Vacuum structure and ether-drift experiments

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Abstract

In the data of the ether-drift experiments there might be sizeable fluctuations superposed on the smooth sinusoidal modulations due to the Earth's rotation and orbital revolution. These fluctuations might reflect the stochastic nature of the underlying "quantum ether" and produce vanishing averages for all vectorial quantities extracted from a naive Fourier analysis of the data. By comparing the typical stability limits of the individual optical resonators with the amplitude of their relative frequency shift, the presently observed signal, rather than being spurious experimental noise, might also express fundamental properties of a physical vacuum similar to a superfluid in a turbulent state of motion. In this sense, the situation might be similar to the discovery of the CMBR that was first interpreted as mere instrumental noise.

1. Introduction

In principle, the physical vacuum might behave as a medium with a non-trivial refractive index. In this case, the speed of light in the vacuum $c_\gamma = \frac{c}{\mathcal{N}_{\rm vacuum}}$ would not coincide exactly with the parameter c entering Lorentz transformations and therefore could propagate isotropically in only one frame Σ. In a moving frame S', there would be an anisotropy of the two-way speed of light $\bar{c}_\gamma(\theta)$

$$\frac{\bar{c}_\gamma(\theta) - \bar{c}_\gamma(0)}{c} \sim \ B\frac{V^2}{c^2}\sin^2\theta \tag{1}$$

with [1]

$$|B| \sim 3(\mathcal{N}_{\rm vacuum} - 1) \tag{2}$$

V being the speed of S' with respect to Σ. This anisotropy could then be measured through the beat frequency $\Delta\nu$ of two orthogonal cavity-stabilized lasers.

In this context, the search for time modulations of the signal induced by the Earth's rotation (and its orbital revolution) has always represented a crucial ingredient for the analysis of the data. For instance, let us consider the relative frequency shift of two optical resonators for the experiment of Ref.[2]

$$\frac{\Delta\nu(t)}{\nu_0} = S(t)\sin 2\omega_{\rm rot}t + C(t)\cos 2\omega_{\rm rot}t \tag{3}$$

where $\omega_{\rm rot}$ is the rotation frequency of one resonator with respect to the other which is kept fixed in the laboratory and oriented north-south. If one assumes that, for short-time observations of 2-3 days, the time dependence of a hypothetical physical signal can only be due to (the variations of the projection of $\mathbf{V}$ in the interferometer's plane caused by) the Earth's rotation, $S(t)$ and $C(t)$ admit the simplest Fourier expansion ($\tau = \omega_{\rm sid}t$ is the sidereal time of the observation in degrees) [2]

$$S(t) = S_0 + S_{s1}\sin\tau + S_{c1}\cos\tau + S_{s2}\sin(2\tau) + S_{c2}\cos(2\tau) \tag{4}$$

$$C(t) = C_0 + C_{s1}\sin\tau + C_{c1}\cos\tau + C_{s2}\sin(2\tau) + C_{c2}\cos(2\tau) \tag{5}$$

with time-independent C_k and S_k coefficients. Therefore, by accepting this theoretical framework, it becomes natural to average the various C_k and S_k over any 2-3 day period. By further performing inter-session averages over many short-period experimental sessions (see Fig.2 of Ref.[3]) the general conclusion [3] is that, although the typical instantaneous signal is $\mathcal{O}(10^{-15})$ or larger, the average C_k and S_k coefficients are at the level $\mathcal{O}(10^{-17})$ and, with them, the derived parameters entering the SME [4] and RMS [5] models.

However, as we shall argue in Sect.2, in an alternative picture of the vacuum, one could consider different types of ether-drift. In this case, the same experimental data could admit a completely different interpretation. This possibility will be illustrated in Sects.3 and 4 where, by comparing with the typical stability limits of the individual optical resonators, we shall argue that the presently observed signal is unlike to represent just spurious instrumental noise. For this reason, in Sect.5, we shall discuss a possible theoretical framework that can explain the present data. In this sense, as discussed in the final Sect.6, the situation with the ether-drift experiments might resemble the discovery of the CMBR that, at the beginning, was also interpreted as mere instrumental noise.

