The effect of solar motion upon the fringe-shifts in a Michelson-Morley interferometer à la Miller

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ABSTRACT. The paper quantitatively describes a crucial experiment to measure the combined effect of solar motion and earth rotation upon the magnitude and direction of velocity on the plane of a *stationary* Michelson-Morley interferometer. Following Miller's idea, the variation of fringe-shift is continuously measured during 24-hours observation periods. From the shape of the fringe-shift curves the absolute terrestrial motion may be calculated. The proposed experiment improves several aspects of the original design by Miller.

1 Introduction

An overwhelming body of experimental evidence consistent with the predictions of Einstein's special theory of relativity (STR) was amassed during the twentieth century. This evidence pertains, among other aspects, to length contraction, time dilation, and velocity-dependence of mass. Regarding the interpretation of the empirical evidence, many authors follow Robertson's test theory that classifies the experiments consistent with STR as belonging to one of three classes: Michelson-Morley (MM), Kennedy-Thorndike (KT), or Ives-Stilwell (IS).[1] The majority view is that the evidence available up to date provides an undisputable proof that STR is *correct*.

However, during the last quarter of the past century, some ideas of Poincare's were revived. It was noted that, from a mathematical point of view, there may exist a whole class of "relativity theories", consistent both with Lorentz transformations and with a preferred frame; Einstein's STR being the only relativistic theory with no preferred frame.[2, 3, 4] The implication is that, within the accuracy of the available experiments, the empirical evidence cited as confirmatory of STR is also consistent with at least some of the other theories belonging to the extended class; new crucial experiments and/or higher accuracy are required to distinguish among them.

The absence of a preferred frame in Einstein's STR may be traced to the second postulate, usually interpreted as implying that the two-way speed of light equals the one-way speed of light (see, for instance, ref 3a, page 1005). Although various suggestions to measure the one-way speed of light have been advanced long ago,[5, 6] to our knowledge, the experiments have never been carried out. This is a significant loop-hole in the empirical evidence supporting Einstein's STR viz-à-viz the other "relativity theories".

More disturbing is the existence of one set of empirical evidence that is not consistent with the predictions of STR: Miller's experiments.[7] Within a Popperian epistemological context,[8] scientific theories are never "correct". A given theory may be consistent with many independent measurements at various locations, at different epochs, and related to completely different phenomena, but the theory never becomes correct or true. Of course, the largest the number of measurements consistent with a theory, the hardest it is to find an experiment that may *falsify* it.

Miller's experiments challenge the only *direct* empirical evidence that supports Einstein's postulate that the value of the velocity of light is the same for all observers in relative motion. According to the conventional interpretation, the result of the Michelson-Morley (MM) experiment was null.[9] That is, the speed of light measured along the arm of the interferometer parallel to the motion of the laboratory relative to the fixed stars has the same numerical value as the speed of light along the other arm of the interferometer (perpendicular to the laboratory motion). Hence, the speed of light is independent of the observer's state of motion confirming Einstein's second postulate.

However, Miller (who was Prof. Morley's collaborator) always insisted that the results never were null. Indeed, the fringe-shifts initially observed by MM, then by Morley and Miller, and, later on by Miller himself were consistently smaller than the fringe-shift to be expected from earth's orbital motion (30 Km/s). But it must be stressed that the fringe-shift always existed and that it was equivalent to a difference in the speed of light along the two perpendicular arms of the interferometer of the order of 8 to 11 Km/s.[7] Moreover, there appeared some unexpected seasonal variations along the year. These empirical observations do not agree with the predictions of STR.[1]

The prediction of the expected fringe-shifts in the original MM experiment, [9] and in the majority of repetitions up to 1930,[10, 11] was made under the assumption that the motion of the laboratory was produced by earth's orbital speed only; for additional references see Múnera.[12] It took almost 40 years of repetitions of the MM experiment until Miller introduced (around 1925) solar motion as a new component of velocity into the interpretation of the MM experiment.[7, 10] In Miller's opinion, the vector addition of solar motion and earth's orbital motion would lead to the seasonal variations that he discovered; some critics of Miller's work[13] did not fully grasp this straightforward explanation, and criticized Miller's observations for obtaining such unexplained results.[2]

Many authors do not take seriously Miller's experiments because they claim that after 1930 the MM experiment has been repeated many times using modern technology, and that the results have always been in accordance with the original MM experiment. A precision is required here. Starting with the Kennedy-Thorndike (KT) experiment,[14] the data reduction process suffered a change. Up to this turning point, the fringe-shifts were analyzed in an effort to detect variations that would lead to a measurement of different velocities of light along the two arms of the interferometer. About that time a consensus emerged that the (presumably) null-results of the MM experiments could be interpreted as empirical proof of the length-contraction predicted by STR.[3] The experimental setup in the KT experiment is very similar to previous MM experiments (except for the length of the arms which is not the same[4]), but the analysis of data is quite different. In the KT experiment, it is assumed that

[1] STR predicts that the speed of light is always the same, independently of time of day and season of the year. Hence, MM experiment must always yield null results.

[2] Of course, the results cannot be explained in the context of STR; but they are natural within a preferred frame theory.

[3] For instance Robertson[1] stated: "No significant difference in times was found, and since the original experiment and its repetitions were carried out at various orientations and at various times of the year, we would seem justified in interpreting this null-result as [independence of direction]" (page 380). It is noteworthy that Robertson completely ignored Miller's experiments.

[4] For most authors this is a very important difference; in our opinion it is negligible. The reason is that in the MM experiment the length of arm 1 equals the length of arm 2 up to macroscopic accuracy (at best, some tenths of millimeters). At the level of accuracy implicit in an interference pattern (of the order of tenths of the wave-length of visible light), the lengths of the two arms of the interferometer never are the same: either in a MM experiment, or in a KT experiment.

the length of the arms of the interferometer are shorter (according to the Lorentz length-contraction) than the physical value; hence, light *apparently* takes a shorter time to travel along the shortened arms. The observed fringe-shift (null, or otherwise) is then interpreted as a *measure of time dilation* with respect to the difference of apparent travel times along the two shortened arms. Since the observed data are subject to calculational manipulation during the interpretation of a KT experiment, it is quite difficult to assert from the data reported in the open literature whether a particular KT experiment exhibited fringe-shift or not.

