Machine Systematics in Dayton Miller's "Ether Drift" Interferometer Revealed by Analysis of Variance

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Abstract

The copious data records from Dayton Miller's heroic experiments have been analyzed and re-analyzed for nearly a century by authors wishing to reinstate some version of an ether theory with a preferred frame of reference. These authors claim that a small but significant signal at the period of half a rotation in the Miller data represents anisotropy in the propagation of light, the "ether drift" effect sought in Michelson and Morley's 19th century experiment. The analysis of variance presented in this paper, however, shows a component at the period of a full rotation, which can only be a systematic in the machine or the observer. The magnitude of the systematic matches that of the component at the half-rotation period. The remarkable aspect of the story is that the implications of the full rotation systematic, which comprehensively invalidates the claim that the data reveals an "ether drift," or any other meaningful physics, has gone virtually unnoticed for nearly 100 years.

Introduction

Since the iconic Michelson-Morley experiment of 1887 failed to find anisotropy of light propagation commensurate with the orbital motion of the Earth through a hypothetical preferred frame, the small residuals seen in data from interferometric experiments have been regarded in the mainstream as instrumental defects which tended to diminish with progressive refinement of apparatus over the succeeding decades.

A few authors, however, have argued that the residuals in the data from the early 20th century studies, particularly from Dayton Miller's gigantic Michelson interferometer, represent real physics. Ingenious explanations have been proposed, all focusing on the presence of a gas in the optical pathway.

Roberts (2006) presented a more conventional interpretation, re-analyzing Miller's data using digital signal processing techniques to conclude that the reported signal was statistically insignificant, resulting merely from the filtering of random noise by the data processing algorithm used by Miller (and others of the era).

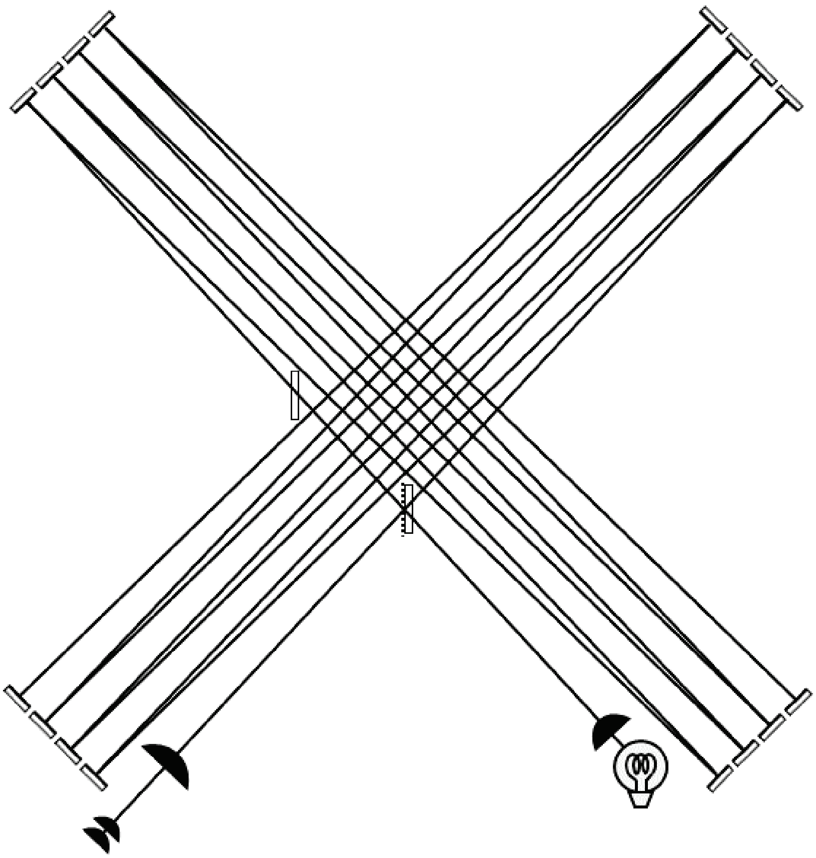
In the present paper, we take a different approach, using variance techniques to show that Miller's data does indeed contain a statistically significant signal, with sinusoidal components at the period of a half rotation and a full rotation of the instrument. A Michelson interferometer is symmetrical on a 180 degree rotation and should therefore not produce any signal with the period of a full rotation. Such a signal must be a systematic effect in the machine or the observer. It has occasionally been noticed, but never confronted, and presents a severe challenge to any thesis that interferometric experiments provide evidence for a preferred frame of reference.

Miller's Interferometer

The Michelson interferometer was the basis of all the early searches for an "ether drift." The target speed was that of the orbital motion of the Earth around the Sun, 30 km/s, four orders of magnitude less than light velocity. The expected fringe shift on rotating an interferometer was second order in v/c, indicating that a path length of 10^8 wavelengths, around 50 m for visible light, would be needed to observe a shift of a single fringe period.

By the use of multiple reflections, the light path could be increased beyond the physical dimensions of the machine. Michelson and Morley's 1887 experiment, mounted on a sandstone block with dual mirrors at the ends of each diagonal, had a light path of 22 m.

Dayton Miller's gigantic instrument (Miller, 1933) achieved an optical path of 64 m by mounting four mirrors at each end of steel girders 4.3 m long. A compensating plate of plane glass was included to balance the asymmetry of the beam splitter, a glass plate half-silvered on the side away from the light source.



Aligning the instrument was a challenging process typically requiring more than two hours before adjustments were satisfactory (Miller, 1933). After initial alignment using monochromatic light from a sodium lamp, the actual data were taken with the white light of an acetylene flame. After the instrument was set in motion, it continued to rotate by its own momentum over the next 20 minutes as the observer walked beside it, viewing the interference pattern through a telescope. The data recorded were the position of the central fringe against a fixed pointer, estimated in tenths of the fringe period. Since the slide rule was the universal aid to computation in that era, observers were probably better at estimating fractions of an interval than we might expect today.

With steel supporting beams and a long optical path, Miller's instrument suffered from thermal drift, being usable only on cloudy days and evenings with a minimal temperature cycle. When the fringe pattern drifted too far during an observation session, adjustment was made by placing small weights on one of the arms to restore the alignment.