2. The vacuum as a turbulent superfluid

By accepting the idea that there might be a preferred reference frame, which is the modern denomination of the old ether, one could also change perspective and, before assuming any definite theoretical model, first ask: if light were really propagating in a physical medium, an ether, and not in a trivial empty vacuum, how should the motion of (or in) this medium be described ? Namely, could this relative motion exhibit variations that are *not* only due to known effects as the Earth's rotation and orbital revolution ?

Without fully understanding the nature of that substratum that we call physical vacuum, it is not possible to make definite predictions. Still, according to the standard model of electroweak and strong interactions, this physical vacuum could be considered as a superfluid medium [6] filled by those particle condensates that play a crucial role for many fundamental phenomena such as mass generation and quark confinement. By further considering the idea of a non-zero vacuum energy, this physical substratum could also represent a preferred reference frame [7]. In this picture, the standard assumption of smooth sinusoidal variations of the signal, associated with the Earth's rotation and its orbital revolution, corresponds to describe the superfluid motion in terms of simple regular flows.

However, visualization techniques that record the flow of superfluid helium show [8] the formation of macroscopic turbulent structures with a velocity field that fluctuates randomly around some average value. The same idea of turbulence, that dates back to the original Lord Kelvin's attempts to generate transverse waves in the ether [9], is also suggested by the formal equivalence that one can establish [10, 11] between the propagation of small disturbances in a turbulent fluid and the propagation of electromagnetic waves as described by Maxwell equations.

To exploit the possible implications for the ether-drift experiments, let us first recall the general aspects of a turbulent flow. This is characterized by extremely irregular variations of the velocity, with time at each point and between different points at the same instant, due to the formation of eddies [12]. For this reason, the velocity continually fluctuates about some mean value and the amplitude of these variations is *not* small in comparison with the mean velocity itself. The time dependence of a typical turbulent velocity field can be expressed as [12]

$$\mathbf{v}(x,y,z,t) = \sum_{p_1 p_2 .. p_n} \mathbf{a}_{p_1 p_2 .. p_n}(x,y,z) \exp(-i \sum_{j=1}^{n} p_j \phi_j) \tag{6}$$

where the quantities $\phi_j = \omega_j t + \beta_j$ vary with time according to fundamental frequencies ω_j and depend on some initial phases β_j. As the Reynolds number $\mathcal{R}$ increases, the total number n of ω_j and β_j increases. In the $\mathcal{R} \to \infty$ limit, their number diverges so that the theory of such a turbulent flow must be a statistical theory.

As discussed by Feynman [13], the idea that there might be a rich structure of turbulent eddies for very large Reynolds numbers is, at first sight, quite surprising. After all, starting from the Navier-Stokes equation, the eddies are generated, in the equation for the vorticity $\mathbf{\Omega} = \nabla \times \mathbf{v}$, by the viscous term which formally vanishes in the $\mathcal{R} \to \infty$ limit. However, there is a subtlety. The right-hand term of the equation

$$\frac{\partial \mathbf{\Omega}}{\partial t} + \nabla \times (\mathbf{\Omega} \times \mathbf{v}) = \frac{1}{\mathcal{R}} \Delta \mathbf{\Omega} \tag{7}$$

has $\frac{1}{\mathcal{R}}$ times a second derivative. This is the higher derivative term in the equation. Thus, although $\frac{1}{\mathcal{R}}$ becomes smaller and smaller, there can be rapid variations of $\mathbf{\Omega}$, producing larger and larger $\Delta \mathbf{\Omega}$, that compensate for the small coefficient. For this reason, the solutions of the viscous equation do *not* approach the solutions of the equation

$$\frac{\partial \mathbf{\Omega}}{\partial t} + \nabla \times (\mathbf{\Omega} \times \mathbf{v}) = 0 \tag{8}$$

when $\frac{1}{\mathcal{R}} \to 0$.

Now, due to the presumably vanishingly small viscosity of a superfluid ether, the relevant Reynolds numbers are likely infinitely large in most regimes and we might be faced precisely with such limit of the theory where the physical vacuum behaves as a *stochastic* medium.

In this case random fluctuations of the physical signal, superposed on the smooth sinusoidal behaviour associated with the Earth's rotation (and orbital revolution), would produce deviations of $S(t)$ and $C(t)$ from the simple structure in Eqs.(4) and (5) and an effective temporal dependence of the fitted $C_k = C_k(t)$ and $S_k = S_k(t)$ vectorial coefficients. In this situation one could easily get, due to phase interference, vanishing average values $\langle C_k \rangle = \langle S_k \rangle = 0$.

