Re-examination of the 1887 Michelson–Morley experiment

M. A. Handschy
Department of Physics, University of Colorado, Boulder, Colorado 80309

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In 1887 Michelson and Morley presented the results of their now famous experiment that led them to conclude there was no significant relative motion between the earth and the ether. However, the data they published show large systematic trends. Michelson and Morley do not explain how they removed these trends in their analysis. The present work attempts to reconstruct this missing part of the analysis. In addition, modern statistical hypothesis testing and estimation methods are applied to the published data. This new analysis confirms the original null conclusion.

I. INTRODUCTION

The experimental tests of Einstein's special theory of relativity are given particular significance by the fundamental role the theory plays in modern physics. The Michelson–Morley ether drift experiments, which were completed before Einstein's theory was formulated, have historically been regarded as one of the most important of these tests. The close connection between the experiments and the special theory of relativity has led some scientists to believe that the experiments inspired Einstein to develop his theory, but this is most probably wrong.[1] Nevertheless, the experiments allow a sensitive discrimination between the Galilean relativity of the hypothesized luminiferous ether, and the constant speed of light required by special relativity. The experiment Michelson and Morley performed in 1887[2] indicated that the speed of light was constant for all directions in the horizontal plane of their laboratory, and led Michelson and Morley to conclude that there was no significant relative motion between the earth and the ether. Michelson and Morley estimated that their experiment was sensitive enough to detect velocities greater than about 1/6 the orbital velocity of the Earth around the sun. However, these conclusions were apparently drawn on the basis of rather qualitative criteria; statistics were not as standard a part of the scientist's repertoire in 1887 as they are now. Although the ether drift experiment has been repeated many times (subsequent trials are summarized by Shankland *et al.*[3]), the 1887 experiment is still of pivotal importance for many. In their introductory physics text, Sears, Zemansky, and Young state, "...to this day, the Michelson–Morley is the most significant 'negative result' experiment ever performed."[4] The modern scientist then needs to understand the analysis methods used by Michelson and Morley in order to accept their conclusions. Further, it is interesting to bring the methods of modern statistics to bear on the results of the Michelson–Morley experiment.

II. METHODOLOGY OF MICHELSON AND MORLEY

A reanalysis of the 1887 Michelson–Morley experiment is complicated by the fact that the published observations, reproduced here as Fig. 1, are by the authors own account not in "raw" form. On each of the six occasions recorded in Fig. 1, the authors recorded the fringe shift at 16 orientations of the interferometer for six complete revolutions. The mean of the six observations made at a given orientation on sequential revolutions, at noon on a given day, is recorded in the first three lines in Fig. 1, the means of the evening observations are recorded in the lower half of the same figure. Apparently, the unreduced record of the fringe positions, before averaging, has not survived.[5] The fourth line of each set is the average, column by column, of the three lines above it. The fifth line merely represents the conversion of micrometer readings into wavelengths. The sixth line is a repetition of the last half of the fifth line, and the seventh line is thus an average of the first and last halves of the fifth line. These final means are plotted in Fig. 2. If there were no ether drift, the fringe position should remain constant. A nonzero ether drift would produce a sinusoidal variation in fringe position, with two complete cycles in one rotation of the interferometer. As can be seen, there are nearly monotonic trends much larger than any evident periodic variations. Michelson and Morley present a similar plot, reproduced here as Fig. 3. However, the monotonic trends are mysteriously missing. No explanation of their removal is offered by the authors. Presumably, they subtracted off some linear estimate of drift. Similar drifts are found in the later collaboration of Morley and D. C. Miller. In Miller's account of this work,[6] in the section entitled "Reduction of the interferometer observations," p. 213, Miller detailed how they handled this drift:

> A compensation for the shift is made by adding to the sum of the seventeeth column such a number as will make it equal to the sum of the first column and by adding one-sixteenth, two-sixteenths, etc. of this compensating number of the second, third, etc. columns; this renders the axis of reference horizontal.

Perhaps this method was carried over by Morley from his original work with Michelson.