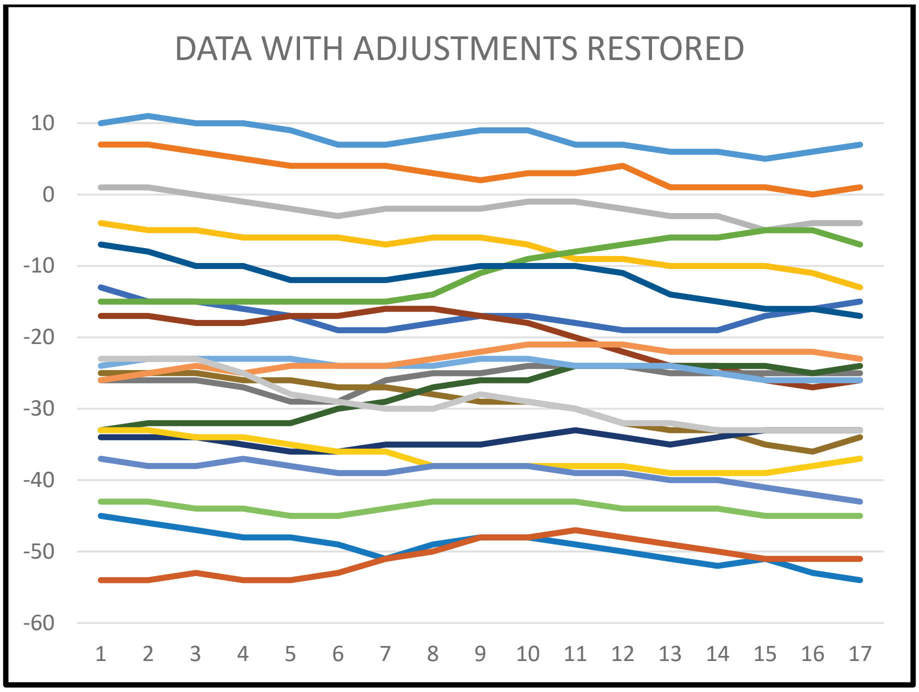
Observations were taken at 16 positions through the rotation of the instrument, with a 17th being a re-measurement of position 1, for a total of 20 rotations. The ether theory predicted a cyclic deflection with a period of half a rotation, i.e. 8 readings.

A Michelson interferometer should not record signals with a period of a full rotation. The machine, by design, is symmetrical on 180 degrees of rotation. Any signal with a period of a full rotation must be an artefact: a machine systematic or a subjective effect in the observer.

A Data Set

The data in the table below were transcribed from Figure 8 of Miller (1933), the record from September 23, 1925, taken at the Mt Wilson site.

10	11	10	10	9	7	7	8	9	9	7	7	6	6	5	6	7	
7	7	6	5	4	4	4	3	2	3	3	4	1	1	1	0	1	
1	1	0	-1	-2	-3	-2	-2	-2	-1	-1	-2	-3	-3	-5	-4	-4	
-4	-5	-5	-6	-6	-6	-7	-6	-6	-7	-9	-9	-10	-10	-10	-11	-13	
-13	-15	-15	-16	-17	-19	-19	-18	-17	-17	-18	-19	-19	-19	-17	-16	-15	Adj
0	0	0	0	0	0	0	1	4	6	7	8	9	9	10	10	8	
8	7	5	5	3	3	3	4	5	5	5	4	1	0	-1	-1	-2	
-2	-2	-3	-3	-2	-2	-1	-1	-2	-3	-5	-7	-9	-9	-11	-12	-11	
-11	-11	-11	-12	-14	-14	-11	-10	-10	-9	-9	-9	-10	-10	-10	-10	-10	Adj
8	8	8	7	7	6	6	5	4	4	3	1	0	0	-2	-3	-1	
-1	-1	-1	-2	-3	-3	-2	-2	-2	-1	0	-1	-2	-1	0	0	0	
0	1	1	1	1	3	4	6	7	7	9	9	9	9	9	8	9	
9	10	10	10	10	9	9	9	10	10	9	9	9	8	7	7	7	
7	8	9	8	9	9	9	10	11	12	12	12	11	11	11	11	10	
10	10	10	8	5	4	3	3	5	4	3	1	1	0	0	0	0	
0	0	-1	-1	-2	-3	-3	-5	-5	-5	-5	-5	-6	-6	-6	-5	-4	
-4	-5	-5	-4	-5	-6	-6	-5	-5	-5	-6	-6	-7	-7	-8	-9	-10	
-10	-10	-11	-11	-12	-12	-11	-10	-10	-10	-10	-11	-11	-11	-12	-12	-12	
-12	-13	-14	-15	-15	-16	-18	-16	-15	-15	-16	-17	-18	-19	-18	-20	-21	Adj
1	1	2	1	1	2	4	5	7	7	8	7	6	5	4	4	4	



The thermal drift, predominantly in a negative direction, is apparent. Three adjustments were made during the experimental run. The graph plots the readings with the adjustments restored.

The drift must be modelled out before any interesting signal (whether machine/observer systematics or meaningful physics) can to be recovered. Adjusting the means for each rotation is a simple matter of subtraction, but four possibilities present themselves for estimation of the slope.

1. A linear model with a slope calculated across the entire data set.
2. A separate model for each of the 20 rotations with the slope calculated by linear regression across the 17 readings.
3. A model for each rotation with the slope calculated from the difference of readings 1 and 17.
4. A model of the entire data set in parameter space, allowing the means and slopes of 20 rows to be adjusted, along with phase and amplitude of cosine wave terms, to minimize the sum of squared deviations of the model from the actual data.

Each of these options has problems. Option 1 can be ruled out by inspection of the trends in the graphed data: the slope is not constant throughout the 20 rotations. Option 2 fails because any sinusoidal signal could generate a non-zero slope, depending on phase, biasing the estimate of the drift.

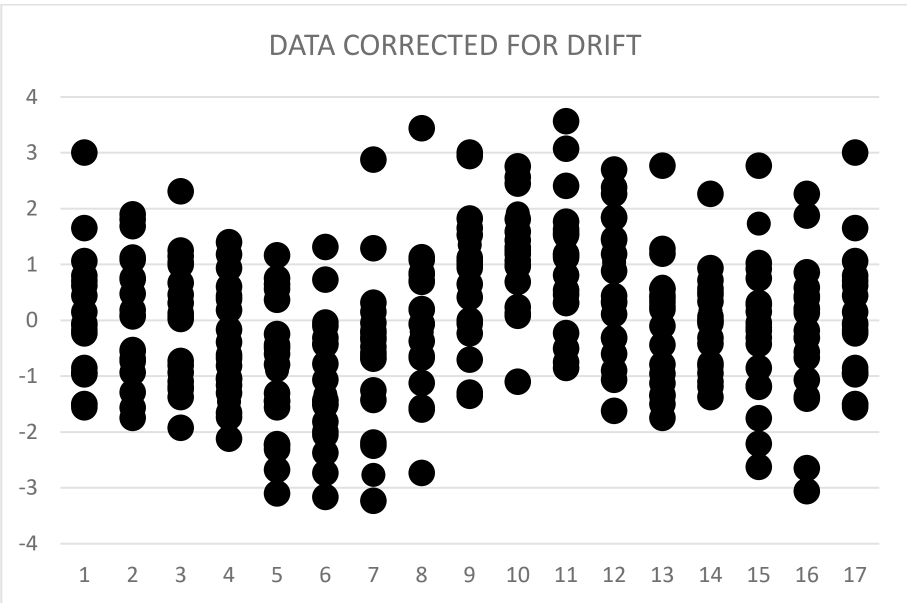
Option 3 avoids introducing the artefact related to phase and amplitude of signal components, but bases the slope estimate on a single pair of points.

Option 4, modelling in parameter space, appeals as the most statistically robust. Unfortunately, however, it is still vulnerable to the difficulty with option 2: the distortion of the slope estimate by sinusoidal components of the signal.

Fortunately for our collective sanity, all four of these methods yield results which are visually comparable, though their statistical power varies.

We will proceed with option 3, as it is least likely to introduce biases. The important components of the signal from a rotating interferometer are the periodicities on rotation. Thermal drift, which is likely to be roughly linear over any short time period, is a nuisance, but remains irrelevant to the interpretation.