As an example consider the excellent, and often quoted, experiment by Brillet and Hall (BH).[15] They start the paper stating that: "Our conventional postulate that space is isotropic represents an idealization of the null experiments of Michelson and Morley" (page 549). Note that BH are talking about and "idealization", and do not claim that their experiment is *exactly the same* as MM experiment; indeed, a couple of paragraphs below this openening statement they explicitly compare their results to the experiment of Jaseja and co-workers using infrared masers. [16] The latter belongs to a group of experiments headed by Prof. Townes on the isotropy of space.[16, 17, 18] Cedarholm and Townes explicitly state that "the experiment is more closely related to the Kennedy-Thorndike experiment than to that of Michelson and Morley" (ref. 18, page 1351, first column). Other contemporary experiments either belong to the KT class,[19] or have built-in corrections, whose interpretation is not clear-cut.[20] A recent paper even suggests that theory behind resonant cavity experiments (as BH experiment) may be more complicated than expected.[21]

Summarizing the previous discussion, the fact that there is one experiment (Miller's) that *apparently* contradicts the predictions of STR warrants, in our opinion, a repetition of Miller's experiment using modern technology. Our belief is strengthened because our own revision of all the true MM experiments (up to 1930) indicates that the experiments *actually* yielded non-null differences of light speed that consistently were *interpreted* as null results.[12] Our calculation of the expected fringe-shift for the date and location of the actual experiments uncovered several factors that had been unnoticed thus far, in particular a strong diurnal variation of the fringe-shift for a given orientation of the interferometer. Such variations amount to apparent velocities of the earth relative to the sun in the range from 0 to 30 Km/s, instead of the conventionally expected 30 Km/s.

Therefore, the objective of this paper is to describe a new crucial experiment based on a stationary MM interferometer, that (hopefully) improves upon Miller's experimental and data-reduction design. The rest of the paper is organized as follows. Section 2 presents, in the first part, a synthesis of Miller's experiments that stresses the main differences with the other MM experiments; the second part gives a detailed calculation for the combined effect of earth rotation and solar motion upon the fringe-shifts in a MM interferometer. Section 3 discusses the implications of the fringe-shift curves obtained in previous section for the interpretation of both the MM and the Miller experiments; some weaknesses in Miller's analysis are uncovered. Section 4 describes a method to obtain the absolute value of the solar velocity from the daily observations in a MM interferometer. A final section 5 summarizes the main findings described in the paper.

2 Diurnal fringe-shifts in a MM interferometer

2.1 Miller's rotating interferometer

As mentioned in the introduction, the MM experiments were initially interpreted in the context of earth's orbital motion only. Around 1925 Dayton C. Miller put forward a different interpretational setup:[7, 10]

> "The ether-drift interferometer is an instrument which is generally admitted to be suitable for determining the relative motion of the earth and the ether, that is, it is capable of indicating the direction and the magnitude of the *absolute motion* of the earth and the solar system in space" (emphasis in original, ref. 7, page 222).

Miller also noted that:

> "The rotation of the earth on its axis produces a velocity of less than four-tenths of a kilometer per second in the latitude of observation and is negligible as far as the velocity of absolute motion is concerned; but this rotation has an important effect upon the apparent direction of the motion and is an essential factor in the solution of the problem. However, since the orbital component is continually changing in

> direction, the general solution is difficult; but by observing the resultant motion when the earth is in different parts of its orbit, a solution by trial is practicable. For this purpose it is necessary to determine the *variations* in the magnitude and in the direction of the ether-drift effect throughout a period of twenty-four hours and at three or more epochs of the year" (emphasis in original, ref. 7, page 223).

The values reported by Miller for the projection of cosmical motion on the plane of the interferometer are in Table 1 (taken from table V in page 235 of ref. 7).

Table 1. Apparent velocity on the plane of the MM interferometer

Date	April 1, 1925	August 1, 1925	Sept. 15, 1925	Feb. 8, 1926
Velocity	10.1 Km/s	11.2 Km/s	9.6 Km/s	9.3 Km/s

To obtain his data Miller *permanently* rotated the interferometer relative to the laboratory. From each rotation he calculated the apparent speed on the plane of the interferometer that was plotted versus sidereal time to obtain curves with periodic variations (see Miller's figure 22 in page 229 of ref. 7); the curves were recently reproduced in a paper by Vigier.[22] Miller also obtained the direction of the motion relative to the plane of the interferometer (this is the azimuth shown in the same figure 22 of the original reference). From the shape of these curves Miller initially concluded that the data was consistent with a solar motion of "200 Km/s, or more, toward an apex in the constellation Draco, near the pole of the ecliptic, which has a right ascension of 255° (17 hours) and a declination of +68°" (page 361, ref. 10). After several additional years of excruciating analysis, Miller concluded that solar motion was in the opposite direction[5] with a "velocity of 208 Km/s, directed to the apex having a right ascension of 4 hours and 54 minutes and a declination of $-70°33'$" (page 234, ref. 7).

For completeness, it is noted that Miller did not calculate *predictions* for the expected shape of his curves (as in figure 1 of this paper). Rather he used the shape of the empirical curves, together with the seasonal variations, to derive solar motion. To help him visualize the process Miller built mechanical models shown in figs. 17,18,19,24 and 29 of ref.

[5] ¿From the equations to be presented in section 4 below, it can be seen that there are two roots for absolute motion, collinear, but in opposite directions.

7. For the formal mathematical analysis, Miller refers to a paper by Nassau and Morse. [23]

Therefore, Miller's research differed from all other MM experiments in two extremely significant aspects:

(1) Identification and measurement of the apparent changes of velocity on the interferometer plane as a function of time. The majority of other experiments measured the fringe-shift at two times of the day (say, separated 6 hours). The temporal evolution of the fringe-shifts identified by Miller was ignored from the outset in the other experiments; for instance, MM averaged out the variations implicit in the two different measurements.[9, 12]

(2) Realization that solar motion and earth rotation have non-negligible contributions to fringe-shift.