Nevertheless, as it happens with random fluctuations, the average *amplitude* of the signal could still be preserved. Namely, by extracting from the data the positive-definite combination

$$A(t) = \sqrt{S^2(t) + C^2(t)} \tag{9}$$

a definite non-zero $\langle A \rangle$ might well coexist with $\langle C_k \rangle = \langle S_k \rangle = 0$.

3. Noise or stochastic turbulence ?

To provide some evidence that indeed we might be faced with this type of situation, let us consider the experimental apparatus of Ref.[14] where the two optical cavities were obtained from the same monolithic block of ULE. Due to sophisticated electronics and temperature controls, the stability limits for the individual optical cavities are extremely high. More precisely, the effect of residual amplitude modulation is below 0.02 Hz for both cavities and thus about $7 \cdot 10^{-17}$ for a laser frequency $2.82 \cdot 10^{14}$ Hz. For the non-rotating set up, and with power stabilization, the laser power fluctuations are below $3 \cdot 10^{-17}$ for cavity 1 and below $1 \cdot 10^{-17}$ for cavity 2. Finally, for the non-rotating set up, also the tilt instabilities are below $1 \cdot 10^{-16}$, or 0.03 Hz, for both cavities. Thus, by adding all effects, one deduces a stability of about ± 0.05 Hz for the individual cavities. This is of the same order of the *mean* frequency shift between the two resonators, say $\langle \Delta\nu \rangle \sim \pm 0.06$ Hz, when averaging the signal over long temporal sequences.

However, the *instantaneous* $\Delta\nu$ is much larger, say ± 1 Hz, and so far has been interpreted as spurious instrumental noise. To check this interpretation, we observe that, in the absence of any light anisotropy, the noise in the beat frequency should be comparable to the noise of the individual resonators. Instead, for the same non-rotating set up, the plateau of the Allan variance for the beat signal was found 10 times bigger, namely $1.9 \cdot 10^{-15}$ with a corresponding typical shift of about 0.56 Hz (see Fig.8 of Ref.[14]). Also the slopes are different in the two cases, indicating noises of different nature. The authors tend to interpret this as cavity thermal noise and refer to [15]. However, if the theoretical estimate of Ref.[15] applies, the relevant effect should be considerably smaller, about $4 \cdot 10^{-16}$ or 0.13 Hz (see the first entry in Table I of [15]). In any case, one can also compare with experiments performed in the cryogenic regime. If this typical $\mathcal{O}(10^{-15})$ beat signal reflects the stochastic nature of an underlying quantum ether, it should be found in these different experiments as well.

4. An alternative analysis of the data

Motivated by the previous arguments, we have explored the idea that the observed beat signal could be due to some form of turbulent ether flow. In principle, in this perspective, one should abandon the previous type of analysis based on a fixed preferred reference frame and extract the average amplitude from the instantaneous data before any averaging procedure. However, these instantaneous data are not available and thus, to extract $\langle A \rangle$, that was never reported by the experimental groups, one can only use the C_k and S_k coefficients averaged within each 2-3 day session. Due to the expected negative phase interference, the resulting $\langle A \rangle$ should represent a lower limit for its true experimental value.

To extract $\langle A \rangle$, one should first re-write Eq.(3) as

$$\frac{\Delta\nu(t)}{\nu_0} = A(t)\cos(2\omega_{\rm rot}t - 2\theta_0(t)) \tag{10}$$

with

$$C(t) = A(t)\cos 2\theta_0(t) \qquad S(t) = A(t)\sin 2\theta_0(t) \tag{11}$$

$\theta_0(t)$ representing the instantaneous direction of the ether-drift effect in the plane of the interferometer. In this plane, the projection of the full $\mathbf{V}$ is specified by its magnitude $v = v(t)$ and by its direction $\theta_0 = \theta_0(t)$ (counted by convention from North through East so that North is $\theta_0 = 0$ and East is $\theta_0 = \pi/2$). If one assumes Eqs.(4) and (5), then $v(t)$ and $\theta_0(t)$ can be obtained from the relations [16, 17]