The following scatterplot shows the data after the slopes had been modelled out and the means for each rotation adjusted to zero.

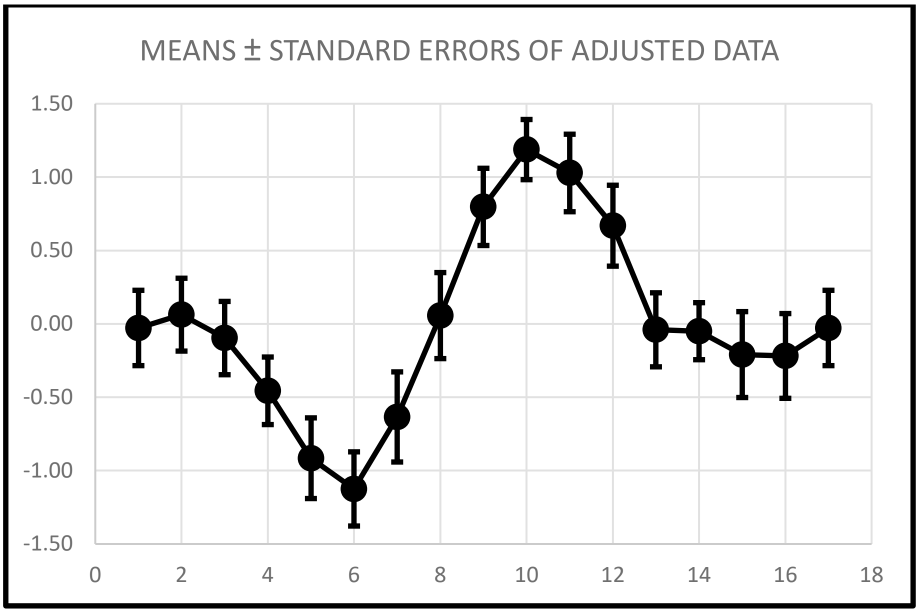


The visual impression is of a small signal buried in a great deal of noise. We use analysis of variance to test this impression. Ignoring the redundant 17th column, which the drift correction has forced to be a duplicate of column 1, we apply a single factor ANOVA over 16 columns with 20 replicates in each column.

ANOVA

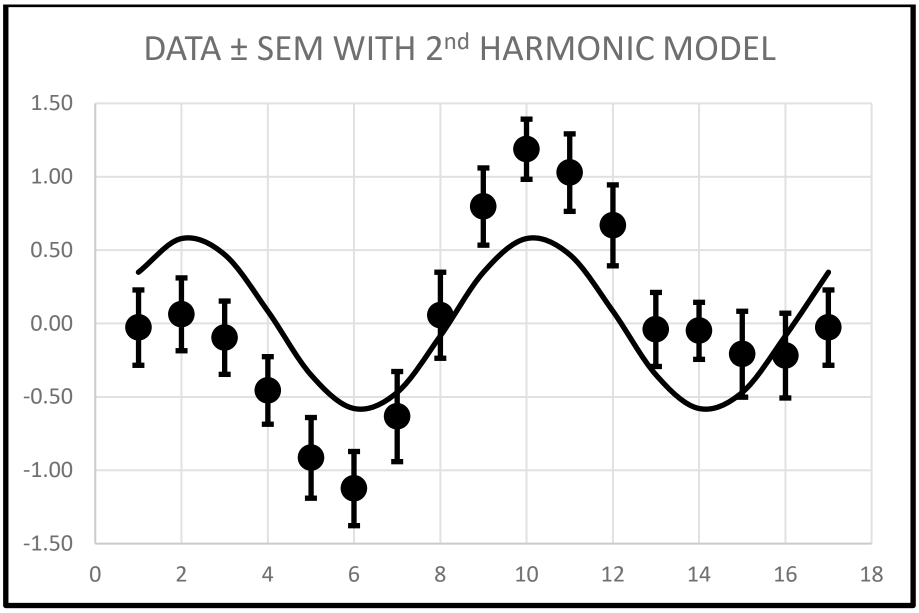
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Between Columns	127.54	15	8.503	6.241	1.73E-11
Within Columns	414.20	304	1.362		
Total	541.74	319			
Total	566.79	339			

The variation between columns is highly significant. A systematic signal must be present. Averaging the repeated readings will reduce the impact of the noise, by a factor of the square root of the number of readings. The standard deviation of the readings, given by the square root of the MS within columns, was 1.2, representing about one eighth of a fringe period in the original measurements. The standard error of the column means was around $1.2 / \sqrt{20} = 0.26$ of the reading units, about one fortieth of a fringe period, as seen in the following graph.



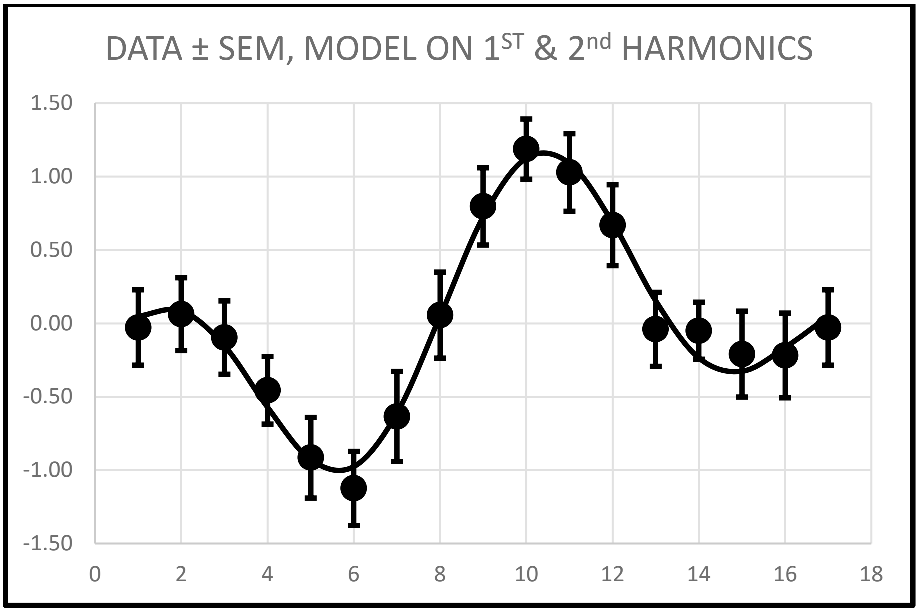
It is apparent that modelling out the drift and averaging masses of noisy data has recovered some kind of a signal. But it certainly does not appear, visually, like the expected sinusoid at twice the rotation frequency.

Modeling the signal as a cosine function whose period is half a rotation (8 readings) illustrates the problem. With the frequency fixed, the variables are the amplitude and phase of the cosine wave. The sum of squared deviations of the model from the data was calculated and the variables adjusted to minimize that sum, using the Solver function in the Data Analysis package of Microsoft Excel. The result is plotted in the following graph.