Turning now to the weaknesses of Miller's work. From the present author's vintage point, there are two aspects that must be emphasized in the data-reduction process, namely:

(a) There are strong oscillations around the mean value of Miller's magnitude-time curves (see his figure 22 in ref. 7). These oscillations may be due in part to unavoidable variations associated with the rotation of the interferometer, but may also result from two additional sources (unnoticed thus far), namely : (i) the recalibration of the instrument during the measurements (see section 3a below), and (ii) Miller's treatment of apparent magnitude and azimuth as separate entities (see section 3c below).

(b) Miller adjusted to his data a curve with one maximum and one minimum (see his figure 26, page 235 of ref. 7); but, the shape of his experimental curves suggests that there are more than one maximum and more than one minimum within any 24-hour period. On the contrary, our calculations described below show that, in general, two equal maxima and two unequal minima are to be expected (see 3b below for further discussion). Hence, our predictions are closer to Miller's data (compare our fig. 1 to Miller's fig. 26).

2.2 Stationary interferometer

This section describes in detail the calculation of the time-delay to be expected in a *stationary* interferometer[6] as a function of time and geographical location. In the language of statistics, the resulting predictions constitute an alternative hypothesis H1 that is to be compared against the null-hypothesis H0 propounded by STR: there are no time-delays.

Consider a preferred frame of reference Σ, where light propagates isotropically with constant velocity c. An observer in relative motion with respect to Σ measures a different velocity, according to simple vector addition.[7]

For the calculations, let us adopt celestial equatorial coordinates (see any book on practical astronomy, for instance [24, 25]) with the celestial equator contained in the $z-x$ plane and the celestial north pole along the $y-$axis; the $z-$axis points in the direction of the sun at noon the day of the vernal equinox in the northern hemisphere (March 21) for an observer on the Greenwich meridian. The origin of time for earth's orbital motion is at the same moment and date.

In Cartesian coordinates, the velocity of the center of mass of the earth relative to Σ is $\mathbf{V}^T = \mathbf{V}^S + \mathbf{V}^O = X\mathbf{i} + Y\mathbf{j} + Z\mathbf{k}$, where

$$X \equiv V_x^T = V_x^S + V_x^O, Y \equiv V_y^T = V_y^S + V_y^O, Z \equiv V_z^T = V_z^S + V_z^O \quad (1)$$

The absolute solar motion $\mathbf{V}^S = (V_x^S, V_y^S, V_z^S)$ is to be determined experimentally with the aid of the MM interferometer, and $\mathbf{V}^O$ is the earth's orbital velocity.

For computational convenience it is customary to use spherical coordinates in terms of magnitude of the velocity V, the right ascension

[6]Note that this experimental design departs from the original Miller's design (a rotating interferometer).

[7]This is the essence of the alternative hypothesis H1. The essence of H0 is that a preferred frame does not exist. Of course, calculation of individual predictions must made within each hypothesis. At this stage of the comparison, hypotheses H0 and H1 are neither right, nor wrong. However, according to the majority view, the existence of an *ether* (identified by many with a preferred frame) has already been ruled out by the existing empirical evidence. As explained in the Introduction, in the opinion of the present writer, the evidence is not compelling enough.

angle α and the declination angle δ, so that

$$V_x^n = V_n \cos\delta_n \sin\alpha_n \tag{2}$$
$$V_y^n = V_n \sin\delta_n \tag{3}$$
$$V_z^n = V_n \cos\delta_n \cos\alpha_n \tag{4}$$

where the index $n = S, T$ corresponds to solar and earth velocity respectively.

To calculate the orbital motion of the earth around the sun, it is assumed that the center of mass of the earth approximately moves with speed $V_0 = 29.8$ Km/s along a circle contained in the plane of the ecliptic with angular speed $\omega_s = 2\pi$ radians/tropical year $= 1.99x10^{-7}$ rad/s. Let the inclination of the plane of the ecliptic relative to the equatorial coordinates be $\epsilon = 23.44°$, then the components of orbital velocity in celestial equatorial coordinates are

$$V_x^O = -V_0 \cos\epsilon \cos\omega_s t \tag{5}$$
$$V_y^O = +V_0 \sin\epsilon \cos\omega_s t \tag{6}$$
$$V_z^O = +V_0 \sin\omega_s t \tag{7}$$

Although the magnitude of earth's rotational velocity is negligible, it has an extremely significant effect on the value of the projection of $\mathbf{V}^T$ on the plane of the interferometer (recall Miller's quotations above). The angular speed of earth's diurnal rotation is $\omega_r = 2\pi$ radians/day $= 7.27x10^{-5}$ rad/s. A measurement performed at civil time t (in hours) in a laboratory located at longitude ρ (in °) has an angular rotation ϕ relative to the Greenwich meridian approximately given by

$$\phi = \frac{\pi(\rho_{geo} - \rho_{nom})}{180} + \frac{2\pi(t_{local} - 12)}{24} \tag{8}$$

where ϕ is in radians and ρ is positive(negative) to the east(west) of Greenwich meridian. The subscript "geo" refers to the actual geographical location, while the subscript "nom" refers to the nominal longitude associated with the local civil time.

