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# Science and the Instrument-maker

## MICHELSON, SPERRY, AND THE SPEED OF LIGHT

*Thomas Parke Hughes*

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# ABSTRACT

Hughes, Thomas Parke. Science and the Instrument-maker: Michelson, Sperry, and the Speed of Light. *Smithsonian Studies in History and Technology,* number 37, 18 pages, 9 figures, 2 tables, 1976.—This essay focuses on the cooperative efforts between A. A. Michelson, physicist, and Elmer Ambrose Sperry, inventor, to produce the instrumentation for the determination of the speed of light. At the conclusion of experiments made in 1926, Michelson assigned the Sperry instruments the highest marks for accuracy. The value of the speed of light accepted by many today (299,792.5 km/sec) varies only 2.5 km/sec from that obtained using the Sperry octagonal steel mirror. The main problems of producing the instrumentation, human error in the communication of ideas to effect that instrumentation, a brief description of the experiments to determine the speed of light, and the analysis and evaluation of the results are discussed.

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# Contents

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## INTRODUCTION

Science is popularly conceived of as a cerebral activity. The image of Einstein superimposed upon a background of esoteric notation dominated by the formula $E = mc^2$ has become an item of popular culture. However, many scientists—especially experimental as contrasted with theoretical physicists—would be among the first to acknowledge their reliance upon instruments and, recently, big machines like particle accelerators. In many instances the physicists have designed and even built their own apparatus, but in many others they have depended upon the skilled instrument-maker and engineer. Only infrequently has the public been made aware of the role of these craftsmen, and many of their names have been lost to history.

This essay * tells of a distinguished scientist's dependence upon the mechanical ingenuity of the maker of instruments. After World War I Albert Abraham Michelson, America's first Nobel prize winner, embarked upon a renewed attempt to establish the speed of light. For this endeavor he used a greatly improved light source made by the Sperry Gyroscope Company, which was established by Elmer Sperry, one of America's most famous twentieth-century inventors.

* I appreciate comments from Preston Bassett, Leon Cooper, D. Theodore McAllister, and R. S. Shankland on early drafts of this essay.

*Thomas Parke Hughes, Department of History and Sociology of Science, University of Pennsylvania, Philadelphia, Pennsylvania 19174.*

Pleased by the results with the searchlight, Michelson again, in 1924, turned to Sperry for another instrument, a high-speed revolving steel mirror. The mirror, like the searchlight, was a critically important component in the experimental system designed by Michelson to measure the speed of light. His resorting to Sperry for a high-speed, multifaced, steel mirror was quite appropriate, for the Sperry Gyroscope Company was the manufacturer of highly precisioned devices, such as a gyrocompass (invented by Sperry) with its high-speed, perfectly balanced rotor. When Michelson sought assistance, the mechanical skill and the precision machine tools used to make gyrocompasses at Sperry Gyroscope were enthusiastically committed to a challenging pure-science problem. In providing Michelson with the searchlight and, later, the steel mirror, Sperry, his engineers, and master machinists were playing the role that scientific instrument-makers had assumed since the 15th century for such observers of natural phenomena as Galileo Galilei, Tycho Brahe, and J. B. Leon Foucault. The instrument-makers' exhilaration of contributing to and participating in the search for abstract truth on a grand scale still stirred the imagination of Sperry and his employees. This cooperative spirit between the instrument-maker and the scientist was expressed most positively by Sperry, who—after learning of how well the revolving mirror performed—wrote, "to think that we have been in any way helpful in this great work fairly takes our breath away." [1]

Due to human fallibility, however, the quest for precision, even perfection, by all those involved—but especially Michelson—suffered many a setback. Dedicated to the determination of what was thought to be an eternal constant (the velocity of light), a fundamental needed by physicists, astronomers, navigators, and in the Einstein equation ($E = mc^2$), Michelson was attempting to reduce the margin of computational error from about 100 to one or two kilometers in several hundred thousand. But ironically, his specifications regarding the instrumentation were so vague that the first model built from them proved useless. Other human "frailties" also threatened to add their bias to the determination of the speed of light.

It was necessary, for example, to ship the mirrors from their place of manufacture, Brooklyn, New York, to California. The freight handlers, insensitive to the prize they bore, delivered one mirror in such a lamentable condition that Sperry had to seek new methods of packing to prevent damage in transit. To compound the confusion, Michelson, after he had a properly functioning mirror, reported one set of data privately to Sperry and published another. Furthermore, the published results contained discrepancies and raised questions about Michelson's judgments, or evaluations. All of this is a part of the story of frail men striving with instruments of the highest obtainable precision to establish truths far removed from the uncertainties of a world—including freight handlers—in which they live and work.

## BACKGROUND FOR COOPERATION

### The Men

By the mid-twenties, Elmer Ambrose Sperry (1860–1930), inventor and engineer, was world famous for his applications of the gyroscope for guidance and control of ships and airplanes. The Sperry Gyroscope Company of Brooklyn, New York, supplied the world's navies with gyrocompasses, and the company had an established reputation for the precision manufacture, as well as for research and development, of these tools. Skilled machinists, clever young design engineers, and the ever-resourceful and widely experienced inventor and engineer, Sperry, gave the company a unique character. Guided by Sperry's known preference for difficult problems, the company was noted for the kind of technology the mass manufacturers would not attempt.[2]

Albert A. Michelson (1852–1931), America's first Nobel laureate (1907), fully appreciated the dependence of his experiments on highly precisioned instrumentation. His Nobel Prize was awarded "for his optical precision instruments and the spectroscopic and meteorological investigations carried out with their aid." [3] Michelson's eminence, especially his reputation for instrumentation, stemmed not only from his velocity of light determinations, but also from his series of experiments carried out from 1881 to 1927 on another fundamental problem: the effects of relative motion on the velocity of light. The instrument he had designed for this work, the inferometer, has been called "a lovely thing." [4] Michelson, famous for this and his other instruments, came "to regard the machine as having a personality . . . almost . . . a feminine personality—requiring humoring, coaxing, cajoling—even threatening! [sic]" [5]

Michelson's attitude toward his instruments was shared by Sperry, who also personified machines, on occasions calling them "little fellows," and, at more exasperating times, "brutes." [6] Sperry had an affection and respect for complex, high-quality machines and instruments and for the fine machinists and craftsmen who made them. From his beginnings as an inventor, he depended upon the forge and machine shop to fulfill his inventive concepts. In order to have his first invention built, he helped in the shops of the Cortland (N.Y.) Wagon Company, his home town's leading industry. He learned then, that an experienced machinist could modify his designs so that the potential of his inventions could be most fully exploited. In 1910, after Sperry formed the Sperry Gyroscope Company, which grew to employ thousands of workers, he continued to "talk out" with his head machinist the design of a new device, rather than to hand down drawings and specifications. When his company was young, its capital assets were simply Sperry's patents and its machine tools. Sperry's son, Elmer, Jr., attributed the success of the company in discouraging competition to the fine Swiss machine tools and German machinists at Sperry.

Another common bond between the scientist Michelson and the engineer Sperry was the pioneering work of J. B. Léon Foucault (1819–1868), upon which they both drew. Sperry's major gyrocompass patent, applied for in June 1911,[7] begins with acknowledgement of his indebtedness to Foucault for his basic ideas about the gyrocompass. Michelson, for his first determination of the velocity of light in 1877, used apparatus based upon a minor, but critical, modification of the revolving mirror technique employed by Foucault.[8] Foucault had employed a revolving mirror in 1862 to determine the velocity of light. Earlier, in 1850, he had used the mirror to establish whether light traveled with greater or lesser velocity in a refractive medium, such as water, than it did in air.[9] Foucault also set a precedent for Sperry. In 1852, Foucault used a freely suspended gyroscope with its orientation fixed in space to demonstrate the relative motion of the earth. Then—and this later proved helpful to Sperry—Foucault showed how the gyroscope could be modified (weighted, or made pendulous) and used as a compass indicating true north, as it aligned its axis of rotation with the axis of the earth.

A two year period of cooperation between Sperry and Michelson began in 1924, when Michelson asked the engineer to supply him with a steel revolving mirror to use in his new series of velocity of light experiments begun in 1921. The request for a Sperry steel mirror was probably stimulated by the good impression that a Sperry searchlight, already put to use in the new experiments, had made on Michelson. It is not unlikely that the scientist had first decided upon a new determination when he learned of the remarkable improvements of searchlights during World War II,.for a more intense light source would allow the experimenter to use a longer base line over which the light to be measured would travel. Before following the story of the steel revolving mirrors, therefore, a brief account of the Sperry searchlight is in order.

## Sperry's Searchlight

In 1914, the United States Navy had tested a high-intensity searchlight patented by a German inventor, Heinrich Beck, and found it to have an illuminating capacity five times that of the light then standard on Navy ships. With the war in Europe increasing the Navy's interest in preparedness, it contracted with General Electric for the purchase of Beck lamps, which the electrical manufacturer was making under the Beck patents. Sperry, familiar with the Beck lamp, saw several ways to improve it. Arc lighting was not a new field for Sperry who, when he was only twenty-one, had patented an automatically regulated arc lamp in 1881. Not only did Sperry believe he could improve upon the Beck lamp and obtain patents on the improvements, but he knew that his close contacts with the Armed Forces resulting from his invention and manufacture of sophisticated gyroscopic and fire-control devices would obtain for him a good hearing and a fair trial of his own lamp. By 1916 he was ready to have his searchlight entered into competitive trials. He had been assisted in developing the device by several members of his staff of engineers, among them Preston Bassett, a young chemistry graduate from Amherst College. (Later, Bassett had the privilege of demonstrating the searchlight for Michelson.)