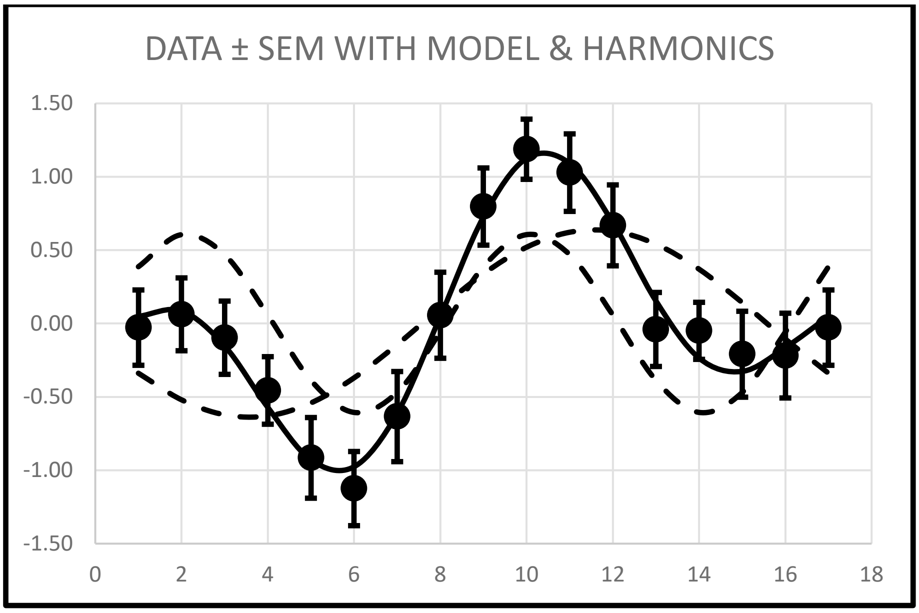
The fit of the model to the data is poor. Adjusting the amplitude to match the data around the 6th and 10th readings would make the mismatch around the 2nd and 14th even worse. With a sum of squared deviations from the observed means of 3.515, the model is only a marginal improvement over the null model, a straight line, which gave a sum of squares of 6.378 (F = 1.815, df = 15 & 13, P = NS).

A component at a lower frequency must be present. In the graph below, a cosine wave with a period of a full rotation (16 readings) was added. There were 4 parameters to adjust: two magnitudes and two phase values.



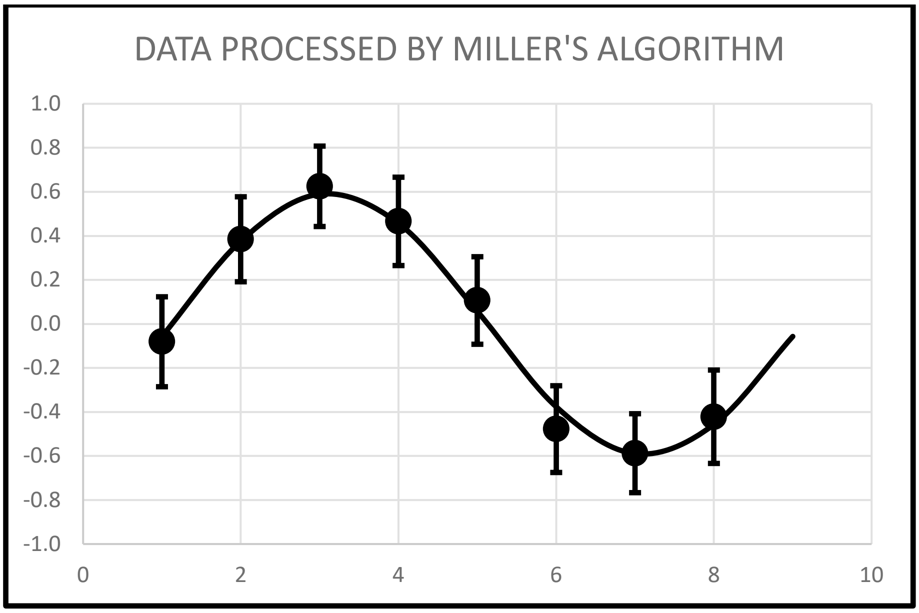
The model fits the data very well, the line lying within the standard error of every data point. The improvement in the fit was statistically significant. The sum of squared deviations of the model from the column means was reduced to 0.154, a variance ratio with respect to a null model, F = 41.42, df =15 & 11, P << 0.001, and with respect to the single frequency model, F = 22.88, df = 13 & 11, P << 0.001.

The components of the dual frequency model are shown as the dashed lines in the graph below. The magnitudes are comparable.



This is fatal for any contention that Miller's interferometer was recording meaningful physics. The symmetry of a Michelson interferometer on a 180 degree rotation precludes the detection of any genuine signal whose period is a full rotation. A systematic in the machine, or the observer, is the only plausible explanation.

Miller's 1933 publication briefly mentions a harmonic analysis, but offers no explanation for the unexpected signal component. Notably, it is suppressed by Miller's data processing algorithm: averaging readings in the pattern 1 & 9, 2 & 10 … 8 & 16.

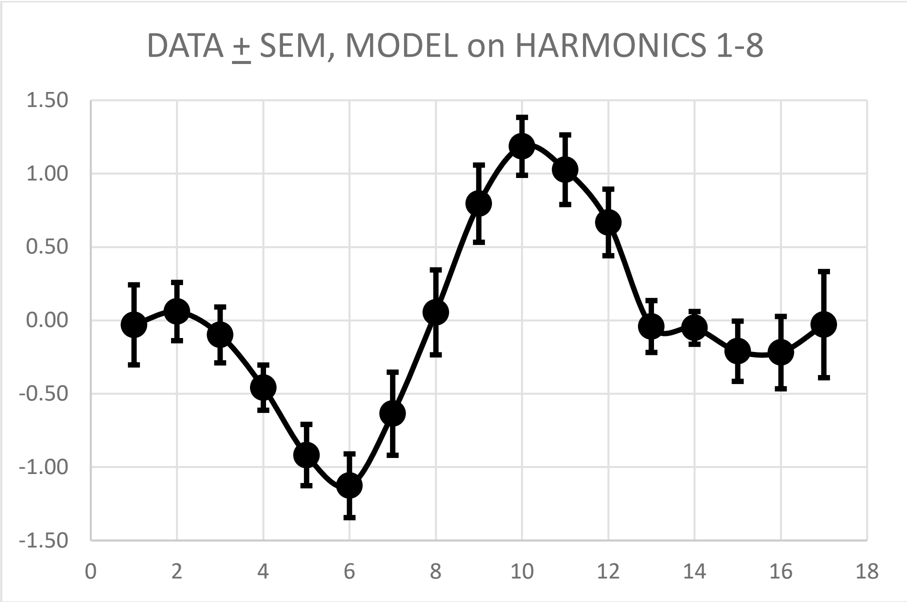


Unsurprisingly, granted the processing, the fit of the data to a single cosine wave at twice the rotation frequency, as in the graph above, is exemplary.

