Re-examination of the Experimental Evidence for a Nonzero Aether Drift

Part 1: Michelson-Morley-type experiments 1881-1930

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ABSTRACT

This is the first of a three-part review of aether-drift and light Doppler experiments conducted from the early 1880s to the present day. Part 1 examines the controversy surrounding contradictory interpretations of Michelson-Morley-type experiments. In particular, it re-analyzes the 1887 Michelson-Morley experiment and selected experiments by Miller. It concludes that none of the Michelson-Morley-type experiments conducted from 1881 to 1930 detected a significant aether drift.

1. THE MICHELSON-MORLEY (MM) EXPERIMENT

In the latter part of the 19th century it became widely believed that light consisted of wave motion in a “luminiferous aether” that filled all space. This led to the hypothesis that, if the aether is stationary, the earth’s motion through it should generate an appreciable “aether wind”, which would cause light to travel slightly more slowly in the direction of the earth’s motion than at right

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angles to it. The first experiments to test this hypothesis were conducted by Albert Michelson in 1881 (Michelson, 1881) and by Michelson and Edward Morley in 1887 (Michelson & Morley, 1887). The aim was to compare the round-trip speed of two light beams traveling along the two perpendicular arms of an interferometer. It was therefore a second-order experiment, i.e. one in which the possible travel-time difference in the two light paths is proportional to $(v/c)^2$.

The 1881 experiment involved measuring the extent to which the interference pattern produced by the two light rays shifted when the interferometer was rotated through 90° (see Fig. 1A). The interferometer had a total light path of 2x1.2 m and was extremely sensitive to vibrations. Michelson (1881) reported a fringe shift of 0.004 to 0.015 of a fringe width, whereas the earth's orbital velocity of some 30 km/s was expected to produce a fringe shift of 0.04 [1]. He attributed the observed displacement to "the errors of experiment", and concluded that the experiment falsified the hypothesis of a stationary aether. This is only true if it is assumed that no instrument or measurement artifact and no physical process (e.g. aether drag or length contraction) decreased the expected value or its detection.

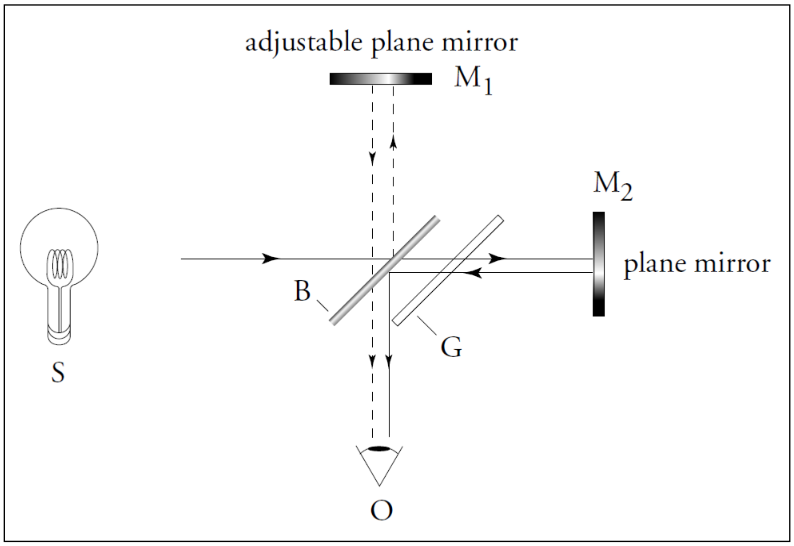

Figure 1A Michelson interferometer used for the 1881 experiment in Berlin. *S*, light source; *B*, semitransparent mirror (beam splitter); M_1 and M_2, plane mirrors; *G*, glass compensating plate; *O*, observer.

The 1887 experiment was carried out at the Adelbert College of Western Reserve University in Cleveland. The observations reported by MM lasted 6 hours: one hour at noon on July 8, 9, and 11, and one hour on the evening of July 8, 9, and 12. They involved 36 turns of the interferometer, readings being made at 16 equidistant points in each turn. The total light path was extended to 2x11 m so that the expected fringe shift was 0.4 of the fringe width. As far as the resolution of their experiments was concerned, Michelson & Morley (1886) indicated that, for a 10 m light path, the intrinsic error of measurement was probably between 0.004 and 0.02 of a fringe width. They concluded (p. 341): "The actual displacement was certainly less than the

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[1] The formula is: fringe shift = (total light path divided by wavelength) * (v^2/c^2). Michelson & Morley used yellow light (wavelength = 5.7×10^{-7} m) in their experiments.

twentieth part of this [i.e. <0.02], and probably less than the fortieth part [i.e. <0.01]. But since the displacement is proportional to the square of the velocity, the relative velocity of the earth and the ether would have to be probably less than one-sixth of the earth's orbital velocity [i.e. <5 km/s], and certainly less than one-fourth [i.e. <7.5 km/s]." This means that if there were an attenuated aether wind of less than 7.5 km/s, the 1887 MM experiment would not have been able to detect it as it would not be distinguishable from a zero or near-zero result. So the observed fringe shifts in the 1887 experiment were, at best, of borderline significance. The result of these experiments was not "null" in the sense of zero (since zero could not be resolved), but null in the sense that it falsified the hypothesis of a 30 km/s aether drift. But the experiment left open the possibility of an aether wind of up to 7.5 km/s, attenuated by aether drag.

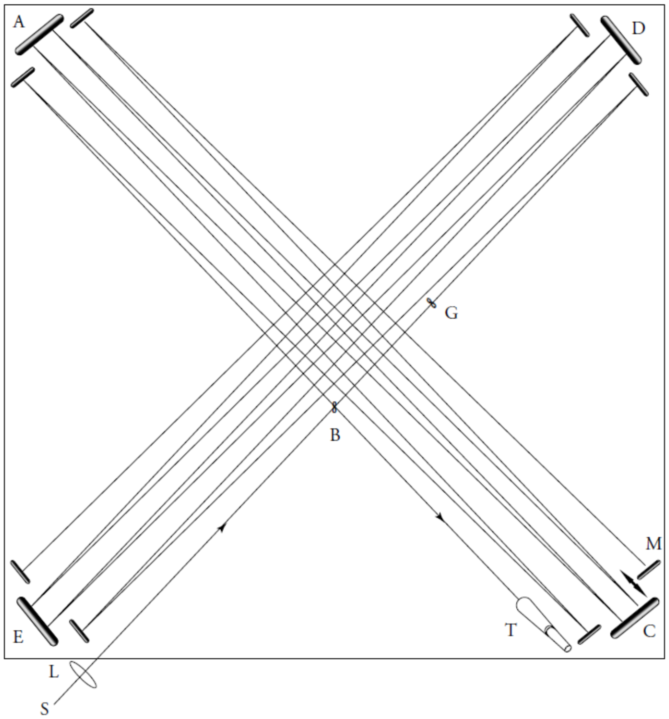

Figure 1B Interferometer used in the 1887 Michelson-Morley experiment. *S*, light source; *L*, collimating lens; *B*, beam splitter; *G*, glass compensating plate; *M*, adjustable mirror; *T*, telescope. Plane mirrors at points *A*, *C*, *D*, and *E* fold the light path so that the total length in each arm is 11 m.

In the 1881 experiment, Michelson (1881, p. 124-5) based his estimate of the fringe shift on the earth's orbital velocity around the sun and the solar system's estimated velocity towards the constellation Hercules. In the 1887 MM experiment, only the earth's orbital motion was taken into account, but the authors noted (Michelson & Morley, 1887, p. 341): "If this is combined with the motion of the solar system, concerning which but little is known with certainty, the result would have to be modified; and it is just possible that the resultant velocity at the time of the observations was small though the chances are much against it. The experiment will therefore be repeated at intervals of three months, and thus all uncertainty will be avoided." This intention was never carried out. Presumably they did not feel the need to do so since, according to Jaffe, they had made “thousands of observations” at noon and 18:00, for 16 directions, from April up until July (Jaffe, 1960, p. 87) but failed to observe any trend in the data that justified such a systematic approach with the means at their disposal.

On the assumption that the original MM experiment gave a valid null result, G.F. Fitzgerald and H.A. Lorentz (Lorentz, 1909) tried to salvage the notion of a stationary aether by “inventing” the *ad hoc* concept of length contraction: motion through the aether caused the experimental apparatus to contract in the direction of the earth’s motion by just the right amount to prevent detection of the stationary aether. Length contraction has never received direct experimental verification. The conventional interpretation of the 1938 Ives & Stilwell experiment on the transverse Doppler shift is that it provides indirect evidence for time dilation as the correlate of length contraction (Ives & Stilwell, 1938). However, an alternative model (Aetherometry) has been proposed that more closely matches the results of this experiment and does not invoke time dilation or length contraction. It proposes a theory of photon emission and of the Doppler effect of light that is based solely on a consistent application of the law of geometric-mean composition of velocities of source and receiver (Correa & Correa, 2008; Correa et al., 2008).

Widespread acceptance of the Lorentz transformations (length contraction in the direction of motion, and time dilation) is largely due to Einstein’s Special Relativity (SR) theory. SR assumed that the 1887 MM experiment failed to detect any aether drift, and insisted that the speed of light in a vacuum is a constant for every inertial frame of reference, i.e. is the same in all directions and for all nonaccelerated observers, and is independent of the motions of the light source and the receiver. Einstein (1956, p. 65) comments that “Michelson and Morley’s system of mirrors is not contracted with respect to a reference system that moves with the earth, but with respect to a reference system that is at rest with respect to the sun”. In our view, in order to predict a null result from the MM experiment, it would have sufficed to assume that light is referenced to the inertial frame of its emitter and shares its state(s) of motion, and that when emitter, mirrors (transmitters) and receiver all share the same state of motion, light speed will remain invariant.

Michelson himself favored George Stokes’s hypothesis that the earth might drag a portion of the otherwise stationary aether along with it as it orbits the sun. If the entrainment of the aether were less than perfect, this could account for all or part of the small residuals found in the MM experiment. However, Michelson & Morley (1886) had earlier concluded that if Fizeau’s explanation of stellar aberration in terms of a stationary aether is essentially correct, then “the luminiferous aether is entirely unaffected by the motion of the matter which it permeates”.

2. ANALYSIS OF THE MM EXPERIMENT

Múnera (1998) has argued that Michelson & Morley committed two systematic errors that were subsequently repeated by many experimenters. The first was inter-session averaging: in the 1887 MM experiment two series of readings (noon and pm) were taken on three separate days (three sessions); the results from the noon sessions and the pm sessions were then averaged.

A potential problem with this was that there could be two different types (z^+ and z^-) of curves or fringe-shift families for each time group [2]. Hicks (1902, p. 34) drew attention to this potential error, which would be demonstrable in principle by the existence of different families of calibration curves [3]: "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 – at least if a large number are averaged." Múnera says that this error recurred in all experiments from MM to Illingworth (1927), with the notable exception of Miller (1933).

We have statistically treated the MM 1887 data for both the noon and the 18:00 sessions of three separate days. Michelson & Morley processed the data for each time of day by first amalgamating them into a single series of the means of the three "raw" series obtained for that time of day and then averaging these means for the 1st and 2nd half-turns of the interferometer. We, on the other hand, applied a treatment similar to that employed by Miller (1933): first we formed either a single amalgamated series as MM did, or amalgamated only data that belonged to the same type of curve (see below); then we corrected for noise drift (i.e. determined and deducted the range of drift based on the difference – in the amalgamated data – between the first turn and its repetition as the last turn of the series); then we normalized the corrected data by subtracting their overall mean value from each data item; finally, we averaged these "denoised" and normalized means for the 1st and 2nd half-turns (a step we will refer to as "folding"). Note that although normalization brings the mean of the full data set to 0, the mean of the final "folded" data is no longer 0. This is due to the fact that during the folding, the data item at position 8 – which corresponds to a turn of 180 degrees – is used twice.

When the two types of curves (z^+ and z^-) for the noon sessions of the 1887 experiment are amalgamated and processed in this fashion, the resulting curve – with the ordinate expressed in screwhead divisions [4] – is that shown in Fig. 2 as curve 1. The curve presents two peaks, and ranges from -0.66 to 0.84 div (corresponding to -5.5 to 6.3 km/s, i.e. a range of 11.8 km/s); as may be seen from Table 1, the mean of the "folded" or final curve is -0.06 div (-1.7 km/s) ± standard error of mean (SEM) 0.16 div (±2.7 km/s), with a standard deviation (SD) of 0.49 div (4.8 km/s). The distribution width (dw) is 6.8 km/s.

If we now apply the distinction between the two families of curves, and amalgamate (by the procedure described) just the two noon z^- curves (July 8 and 11), we obtain curve 2 in Fig. 2. The curve also presents two peaks and has a range of -0.69 to +1.02 div (-5.7 to 6.9 km/s, range of 12.6 km/s); its zeroing mean is -0.03 div (-1.2 km/s) ±SEM 0.2 div (±3 km/s), with an

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[2] The z^+ curves present a mean deviation from the mean overall curve (which lumps together data from both z^+ and z^- curves) that is positive along the Y-axis, and the z^- curves present a mean deviation that is negative.

[3] The initial calibration focuses the interferometer to observe a displacement when the reference arm is typically oriented towards local north. For other positions of the apparatus, the experimenter observes relative fringe shifts.

[4] One fringe shift corresponds to 50 divisions.

SD of 0.59 div (5.2 km/s), and a dw of 7.4 km/s (see Table 1). The third curve (curve 3) in Fig 2 is the z^+ curve obtained from the noon data of July 9. This curve, too, presents two peaks; it has the widest range of the three, from -0.9 to 1.08 div (-6.5 km/s to 7.1 km/s, range of 13.6 km/s); its zeroing mean is -0.14 div (-2.6 km/s) ±SEM 0.24 div (±3.3 km/s) with an SD of 0.71 div (5.75 km/s) and a dw of 8.1 km/s (see Table 1).

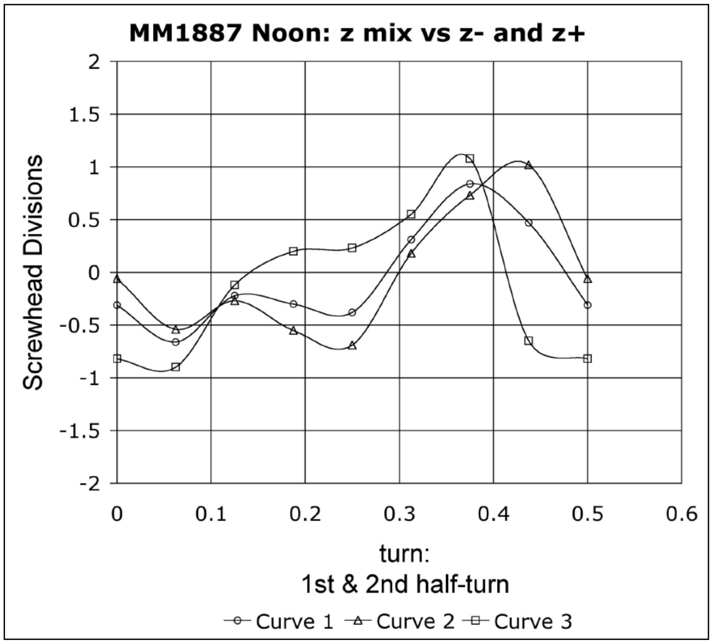

Figure 2 Normalized and drift-noise corrected noon curves from the 1887 MM experiment. Curve 1 amalgamates z^- and z^+ results (the "MM curve"), whereas curves 2 and 3 (single curve of July 9) are, respectively, for separate z^- and z^+ data. Curve 1 SD: 4.8 km/s; curve 2 SD: 5.2 km/s; curve 3 SD: 5.8 km/s.

With corresponding SEMs of ±3.0 to ±3.3 km/s, the normalized and corrected means of the separate z^- and z^+ curves cannot have a resolution greater than ca. 3.15 km/s about the mean velocity (bandwidth of 6.3 km/s). Any measurement falling within 2 standard deviations (to include 95.44% of the data) from the mean (i.e. within twice the mean SD, 1.33 div or 6.8 km/s – see Table 1) would likely fall within the random distribution. This, of course, should be enough to detect the full velocity of the earth around the sun if this were measured against a stationary aether, but not if aether drag reduced an aether wind to less than 6.8 km/s. The similar shape of all three curves suggests a possible common pattern involving at least one harmonic and subharmonic oscillations. However, all points fall within 2 standard deviations of the mean for each curve type. Two-tailed t-tests indicate that, with df (degrees of freedom) = 7 and a cut-off of p=0.02 or greater, points #7 and #8 of the z^- curve are significantly different from the null hypothesis (#7: $3.4>t_{0.02}$; #8: $4.7>t_{0.02}$). Likewise for point #7 of the z^+ curve ($4.7>t_{0.02}$) – but not so for point #2 ($2.83<t_{0.02}$).