The improvements made by Sperry, Bassett, and others upon the Beck lamp included the use of air instead of alcohol for cooling the electrodes in order to keep the flame, or arc, at the tip of the electrodes. The result was a more intense light. In substituting air for alcohol, Sperry simplified the searchlight mechanism, a technique (simplification) he frequently resorted to when he found himself competing with German inventors who tended to be perfectionists (and unrealistic, Sperry would add). Sperry also introduced a different means for feeding the electrodes to maintain the arc gap as they burnt down. He also used a different way than Beck for positioning the positive electrode so that the concentrated arc would be at the focal point of the reflector mirror of the searchlight. Preston Bassett at the same time worked upon the design and chemical composition of the electrodes. During World War I, with support from the U.S. Army, Sperry and his engineers further improved the design and manufacture of the searchlight for coast defense, anti-aircraft, and use in the field. After the war, Sperry adapted the searchlight for peacetime purposes by promoting its use as a beacon for guiding airmail planes on their lonely night flights across country, and adapting the lamp mechanism for use in movie projectors.[10]

Michelson utilized the Sperry searchlight for his velocity of light experiments before asking the inventor for a revolving mirror. However, Michelson's experimental team seems not to have fully understood the operation of the lamp. After it had been used in the experiments for a time, Bassett found that the lamp was being operated without the automatic control for positioning the electrodes, and he showed the Michelson staff how to use it properly. Nevertheless, Francis G. Pease, Michelson's assistant at the Mount Wilson Observatory in Pasadena, California, had informed Sperry, after trials in 1924, that "brightness of the arc gave him all he desired in the way of light and 'then some' and the rough preliminary results are better than any heretofore." [11] No wonder that Michelson turned to Sperry, the inventor and manufacturer of complex, precision, technological devices, when Michelson encountered a serious problem with one of the instruments in his experimental system.

# DETERMINATION OF THE SPEED OF LIGHT

## Nature of the Experiment

The design of Michelson's experiment can be described briefly in order to define better the problem encountered in the summer of 1924.[12] The apparatus of 1924 differed in particulars from that used by Michelson between 1878 and 1882 when he made his first determinations of the speed of light. However, the essential principle was the same: measure the time elapsed as light travels from a source out to a reflecting mirror and returns to the place of origin. This was also the essential means used for determination by Foucault in 1862, A. Hippolyte L. Fizeau in 1849, and Marie A. Cornu in 1872.[13] Michelson's 1924 apparatus differed from the earlier ones in the more accurate measurement of the time elapsed, the greater distance over which the light traveled, and, as noted, in the power of the light source used, which made possible the sending of the light over a greater distance. In the experiments of Foucault and Michelson before 1924, the experimenter determined the elapse of time by measuring the angle through which a revolving mirror rotated during the interval it took light to travel over a precisely measured distance. The angle of rotation was measured by noting the displacement of the beam of light by the rotating mirror. A stationary mirror would cause no displacement. The amount of displacement depended upon the velocity of rotation of the mirror, the distance traveled, and the speed of light. Because the first two could be measured the last could be calculated. The apparatus of Fizeau and Cornu, by contrast, employed a revolving gear wheel. The beam of light that passed between the teeth of the wheel on its outward journey was interrupted by the succeeding tooth of the revolving gear, resulting in a flash to a reflecting mirror at a precisely measured distance. When the gear wheel was revolved at a particular velocity—by the experimenter—then the flash passed through the next opening between the teeth upon its return. Knowing the distance traveled and the velocity of the gear wheel, the experimenter calculated the speed of light.[14]

In 1924 Michelson's apparatus employed a revolving mirror in the manner of Foucault and his own earlier experiments, but the new mirror was multifaceted so that Michelson could use it in a manner similar to that of Fizeau's gear wheel. "The advantage of the octagonal revolving mirror . . . ," he explained, "lies in the possibility of receiving the return light on a succeeding face, thus eliminating the measurement of the angular deflection of the returned beam. . . ." [15] The accuracy now depended upon the construction of the octagon, a responsibility that fell to the instrument-makers, including Sperry, his engineers, and machinists.

Michelson introduced slight variations in the arrangement of his system during the period 1924 to 1926, when he was conducting the velocity observations.[16] When making his definitive measurements using the Sperry apparatus, the system (Figure 1) included a multifaceted rotating mirror, an arc lamp (S) casting its beam through a narrow slit, reflecting mirrors ($b,c,b_1$) to direct the beam of light along a desired path, a reflecting concave mirror (D), and a prism to direct the beam of light into the observing eyepiece (O). All of the foregoing apparatus was on Mt. Wilson. Twenty miles away on Mt. San Antonio was a concave mirror (E) and a reflecting mirror (f). The light path was—as shown in Figure 1—from the surface *a* of the revolving mirror to *b c D E f E D c* $b_1$ and to surface *a′* of the revolving mirror. $B_1$ and *B* on the figure are bench marks for measuring distance. The slit through which the arc lamp beam passed was extremely narrow (0.5 to 0.1 mm)[17] so that the location of its return image on the eyepiece could be observed with precision.

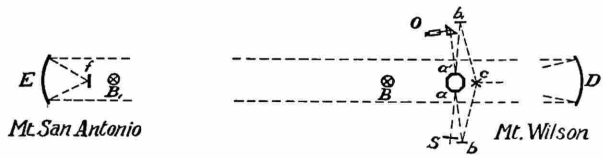



FIGURE 1.—Arrangement of Michelson apparatus. (From A. A. Michelson, "Measurement of the Velocity of Light between Mount Wilson and Mount San Antonio," *The Astrophysical Journal*, volume 65 (1927), page 4.)

For his definitive experiments in 1926, Michelson used revolving mirrors of 8, 12, and 16 facets. The angular velocity imparted to these was such that the mirrors turned through a distance equal to the distance between the centerlines of adjacent facets, while the light was traveling out from Mt. Wilson, to Mt. San Antonio, and back (about 0.00023 seconds). After Michelson adjusted the rate of revolution, the rotating mirror presented "the succeeding face of the mirror to the returning beam at (very nearly) the same angle as at rest."[18] In conjunction with a prism, the eyepiece was positioned to observe the beam as it was reflected off the facet. When the light beam returned to the observer's eyepiece, he then knew that the mirror was revolving at the rate that would turn the mirror one-eighth, one-twelfth, or one-sixteenth of a turn (according to the revolving mirror used) during the time the light beam passed over the measured course. Extremely small angular deviations of the return image from the centerline were measured in order to ascertain precisely the angular distance moved by the mirror during the travel of the beam of light.

Measurement of the distance between stations and the measurement of the speed of rotation of the revolving mirror also had to be determined with precision. The United States Coast and Geodetic Survey established the length of the light path with a result estimated to be accurate within one part in two million.[19] During the definitive observations, the angular velocity of the mirrors was regulated by a stroboscopic comparison of the revolving mirror (528 rps for the octagonal mirror) with an electric fork vibrating at a fixed rate (528 vibrations per second for the octagonal mirror). The rate of the vibrating fork was controlled by comparisons with a free seconds pendulum which was compared with "an invar gravity pendulum furnished and rated by the Coast and Geodetic Survey."[20]

## Trials of Instrumentation

Early in his experiments, Michelson encountered a serious problem with an octagonal glass mirror. When run up to speed, the relatively large mirror flew to pieces. Hence, his requests to Sperry for a mirror of steel. Michelson specified that it had to withstand a peripheral speed of 27,500 feet per minute (540 turns per second), a diameter of 3 inches, and a face of about 1¼ inches.[21] The mirror was to be rotated on a vertical axle, driven by an electric motor or by an air blast upon turbine blades. Michelson considered using an electric motor in order to operate the mirror in a vacuum. He asked if it would be necessary to provide electric motors both above and below in order to have both positive and negative rotation. His remark about positive and negative rotations only in conjunction with motors would prove ambiguous and unfortunate.

Sperry accepted the assignment, confident that his company could do the engineering and drafting, make the patterns, perform the machine work, and take care of the high-speed dynamic and static balancing. "Our investigation shows," Sperry wrote, "that the little apparatus you require is no exception to the rule of machines that have to be made with a high degree of precision. As time goes on we find that our gyro compasses are no exception to this rule either."[22] Louis Malkovsky, Sperry's brilliant master mechanic, who later became company vice-president for manufacturing, also accepted the problem enthusiastically, certain that he could machine and dynamically balance the high-speed rotor.[23]

Sperry took pride in the assignment. Of a younger generation than that of Thomas Edison's, Sperry and his engineers eagerly associated themselves with pure science, while Edison's indifference—even animosity—seemed to increase. Sperry shared his enthuasism—and information about the importance of his company's contribution—with Professor Hantaro Nagaoka, called the "Lord Kelvin of Japan." (Sperry was greatly admired in Japan, not only for his invention, but also because he symbolized the practical application of science.)