Hence, the motion of the earth relative to Σ, as seen from local horizon coordinates in a laboratory located at latitude λ, is $\mathbf{V}^H = (V_x^H, V_y^H, V_z^H)$ given by

$$\mathbf{V}^H = R_\lambda R_\phi \mathbf{V}^T = R_\lambda R_\phi (\mathbf{V}^O + \mathbf{V}^S) \tag{9}$$

where the rotation matrices R are

$$R_\lambda = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\lambda & -\sin\lambda \\ 0 & \sin\lambda & \cos\lambda \end{pmatrix}, R_\phi = \begin{pmatrix} \cos\phi & 0 & -\sin\phi \\ 0 & 1 & 0 \\ \sin\phi & 0 & \cos\phi \end{pmatrix} \tag{10}$$

Let the two arms of a MM interferometer have lengths L_1 and L_2, respectively aligned towards the local east (E) and north (N); the third component of the horizon coordinates points towards the zenith (C). Explicitly, the components of absolute motion at the location of the interferometer are:

$$V_E \equiv V_x^H = X\cos\phi - Z\sin\phi \tag{11}$$
$$V_N \equiv V_y^H = -[X\sin\phi + Z\cos\phi]\sin\lambda + Y\cos\lambda \tag{12}$$
$$V_C \equiv V_z^H = +[X\sin\phi + Z\cos\phi]\cos\lambda + Y\sin\lambda \tag{13}$$

The interference pattern in a *stationary* interferometer depends upon V_E and V_N. Equivalently, the pattern is controlled by the value and direction of the projection of absolute velocity on the plane of the interferometer, given by V_I in a direction γ relative to the local east:

$$V_I = \left[V_E^2 + V_N^2\right]^{1/2} \tag{14}$$
$$\tan\gamma = \frac{V_N}{V_E} \tag{15}$$

Let T_j be the time of transit of a light-ray along arm $j = 1, 2$ of the interferometer. Then, the difference in the time of transit is given by the time-delay of the light signal as

$$\Delta T \equiv T_1 - T_2 = \frac{\overline{L}\beta_I^2 \cos 2\gamma}{c(1-\beta_I^2)} + \frac{\Delta L(4-\beta_I^2)}{c(1-\beta_I^2)} \tag{16}$$

where

$$\Delta L \equiv \frac{L_1 - L_2}{2}, \overline{L} \equiv \frac{L_1 + L_2}{2}, \beta_I \equiv \frac{V_I}{c} \tag{17}$$

As usual, the fringe-shift F is proportional to the time delay

$$F(t) = \nu\Delta T \tag{18}$$

where ν is the frequency of the light used in the interferometer, and the time dependence has been made explicit.

The standard approach is to observe the variations in the fringe-shift with respect to some arbitrary reference time, for instance the beginning of the experimental session. Then, the relative finge-shift ΔF is given by

$$\Delta F(t) = F(t) - F_0 = \nu(\Delta T(t) - \Delta T(t_0)) \tag{19}$$

In summary, in the context of the model just described, the fringe-shifts on a stationary interferometer exhibit diurnal variations, that depend upon the absolute motion of earth. Assuming that X, Y, Z are constant during a sidereal day, the problem reduces to obtaining the triplet X, Y, Z from the shape of ΔF; therefrom, $\mathbf{V}^S$ immediately obtains. As can be seen from figure 1, the shape of the diurnal $\Delta F(t)$ is very sensitive to the particular value of absolute solar motion used in the calculation. Four examples are shown, namely:

a) Miller 1. Initial results of Miller's (see 2.1 above, or page 361 of ref. 10): $V_S = 200$ Km/s, $\alpha_S = 17h = 255°$ and $\delta_S = +68°$.

b) Miller 2. Final results of Miller´s (see 2.1 above, or pages 232-234 in ref. 7): $V_S = 208$ Km/s, $\alpha_S = 4.9h = 73.5°$ and $\delta_S = -70.55°$.

c) Marinov. Using his two coupled-interferometers experiment, Marinov[26] found that absolute solar motion may be described by $V_S = 303 \pm 20$ Km/s, $\alpha_S = 14.28 \pm 0.33h$ and $\delta_S = -23° \pm 4°$.

d) SGM. There exists a lot of astronomical evidence indicating that the earth is moving towards some cosmological direction, for instance [27, 28, 29, 30]; for the illustrative purposes of this section we selected one of them at random. From an analysis of the anisotropy of cosmic background radiation, Smoot, Gorenstein and Muller (SGM)[27] concluded that their observations could be interpreted as a motion of earth relative to the background radiation with velocity $V_T = 390 \pm 60$ Km/s, $\alpha_T = 11.0 \pm 0.6h$ and $\delta_T = 6° \pm 10°$.[8] We arbitrarily assumed in fig.1d that solar motion is described by the values given by SGM for the earth. For completeness, it is noted in passing that the speed for solar and/or earth motion obtained from astronomical observations is consistent both with Galilean and with Einsteinian addition of velocity. There are two

[8] The corresponding galactic direction is l=248°, b=56°, which is roughly in the same direction as the values l=264.3°, b=48.2° given by more recent papers.[30]

reasons: (i) the order of magnitude of $\beta = V/c \approx 1x10^{-3}$ to $2x10^{-3}$ is too small to make any difference in the calculations by one theory or the other, and (ii) the accuracy of astronomical observations (tens to hundreds of km/s) is not high enough to distinguish among the two models.

3 Interpretation of diurnal fringe-shift curves

The four curves in figure 1 were calculated for an interferometer similar to the original apparatus of MM, located at Mount Wilson ($\lambda = +34.217°$, $\rho_{geo} = -118°$, $\rho_{nom} = -120°$), where Miller undertook a large part of his observations. The calculation corresponds to a 24-hour period from midnight to midnight on August 1, 1925. Direct inspection of Figure 1 prompts three remarks:

a) Thermal drift versus absolute motion drift. There may exist steep fringe-shift gradients, up to 10 wavelengths per hour (say, in figure 1d). In the original MM experiment there was a consistent drift in the fringe-shift for positions 0 and 16 (both correspond to the same local orientation of the apparatus). For instance, in the noon session of July 8, 1887, the average micrometer reading for positions 0 and 16 respectively were 44.7 and 13.7 divisions; this drift corresponds to 0.6 wavelength (see page 340, ref. 9). The average duration of a run was around 6 minutes, so that the fringe-shift gradient amounts to 6 wavelengths per hour duration. This fringe-shift variation was much larger than the (expected) 0.4 wavelength displacement due to the time-delay difference along the arms (see page 341, ref. 9). However, despite the obviously large drifts, Michelson and Morley simply ignored the unwelcome variations, and averaged them out. [9]

Hicks[31] interpreted the drift observed by MM as due to environmental thermal effects, and suggested a linear correction, that was incorporated by Miller in his analyses.[7] Other authors (e.gr. Illingworth [11]) do not refer to Hicks but use a method of data reduction that effectively implements a similar thermal correction.[12]

During his experimental sessions, Miller typically observed consistent drifts of the reference fringe; as soon as the fringe shifted by two wavelengths Miller recalibrated the apparatus and continued recording his measurements in fractions of wavelength only, i.e. without taking into account the two integer wave-lengths already shifted.[9] The remarkable fact is that Miller did not even consider the possibility that the drift could be a manifestation of absolute motion; rather, he continued using the original expectation that the shift for a single rotation of the interferometer would be around 0.4 wavelengths, without ever realizing that solar motion induces a background shift of the reference fringe, as shown by our figure 1.