Fig. 3 presents a parallel treatment of the 18:00 sessions of the MM 1887 experiment. Curve 4 represents the denoised, normalized and folded results of the amalgamation of the complete 18:00 data. It has a mean of -0.06 div (-1.7 km/s) ±SEM 0.10 div (2.2 km/s), an SD of 0.31 div

(3.8 km/s), a dw of 5.4 km/s, and a range from -0.44 to 0.49 (-4.5 to 4.8 km/s, i.e. 9.3 km/s; see Table 1). It has essentially no distinctive features.

Table 1

Curve Type	Fig.s 2 & 3 curve #	Time	Mean , $\overline{M}_1$		SEM		SD		dw (from div)	Range	n
			div	km/s	div	km/s	div	km/s	km/s	km/s	
z^-	2	noon	-0.03	-1.2	0.20	3.0	0.59	5.2	7.4	12.6	2
z^-	6	18:00	-0.08	-2.0	0.31	3.8	0.93	6.6	9.3	15.9	1
z^+	3	noon	-0.14	-2.6	0.24	3.3	0.71	5.8	8.1	13.6	1
z^+	5	18:00	-0.05	-1.5	0.14	2.6	0.43	4.5	6.3	9.7	2
$\overline{M}_2$ ± SEM (calculated in div)	NA	NA	-0.075 ± 0.024	-1.9 ± 1.1	0.225 ± 0.04	3.3 ± 1.3	0.665 ± 0.105	5.6 ± 2.2	7.9	12.95	4
$z^- z^+$	1	noon	-0.06	-1.7	0.16	2.7	0.49	4.8	6.8	11.8	3
$z^- z^+$	4	18:00	-0.06	-1.7	0.10	2.2	0.31	3.8	5.4	9.3	3
$z^- z^+$ Average	NA	NA	-0.06	-1.7	0.13	2.5	0.40	4.3	6.1	10.6	2

Final statistics for all the curves of Figs. 2 & 3 from the 1887 MM experiment.

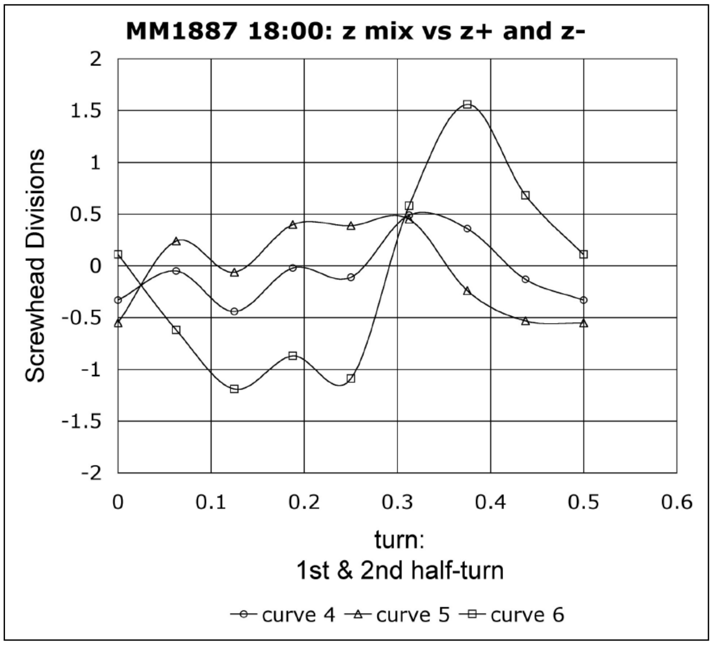

Figure 3 Normalized and drift-noise corrected 18:00 curves from the 1887 MM experiment. Curve 4 amalgamates z^- and z^+ results (the second "MM curve"), whereas curves 5 and 6 (single curve of July 11) are, respectively, for separate z^+ and z^- data. Curve 4 SD: 3.8 km/s; curve 5 SD: 4.5 km/s; curve 6 SD: 6.6 km/s.

Once we distinguish between the two families of curves, we obtain for the two 18:00 z^+ curves (July 8 and 9) an average curve shown as curve 5 in Fig 3. The curve presents no well-defined peaks and has a range of -0.55 to +0.45 div (-5.1 to 4.6 km/s, i.e. 9.7 km/s), with a mean of -0.05 div (-1.5 km/s) ±SEM 0.14 div (2.55 km/s), an SD of 0.43 div (4.5 km/s) and a dw of 6.3 km/s (see Table 1). In contrast to the random aspect of curves 4 and 5, the single 18:00 z^- curve (shown as curve 6 in Fig. 3), presents a well-defined trough and a distinctive peak. It has a range of -1.19 to 1.56 div (-7.4 to 8.5 km/s, i.e. 15.9 km/s), a mean of -0.08 div (-2 km/s) ±SEM 0.31 div (3.8 km/s), an SD of 0.93 div (6.6 km/s) and a dw of 9.3 km/s (see Table 1). In contrast to Fig. 2, no consistent pattern is shared between the two curve types in Fig. 3.

Again, all points fall within 2 standard deviations of the mean. Two-tailed t-tests indicate that, with df=7 and with a cut-off of p=0.02 or greater, only point #3 of the z^- curve is significantly different from the null hypothesis ($3.5>t_{0.02}$); all points of the z^+ curve abide by the null hypothesis at the same level of significance.

From these results, it is apparent that all the normalized and corrected means of the separate z^- and z^+ curves are negative in sign and range from -1.2 to -2.6 km/s. As shown in Table 1, the mean of all separate means is -0.075 div (-1.9 km/s) ±SEM 0.024 div (1.1 km/s for the mean of means). With corresponding sample SEMs of ±2.6 to ±3.8 km/s, the instrument cannot have accuracies smaller than 3.2 km/s – which means an error band identical to that found for the noon curves, with an amplitude of 6.4 km/s in the zeroing of the instrument. The mean (calculated in div) of the SD values of all four corrected denoised and normalized curves (see Table 1) is 0.665 div or 5.6 km/s ±SEM 0.1 div (2.2 km/s). Thus, we should expect the instrument to register values corresponding simply to a normal random distribution in a band with a width of twice the mean SD in either direction, and thus a mean span of 7.9 km/s (see Table 1, fifth entry) centered on the mean of means. Effectively, no aether wind below 7.9 km/s, in either direction, could be reliably detected. This is confirmed by a more stringent test – taking the square root of the mean of the variances (or SD^2) for all four curve types, as a measure of the SD of the population. The mean of the 4 variances is found to be 0.48 div ±SEM 0.14 div, putting the population SD at 0.69 div or 5.7 km/s, and the width of 2 standard deviations at 1.38 div or 8 km/s. A tabulation of the points that in single-tailed tests were significantly different at a 0.01 level (see Table 2) shows that, while the noon sessions could have been consistent with a borderline detection of an aether drift of 6 to 7.5 km/s (just within 2 standard deviations) at azimuth indices #7 and 8, there is no evidence for such a drag in the 18:00 sessions. By taking the means of the amalgamated noon and 18:00 sessions and adding their respective standard errors (see Table 1, fifth entry), one can say with confidence that no aether wind was detected down to 2.3 km/s for the noon data, and down to 1 km/s for the 18:00 data.

Therefore, nothing in these results suggests an aether drift of 8 to 10 km/s, as some authors have claimed (see below). Roberts (2006) computes error bars for MM's results and also concludes that "there is no statistically significant signal in their data", though – in his view – the upper bound of 7.5 km/s that MM had placed on the earth's speed relative to the aether was valid. From our analysis, the MM 1887 experiment presented no evidence of an aether drag down to some 6 km/s or less. Any aether drag below 3.2 km/s would be indistinguishable from instrument error. And any value registered up to 8 km/s in either direction from the mean would likely be the result of a random distribution of measurements.

Table 2

Time	Curve Type	Points	$i_{div} - \bar{x}_{div}$	km/s
noon	z^-	#7	0.76	5.95
		#8	1.05	7.0
noon	z^+	#7	1.22	7.5
18:00	z^-	#3	-1.11	-7.2
18:00	z^-	0	0	0

Comparison of azimuth index points in the 1887 MM experiment that were significantly different from the null hypothesis in two-tailed t-tests with p=0.02. The fourth column shows the mean difference of the division (div) data (i) from the mean ($\bar{x}$) of both z^+ and z^- curves.

The second error claimed by Múnera is that the phase angle (ω_N) between (1) the earth's velocity (v_l) [5] projected on the plane of the interferometer and (2) the reference arm (RA) of the apparatus may display strong variations even during a single session, but these variations were virtually ignored. Múnera (1998, p. 43) argues that the projected speed of aether drift (relative solely to the earth's orbital velocity around the sun) during the MM experiment on July 9 changed from 18.1 to 16.8 km/s between 12:00 and 13:00, and from 28.4 to 29.6 km/s between 18:00 and 19:00.

To see whether the corresponding MM 1887 "raw" results for July 9 noon and 18:00 agree with these postulated values, we normalized the raw data by subtracting from each raw data value the mean of all 17 data points. The resulting normalized but *non-denoised* data nowhere present the speed values postulated by Múnera (1998):

- a mean -0.41 div or -4.4 km/s ±SEM 7.9 km/s is observed at noon, with an SD of 5.52 div or 16 km/s, and a dw of 22.7 km/s;
- a mean of -0.3 div or -3.8 km/s ±SEM 8.3 km/s is observed at 18:00, with an SD of 5.9 div or 16.6 km/s, and a dw of 23.4 km/s;
- the difference between means (or, effectively, curve levels) is only 0.6 km/s.

None of these results matches Múnera's projections.

Hicks (1902, p. 36) interpreted the continuous increase or decrease of the MM curves as evidence of a thermal artifact ("noise"), for which he applied a linear correction. He (1902, p. 34) also proposed a different interpretation of the physical significance of the z curve types, and was the first one to separate these types (formally, he did not average any inter-session curves, even for the same type). However, his method only normalizes the data after correcting for "the

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[5] The formula is: $v_l = v_{orbital} + v_{solar}$, and it should, at the very least, be a proper vector quantity with trigonometric phase operators, on the order of $v_l = v_{Eorbital} + v_{SolarApex} + v_{GalApex} + v_{ERot}$.

effect of cos α" (optical aberration that causes the apparent position of the central fringe or "bright band" to be tendentially displaced off-center and is corrected by the "folding" of the series). Thus he obtains different results and curves from ours. For a comparison of our approach or algorithm and that of Hicks, see Table 3.

Miller (1933) processed the MM data (after analysis with his algorithm, see Table 3) with a Henrici harmonic analyzer to evaluate the second-harmonic component, which represents the second-order, half-period "aether-drift effect". He obtained a velocity of 8.8 km/s for the noon observations, and 8.0 km/s for the evening observations, and claimed that the 1887 MM experiment had detected a nonzero aether drift. In light of our analysis above, this claim cannot be correct. As said above, our results indicate that if a nonzero velocity indicative of aether drag had been detected, it could *not have been smaller than the amplitude of the error band (6.4 km/s)*, and would have to be consistently greater than twice the population SD of 8 km/s in either direction. No measurement with these qualifications was observed in the MM experiment, either in the form of a mean aether-drift velocity or in the form of a point or set of points consistent in magnitude and direction.

Table 3

Methodological Steps	M&M (1887)	Hicks (1902)	Present Paper
Readings at 16 + 1 positions	1/position	NA	NA
Separate sets of reading by curve (z) type	ND	+	+
Denoise:			
1. Determine range of (thermal) drift between positions 1 & 17	ND	+	+
2. Divide range linearly over the number of positions (build linear drift curve)	ND	+	+
3. Subtract linear drift curve	ND	+	+
Normalize			
1. Determine mean of resulting denoised curve	ND	ND	+
2. Subtract mean	ND	ND	+
Eliminate cos α effects (folding)			
1. Sum 1st & 2nd half-turns	+	+	+
2. Average 1st & 2nd half-turns	+	+	+
Normalize			
1. Determine mean of half-turns	ND	+	NA
2. Subtract mean	ND	+	NA

ND - Not Done

NA - Not Applicable

Comparison of analytical methods applied by MM, Hicks and the present paper.

Using a linear correction method similar to Miller's to produce "correct entries", and then fitting all six borderline fringe shifts of the 1887 MM experiment to a Fourier expansion based on that linear correction, Consoli & Costanzo (2003) obtained mean velocity values of 8.7 km/s for

MM's noon sessions, and 8.0 km/s for the evening sessions (they reported an error on the order of ~0.5 km/s, but failed to indicate whether the error is an SEM, an SD, or something else). Our above criticism of Miller's interpretation also applies to Consoli & Costanzo's interpretation. Similar objections can be made to Múnera's (1998) application of Illingworth's method to the analysis of MM's data, which yielded 6.22 km/s for the noon observations, and 6.80 km/s for the evening observations.

Roberts (2006) has argued that subtracting the thermal drift-noise curve assumes that the noise is linear whereas the data presents nonlinear and erratic variations. In the absence of evidence for a model of nonlinear correction, however, the linear correction has two advantages: (1) it prevents the blatant and otherwise irresistible error of taking the normalized value as an absolute value having a corresponding speed; (2) it restricts the drift noise to the observed range of the variation between screwturns 1 and 17 (note that Michelson & Morley did not employ any drift-noise correction; see Table 3 for a comparison of their algorithm). However, if a model of nonlinear correction is employed – such as a harmonic one – then employing a linear correction beforehand (as Miller and Múnera did) could indeed be construed as an error or the wrong procedure.

Roberts also criticized Michelson & Morley for having subtracted the mean for the orientation of each data point (thus canceling the real signal). This was indeed a poor normalization, but one which Roberts fails to stress was different from the correct normalization first employed by Miller (see below, and also Table 3), which involved subtracting only the mean of the curve formed by all the averages (as we did above, while also separating the curves by type). Indeed, correct normalization does not cancel the signal, as the results of our own algorithm demonstrate. On the contrary, it alone may permit its location and correct size estimate.

3. MORLEY AND MILLER'S EXPERIMENTS

From 1902 to 1906 Morley and Dayton Miller conducted further aether-drift experiments that were billed as a test of the Fitzgerald-Lorentz contraction effect rather than as a test of the stationary aether hypothesis. Having built a much larger interferometer (with a total light path of 64 m) on a white-pine framework, they ran tests in the summers of 1902 and 1903 but were dissatisfied because of the difficulty of keeping humidity and temperature constant to prevent warping. However, Miller (1933, p. 207) later reinterpreted the results of his 1902 experiments as being in line with his 1925-26 Mount Wilson experiments.

Commenting on the difficulties of his experiments, Miller (1933, p. 222) wrote: "Half the time, perhaps, the observations are interrupted before they become numerous enough to be useful, because of excessive displacement of the fringes by temperature changes or by earth or aerial vibrations." According to Kennedy (1926), a change in the optical length of one path of less than one part in a billion, or a difference in the average air density along the two arms as would be produced by a pressure difference of 0.002 mm of mercury or a temperature difference of 0.001°C, would suffice to produce a fringe shift corresponding to 10 km/s.

In 1904 Morley and Miller set up a trussed apparatus of tubes by which wooden or metal rods could determine the optical path length, to see whether a fringe shift was produced by different materials contracting to different extents. The new base was made entirely of steel, and floated on a circular bed of mercury. Their observations during 260 rotations of the interferometer in July 1904 led them to conclude (Morley & Miller, 1905, p. 326-7): “the experiment shows that if there is any effect of the nature expected, it is not more than the hundredth part of the computed value. If pine is affected at all, it is affected to an extent comparable to sandstone. If the aether near the apparatus did not move with it, the difference in velocity was less than 3.5 kilometers a second, unless the effect on the materials annulled the effect sought.”

In their experiments, Morley and Miller (1905, p. 54) assumed a magnitude of terrestrial motion of about 33.5 km/s, resulting from “the combination of the diurnal and annual motions of the earth, together with the presumed motion of the solar system toward the constellation Hercules with a velocity of 19 km/sec”. On the date chosen for the 1904 observations “there were two times of the day when the resultant of these motions would lie in the plane of the interferometer, about 11:30 A.M. and 9:00 P.M.” The observations for the two times of day gave results having positive magnitudes but nearly opposite phases, and when combined the result was nearly zero. Miller (1928, p. 353) later said that this procedure was erroneous. In light of his later hypothesis concerning solar motion, Miller (1933, p. 217) concluded that the morning and evening observations each indicated an aether-drift velocity of about 7.5 km/s.

In 1905, Morley and Miller moved the interferometer from the basement of the main building of the Case School of Applied Science in Cleveland to Euclid (later Cleveland) Heights (about 285 m above sea level), and continued their tests of the contraction hypothesis. They discarded the pine rods and trussed-brass framework they had used the year before to separate the mirror holders. The interferometer was placed in a hut with glass windows at the level of the apparatus “so that there were no opaque screens in the plane of drift”. However, it was difficult to maintain uniform temperature conditions in the flimsy, poorly insulated shack in such a windy environment: “satisfactory observations could only be made on a cloudy evening following a cloudy day, when the temperature changed very slowly. The temperature effects could never be entirely eliminated” (Morley & Miller, 1907).