Did I tell you, that all of Dr. Michelson's tests in his new effort to refine the accuracy of the determination of the velocity of light was done with the Sperry arc? He told the great scientific gathering at the time of the Franklin Institute Centenary that the work would have been entirely impossible without this light. I was so surprised and embarrassed when he mentioned this that I could almost have sunk through the floor. He went on to say that with my arc he could easily have carried out the experiment on a base line of 100 miles. You probably heard about the rotor that ran some 530 revolutions per second and exploded. We are now making him an entirely new apparatus here at our works and will have it under test in a couple of weeks. In this we use steel as the eight-sided mirror, about 3 inches in diameter at the corners. . . He expects to continue the experiments this June.[24]

In April 1925, eight months after Michelson's request, Sperry reported the mirror ready. "We all feel very happy over the outcome of this device," he wrote, and "we have it in such a complete state of balance, both dynamic and static, that we can find no evidence whatever of vibration. . . ." The mirror was air driven because Michelson decided to keep the cost down; an electric motor would have to have been especially built. Sperry hoped that the machining of the facets was so fine that little polishing would be necessary, for polishing might disrupt the balance. Because there was a tendency toward heating within the casing and around the upper bearing, the casing was provided with a jacket for air cooling.[25]

Ready for shipment, the apparatus was a handsome example of highly skilled craftsmanship (Figure 2). Beneath the mirror, a single row of turbine buckets received the air jets from four nozzles projecting from a ring casing. Air at 65 psi had been found to drive the mirror at about 600 rps. In the casing, two diagonally opposed windows permitted the light beam to be directed upon one facet of the mirror and to be observed reflected upon another.[26] External fixtures provided for air to drive the mirror and cool the casing.

The apparatus—so carefully and tenderly made—reached Michelson in sad condition. It had not been

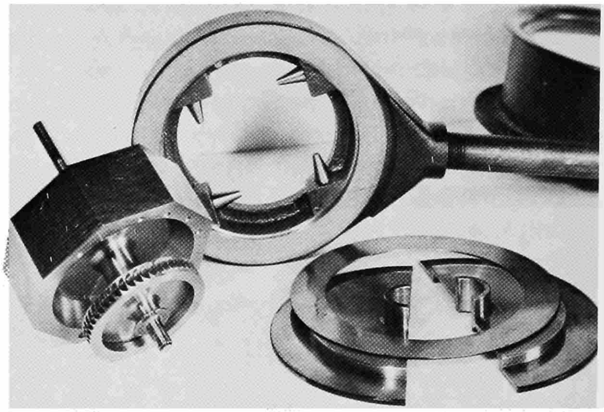


FIGURE 2.—The 8-sided Sperry mirror with single row of turbine buckets. A part of the housing, including the ring with air nozzles, is also shown. (Courtesy Michelson Museum, Naval Weapons Center, China Lake, California)

disassembled in the Sperry packing room, as directed, and it arrived with the upper end of the shaft tightly imbedded in the shipping crate. As a result, the shaft was sprung several hundredths of an inch. Furthermore, Michelson noted that the mirror surfaces did not appear to be hardened by heat treatment (nor had he so specified), and he doubted that unhardened mirror facets could be optically polished. The instrument was returned "via American Express." [27]

Alexander Schein, a Sperry engineer, assuming responsibility during Sperry's temporary absence, thought Michelson wrong in asking that the octagonal surfaces of the rotor be hardened, so that they could be optically polished to obtain the mirror surface. Schein believed that the nickel steel used could be lapped very fine to a mirror-like condition without hardening, but he instructed the shop to proceed immediately with comparison tests of the brilliancy of unhardened and heat-treated mirror surfaces.[28] The test proved Michelson correct. Sperry, upon his return to the city, promised to give Michelson the "maximum hardness, which works about 85 on the scleroscope." [29] By heating to about 1600° in an electric furnace by 40° to 50° steps and by various quenching techniques, the surface was brought up to glass hardness.[30] Despite successful hardening, Michelson later observed that the lack of homogeneity of the steel surface made figuring and polishing steel more difficult than glass.

The misunderstanding concerning hardening resulted from the lack of detail in Michelson's original specifications.[31] Michelson cheerfully admitted "that he had not been sufficiently definite" on the hardening.[32] Sperry responded by admitting that he had been mistaken in assuming that nickel steel did not need hardening for the polishing.[33]

The lack of specific instructions led to other wrong turns and backtracking by the distinguished inventor and the Nobel laureate. For instance, Sperry took the request for windows in the housing as one for "openings," and he initially advised Michelson against glazing or putting glass in them. He reasoned as follows:

> Now, do you really need any provision for glazing these windows? You understand that there are no oil fumes or anything of that kind coming out of this structure. The only thing that will manifest itself is the fan action of the eight sides of the mirror, and inasmuch as your eye is not near the window and no observation is made close up, I don't see why two plain openings are not all that you require. We take it that these two windows must be exactly opposite each other, but if they need to be at any particular angle, you will of course have to tell us what angle. The main thing we want to know is, won't a plain opening do? The only difference that we can think of here with our experience in running the thing is that with the opening on the exterior of this drum it will have a slight blower action, and therefore require a little higher air pressure to maintain the same speed. This, however, will only be a small item.[34]

Several weeks later, however, experience proved a truer guide than reason, and Sperry cautioned Michelson:

> We are now writing you, principally to urge you not to think of running this job without the windows because of the enormous handling of air and the increased pressure required to operate. Moreover, large suctions are produced in the blower actions which tend to suck out all the oil from the bearings and put them in inoperative condition by drying them up in a very short time, but above everything is the terrible screech of the machine, acting as a siren. I think this would soon get on the nerves of anybody within half a block. It is astonishing how penetrating this noise is. You see the note that it makes is about 4300 a second and way up 'in the top of your head.' You are so familiar with optical glass and our light source is so powerful that I believe you will find it all right to run with these windows closed, as only an extremely thin film of glass is required over the openings.[35]

On 27 May, the "beautifully running" instrument was repacked in "April fool" packages (one box within another) and sent to Michelson, who was advised, "You will finally find the little device somewhere inside." [36] Sperry offered to contribute the device, if payment was to be from Michelson's personal account, for Sperry begged "the honor of considering this apparatus as my little contribution [c. $400] towards your wonderful work along the line of giving the astronomer greater accuracy as to his yardstick." [37]

Michelson, aged 73, was ill in the summer of 1925 and was not able to inspect the instrument until late August. "Much to my chagrin and owing to an oversight which I trust your generosity will attribute to my illness," Michelson wrote, "I find it necessary to return to you again the revolving mirror . . . ." [38] It had been provided with only one row of turbine buckets (Figure 2); two rows were needed to allow for a counter air blast to adjust speed and for rotation in the negative and positive directions (Michelson did not—or did not choose to—recall his penciled letter of 23 August 1924, to Sperry in which he asked for both positive and negative rotations, but only in connection with an electric motor drive).[39] Sperry, a veteran of countless mishaps during decades of invention and development, replied: "As to the little mirror, my dear Michelson, you know that your merest desire is our command, so that the moment it gets here we will see just what is necessary to accomplish what you wish. . . ." [40]

Considering Michelson's work as an exciting challenge, Sperry, his engineers, and technicians did not lament the extra effort and expense. Preston Bassett, who headed the Sperry searchlight department and later the Sperry Gyroscope Company, expressed their sentiments well after visiting the Mt. Wilson Observatory to overhaul and adjust the Sperry searchlight. Bassett spent three days there working with Michelson's assistant, Fred Pearson, and he was thrilled to see the Sperry light reflected from "Old Baldy" 22 miles away. "I doubt," the young engineer wrote, "If I ever enjoyed three days as much as these." [41] Later, in a similar vein, Sperry told Michelson:

> The superintendent of our grinding department has personally spent more than a week in continuous work on the final grinding of the facets on the mirrors and, incidentally, I might confide in you that he is nearly a wreck as a result. Our boys have all become so intensely interested in the production of these mirrors that they want to know what it is that you do next and how you make the final determinations of accuracy. We have gone up, Mr. Schein and I believe, almost beyond the accuracy possible with any in-

struments that we can obtain or money can buy in this country, so you don't know how much I would appreciate some little word from you that I could pass on to the boys, giving us an insight into the farther history of these two exotic plants that have been brought forth and nurtured with the greatest labor and the tenderest care.[42] [Figures 3, 4.]

After the instrument with the single row of turbine buckets was returned, Michelson inquired about a 12-faceted mirror, as well as an octagonal one. Michelson and Sperry agreed that the two mirrors could be interchangeably operated in the same housing. When Michelson had expressed concern about costs, Sperry replied:

You ask for an estimate. The boys have gone through the costs very carefully and of course you can appreciate that the experimentation on the first one ran the cost very high. That experience, however, will help to cut the cost of the new apparatus. You may be interested to know that the hardest job about the whole matter is grinding the surface with the accuracy that we secured before and getting a running balance at the extremely high speeds, but having had experience with the other, we are hoping that it will help us with the new one.