Therefore, figure 1 in this paper opens up a *new interpretational* possibility: at least part of the drift observed in MM experiments may be attributed to absolute motion (as opposed to the conventional thermal drift interpretation),

b) *Daily variations of fringe-shift are not sinusoidal.* Figure 1 shows that the shape of the fringe-shift curves is very sensitive to the value of the solar velocity $\mathbf{V}^S$; in general, the shape of the curves is not sinusoidal. It is well-known that the variation of fringe-shift for one *quick* rotation of the interferometer follows a $\cos 2\theta$ expression, but it does not follow that a *slow* rotation (say, in 24-hours), also follows the same law. The reasons should be clear from the model described in section 2 above. Of course, for some particular conditions the shift curve may be close to a sinusoidal curve in 2θ, for instance figure 1d.

Miller's raw observations are summarized in his Fig. 22 (page 229, ref. 7); it may be seen that the dots that represent the average magnitude are closer to a curve having two maxima and two minima than to a curve having one single maximum and one minimum. Miller's Fig. 26 (page 235) shows the single-maximum curves that he adjusted to his data. It may be seen that the fit is reasonable for the April and September observations; but it is not good for the February and August observations that definitely depict two maxima and two minima.

[9] Miller describes in detail the procedure for data recording in pages 210-213 of ref. 7. His figure 8 (page 213) is a photograph of the records for Sept. 23, 1925. The interferometer was adjusted three times during an observation period of 16 minutes.

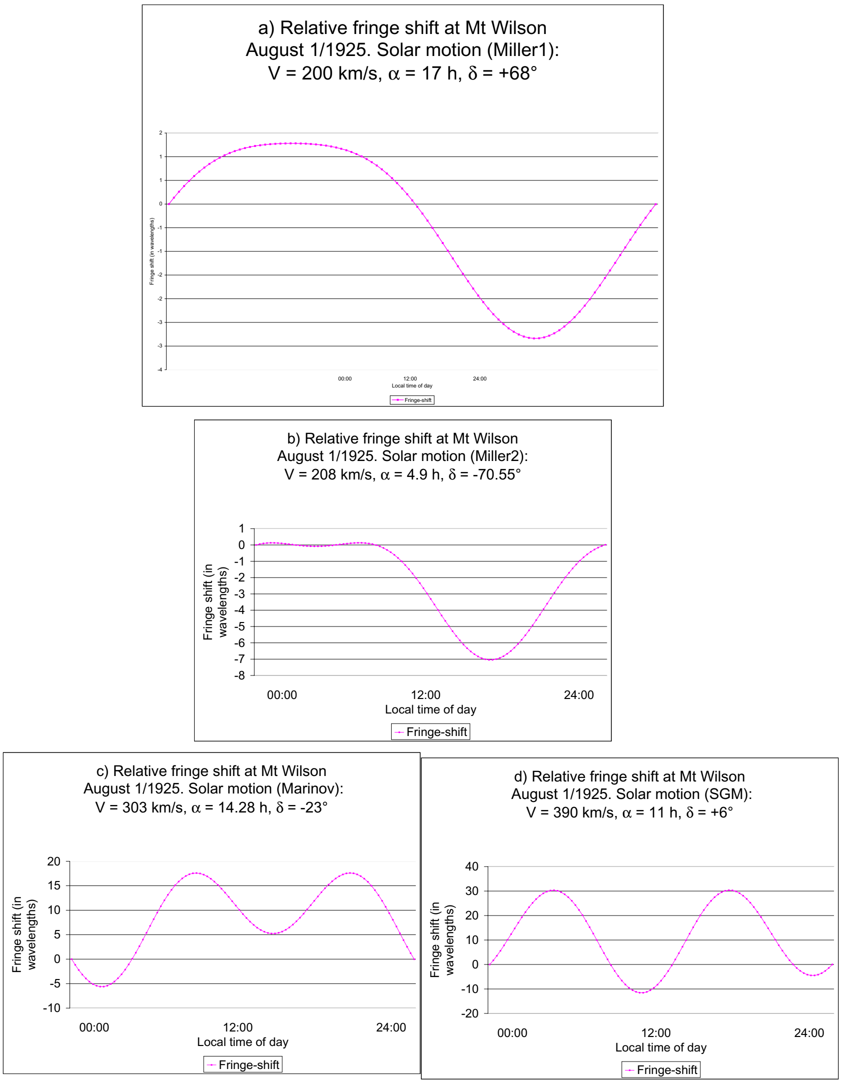

Figure 1. Prediction of relative fringe-shifts to be observed on August 1 (1925) in a stationary Michelson-Morley interferometer located at Mount Wilson, Pasadena, California, as function of time of day, from midnight to midnight. Four scenarios for solar motion are shown: (a) Miller1: V_S =200 km/s, $\alpha_S = 17$ h, $\delta_S = +68°$, (b) Miller2: V_S =208 km/s, $\alpha_S = 4.9$ h, $\delta_S = -70.55°$, (c) Marinov: $V_S = 303$ km/s, $\alpha_S = 14.28$ h, $\delta_S = -23°$, (d) Smoot, Gorenstein and Muller: $V_S = 390$ km/s, $\alpha_S = 11$ h, $\delta_S = +6°$.