$$\cos z(t) = \sin\gamma\sin\phi + \cos\gamma\cos\phi\cos(\tau - \alpha) \tag{12}$$

$$\sin z(t)\cos\theta_0(t) = \sin\gamma\cos\phi - \cos\gamma\sin\phi\cos(\tau - \alpha) \tag{13}$$

$$\sin z(t)\sin\theta_0(t) = \cos\gamma\sin(\tau - \alpha) \tag{14}$$

$$v(t) = V\sin z(t), \tag{15}$$

where α and γ are respectively the right ascension and angular declination of $\mathbf{V}$. Further, ϕ is the latitude of the laboratory and $z = z(t)$ is the zenithal distance of $\mathbf{V}$. Namely, $z = 0$

corresponds to a $\mathbf{V}$ which is perpendicular to the plane of the interferometer and $z = \pi/2$ to a $\mathbf{V}$ that lies entirely in that plane. From the above relations, by using the $\mathcal{O}(v^2/c^2)$ relation $A(t) \sim \frac{v^2(t)}{c^2}$, the other two amplitudes $S(t) = A(t)\sin 2\theta_0(t)$ and $C(t) = A(t)\cos 2\theta_0(t)$ can be obtained up to an overall proportionality constant. By using the expressions for $S(t)$ and $C(t)$ reported in Table I of Ref. [2] (in the RMS formalism [5]), this proportionality constant turns out to be $\frac{1}{2}|B|$ so that we finally find

$$A(t) = \frac{1}{2}|B|\frac{v^2(t)}{c^2} \tag{16}$$

where B is the anisotropy parameter entering the two-way speed of light Eq.(1). It is a simple exercise to check that, by using Eqs.(11), Eqs.(12)-(16) and finally replacing $\chi = 90^o - \phi$, one re-obtains the expansions for $C(t)$ and $S(t)$ reported in Table I of Ref. [2].

We can then replace Eq. (15) into Eq. (16) and, by adopting a notation of the type in Eqs.(4)-(5), express the Fourier expansion of $A(t)$ as

$$A(t) = A_0 + A_1 \sin\tau + A_2\cos\tau + A_3\sin(2\tau) + A_4\cos(2\tau) \tag{17}$$

where (the daily averaging of any quantity is here denoted by $\langle .. \rangle$),

$$\langle A\rangle = A_0 = \frac{1}{2}|B|\frac{\langle v^2(t)\rangle}{c^2} = \frac{1}{2}|B|\frac{V^2}{c^2}\left(1 - \sin^2\gamma\cos^2\chi - \frac{1}{2}\cos^2\gamma\sin^2\chi\right) \tag{18}$$

$$A_1 = -\frac{1}{4}|B|\frac{V^2}{c^2}\sin 2\gamma\sin\alpha\sin 2\chi \qquad A_2 = -\frac{1}{4}|B|\frac{V^2}{c^2}\sin 2\gamma\cos\alpha\sin 2\chi \tag{19}$$

$$A_3 = -\frac{1}{4}|B|\frac{V^2}{c^2}\cos^2\gamma\sin 2\alpha\sin^2\chi \qquad A_4 = -\frac{1}{4}|B|\frac{V^2}{c^2}\cos^2\gamma\cos 2\alpha\sin^2\chi \tag{20}$$

To obtain A_0 from the C_k and S_k, we observe that by using Eq.(17) one obtains

$$\langle\ A^2(t)\ \rangle = A_0^2 + \frac{1}{2}(A_1^2 + A_2^2 + A_3^2 + A_4^2) \tag{21}$$

On the other hand, by using Eqs.(4), (5) and (11), one also obtains

$$\langle\ A^2(t)\ \rangle = \langle\ C^2(t) + S^2(t)\ \rangle = C_0^2 + S_0^2 + Q^2 \tag{22}$$

where

$$Q = \sqrt{\frac{1}{2}(C_{11}^2 + S_{11}^2 + C_{22}^2 + S_{22}^2)} \tag{23}$$

and

$$C_{11} \equiv \sqrt{C_{s1}^2 + C_{c1}^2} \qquad C_{22} \equiv \sqrt{C_{s2}^2 + C_{c2}^2} \tag{24}$$

$$S_{11} \equiv \sqrt{S_{s1}^2 + S_{c1}^2} \qquad\qquad S_{22} \equiv \sqrt{S_{s2}^2 + S_{c2}^2} \tag{25}$$

