Chapter 3 Measuring Light
Albert A. Michelson

1882 – 1889

When the Case School of Applied Science (CSAS) was formed, John Stockwell, a self-educated astronomer, was its *de-facto* president. He essentially single-handedly "formulated a curriculum, bought equipment and established laboratories and hired a faculty that was small but brilliant" (according to historian C. H. Cramer). The first faculty, in 1881, consisted of Stockwell, Charles Maberry (chemist-Harvard), John Eisenmann (civil engineer-University of Michigan), and Albert Michelson (physicist-U.S. Naval Academy). Michelson was an extraordinary catch for the brand-new school. In the eight years following his graduation from Annapolis, Michelson had caught the attention of the international physics community, beginning with his measurements of the velocity of light at Annapolis and at the Naval Observatory in Washington.

Interferometry

Michelson's youth was very much different from those of the New Englanders described in the first two chapters. He was born in Prussian Strelno (now Strzelno in Poland), brought by his parents to America at age two, raised in Nevada, finished high school in San Francisco, and appointed to the Naval Academy by President Grant, graduating in 1873. **Fig. 3-1.** After a stint at sea and another teaching at the Academy, he was transferred to the Nautical Almanac Office where he and astronomer Simon Newcomb used the rotating-mirror method to measure the velocity of light. (His subsequent work on the velocity of light which was done at Case will be detailed later.) He traveled to Europe in 1880 where he was to remain for two years, first in Berlin, then in Paris. It was during this period that Michelson invented his interferometer.

Fig. 3-1. Midshipman Michelson portrays himself.

An aside on what an interferometer does. This device consists of a light source, a telescope, and some mirrors. The incident light beam is split at a partially silvered mirror, the two beams traveling by different paths to be subsequently rejoined into a single beam which is observed in the telescope. To put it rather simply, if the two paths differ in total length by one-half wavelength or three-halves or any odd number of half wavelengths, the two beams will cancel one another upon rejoining, and no light is observed in the telescope. As one slowly changes the length of one of the paths, the observed light will vary between bright and nil. The device could thus be used to measure the length of an object in terms of the wavelength of a selected spectral line, or conversely to measure a wavelength in terms of a standard length.

The money for the construction of this first interferometer was provided by Alexander Graham Bell who had heard of the young naval officer's talents. Michelson demonstrated his invention in Paris to Marie Alfred Cornu and other distinguished French physicists. Michelson made the acquaintance of Lord Rayleigh when they met in Germany. Rayleigh encouraged him to continue his velocity of light measurements. He was especially interested in having Michelson check on recent claims by other experimenters of significant dispersion of light traveling through air. *(Dispersion refers to different light-speeds for different wavelengths – resulting, for example, in the separation, or dispersion, of colors by a prism.)* Michelson and Rayleigh continued their friendly correspondence for many years.

Michelson's first attempts to use the interferometer to detect the motion of the earth through the ether were made in Berlin and then in Potsdam in 1881. It was generally believed that light must have a medium of some kind through which it moves, just as sound propagates by moving the molecules of the air. This medium was referred to as the ether (or aether).

An aside on detecting motion through the ether. If the speed of light relative to an all-pervading ether is a constant, and if the earth moves through the ether in its travels around the sun, then the speed of a beam of light relative to the earth should have one value when the light travels parallel to the earth's orbital motion, and another when the light travels at right angles to that motion. This effect can be observed if one sets up an interferometer so that one light beam travels parallel to the earth's orbital motion and the other travels at right angles. One then watches the two interfering light beams in the telescope while at the same time rotating the whole device so that the beams exchange directions. The amounts of time it takes to travel along the two paths will also be switched, and there will be a small change in the pattern of the recombined light as seen in the telescope. This is usually referred to as a shift in the interference pattern, or simply a "fringe-shift". A photograph of what one sees in the telescope is shown in ***Fig. 4-7*** *in the next chapter..*

When Michelson tried this experiment in Germany, he did not observe the expected shift in the interference pattern. The famous repetition of this experiment by Michelson and Morley will be described later in this chapter.

Fig. 3-2. A.A. Michelson

Velocity of light measurements at Case

Michelson received word of his official appointment to the CSAS faculty while still in Europe and he was given a year's leave of absence to conclude his work there. He arrived in Cleveland in September 1882. **Fig. 3-2**. He quickly began setting up for a new measurement of the velocity of light. What is remarkable is the speed with which Michelson got his work underway: he arrived in September, made his measurements in October and November, and wrote his first report in January.