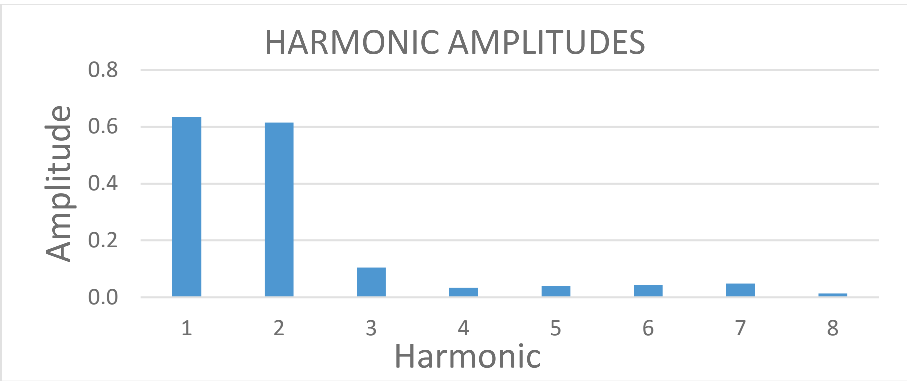
Modeling in Parameter Space

With 340 readings in an observation set, we have ample degrees of freedom to model the data with a slope and offset value for each row and cosine waves at frequencies from the rotation period up to the Nyquist limit (8^{th} harmonic, with 16 readings per rotation). We lose 40 df modelling the means and slopes for each data row, and 2 further df for each frequency included in the model.

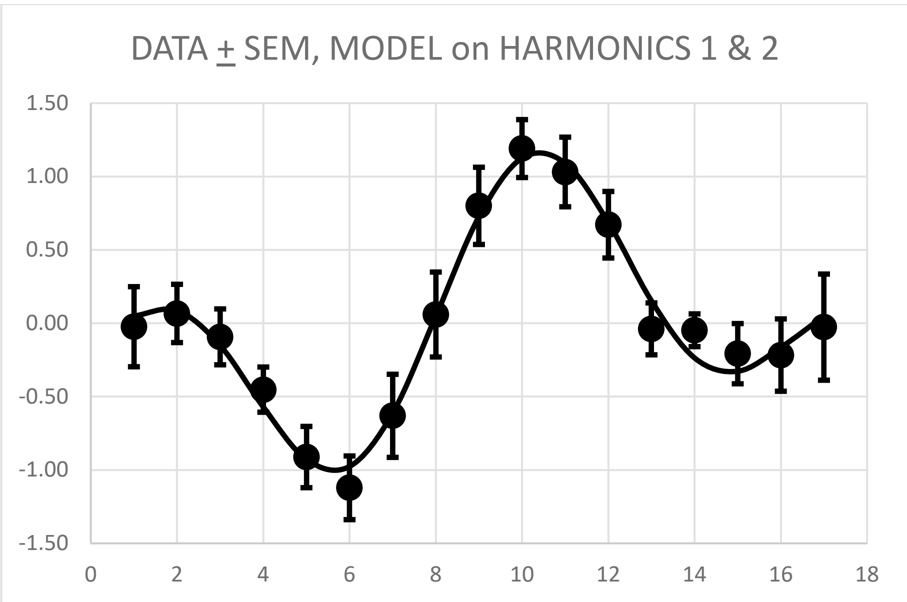
The graph below shows the fit obtained by modelling all available frequencies. The fit is perfect, of course, for the trivial reason that 16 points on the waveform were modelled by 8 + 8 = 16 adjustable parameters (the frequencies and phase offsets).



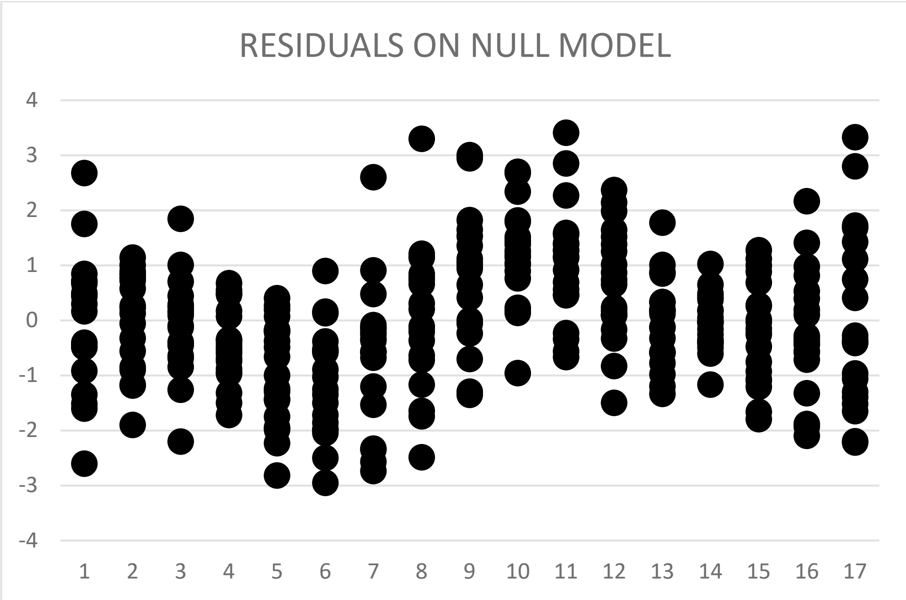
The model is dominated by the fundamental and second harmonic.

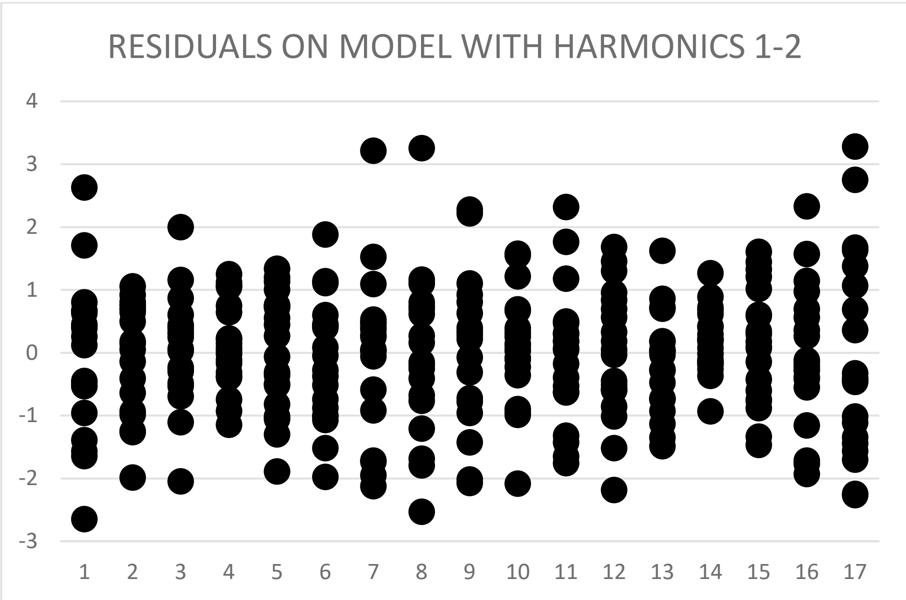


Since harmonics 3 through 8 are making little contribution, the data can be adequately modelled with only the 1st and 2nd harmonics, as in the graph following.



Scatter plots of the residuals on a null model, which minimizes variance simply by adjusting means and slopes, and with the model on harmonics 1 and 2, are shown below.