Applying this method to the lines labeled "final mean" produces the graph in Fig. 4, which can be compared to the points from Michelson and Morley's graph (Fig. 3) plotted in the same figure. The close correspondence argues that Michelson and Morley used some similar method. The variations around zero remaining in the plots of Fig. 4 could arise from a combination of random and ether drift effects. An ether drift would produce a sinusoidal variation in fringe shift, with one period in the length of the plot. The phase of this sinusoid depends on the direction of the ether drift, and hence is unknown. The peak variation is about 0.02 and 0.015 wavelengths for the noon and evening plots, respectively. Michelson and Morley stated, "It seems fair to conclude from the figure that if there is any displacement due to relative motion of the earth and the luminiferous

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. 1. The published observations of the 1887 Michelson–Morley experiment. This is a facsimile of the table in Ref. 2. The column headings denote the 16 different orientations of the interferometer at which the fringe shift was recorded. Each number in the first three lines of each set is an average of six observations taken during six revolutions of the apparatus.

ether, this cannot be much greater than 0.01 of the distance between fringes." Considering that these variations arise from a combination of random and systematic effects, the preceding statement seems plausible. Michelson and Morley give the expected fringe shift as $2Dv^2/c^2$; hence, with $D = 2\times 10^7$ wavelengths, the above quoted displacement of 0.01 fringes corresponds to an ether drift velocity of 4.7 km/s, or about 1/6 of the orbital velocity of the Earth.

III. MODERN REANALYSIS

Modern analysis methods provide a more quantitative evaluation of random and ether drift effects on the observations. The feature that identifies relative motion between the Earth and the ether is the observation of a fringe shift that varies with twice the frequency of the interferometer rotation. One way to separately examine variations of a given frequency is to calculate the frequency spectrum. This calculation is complicated by the presence of the monotonic trends mentioned earlier. These trends are presently removed by least-squares fitting a straight line to each of the three sets of observations taken at a given time of day, and then subtracting the appropriate amount from each term. A simple way to include all of the observations taken at the same time of day in a single calculation is to eliminate the 17th column of the observations of all three days, and then to concatenate the three sets. Assuming that the direction of the ether drift does not change significantly from 8 July to 12 July, this procedure gives a sequence of 48 elements, where the ether drift effect should produce six continuous cycles, since it goes through two cycles per rotation of the interferometer table. The succeeding computations are further simplified by subtracting the average of all 48 elements from each element of the sequence, to ensure that the mean of all the observations taken at the same time of

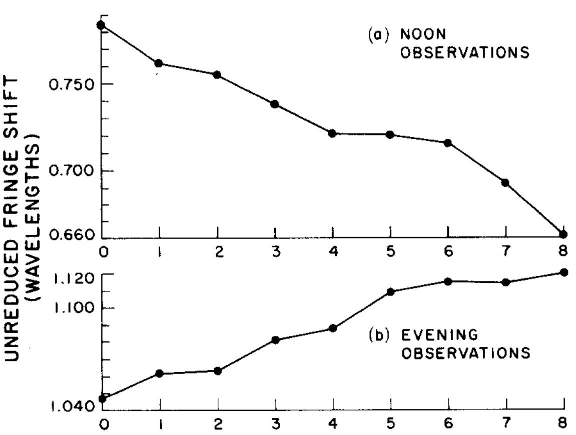

Fig. 2. A plot of the lines labeled "Final mean" in Fig. 1, showing large linear trends.

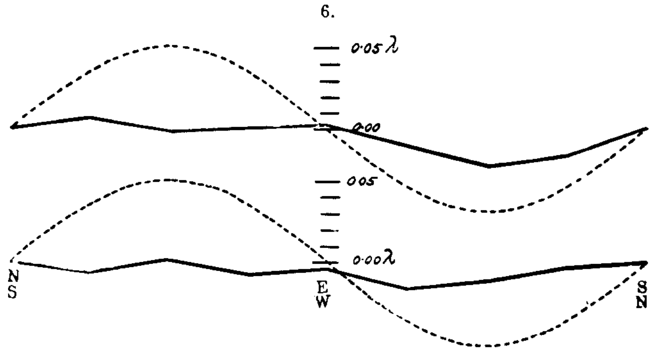

Fig. 3. Michelson's and Morley's graphical expression of their results with trends removed. This graph is a facsimile of Fig. 6 in Ref. 2.