This was possible because most of the principal components of the setup were the same as those he had used with Newcomb two years earlier in Washington. In the report which he sent to Newcomb, Michelson described exactly what he had done, including details of several significant improvements of his own design. *Proc. of the AAAS* **28** 124-160 1879.

With the help of his new colleague, the engineer John Eisenmann, Michelson laid out an optical path along the railway tracks which still border the south edge of the Case campus. Eisenmann's survey indicated that the baseline was 2049.532 feet in length. This was the distance between X-marks inscribed on the heads of copper tacks set in two brick piers, one to hold a revolving mirror, the other to hold a fixed mirror. The separation was determined by using a 300-foot steel tape to measure the distance between two marks inscribed directly on the top of the steel rail. Corrections were made for temperature for both the tape and the rail and for tension applied to the tape. This measurement was then transferred by theodolite to the X-marks on the stone caps on the two brick piers which were placed some 50 feet north of the railroad track. *(No uncertainty is quoted in this report from Eisenmann, but I have my doubts about the significance of the last two decimal places.)*

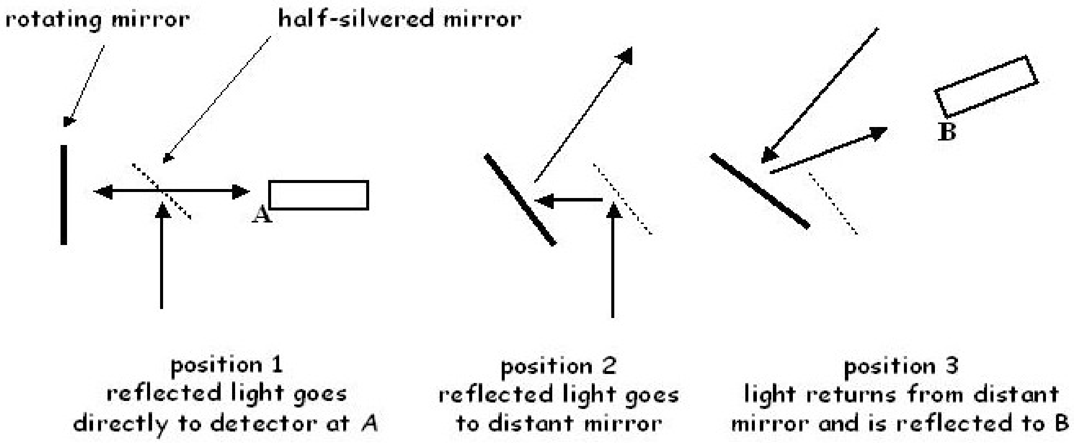


Fig. 3-3. Rotating mirror system for measuring the speed of light.

The following is a much-simplified description of the technique Michelson used. Light, from an electric arc, or from the sun, is incident on a slit. It is then directed via a half-silvered mirror to a mirror which is rotating around a vertical axis. This mirror is actually a polished nickel box with four reflecting faces, driven by compressed air.

In the three plan-view drawings of **Fig. 3-3**, the heavy line represents the rotating mirror which is spinning counterclockwise; the dotted slanted line is a fixed half-silvered mirror. The little rectangle is the viewing telescope. When the rotating mirror is in position #1, the light is reflected back through the half-silvered mirror toward the viewing telescope A placed about 33 feet away. When the mirror is in position #2, the light is reflected toward a distant fixed 15-inch diameter mirror (L=2050 feet away). When the rotating mirror is in position #3, the light returning from the distant mirror (at a time 2L/c later) is reflected back toward the viewing telescope, but at an angle about half a degree different from the prompt beam. This deflection angle is twice the angle through which the mirror rotated between positions #2 and #3. Thus there are *only two* positions of the viewing telescope (pos 1 and pos 3 in the sketch) at which light can arrive from the rotating mirror: one beam traveling a short distance, the other traveling over 4000 feet. Michelson would move the telescope until he found the two places where he could see the blinking light. Knowing the angle between these two beams and the rate of rotation of the mirror, one can then determine the time it took the light to make the round trip to the distant fixed mirror, and thus calculate the speed of light. The angular separation between the two beams of light which reach the viewing telescope is measured by a micrometer which moves the telescope across the beams. The displacement between the two beams, combined with a precise measurement of the radial distance (~33 ft) from the rotating mirror face to the axis of the screw of a micrometer, defines the desired angle.

