Michelson-Morley Experiments Revisited:

Systematic Errors, Consistency Among Different Experiments, and Compatibility with Absolute Space

Héctor A. Múnera

Centro Internacional de Física
A.A. 251955, Bogotá D.C., Colombia

Despite the null interpretation of their experiment by Michelson and Morley, it is quantitatively shown that the outcomes of the original experiment, and all subsequent repetitions, never were null. Additionally, due to an incorrect inter-session averaging, the non-null results are even larger than reported. Contrary to the received view, Illingworth's and other repetitions of the experiment were consistent with Miller's positive results. On the theoretical side, a new systematic error is uncovered: the angle between the projection of earth's velocity on the plane of the interferometer and the reference arm of the apparatus has been practically ignored. This phase angle produces a noticeable change in the position of the peaks from one turn to the next of the interferometer. Hence, the data analysis cannot be based on the average of fringe shifts during a session, but rather on the calculation of individual speed for each turn. This procedure was applied to the only two sessions reported in detail in the literature: Miller's September 23, 1925 at 03:02 in Mount Wilson and Illingworth's July 9, 1927 at 11:00 in Pasadena. Surprisingly, it was found that in both cases the measured speeds exactly correspond to the projection of earth's orbital velocity only. As a result, the evidence against a preferred frame completely disappears.

1. Introduction

To the best of our knowledge, the only empirical evidence against the existence of absolute space (= ether in this paper) is the null interpretation given to the interferometry experiment carried out by Michelson in 1881[1], repeated with experimental and theoretical improvements by Michelson and Morley (M-M) in 1887 [2]. A hundred and ten years later, there is still controversy: some people argue that results were non-null and try to derive implications thereof [3], while others strongly maintain that results were null, and dismiss evidence to the contrary as experimental artifact [4].

To avoid second-hand interpretations, we revisited the original literature on M-M. It was found that a systematic application of standard statistical tests to the values originally reported does not support the null interpretation. Furthermore, two systematic errors were identified, one of them new to the best of our knowledge. Systematic error 1 (SE1) pertains to data reduction, while systematic error 2 (SE2) belongs to the theory. After removing SE1, speeds become larger than reported, hence closer to Miller's results. The SE2 implies that fringe-shifts during an experimental session present strong variations due to changes in magnitude and direction of the projection of velocity on the plane of the interferometer.

Section 2 begins with a brief summary of the theory behind the experiment, leading to identification of SE1 and SE2. It continues with a critical review of the class of M-M experiments to show that (1) all experiments were qualitatively compatible with absolute space, and (2) the results never were null, neither in the original version [2] nor in the subsequent repetitions [5-15]. Section 3 contains our contribution to the controversy. Section 4 closes the paper.

2. M-M Experiments Critically Revisited

Attention is restricted to experiments using local light sources, as the original M-M experiment [2], Morley and Miller's repetitions [5], Miller's work alone [6-8], the experiments of Piccard and Stahel [9-11], the refinement of Kennedy [8,12] and Illingworth [13], the repetitions of Michelson et al. [14], up to Joos [15]. As explained long ago by Robertson [16], Kennedy and Thorndike [17] started a new class of experiments.

Initial criticisms to M-M results addressed the design and operation of the interferometer [23-27], leading to improvements in subsequent repetitions of the experiment [5-15]. However, there is still a systematic error (SE1), discovered a century ago by Hicks [23]: the inter-session averaging includes curves from two different calibration families.

2.1. Summary theory of experiments

Let M-M experiment be carried out in right-handed horizon coordinates $S(\phi)$, located at latitude ϕ on the earth, with X-axis oriented towards local east, Y-axis towards local geographical north, and Z-axis along the earth's radius. For an observer at rest in a preferred frame Σ attached to absolute space, the time for light to travel length L of the reference arm (RA) depends on ω, the angle between the direction of RA and $\mathbf{V}_I$. Velocity $\mathbf{V}_I$ is the projection onto the plane of the interferometer of $\mathbf{V}$, the velocity of earth in Σ, given by $\mathbf{V} = \mathbf{V}_s + \mathbf{V}_o + \mathbf{V}_r$. Let ΔT be the difference in the time-of-travel over the closed paths along the two perpendicular arms of the apparatus, given by

$$\Delta T = (L/c)\beta^2 \cos 2(\Delta\omega) = A \cos 2(\Delta\omega - \omega_N) \qquad (1)$$

where $\beta = V_I/c$, $\Delta\omega$ is the angular position of RA relative to the Y-axis, and $\omega_N(\alpha,\delta,\phi)$ is the counterclockwise angle from the Y-axis to $\mathbf{V}_I$.