The observations made in July, October, and November 1905, consisting of 230 turns of the interferometer, yielded an aether drift of about 3.9 km/s (Morley & Miller, 1907), slightly larger than what had been measured a year earlier in the basement location. Morley considered that the small positive residuals during the 1905 Euclid Heights observations “were almost certainly due to temperature effects” (Swenson, 1972, p. 192-3). However, Miller (1933, p. 217) later reinterpreted this result, too, and said that the October observations gave a drift of 8.7 km/s. Miller (1926, p. 435) stated that there was a suspicion that the lower-than-expected fringe shift “might be due to a temperature effect, though there was no direct evidence of this”.

4. MILLER’S 1921 AND 1922-24 EXPERIMENTS

In April 1921 Miller used the same steel-base interferometer to conduct observations on Mount Wilson, involving 350 rotations. The apparatus was located on the eastern edge of the mountaintop, inside a hut at the edge of a precipice, which once again afforded inadequate protection against the mountain winds. Readings on April 8-21 indicated a drift four times larger than in Cleveland (a figure Miller later reduced to three times), but Miller found that the large periodic effect appeared once per revolution – instead of twice, as was expected for an aether-drift effect (Swenson, 1972, p. 194-5). Miller made the following entry in his laboratory notebook for April 14, 1921: “Sun shining full on side of house. There was a very large drift which seems to be in the direction of the sun; indicating possibility that the entire effect is due to temperature!” (Shankland et al., 1955, p. 174). This was an admission that the interferometer was not shielded from diurnal variations, whose intensity would vary with cloud cover, and also that the interferometer was still not optimally shielded from thermal artifacts.

Miller then had a new base for the interferometer cast in concrete to check whether magnetostriction (ferromagnetic distortion) might have caused the slight positive fringe shift found in April 1921. All metallic parts were remade of low-expansion materials (brass or aluminum). Observations were made on December 4-11, but “much of the time the interferometer behaved poorly, the fringes were often unsteady, temperature variations near the instrument were troublesome, and vibrations caused by high winds often made observation entirely impossible” (Shankland et al., 1955, p. 168).

However, on December 9-11, 1921, 13 sets of readings comprising 153 turns of the interferometer were made “under fairly favorable conditions”. They gave an average periodic amplitude of 0.04 fringe (5.7 km/s), nearly the same as the April 1921 result. Miller wrote in his research notebook: “all effects are probably due to the instrument. This is the end” (Swenson, 1972, p. 200). However, after having second thoughts, Miller (1922, p. 407) announced that, although he was unable to eliminate a small systematic azimuth disturbance, his results showed “a definite displacement, periodic in each half revolution of the interferometer, of the kind to be expected, but having an amplitude of one tenth the presumed amount”. Miller (1933, p. 218-9) stated that the positive effect detected in April and December 1921 corresponded to an aether drift of about 10 km/s.

Miller (1933, p. 220) reverted to the more rigid steel base for his interferometer, and from 1922 to 1924 he carried out a variety of laboratory tests with it in Cleveland, and convinced himself that “the periodic displacements could not possibly be produced by temperature effects” or by any other experimental artifacts. Shankland et al. (1955, p. 168) write: “In many of the Cleveland trials of 1923-24, especially those for which the data sheets record the best ‘seeing’ of the interference fringes, the periodic effects are very small. These data were not analyzed in detail by Miller as he considered them only preliminary to the later work at Mount Wilson. However, 19 sets of observations made from August 23 to September 4, 1923, and 42 sets of data taken from June 27 to July 26, 1924, including those made with sunlight, for which the interferometer was in the best adjustment and the fringes were often noted as ‘good’ or ‘excellent,’ constitute some of the best data obtained with Miller's interferometer." The unpublished 1923-24 experiments gave a fringe shift of 0.030, while the observations in sunlight in 1924 gave 0.014 (Shankland et al., 1955, p. 168; Swenson, 1972, p. 242), corresponding to velocities of 4.9 km/s and 3.3 km/s respectively.

After several improvements had been made to the interferometer, it was taken back to Mt Wilson and placed in a wooden hut with canvas windows, at a new site removed from the canyon edge. Observations were carried out in September 1924, which Miller (1933, p. 221) claimed showed an aether drift of about 10 km/s.

5. MILLER'S 1925-26 EXPERIMENTS

Miller's most extensive series of observations were conducted on Mt Wilson at four epochs (see Fig. 4): March 27 – April 10, 1925; July 24 – August 8, 1925; September 10-23, 1925; and February 3-12, 1926 (see Shankland et al., 1955, p. 169). The data he used for analysis came from periods of "six or eight days" centered on April 1, August 1, and September 15, 1925, and February 8, 1926 (Miller, 1933, p. 213). He therefore excluded data from over 40% of the days on which observations were made. Miller made further (unpublished) observations in Cleveland in 1927 and 1929, and published his final report in 1933.

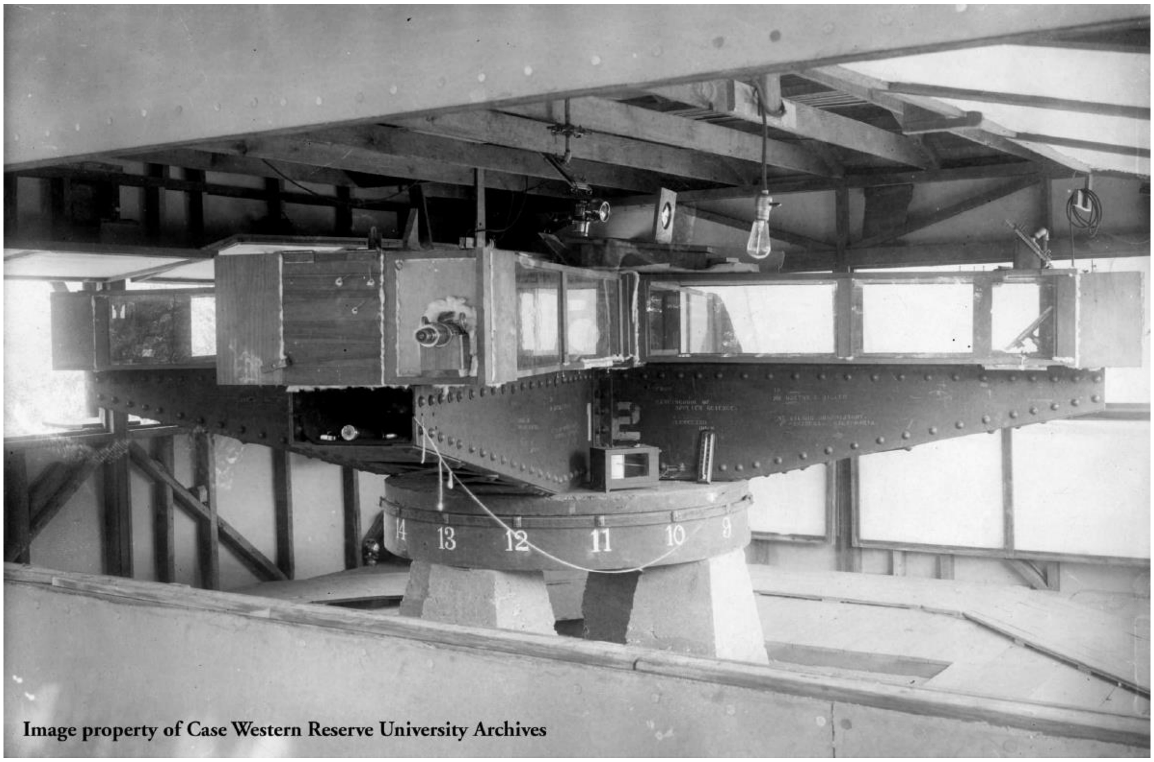


Image property of Case Western Reserve University Archives

Figure 4 The interferometer used by Miller to perform the 1925-26 aether-drift observations on Mt Wilson was the most massive and sensitive ever constructed. The steel arms, 4.3 m across, weighed 1200 kg and floated in a tank of 275 kg of mercury. It had an effective arm length of 32 m, achieved by multiple reflections.

The data he used comprised readings from a total of 6402 rotations of the interferometer, recorded on 316 data sheets with approximately 20 turns per sheet, and 16 azimuthal positions per turn. Miller's data sheet no. 79 (see Fig. 7) (Miller, 1933, fig. 8) shows that it took him about 14 minutes to record a total of 320 readings, or an average of 2.6 seconds per reading, including 3 mirror readjustments made by adding weights to the interferometer arms; this gives a measure of Miller's athleticism.

Miller's standard procedure for making and analyzing observations was as follows. Fringe-shift readings were made at 16+1 azimuth positions (the 17th position repeats the 1st position) starting from the north and measured clockwise. In the final design, he used a telescope to read the fringe shift in tenths of a fringe. Miller summed the readings, determined the range of the drift between positions 1 and 17 (in essence what Hicks had suggested was a basic correction for thermally-induced drift), divided the range linearly between all 16 positions (so that the final averages closed as a periodic function in each 360° rotation of the interferometer), subtracted the linear drift curve, and determined the mean of the resulting curve of the averages. To normalize the results, the mean was subtracted from the averages at all 16 positions. Finally, the 1st and 2nd half-turns were summed, averaged and their means determined. Miller's methodological steps, but not his statistical calculations, are identical to those we employed in Table 3. These means were plotted in azimuth and connected by straight lines to give a graph for harmonic analysis with the Henrici harmonic analyzer.

Miller (1928, p. 356-7) stated that it was not until the end of 1924, “when a solution seemed impossible”, that he first calculated the expected effect of solar motion on aether drift for each month of the year. The calculation showed that the effect should have a maximum about April 1, and that its direction should rotate completely around the horizon in the course of each day. Miller (1933, p. 223) inferred from his earlier experiments that the sun's relative motion toward Hercules “was not a component of the absolute motion of the earth”. He noted that G. Strömberg had found evidence that the solar system was moving toward RA = 20.5h, Dec = +56°, with a velocity of 300 km/s, and that Lundmark's study of the spiral nebulae indicated a velocity of 400 km/s (Miller, 1928, p. 365).

Miller (1928, p. 357) stated that his observations in March and April 1925 yielded a large effect but did not point successively to all points of the compass, i.e. did not point in directions 90° apart at 6-hour intervals. Instead, “the direction merely oscillated back and forth through an angle of about 60°, having, in general, a northwesterly direction”. He proceeded to make further observations in July, August, and September 1925, and February 1926. A new feature of his 1925-26 experiments was that measurements were repeated for long periods of time, day and night.

Miller (1933, p. 228-238) presented the final results of his 1925-26 experiments in the form of Fig. 5, and in three tables (Tables 4 to 6, right ascension of apex, declination of apex, velocities and displacements). He reported the average aether drift detected as being 10 km/s. He also reported that the magnitude and azimuth data from the four epochs showed periodicity when plotted against sidereal time (pointing to a cosmic cause) but not when plotted against civil time (see Fig. 6 and discussion below). On the basis of the theory developed by Nassau & Morse (1927), Miller determined that the magnitude and azimuth data independently gave the same direction of “absolute” motion, and he then worked out the best-fit velocity.

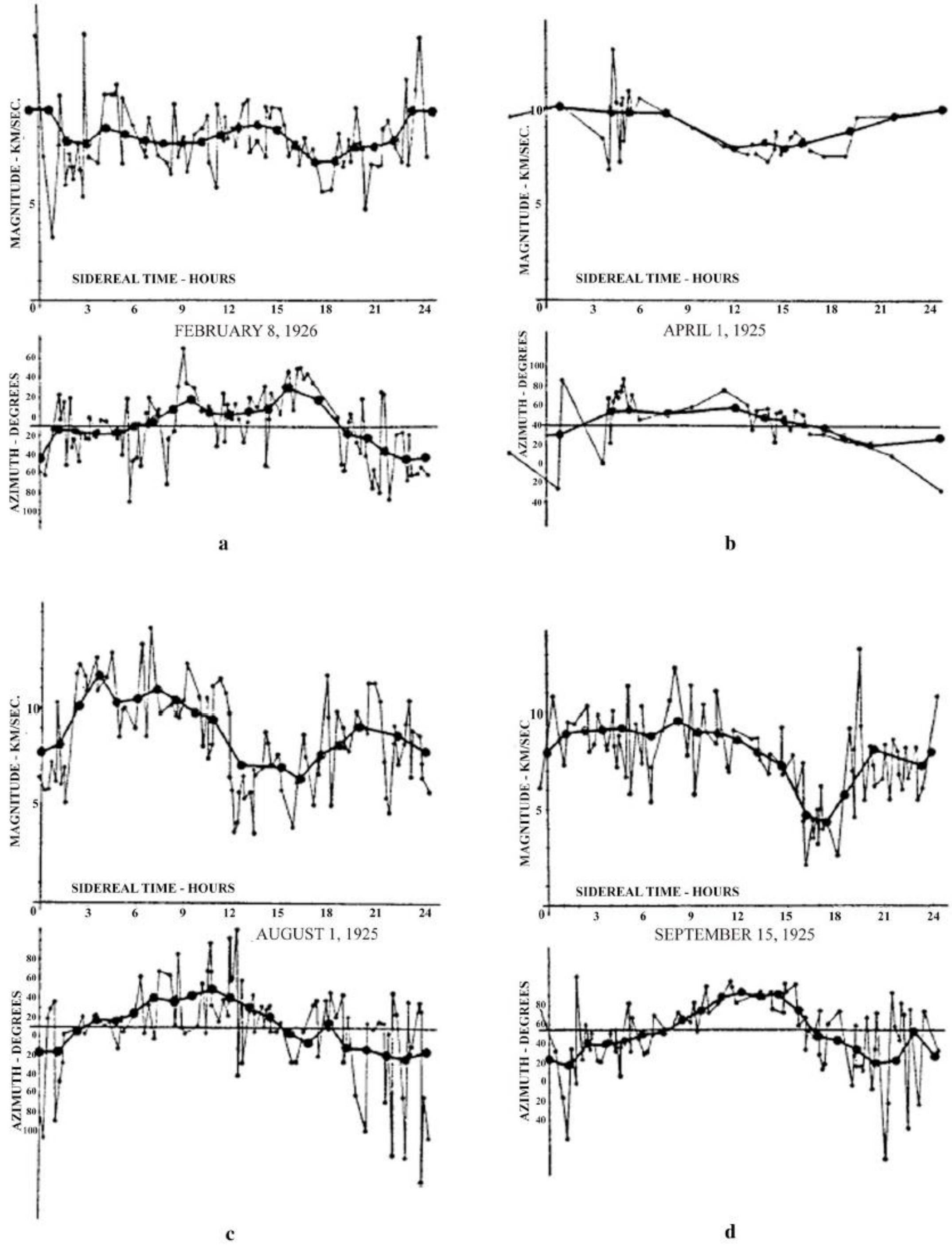


Figure 5 Single observations and average curves showing aether-drift velocities and azimuths measured during Miller’s 1925-26 experiments on Mt Wilson. Note the absence throughout of error bars. Roberts (2006) comments that if Miller had computed and plotted error bars, “they would be

so large that in no case would they fit on the plot, and often would not even fit on the page. His ‘determination of the absolute motion of the earth’ is not statistically significant.”