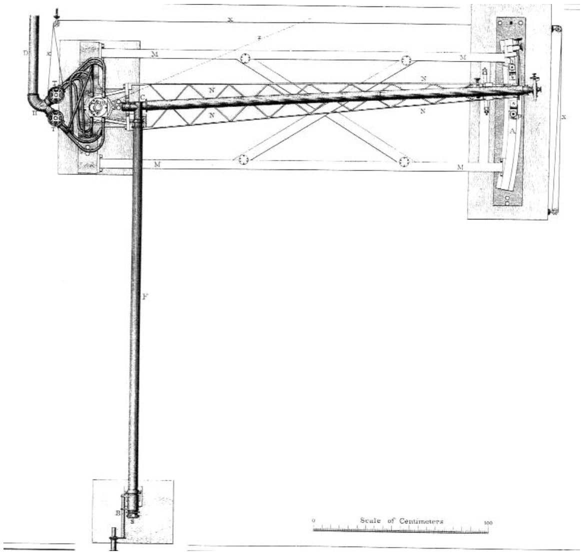


Fig. 3-4. Source, rotating mirror and viewing telescope.

The beautifully drawn plan of the experiment in **Fig. 3-4** is from Newcomb's report on the earlier Washington measurements. It shows the light source at the bottom, the four-sided rotating mirror at the left, and the viewing telescope with micrometer at the right. The distant fixed mirror is far away off to the upper right. **Fig. 3-5** shows two views of the viewing telescope and the micrometer with its two reading microscopes. Details of the rotating mirror and its position relative to the light tubes are shown in **Fig. 3-6.** The half-silvered mirror is enclosed in the right-angle junction of the tubes at the right.

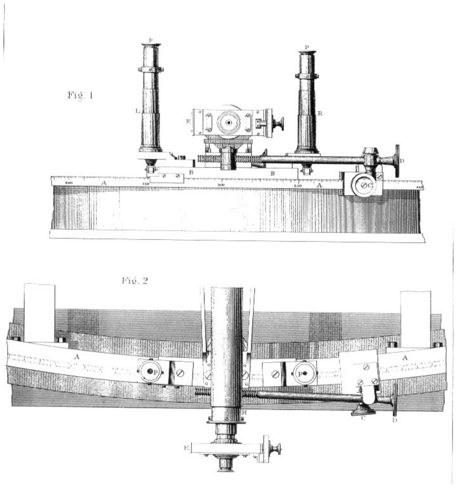


Fig. 3-5. Two views of viewing and reading telescopes.

The rate of rotation of the mirror was controlled by adjusting the flow of compressed air directed at vanes attached to the mirror's shaft; one valve controlled the main flow, and a second, "fine-tuning" valve controlled a small flow opposing the main flow.

The angular speed of the mirror was measured by comparison with a calibrated tuning fork. *(The 128 Hz fork, made in Paris by the famous instrument maker Rudolph Koenig, is preserved in the CWRU physics department archives.)* To compare the mirror rotation rate with the tuning fork, Michelson attached a tiny mirror to the fork and directed a narrow light beam first onto the spinning mirror and then onto the “fork mirror”. The fork is positioned so that the two motions are mutually perpendicular. The twice reflected light beam moves with two components: a linear (sawtooth) sweep from the rotating mirror and a sinusoidal sweep from the fork.. When the frequencies of the two motions are equal, the light beam is locked in a stationary pattern.

Three rotation rates were used: 1.0, 1.5 and 2.0 times 128 rev/s. The tuning fork was calibrated by a very elaborate scheme involving beating it against an electrically driven fork which in turn was compared to an astronomical “seconds” clock accurate to one-half second per day. (The temperature dependence of the fork’s frequency was determined to be 0.0079 Hz/degree F.)

Here are some typical numbers from one trial. The frequency of the standard fork 129.127 Hz; the rate of rotation set at twice the fork frequency or 258.254 Hz. The linear deflection of reflected beam is 137.920 mm at a radius of 33.350 feet, giving an angular deflection of 2788.7 arcsec; resulting in a velocity of light for this measurement of 299 883 km/s. The weighted mean of 23 such measurements was 299 853 ± 60 km/s. Thus, the quoted uncertainty is 2 parts in 10,000, a remarkable accomplishment for a purely mechanical measurement. (This corresponds to about one inch in 2000 feet, so the Eisenmann survey was more than sufficient.) This value of c was the accepted standard until Michelson’s later measurement in 1926 (299 796 ± 4 km/s; the uncertainty on the earlier measurement uncannily just reaches the later value). (“Albert A. Michelson at Case”, R. S. Shankland, *Amer. Jour. of Phys.* **17** 487 (1949))