Since M-M could not measure ΔT, they resorted to measuring the shift of interference patterns. Following Hicks [23], let the displacement of the central interference band from a reference point P_0 be

$$z \approx (\beta^2 \cos 2\Delta\omega) / (2\Delta\theta - \beta^2 \cos 2\Delta\omega) \qquad (2)$$

The small angle $\Delta\theta \approx \pm 10^{-5}$ radians is a deviation from ideal mirror orientation. For $\beta^2 < \Delta\theta$, the denominator is controlled by $\Delta\theta$:

$$z \approx K\beta^2 \cos 2\Delta\omega = \pm |K|\beta^2 \cos 2(\Delta\omega - \omega_N) \qquad (3)$$

The sign of $K = P_0/2\Delta\theta$ depends on the sign of $\Delta\theta$. Hence, for a given velocity, z may be positive or negative, leading to two families of displacements z^+ and z^-.

The existence of the two families $z^\pm$ is the origin of systematic error 1 (SE1) in data reduction, recurrent in all experiments from M-M to Illingworth [13], with the notable exception of Miller's work [7]. In Hicks's words:

> *"the adjustment of the mirrors can easily change from one type to the other on consecutive days. It follows that averaging the results of different days in the usual manner is not allowable unless the types are all the same. If this is not attended to, the average displacement may be expected to come out zero" [23, page 34].*

In practice, the initial calibration focuses the interferometer to observe a displacement at $\Delta\omega = 0$:

$$Z_0^{\pm} = \pm A \cos^2(\omega_N) \qquad (4)$$

where $A = |K|\beta^2$. For other positions, the relative fringe-shift is:

$$\Delta Z(\Delta\omega) = z - Z_0^{\pm} = \pm A\{\cos 2(\Delta\omega - \omega_N) - \cos 2\omega_N\} \qquad (5)$$

Then, eq. (5) shows that a rotation of RA through $\pi/2$ produces a shift:

$$D = Z^{\pm}(\Delta\omega = \pi/2) = -/+2A \cos 2\omega_N \neq 2Z_0 \qquad (6)$$

Note that, contrary to M-M expectations, $|D| < 2A$, except for $\omega_N = 0$. Although M-M were aware of diurnal variations of ω_N, they chose to ignore them. This is the origin of systematic error 2 (SE2).

Illingworth [13] did not measure the entire curve. Rather he estimated D directly from 90°-rotations from two initial positions: (A) RA towards north, then

$$D_A = 2A \cos 2\omega_N \qquad (7a)$$

(B) RA towards north-east, then

$$D_B = 2A \sin 2\omega_N \qquad (7b)$$

Thus, contrary to conventional belief, the results from Illingworth experiment [13] cannot be directly compared to those based on $D_0 = 2A$. From the empirical D, V is obtained as:

$$V = V_o |D|/D_R = C |D| \qquad (8)$$

where $C = V_o D_R^{1/2}$. In the original experiment, M-M used orbital speed $V_o = 29.8$ km/s to calculate a reference fringe displacement $D_R = \pm 2L\beta_o^2/\lambda = \pm 0.4$ wavelength. Summarizing the previous discussion:

$$V_0 = V_I \text{ for } D = D_0 \qquad (9a)$$

$$V_A = V_I |\cos 2\omega_N| \text{ for } D = D_A \qquad (9b)$$

$$V_B = V_I |\sin 2\omega_N| \text{ for } D = D_B \qquad (9c)$$

2.2. Michelson-Morley expectations

M-M expected that V_I would be approximately parallel to RA at the beginning of an experimental session, and that it would stay approximately constant throughout. In particular, they expected $V_I \approx V_o \approx 30$ km/s. However, M-M's expectations were unwarranted.

Let the center of earth move with constant angular speed ω_o = 360°/365.2422 days on a circular trajectory on the plane of the ecliptic, and let time t be measured at the observer's meridian from midday March 21. Let $\varepsilon = 23.45°$ be the obliquity of the ecliptic. Then, the projection of V_o along the X-, Y- and Z-axes are V_E, V_N and V_P respectively:

$$V_E/V_o = f_E(t) \qquad (10a)$$

$$V_N/V_o = f_N(t,\phi) \qquad (10b)$$

$$V_P/V_o = f_P(t,\phi) \qquad (10c)$$

Therefrom, V_I and ω_N immediately follow. Contrary to M-M's expectations, there may exist strong variations during a single session. Several remarks arise:

Remark A. The magnitude of V_I and the position of the peak is not the same from one turn of the interferometer to the next within a session, much less from session to session.

Remark B. Results from different sessions, even in the same day cannot be averaged. The average of readings at a given $\Delta\omega$ necessarily is smaller than the maximum reading.