We should like again to make a financial contribution towards this matter, but I do not think you wish us to make as great a one as before. The price we are quoting does not cover the entire cost, but we are prepared to build the two reversible mirrors which would fit the same casing and strive for about the same accuracy that we had before throughout, for $665. You understand that this includes the 8-sided revolving mirror which will run in both directions and also another 12-sided mirror which will run in the two directions, both organized to operate in the present modified casing and on the same journals. We are happy to say that we have found a way whereby this can be done very nicely.[43]

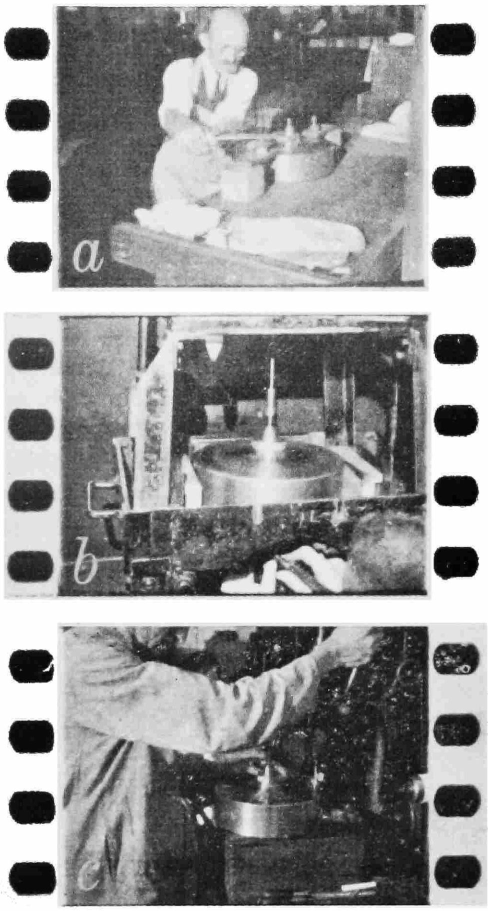



FIGURE 3.—The film sequence indicates the precision work done at Sperry Gyroscope Company on the rotors of gyrocompasses. These expert craftsmen and highly developed precision machine tools made the revolving mirrors for Michelson. *a*, "The rotor, after being heated, is shrunk on the armature shaft." *b*, "The rotor must be accurately balanced to eliminate all vibrations. It is suspended on a flexible cable and spun at 6000 r.p.m. The slight touch of the balancer's pencil marks the high sides of the shaft, detecting the most minute vibrations." *c*, "A little metal is drilled from the heavy side. This process is repeated until the rotor is perfectly balanced." (From *The Sperryscope*, volume 3, number 12 (1923), page 13.)

Michelson wired two days later that he would like to know the price of the reversible 8-sided mirror omitting the order for the 12-sided one. Sperry telegraphed immediately, "Will you kindly permit me to donate double eight-sided and twelve-sided equipment to the great scientific work you are doing? [44]

Three months were needed at the Sperry company to complete the work, which was ready late in January 1926. On the eve of shipment, Sperry reported that the 8-sided mirror had been run up to almost 600 rps with 60 psi and the 12-sided to the same speed with 40 psi. The balancing was so well done that there was no apparent evidence that there was motion in the case. The two mirrors operated equally well in either direction (Figures 5–9).[45] In a formal letter of appreciation entered by Michelson in the record of the Board of Trustees at the University of Chicago, Michelson's university, he acknowledged Sperry's gift of "two beautiful specimens of workmanship" and the loan of "a magnificent arc-light" to which Michelson attributed "a large measure of the success of last year's [1925] work on Mt. Wilson." [46]

Observations using the Sperry mirrors—and glass

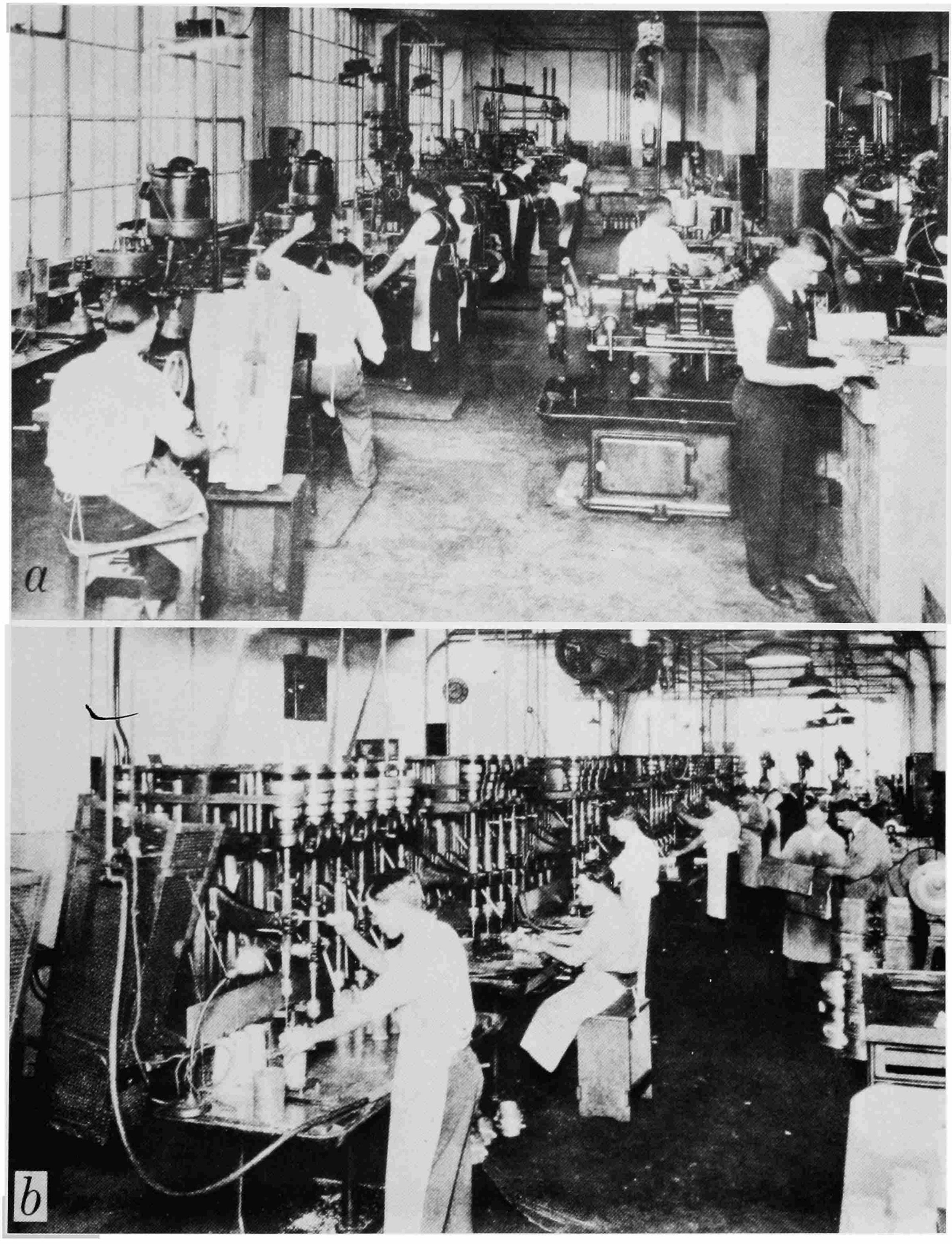



**Figure 4.**—Scenes from the general machine shop at Sperry Gyroscope Company where machinist-artisans made precision devices in the tradition of scientific instrument-makers: *a*, jig-borers section; *b*, multiple-drill presses section.

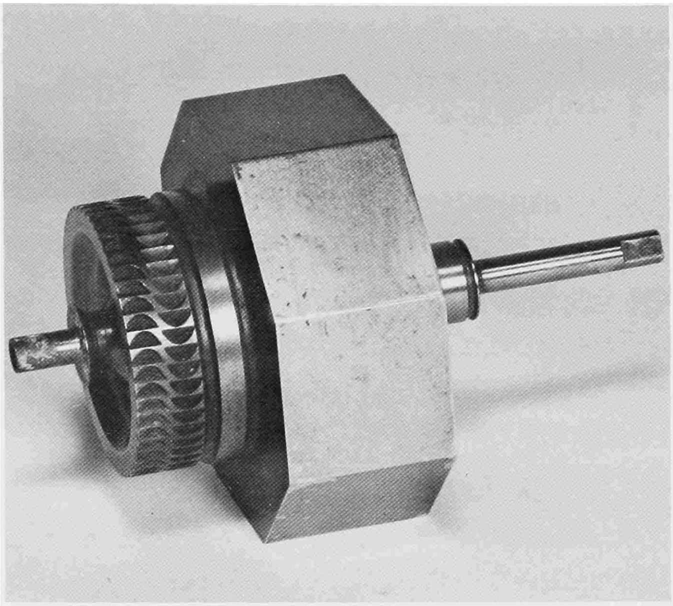


FIGURE 5.—The 8-sided Sperry mirror with double row of turbine buckets. (NMHT 319,992, Smithsonian photo 59416)

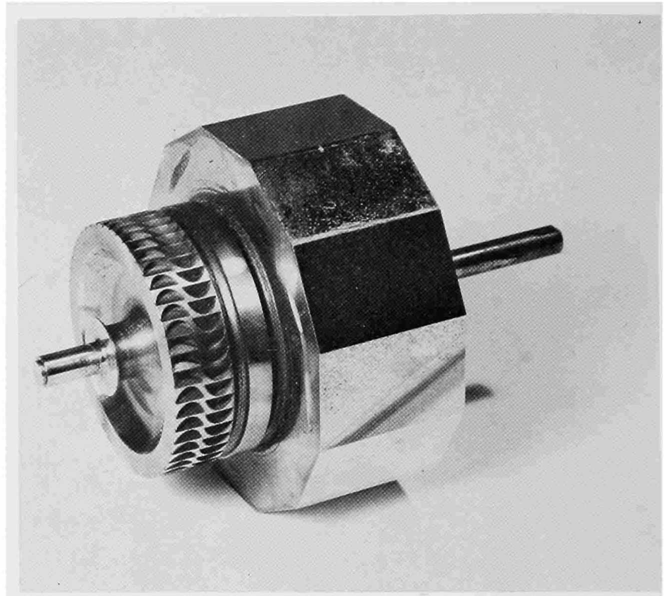


FIGURE 6.—The 12-sided Sperry mirror. (Courtesy Michelson Museum, Naval Weapons Center, China Lake, California)