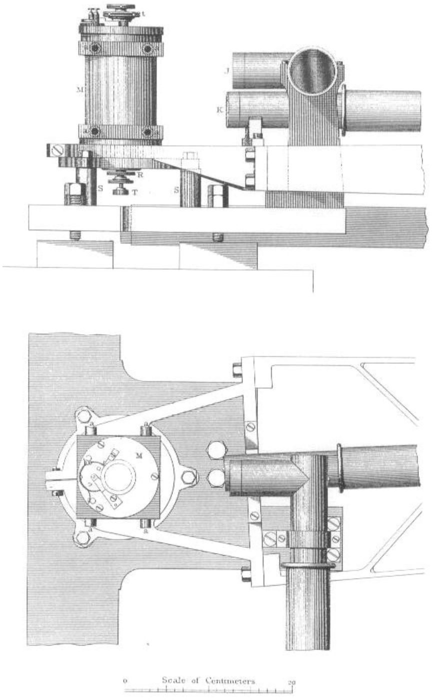


Fig. 3-6. Side and top view of rotating mirror.

At the end of his report to Dr. Newcomb, his mentor at the Navy Department, Michelson writes, “I would take this opportunity of expressing my obligation to ....several of the students of the Case Institute for their cheerful aid in carrying out the work ....” Thus begins the long history of research experiences for Case undergraduate physics students.

The velocity of light in water and in a dispersive medium

In a further report to Newcomb sent the following August, Michelson describes an experiment in which the light path to the fixed mirror included ten feet of distilled water. The same arrangement of rotating mirror, fixed mirror, and telescope were used as before in this quick “one part per thousand” measurement. The resulting ratio of c/v_{water}

= 1.330 ± 0.003 was in good agreement with the measured index of refraction of water (1.334). This was the first quantitative demonstration of that equality.

Next, Michelson replaced the water by 3.07 m of carbon disulphide. (All the data for this experiment are given in metric units, in contrast to the inches and feet of his earlier reports.) Different mirror rotation rates were used (from 128 to 320 per sec), as well as different distances from rotating mirror to telescope (from 3 to 6 m), and the results for the velocity of light v in CS_2 were consistent, giving a mean value of c/v of 1.77 ± 0.02. The measured value of the refractive index of CS_2, however, is 1.64, six standard deviations away. Nonetheless, Michelson stood by his measurement. The disagreement had in fact been resolved by Rayleigh's theory (1881) for the propagation of light in a dispersive medium. Rayleigh had shown that the index of refraction is related to the *phase* velocity (ω/k) while the propagation speed is the *group* velocity ($d\omega/dk$). (Here $\omega = 2\pi$ times the frequency and $k = 2\pi$ over the wavelength.) His calculations agreed with the Michelson result. In their famous textbook on physical optics, Jenkins and White mention that, since water is also slightly dispersive, Michelson should have measured something like 1.35, rather than 1.33; Michelson must have wondered about this, given the better agreement for the CS_2 measurement.

Completing this series of measurements, Michelson looked for a dependence of the speed of light in CS_2 on the wavelength of the light. He placed a small prism in front of the slit, with which, by small rotations of the prism, he illuminated the slit with blue and then with red light. His result was $v_{red}/v_{blue} = 1.014$, the first quantitative measurement of dispersion.

Michelson and Morley team up: Light in a moving medium

Michelson had made the acquaintance of Edward W. Morley, the eminent physical chemist at the neighboring institution, soon after his arrival at Case in 1882. The two men shared a passion for the development and application of precise measuring instruments. They traveled together to scientific meetings in Baltimore and Montreal. Their first joint effort was to repeat an earlier (1859) experiment by Fizeau to check on the theory developed by Fresnel (1818) for the propagation of light through a moving medium. Michelson devised an arrangement in which a beam of light was split into two beams, one of which traveled through water in the direction of the water flow, the other against the water flow. The beams were recombined to give an interference pattern. The pattern shifted as the water velocity was changed. (*Amer. J. Sci.* **31** 377 (1886))

The result was extremely gratifying: the predicted change in the speed of light was $v_{water}(n^2-1)/n^2 = 0.438\, v_{water}$ where n is the index of refraction of water; the measured coefficient was 0.434 ± 0.02.