Therefore, one can combine the two relations and get

$$A_0^2(1+r) = C_0^2 + S_0^2 + Q^2 \tag{26}$$

where

$$r \equiv \frac{1}{2A_0^2}(A_1^2 + A_2^2 + A_3^2 + A_4^2) \tag{27}$$

By computing the ratio $r = r(\gamma, \chi)$ with Eqs.(18)-(20), one finds

$$0 \leq r \leq 0.4 \tag{28}$$

for the latitude of the laboratories in Berlin [2] and Düsseldorf [18] in the full range $0 \leq |\gamma| \leq \pi/2$. We can thus define an average amplitude, say $\hat{A}_0$, which is determined in terms of Q alone as

$$\hat{A}_0 = \frac{Q}{\sqrt{1+r}} \sim (0.92 \pm 0.08)Q \tag{29}$$

where the uncertainty takes into account the numerical range of r in Eq.(28). This quantity provides, in any case, a *lower bound* for the true experimental A_0 since

$$A_0 = \sqrt{\frac{C_0^2 + S_0^2 + Q^2}{1+r}} \geq \hat{A}_0 \tag{30}$$

At the same time Q is determined only by the C_{s1}, C_{c1},... and their S-counterparts. According to the authors of Refs.[2, 3], these coefficients are much less affected by spurious effects, as compared to C_0 and S_0, and so will be our amplitude $\hat{A}_0$.

We have computed the Q values for the 27 short-period experimental sessions of Ref.[3]. Their values are reported in Table I. Although more recent data were announced in Ref.[4], only the results of fits within the SME model, and not the data themselves, are explicitly reported. In any case, the data of Ref.[3] represent, within their statistics, a sufficient basis to deduce that a rather stable pattern is obtained. This is due to the rotational invariant character of Q in the 8-th dimensional space of the C_{s1}, C_{c1},...S_{s2}, S_{c2} so that variations of the individual coefficients tend to compensate. By taking an average of these 27 determinations one finds a mean value

$$\bar{Q} = (13.0 \pm 0.7 \pm 3.8) \cdot 10^{-16} \qquad\qquad \text{Ref.[3]} \tag{31}$$

where the former error is purely statistical and the latter represents an estimate of the systematical effects. Such systematic uncertainty, deduced from the data of Ref.[3], is also completely consistent with the comparable stability limit $4 \cdot 10^{-16}$ of reference optical cavities [19] for integration times $\mathcal{O}(10^2)$ seconds as those appropriate for the basic data of the Berlin experiment (collected with sets of 10 turntable rotations of 43 seconds each).

As anticipated, for a further control of the validity of our analysis, we have compared with the cryogenic experiment of Ref.[18]. In this case, we have obtained the analogous value

$$Q = (13.1 \pm 2.1) \cdot 10^{-16} \qquad \text{Ref.[18]} \tag{32}$$

from the corresponding C_k and S_k coefficients. Thus, by using Eq.(29) and the two values of Q reported above, we obtain

$$\hat{A}_0^{\rm exp} = (12.0 \pm 1.0 \pm 3.5) \cdot 10^{-16} \qquad \text{Ref.[3]} \tag{33}$$

$$\hat{A}_0^{\rm exp} = (12.1 \pm 1.0 \pm 2.1) \cdot 10^{-16} \qquad \text{Ref.[18]} \tag{34}$$

where the former uncertainty takes into account the variation of r in Eq.(28) and the latter is both statistical and systematical.

We emphasize that this stable value of about $12 \cdot 10^{-16}$ is a lower limit for the true experimental A_0. At the same time, it could hardly be interpreted as a spurious effect of experimental noise. In fact, from the estimates of Ref.[15], based on the fluctuation-dissipation theorem, there is no reason to expect that experiments running in so different conditions should exhibit the same experimental noise.