Being an astronomer, Miller was fully aware of the complex nature of the daily variation of the shift curve (recall the quotations in section 2.1). However, for unknown reasons, Miller decided to fit an almost sinusoidal curve with a single maximum to his data. Of course, since our figures 1a and 1b are based on Miller's solar velocity, they show fringe-shift curves having a single maximum. However, the maximum resembles a plateau; a close analysis reveals that this plateau is produced by the coalescence of the two maxima and a local minimum (see figure 1b for a qualitative argument, and the end of section 4 for the quantitative discussion). Our figure 1a has exactly the same shape as the curve that Miller fitted to his September observations.

c) *Miller curves are not direct fringe-shift curves.* For completeness, it is noted that Miller did not carry out his measurements with the interferometer at rest with respect to local horizon coordinates, as in the calculations of section 2.2 leading to our figure 1. Rather, he rotated the interferometer at regular intervals during the day; from each rotation Miller obtained a value for the magnitude V_M of an *apparent* velocity on the interferometer plane. Miller knew that the direction of the projection of earth's absolute motion on the plane of the interferometer was not along the reference arm at the beginning of each rotation (indeed, he obtained the variation of azimuth with time). However, he ignored this fact and used for his calculation the same "relation developed in the elementary theory of the experiment" (see page 227, ref. 7). The equation is the same one used by Michelson and Morley in their original paper.[9] As discussed elsewhere by the present author,[12] Miller's choice amounts to

$$V_M = V_I \sqrt[2]{\cos 2\gamma} \tag{20}$$

Miller was aware that the observed velocity V_M on the interferometer plane was significantly smaller than his calculated velocity (see, for instance, table V, page 235 in ref. 7); however, he could not find a reason for this finding. In the present section 3, we have identified two factors that may help explain the difference: the cosine term in equation 20, and the interferometer recalibration during measurements, as mentioned in paragraph (a) above.

Comparing eqs. (16) and (18) with eq. (20), it follows that for a MM interferometer with two equal arms, the fringe shift F is proportional to V_M^2. Then, Miller's curves for magnitude V_M are proportional to $F^{1/2}$.

This implies that large values for F appear decreased in Miller's curves, while values of F close to zero appear enlarged in Miller's curves. These two traits make it difficult to identify maxima and minima in Miller's curves. This difficulty is compounded with the fact, remarked already in (a), that the fringe-shift amplitude used by Miller to calculate V_M from individual rotations may be smaller than it should be (recall the recalibration procedure).

4 Absolute velocity from fringe-shift curves

The first purpose served by an experimental determination of the fringe-shift curves is to show in a qualitative way that there exists a variation of the predicted kind, thus providing empirical support for the model of light propagation underlying section 2. Additionally, one of the goals of Miller's lifelong research carrer was the quantitative measurement of the absolute velocity of the laboratory. This value may be obtained from measuring the main features determining the shape of the fringe-curves: the position and the relative height of maxima and minima.

As seen in figure 1, the fringe-shift curves $\Delta F(t)$ exhibit two maxima and two minima over a sidereal day. Recalling that F_0 is a constant, maxima and minima appear when $\frac{dF}{dt} = 0$. This condition leads to

$$K\omega_r V_E \left(\frac{V_N}{\sin\lambda} + V_N \sin\lambda - Y \cot\lambda \right) = 0 \tag{21}$$

where K is a calibration constant relating the position of a reference fringe in the interference pattern to shift, expressed in wavelengths.

The two minima correspond to $V_E = 0$.[10] In spherical coordinates it leads to

$$V_E = V_T \cos\delta_T \sin(\alpha_T - \phi) = 0 \tag{22}$$

Neglecting the two trivial situations $V_T = 0$ and $\cos\delta_T = 0$, the two interesting solutions correspond to

$$\alpha_T = \phi_{\min} \tag{23}$$

$$\alpha_T = \phi_{\min} + \pi \tag{24}$$

[10]In astronomical parlance, this condition corresponds to the apex of the motion crossing over the local meridian.

Equations 23 and 24 imply that the two crossings over the local meridian are separated by 12 hours (this is a fact clearly stated by Miller, see page 225, ref. 7). Then, the right ascension of absolute earth motion α_T may be directly obtained from $\phi_{\min}$, the position of the first minimum in the fringe-shift curve. It is noted with Miller that the time of meridian crossing only depends of the direction of earth's motion, and is completely independent of the magnitude of the earth's velocity.

The term in parentheses in eq. 21 yields the condition for the two maxima of the fringe-shift curves. Substituting V_N and Y expressed in spherical coordinates one obtains:

$$\tan\delta_T = H(\lambda)\cos(\alpha_T - \phi_{\max}) \tag{25}$$

$$H(\lambda) = \frac{2(1+\sin^2\lambda)}{\sin 2\lambda} \tag{26}$$

A direct measurement of $\phi_{\max}$ in the fringe-shift curve allows calculation of declination δ_T from eq. 25. Substituting the two possible solutions for right ascension from eqs. 23 and 24, one obtains two collinear directions of earth motion:

$$\alpha_T = \phi_{\min}, \delta_T = \arctan\left[H(\lambda)\cos(\phi_{\max} - \phi_{\min})\right] \tag{27}$$

$$\alpha_T = \phi_{\min} + \pi, \delta_T = \arctan\left[-H(\lambda)\cos(\phi_{\max} - \phi_{\min})\right] \tag{28}$$

These two solutions were clearly identified by Miller, and led to his two values for solar motion (Miller1 and Miller 2 in Figures 1a and 1b). The explicit values of the two fringe-shift minima are given by

$$F_{\min} = -\frac{KV_T^2}{c^2}\sin^2(\delta_T \pm \lambda) \tag{29}$$

Measurement of the difference of height $D_{\min}$ between the two fringe-shift minima immediately leads to the magnitude of earth's motion

$$D_{\min} = |F_{\min,1} - F_{\min,2}| = \frac{KV_T^2}{c^2}|\sin 2\lambda \sin 2\delta_T| \tag{30}$$

It is noted that Miller did not use eq. 30 to calculate the magnitude V_T. Instead, he obtained the magnitude by comparing the fringe-shift curves at different epochs during the year.[11] It is conjectured that the

[11] A similar method may be also implemented for our fringe-shifts, and will be applied as a check in the interpretation of our experimental measurements. In this approach it is not necessary to know the calibration constant K.

reason for this decision may be the fact that Miller's curves are not direct fringe-shift curves as already explained in section 3 above.