In pursuit of the ether: the Michelson-Morley experiment

It was time for Michelson to give the ether-drift experiment another try. He realized that he had overestimated the expected effect when he was in Germany. He had believed that the shift in the light speed should be in the order $v_{earth}/c = 10^{-4}$, but, as was pointed out by H.A. Lorentz, the size of the effect should actually be only 10^{-8}. Lorentz showed that the light travel-time in the interferometer arm *perpendicular* to the earth's motion should *also* be affected by the motion of the apparatus through the ether. The displacement of the fringes in the 1881 attempt at Potsdam should have been only four hundredths of a fringe, well below the sensitivity of the experiment.

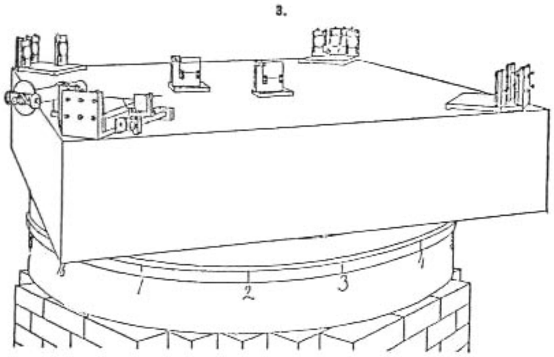


Fig. 3-7. MM experiment setup.

With Morley, Michelson designed a much improved arrangement. Here is the Michelson-Morley description of the situation: "In the first experiment one of the principal difficulties encountered was that of revolving the apparatus without producing distortion; and another was its extreme sensitiveness to vibration .... Finally .... the quantity to be observed, namely, a displacement of something less than a twentieth of the distance between the interference fringes may have been too small to be detected when masked by experimental errors. The first named difficulties were entirely overcome by mounting the apparatus on a massive stone floating on mercury; and the second by increasing, by repeated reflection, the path of the light to about ten times its former value." The expected fringe shift was thus increased by a factor of ten, to four tenths of a fringe, well within the experimental sensitivity.

The line-drawings of the setup **(Fig. 3-7, 8** and **9)** are from their famous paper. (*Amer. Jour. Sci. 3*rd *Series* **34** 273 (1887)) The paper is available on the internet at: http://www.aip.org/history/gap/Michelson/Michelson.html

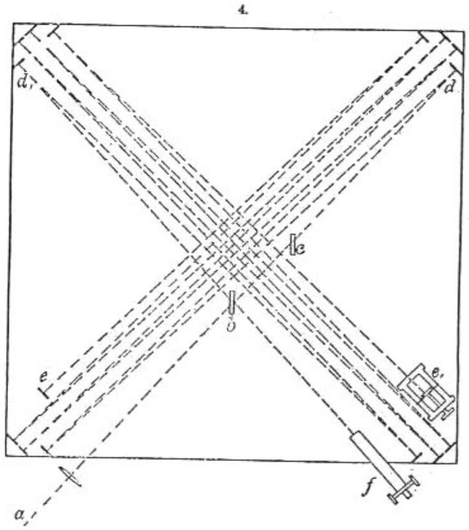


Fig. 3-8. The light paths in the MM experiment; source lower left, telescope lower right.

The authors' description of the procedure is straightforward: "The observations were conducted as follows: Around the cast-iron trough were sixteen equidistant marks. The apparatus was revolved very slowly (one turn in six minutes) and after a few minutes the cross wire of the micrometer was set on the clearest of the interference fringes at the instant of passing one of the marks. The motion was so slow that this could be done readily and accurately. The reading of the screw-head on the micrometer was noted, and a very slight and gradual impulse was given to keep up the motion of the stone; on passing the second mark, the same process was repeated, and this was continued till the apparatus had completed six revolutions. It was found that by keeping the apparatus in slow uniform motion, the results were much more uniform and consistent than when the stone was brought to rest for every observation; for the effects of strains could be noted for at least half a minute after the stone came to rest, and during this time effects of change of temperature came into action."