Remark C. Magnitude of V_I drifts during a given session, leading to a hitherto unrecognized component of total drift.

Remark D. Experiments carried out at different latitudes and times do not necessarily produce the same results.

Remark E. In general, the daily variation of V_I does not have a sinusoidal shape.

2.3 Summary review of all M-M experiments

Original Michelson-Morley experiment. M-M obtained their noon and afternoon curves via an incorrect inter-session average noted by Hicks [23]. M-M concluded that "*the relative velocity of the earth and the ether is probably less than one sixth the earth's orbital velocity, and certainly less than one fourth*" [2]. Assuming that they measured the amplitude, then 5 km/s $\approx V_I <$ 7.5 km/s. *Despite the incorrect averaging procedure, this is a non-zero result.*

Miller measured the amplitude of M-M curves with his mechanical harmonic analyser to obtain "a velocity of 8.8 km/s for the noon observations, and 8.0 km/s for the evening observations" [7]. Elimination of the cancelling error (SE1) leads to speeds higher than those obtained by M-M.

Miller experiments. He carried out a life-long series of experiments at Cleveland and Mt. Wilson [6-8]. Table 1 shows his measurements at different epochs. The probable error for these measurements is ±0.33 km/s [7, page 238].

Table 1. Miller measurements at Mt. Wilson (95% C.L.)

Date	V_I, km/s	Lower	Upper
April 01/25	10.1	9.1	11.1
Aug. 01/25	11.2	10.2	12.2
Sept. 15/25	9.6	8.6	10.6
Feb. 08/26	9.3	8.3	10.3

Piccard and Stahel's experiments. From 96 turns of an interferometer in a balloon over Belgium they obtained a speed of 6.9 km/s with a probable error of 7 km/s. Piccard and Stahel result is completely consistent with those of Miller.

Kennedy's experiment. Kennedy developed an accurate small apparatus with temperature control [12]. He carried out measurements at Pasadena and reports that "*there was no sign of a shift depending of the orientation.*" To our knowledge, this is the only experiment that ever reported a null result.

Illingworth experiment. Illingworth did not measure the whole ΔZ vs. $\Delta\omega$ curve, but estimated the average displacement by D = ky, where y is the statistic:

$$y = (x_E + x_W)/2 - (x_N + x_S + x_N)/3 \qquad (11)$$

3. Reinterpretation of some experiments

3.1. Inter-session averages

Illingworth's paper. The correct method is to use |y|, and always report a positive V. We have applied this correction to Illingworth's Table III. Results are in Table 3, where the calculated velocity is either V_A or V_B, not V_I.

Velocities are now clustered in the range [1.4, 2.2] km/s, and not around zero, thus vindicating Hicks [23] prediction.

Table 3. Inter-session averages based on $|y_n|$

Session	1A	1B	2A	2B	3A	3B	4A	4B
$<|y_n|>$	0.187	0.120	0.122	0.115	0.185	0.143	0.198	0.085
V_A,V_B	2.16	1.74	1.75	1.70	2.15	1.89	2.23	1.46
Upper 95%	3.24	2.55	2.26	2.06	2.87	2.39	3.31	1.85
Lower 95%	0	0	1.00	1.24	1.02	1.21	0	0.92

3.2 Intra-session averages

Table 4 shows the values of y_j for each individual turn j in session 2A of July 9, 1927. The sign changes several times. Illingworth's average $<y_j> = -0.03$ is quite different from the correct average $<|y_j|> = 0.47$.

Miller's paper. We calculated Miller's velocity for his session of September 23, 1925 at 03:02 using Illingworth's procedure. There were 20 turns in the session (see Table 4).

Table 4. Intra-session variability of velocity

Turn	Miller y_j	$|y_j|$	V_A	Illing. y_j	$|y_j|$	V_A
1	-1.17	1.17	9.62	-0.50	0.50	3.54
2	-0.83	0.83	8.13	+0.33	0.33	2.89
3	-0.83	0.83	8.13	-0.33	0.33	2.89
4	-0.33	0.33	5.14	-0.33	0.33	2.89
5	-3.00	3.00	15.42	-0.83	0.83	4.57
...	...	...	...	...	...	...
Avg	-0.72	0.96	8.22	-0.03	0.47	3.13
U.B.	1.17	1.29	9.61	0.45	0.71	4.17
L.B.	0.28	0.63	6.83	0	0.23	2.09

The average velocity based on |y| and V_A are 8.72 and 8.22 km/s. These values must be compared to V_A from eqs. (9b) and (10) which varied from 8.00 to 11.88 km/s during the observation period. *Miller's observations coincide with the projection of orbital speed.*

4. Concluding remarks

In this note we analysed each one of the individual papers in the class of M-M experiments to find that all observed a non-zero velocity, but—with the notable exception of Miller—also all interpreted their results as zero. The qualitative shape of the curves produced by rotation of the interferometer exhibits the theoretical 2ω-dependence (with amplitude smaller than expected).

