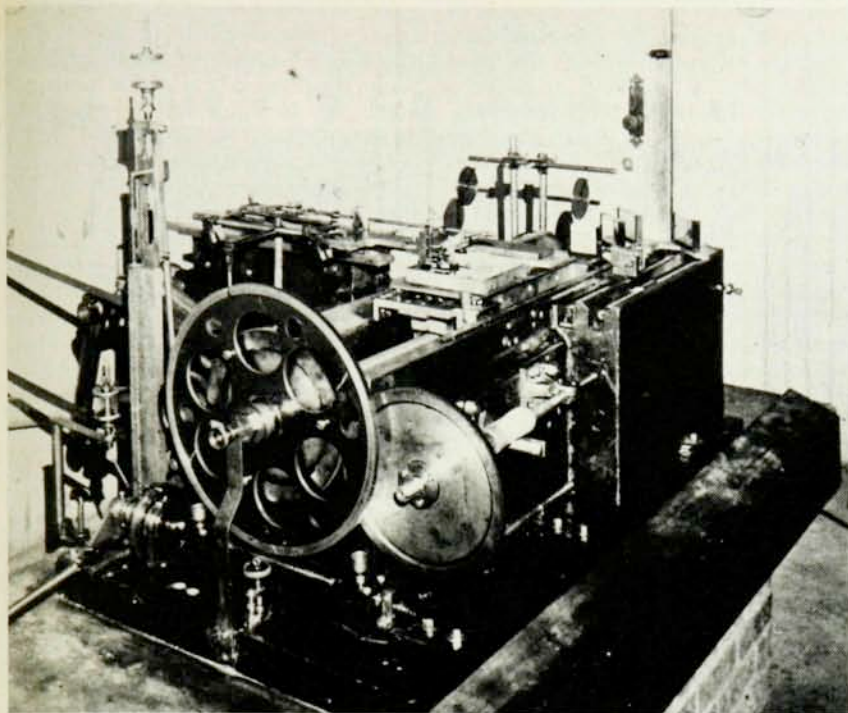
Already in the late summer of 1880 Michelson must have conceived his hope of comparing the paths of light at right angles as a method for finding the



Ether drift apparatus and light path. The optical bench is atop a massive stone slab that floats on mercury (top drawing). The multiple mirror configuration (bottom drawing) increases the path length by a factor of about ten. (From Michelson's 1903 book, *Light Waves and Their Uses*.)

motion of the Earth relative to the ether, for he wrote to Newcomb from Berlin on 22 November 1880 saying that Helmholtz "could see no objection to it, except the difficulty of keeping a constant temperature." That objection, it turned out in the long run over the next half-century, was to be a major one indeed. Throughout the few years (1883–89) that Michelson collaborated with his neighboring chemist Edward W. Morley, temperature control plagued their experiments. And until the end of Dayton C. Miller's complementary work in the 1930s, temperature control was a perpetual problem in interferometry.

Serendipity was never more evident in experimental science than here, for Michelson was in the process of discovering, at least for himself, that one could convert any microscope or any telescope into an interferometer simply



Ruling engine for making diffraction gratings. Michelson built the device at the University of Chicago. (Courtesy of AIP Niels Bohr Library.)

by using only diametrically opposed portions of its lenses. After the disappointments of the ether drift tests in 1881 and 1887, Michelson created at least two dozen different designs for interferometers to illustrate "Light waves and their uses." That was the title of his Lowell Lectures at Harvard in 1899 and of his first book, published by the University of Chicago Press in 1903. Thus Michelson turned his lemon into lemonade.

By 1930 it was common to explain all interferometers either as devices for dividing wavefronts or separating different frequencies from point or line sources, or as instruments for dividing amplitudes by partial reflection from two or more multiple-path beams. Michelson's original interferometer of 1881 was considered the exemplar of the latter category. His stellar interferometer, conceived in 1890 and applied to satellites of Jupiter (but not to stars until the early 1920s), was considered an exemplar of the former category. The technical heart of most earlier amplitude dividers was some sort of beam splitter, usually a half-silvered mirror. Fizeau, Jamin and Mascart had been the pioneer inventors of such devices. Then in the 1890s Michelson, Rayleigh, Ernst Mach, Otto R. Lummer, J.-M. Rene Benoit, and Ernst Pringsheim, among others, picked up the pace of development.