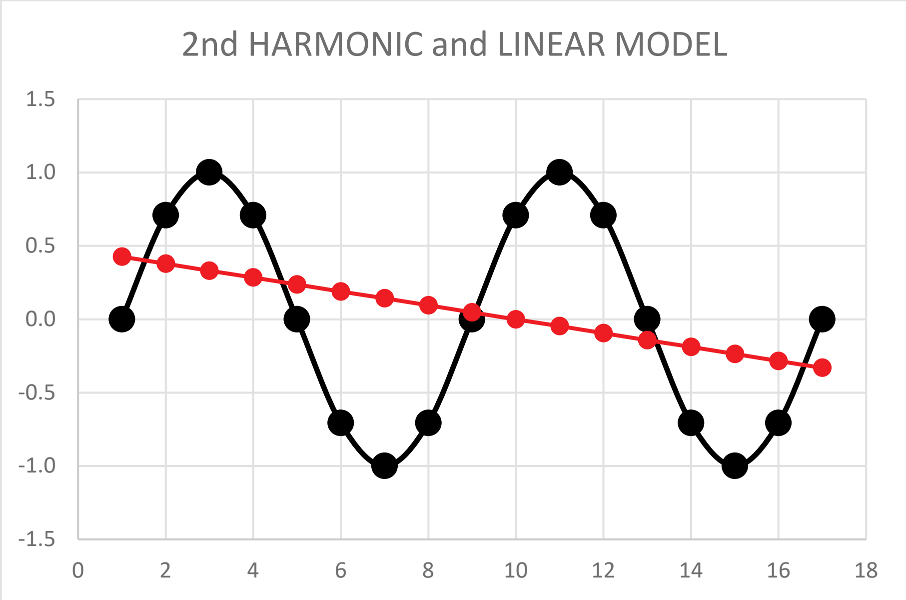


Residuals on the null model show an obvious systematic trend with an undulation submerged in the noise, but with modelling on the first and second harmonics, the residuals show no visible pattern.

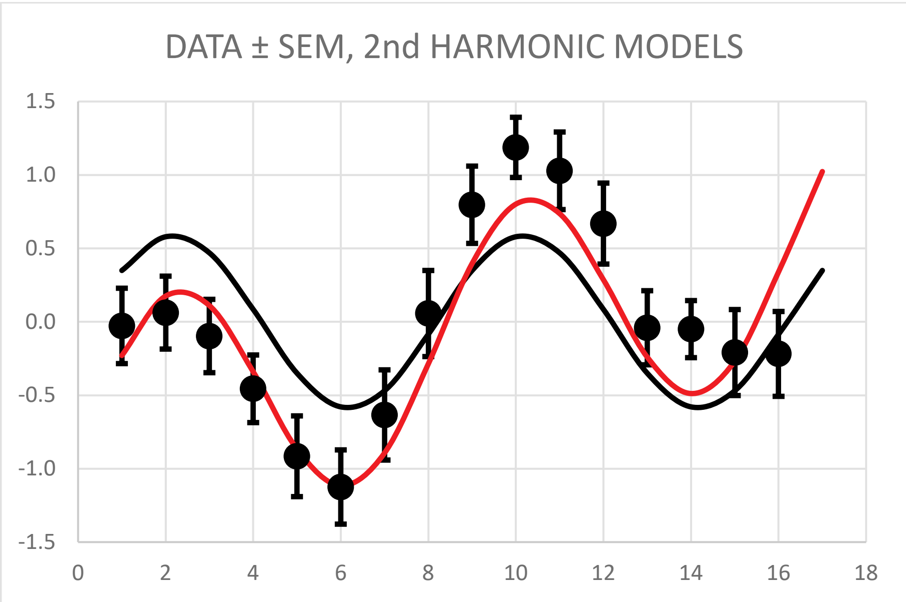
Analysis of variance reveals the significance of the improvement of the harmonic model over the null. The residual variance with the null model was 1.571, reducing to 1.198 with the 1st and 2nd harmonics modelled. The F ratio was a modest 1.312, but with the large numbers of degrees of freedom (299 & 295) was significant, $P \approx 0.01$.

Although parameter space modeling appeals from the point of view of the statistical purist, it does involve a trap for the unwary. When the slopes for the thermal drift correction are determined by minimizing variance, a bias may be introduced.

The bias arises because a sinusoidal wave may have a non-zero slope for its first order trend-line, depending on phase. The graph below shows a second harmonic wave and its best-fitting linear model.



The way this effect can distort the fitting of a model to the interferometric data is illustrated in the following graph.

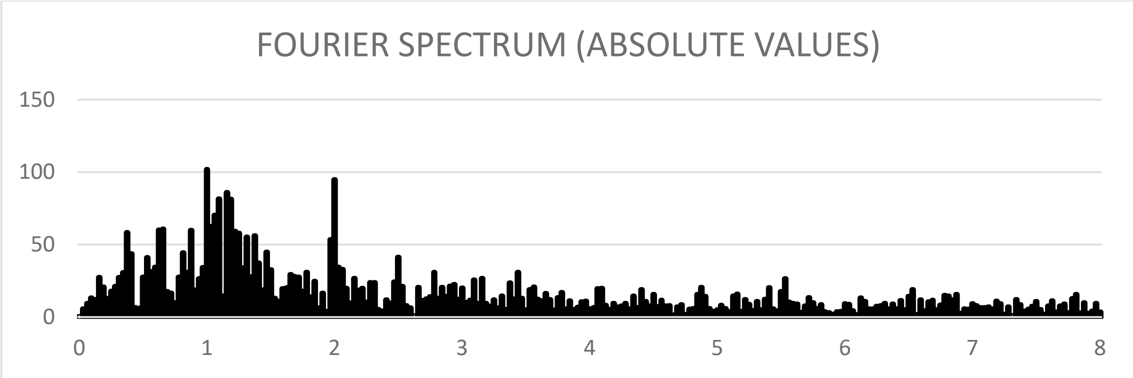


The black line is the best fit of a model containing the second harmonic only, applied without distortion of the slope. The red line was generated by allowing the slope to vary, minimizing the variance. Although the result is closer to the data points, it is clearly unphysical, being discontinuous (values 1 and 17 do not match).

Spectral Analysis

The complete spectrum of the signal in the interferometer data can be recovered, either by modelling, as above, or by Fourier analysis.

To apply Fourier algorithms, we must first reassemble the data into a linear stream of evenly-spaced data points. We delete the redundant 17th reading in each row. The Fast Fourier Transform (FFT) requires the number of data points to be a power of 2, so the data array was padded out to 512 values with zeroes – a well-known technique with FFT, narrowing the frequency bins without distorting the spectrum. The output of the algorithm is a series of complex numbers which can conveniently be displayed as their absolute value (e.g. using the IMABS function in Excel).



Since the input was the full array of 320 data points (plus zeroes) rather than the averages of 20 readings, the spectrum is much noisier than that derived by modelling and analysis of variance, but confirms the presence of peaks at the fundamental and second harmonic.