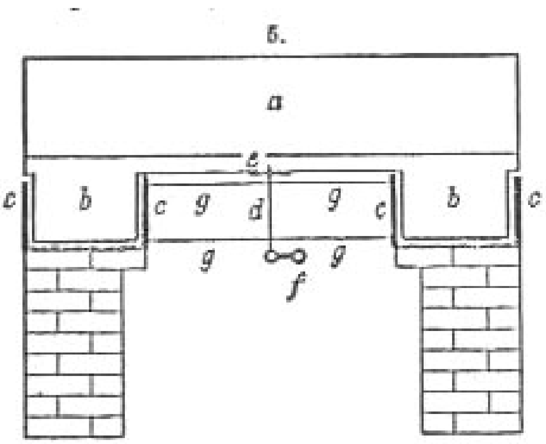
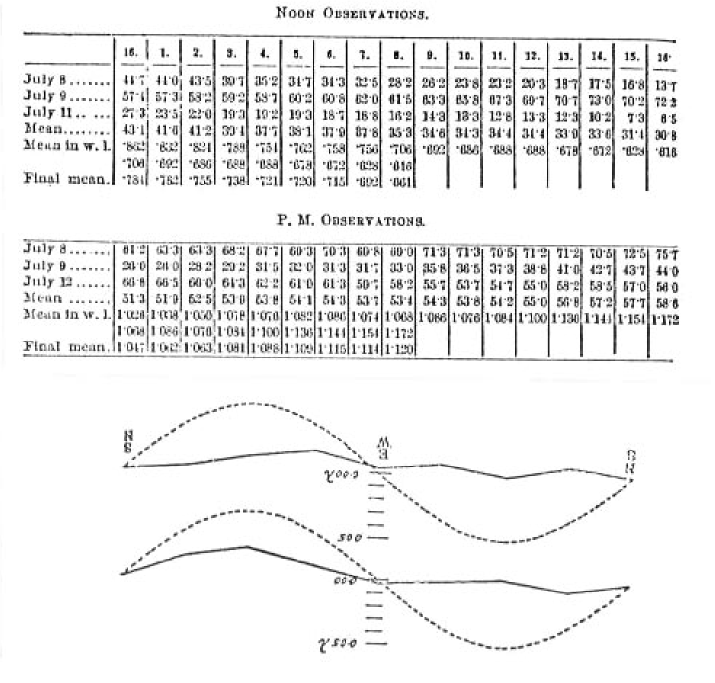


Fig. 3-9. Cut-away side-view of stone block floating on mercury.

The resulting data consisted simply of several series of micrometer readings. The entire set is shown in the table **(Fig. 3-10)**, as printed in the 1887 publication. Readings were taken at noon and later at six in the evening, allowing the earth to rotate through 90 degrees. The readings are in divisions on the micrometer. The approximate width of a single fringe is about 50 divisions. The mean readings are then converted to wavelengths (for sodium light). The data are first shown for the sixteen positions, and then, in the bottom line, are folded around the 180 degree position. Thus, the noon and evening runs are reduced to 8 numbers each. These are constant to within 0.02 wavelengths, twenty times smaller than the expected variation of 0.4 wavelengths. The two sets of eight numbers are shown graphically in the bottom half of **Fig. 3-10**, along with the expected signal **reduced by a factor of eight**. *(If I were teaching a class now, I would repeat the last phrase two or three times!)*

The conclusion is straightforward, without any complicated calculations or error analysis. The clear difference between the observed and the predicted effect allows the authors to state, "the relative velocity of the earth and the ether is probably less than one



NOON OBSERVATIONS.

	16.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.
July 8.......	44·7	44·0	43·5	39·7	35·2	34·7	34·3	32·5	28·2	26·2	23·8	23·2	20·3	18·7	17·5	16·8	13·7
July 9.......	57·4	57·3	58·2	59·2	58·7	60·2	60·8	62·0	61·5	63·3	65·8	67·3	69·7	70·7	73·0	70·2	72·2
July 11.. ...	27·3	23·5	22·0	19·3	19·2	19·3	18·7	18·8	16·2	14·3	13·3	12·8	13·3	12·3	10·2	7·3	6·5
Mean........	43·1	41·6	41·2	39·4	37·7	38·1	37·9	37·8	35·3	34·6	34·3	34·4	34·4	33·9	33·6	31·4	30·8
Mean in w. l.	·862	·832	·824	·788	·754	·762	·758	·756	·706	·692	·686	·688	·688	·678	·672	·628	·616
	·706	·692	·686	·688	·688	·678	·672	·628	·616								
Final mean.	·784	·762	·755	·738	·721	·720	·715	·692	·661								