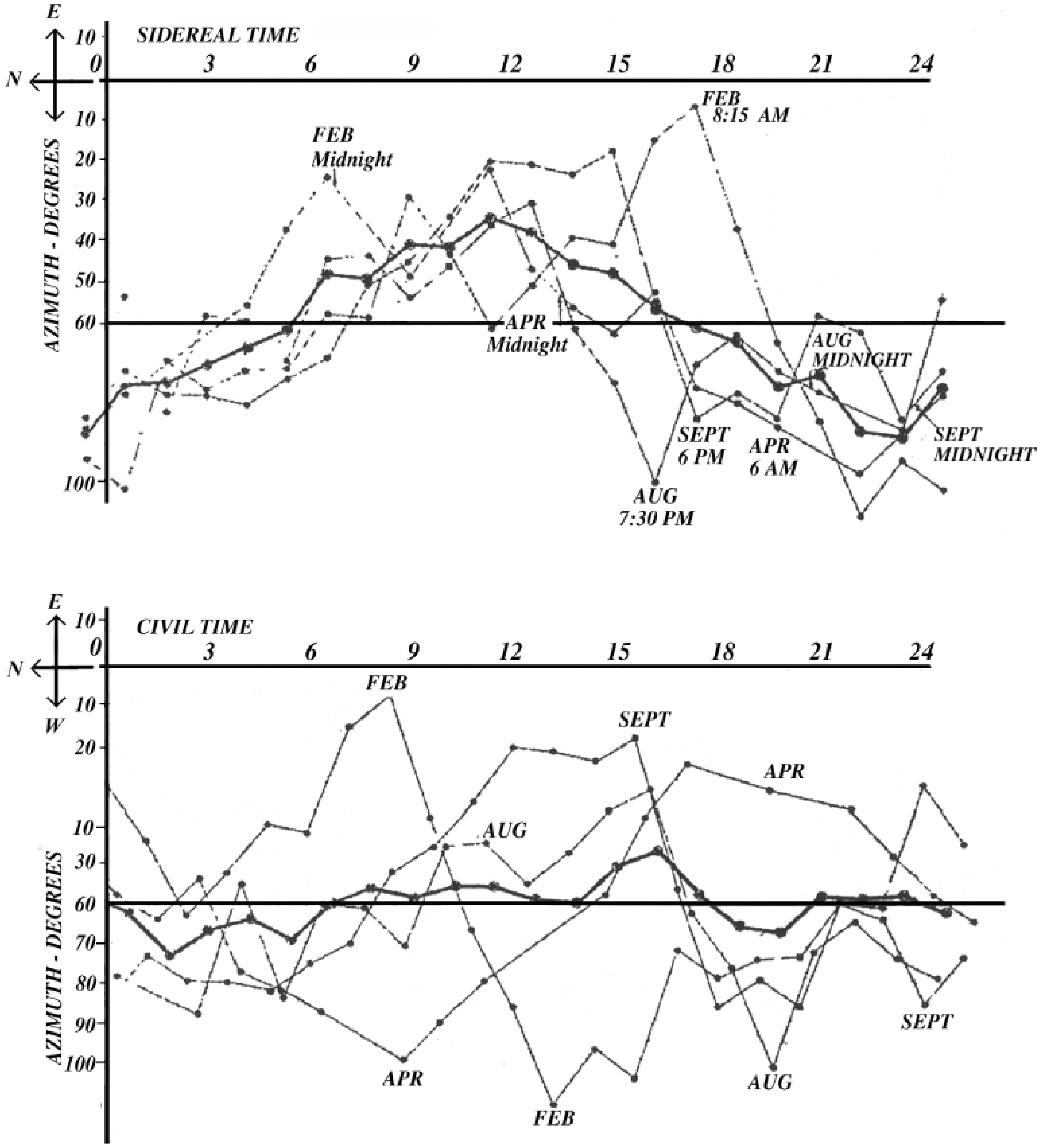


Figure 6 Top figure: When aether-drift data from Miller’s 1925-26 Mt Wilson experiments are plotted against sidereal time, a periodicity is seemingly discernible (the heavy line is the mean of all four epochs). Bottom figure: When plotted against civil clock time, the periodicity seemingly disappears. Note that the April curves in the two panels do not match. In addition, the label “Feb midnight” in the top panel points to the wrong curve. (Miller, 1928, p. 362)

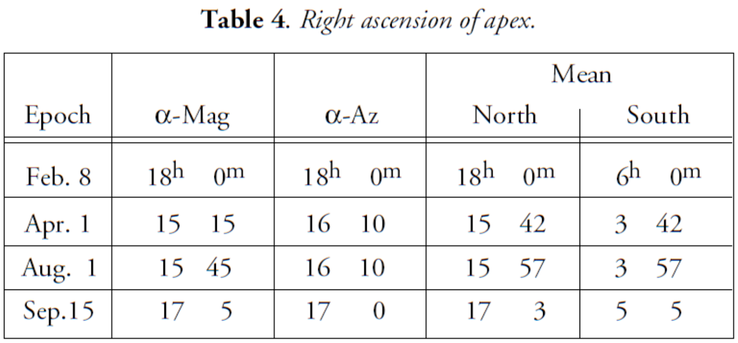


Table 4. *Right ascension of apex.*

Epoch	α-Mag	α-Az	Mean North	 South
Feb. 8	18^h 0^m	18^h 0^m	18^h 0^m	6^h 0^m
Apr. 1	15 15	16 10	15 42	3 42
Aug. 1	15 45	16 10	15 57	3 57
Sep.15	17 5	17 0	17 3	5 5

Miller’s table of right ascension of apex, 1925-26 Mt Wilson experiments. (Miller, 1933)

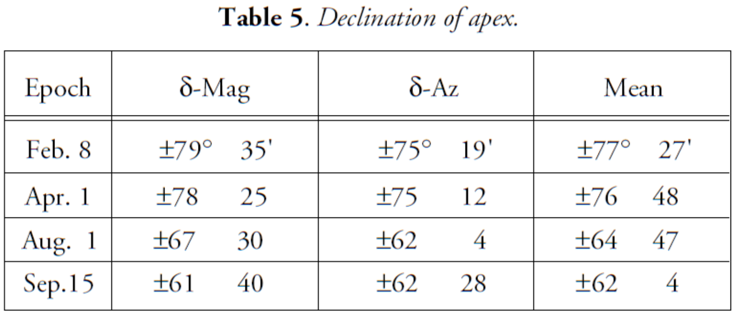


Table 5. *Declination of apex.*

Epoch	δ-Mag	δ-Az	Mean
Feb. 8	±79° 35'	±75° 19'	±77° 27'
Apr. 1	±78 25	±75 12	±76 48
Aug. 1	±67 30	±62 4	±64 47
Sep.15	±61 40	±62 28	±62 4

Miller’s table of declination of apex, 1925-26 Mt Wilson experiments. (Miller, 1933)

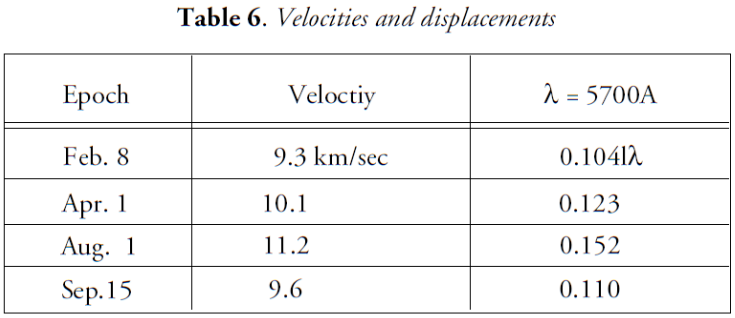
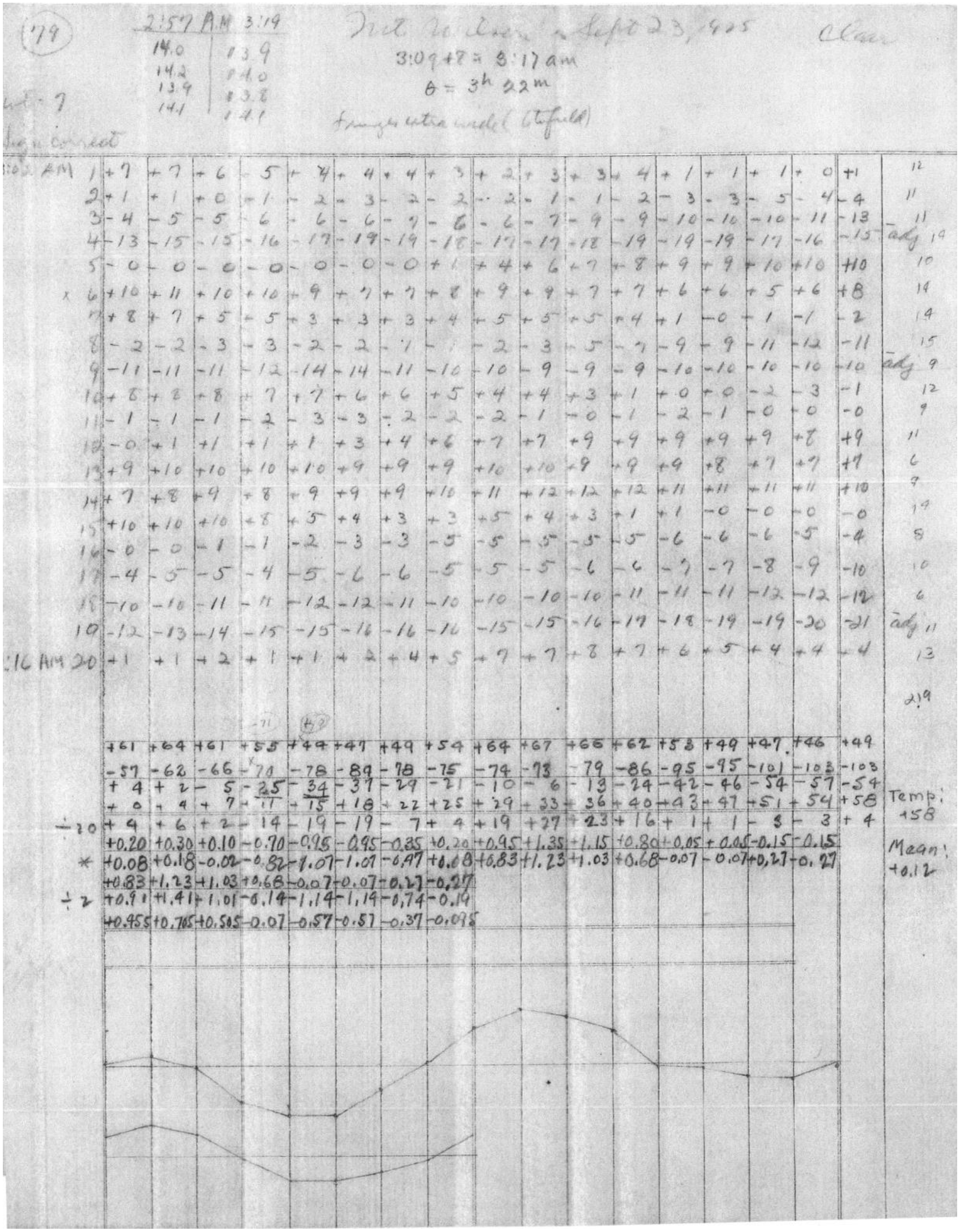


Table 6. *Velocities and displacements*

Epoch	Veloctiy	λ = 5700A
Feb. 8	9.3 km/sec	0.104lλ
Apr. 1	10.1	0.123
Aug. 1	11.2	0.152
Sep.15	9.6	0.110

Miller’s table of velocities and displacements, 1925-26 Mt Wilson experiments. (Miller, 1933)

Miller (1928, p. 361) initially concluded that the earth and solar system were moving with a velocity of 200 km/s or more toward RA = 17h, Dec = +68°, an apex in the constellation Draco, near the north ecliptic pole, about 26° from the apex found by Strömberg. But he felt that this solution failed to account for the effects of the earth’s orbital motion. His final conclusion (Miller, 1933, p. 234, 238) was that the earth and solar system were moving at 208 km/s (no error margin was reported) in the *opposite* direction: i.e. toward RA = 4.9 ± 0.03h, Dec = -70.55 ± 0.5°, a point in the constellation Dorado, about 7° from the south ecliptic pole. Miller thought that the velocity and azimuth curves for the four epochs of observation calculated on the basis of this cosmic solution matched the actual curves “remarkably well, considering the nature of the experiment”. He considered the internal consistency of his cosmic solution as conclusive evidence of its validity. Múnera, however, has argued that Miller was mistaken in trying to fit a single sinusoidal curve to all his data (see below).



(79)

2:57 A.M 3:19

14.0	13.9
14.2	14.0
13.9	13.8
14.1	14.1

Mt. Wilson ~ Sept 23, 1925 Clear

3:09+8 = 3:17 am

θ = 3h 22m

fringes extra wide (Stifield)

t. 7

g is correct

:02 AM 1	+7	+7	+6	-5	+4	+4	+4	+3	+2	+3	+3	+4	+1	+1	+1	+0	+1	12
2	+1	+1	+0	-1	-2	-3	-2	-2	-2	-1	-1	-2	-3	-3	-5	-4	-4	11
3	-4	-5	-5	-6	-6	-6	-7	-6	-6	-7	-9	-9	-10	-10	-10	-11	-13	11
4	-13	-15	-15	-16	-17	-19	-19	-18	-17	-17	-18	-19	-19	-19	-17	-16	-15	adj 19
5	-0	-0	-0	-0	-0	-0	-0	+1	+4	+6	+7	+8	+9	+9	+10	+10	+10	10
x 6	+10	+11	+10	+10	+9	+7	+7	+8	+9	+9	+7	+7	+6	+6	+5	+6	+8	14
7	+8	+7	+5	+5	+3	+3	+3	+4	+5	+5	+5	+4	+1	-0	-1	-1	-2	14
8	-2	-2	-3	-3	-2	-2	-1	-1	-2	-3	-5	-7	-9	-9	-11	-12	-11	15
9	-11	-11	-11	-12	-14	-14	-11	-10	-10	-9	-9	-9	-10	-10	-10	-10	-10	adj 9
10	+8	+8	+8	+7	+7	+6	+6	+5	+4	+4	+3	+1	+0	+0	-2	-3	-1	12
11	-1	-1	-1	-2	-3	-3	-2	-2	-2	-1	-0	-1	-2	-1	-0	+0	-0	9
12	-0	+1	+1	+1	+1	+3	+4	+6	+7	+7	+9	+9	+9	+9	+9	+8	+9	11
13	+9	+10	+10	+10	+10	+9	+9	+9	+10	+10	+9	+9	+9	+8	+7	+7	+7	6
14	+7	+8	+9	+8	+9	+9	+9	+10	+11	+12	+12	+12	+11	+11	+11	+11	+10	9
15	+10	+10	+10	+8	+5	+4	+3	+3	+5	+4	+3	+1	+1	-0	-0	-0	-0	14
16	-0	-0	-1	-1	-2	-3	-3	-5	-5	-5	-5	-5	-6	-6	-6	-5	-4	8
17	-4	-5	-5	-4	-5	-6	-6	-5	-5	-5	-6	-6	-7	-7	-8	-9	-10	10
18	-10	-10	-11	-11	-12	-12	-11	-10	-10	-10	-10	-11	-11	-11	-12	-12	-12	6
19	-12	-13	-14	-15	-15	-16	-16	-16	-15	-15	-16	-17	-18	-19	-19	-20	-21	adj 11
:16 AM 20	+1	+1	+2	+1	+1	+2	+4	+5	+7	+7	+8	+7	+6	+5	+4	+4	+4	13
																		219
				-71	+9													
	+61	+64	+61	+55	+44	+47	+49	+54	+64	+67	+66	+62	+58	+49	+47	+46	+49	
	-57	-62	-66	-70	-78	-89	-78	-75	-74	-73	-79	-86	-95	-95	-101	-103	-103	
	+4	+2	-5	-25	-34	-37	-29	-21	-10	-6	-13	-24	-42	-46	-54	-57	-54	
	+0	+4	+7	+11	+15	+18	+22	+25	+29	+33	+36	+40	+43	+47	+51	+54	+58	Temp: +58
÷20	+4	+6	+2	-14	-19	-19	-7	+4	+19	+27	+23	+16	+1	+1	-3	-3	+4	
	+0.20	+0.30	+0.10	-0.70	-0.95	-0.95	-0.35	+0.20	+0.95	+1.35	+1.15	+0.80	+0.05	+0.05	-0.15	-0.15		Mean: +0.12
*	+0.08	+0.18	-0.02	-0.82	-1.07	-1.07	-0.47	+0.08	+0.83	+1.23	+1.03	+0.68	-0.07	-0.07	+0.27	+0.27		
	+0.83	+1.23	+1.03	+0.68	-0.07	-0.07	+0.27	+0.27										
÷2	+0.91	+1.41	+1.01	-0.14	-1.14	-1.14	-0.74	-0.19										
	+0.455	+0.705	+0.505	-0.07	-0.57	-0.57	-0.37	-0.095										

Figure 7 Miller's data sheet for his session 79, on September 23, 1925, courtesy of Case Western Reserve University Archives.

We have re-analyzed Miller's data sheet no. 79 (see Fig. 7), which Miller describes as "a fair sample". We employed the same method as used above to analyze the MM experiment, which is essentially the same method as employed by Miller to analyze his own experiments. We obtain slightly different results because of two mistakes made by Miller in the data for points 4 and 5 of the folded curve, and in the determination of the mean (by 0.05 div). Sheet no. 79 contains, at the bottom, Miller's graph of this typical experimental run that presents an almost perfect single sine curve (see Fig. 8A). This could be seen as indicative of the balanced nature of the oscillation (~0.6 to -0.6 div) and of the possibility of seeing this pattern increase or decrease in amplitude, and move back and forth along the abscissa, if it varied with time of day or season of the year. The presence of such a pattern alone justified application of the harmonic analysis. However, the fact that the curve is nearly perfectly balanced around 0 div suggests a compensatory instrument fluctuation (residual noise). The curve has a mean of 0.001 div (0.28 km/s) ±SEM 0.16 div (±3.6 km/s), an SD of 0.46 div (6.1 km/s) and a dw of 0.92 div or 8.6 km/s (this is graphically represented in Fig. 9).