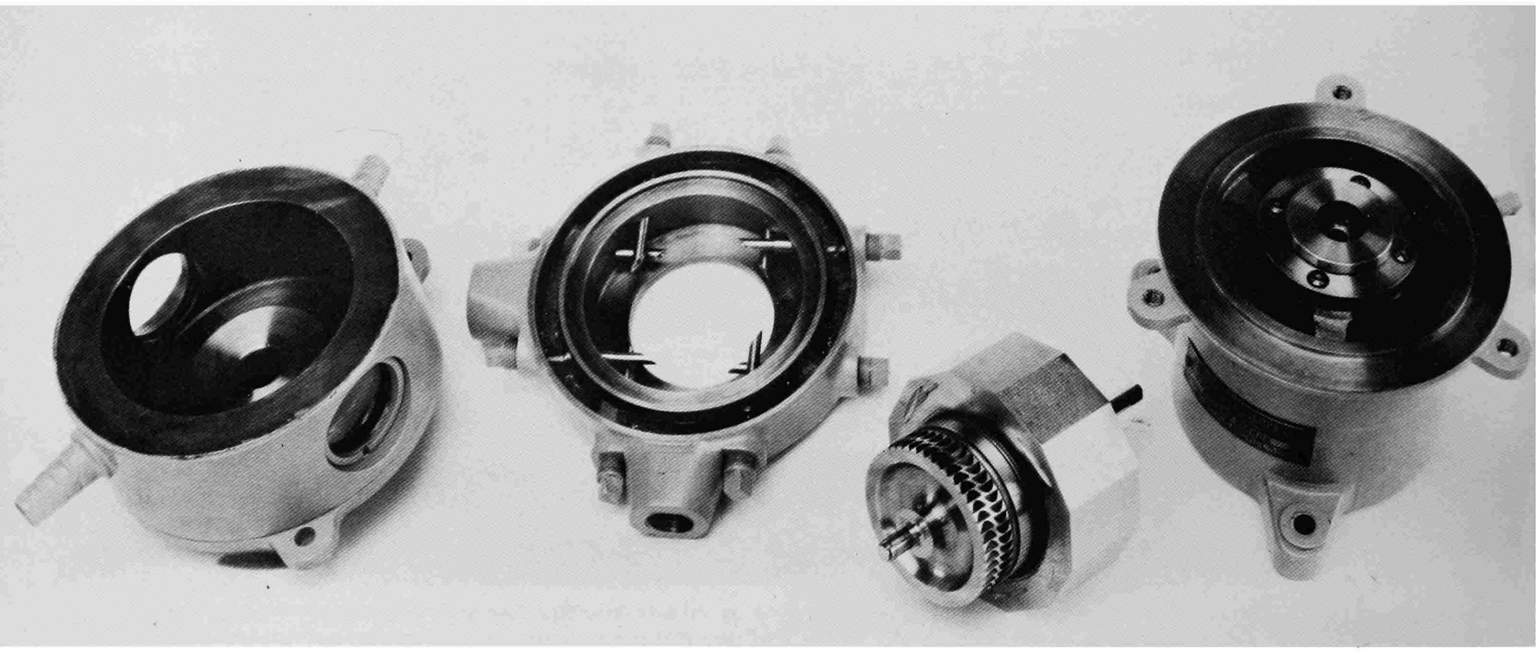


FIGURE 7.—The 12-sided Sperry mirror with housing disassembled. (Courtesy Michelson Museum, Naval Weapons Center, China Lake, California)

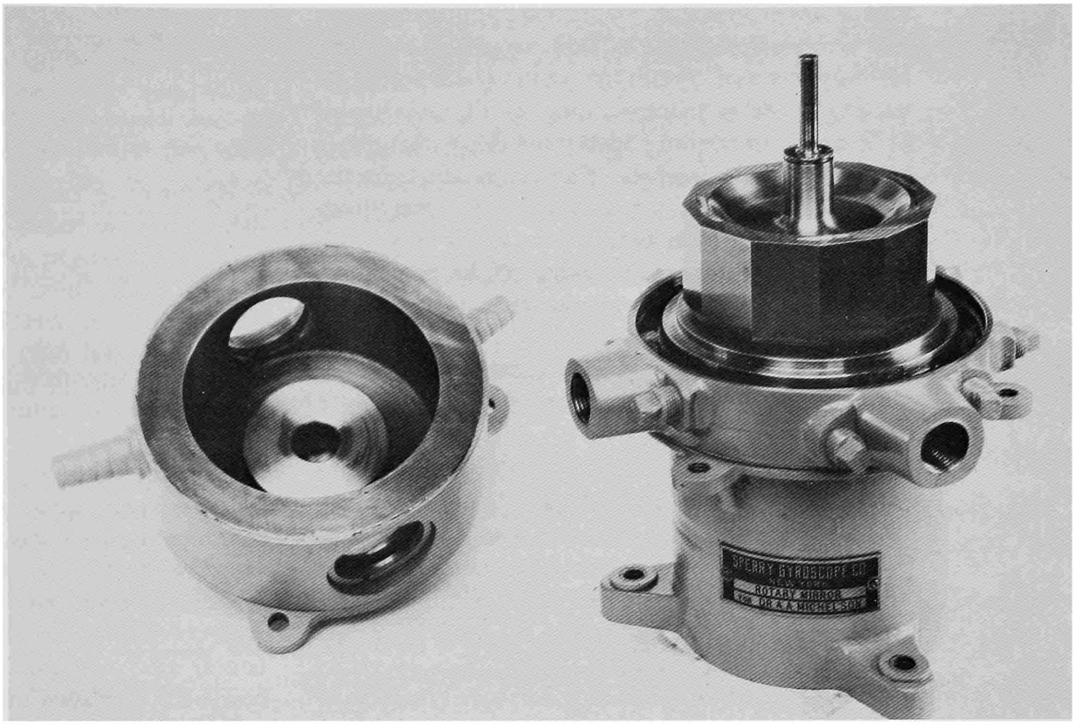



FIGURE 8.—The 12-sided Sperry mirror with housing and mounting. (Courtesy Michelson Museum, Naval Weapons Center, China Lake, California)

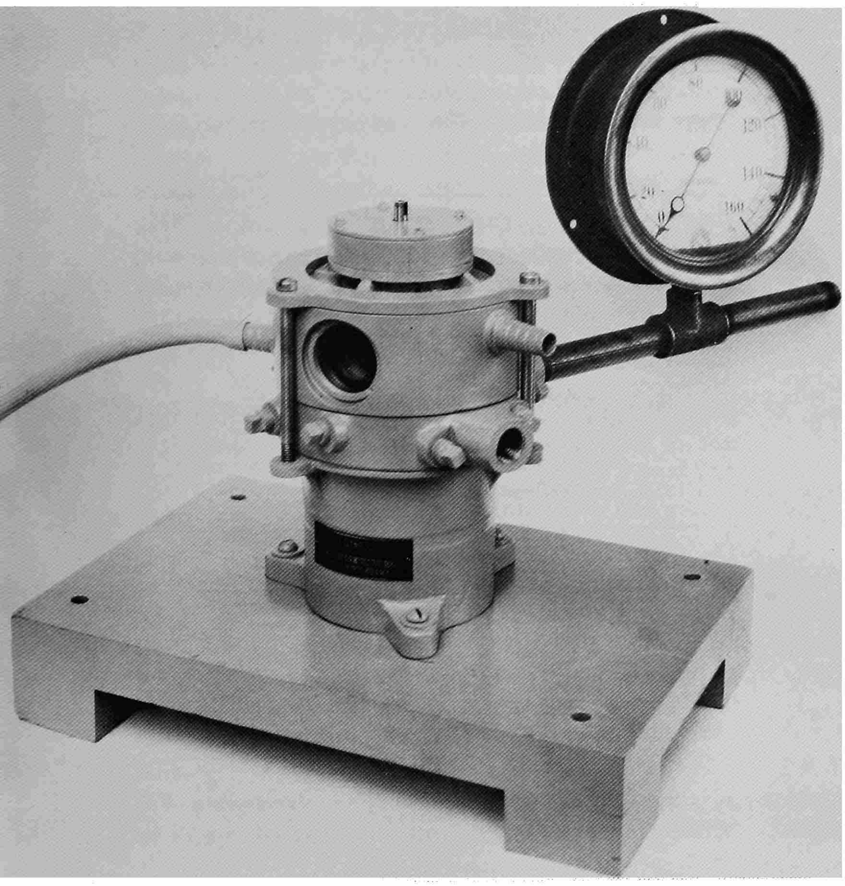



FIGURE 9.—The 12-sided Sperry mirror assembled. The gauge measures the air pressure that drives the mirror; other air intake is for cooling. (Courtesy Michelson Museum, Naval Weapons Center, China Lake, California)

mirrors—were made in the summer of 1926. Upon his return from Mt. Wilson on 22 September, Michelson wrote Sperry an enthusiastic letter reporting the new determination of the velocity of light and commending Sperry for the performance of his revolving mirrors. The uncertainty in the velocity of light has been reduced, he wrote, "from something like 100 kilometers to one or two." "Allow me to express my gratification," he continued, "at the results given by your steel mirrors. Notwithstanding the great difficulty in figuring [precisely finishing] these to the necessary degree of accuracy, the results, as you see by the table, were given the highest weight."[47] Sperry, enthusiastically, replied:

You don't know what great joy you have brought to the house of Sperry, I mean the official house as well, by your wonderful letter of September 22nd. To think that we have been in any way helpful in this great work fairly takes our breath away, especially to find that the steel mirrors have been operating with high precision, absolutely in the middle of the loaded average. That is certainly wonderful.[48]

## Analysis and Evaluation of the Data

How Michelson assigned weights to obtain loaded averages is not easily determined. The weight assigned a determination made with a particular mirror was not a direct function of the number of observations made with that mirror, as Tables 1 and 2 clearly show. In an article subsequently published in *The Astrophysical Journal* (1927) about the series of experiments of 1924–1926, Michelson did not reveal his method. A sentence in his letter to Sperry of 22 September 1926, however, suggests that Michelson's estimate of precision of his instrumentation was a factor in his evaluation. He judged the performance of the instruments, especially the mirrors, with the keen eye of experience and then assigned weights. In the September letter, he disclosed that he gave the steel mirrors the highest weights despite the great difficulty in figuring them; a clear indication that other characteristics of the mirrors offset this physical flaw. Another indication that his evaluation of instrumentation affected his weighting is in Michelson's article of 1924 discussing his preliminary results where he wrote:

The principal source of error was found to be in the maintenance of a sufficiently constant speed of the revolving mirror. This was doubtless due to lack of proper provision for a constant pressure of the air blast and not to any lack of precision in the measurements of the displacement of the image. This difficulty will be eliminated in the work for next summer, when, it is hoped, the uncertainty of the result will be reduced to one in one hundred thousand.[49]

His drive to improve instrumentation, to weigh determinations more heavily, and thereby, hopefully, the precision of his value for the velocity of light is also shown by his introduction, in July 1925, of a vacuum-tube circuit to drive the electric fork, which was used to time the revolution of his mirrors. (Earlier he had used a make-and-break con-

TABLE 1.—Michelson's results from observations made in 1925–1926 (from A. A. Michelson, "Measurement of the Velocity of Light between Mount Wilson and Mount San Antonio," *The Astrophysical Journal,* volume 65 (1927), page 12)

| Mirror | Year | N | $n$ | $V$ (km/sec) | Weight |
|---|---|---|---|---|---|
| Glass 8 ........ | 1925 | 528 | 150 | 299,802 | 1 |
| Glass 8 ........ | 1925 | 528 | 200 | 299,756 | 1 |
| Glass 8 ........ | 1926 | 528 | 216 | 299,813 | 3 |
| Steel 8 ......... | 1926 | 528 | 195 | 299,795 | 5 |
| Glass 12 ....... | 1926 | 352 | 270 | 299,796 | 3 |
| Steel 12 ........ | 1926 | 352 | 218 | 299,796 | 5 |
| Glass 16 ....... | 1926 | 264 | 270 | 299,803 | 5 |
| Glass 16 ....... | 1926 | 264 | 234 | 299,789 | 5 |
| Weighted mean ....... | | | | 299,796±4 | |

When grouped in series of observations with the five mirrors the results show a much more striking agreement, as follows. Glass 8: 299,797; Steel 8: 299,795; Glass 12: 299,796; Steel 12: 299,796; Glass 16: 299,796.

N=times per second; $n$=number of observations; $V$= velocity of light in vacuo.

TABLE 2.—Michelson's results from observations made in 1925–1926 (from Michelson to Sperry, 22 September 1926)

| Mirror | N | $n$ | $V$ (km/sec) | Weight |
|---|---|---|---|---|
| Glass oct ............ | 528 | 576 | 299,799 | 2 |
| Steel oct ............ | 528 | 195 | 299,800 | 5 |
| Glass 12 ............ | 352 | 270 | 299,797 | 3 |
| Steel 12 ............. | 352 | 218 | 299,800 | 5 |
| Glass 16 ............ | 264 | 504 | 299,802 | 5 |
| Weighted mean .... | | | 299,800±1 | |

N=times per second; $n$=number of observations; $V$= velocity of light in vacuo.

tact between platinum points to drive the electric fork.) The new rate was far more nearly constant,[50] but this improvement, for reasons unexplained, is not obvious in the weight Michelson assigned to the new series (compare the first and second series in Table 1). After the apparatus at the home station was slightly rearranged, however, and an increase "in intensity in consequence of greater effective width of the light beam falling on the revolving mirror at nearly normal incidence, as well as greater symmetry" [51] resulted, the subsequent series of observations with the same octagonal mirror was weighted three, instead of one, as formerly.

Additional evidence of the way in which a judgment about the precision of the apparatus probably influenced the significance attached to—or the weight assigned to—experimental results is found in an early *Encyclopaedia Britannica* article on "light" written by Simon Newcomb (1835–1909), the distinguished American astronomer who joined Michelson in making a determination of the speed of light in 1880–1882. Newcomb weighted two series of observations zero and a third unity because distortion was removed from the revolving mirror by eliminating torsional vibration by regrinding the pivots of the mirror.[52] The importance attached by Newcomb to variations in experimental apparatus is clear from his statement published in 1910: "It seems remarkable that since these determinations [1880–1882] were made, a period during which great improvements have become possible in every part of the apparatus, no complete redetermination of this fundamental physical constant has been carried out." [53] Using a Sperry searchlight and a Sperry mirror, Michelson, in 1926, was responding to the opportunity.

In 1927, Michelson published his results in the *Astrophysical Journal.* Curiously, he gave a different value, 299,796 km/sec, *in vacuo,* from the value, 299,800 km/sec, reported to Sperry in his letter of 22 September 1926, despite the fact that the values were calculated from the same observations (compare Tables 1 and 2). The only difference in figures for the number of observations (*n*) in the published article and in the letter was that the total for the octagonal glass mirror in the published table adds to 566, while the number given to Sperry was 576—possibly a notational error or a simple one of addition. In the published series of observations, grouped according to the mirror used, each one differed from the value supplied Sperry: for instance, the published figure of 299,797 for the "Glass 8" differed from that of 299,799 for "glass oct." sent Sperry.

There were also errors and inconsistencies within the Michelson *Astrophysical Journal* article of 1927. On page 5 the three sets of observations made with the glass octagonal mirrors were reported as having been given weights 1, 2, and 5, respectively, while in the summary table on page 12 (Table 1), the weights assigned were 1, 1, and 3. (If the weights 1, 2, and 5 are used, then the value of 299,797 is obtained, which is the value given in the grouped results for the octagonal glass mirror, but is not the value, 299,799, that is obtained by using the weights (1, 1, 3) assigned in the summary table). The difference is of significance, when it is recalled that Michelson told Sperry with great satisfaction that the new determinations had reduced the uncertainty to one or two kilometers. Michelson also erroneously reported that the first series of observations done with the glass mirror was made in 1925 (Table 1), while an earlier article in the same journal, establishes that the series was run in 1924.[54] Michelson's chronology was erroneous in another instance: in the 1927 article, he wrote that the large octagonal glass mirror failed in the summer of 1925;[55] the Sperry correspondence shows the event occurred in 1924, after which, in August, Michelson wrote to Sperry requesting a steel mirror. Also in the earlier article, he published a preliminary determination of the velocity of light that was erroneous because he used an incorrect figure to convert the velocity in air to vacuum (the error was corrected in the 1927 article).[56]

Another inconsistency is that Michelson's limits of uncertainty given in the letter to Sperry and in the 1927 article not only differ ($\pm 1$ as compared to $\pm 4$) but are not conventional standard deviations, nor weighted standard deviations; they appear to be a rather esoteric standard deviation of the mean.[57] Less significant but curious is the use in the 1927 *Astrophysical Journal* article of a full page photograph of the first ill-fated steel octagonal mirror sent by Sperry, the mirror that would not function because no turbine buckets were provided for reversing the mirror. Only an inconspicuous footnote explains that the mirror shown was not used.

This episode in the quest to determine the speed of light is punctuated by instances of human mistake and misunderstanding, but the major theme to emerge is Michelson's drive to achieve more precision by using improved instrumentation. The drive for—and anticipation of—improved instrumentation helps explain Michelson's dogged repetition of the "V" experiments, beginning in 1878 and ending only with his death. The Michelson-Sperry correspondence shows concern for near-perfect dynamic balance, minimal mechanical deflection of precisely machined and highly polished surfaces, and the elimination of distortion by the finest figuring. The dependence of the scientist upon the instrument maker and his tools is obvious. Michelson was known as a superbly resourceful designer of experiments; surely his reputation in this regard rested in no small measure upon his electing designs that exploited ingeniously the state of machine, tool, and material technology. In this episode, it was Sperry's searchlight and his precision manufacture that provided the technology.

Michelson's endeavor did not end with the observations of 1926. Despite failing health ( he suffered a cerebral hemorrhage at age 77) he designed apparatus for another determination. This time, desirous of avoiding the obstruction of haze and smoke and the effects of atmosphere, he used a mile-long pipe through which the light beam passed in multiple reflections in a near vacuum. Throughout 1930 and in 1931 Michelson directed the experiments from his sickbed. He died on 9 May 1931, but his assistants, F. G. Pease and F. Pearson, continued the work, finally obtaining a value of 299,774 km/sec, *in vacuo*.[58]

Sperry had died on 16 June 1930. If he had lived on, the exhilaration he knew when he had learned that his mirrors were assigned the highest weight and operated "absolutely in the middle of the loaded average," [59] would not have been dampened by new results with new instruments. Today, the value of 299,792.5 km/sec, *in vacuo,* has been adopted by the International Union of Geodesy and Geophysics and by the International Scientific Radio Union. This varies only 2.5 km/sec from that Michelson published in 1927 for the Sperry octagonal steel mirror. It is also noteworthy that Professor R. S. Shankland, who has studied Michelson and his work, urges that the determination made by Michelson from the 1924–1926 observations be accepted as his best result rather than the later determination made when he was ill, unable to fully participate, and completed after he died.[60]

# Appendix

## LETTER A

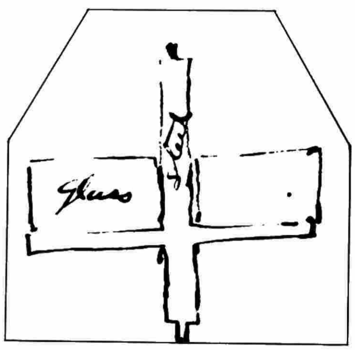
The University of Chicago
Ryerson Physical Laboratory
Aug. 23, 1924.