At first Michelson called his inven-

tion an "interferential refractometer," in honor of Jamin's apparatus for measuring indices of refraction of various gases and liquids. However, when he began to think of using interference methods to measure the standard meter bar in Paris, he called his modified device an "interferential comparator." As its versatility increased and became more obvious, others began to call it simply the Michelson interferometer. Although Michelson himself had too many versions in mind and in operation to glorify any one of them, he did admit that one clone, commercially produced by Hilger and Watts, had "proved most generally useful." Later modifications by others produced the Fabry-Perot interferometer after 1896 and the Lummer-Gehrcke multiple-beam interferometer after 1903. The Twyman-Green (1919), Meggers-Peters (1918) and Gehrcke-Lau (1927) modifications later served as optical machines to help make other, better, more precise optical machines.

Precision length measurements

Perhaps the most significant achievement of Michelson's interferometry in the context of his times was not the ether drift tests but rather the measurement of the platinum-iridium standard meter bar in terms of immaterial light waves. Since at least 1827, scientists had realized that a wavelength definition of the meter (suppo-

sedly one forty-millionth of the Earth's circumference) would be preferable to defining it as the distance between two lines inscribed on a bar made of an alloy and housed in some bureau somewhere. Not only would a wavelength definition for the metric system be far more precise, it might be inherently free from secular variations with time and it would be easily available in any laboratory anywhere. If the fundamental standard were lost or destroyed, Michelson's method could replace it with duplicates, he bragged, "which could not be distinguished from the originals."

Morley and Michelson in 1887 and 1889 published essays on the feasibility of establishing a light wave as the "ultimate standard of length," and then Michelson, with other assistants, proceeded to do the job. Using his basic interferometric scheme of counting fringes past a fiducial mark in his eyepiece, Michelson was able to devise a decimal series of intermediate standards, "etalons," that allowed him to perform this delicate and difficult task. He eventually settled on the homogeneous red radiation of cadmium vapor as his source (vacuum tubes had just been invented!). He discovered some ingenious ways of arranging his beam splitter, mirrors, mirror carriages, spectroscope and microscope, and created an elaborate apparatus for temperature control and internal manipulation. Michelson and Benjamin A. Gould used American instrument makers to fabricate many of the accessories for this instrument. The final result? "The number of light waves in a standard meter was found to be, for the red radiation of cadmium 1 553 163.5, for the green 1 966 249.7, for the blue 2 083 372.1—all in air at 15 °C, and at normal atmospheric pressure."

This value, checked and rechecked through the years, stood the test of time until 1960, when a spectral line of krypton was chosen to replace the cadmium red. No wonder the world of science and technology was so impressed by Michelson's expertise.

Why go to all this trouble when the most extreme variation of the standard meter was known to be only about one-thousandth of a millimeter in any of its copies? Michelson wrote in 1899:

The answer is that the requirements of scientific measurement are growing more and more rigorous every year. A hundred years ago a measurement made to within one thousandth of an inch was considered rather phenomenal. Now it is one of the modern requirements in the most accurate machine work. At present a few

measurements are relied upon to within one ten-thousandth of an inch. There are cases in which an accuracy of one-millionth of an inch has to be attained and it is even possible to detect differences of one five-millionth of an inch. Past experience indicates that we are merely anticipating the requirements of the not-too-distant future in producing means for the determination of such small quantities.

Analogy with sound

Michelson was a violinist, Morley was a pianist and Miller was a flautist—all amateurs to be sure, but musicians nonetheless, who thought continuously of sound and light wave motions. The musical talents of these three protagonists of the classical ether drift experiments were considerable, and their commitment to acoustics as well as optics was formidable. Thinking analogously about waves (even though these are longitudinal for sound and transverse for light), could hardly have been avoided without split-brain surgery. Acoustical interference studies, especially researches on reverberation in architectural acoustics, and the beginnings of anechoic chambers for exploring noise, “beats” in music and sound shadows must have had much influence on the trio.

In fact, Michelson began his first Lowell Lecture in 1899, “Wave motion and interference,” by predicting that someday soon there would be “a *color music*, in which the performer, seated before a literally chromatic scale, can play the colors of the spectrum in any succession or combination... producing at will the most delicate and subtle modulations of light and color, or the most gorgeous and startling contrasts and color chords.” Michelson thus foresaw the gigantic sound and light shows that are so popular now throughout Europe, Asia and the United States, especially at historical monuments.