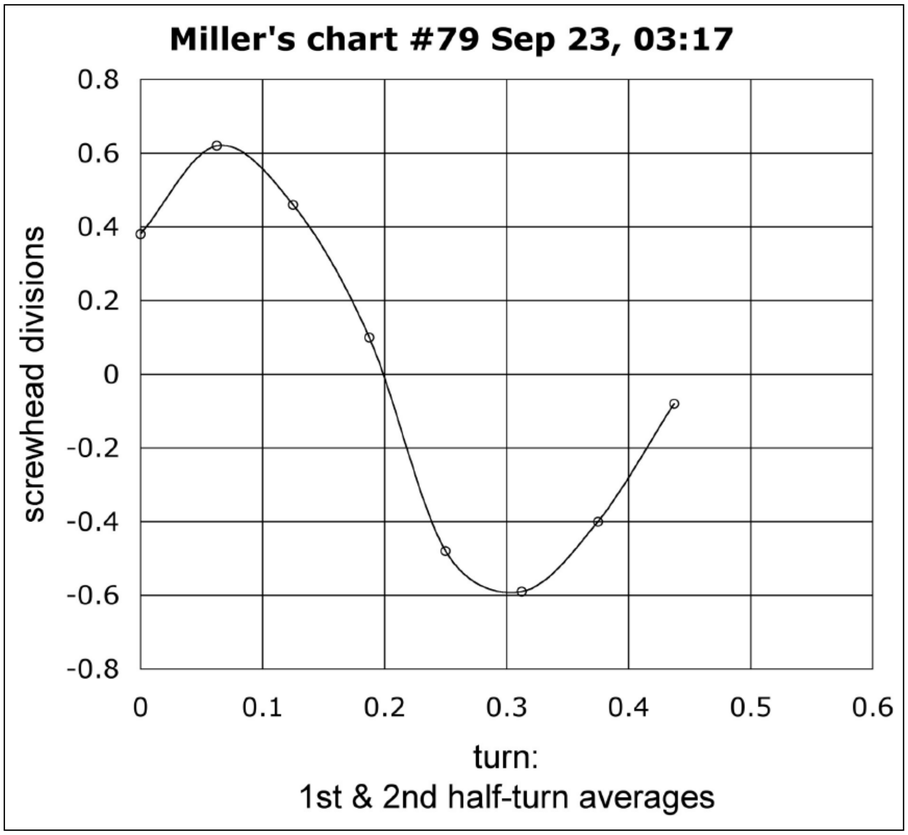


Figure 8A Correct graph for the mean 1st and 2nd half-turns of Miller's session 79 (corresponding to the curve at the bottom of the data sheet in Fig. 7). Mean, SEM, SD, dw and range are shown in Fig. 9. Note that 1 screwhead division in the Miller experiment is one tenth of a fringe.

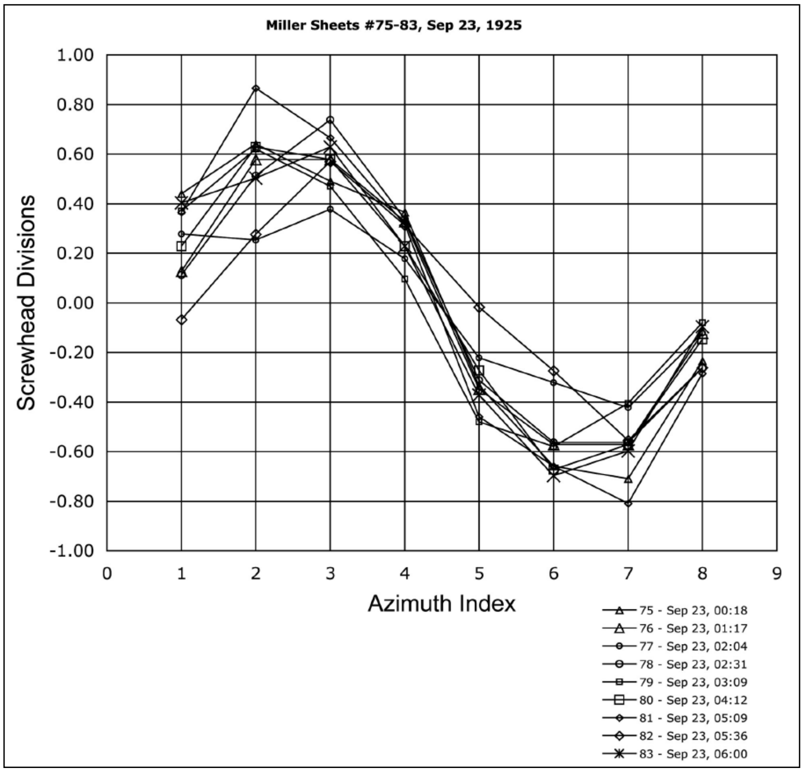


Figure 8B Correct graphs of the mean 1st and 2nd half-turns for the night to early morning sequence of Miller's sessions 75 to 83, on September 23, 1925.

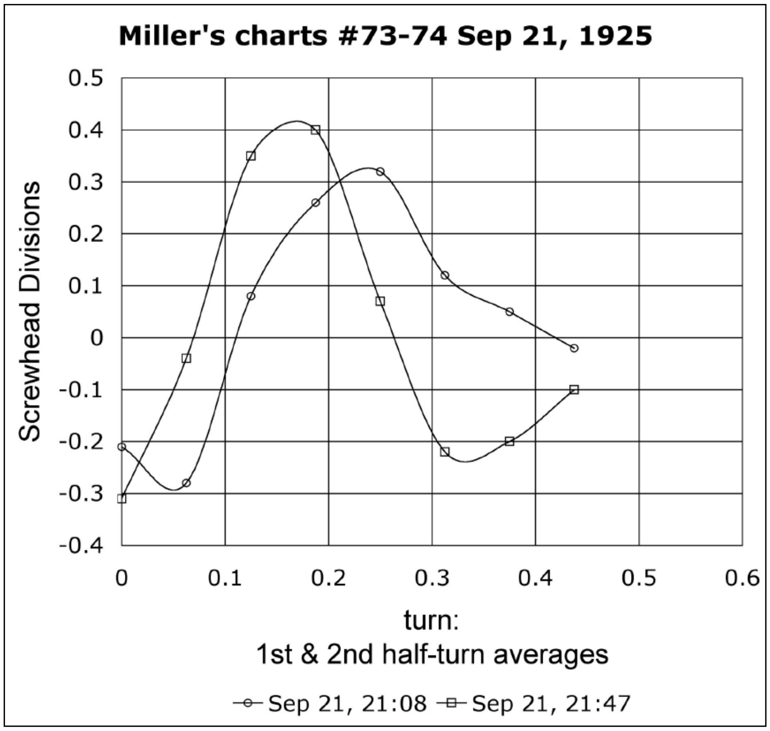


Figure 8C Correct graphs of the mean 1st and 2nd half-turns for Miller's night sessions 73 and 74, on September 21, 1925.

Two-tailed t-tests indicate that, with df=7 and with a cut-off of p=0.02 or greater, only azimuth indices #2 and #6 significantly differ from the null hypothesis (#2: $3.57>t_{0.02}$; #6: $3.39>t_{0.02}$). With the cut-off placed at p=0.01, only point #2 remains significant. The corresponding velocities are 7 km/s for point #2 and -6.9 km/s for point #6. Given the opposing velocity vectors of these two points (in fact they define the range as 13.8 km/s, see Fig. 9), their equal magnitude, and the fact that neither point lies beyond 2 standard deviations (0.92 div or 8.6 km/s) from the mean, there is no evidence for an aether drift in these data. Miller's claim that session #79 detected a 9.3 km/s aether drag is, therefore, entirely unfounded. By taking the mean of this session and adding its SEM, one can say with confidence that no aether wind was detected down to 3.9 km/s (see Fig. 9).

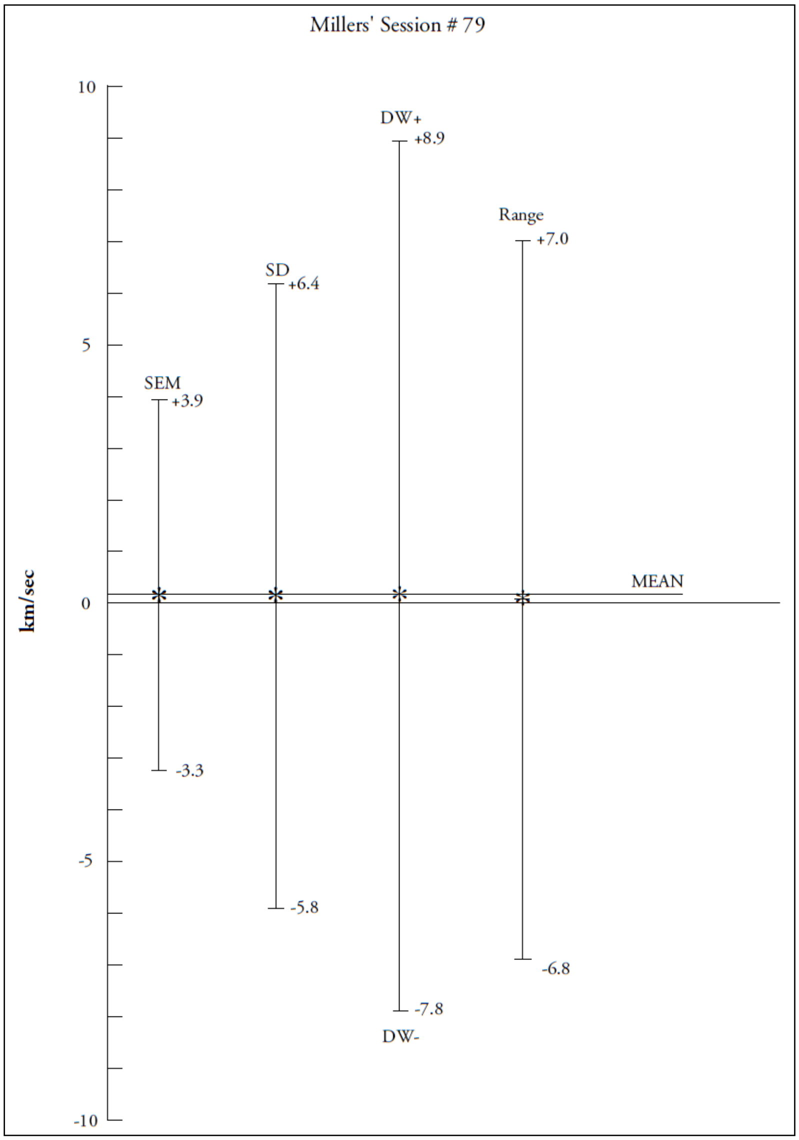


Figure 9 Mean, SEM, SD, dw and range of Miller's curve data, normalized and drift-noise corrected for the mean 1st and 2nd half-turns of his session #79.

What, then, is observed with the continuous measurements made by Miller? Does the sine-pattern shift along the abscissa or in amplitude, or both? To answer this question we looked at a series of 11 consecutive sessions corresponding to Miller's sheets numbered 73 to 83; two were performed at night on September 21, and the rest in the first six hours of the morning of September 23. In particular, the last 9 sheets should permit one to visualize either displacement of the sine pattern by 2 azimuth index positions (e.g. from #3 to #5) along the abscissa in the interval of 6 hours, or any increase or decrease in amplitude of the peaks and troughs during the same time period. As shown in Fig. 8B and Table 7, neither of these variations is observed between 00:18 and 06:00 on September 23. In all cases (one, rather imperfectly) single sine patterns are observed, but the pattern is fixed and does not move. Shankland et al. (1955, fig. 4b) had already graphed the 9 curves of September 23, but they employed Miller's analytical results that have a multiplicity of small errors. Shankland et al. observed that, given stable temperature conditions, a set of midnight-dawn experiments should show a second harmonic "due primarily" to temperature effects in the steel base of the interferometer, and having "almost identical" phase and amplitude "throughout the series". Table 7 gives the location of the sine peaks and troughs (columns 3 and 4) of the entire September 23 series as a function of time; they can be seen to remain stable, indicating no displacement along the abscissa. Similarly, the amplitude of peaks and troughs remains constant (columns 5 and 6, Table 7), thus the sine pattern neither expands nor contracts in amplitude over time. We are forced to conclude that Shankland et al. (1955, p. 177) were correct when they stated that "the behavior throughout nearly six hours of sidereal time conclusively rules out cosmic effects". In the nighttime to early morning runs of September 23, 1925, and also of April 2, 1925, the maxima of the second-harmonic curves were definitely removed from the north point. Shankland et al. (1955) argued that Miller's results were largely the result of temperature artifacts. Their objections to Miller's interpretation of his own results will be further considered in section 7.

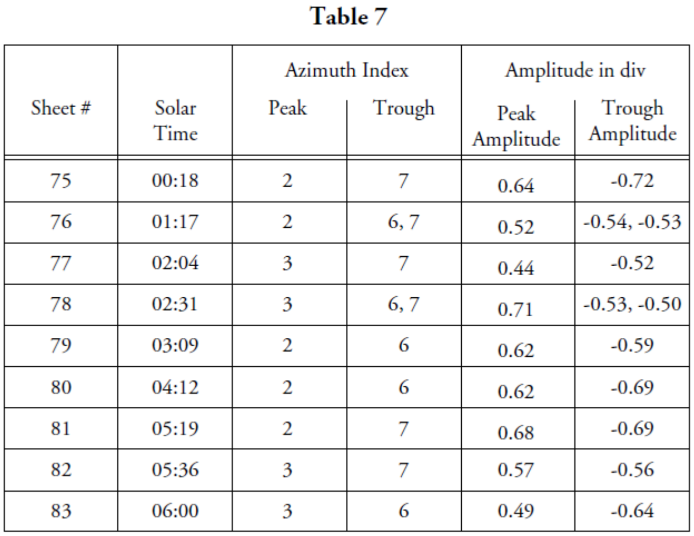


Table 7

Sheet #	Solar Time	Azimuth Index Peak	Azimuth Index Trough	Amplitude in div Peak Amplitude	Amplitude in div Trough Amplitude
75	00:18	2	7	0.64	-0.72
76	01:17	2	6, 7	0.52	-0.54, -0.53
77	02:04	3	7	0.44	-0.52
78	02:31	3	6, 7	0.71	-0.53, -0.50
79	03:09	2	6	0.62	-0.59
80	04:12	2	6	0.62	-0.69
81	05:19	2	7	0.68	-0.69
82	05:36	3	7	0.57	-0.56
83	06:00	3	6	0.49	-0.64

Comparison of azimuth index location and amplitude for all peaks and troughs in Miller's sessions 75 to 83 (September 23, 1925). No variation in phase or amplitude was observed for peaks or troughs.

The absence of dynamic aspects in these data of Miller's is also conclusive evidence that a single example (i.e. session #79) cannot establish what is a "fair sample" – since all that the example in fact shows, and which the full sample of the 9 curves (representing sessions immediately before and after session #79) alone can confirm, is that the pattern was, in this case, a *static* instrumental artifact. How, then, are we to understand the two results of the two sessions (#'s 73 and 74) on September 21, at night (see Fig. 8C)? Here, the pattern again is shared by the two curves, but is not a sine; its amplitude is also decreased when compared to the curves of September 23. Given the similarity of the September 21 curves (Fig. 8C) to the curve observed by Miller when the sun unevenly heated the apparatus (see Shankland et al., 1955, fig. 4C), as well as the similarity to curves observed by Miller when the laboratory was heating and the greatest differences were observed between the 4 wall thermometers (see the two heating curves from July 30, 1925, also in Shankland et al.'s fig. 4C), we suggest that the 2 runs of September 21 suffered from uneven heating of the instrument.

A variance analysis of the September 23 series of 9 curves gives the population SD as 0.46 div (6.1 km/s), placing the dw of the instrument at 8.6 km/s. No aether drift was found above this value (whether negative or positive), and no aether drift greater than 3.6 km/s was found below the dw of 8.6 km/s, either. In light of the preceding analysis, we are forced to conclude that Miller's claim for an aether drift of 8-10 km/s from these experiments is totally unwarranted.

Miller claimed that his experiments from 1902 to 1926 involved over 200,000 individual readings from over 12,000 turns of the interferometer. In 1926, Miller (1926, p. 443) re-analyzed and reinterpreted his early experiments in light of the hypothesis that the earth's absolute velocity was several hundred kilometers per second. He concluded that the 1887 MM experiment and all his later published experiments had detected a small but persistent aether drift of around 7 to 11 km/s. (Since he never published the details of his re-analysis, it is impossible to verify this claim.) Miller argued that since he had rebuilt his own interferometer during that period, tried different illumination and observations systems, set it up at various sites and with different orientations, his results were not experimental artifacts, and he had succeeded in detecting a genuine aether drift.

Miller contended that the reduction from the earth's calculated velocity of 208 km/s to the measured aether drift of 10 km/s was caused either by the earth partially entraining the otherwise stationary aether, or by the interferometer arms undergoing length contraction as a result of motion through the aether, but not by the full Lorentz factor (which would have led to a perfect null result). However, it is hard to envisage how a body rotating with surface speeds no greater than 0.46 km/s (at the equator) could slow down a drift of 208 km/s to about 10 km/s at 1.8 km altitude, and virtually the same value at sea level.