Dear Mr. Sperry:—

Thanks for your prompt reply to my letter. I proceed to answer your queries.

1) With the peripheral speed you quote 27500 ft. per minute; the rotor which is to make 540 turns per second could be 3 inches in diameter giving a face of the octagon of about 1¼ inches. The thickness should be also 1¼ in.

2) We have been making the octagon of glass, and mounting on the steel axle thus:




and this was found to work very well—with an air blast—for an octagon one and a half inches diameter but tried with a three inch octagon it flew to pieces at about 500 turns. We were thinking of trying fused quartz—but I'd be glad to have your opinion. (The quartz can be a little more easily polished.)

If it would be possible to make the axle and the octagon separately *we* can make the latter here and. send it on to you to be mounted on the axle and balanced.

3rd. A temperature elevation would not interfere materially with the accuracy.

4th. Two windows will be required in the case (if a vacuum is used) and these we will furnish.

5th The axle of the mirror is to be vertical— No special treatment of frame which is to rest clamped to the iron table supporting the whole arrangement. (Probably foot screws might be a convenience)

6th The motor may be below the octagon—we placed the paddlewheel for air blast above.

7th It will be necessary to provide for both positive and negative rotations which may require motors above and below?

Trusting for a speedy reply and an estimate of cost—and with kind regard

Very sincerely yours

A. A. Michelson

## LETTER B

Mount Wilson
California
July 31, 1925

My dear Mr. Sperry—

In more ways than one this is the high point of my trip. This is the third wonderful day up here on Mount Wilson & I doubt if I ever enjoyed three days as much as these.

In addition to my own profit & enjoyment, however, I think I have been of considerable assistance to the folks here. They had not been getting the best out of the lamp & had even been feeding it by hand, as well as burning with very shallow crater. I overhauled the lamp & readjusted it the first day. Last evening we had a very satisfactory run & the arc behaved like its old self. The first time it has operated automatically since they have had it. There is no doubt that their light troubles are solved for we could actually see with our naked eye the return beam from "Baldy" 25 miles away. Not so remarkable sounding until you realize that that distant gleam is actually coming from the light that is squeezed thru a slit 0.2 mm wide. I wouldn't have believed it possible if I hadn't actually seen it.

This afternoon I have been giving Mr. Pearson & Mr. Dowd some instructions on the operation of the lamp. Tonight we will have another test & if all goes well, I will go down the Mountain tomorrow morning & look up Selover at our Wilmington office.

Dr. Michelson has not yet been able to get up the mountain & his assistant Mr. Pearson is carrying on the work. They have not yet tried out our spinning mirror as they are still using their small one until they can perfect their timing devices. The main problem now is to know accurately the speed of the mirror & they have a room full of clocks, tuning forks & other gear in their attempts to get accurate timing. It is a tremendous undertaking as there are so many factors to be accurately controlled. There is a troublesome haze that rolls in & shortens the working time very frequently, even though it remains clear overhead. Last evening we had to stop work about 9:30 PM on this account, but the big 100″ telescope was tending to business as usual & I sat up on the platform with Dr. Joy, the astronomer of the evening, & helped him keep his lone watch most of the rest of the night. He was taking spectrum photographs of 10th magnitude stars, stars not even visible in a small telescope.

Dr. Dayton C. Miller is also here and inquired about you. He is working on a very interesting experiment to confirm (or otherwise) Einstein's Theory.

I can't begin to tell of the interesting things going on on the top of this single Mountain. Even my three days is too short to learn of them all.

I have reported my outbound progress in various letters to Mr. Morgan & Mr. Mahoney. I learned considerable about the trend of development in the night air mail and have enjoyed discussing floodlighting etc with the Westinghouse folks in the different cities on the way out. We can undoubtedly cooperate with them to good advantage, as at present they have to turn over most big illuminating projects to G.E. without even a fight.

After a day in Hollywood & the Studios I am going to San Francisco where I will spend a day or possibly two if I can make connections with the Coast Artillery Antiaircraft folks.

Then one day in Seattle, and the Canadian Pacific home.

I cannot thank Mr. Doran and yourself enough for making this trip possible for me. It is being of utmost value to me and I hope it will also prove not without values to the Company.

Very truly yours

Preston R. Bassett

## LETTER C

Aug 22 1925

Dear Mr. Sperry:—

Much to my chagrin and owing to an oversight which I trust your generosity will attribute to my illness—I find it necessary to return to you again the revolving mirror for alteration which will allow for rotation in the negative as well as the positive direction. Hope this may not be as serious a matter as it looks to me—but I am willing to meet whatever extra cost this may involve.

(Mr. Pearson reported that the mirror was O.K. but asked me to verify this—which I neglected to do—whence the trouble.)

I'm up on the Mountain and almost restored to health—and the work (with our small mirror) is going on very well

We have already a pretty good result with the original set-up and are now in the midst of a series of measurements with a modification which looks very promising.

Nothing seems likely to prevent a determination of "V" which is likely to be accurate to within four or five miles—except the effect of haze due to forest fires—we are just now experiencing one of rather serious character.

With kind regard
Sincerely yours

A. A. Michelson

## LETTER D

October 14. 1925.

Mr. Fred Pearson,
The University of Chicago,
Ryerson Physical Laboratory,
Chicago, Illinois.

My dear Mr. Pearson:

We are writing this letter to you, preferring not to bother the dear old Doctor about little items that are perfectly clear in your mind, but not quite clear to us.

In order to convert the present eight-faced revolving mirror into one that may be rotated in either direction, it is necessary that a new revolving element be made in order to obtain space for two sets of turbine buckets; at the same time the web portion of the mirror will be made heavier so as to decrease the face deflection at high speeds. This will make a slight change in the upper oil chamber casting that is easily taken care of. A new casting, between the upper and lower casing, is also necessary to provide for the double set of nozzles and double air entrance. The distance across flats of the mirror will remain the same as in the present mirror (3″) as well also the vertical face (1¼″).

Is it your intention to operate the eight and twelve-faced mirrors simultaneously, or one at a time?

If operated singly, a second rotating element can be provided to go in the same case having a mirror of twelve faces, the distance across flats being the same as for the eight-faced mirror (3″) and the vertical height of the face 1¼″ as before. Is there any objection to making the vertical face measurement, say ⅞″, instead of 1¼″, for the twelve-faced mirror so that the faces become nearly square, as in the present eight-faced mirror?

If the two mirrors are to be used simultaneously, this will necessitate a complete new machine for the twelve-faced mirror.

In the present machine there are two windows for the mirror 180° apart. If a new machine is built for the twelve-faced mirror, do you want the two openings 180° apart as before, or with 90° spacing?

If we convert the present machine and provide a second mirror, we can have it ready in about five weeks. If we convert the present machine and make up a second machine, it will require about eight weeks.

Please drop us a line as soon as possible and set us right on just which proposition you have in mind.

Sincerely yours,

[unsigned]

EAS.S.

# Notes

1. Sperry to Michelson, 30 September 1926. This letter and the Sperry correspondence hereafter cited are from the Sperry Papers at the University of Pennsylvania, Philadelphia, Pennsylvania.
2. On Sperry, see THOMAS PARKE HUGHES, *Elmer Ambrose Sperry: Inventor and Engineer* (Baltimore, Maryland: Johns Hopkins Press, 1971).
3. NOBELSTIFTELSEN, STOCKHOLM, *Les Prix Nobel en 1907* (Stockholm: Imprimerie, 1909), page 8. On Michelson's several determinations, see BERNARD JAFFE, *Michelson and the Speed of Light* (Garden City, New York: Anchor, 1960), and items in the bibliography of Michelson publications appended to ROBERT A. MILLIKAN, "Biographical Memoir of Albert Abraham Michelson, 1852–1931," *National Academy of Sciences Biographical Memoirs* (Washington, D.C.: National Academy of Sciences, 1938), volume 19. On Michelson, see D. THEODORE MCALLISTER, *Albert Abraham Michelson: The Man Who Taught a World to Measure,* Publication No. 3 of the Michelson Museum, Naval Weapons Center (China Lake, California: Technical Information Department, Naval Weapons Center, 1970), an imaginatively illustrated biographical booklet. Also on Michelson, see DOROTHY MICHELSON LIVINGSTON (his daughter), *The Master of Light: A Biography of Albert A. Michelson* (New York: Charles Scribner's Sons, 1973). In addition, see GERALD HOLTON, "Einstein, Michelson, and the 'Crucial' Experiment," *Isis,* volume 60 (1969), especially pages 147–148. Simon Newcomb-Michelson correspondence is in NATHAN REINGOLD, *Science in Nineteenth-Century America* (New York: Hill and Wang, 1964), pages 275–306.
4. Gerald Holton in the foreword to LOYD S. SWENSON, JR., *The Etherial Aether: A History of the Michelson-Morley-Miller Aether-Drift Experiments, 1880–1930* (Austin, Texas: University of Texas Press, 1972), page xix. Swenson's study provides an interesting scholarly account of Michelson's experimental testing of the ether theory, for which he is perhaps better known than for his velocity of light determinations. Swenson discusses the dependence of Michelson and other scientists upon the greatly improved instruments made possible by the machines and tools of the Industrial Revolution in the nineteenth century and after, pp. 58–61.