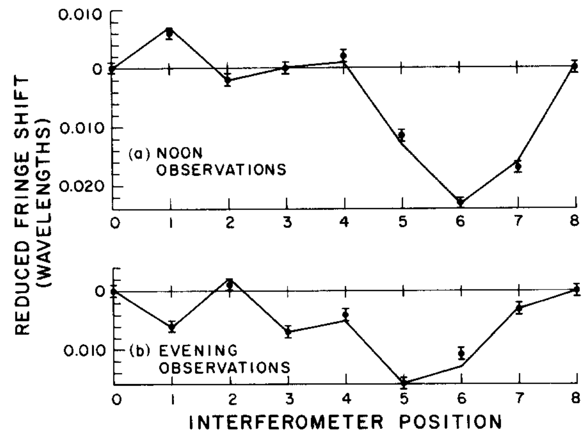

Fig. 4. Graph of the observations plotted in Fig. 2, with the trends removed by the prescription of Miller.[6] Also plotted for comparison are points measured from Michelson's and Morley's graph (Fig. 3). The magnitude of the error bars shown corresponds to the width of the bold line in Fig. 3.

day is zero. From this sequence, the sine and cosine frequency spectra were calculated by an algorithim similar to that of Ralston and Wilf.[7] The magnitudes are computed by taking the square root of the sum of the squared sine and cosine amplitudes, for a given harmonic, and plotted in Fig. 5. If there were any ether drift effect in the observations, one would expect a relative maximum in the spectra at the sixth harmonic. The adjacent fourth, fifth, seventh, and eighth harmonics represents variations in the observations that are not commensurate in frequency with the table rotation; hence, they are probably due to random variations. The fact that the six harmonic is smaller in magnitude than random variations of nearly the same frequency indicates there is no significant ether drift velocity.

This inference can be demonstrated more conclusively by the methods of statistics. The problem of detecting an ether drift in the observations of Michelson and Morley is very similar to a class of problems in signal detection theory. The present development will largely follow Whalen.[8] The typical method of statistical decision making is hypothesis testing. Here we wish to decide between the null hypothesis that the ether is stationary relative to the earth, and the alternate hypothesis that there is relative motion. The methods of statistics prescribe that this is done by comparing the probabilities of obtaining the observed results under the two hypotheses. To calculate the relevant probabilities, assume that after the trends are removed as detailed above, under the null hypothesis all the observations taken at the same time of day are independent and normally distributed, with zero mean and unknown variance, σ.[2] The effect of an ether drift is to add a sinusoidal "signal" of random phase at twice the frequency of the table rotation. The amplitude of the signal is given by $A = 4\times 10^7 v^2/c^2$, from the sensitivity quoted by Michelson and Morley. Thus, under the alternate hypothesis, the observations are assumed to have the distribution of the sum of a sine wave of random phase and white Gaussian noise. Under these circumstances, an appropriate statistic is

$$\eta^2 = \left(\frac{q^2}{N}\right) \Bigg/ \left(\sum_{i=1}^{N} r_i^2/(N-8)\right),$$

as shown by Kendall and Stuart.[9] The variable q^2 is defined as

$$q^2 = \left[\sum_{i=1}^{N} r_i \sin\left(\frac{12\pi i}{N}\right)\right]^2 + \left[\sum_{i=1}^{N} r_i \cos\left(\frac{12\pi i}{N}\right)\right]^2,$$

where r_i denotes, for instance, the elements of the noon observation set, and i runs from 1 to $N = 48$. q^2 is a measure of the component of the observations that has a frequency of two cycles per interferometer table rotation. Under the null hypothesis, $2q^2/N\sigma^2$ has the chi-square distribution, with two degrees of freedom, and

$$\sum_{i=1}^{N} r_i^2/\sigma^2$$

has the chi-square distribution with N–8 degrees of freedom. Thus η^2 has the F distribution, with 2 and 40 degrees of freedom. The critical values of the F test are tabulated by Abramowitz and Stegun.[10] For the noon observations, η^2 has the value of 0.84, and for the evening observations, 1.15 Even when the significance level (probability of incorrectly accepting the alternate hypothesis) is allowed to rise as high as 25%, η^2 would have to be greater than 1.42 in order to reject the null hypothesis and conclude that the ether drift velocity was nonzero. The power of this test can be calculated, assuming that σ^2 has the value of the average of its noon and evening maximum likelihood estimates calculated below, by numerically integrating the appropriate probability density functions given by Whalen.[8] In Fig. 6, the probability of detecting an ether drift (the power) is plotted against the hypothetical ether velocity, for two significance levels, 5% and 25%. The 25% significant test has a probability of 65% of detecting an ether drift velocity of 1/6 the orbital velocity of the Earth (5 km/s). Both the 25% and 5% tests have nearly unit power at 10 km/s (1/3 the Earth's orbital velocity). Thus a sensitive and powerful sta-

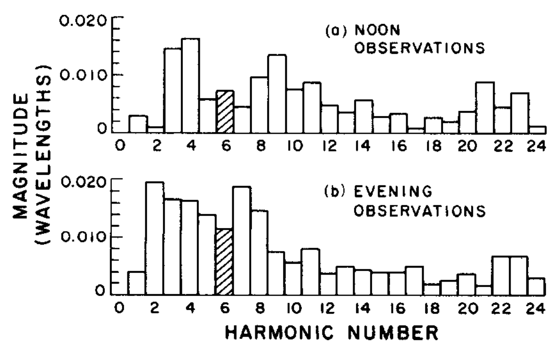

Fig. 5. Frequency spectrum of noon and evening observations. The magnitudes are the square root of the sum of the squared sine and cosine amplitudes.

