Precision test for the new Michelson-Morley experiments with rotating cryogenic cavities

M. Consoli

Istituto Nazionale di Fisica Nucleare, Sezione di Catania Via Santa Sofia 64, 95123 Catania, Italy

Abstract

A new ether-drift experiment in Düsseldorf is currently measuring the relative frequency shift of two cryogenic optical resonators upon active rotations of the apparatus. I point out that the observed fractional amplitude of the sidereal variations of the signal in February, $C_{\rm sid} \sim$ $(11 \pm 2) \cdot 10^{-16}$, is entirely consistent with the expectations based on Miller's observations in the same epoch of the year. This leads to predict that, with future data collected in August-September, the observed sidereal variations should increase by ~ +70%, i.e. up to $C_{\rm sid} \sim (19 \pm 2) \cdot 10^{-16}$ retaining the present normalization. This would represent clean experimental evidence for the existence of a preferred frame.

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1. Modern ether-drift experiments look for a preferred frame by measuring the relative frequency shift $\delta\nu$ between two cavity-stabilized lasers upon local rotations [1] or under the Earth's rotation [2]. Today, by combining the possibility of active rotations of the apparatus with the use of cryogenic optical resonators, a new experiment [3] is currently trying to push the relative accuracy of the measurements to the level $\mathcal{O}(10^{-16})$. It is generally believed that such an extremely high precision, that strongly constrains the anisotropy of the speed of light, can also rule out the idea of a preferred frame.

However, as discussed in Refs.[4, 5] (see also [6]), vanishingly small values of $\delta \nu$, by themselves, cannot rule out the old Lorentzian formulation of Relativity. In fact, if light propagates isotropically in a preferred frame Σ , the relative frequency shift observed on the Earth is given by

$$\frac{\delta\nu}{\nu} \sim (\mathcal{N}_{\rm medium} - 1) \frac{v_{\rm earth}^2}{c^2} \tag{1}$$

where $\mathcal{N}_{\text{medium}} \sim 1$ is the refractive index of the medium where light propagation takes place and v_{earth} denotes the Earth's velocity with respect to Σ (value projected in the plane of the interferometer).

This frequency shift vanishes identically when the speed of light coincides with the same parameter "c" entering Lorentz transformations, i.e. in an ideal vacuum where $\mathcal{N}_{\text{vacuum}} =$ 1. Starting from this observation, one can re-read [4, 5] the classical and modern etherdrift experiments in a consistent framework where there is a preferred frame relatively to which the Earth is moving with a velocity ~ 200 km/s (value projected in the plane of the interferometer). This velocity is consistent with the values deduced by Miller (see Table V of Ref.[7]) on the base of the sidereal variations of the ether-drift effect in different periods of the year.

The aim of this Letter is to show that the sidereal variations observed in February by the authors of Ref.[3] are completely consistent with Miller's observations in the same epoch of the year. This also suggests a precise prediction to be tested with future data collected in the period of August-September. A confirmation of this prediction would represent clean experimental evidence for the existence of a preferred frame.

2. The basic ingredient for our analysis is the relation [4] for the frequency shift of two orthogonal optical resonators to $\mathcal{O}(\frac{v_{\text{earth}}^2}{c^2})$

$$\frac{\delta\nu(\theta)}{\nu} = \frac{\bar{u}'(\pi/2 + \theta) - \bar{u}'(\theta)}{u} \sim |B_{\text{medium}}| \frac{v_{\text{earth}}^2}{c^2} \cos(2\theta)$$
(2)

Here $\theta = 0$ indicates the direction of the ether-drift, $\bar{u}'(\theta)$ is the two-way speed of light (as measured on the Earth) in a medium of refractive index $\mathcal{N}_{\text{medium}} \sim 1$, $B_{\text{medium}} \sim -3(\mathcal{N}_{\text{medium}} - 1)$ and $u = c/\mathcal{N}_{\text{medium}}$ indicates the isotropical value. Eq.(2) is derived under the assumption that light is seen isotropical in a preferred frame Σ and that the required transformation law to the Earth's frame is a Lorentz transformation.

In this way one obtains an amplitude of the ether-drift effect

$$\frac{A_{\rm th}(t)}{\nu} = |B_{\rm medium}| \frac{v_{\rm earth}^2(t)}{c^2} \tag{3}$$

that vanishes identically in a vacuum.

However, as originally suggested in Ref.[6], even in the case of an extremely high vacuum (such as the one existing in the resonating cavities of Ref.[3]) one can argue that the speed of light differs from the parameter "c" entering Lorentz transformations. In fact, for an apparatus placed on the Earth's surface (but otherwise in free fall with respect to any other gravitational field), General Relativity predicts a tiny refractive index

$$\mathcal{N}_{\text{vacuum}} \sim 1 - 2\varphi$$
 (4)

with

$$\varphi = -\frac{G_N M_{\text{earth}}}{c^2 R_{\text{earth}}} \sim -0.7 \cdot 10^{-9} \tag{5}$$

so that

$$B_{\rm vacuum} \sim 6\varphi \sim -4.2 \cdot 10^{-9} \tag{6}$$

In this way, for a mean reference value $v_{\text{earth}} = 210 \text{ km/s}$, and a mean frequency $\nu \sim 2.8 \cdot 10^{14}$ Hz, as in Ref.[3], Eq.(3) implies

$$\langle A_{\rm th} \rangle \sim 0.58 \; {\rm Hz}$$
 (7)