Summarizing, from observations in a single day, it is possible to obtain two solutions of earth's velocity, given by eqs. 27, 28, and 30. Therefrom, the absolute motion of the sun may be obtained using eqs. 1 through 4.

For completeness, the fringe-shift at the two maxima have the same amplitude given by

$$F_{\text{max}} = \frac{KV_T^2}{c^2}\left(1 - \frac{2\sin^2\delta_T}{1+\sin^2\lambda}\right) \tag{31}$$

The larger value of F_{min} (given by eq. 29 with $\delta_T - \lambda$) equals F_{max} when

$$\tan\delta_T = H(\lambda) \tag{32}$$

Therefore, eq. 32 is the condition for the coalescence of three points with $\frac{dF}{dt} = 0$ into a single point. For such condition the fringe-shift curve has one maximum and one minimum. As mentioned above, Miller adjusted such a curve to his data; for Mount Wilson latitude ($\lambda = 34.217°$), eq. 32 yields $\delta_T = 70.5°$. The latter value is consistent with the values found by Miller for the declination δ_S of his solar motion in his two estimates Miller1 and Miller2.

5 Concluding remarks

Dayton C. Miller steadfastly maintained throughout his scientific carrer that there existed a non-null result in the Michelson-Morley (MM) experiment that he attributed to absolute solar motion.[7] Some critics of Miller acknowledged that "the periodic effects observed by Miller cannot be accounted for entirely by random statistical fluctuations in the basic data," but they attributed the periodic variations to periodic thermal fluctuations.[13] The controversy is still alive as witnessed by the several papers with completely different veiwpoints appearing during the past decade.[12, 21, 22, 32, 33, 34]

¿From an epistemological point of view,[8] the existence of a single experiment whose results do not easily agree with the special theory of relativity (STR) merits a repetition using modern technology. Miller's experiment differs from all other MM experiments in two aspects: continuous monitoring of the component of the laboratory velocity on the plane of the interferometer, and inclusion of solar velocity into the interpretation. The present paper describes a crucial experiment that contains these two special traits.

The model described inhere combines absolute solar motion with earth's orbital and rotational motions to predict the quantitative fringe-shift to be expected in a *stationary* MM interferometer. The variation of fringe-shift within a 24-hour period can be used to calculate the absolute motion of earth. Thence, the absolute solar velocity is obtained from the data collected in a single day. The prediction of the paper constitutes an alternative hypothesis H1 to be compared against the null hypothesis H0 provided by STR: there are no fringe shifts.

The experimental design presented in the paper tries to improve with respect to Miller's original experiment in several aspects: (a) The interferometer is always stationary with respect to the laboratory, thus decreasing observational uncertainties. (b) The data reduction process does not impose a curve with a single maximum and a single minimum during a sidereal day, but also allows for a variation with two maxima and two minima in a 24-hr period. Miller's own observations hint this shape. (c) Repetition of the experiment at different epochs is not mandatory. However, the repetition is useful because it may confirm whether the absolute solar motion is constant. (d) The obvious use of modern technology (laser and video equipment) in the experiment to be performed.[12]

The results of our experiment may be consistent with the STR if they are null. On the contrary, if the results agree with the predictions described in this paper, they strongly hint the existence of a preferred space in the context of Galilean relativity. Such interpretation would be in accordance with the accepted existence of a preferred frame for rotation as in Newton's bucket and in the Foucault pendulum; for additional empirical evidence see Vigier[22] and Allais.[34] The existence of a preferred frame for linear motion is philosophically consistent, for if one considers that linear motion is the limit of rotational motion when the radius becomes very large, there is no reason to expect that space has different properties for rotational and linear motions; Selleri[35] recently

[12] We are in the final adjustments of the experimental setup at the Centro Internacional de Física in Bogotá, Colombia.

recast the same argument as a discontinuity paradox. The empirical values to be obtained from our experiment will be compared to available solar velocities from interferometric measurements,[7, 26] to cosmological local anisotropies, [27, 28, 29, 30] and, if necessary, to the suggested cosmological rotation. [36, 37]

There is a third possibility. The empirical observations agree neither with H0 nor with H1. Then other explanations may be sought. For instance, the existence of gravitational gradients in the context of STR,[32] or the existence of a non-zero photon mass in the context of Lorentzian relativity, [22, 33] and so on. Additional evidence would be required to decide among so many different possibilities. Sooner or later, Occam's razor should be invoked .

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References

[1] H. P. Robertson, "Postulate versus observation in the special theory of relativity", *Revs. Mod. Phys.* **21**, No 3 (1949) 378-382.

[2] J. P. Hsu, (a) "New four-dimensional symmetry", *Found. Phys.* **6**, No. 3 (1976) 317-339. (b) "Erratum and addendum", *Found. Phys.* **7**, Nos. 11/12 (1977) 953-954. (c) "Laser experiments and various four-dimensional symmetries", *Found. Phys.* **7**, Nos. 3/4 (1977) 205-220.

[3] J. G. Vargas, (a) "Kinematical and gravitational analysis of the rocket-borne clock experiment by Vessot and Levine using the revised Robertson's test theory of special relativity", *Found. Phys.* **16**, No. 10 (1986) 1003-1030. (b) "Revised Robertson's test theory of special relativity: supergroups and superspace", *Found. Phys.* **16**, No. 12 (1986) 1231-1261.

[4] J. G. Vargas and D. G. Torr, "Revised Robertson's test theory of special relativity: space-time structure and dynamics", *Found. Phys.* **16**, No. 11 (1986) 1089-1126.