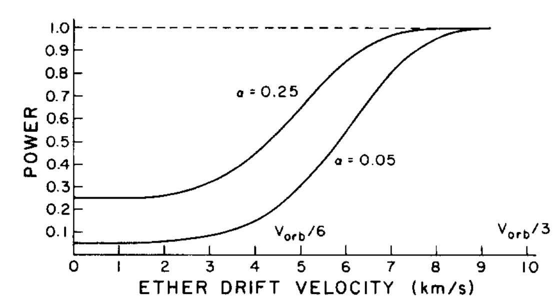

Fig. 6. Power of F test for two significance levels, $\alpha = 0.05$ and $\alpha = 0.25$, versus hypothetical ether drift velocity.

tistical test decides in favor of the null hypothesis: the ether drift velocity is zero.

Another statistical technique that can be used to interpret the results of the ether drift experiment is that of estimation. For instance, what value of the ether drift velocity would be most likely to produce the observed results? This may be calculated by simultaneously maximizing the likelihood ratio, given by Whalen,[8] $\rho = \exp(-A^2N/4\sigma^2)I_0 \times (Aq/\sigma^2)$, with respect to A and σ^2 (I_0 is the zeroth order modified Bessel function of the first kind). This "maximum likelihood" estimate gives an ether drift velocity of 1.5 km/s for the noon observations, and 4.2 km/s for the evening observations. The estimates of σ^2 correspond to velocities of 7.5 km/s for the noon observations and 8.6 km/s for the evening observations. 1.5 and 4.2 km/s are, respectively, about 20 and 7 times smaller than the orbital velocity of the earth. The velocity estimated at noon is smaller than Michelson's and Morley's upper bound by a factor of about four, while the evening estimate is roughly comparable. These values disagree with the 8.8- and 8.0-km/s velocities that Miller claims to have determined from his reanalysis of the 1887 data.[6]

IV. DISCUSSION

The modern approaches discussed above yield the emphatic conclusion: the 1887 observations of Michelson and Morley are not consistent with an ether drift velocity significantly different from zero. This confirms the conclusion drawn by Michelson and Morley, and refutes the one drawn by Miller about their observations. The conclusion drawn by Michelson and Morley has been accepted by most physicists. Miller's conclusions about his own ether drift experiments, namely that there was significant relative motion between the earth and the ether have met with a very different reception. Miller's results were carefully scrutinized by R. S. Shankland *et al.*,[3] who concluded that the apparent either drift velocity was in fact a spurious result of temperature gradients across the interferometer. It is Shankland's appraisal that is most widely accepted. Although the Michelson–Morley experiment has been reviewed,[11,12] neither reviewer mentioned the incompletely detailed data reduction. This is a contrast to the criticism earned by the meticulously described results of Miller, which encourages the speculation that observations supporting a well accepted theory received much less scrutiny than those that do not, regardless of their true individual merits.

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Fourier transforms and the use of a microcomputer in the advanced undergraduate laboratory

D. R. Matthys and F. L. Pedrotti
Marquette University, Milwaukee, Wisconsin 53233

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An experiment using a standard Michelson interferometer and a microcomputer to produce and display Fourier transform spectrograms in the advanced undergraduate laboratory is described. Fourier transforms of laser and mercury light sources, as well as simulated data from a function generator, are presented and discussed. The computer program used is designed to be highly interactive and to allow the student a wide range of performance options.

INTRODUCTION

Fourier transform spectrometry represents an elegant alternative to traditional methods of spectrum analysis. The special advantages of this technique have led to widespread applications in research and industry. Both its current relevance and the necessary use of a computer in data manipulation make it an attractive experiment for the advanced undergraduate laboratory.

Several papers have appeared[1–5] in this journal elaborating various theoretical and experimental aspects of such an experiment. This paper describes the incorporation of