Random Data

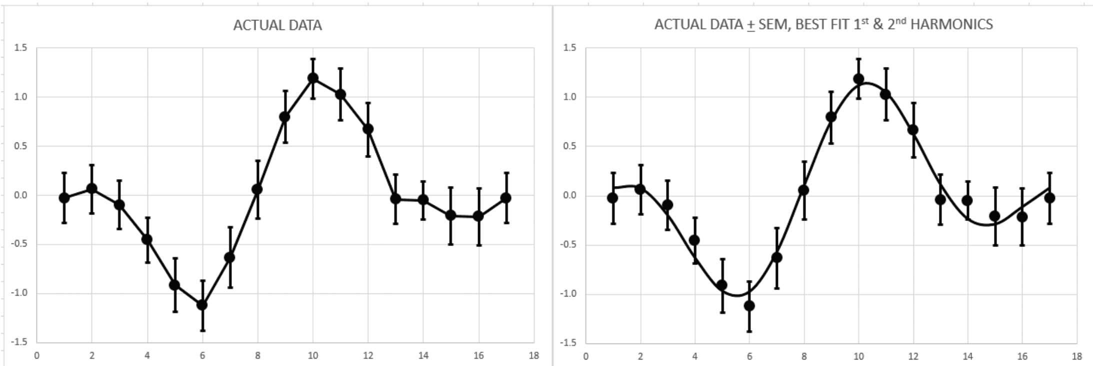
In his 2006 analysis, Roberts points out that broadband noise can appear as a sinusoidal signal if put through a sufficiently narrow filter. This is a truism. As is the fact that averaging the 20 readings in each column of the interferometer data is equivalent to applying a comb filter which responds only to the fundamental and harmonics of the rotation frequency.

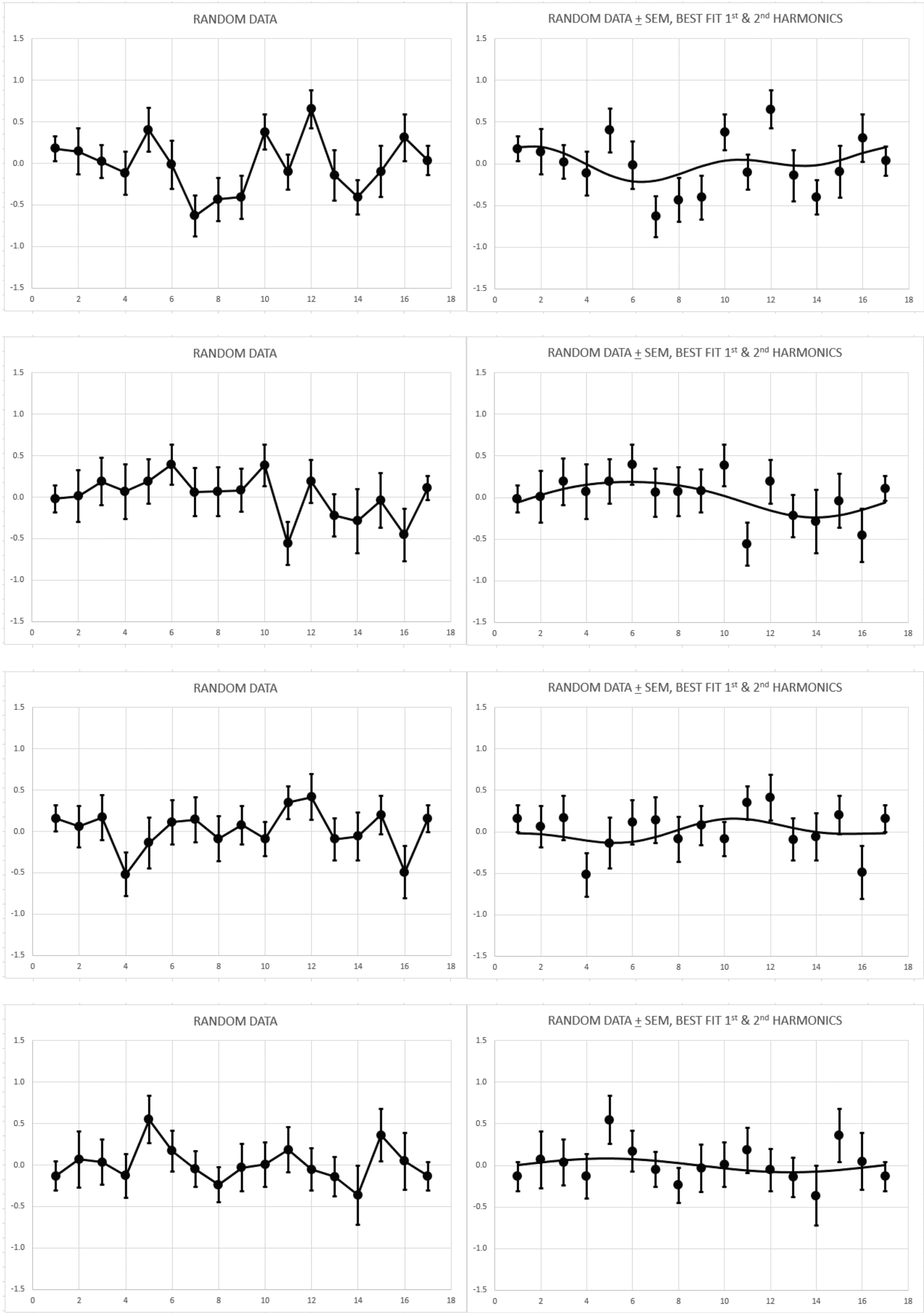
This raises the possibility, which Roberts (2006) strongly favors, that Miller's data consisted only of random numbers plus a systematic drift, implying that the apparently consistent signals Miller reported were entirely a product of his processing algorithm.

To test this possibility, we set up an Excel spreadsheet with 16 columns of 20 random number values, adjusting the scaling factor to give an error standard deviation matching that of Miller's actual data (1.2), so that the standard errors of the means are comparable (around 0.26).

In the panels following, each left hand graph shows the data ± standard errors, while the right hand graph shows the best fitting model with cosine functions at the fundamental and second harmonic of the rotation frequency.

The first panel shows Miller's actual data and its model. The succeeding four panels show different sets of random data, recalculating the random numbers for each run.





The results of the simulation were quite convincing, the more so when seated at the computer, repeatedly hitting *Recalculate*. Despite the error bars matching those in the actual data, the pattern of the means consistently fails to reproduce a wave-like signal.

Discussion

In the late 19th century, it was expected that the orbital motion of the Earth with respect to a preferred frame of reference – the "ether" in which electromagnetic waves were believed to propagate – would result in anisotropy of light propagation. This would be manifest in the laboratory as the shifting of interference fringe patterns in a rotating Michelson interferometer. The failure of Michelson and Morley's (1887) experiment was the beginning of the end for the concept of a preferred frame of reference. The concept was definitively laid to rest by Einstein's (1905) derivation of Special Relativity from two simple postulates: the equivalence of inertial frames and the constancy of the speed of light, independent of the motion of the source or observer.

The small residuals observed in the ether-drift interferometer experiments have since been regarded in the mainstream literature as instrumental defects which tended to decrease with improvements in the apparatus over time. Modern studies with cavity resonators operating in vacuum at cryogenic temperatures set impressive limits on possible Lorentz symmetry violations. Nagel et al. (2015) pushed the bounds down to 10^{-18}, some 9 orders of magnitude better than the most sensitive of the early interferometric experiments.