5. A possible theoretical framework

Let us now explore a possible theoretical framework that can explain the above experimental values. To this end, we shall first use Eq.(18) and Eq.(2) and re-write the theoretical prediction as

$$A_0^{\rm th} = \frac{3}{2}(\mathcal{N}_{\rm vacuum} - 1)\frac{V^2}{c^2} f(\gamma, \chi) \tag{35}$$

with

$$f(\gamma, \chi) = \left(1 - \sin^2\gamma \cos^2\chi - \frac{1}{2}\cos^2\gamma \sin^2\chi\right) \tag{36}$$

Then, in a flat-space picture of gravity, for an apparatus placed on the Earth's surface the vacuum refractive index was estimated to have the value [1]

$$\mathcal{N}_{\rm vacuum} - 1 \sim \frac{2GM}{c^2 R} \sim 1.4 \cdot 10^{-9} \tag{37}$$

G being Newton's constant and M and R the Earth's mass and radius. Since the meaning of "flat-space picture of gravity" might be ambiguous, we shall repeat here the basic derivation.

The usual interpretation of phenomena in gravitational fields is in terms of a fundamentally curved space-time. However, some authors [20, 21, 22] have argued that, as light in Euclidean space deviates from a straight line in a medium with variable density, an effective curvature might also be the consequence of a suitable polarization of the physical flat-space vacuum. The substantial phenomenological equivalence with the standard interpretation was well summarized by Atkinson as follows [23] : "It is possible, on the one hand, to postulate that the velocity of light is a universal constant, to define *natural* clocks and measuring rods as the standards by which space and time are to be judged and then to discover from measurement that space-time is *really* non-Euclidean. Alternatively, one can *define* space as Euclidean and time as the same everywhere, and discover (from exactly the same measurements) how the velocity of light and natural clocks, rods and particle inertias *really* behave in the neighborhood of large masses." In this sense, in the flat-space approach, one is adopting a "Lorentzian perspective" where physical rods and clocks are held together by the same forces underlying the structure of the "ether" (the physical vacuum). Thus the Equivalence Principle actually means that the effect of an external gravitational field can be re-absorbed into the space-time units of a freely-falling observer so as to preserve local Lorentz covariance.

Notice that the Equivalence Principle was introduced [24] before General Relativity and, as such, does not rely on the notion of a fundamentally curved space-time. Actually, it could even be considered misleading within a pure, curved space-time context described by a given Riemann tensor [25]. For this reason, it has also been interpreted in terms of an ether flow [26]. Nevertheless, regardless of its ultimate physical origin, this fundamental principle implies that in a freely-falling frame, given two space-time events that differ by (dx, dy, dz, dt) and the local space-time metric

$$ds^2 = c^2dt^2 - (dx^2 + dy^2 + dz^2) \tag{38}$$

one gets from $ds^2 = 0$ the same speed of light as in the absence of any gravitational effect.

However, to a closer look, an observer placed on the Earth's surface is equivalent to a freely-falling frame *up to the presence of the Earth's gravitational field*. This leads to the weak-field, isotropic modifications of the metric

$$ds^2 = c^2dt^2(1 - \frac{2GM}{c^2R}) - (1 + \frac{2GM}{c^2R})(dx^2 + dy^2 + dz^2) = c^2dt_0^2 - dl_0^2 \tag{39}$$

Here dt_0 and dl_0 denote respectively the elements of proper time and proper length in terms of which, in General Relativity, one would again deduce from $ds^2 = 0$ the same universal value $\frac{dl_0}{dt_0} = c$. On the other hand, in the flat-space approach the condition $ds^2 = 0$ is now interpreted in terms of a refractive index for the vacuum as in Eq.(37) and thus light can be seen isotropic in *only one* reference frame, say Σ. This means that isotropy is only valid if the Earth were at rest in the hypothetical Σ. Otherwise, by introducing the Earth's velocity components V_i, off-diagonal elements $g_{0i} \sim V_i/c$ in the effective metric are generated by the Lorentz transformation for the observer placed on the Earth. These non-zero g_{0i} can be imagined as being due to a directional polarization of the vacuum induced by the now moving Earth's gravitational field and express the general property [27] that any metric, locally, can be brought into diagonal form by suitable rotations and boosts. By starting in Σ with the diagonal and isotropic form Eq.(39), one obtains

$$g_{0i} \sim 2(\mathcal{N}_{\text{vacuum}} - 1)\ \frac{V_i}{c} \tag{40}$$

and an anisotropy of the speed of light. The value of light anisotropy can also be computed by simply composing the isotropic speed $c/\mathcal{N}_{\text{vacuum}}$ with a given velocity $\mathbf{V}$. In this way, one predicts a two-way speed of light as in Eqs.(1) and (2).