Let us now compare this with the basic Eq.(1) of Ref.[3] for the frequency shift at a given time t

$$\frac{\delta\nu[\theta(t)]}{\nu} = \hat{B}(t)\sin 2\theta(t) + \hat{C}(t)\cos 2\theta(t)$$
(8)

where $\theta(t)$ is the angle of rotation of the apparatus, $\hat{B}(t) \equiv 2B(t)$ and $\hat{C}(t) \equiv 2C(t)$ so that one finds an experimental amplitude

$$A_{\exp}(t) = \nu \sqrt{\hat{B}^2(t) + \hat{C}^2(t)}$$
(9)

Taking into account the experimental results [3] $\langle \hat{B}\nu \rangle \sim 2.8$ Hz and $\langle \hat{C}\nu \rangle \sim -3.3$ Hz, one finds

$$\langle A_{\rm exp} \rangle \sim 4.3 \, \text{Hz}$$
 (10)

which is much larger than the theoretical prediction in Eq.(7). Therefore, as suggested by the same authors of Ref.[3], for a meaningful comparison, one has to subtract the mean value and restrict to the sidereal modulations of the signal.

To predict the variations of the ether-drift effect, I shall use the average data and the theoretical curves reported by Miller in Figs.26 of Ref.[7]. To compare with the data collected around February 6th (of 2005) by the authors of Ref.[3], I'll also restrict to Miller's observations around February 8th (of 1926). In this case, the sidereal variations of the ether-drift effect are modest and the profile of the observable velocity is found in the range 7.5 km/s $\leq v_{\rm obs}(t) \leq 10$ km/s. Using Eq.(13) of Ref.[4], $v_{\rm obs}^2 \sim 3(\mathcal{N}_{\rm medium}^2 - 1)v_{\rm earth}^2$ (for Miller's interferometer that was operating in air where $\mathcal{N}_{\rm air} \sim 1.00029$), this range of observable velocities is found to correspond to the range of kinematical velocities

$$180 \text{ km/s} \le v_{\text{earth}}(t) \le 240 \text{ km/s} \tag{11}$$

Therefore, taking into account Eqs.(3) and (6), the amplitude of the signal should lie in the range 0.42 Hz $\leq A_{\rm th}(t) \leq 0.76$ Hz, with an overall daily variation

$$\Delta A_{\rm th} \sim \pm 0.17 \; \rm Hz \tag{12}$$

that represents a fractional change

$$\frac{\Delta A_{\rm th}}{\nu} \sim \pm 6 \cdot 10^{-16} \tag{13}$$

An experimental check of this prediction can be found in Table I of Ref.[3]. There one finds a clear indication for a non-zero value of the parameter

$$C_{\rm sid} \equiv \sqrt{C_1^2 + C_2^2} \tag{14}$$

that controls the sidereal modulation of the signal

$$\hat{C}(t) = C_0 + C_1 \sin(\omega_{\rm sid} t) + C_2 \cos(\omega_{\rm sid} t) + \dots$$
(15)

In this case, the result

$$C_{\rm sid} \sim (11 \pm 2) \cdot 10^{-16}$$
 (16)

implies a daily variation of the amplitude

$$\Delta A_{\rm exp} \sim \pm \nu C_{\rm sid} \sim \pm 0.31 \text{ Hz}$$
(17)

that is entirely consistent with the theoretical value in Eq.(12).

By itself, this result might be considered a first experimental check of the ether-drift observations reported by Miller. However, for a real precision test, one has still to wait a few months. In fact, looking again at Figs.26 of Ref.[7], one discovers that the sidereal variations in August-September were considerably larger with a profile of the observable velocities lying now in the range 5.0 km/s $\leq v_{obs}(t) \leq 10$ km/s. This range corresponds to

$$120 \text{ km/s} \le v_{\text{earth}}(t) \le 240 \text{ km/s} \tag{18}$$

and to

$$\Delta A_{\rm th} \sim \pm 0.29 \text{ Hz} \tag{19}$$

with fractional changes of $\sim \pm 10 \cdot 10^{-16}$. In this case, the fitted value of the coefficient $C_{\rm sid}$ should increase by $\sim +70\%$. Retaining the present normalization, this means up to

$$C_{\rm sid} \sim (19 \pm 2) \cdot 10^{-16}$$
 (20)

that represents a 3-4 σ change relatively to the present value and might be observable with future data taken in the next few months.

3. The new generation of Michelson-Morley experiments with rotating cryogenic optical resonators will likely definitely resolve, in one way or the other, the old controversy (Einsteinian vs. Lorentzian) on the interpretation of the relativistic effects. In this Letter, I have illustrated the implications of Miller's observations for the present experiment in Düsseldorf of Ref.[3] and the forthcoming one in Berlin [8]. The present amplitude of the sidereal variations observed in February 2005 by the authors of Ref.[3], as embodied in the parameter $C_{\rm sid} \sim (11 \pm 2) \cdot 10^{-16}$, is completely consistent with the prediction based on Miller's data collected in the same epoch of the year.

However, for a real definitive check, the fitted value of $C_{\rm sid}$ should also increase by ~ +70% when taking data in August-September, i.e. up to $C_{\rm sid} \sim (19 \pm 2) \cdot 10^{-16}$ retaining the same normalization. This prediction will be tested in the next few months and, whenever confirmed, would represent clean experimental evidence for the existence of a preferred frame. If this will happen, further checks will require to determine the azimuth of the ether-drift effect and, with it, the cosmic component of the Earth's velocity. To this end, the data should be analyzed in a model-independent way without necessarily restricting the preferred frame to coincide with the CMBR.

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