Múnera (2002), a proponent of Newtonian absolute space, suggested several reasons why the observed velocity in the plane of the interferometer was significantly smaller than the calculated "absolute" velocity. First, as soon as the fringe shifted by two wavelengths, Miller recalibrated the apparatus and continued recording his measurements in fractions of a wavelength only (see Fig. 7). This criticism is misguided. Miller's intervention likely reflects the instrument's tendency to drift negatively; in session #79 alone Miller readjusted the mirrors 3 times – the first after a net negative drift of 2.5 fringes, the second after a net negative drift of 1 fringe, and the third, at the end of the session, after a net negative drift of almost 3 fringes – giving a total net negative slip of 6.5 fringes. During the same session, he also observed one positive drift of 1 fringe. If the instrument will go on drifting through many wavelengths with a negative tendency, as Miller's did, one must have an operational cut-off, and since the calibration can only be extended for certain over one wavelength, or two at most, two wavelengths may have been the right cut-off point. Miller followed Hicks (1902) (see Table 3) in applying a linear correction for drift, but Múnera believes that at least part of this drift might be due to the earth's motion, as opposed to the conventional view that it was due to thermal effects.

Múnera's second point is that the formula Miller used to derive velocity from the fringe-shift magnitude took no account of the fact that the direction of the projection of the earth's absolute motion on the plane of the interferometer was likely not along the reference arm at the beginning of each rotation of the apparatus. Thirdly, Miller adjusted to his data a curve with one maximum and one minimum within any 24-hour period, but Múnera (2002, fig. 1) claims that the daily variations in fringe shift resulting from the earth's "absolute" motion need not be perfectly sinusoidal; the curves at certain epochs may have two equal maxima and two unequal minima. The fact remains, however, that Múnera's curves are still quasi-sinusoidal because they are assumed to be harmonic patterns.

The first comprehensive error analysis of Miller's aether-drift results was conducted by Roberts (2006). Previously, "acceptance or rejection of Miller's result has been based primarily on whether or not it conforms to a person's prejudices, and not on any solid, objective criteria". He says that Shankland et al.'s examination of Miller's data did not fully resolve the issue, because they merely showed a loose correlation between signal and temperature drift, but failed to explain how that could generate Miller's result. Roberts begins by discussing Miller's data reduction algorithm; an error analysis based on sine-wave modeling shows that the error bars are enormous and Miller's results are not statistically significant (see Fig. 10). We should emphasize that these error bars are not SEM or SD values. They vary between 0.8 and 0.9 fringe (8 or 9 div), i.e. 25 to 26.8 km/s, and do not correspond to any values in our re-analysis or Miller's own analysis.

Roberts then discusses Miller's data analysis in the frequency domain using digital signal processing (DSP) techniques (which did not exist in Miller's day), and claims to demonstrate that Miller's algorithm causes the noise in the apparatus to mimic the signature of a real signal. According to his reanalysis of Miller's data, a direct quantitative model of Miller's systematic instrument drift accounts for 100% of the usable data, leaving no real signal. Roberts' re-analysis derives a value of zero with an upper limit of 6 km/s (90% confidence level) for the "absolute motion of the earth", which is "fully consistent with related experiments and the prediction of Special Relativity". He concludes that Miller "was a victim of every experimenter's nightmare, and was unknowingly looking at statistically insignificant patterns in his systematic drift that mimicked the appearance of a real signal".

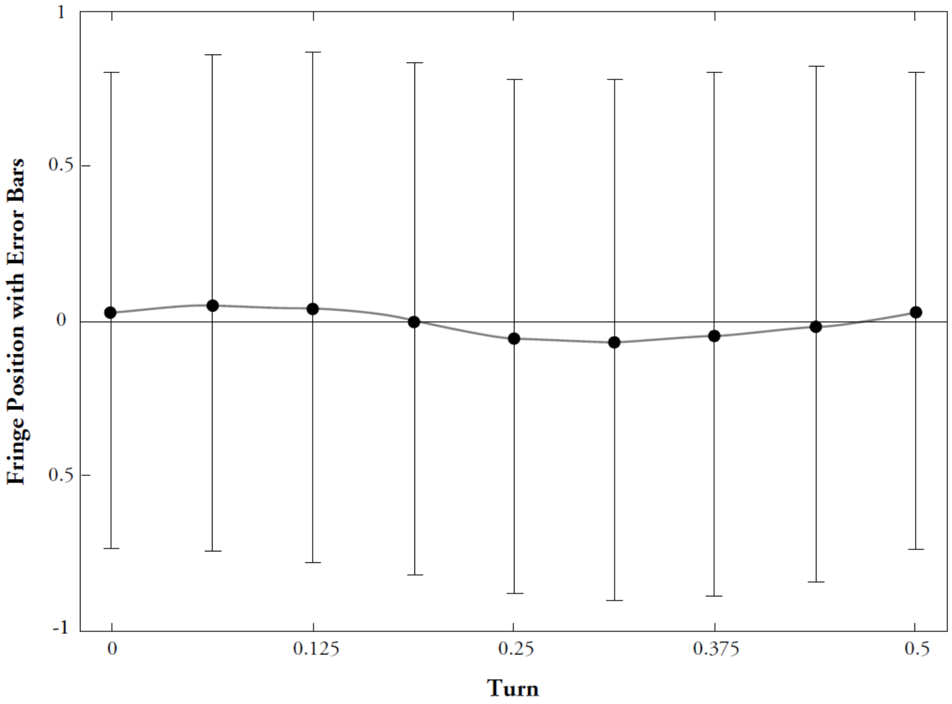


Figure 10 Plot of Miller’s curve 1 shown in Fig. 8A, but with the error bars computed by Roberts (2006, fig. 5), which correspond to the SDs of the normalized but non-denoised curve for Miller’s session 79.

6. OTHER MM-TYPE EXPERIMENTS

After Miller’s initial announcement of his Mt Wilson results in 1925, several other scientists conducted MM-type experiments (i.e. using local light sources), and generally detected much smaller values of aether drift, which they regarded as null results.

Piccard & Stahel (1926) reported an aether-drift experiment in a balloon over Belgium. The interferometer, with a light path of 2.8 m, had a self-recording device and a thermostat control, and was enclosed in an evacuated metal case. From 96 turns of the interferometer, they obtained a speed of 6.8 km/s with a very large probable error of 7 km/s. They concluded that the accuracy of the experiment was not sufficient to confirm or refute Miller’s results. They repeated the experiment in a laboratory in Brussels (Piccard & Stahel, 1927). 60 turns of the interferometer produced an average displacement of 0.0002 ± 0.0007 of a fringe, corresponding to 1.7 ± 3.1 km/s. The experiment was then repeated on Mt Rigi in Switzerland (Piccard & Stahel, 1928). The data from 120 turns of the interferometer produced a sinusoidal curve corresponding to 1.45 km/s (they did not report a probable error). Whereas Miller used a mechanical harmonic analyzer to analyze his data, Piccard and Stahel used the least-squares method, which makes no assumptions about curve shapes.

Kennedy (1926) developed a small, accurate apparatus with a total light path of about 4 m. The optical system was sealed in a small metal case containing helium, and the apparatus was placed in a constant-temperature room at the California Institute of Technology in Pasadena. He then repeated the experiment in the 100-inch telescope building at Mt Wilson Observatory. He reported finding no nonzero aether drift as great as 1 km/s (Michelson, 1928, p. 373), but failed to provide any details of his results.

In 1927, Illingworth (1927) conducted an experiment using a modified Kennedy apparatus. He concluded: “Additional readings, which eliminate steady thermal shifts of the fringes, have been made and these show no ether drift to an accuracy of about one kilometer per second.” Roberts (2006) points out that since Illingworth took data at only four points around the circle, it is impossible to extract the Fourier amplitude from his measurements. He computes the error bars and concludes that “there is no significant variation in these data”, though in his view the upper bound Illingworth places on any signal remains valid. We would observe that the upper bound on the mean signal is only valid if all numbers are treated as absolute numbers. We consider this to be a basic error, since the results are based on differences (and there are observed negative and positive drifts), and all differences are inverted when absolute numbers are used. If this is not done, the mean of the Illingworth experiments is: 0.36 km/s ±SEM 0.5, SD 1.32, not 1.08±0.28. Here, too, Roberts reports much larger errors in his analysis of the Illingworth experiment because he uses the normalized but not denoised values.

Michelson, Pease, and Pearson (MPP) carried out three interferometer experiments in 1926-28, which they reported in two almost identical, very sketchy papers (Michelson et al., 1929a; Michelson et al., 1929b). A fringe shift of 0.017 was predicted for the first experiment, but “no displacement of this order was observed”. The second experiment, like the first, employed a round-trip light path of about 32.3 m, but again “no displacement of the order anticipated was obtained”. The next year, a third experiment was conducted in “a well-sheltered basement room of the Mount Wilson Laboratory”, with a round-trip light path of 51.8 m. Michelson et al. (1929a) wrote: “The results gave no displacement as great as one-fifteenth of that to be expected on the supposition of an effect due to a motion of the solar system of three hundred kilometers per second.” This corresponds to 77.5 km/s (= 300/(√15). However, shortly thereafter, Michelson et al. (1929b) reported that the relative displacement was less than 1/50 (rather than 1/15) of that expected, corresponding to a velocity of 42.4 km/s [6]. The actual fringe shift data were not reported.

It appears that MPP may have misreported the results of their experiments in their two official papers. At a meeting in honor of Michelson, held in November 1928, Michelson “reaffirmed the null results for which he was most famous” (Swenson, 1972, p. 221). At a press conference afterwards, Michelson repeated that his latest experiments had given negative results, while Miller insisted that his own results had been positive, but “conceded that the cause of his positive results might have been periodic temperature fluctuations” (Swenson, 1972, p. 222). In

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[6] Note that DeMeo (2001, p. 76-7) erroneously converts the first figure (1/15th of the expected fringe shift) into a velocity of 20 km/s (= 300/15), overlooking the fact that MM-type experiments are measuring a second-order effect, and that the fringe displacement is therefore proportional to the square of the velocity.

his 1933 paper, Miller (1933, p. 240) cited the MPP experiment as one of the aether-drift experiments that had given far smaller values than his own.

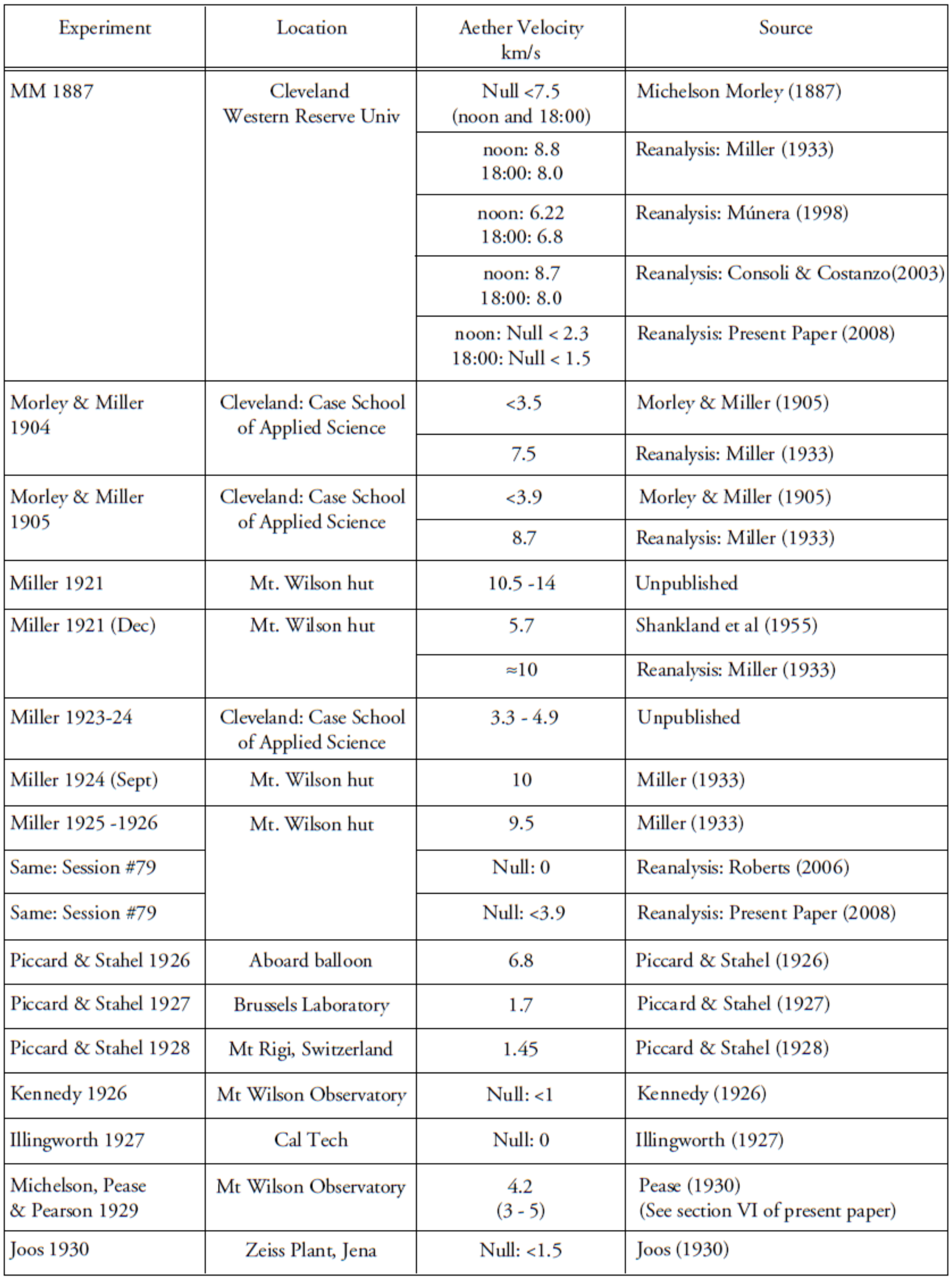
Swenson (1972), following Shankland et al. (1955), says that the fringe shift for MPP's Mt Wilson experiment was 0.01. In fact the observed fringe shifts were much smaller, as reported by Pease (1930). Four sets of trials (each set consisting of 14 to 71 sessions) for two different epochs of the year (Oct./Feb. and July/Aug.) were performed, with 3 sets carried out at the times corresponding to Miller's maximum and minimum effects, i.e. 05:30 and 17:30 sidereal time. The first of the 3 sets was expected to give a 0.021 fringe shift on the assumption of a Miller aether drift of 10 km/s, and the last two were expected to give a 0.035 fringe shift. The observed maximum amplitude shifts for all 3 tests of Miller's model yielded different azimuths with $\Delta_{\text{Max-Min}}$ values, respectively, of 0.0056, 0.0013 and 0.0043 fringe – between 4 and 10 times smaller than the expectations (the corresponding mean shifts per quadrant for the three sets were 0.0019 ±SEM 0.0014, 0.0004 ±SEM 0.0003 and 0.0006 ±SEM 0.0001 fringe). The set performed under conditions when zero fringe displacement should have resulted also yielded values comparable to the other 3 sets. These results directly contradicted Miller's model and findings. They also suggested that the upper boundary, at the time, on any remaining aether-drift residual could not have a speed greater than 3 to 5 km/s.

Pease (1930, p. 199) wrote: "At first the interferometer was rotated in one direction only and showed a sine curve of large amplitude. Reversing the direction of motion gave a similar curve of about the same amplitude but with reversed signs. Placing a lamp at various distances from the machine and in various azimuths showed that the curve could easily be increased in amplitude and the sine form distorted, but that it could not be reduced in amplitude to any extent. It was noticed that very smooth curves with steady drift were obtained on quiet foggy days and that on days when clouds passed the sun there was an alternate rise and fall in temperature drift. From these experiments it was concluded that temperature effects alone were not responsible for the sine curve." In other words, climatic conditions that produced uncontrolled heating of the interferometer clearly demonstrated that the apparatus was very sensitive to "temperature effects", yet the fact that the curve could not be reduced in amplitude below a minimum suggests that there is a threshold of noise built into the instrument. This minimum noise could still be thermal in nature, and if the instrument were cooled, the amplitude of the signal might well have been reducible. The Pease paper was published before Michelson died in 1931 – firmly convinced that no optical drift had been detected while still believing in the "luminiferous aether".

The interferometer designed by Georg Joos and built at the Zeiss plant in Jena (Germany) was the most elaborate of all optical aether-drift instruments. It was mounted on a quartz base, had helium-filled pathways, a 21 m light path, and operated automatically, with remote-controlled photography. Located in a well-insulated basement laboratory, it ran for a year (Swenson, 1972, p. 225), but Joos (1930) only selected for his analysis a total of 384 readings (8 azimuths per turn) from 48 rotations of his interferometer over a period of 24 hours. Joos's 22 curves are of different amplitudes and shapes. Joos says that the large amplitude obtained in one of the sessions (session 11 at 23:58) was due to problems with the “zero marks”. He concluded that any aether wind would have to be smaller than 1.5 km/s.