Acoustical interferometers appear to have been used before optical ones were common, as evidenced by the apparatuses of Karl Koenig and Georg Hermann Quincke, but apparently they were not so-called.

Null result

Michelson's interferometry grew out of his embarrassment in failing to find “the relative motion of the Earth and the luminiferous ether.” With his 1881 experiment he hoped to discover the resultant velocity of all the Earth's motions through the ether of space. Its null results he interpreted as falsifying the hypothesis of a stationary ether.

After Michelson became a civilian

professor of physics at the Case School of Applied Science in Cleveland and began his collaboration with the older chemist Morley at Western Reserve University, the two in 1886 corroborated Fizeau's work on Fresnel's drag coefficient and published “Influence of motion on the velocity of light.” They reported that light traveling within a stream of flowing water moves fractionally faster (by $7/16$) with the current than outside it or against it. Conclusion? Oddly enough, “that the luminiferous ether is entirely unaffected by the motion of the matter which it permeates.”

Then in the classic Michelson-Morley paper of 1887, “On the relative motion of the Earth and the luminiferous ether,” they set a more modest goal for their improved ether drift experiment. Couching their argument in terms of corpuscular versus undulatory theories of astronomical aberration, their report begins by stating the rationale for testing the hypothesis of a stationary ether through which the Earth moves. Seeking only Earth's orbital velocity (its speed and direction), they designed the apparatus to increase the path length of the cross of light to about ten times its 1881 value. The influences of Potier and Lorentz were here evident. Null results, once again presented in tabular and graphic form, reinforced the fame of their failure, within significant figures. They had expected a change corresponding to about 0.4 wavelength. They observed a change of less than 0.04 wavelength. Less than 10% of their expectation meant a *conclusive* null result. Yet in their supplement to that classic paper, Michelson and Morley offered at least seven ideas—four possibilities for laboratories and three for observatories—for attacking all over again the problem of the motion of the whole Solar System through space!

In his final Lowell Lecture, “The ether,” Michelson confessed:

The experiment is to me historically interesting, because it was for the solution of this problem that the interferometer was devised. I think it will be admitted that the problem, by leading to the invention of the interferometer, more than compensated for the fact that this particular experiment gave a negative result.

Into the 20th century

In 1889 Michelson split from Morley as he left Cleveland for the first chair in physics at the brand new Clark University in Worcester, Massachusetts. Before the break, however, he and Morley had discussed several new applications for interferometry that should give

positively stunning results. One was an experiment to measure the angular diameter of heavenly bodies; Michelson tested the feasibility of such a measurement by focusing on a moon of Jupiter.

Michelson was again lured away to a new home when the University of Chicago was established along with the Columbian Exposition in 1892-93 (which marked the 400th year since 1492). Incredibly busy organizing a new physics department and supervising the completion of the new Ryerson Physics Laboratory, Michelson nonetheless began to build an engine to rule the tiny grooves for diffraction gratings. He also built and tested a large vertical interferometer beside his building, and he laid plans for the construction of two more major inventions: an echelon spectroscope and, with Samuel Wesley Stratton, a large mechanical harmonic analyzer. All this plus personnel and personal matters put a strain on Michelson's marriage, and a painful divorce ensued in 1898. (See Albert Moyer's article on page 50.) The very next year he delivered his series of eight Lowell Lectures at Harvard, was elected president of The American Physical Society and remarried, this time to a socialite Chicago student 28 years of age named Edna Stanton. Michelson's first family became lost in the shuffle as he started his second. While his science meant most to him, it clearly was not an all-consuming passion.

Michelson's professional life, unlike his personal life, appears not to have slowed down after the turn of the century. He was long obsessed by the effort to get his ruling engine for the production of big diffraction gratings working better than Henry Augustus Rowland's engine at Johns Hopkins University. He failed in this. Michelson also became involved—somewhat reluctantly and marginally, but inevitably—in science policy issues, local, regional and national. As his honors accumulated and “little science” grew into bigger if not yet “big” science, Michelson was forced to change his style a bit—in teaching, in research and in service. Demonstrations, grantsmanship and graduate students all demanded more time. He answered the call of duty back to the Navy for optical research on rangefinders in World War I. He encouraged younger colleagues such as George Ellery Hale in their work in astrophysics and in the entrepreneurship required to build bigger telescopes. He ordered Robert A. Millikan to take over all his graduate student duties but cheered him on in his oil-drop experiments on the quantization of charge and in his mobilization