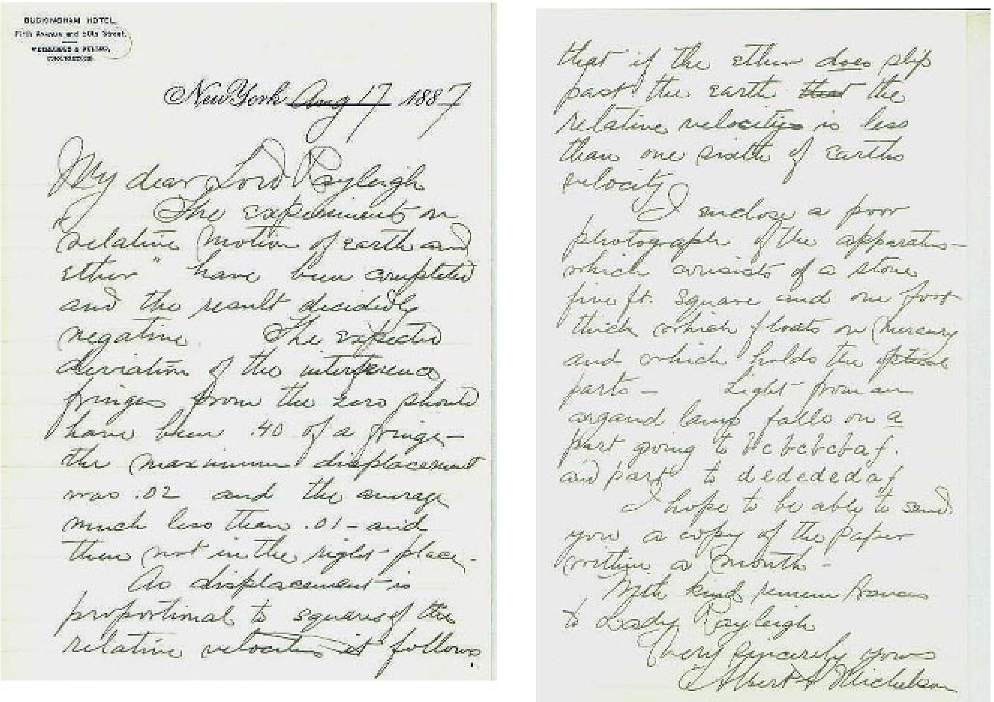
P. M. OBSERVATIONS.

July 8.......	61·2	63·3	63·3	68·2	67·7	69·3	70·3	69·8	69·0	71·3	71·3	70·5	71·2	71·2	70·5	72·5	75·7
July 9.......	26·0	26·0	28·2	29·2	31·5	32·0	31·3	31·7	33·0	35·8	36·5	37·3	38·8	41·0	42·7	43·7	44·0
July 12......	66·8	66·5	66·0	64·3	62·2	61·0	61·3	59·7	58·2	55·7	53·7	54·7	55·0	58·2	58·5	57·0	56·0
Mean	51·3	51·9	52·5	53·9	53·8	54·1	54·3	53·7	53·4	54·3	53·8	54·2	55·0	56·8	57·2	57·7	58·6
Mean in w. l.	1·026	1·038	1·050	1·078	1·076	1·082	1·086	1·074	1·068	1·086	1·076	1·084	1·100	1·136	1·144	1·154	1·172
	1·068	1·086	1·076	1·084	1·100	1·136	1·144	1·154	1·172								
Final mean.	1·047	1·062	1·063	1·081	1·088	1·109	1·115	1·114	1·120								

Fig. 3-10. Original 1887 MM data. Expected signal (dashed curve) **reduced** by a factor of 8.

sixth the earth's orbital velocity, and certainly less than one-fourth." It is remarkable that this very straightforward experiment, involving rather simple instrumentation and essentially no data analysis, opened a new era in physics.

Michelson and Morley pointed out at the end of their paper that they planned to repeat their observations at three month intervals to sample different relative velocities of the earth through space. They also mention the possibility that the ether may be carried along with the earth (ether drag). In a supplementary paragraph, they add that one might want to repeat the experiment at higher altitudes to reduce the effect of ether drag. In addition, they discuss the possibility of designing experiments to measure the speed of light with a precision sufficient to observe a direction-dependent variation. Interestingly, they further suggest a precision repetition of the Römer experiment (1676) which determined the speed of light (to within about 40%) by observation of the moons of Jupiter.



BUCKINGHAM HOTEL,
Fifth Avenue and 50th Street,

New York Aug 17 1887

My dear Lord Rayleigh

The experiments on "relative motion of earth and ether" have been completed and the result decidedly negative. The expected deviation of the interference fringes from the zero should have been .40 of a fringe – the maximum displacement was .02 and the average much less than .01 – and then not in the right place.