6. Conclusions

Let us now collect all previous results. For an average colatitude $\chi \sim 38$ degrees (as for the average location of the Berlin and Düsseldorf laboratories) one finds $f(\gamma, \chi) = (0.60 \pm 0.22)$ in the whole range $0 \leq |\gamma| \leq \pi/2$. Therefore, by using (37) in Eq.(35), one finds

$$A_0^{\text{th}} = (12.6 \pm 4.6) \cdot 10^{-16}\ (V/300\ \text{km} \cdot \text{s}^{-1})^2 \tag{41}$$

in units of the typical speed 300 km/s of most cosmic motions. This estimate is equivalent to the previous prediction [28] for the amplitude of the frequency shift measured in a symmetrical apparatus (i.e. with two orthogonal rotating resonators)

$$A_0^{\text{symm}} = |B|\frac{\langle v^2 \rangle}{c^2} = 2A_0^{\text{th}} = (1.9 \pm 0.7) \cdot 10^{-15} \tag{42}$$

in terms of the average projected speed $\sqrt{\langle v^2 \rangle}$=(204 ± 36) km/s obtained from a re-analysis of the classical experiments.

Since these theoretical estimates agree well with the experimental values (33)-(34) extracted from Refs.[3, 18], and with the mean amplitude $1.9 \cdot 10^{-15}$ of the signal measured in the symmetric apparatus of Ref.[14], we conclude that the observed frequency shift, rather than being spurious noise of the underlying optical cavities, might also reflect basic properties of the vacuum. On the one hand, this appears as a polarizable medium responsible for the apparent curvature effects induced by a gravitational field. On the other hand, the observed strong random fluctuations of the signal support the view of a stochastic medium, similar to a superfluid in a turbulent state of motion. In this sense, the situation might be similar to the discovery of the CMBR that, at the beginning, was also interpreted as mere instrumental noise.

A crucial test of our interpretation can be performed in a freely-falling spacecraft. In this case, where the vacuum refractive index $\mathcal{N}_{\text{vacuum}}$ for the freely-falling observer is exactly unity, the typical instantaneous $\Delta\nu$ should be much smaller (by orders of magnitude) than the corresponding $\mathcal{O}(10^{-15})$ value measured with the same interferometer on the Earth's surface.

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List of Tables

1 By using Eqs. (23), (24) and (25), we report the values Q_i, their uncertainties ΔQ_i and the ratio $R_i = Q_i/\Delta Q_i$ for each of the 27 experimental sessions of Ref.[3]. These values have been extracted, according to standard error propagation for a composite observable, from the basic C_k and $S_k \equiv B_k$ coefficients reported in Fig.2 of Ref.[3]. 14

Table 1: By using Eqs. (23), (24) and (25), we report the values Q_i, their uncertainties ΔQ_i and the ratio $R_i = Q_i/\Delta Q_i$ for each of the 27 experimental sessions of Ref.[3]. These values have been extracted, according to standard error propagation for a composite observable, from the basic C_k and $S_k \equiv B_k$ coefficients reported in Fig.2 of Ref.[3].

Q_i[x10^{-16}]	ΔQ_i[x10^{-16}]	$R_i = Q_i/\Delta Q_i$
13.3	3.4	3.9
14.6	4.8	3.0
6.6	2.6	2.5
17.8	2.8	6.3
14.0	5.8	2.5
11.1	4.2	2.6
13.0	4.2	3.1
19.2	6.1	3.1
13.0	4.7	2.8
12.0	3.5	3.4
5.7	2.4	2.4
14.6	5.2	2.8
16.9	3.3	5.1
8.3	2.4	3.4
27.7	4.5	6.2
28.3	5.7	5.0
12.7	2.5	5.1
12.1	5.3	2.3
13.7	6.0	2.3
23.9	5.7	4.2
28.9	4.3	6.7
18.4	5.1	3.6
19.2	6.2	3.1
11.9	2.7	4.4
18.1	5.4	3.3
4.2	2.9	1.4
31.6	7.9	4.0