Table 8 lists all the above results.

Table 8



Experiment	Location	Aether Velocity km/s	Source
MM 1887	Cleveland Western Reserve Univ	Null <7.5 (noon and 18:00)	Michelson Morley (1887)
		noon: 8.8 18:00: 8.0	Reanalysis: Miller (1933)
		noon: 6.22 18:00: 6.8	Reanalysis: Múnera (1998)
		noon: 8.7 18:00: 8.0	Reanalysis: Consoli & Costanzo(2003)
		noon: Null < 2.3 18:00: Null < 1.5	Reanalysis: Present Paper (2008)
Morley & Miller 1904	Cleveland: Case School of Applied Science	<3.5	Morley & Miller (1905)
		7.5	Reanalysis: Miller (1933)
Morley & Miller 1905	Cleveland: Case School of Applied Science	<3.9	Morley & Miller (1905)
		8.7	Reanalysis: Miller (1933)
Miller 1921	Mt. Wilson hut	10.5 -14	Unpublished
Miller 1921 (Dec)	Mt. Wilson hut	5.7	Shankland et al (1955)
		≈10	Reanalysis: Miller (1933)
Miller 1923-24	Cleveland: Case School of Applied Science	3.3 - 4.9	Unpublished
Miller 1924 (Sept)	Mt. Wilson hut	10	Miller (1933)
Miller 1925 -1926	Mt. Wilson hut	9.5	Miller (1933)
Same: Session #79		Null: 0	Reanalysis: Roberts (2006)
Same: Session #79		Null: <3.9	Reanalysis: Present Paper (2008)
Piccard & Stahel 1926	Aboard balloon	6.8	Piccard & Stahel (1926)
Piccard & Stahel 1927	Brussels Laboratory	1.7	Piccard & Stahel (1927)
Piccard & Stahel 1928	Mt Rigi, Switzerland	1.45	Piccard & Stahel (1928)
Kennedy 1926	Mt Wilson Observatory	Null: <1	Kennedy (1926)
Illingworth 1927	Cal Tech	Null: 0	Illingworth (1927)
Michelson, Pease & Pearson 1929	Mt Wilson Observatory	4.2 (3 - 5)	Pease (1930) (See section VI of present paper)
Joos 1930	Zeiss Plant, Jena	Null: <1.5	Joos (1930)

Analytical results of Michelson-Morley-type experiments on the detection of a stationary aether or aether drag.

Esclangon (1927) made 40,000 measurements of the reflection of light when a telescope was pointed northwest or northeast, and observed a systematic variation in the position of the optical image; the “optical dissymmetry of space” had its axis of symmetry in the meridian of about 9 hours and 21 hours sidereal time. Miller (1933) suggested that this effect could be explained by aether drift and claimed the results were “in striking agreement” with his own 1925-26 experimental results; these placed the maxima and minima at about 5 and 17 hours sidereal time, compared to about 3 and 15 hours for Esclangon (but with a huge amount of data scatter in the latter).

7. A CRITICAL REVIEW OF MILLER AND HIS REVIEWERS

Miller (1933, p. 239-40) referred briefly to the Kennedy (1926), Piccard & Stahel (1927, 1928), MPP (Michelson et al., 1929a, b) and Joos (1930) experiments. He noted that in three of these experiments the interferometers were enclosed in heavy, sealed metal housings and located in basement rooms in the interior of heavy buildings below ground level. In the Piccard & Stahel experiment a metal vacuum chamber alone was used and in the MPP experiment the interferometer was in a constant temperature vault but without a vacuum case. Miller stated that “If the question of an entrained ether is involved in the investigation, it would seem that such massive and opaque shielding is not justifiable”, as it would obstruct the flow of aether. However, abandoning all shielding results in exposure to weather conditions, the diurnal cycle of solar radiation, and all sorts of thermal instabilities. This creates a classical “Batesian” double-bind situation.

It is worth noting that the 1887 MM experiment was carried out in the below-ground basement of the Main Building of Adelbert College in Cleveland, and the Morley-Miller 1902-04 experiments were carried out in the basement of the main building of the Case School of Applied Science in Cleveland. Yet according to Miller’s later analysis, these experiments yielded an aether drift that did not differ much from his 1905 experiments at Cleveland Heights or his later experiments on Mt Wilson. So Miller’s interpretation of his own experiments, along with his reinterpretation of the MM experiment and his prior experiments with Morley, would seem to indicate that the housing/shielding factor did not have a significant effect on the results.

Likewise, Miller once considered that the aether drift was greater at higher altitudes. But after his 1925-26 experiments he wrote: “The evidence now indicates that the drift at Mount Wilson [1750 m] does not differ greatly in magnitude from that at Cleveland [285 m] and that at sea-level it would probably have about the same value” (Miller, 1926, p. 443; 1933, p. 239); “The numerical values of the positive effect at Cleveland and at Mount Wilson are so nearly equal that with the observations now available (those at Cleveland being relatively few in number) it is impossible to state that there is any effect due to altitude” (Miller, 1928, p. 364).

Placing wooden covers over the light-beam paths also does not seem to have led to a significant reduction in the magnitude of the observed signals, since this was done in the 1887

MM experiment and in the Morley-Miller experiments up to and including 1904. Thereafter, Miller used glass for the sides of the light-path covers. He did not perform any control experiments with metal shielding. In his 1933 paper (p. 239-40) he announced his intention to make a full study of the shielding factor, but if he did so, he never published the results. DeMeo's claim (2001, p. 81) that "Miller found the ether-drift effect to be stronger at higher altitudes and also to be small when the experiment was undertaken in heavy stone buildings or when the interferometer light-path was encased in metal shielding" is therefore false in every respect. It is certainly possible that metal shielding *could* restrict the flow of aether, but Miller himself did not confirm this experimentally, nor to our knowledge has anyone else [7].

By the time of his 1933 paper, Miller was one of a dwindling group of scientists who still believed in a stationary electromagnetic aether. Einstein's Special and General Relativity theories had long since convinced the majority of scientists that they could "explain" all experimental results in terms of an invariant light speed and the Lorentz transformations in a curved, aetherless space – even if this involved abandoning consistent models of physical reality. Miller's 1933 paper is perhaps the most detailed case ever presented for the existence of an aether drift. Einstein was reluctant to accept that Miller had ruled out temperature artifacts, stating that if the fringe shifts were genuine "the whole relativity theory collapses like a house of cards" (Clark, 1971, p. 328).

Shortly before Miller died in 1941, he gave all his interferometer data sheets to Robert Shankland, one of his former students, telling him to "either analyze the data, or burn it". With Einstein's encouragement, Shankland et al. (1955) published an analysis that attributed Miller's findings to local temperature conditions. They concluded (p. 171) that "there can be little doubt that statistical fluctuations alone cannot account for the periodic fringe shifts observed by Miller". They noted (p. 169) that the readings usually "show considerable variation, having the general character of random fluctuations superimposed on an irregular drift". But although there was considerable scatter in the data at each azimuth position, the average values showed "a marked second harmonic effect". They argued that the observed harmonics in the fringe displacements were not caused by magnetostriction or mechanical causes, but were most likely due to temperature effects on the interferometer: "These disturbances were much more severe at Mount Wilson than those encountered by other observers in their repetitions of the Michelson-Morley experiment performed in laboratory rooms" (p. 178).

In 1923 Miller carried out laboratory tests of the effects of thermal variations on the interference fringes. If powerful radiant heat sources were focused on one arm or pair of arms of the iron cross-beams, a shift of 0.35 of a fringe (equivalent to 5.3 km/s) was produced when the interferometer was uninsulated. But this was reduced to 0.07 of a fringe when the light paths were enclosed in a glass housing covered with corrugated paper, and the metal parts covered with one-inch cork panels. However, Shankland et al.'s (1955, p. 174) analysis of these tests

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[7] Suppose there is an aether drift and the aether is conceived as having ordinary net electric charge; the presence of metal shielding could then make a difference by canceling out aether flow. Suppose instead there is no aether drift and that the major source of errors is thermal; then, a metal case is a must in order to equalize temperature differences. Still other possibilities exist.

“reveals small but certain temperature effects in contrast to Miller’s statement that he had shown the absence of periodic effects caused by artificial heating when the light path was thermally insulated”. They state that periodic temperature variations of only 0.001°C in the air of the optical arms would produce fringe shifts as large as the average effects observed at Mt Wilson.

Shankland et al. searched through the data sheets to see if they could establish a pattern between temperature conditions and fringe shifts. They concluded (p. 175):

> [We] must admit that a direct and general quantitative correlation between amplitude and phase of the observed second harmonic on the one hand and the thermal conditions in the observation hut on the other hand could not be established. The reason for this failure lies in the inherent inadequacy, for our purpose, of the temperature data available. ...
>
> It is practically impossible to carry through calculations which would predict the over-all behavior of the interferometer due to temperature anomalies, since hardly any of the necessary data for such calculations exist. In fact, the readings of the four thermometers constitute all of the available information about the temperature (and radiation) pattern in the hut. They give essentially the air temperature along the wall (but not the wall temperature), and say nothing about the temperature distribution along the roof ... We conclude from the foregoing estimate that an interpretation of the systematic effects in terms of the radiation field established by the nonuniform temperatures of the roof, the walls and the floor of the observation hut is not in quantitative contradiction with the physical conditions of the experiment.

Using Miller’s inadequate data, Shankland et al. found that small fringe-shift values usually went with small temperature differences, though the correlation was very incomplete. As far as the largest fringe-shift values are concerned, one group of data sets correlated with slightly higher temperature differences, while another correlated with lower temperatures. The authors stated that “no temperature data are available to reveal thermal conditions at the roof, which may be responsible for the large fringe displacements at the times of highest altitude of the sun” (p. 176).

Turning to midnight-dawn experiments, Shankland et al. found that the fringe behavior was the same, within experimental uncertainties, on nights when the temperature conditions remained fairly constant. In the case of 10 sets of observations from Cleveland (August 30, 1927) – like that of September 23, 1925, examined above – the second harmonics remained almost identical in both phase and amplitude throughout nearly five hours of sidereal time – something “extremely unlikely if the fringe shifts were due to any cosmic effect” (p. 177). Similar correlations between the observed second harmonics and the temperature conditions between midnight and dawn were found in each of the four epochs of the Mt Wilson experiments.

Miller (1933, p. 235) found that the direction of the aether drift did not point successively to all points of the compass (i.e. in directions 90° apart at six-hour intervals): “When the observed azimuth of motion is charted, the resulting curve of directions crosses *its own axis* twice in each day, … but this axis is variously displaced from the meridian.” The displacement was: 10° west of north for February; 40° east for April; 10° east for August; and 55° east for September (see Fig. 5). Shankland et al. (1955, p. 169) state: “The second-harmonic phases obtained by Miller from harmonic analysis of his data were never capable of being fitted into a logical relationship corresponding to an oscillation about the north point during the course of a sidereal day. ... This azimuth anomaly has been the greatest obstacle to the acceptance of the small periodic amplitude reported by Miller as having relevance to an aether-drift effect.” Miller (1933, p. 235) said that the displaced azimuths were “unexplained,” but he did say that it was only according to “the simple theory” that “the direction of cosmic motion should swing back and forth across the north and south line once in each sidereal day, because of the rotation of the earth on its axis”.

Shankland et al. (1955, fig. 3) plotted the average fringe shift against azimuth for the four epochs of 1925-26 (see Fig. 11). They found that the resulting periodic functions had amplitudes between 0.02 and 0.03 of a fringe, but differed in phase. The July, September, and April curves differ only slightly in phase, whereas the February curve is almost completely out of phase with the other three. The authors stated: “the four curves should have a common maximum (or minimum) at i = 1 [i.e. $\omega_N = 0$]; only the [speed] amplitude may be different at different epochs” (p. 172). Múnera (1998, fig. 1) suggests that the phase angle ω_N is epoch-dependent. Miller (1933, p. 236) emphasized that the phase of the four curves remains nearly constant when plotted against sidereal time, with the speed minima all occurring at about 17 hours. However, as can be seen in Fig. 5:

- Feb. 8: speed reaches the lowest value at 01:00 by range, and 17:00 by moving average.
- April 1: speed reaches the lowest value at 04:00 by range, and 12:00-15:00 by moving average.
- August 1: speed reaches the lowest value at 12:00-13:00 by range, and 16:00 by moving average.
- September 15: speed reaches the lowest value at 16:00 by range, and 17:00 by moving average.

The mean, by moving average, appears to be 15.9h; and by range, some 8.4h. Also, two of the curves (Feb. and Aug.) present minima at other times.

Shankland et al. (1955, p. 175) suggested that the considerable difference in phase between the February curve and the other curves correlates with the fact that throughout the February experiments the thermometers on the north and west walls of the observation hut consistently registered temperatures from 1 to 2°C lower than the south and east wall thermometers. This was because the ground on the northwest side of the hut was covered with snow, and the west wall was water-soaked throughout the February runs. As a result, the average temperature gradient through the hut was in the general SE to NW direction in February, while in July and September 1924 it was more nearly along the N-S line.

Shankland et al. identified one unusual series of observations among the Mt Wilson night sets: nos. 21 to 28, made between 01:43 and 06:04 on July 30, 1925. This dataset contained an extremely large peak where Miller noted “Sun shines on interferometer”. Within the bounds of the paucity of thermal data recorded by Miller, the temperature criteria are partly violated (but not very strongly), and partly satisfied, yet the run shows an extremely erratic behavior. The authors said that they had no ready explanation for this, but wondered whether it might be due to the fact that the canvas had not yet been installed over the roof, or whether canyon winds may have been unusually troublesome and lifted the canvas.

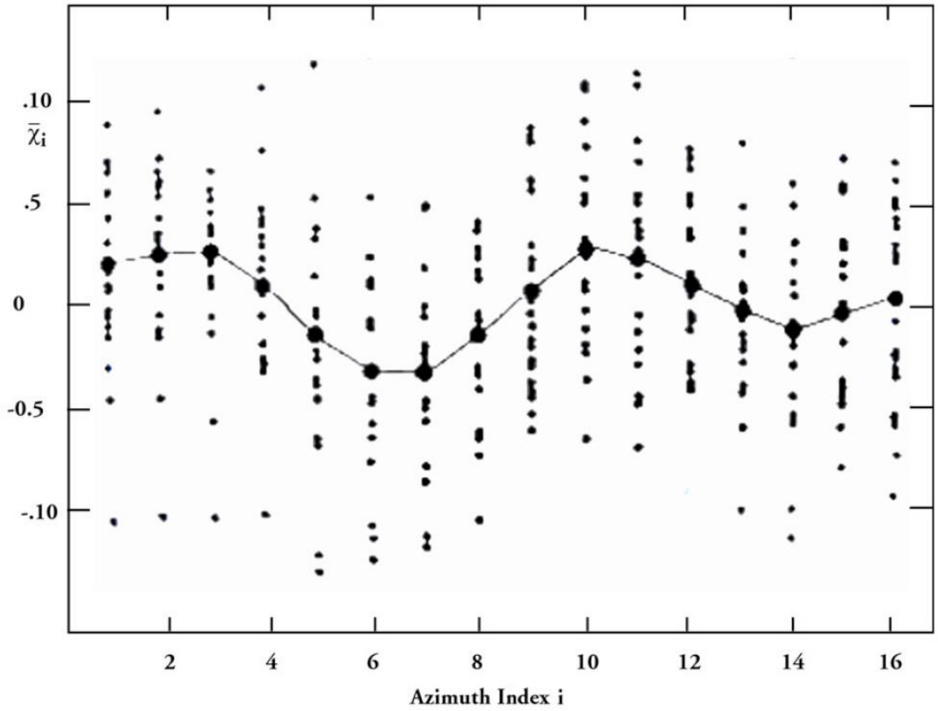

Figure 11 After Shankland et al. (1955, fig. 2): "The individual column means $\bar{x}_i$ are plotted as a function of azimuth position for the July, 1925 observational data. Large circles and the connecting curve show the second harmonic effect exhibited by the averages, ‹$\bar{x}_i$›, due to ordering in azimuth. Units for the ordinate are fringes."

DeMeo (2001) accuses Shankland et al. of "fishing" for anything that might support their argument of a claimed thermal anomaly and allow them to dismiss Miller's findings, which would have posed a major challenge to Einstein's relativity theory. He accuses them of "excluding from discussion perhaps 90% or more of Miller's extensive Mt. Wilson data", and says that their analysis was "so unsystematic and biased" that their conclusions are "meaningless". He also reproaches Shankland et al. for not clearly distinguishing Miller's 1925-26 Mt Wilson data from his "earlier, less significant work", including various control experiments in Cleveland, and says that they "willy-nilly lumped together both published and unpublished data, without comment" (p. 80-1).