   I have not discussed the work of Thomas J. O'Donnell, Michelson's regular expert instrument-maker here because of the absence of information on him and his contribution in the Sperry-Michelson correspondence at the University of Pennsylvania and other sources available to the author. The importance of his contribution at Mt. Wilson, however, is indicated by R. S. Shankland who believes that his participation in these experiments helps explain the excellence of the results. R. S. SHANKLAND, "Final Velocity-of-Light Measurements of Michelson," *American Journal of Physics,* volume 35 (1967), pages 1095–1096.
5. MCALLISTER, *Michelson,* p. 19 [note 3], quoting Michelson from "Recent Progress on Spectroscopic Methods," *Science,* volume 35 (1911), page 901.
6. HUGHES, *Elmer Sperry,* page 291 [note 2].
7. "Gyroscopic Compass," issued September 17, 1918 (Patent No. 1,279,471).
8. JAFFE, *Michelson,* pages 32–33, 51 [note 3].
9. Foucault's use of a revolving mirror had been suggested to him by the employment of one by Charles Wheatstone (1802–1875), the British physicist and telegraph engineer, to measure the propagation of electric current in a wire. "Jean Bernard Léon Foucault," obituary in *Proceedings of the Royal Society* (London, 1869), volume 17, page lxxxiii. Determinations of the speed of light have a long history involving, among others, Ole Roemer (1644–1710), and Galileo Galilei. See I. BERNARD COHEN, *Roemer and the First Determination of the Velocity of Light* (Norwalk, Connecticut: Burndy Library, 1942).
10. The history of the Sperry high-intensity lamp is told in HUGHES, *Sperry,* pages 215–223 [note 2]. See also Appendix, letter B.
11. F. G. Pease to Sperry, 14 August 1924.
12. For more on the apparatus, see A. A. MICHELSON, "Preliminary Experiments on the Velocity of Light," *The Astrophysical Journal,* volume 60 (1924), pages 258–259; A. A. MICHELSON, assisted by F. PEARSON, "Measurement of the Velocity of Light between Mount Wilson and Mount San Antonio," *The Astrophysical Journal,* volume 65 (1927), passim; and JAFFE, *Michelson and the Speed of Light,* pages 161–164 [note 3].
13. MILLIKAN, "Biographical Memoir," page 131 [note 3].
14. SIMON NEWCOMB, "Light: Velocity," *The Encyclopaedia Britannica,* 11th edition (New York, 1911), pages 623–625.
15. A. A. MICHELSON, "Preliminary Measurement on the Velocity of Light," *Science,* volume 60 (31 October 1924), page 391.
16. MICHELSON and PEARSON, *Astrophysical Journal,* page 5 [note 12].
17. Preston Bassett, the Sperry engineer who visited Mt. Wilson to help set up the Sperry arc light, reported the slit as 0.2 mm wide. Preston Bassett to Elmer Sperry, 31 July 1925.
18. MICHELSON and PEARSON, *Astrophysical Journal,* page 3 [note 12].
19. MICHELSON, *Astrophysical Journal,* page 256 [note 12].
20. *Ibid.,* page 257.
21. Michelson to Sperry, 23 August 1924 [Appendix, letter A].

22. Sperry to Michelson, 28 August 1924.
23. Preston Bassett to author, 21 May 1971.
24. Sperry to H. Nagaoka, 9 March 1925.
25. Sperry to Michelson, 17 April 1925.
26. Michelson to A. Schein, Sperry Gyroscope Company, 5 May 1925.
27. Michelson to Sperry, 27 April 1925.
28. Alexander Schein (? no signature) to Michelson, 30 April 1925.
29. Sperry (? no signature) to F. Pearson, 7 May 1925.
30. *Ibid.*; Sperry to Michelson, 7 May 1925; and Sperry to F. Pearson, 8 May 1925.
31. A three-page handwritten letter dated 23 August 1924, from Michelson to Sperry served as specifications for the mirror [Appendix, letter A].
32. Michelson to A. Schein, 5 May 1925.
33. Sperry to Michelson, 7 May 1925.
34. Sperry (? no signature) to F. Pearson, 7 May 1925.
35. Sperry to Michelson, 27 May 1925.
36. *Ibid.*
37. Sperry to Michelson, 10 June 1925.
38. Michelson to Sperry, 22 August 1925.
39. Appendix, letter A.
40. Sperry to Michelson, 27 August 1925.
41. Bassett to Sperry, 31 July 1925.
42. Sperry to Michelson, 23 January 1926.
43. Sperry to Michelson, 20 October 1925.
44. Telegrams: Michelson to Sperry, 22 October 1925, and Sperry to Michelson, 23 October 1925.
45. Sperry to Fred Pearson, 27 January 1926.
46. Quote from Michelson letter in J. Spencer Dickenson, secretary of the Board of Trustees, to Elmer Sperry, 19 February 1926. The 12-sided nickel-steel Sperry mirror is in the collection of the Michelson Museum at the Naval Weapons Center, China Lake, California; the 8-sided steel mirror with a single row of turbine buckets is on exhibit in Michelson Hall at the U. S. Naval Academy; and the 8-sided steel Sperry mirror with the double row of buckets is on display at the Museum of History and Technology, Smithsonian Institution.
47. Michelson to Sperry, 22 September 1926.
48. Sperry to Michelson, 30 September 1926.
49. MICHELSON, *Astrophysical Journal,* page 261 [note 12].
50. MICHELSON and PEARSON, *Astrophysical Journal,* page 2 [note 12].
51. MICHELSON and PEARSON, *Astrophysical Journal,* page 5 [note 12].
52. NEWCOMB, "Light: Velocity," page 625 [note 14].
53. *Ibid.*
54. MICHELSON, *Astrophysical Journal,* page 260 [note 12] gives $V$ (*in vacuo*) as 299,820 km/sec. Later, MICHELSON and PEARSON, *Astrophysical Journal,* page 2, correct the number to 299,802 (Table 1), because an erroneous correction to vacuum was used in the previous article. The 299,802, actually obtained in 1924, then, is given as the 1925 figure in the later *Astrophysical Journal* article.
55. MICHELSON and PEARSON, *Astrophysical Journal,* page 6.
56. See note 54.
57. MICHELSON and PEARSON, *Astrophysical Journal,* page 12 [note 12], gave as his weighted mean, 299,796 $\pm 4$ (Table 1). Dean Leon Cooper of the Institute of Technology, Southern Methodist University, Dallas, Texas, analyzed for me the table of values from which Michelson derived this weighted mean: the Michelson calculations were not straightforward. The $\pm 4$ is not a standard deviation; this would be $\pm 17$. Furthermore, a weighted standard deviation would be $\pm 10.4$. Michelson seems, therefore, to have calculated a "standard deviation of the mean," i.e., an estimate of the accuracy of the mean. This amounts to $\pm 3.7$ and may be the $\pm 4$. In the table in the Sperry letter of 22 September 1926, a weighted mean of 299,800 $\pm 1$ is given. The $\pm 1$ also can be obtained by calculating the "standard deviation of the mean." If the $\pm 4$ and $\pm 1$ are standard deviations of the mean, Cooper believes some qualification relating to confidence intervals would be a more desirable approach. For example, values of $\pm 8$ and $\pm 2$ would indicate, respectively, a 95 percent confidence limit for the mean.
    To calculate the standard deviation:

$$\sigma = \left[ \frac{\sum_{i=1}^{N} (x_i - x_m)^2}{N-1} \right]^{1/2}$$

    To calculate a weighted standard deviation, multiply $(x_i - x_m)^2$ for each set of observations by Michelson's weight for the set given in the table and use the sum of the weights instead of $N-1$.
    To calculate a standard deviation of the mean, use

$$\sigma_m = \frac{\sigma}{\sqrt{N}};$$

    let $x_i = i^{th}$ measurement
    $x_m$ = mean value
    $N$ = number of observations.

    In this essay, the discussion of Michelson's statistical technique has been limited largely to questions raised by the Sperry correspondence. For an exhaustive analysis of Michelson's technique and the nature of systematic errors in the experimental system of 1924–1926, see N. ERNEST DORSEY, "The Velocity of Light," *Transactions of the American Philosophical Society,* volume 34 (1944), pages 1–110 *passim.* See also, R. T. BIRGE, "A Survey of the Systematic Evaluation of the Universal Physical Constants," *Nuovo Cimento,* supplement to volume 6, series 10 (1957), 39–67 *passim.*
58. JAFFE, *Michelson and the Speed of Light,* 165–170; A. A. MICHELSON, F. G. PEASE, and F. PEARSON, "Measurement of the Velocity of Light in a Partial Vacuum," *The Astrophysical Journal,* LXXXII (1935), pages 26–61.
59. Sperry to Michelson, 30 September 1926.
60. ROBERT S. SHANKLAND, "Final Velocity-of-Light Measurements of Michelson," *American Journal of Physics,* volume 35 (1967), pages 1095–1096.

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