Stellar interferometer that Michelson used in 1920 to make the first measurement of a star's diameter. (Courtesy of William Osborn, Case Western Reserve University.)

efforts for the Great War. In a bid to win the directorship of the newly established National Bureau of Standards, Michelson asked Stratton in 1902 to plead his case in Washington, DC. But Stratton himself got the position. Michelson also supported Henry Gordon Gale's big 1914 project to use interferometry to measure the rigidity of the Earth and thus to "smell oil."

Immediately after the war Michelson began the project of using his stellar interferometer to measure the angular diameter of the red giant star Betelgeuse in the shoulder of Orion. Results were formally announced in December 1920: Betelgeuse must be almost as large as the orbit of Mars. Newspaper publicity on that discovery rivaled the noise from Arthur Eddington's 1919 eclipse expeditions to test Einstein's general relativity and prove the bending of starlight by the curvature of space.

In the mid-1920s Michelson supervised several major projects: a new measurement of the velocity of light between two mountains 22 miles apart above Los Angeles; an attempt at a large field in Clearing, Illinois, to measure the effect of the Earth's rota-

tion on the velocity of light; completing original designs for ether drift tests in ongoing attempts to respond to the challenges of Miller's experiments; and as president of the National Academy of Sciences in 1923, to carry through a major fund drive that he inaugurated. In 1927, the year before he retired from the University of Chicago and moved permanently to Pasadena, California, Michelson published his second and last book, *Studies in Optics*. Therein, he summed up his life's work, explained his conservative attitude toward the ether (an attitude he held in spite of the recent achievements of relativity and quantum mechanical theories) and tried to advise physical scientists to pay more attention to better measurements than to mathematical physics.

Michelson, the master of measurement through interferometry, was a rival to Rowland for domination of science in America in the last decade of the 19th century. By the second decade of the 20th century Einstein had appeared to assume that mantle worldwide. But Einstein's theories could not have been accepted without Michelson's measurements.

When Michelson became the first American Nobel laureate in science (President Theodore Roosevelt had won the Nobel Peace Prize the year before), it marked the moment in history that world-class status in scientific research began to be given to the United States. Michelson's inventions and innovations, as well as the technologies and techniques that ensued from his work, were always of such fundamental importance to the progress of physical science "toward the next decimal place" that it is quite fitting to call his flourishing years the Michelson era in American science.

Michelson had important precursors, colleagues, competitors and successors, but he was preeminent, as his daughter's biography, *The Master of Light*, portrays him. Over the years, as the Nobel Prize matured in prestige and remuneration, Michelson, a mere professor but a militant perfectionist, also matured. He played the perfect role model of a meticulous authority and yet he remained a continuously productive artist in physics. Until the day he died, 9 May 1931, Michelson pursued the elusive goal of measuring the velocity of light, perhaps the most funda-



Michelson in his laboratory at the University of Chicago sometime in the period 1900–10. (Courtesy of AIP Niels Bohr Library.)

mental constant in nature, under even better conditions and to ever higher degrees of accuracy. He was indeed, as many of his heirs have said, a virtuoso without a peer in measurement. Perhaps his best judgment of that fundamental constant was his 1926 value, $299\,796 \pm 4$ km/sec.

Michelson's last book was published the year before the Optical Society of America dedicated its annual meeting to him on the 50th anniversary of the beginning of his scientific career. Michelson had used, as he titled one of his last papers, "Light waves as measuring rods for sounding the infinite and the infinitesimal." When he died he was hardly less a believer in the wave theory of light and its concomitant ether. Although he acquiesced in Einstein's relativity theories (with a few reservations), he died confident in the knowledge that he had indeed sounded the nature of light and measured its

velocity as precisely as was then possible.

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I thank my colleagues James H. Cooke and D. T. McAllister and my student David Payne for their insightful critiques.

Bibliography

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- Michelson's two books are *Light Waves and Their Uses* (U. of Chicago P., Chicago, 1903) and *Studies in Optics* (U. of Chicago P., Chicago, 1927). The second book appeared the peak year of the quantum mechanical revolution.
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