In actual fact, Shankland et al. point out that some of the unpublished data were collected under what Miller considered to be very favorable conditions, yet when analyzed gave a much smaller aether drift than Miller claimed to have detected (see above, end of section 4). This suggested that Miller had not been consistent in his data selection, or the exclusion of 40% of all his data (see above). DeMeo also objects to Shankland citing data from 1925-26 which Miller himself excluded from his analysis. Such controversies could have been avoided if Miller had clearly specified the criteria he used for including or excluding experimental data. Consistent with our analysis, the Shankland et al. paper clearly established that thermal effects – including solar-induced ones – *were* at work in Miller's experiments, as Miller himself was aware. The questions that cannot be answered with certainty are: which exact sources and to what extent?

Miller failed to gather sufficient data on ambient and meteorological conditions and controls to definitively prove his borderline aether-drift case, or for others to convincingly refute it. He says that, beginning with his 1921 experiments, "Common and precision thermometers were hung on each side of the house and were read at the beginning and end of each set of observations. A barograph and a thermograph were carried at all times on the interferometer itself. An anemometer was attached to the roof of the house. A copy of the Mount Wilson Observatory meteorological records was also secured for the duration of the observations" (Miller, 1933, p. 218). Some of this information is recorded at the top of his data sheets. However, Miller never published any of it or any examinations of possible correlations between meteorological factors and ambient conditions (temperature, barometric pressure, wind, clouds, etc.) on the one hand, and his fringe-shift readings on the other. Moreover, the data he did record fall far short of what is required: he failed to measure the temperature just below the roof, at the center and near all four walls; between the top and bottom of each wall; at the wall corners, and along the path of the interferometer.

Miller stated that throughout the 1925 observations on Mt Wilson, "conditions were exceptionally good". This seems to mean a lack of weather causes that could amplify thermal variations: "At times there was a fog which rendered the temperature very uniform. Four precision thermometers hung on the outside walls of the house; often the extreme variation of temperature was not more than one tenth of a degree, and usually it was less than four tenths of a degree. Such variations did not at all affect the periodic displacement of the fringes" (Miller, 1926, p. 438). His data sheet 79 (Fig. 7) shows a temperature difference of 0.3°C between the walls at both the beginning and end of the session and a maximum temperature difference of 0.4°C between the beginning and end of the session. Miller (1926, p. 439, 442) concludes: "It has been impossible to specify any effects of temperature, radiant heat, magnetism, gravitation or any other cause, which can produce the systematic variations indicated for the different epochs. ... The fact that the observed effect is dependent upon sidereal time and independent of diurnal and seasonal changes of temperature and other terrestrial causes shows it is a cosmical phenomenon."

Miller presented the data shown in Fig. 6 to demonstrate the correlation with sidereal time. It is certainly true that the top panel appears to be less chaotic than the bottom one. However, there are a number of problems with both panels:

1. Top panel: Each of the four curves (representing means of continuous periods of six or eight days) is missing its standard error of mean (SEM) or standard deviation (SD). The mean of all four curves has no SEM or SD, but the distance of the mean curve to the four lines shows that the error of the mean centered at 60° azimuth would include nearly all points of all the curves, and that they would also fall, *by random fluctuation alone*, within twice the SD about the mean.

2. Bottom panel: The data really ought to be plotted against solar time rather than civil time, while taking note of all the solar-atmospheric conditions and events (for instance, one should not amalgamate high-wind and low-wind days, cyclonic and sunny, anticyclonic days, or clear and hazy anticyclonic days, at least *not* without first testing for their effects on the fringe shifts).
3. Both panels: the April curves in the two panels do not match. The means in bold therefore do not match either. Accordingly, this figure presents an illegitimate, and thus invalid, comparison between sidereal and civil time "results".

Miller criticized other aether-drift experiments because they were not conducted over a sufficiently long period to determine the exact nature of the diurnal and seasonal variations of velocities and azimuths. But even in his own 1925-26 experiments, observations were not made every month, and the intervals between the months in which experiments were conducted are highly uneven (February, April, August, and September).

Significantly, not a single new experiment or modern astronomical observation has confirmed any of the three main findings Miller claimed to have made: an aether drift of some 10 km/s at the earth's surface, an "absolute" velocity of 208 km/s and in the direction of Dorado. The analyses by Allais (1997, 2001) are sometimes cited in support of Miller (DeMeo, 2001, p. 81). But Allais explicitly argues that Miller's cosmic solution is *invalid* as it fails to explain the mean deviations of the azimuths and their variations from one period to another. He contends that the observed velocities and azimuths can be explained by two combined effects: an optical anisotropy of space in the direction of the mean azimuth; and an effect proportional to the total velocity of the earth, which Allais defines as "orbital velocity + cosmic velocity toward the Hercules constellation" – thereby ignoring the far greater orbital velocity of the solar system around the galactic center.

While Miller inclined towards a stationary aether which the earth partially entrains while moving through it, DeMeo (2002) tries to reconcile Miller's work with Wilhelm Reich's view that the aether is a "prime mover" that carries the solar system along with it, though Reich (1973) himself considered the 1887 MM experiment to have given a null result. Although DeMeo regards Miller's Mt Wilson aether-drift experiments as "definitive", he reverts to Miller's original northern apex of solar motion, while admitting that the relative speed between earth and aether might differ from the value of 208 km/s determined by Miller. DeMeo sees some sort of significance in the fact that Miller's original northern apex is fairly close to the solar apex with respect to nearby stars (RA = 18h, Dec = +30°, in Hercules); the two are 39° apart. However, the solar system's accepted velocity towards this apex is only 17-22 km/s (Weissman, 2014), and it is easily swamped by the solar system's velocity around the galactic center, whose official value is 240 ± 8 km/s (Particle Data Group, 2019) in the direction of Cygnus (RA = 21.2h, Dec = +48.3°). Miller's value for the earth's "absolute" motion falls just outside the range of the solar system's currently accepted galactic speed. Moreover, the accepted apex of the solar galactic motion is 36° from Miller's original northern apex, whereas Miller's preferred southern apex lies, of course, at the opposite end of the heavens!

Miller's results also fail to match the officially accepted velocity of the solar system's "absolute" motion (defined as the combination of its orbital velocity around the galactic center, our galaxy's motion with respect to the Local Group, and the latter's motion with respect to its neighbors). Based on the anisotropy of the 2.7 K cosmic microwave background, the solar system is said to be moving at a velocity of 369.82 ± 0.11 km/s in the direction RA = 11.1961 ± 0.0005h, Dec = -6.944 ± 0.007° (Planck Collaboration, 2018) – a point lying 95° from Miller's northern apex, and 85° from his southern apex.

8. CONCLUSION

Whether one expected to electromagnetically detect the orbital motion of the earth in the laboratory frame or with reference to the inertial frame of the earth, or any other of the motions of the earth known to present-day astronomy, with the optical means and methodology of the 1887 MM experiment and Miller's various repetitions, the results of the experiments reviewed here can only be regarded as null.

Given the resolutions of the instruments employed and the limits of the statistical accuracy and significance of the results, the mean values obtained in both the 1887 MM experiment and all of Miller's experiments suggest they failed to detect any significant aether drift: with a resolution of ~3.3 km/s (see Table 1), the zeroing of the instrument presented a consistently negative drift of -1.9 km/s. With a distribution width (dw) of 7.9 km/s, any aether drift with a speed lower than that would be difficult to detect. None of the azimuth index points that might be significantly different from the null hypothesis fall outside the dw value (see Table 3); nor are they consistent between the noon and 18:00 sessions.

As for Miller's results, the variance analysis of the consecutive sessions 73 to 83 indicated that, even though the instrument is better zeroed – near 0.3 km/s – the error associated with the population SD is 3.6 km/s, even larger than in the MM experiment. With a dw of 8.6 km/s, any drift lower than this value would be difficult to detect by Miller's apparatus, and none of the points that might be significantly different from the null hypothesis fell outside the dw value (see Table 7). Nor, as already observed by Shankland et al., were any changes in phase or amplitude detected in the "exemplary" experiments that we analyzed above. Given the unaccounted effect of thermal artifacts, and the variety of thermal sources present in each session, his results provide no convincing evidence for the existence of an aether drift.

The experiments we have reviewed – which have very different and improving resolutions (MM, Miller's, Illingworth's, Joos', etc.) – yielded divergent results, but none significantly different from a null result. Those who believe that Miller's later experiments detected a genuine aether drift face a number of problems, even apart from the serious statistical limitations of his results that our analysis has demonstrated. The apex of the earth's "absolute" motion determined by Miller does not correspond to the accepted direction of solar galactic motion or solar "absolute" motion, and the speed he derived (~10 km/s) is only about 1/24 and 1/37 respectively of the officially accepted speeds of these motions; it is hard to imagine how an aether wind of several hundred km/s could be reduced to so small a value at the earth's surface. The failure of later experimenters to confirm Miller's results is sometimes attributed to the presence or otherwise of shielding around the light paths, the massiveness of the structure enclosing the interferometer, and the altitude at which experiments were conducted, but we have shown that such explanations are invalid. More recent claims to have detected the earth's "absolute" motion through space by means of light anisotropy will be assessed in parts 2 and 3.

A null result from MM-type experiments is compatible with a variety of very different theories. Although both Special Relativity and Lorentz-Larmor Relativity accept length contraction (which has never been experimentally verified), and time dilation as its corollary, LLR accepts a stationary aether while SR rejects an aether altogether (since it is not necessary in order to determine the relativity of motion). On the other hand, Aetherometry – a nonrelativist theory – contends that there is strong experimental evidence for a dynamic electric aether and for the local production of photons, requiring a null result in MM-type experiments on the basis of a consistent application of the law of composition of velocities of source and receiver (Correa & Correa, 2008; Correa et al., 2008). These opposing theories will be considered further in parts 2 and 3.

REFERENCES

Allais, M. (1997). *L'Anisotropie de l'Espace*. Paris: Clément Juglar.

Allais, M. (2001). The experiments of Dayton C. Miller (1925-1926) and the theory of relativity. *Infinite Energy*, v. 7, no. 38, p. 63-67. (Also published in: *21st Century Science and Technology*, spring 1998, p. 26-33.)

Clark, R.W. (1971). *Einstein: The life and times*. New York: World Publishing Co.

Consoli, M., & Costanzo, E. (2003). The motion of the solar system and the Michelson-Morley experiment. http://arxiv.org/PS_cache/astro-ph/pdf/0311/0311576v1.pdf.

Correa, P.N., & Correa, A.N. (2008). Linear and angular light Doppler shifts and the Sagnac experiment: Aetherometry vs. Relativity (1). ABRI monograph AS3-I.3, AKRONOS Publishing.

Correa, P.N., Correa, A.N., Askanas, M., Gryziecki, G., & Sola-Soler, J. (2008). A test of Aetherometry vs Relativity, Special and Larmor-Lorentz: The 1938 Ives-Stilwell experiment – Aetherometry vs. Relativity (2). ABRI monograph AS3-I.4, AKRONOS Publishing.

DeMeo, J. (2001). Dayton Miller's ether-drift experiments: a fresh look. *Infinite Energy*, v. 7, no. 38, p. 72-82. (Updated online version: www.orgonelab.org/miller.htm, 2002.)

DeMeo, J. (2002). Reconciling Miller's ether-drift with Reich's dynamic orgone. www.orgonelab.org/MillerReich.htm.

Einstein, A. (1956). *La Relativité*. Paris: Payot.

Esclangon, E. (1927). Sur la dissymétrie de l'espace et les lois de la réflexion. *Comptes Rendus*, v. 185, p. 1593-1595.

Hicks, W.M. (1902). On the Michelson-Morley experiment relating to the drift of the aether. *Philos. Magazine*, 6th series, v. 3, p. 9-42, 256, 555-556.

Illingworth, K.K. (1927). A repetition of the Michelson-Morley experiment using Kennedy's refinement. *Physical Review*, v. 30, p. 692-696.

Ives, H.E., & Stilwell, G.R. (1938). An experimental study of the rate of a moving atomic clock. *Journal of the Optical Society of America*, v. 28, p. 215-226.

Jaffe, B. (1960). *Michelson and the Speed of Light*. New York: Anchor Books.

Joos, G. (1930). Die Jenaer Wiederholung des Michelsonversuchs. *Annalen der Physik*, S. 5, v. 7, p. 385-407.

Kennedy, R.J. (1926). A refinement of the Michelson-Morley experiment. *Proceedings Nat. Acad. Sciences*, v. 12, p. 621-629.

Lorentz, H. (1909). Michelson's interference experiment. In A. Einstein et al., *The Principle of Relativity*, New York: Dover Books.

Michelson, A.A. (1881). The relative motion of the earth and the luminiferous ether. *American Journal of Science*, 3rd series, v. 22, p. 120-129.

Michelson, A.A. (1928). Conference on the Michelson-Morley experiment, held at the Mount Wilson Observatory, Pasadena, California, February 4 and 5, 1927. *Astrophysical Journal*, v. 68, p. 341-402.

Michelson, A.A., & Morley, E.W. (1886). Influence of motion of the medium on the velocity of light. *American Journal of Science*, 3rd series, v. 31, p. 377-386.

Michelson, A.A., & Morley, E.W. (1887). On the relative motion of the earth and the luminiferous ether. *American Journal of Science*, 3rd series, v. 34, p. 333-345.

Michelson, A.A., Pease, F.G., & Pearson, F. (1929a). Repetition of the Michelson-Morley experiment. *Nature*, v. 123, p. 88.

Michelson, A.A., Pease, F.G., & Pearson, F. (1929b). Repetition of the Michelson-Morley experiment. *Journal of the Optical Society of America*, v. 18, p. 181-182.

Miller, D.C. (1922). Ether-drift experiments at Mount Wilson Solar Observatory. *Physical Review*, v. 19, p. 407-408.

Miller, D.C. (1926). Significance of the ether-drift experiments of 1925 at Mount Wilson. *Science*, v. 63, p. 433-443.

Miller, D.C. (1928). Untitled lecture. In: A.A. Michelson, Conference on the Michelson-Morley experiment, held at the Mount Wilson Observatory, Pasadena, California, February 4 and 5, 1927, *Astrophysical Journal*, v. 68, p. 352-367.

Miller, D.C. (1933). The ether-drift experiment and the determination of the absolute motion of the earth. *Reviews of Modern Physics*, v. 5, p. 203-242.

Morley, E.W., & Miller, D.C. (1905). Report of an experiment to detect the FitzGerald-Lorentz effect. *Proceedings Am. Acad. Arts & Sciences*, v. 41, p. 321-327.

Morley, E.W., & Miller, D.C. (1907). Final report on ether-drift experiments. *Science*, v. 25, p. 525.

Múnera, H.A. (1998). Michelson-Morley experiments revisited: systematic errors, consistency among different experiments, and compatibility with absolute space. *Apeiron*, v. 5, p. 37-54.

Múnera, H.A. (2002). The effect of solar motion upon the fringe-shifts in a Michelson-Morley interferometer à la Miller. *Annales de la Fondation Louis de Broglie*, v. 27, p. 463-484.

Nassau, J.J., & Morse, P.M., 1927. A study of solar motion by harmonic analysis. *Astrophysics Journal*, v. 65, p. 73-85.

Particle Data Group (2019). 2. Astrophysical constants and parameters. http://pdg.lbl.gov/2019/reviews/rpp2018-rev-astrophysical-constants.pdf.

Pease, F.G. (1930). Ether drift data. *Publications of the Astronomical Society of the Pacific*, v. 42, p. 197-202.

Piccard, A., & Stahel, E. (1926). L’expérience de Michelson, réalisée en ballon libre. *Comptes Rendus*, v. 183, p. 420-421.

Piccard, A., & Stahel, E. (1927). Nouveaux résultats obtenus par l’expérience de Michelson. *Comptes Rendus*, v. 184, p. 152.

Piccard, A., & Stahel, E. (1928). L’absence du vent d’éther au Rigi. *Comptes Rendus*, v. 185, p. 1198-1200.

Planck Collaboration (2018). Planck 2018 results. I. Overview, and the cosmological legacy of Planck. *Astronomy & Astrophysics*, in press, https://arxiv.org/pdf/1807.06205.pdf.

Reich, W. (1973). *Ether, God and Devil & Cosmic Superimposition*, Farrar, Straus & Giroux, New York.

Roberts, T.J. (2006). An explanation of Dayton Miller's anomalous "ether drift" result. http://arxiv.org/ftp/physics/papers/0608/0608238.pdf.

Shankland, R.S., McCuskey, S.W., Leone, F.C., & Kuerti, G. (1955). New analysis of the interferometer observations of Dayton C. Miller. *Reviews of Modern Physics*, v. 27, p. 167-178.

Swenson, L.S. (1972). *The Ethereal Aether: A history of the Michelson-Morley-Miller aether-drift experiments, 1880-1930*. Austin: University of Texas Press.

Weissman, P.R. (2014). The solar system and its place in the galaxy. In: T. Spohn, D. Breuer, & T.V. Johnson (eds.), *Encyclopedia of the Solar System*, Elsevier, 3rd ed., p. 3-28.