As displacement is proportional to squares of the relative velocities it follows that if the ether does slip past the earth ~~that~~ the relative velocity is less than one sixth of earth's velocity.

I enclose a poor photograph of the apparatus which consists of a stone five ft. square and one foot thick which floats on mercury and which holds the optical parts – Light from an argand lamp falls on a part going to acbcbcbaf. and part to dededeaf

I hope to be able to send you a copy of the paper written in a month.

With kind remembrances to Lady Rayleigh

Very sincerely yours
Albert A Michelson

Fig. 3-11. Michelson to Rayleigh – August 1887.

Michelson soon wrote to Lord Rayleigh from New York. **(Fig. 3-11)** Here is the text of his letter:

Aug 17 1887

My dear Lord Rayleigh

The experiments on "relative motion of earth and ether" have been completed and the result decidedly negative. The expected deviation of the interference fringes from the zero should have been 0.40 of a fringe – the maximum displacement was .02 and the average much less than .01 – and then not in the right place.

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I hope to be able to send you a copy of the paper within a month.

With kind remembrances to Lady Rayleigh.

Very sincerely yours
Albert A Michelson

While the results of the 1887 experiment appear to be convincing, this is far from the end of the story. Repetitions of the experiment, with various instrumental and analytical improvements, performed in Cleveland, on mountain-tops, and in laboratories in many countries, would continue for the next fifty years. We shall follow some of these efforts in Chapter 4 on Michelson's successor, Dayton Miller.

Michelson left the Case School two years later, in 1889, moving on to Clark University and thence to the new University of Chicago. He continued his work in applied optics until his death in 1931, including refinements of the velocity of light and ether-drift experiments, as well as standardizing the meter in terms of light waves and the first measurement of the diameter of a star. He received the Nobel Prize in 1907. The prize was awarded for his precision optical measurements of the standard meter and of spectroscopic wavelengths. There was no specific mention of his velocity of light work or of the ether-drift experiment. This was only two years after Einstein had explained the null result.

Fig. 3-12. Reines, Shankland and Michelson's daughter, Dorothy M. Livingston.

Fig. 3-12 is a photo taken on the occasion of the 1960 dedication at Case of a portrait of Michelson. Celebrating the event are Frederick Reines (chairman and Nobelist to be), Robert Shankland (chairman emeritus), and Michelson's daughter and biographer, Dorothy Michelson Livingston. (Her book, *Master of Light*, Scribner 1973, contains many interesting insights into the life of her famous father.)

Harry Fielding Reid - Geophysicist

After Michelson had gone, professor of mathematics, **Harry Fielding Reid**, was appointed professor of physics and took over as chairman of the CSAS physics department in 1889. **Fig. 3-13**. Reid had earned his doctorate in physics at Johns Hopkins in 1885 and had spent time at the Universities of Berlin and Cambridge. During his tenure

at Case, Professor Reid's principal research interest was glaciology. In 1890 he took four Case students with him to study the Muir Glacier in Alaska, incidentally taking the opportunity to name a mountain after Case (either Leonard or the school). Reid's work on glaciers is nicely summarized in the following excerpt from the website of the Milton S. Eisenhower Library at the Johns Hopkins University.
http://archives.mse.jhu.edu/mss/ms367.txt

Fig. 3-13. Henry F. Reid physics chair 1889-1893.

"Because of his proficiency in both physics and geology, Reid has been recognized as the first American geophysicist. His work in science fell into two main categories: the study of earthquakes and the study of glaciers. Reid's published writings between 1892 and 1907 deal exclusively with the subject of glaciers. His first glacial study was an extended survey of the Muir Glacier (Alaska) in 1890. With a team of five others, he mapped the glacier area of over 900 square miles. His research continued for several years, and his findings were published in a paper on the Glacier Bay area of Alaska in 1896. (16th Annual Report., U. S. Geological Survey). *He was interested in the problems of glacial accumulation, motion, and wastage."*

Reid left Case in 1893, eventually to become a world-renowned expert on earthquakes as Professor of Dynamic Geology at Johns Hopkins. Today, most of the internet references to Dr. Reid concern his analysis of the 1907 San Francisco earthquake in terms of "elastic rebound" and his model for slippage along tectonic plates. He was appointed in 1915 by President Wilson to study the possibility of landslides into the Panama Canal, and ways to prevent them. Reid died in 1944.