On the quantitative side, the overall conclusion is that the speed was always different from zero. The inter-session averages were consistently lower than expected from orbital motion alone. However, the difference is not tens to hundreds of times lower as suggested in the literature, but somewhere from 2 to 10.

For the only two sessions wholly reported in the literature (Table 4), the calculation based on the individual rotations completely agrees with our predictions (eq. 10) based on earth's orbital motion.

It would be an extraordinary coincidence if the only two complete sessions reported by different experimenters (Miller and Illingworth) constitute an experimental artifact. The standard procedure of averaging simply averages away the observation sought after. This result was foreseen by Hicks [23] a century ago.

From a Popperian view-point [32], a single experiment suffices to demonstrate that absolute space does not exist. Hence, the emphasis in this paper is on demonstrating that the results from M-M experiments are consistent with absolute space.

Acknowledgements

We thank O. Guzman of the Physics Department, National University, Bogotá, for several interesting discussions, and for his translation of Joos' paper.

References

[1] Michelson, A.A.: *Amer. J. Sci.* S. 3 vol. 22 (1881) 120-129.
[2] Michelson, A.A. and Morley, E.W.: *Philos. Mag.* S. 5, vol. 24 (1887) 449-463.
[3] Vigier, J.P.: *Apeiron* 4 (1997) 71-76.
[4] Wesley, J.P.: *Apeiron* 4, No. 2 (1997) 133.
[5] Morley, E.W. and Miller, D.C.: *Philos. Mag.* S. 6, vol. 8 (1904) 753-754.
[6] Miller, D.C.: *Proc. Nat. Acad. Sci.* 11 (1925) 306-314.
[7] Miller, D.C.: *Rev. Mod. Phys.* 5 (1933) 203-242.
[8] Michelson, A.A.: *Astrophys. J.* 68, No. 5 (1928) 342-345.
[9] Piccard, A. and Stahel, E.: *Compt. rend.* 183 (1926) 420-421.
[10] Piccard, A. and Stahel, E.: *Compt. rend.* 184 (1927) 152.
[11] Piccard, A. and Stahel, E.: *Compt. rend.* 185 (1927) 1198-1200.
[12] Kennedy, R.J.: *Proc. Nat. Acad. Sci.* 12 (1926) 621-629.
[13] Illingworth, K.K.: *Phys. Rev.* 30 (1927) 692-696.
[14] Michelson, A.A. et al.: *Nature* 123 (1929) 88.
[15] Joos, G.: *Ann. der Physik* S. 5, vol 7 (1930) 385-407.
[16] Robertson, H.P.: *Rev. Mod. Phys.* 21 (1949) 378-382.
[17] Kennedy, R.J. and Thorndike, E.M.: *Phys. Rev.* 42 (1932) 400-418.
[18] Cedarholm, J.P. et al.: *Phys. Rev. Lett.* 1 (1958) 342-343.
[19] Cedarholm, J.P. and Townes, C.H.: *Nature* 184 (1959) 1350-1351.
[20] Turner, K.C. and Hill, H.A.: *Phys. Rev.* 134 (1964) B252-B256.
[21] Jaseja, T.S. et al.: *Phys. Rev.* 133 (1964) A1221-A1225.
[22] Brillet A. and Hall, J.L.: *Phys. Rev. Lett.* 42 (1979) 549-552.
[23] Hicks, W.M.: *Philos. Mag.* S. 6, vol. 3 (1902) 9-42.
[24] Sutherland, W.: *Philos. Mag.* S. 5, vol. 45 (1898) 23-31.
[25] Sutherland, W.: *Nature* 63 (1900) 205.
[26] Righi, A.: *Compt. Rend.* 168 (1919) 837-842.
[27] Kohl, E.: *Ann. der Physik* S. 4, vol 28 (1909) 259-307.
[28] Shankland, R.S. et al.: *Rev. Mod. Phys.* 27 (1955) 167-178.
[29] ISO: ISO Standards Handbook 3, Genève (1981).
[30] Brylinski, E.: *Compt. Rend.* 184 (1927) 192-193.
[31] Piccard, A. and Stahel, E.: *Compt. rend.* 184 (1927) 451-452.
[32] Popper, K.R.: The Logic of Scientific Discovery, Hutchinson (1959).