[5] C. B. Chiu, J. P. Hsu, and T. N. Sherry, "Prediction of variation of the speed of light measured by stable clocks", *Phys. Rev. D* **16**, No. 8 (1977) 2420-2423.

[6] J. P. Wesley, (a) "Proposed tachometer for absolute velocity", *Phys. Essays* **2** (1989) 334. (b) *Advanced Fundamental Physics*, Benjamin Wesley, Blumberg, Germany (1991).

[7] D. C. Miller, "The ether-drift experiment and the determination of the absolute motion of the earth", *Revs. Mod. Phys.* **5** (1933) 203-242.

[8] K. R. Popper, *The Logic of Scientific Discovery* , Hutchinson, London (1959). Direct translation of original German text (1934).

[9] A. A. Michelson and E. W. Morley, "On the relative motion of the earth and the luminiferous ether", *Am. J. Sci. 3rd. Series* **34**, No 203 (1887) 333-345.

[10] A. A. Michelson, H. A. Lorentz, D. C. Miller, R. J. Kennedy, E. R. Hedrick, and P. S. Epstein, "Conference on the Michelson-Morley experiment", *Astrophys. J.* **68**, No. 5 (1928) 341-402.

[11] K. K. Illingworth, "A repetition of the Michelson Morley experiment using Kennedy's refinement", *Phys. Rev.* **30** (1927) 692-696.

[12] H. A. Múnera, "Michelson-Morley experiments revisited: systematic errors, consistency among different experiments, and compatibility with absolute space", *Apeiron* **5**, No. 1-2 (1998) 371-76.

[13] R. S. Shankland, S. W. McCuskey, F. C. Leone, and G. Kuerti, "New analysis of the interferometic observations of Dayton C. Miller", *Revs. Mod. Phys.* **27**, No. 2 (1955) 167-178.

[14] R. J. Kennedy and E. M. Thorndike, "Experimental establishment of the relativity of time", *Phys. Rev.* **42** (1932) 400-418.

[15] A. Brillet and J. L. Hall, "Improved laser test of the isotropy of space", *Phys. Rev. Lett.* **42,** No. 9 (1979) 549-552.

[16] T. S. Jaseja, A. Javan, J. Murray, and C. H Townes, "Test of special relativity or of the isotropy of space by use of infrared masers", *Phys. Rev.* **133**, No. 5A (1964) A1221-A1225.

[17] J. P. Cedarholm, G. F. Bland, B.L. Havens, and C. H Townes, "New experimental test of special relativity", *Phys. Rev. Lett.* **9** (1958) 342-343.

[18] J. P. Cedarholm and C. H Townes, "A new experimental test of special relativity", *Nature* **184** (1959) 1350-1351.

[19] J. Müller and M. H. Soffel, "A Kennedy-Thorndike experiment using LLR data", *Phys. Lett. A* **198** (1995) 71-73.

[20] P. Wolf and G. Petit, "Satellite test of special relativity using the global positioning system", *Phys. Rev. A* **56**, No. 6 (1997) 4405-4409.

[21] C. Lämmerzahl and M. P. Haugan, "On the interpretation of Michelson-Morley experiments", *Phys. Lett. A* **282** (2001) 223-229.

[22] J.-P. Vigier, "Relativistic interpretation (with non-zero photon mass) of the small ether drift velocity detected by Michelson, Morley and Miller", *Apeiron* **4**, No. 2-3 (1997) 71-76.

[23] J. J. Nassau and P. M. Morse, "A study of solar motion by harmonic analysis", *Astrophys. J.* **65**, No. 2 (1927) 73-85.

[24] D. H. DeVorkin, *Practical Astronomy*, Smithsonian Institution Press, Washington and London (1986) 109 pp.

[25] P. Duffett-Smith, *Practical Astronomy With Your Calculator*, 3rd. Edition, Cambridge University Press (1988) 185 pp.

[26] S. Marinov, "Measurement of the laboratory's absolute velocity", *Gen. Rel. and Grav.* **12**, No. 1 (1980) 57-66.

[27] G. F. Smoot, M. V. Gorenstein and R. A. Muller, "Detection of anisotropy in the cosmic blackbody radiation", *Phys. Rev. Lett.* **39**, No. 14 (1977) 898-901.

[28] E. K. Conklin, "Velocity of the earth with respect to the cosmic background radiation", *Nature* **222** (1969) 971-972.

[29] P. S. Henry, "Isotropy of the 3 K background", *Nature* **231** (1971) 516-518.

[30] H. V. Klapdor-Kleingrothaus and K. Zuber, *Teilchenastrophysik*, B. G. Teubner GmbH, Stuttgart, Germany (1997).

[31] W. M. Hicks, "On the Michelson-Morley experiment relating to the drift of the aether", *Philos. Mag. Series 6* **3** (1902) 9-42 and 256.

[32] L. Bel, J. Martin, and A. Molina, "Rigid motion in special and general relativity", *J.Phys.Soc.Japan* **63**, No.12, (1994) 4350-63.

[33] J. V. Narlikar, J. C. Pecker, and J. P. Vigier, "Does a possible laboratory observation of a frequency anisotropy of light result from a non-zero photon mass m?", *Phys. Lett. A* **154**, No.5,6 (1991) 203-209.

[34] M. Allais, (a) *L'Anisotropie de L'Espace*, Editions Clément Juglar, Paris (1997) 757 pp. (b) "Des regularités très significatives dans les observations interférométriques de Dayton C. Miller 1925-1926" *C. R. Acad. Sci. Paris*, Série II **327** (1999) 1405-1410 and 1411-1419.

[35] F. Selleri, "Space and time should be preferred to spacetime", presented at *Storrs 2000*, a Meeting of the Natural Philosophy Alliance convened at the University of Connecticut (5-9 June 2000).

[36] S. Hawking, "On the rotation of the universe", *Mon. Not. R. Astr. Soc.* **142** (1969) 129-141.

[37] C. B. Collins and S. W. Hawking, "The rotation and distortion of the universe", *Mon. Not. R. Astr. Soc.* **162** (1973) 307-320.

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