A few dissident authors, however, contend that the residuals in the interferometric data represent real physical effects, dependent on the presence of a gas (air, helium) in the optical pathway. The most impressive body of data inspiring such proposals comes from the work of Dayton Miller in the 1920s and 30s (Miller, 1933). Shankland (1955), reanalyzing Miller's data, concluded that thermal gradients of a few mK, affecting the air in the optical path, could account for the apparent signal. DeMeo (2002), in a careful review of Miller's data and the Shankland rebuttal, argued that Shankland had been concerned more to silence a critic of Special Relativity than to provide an objective analysis.

Cahill and Kitto (2002) proposed an ingenious hypothesis that might, arguably, have opened a way to distinguishing between the orthodox (Einstein, 1905) version of Special Relativity and a model with a preferred frame of reference concealed by clock aberration and length contraction (essentially the Lorentz-Fitzgerald-Poincare theory of around 1900 AD). In this proposal, the slowing of light by the refractive property of a gas would prevent the Lorentz-Fitzgerald length-contraction from exactly cancelling the effect on light propagation of motion against a preferred frame of reference.

In the Cahill theory, an interferometer filled with a medium of refractive index, n, underestimates the drift velocity by a factor of $1/\sqrt{(n^2 - 1)}$. For air, with an index of 1.00029, the factor would be about 42. Dayton Miller's claimed drift velocities, around 9 km/s, would thus be rendered consistent with the 369 km/s velocity of the solar system (Hinshaw et al., 2009) with respect to the Cosmic Microwave Background (CMB) radiation. For a vacuum, the correction factor would be infinite, accounting for the null results of modern experiments.

If it had been confirmed, Cahill's idea would have upturned much of modern physics. Experiments with different refractive media, however, were either negative or difficult to interpret. Demjanov (2011) advanced an idea similar to Cahill's, giving a summary of positive results with gases and solid dielectrics: remarkable claims which remain unverified.

Cahill (2004) reported null results with an optical fiber analog of the Michelson interferometer, an outcome discordant with the hypothesis that refractive media would allow detection of an ether drift. Later, however, Cahill (2006) described differential effects of spatial orientation on the propagation of signals in optical fibers versus coaxial cables. Such effects might arguably be attributed to motion against a preferred frame of reference. Noise in the data was interpreted, rather puzzlingly, as "gravitational waves," which were certainly not the astrophysical variety predicted by General Relativity and lately detected by the LIGO and VIRGO vacuum-mode interferometers.

More recently, Consoli proposed a non-local coupling of gaseous media to the CMB radiation, such that the dipole velocity of 369 km/s would induce thermal gradients of a few mK (Consoli et al., 2013, 2016, 2018-A, B). This suggestion seems not, to date, to have prompted definitive experimental tests.

Dissident authors have displayed great ingenuity is their attempts to rehabilitate Miller's heroic experiment, but have failed to convince the mainstream. The hypotheses advanced are complicated, lacking the elegant simplicity of Special Relativity, and new experiments testing these ideas have yielded data of unimpressive quality.

Roberts (2006) presented an analysis of Miller's data by Fourier techniques, concluding that the apparent signal Miller reported was entirely a creation of the processing algorithm, effectively filtering random noise into components at the harmonics of the rotational frequency of the instrument. Roberts was also critical of averaging repeated measurements to recover a signal from noisy data, though the technique is widely applied in biology to improve the power of statistical analyses and in electronics to improve signal-to-noise ratios (e.g. most Digital Storage Oscilloscopes have a Signal-Averaging function).

In the present paper, we reanalyzed a sample of Miller's data by variance methods that were not routinely applied in the physics of Miller's era.

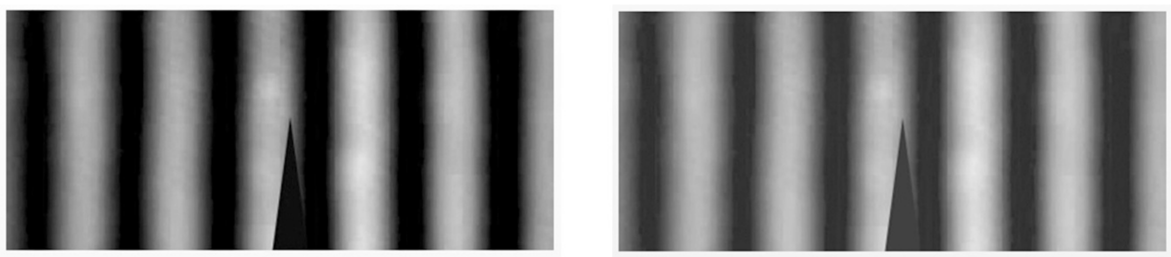
In contrast to the deductions of Roberts (2006), we find that random noise cannot reproduce Miller's signals with the corresponding amplitudes and standard errors of means. Some systematic effect must be invoked to explain the signal.

We find, however, that the signal's spectral characteristics are highly discordant with the predictions of an ether-drift theory. We demonstrate that in addition to a component of the signal with a period corresponding to a half rotation of the interferometer, there is a statistically significant component with the period of a full rotation.

Since a Michelson interferometer is symmetrical on 180-degree rotation, no signal at the fundamental of the rotation frequency is expected: only the second harmonic can be accommodated by any plausible theory of the machine's operation. This fundamental frequency has been noted occasionally but never adequately confronted. Miller (1933) mentions it briefly, but offers no explanation.

Cahill (2009) acknowledged the fundamental component of Miller's signal, attributing it to a slight misalignment of the mirrors, necessary for an interferometer to display interference fringes, which would break the strict 180-degree symmetry of the device. Hicks (1902) had developed the theory of such an effect: it required an extra term in $\cos(\theta - \beta)$ in the fringe shift equation, where θ is the azimuth of the drift and β is the misalignment. The implausibility of this suggestion is apparent to anyone familiar with setting up interferometers for student practical labs: the misalignment is a few wavelengths in the width of the beam, an angle of less than a milliradian.

An optical illusion which may have influenced the observer is illustrated in the following digitally-simulated images.



The observer's task was to read the position of interference fringes against a fixed pointer. At first glance, the relative positions of the pointer and the fringes seem different between the two images. But in fact, the images are identical except for the background illumination being increased on the right. With the ambient lighting in the observatory brighter on the side towards the sun, such an illusion may have produced an apparent periodic shift with an amplitude of about one tenth of a fringe and a period of a full rotation.

The mechanisms producing the signals in Miller's interferometric data remain a subject of speculation. But unless the advocates of ether-drift theories can provide a satisfactory explanation for the signal component with the period of a full rotation, that component is fatal for any contention that Miller's heroic experiments were measuring meaningful physics.

Conclusions

Modelling and analysis of variance demonstrate that Dayton Miller's interferometric data does indeed show statistically significant signal components, periodic on the rotation of the instrument, that are submerged in the random fluctuations and thermal drift which dominate the readings. While the component with the period of half a rotation might have been argued to represent anisotropy in the propagation of light – the "ether drift" effect sought by Michelson and Morley's iconic 19th century experiment – the component with the period of a full rotation has no plausible explanation other than a systematic in the machine or the observer. The conclusion of Shankland (1955) that the signal was entirely generated by thermal gradients remains plausible and the contention of dissident authors that the signal represents meaningful physics faces a severe challenge.

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