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Quadratic Sagnac effect — the influence of the gravitational potential of the Coriolis force on the phase difference between the arms of a rotating Michelson interferometer (an explanation of D C Miller's experimental results, 1921 – 1926)

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Abstract. It is shown that when an equal-arm Michelson interferometer is involved in rotation (for example, Earth's rotation around its axis or around the Sun) and its arms are oriented differently with respect to the plane of rotation, a phase difference arises between the light rays that pass through different arms. This phase difference is due to the fact that the arms experience variously the Newtonian (nonrelativistic) scalar gravitational potential of the Coriolis forces. It is shown that the phase difference is proportional to the length of the interferometer arm, the square of the angular velocity of the rotation, and the square of the distance from the center of rotation — hence, the proposal to call this phenomenon the quadratic Sagnac effect. In the present paper, we consider, as an illustrative example, the results of the once well-known experiments of D C Miller, who claimed to observe the translational motion of Earth relative to the hypothetical 'luminiferous ether'. It is shown that this claim can actually be explained by the fact that, because of the orbital revolution of Earth, the time dilations in the orthogonal arms of the Michelson interferometer are influenced differently by the scalar gravitational potential of the Coriolis forces.

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> "...If you, dear reader, wanted to use this extremely interesting scientific situation for placing a bet, I would recommend you wagers that Miller's experiments will prove to be faulty, or his results have nothing to do with an 'ether wind'! I at least would be very ready to make such a bet."
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> A Einstein [1] (Einstein, op. cit., note 40)

> "...Miller's interpretation does not agree with his observations which remain bare facts and need to be explained."
>
> S I Vavilov [2]

1. Introduction

The special theory of relativity (STR) states that no experiment, not even the interferometric one, can detect translational motion. However, if a Michelson interferometer (MI) is located on the surface of the Earth, it executes not only translational motion but also rotational motion. This latter motion is absolute and can be detected, because it gives rise to the centrifugal acceleration $\Omega^2 R$ and the Coriolis acceleration $2\Omega Rc$ for traveling photons (where c is the speed of light in a vacuum, Ω is the angular velocity, and R is the rotation radius). If the MI is filled with an optical medium with the refractive index n, then the speed of light and, correspondingly, the Coriolis acceleration for traveling photons would be $1/n$ their values. This article considers only an MI without an optical medium.

As will be shown in Section 3, the centrifugal acceleration is negligible compared to the Coriolis acceleration for traveling photons in an MI. It will also be demonstrated in

Section 3 that the phase difference, which arises for two arms of the rotating MI, is not caused directly by the accelerations mentioned above, but is connected with the gravitational (Newtonian) potentials of the appropriate forces: Coriolis and centrifugal forces. An MI executes three rotational motions at the same time: (1) Earth's rotation around its axis ($\Omega = 7.27 \times 10^{-5}$ rad s^{-1}, on the equator $R = 6.3 \times 10^3$ km, and the rotational velocity is $v_{\mathrm{Earth}} = 458$ m s^{-1}); (2) orbital revolution of Earth around the Sun ($\Omega = 1.97 \times 10^{-7}$ rad s^{-1}, $R \approx 1.5 \times 10^8$ km, $v_{\mathrm{orbit}} \approx 30$ km s^{-1}), and (3) rotation of Earth and the Solar System around the Galaxy (Milky Way) center ($\Omega \sim 8 \times 10^{-16}$ rad s^{-1}, $R \sim 2.5 \times 10^{17}$ km, and $v_{\mathrm{Gal}} \sim 220$–$240$ km s^{-1}).[1]

Due to the Sagnac effect [4–11], the rotation gives rise to the emergence of a phase difference for counterpropagating waves in a ring interferometer (RI). In a fixed (laboratory) frame of reference, the Sagnac effect results from the relativistic composition law for the velocities of the light wave and the angular velocity of the RI [7, 8, 10, 11]. In a frame of reference corotating with the RI, the Sagnac effect results from the difference in the Newtonian (nonrelativistic) scalar gravitational potential of the time-dilating Coriolis forces for counterpropagating waves [7, 9–11]. The interferometer is motionless in this reference frame and there is no need to calculate the offsets and rotations of its optical elements. In Sections 3 and 4 we will apply the method, developed in Refs [7, 9–11] for the case of a rotating MI.

The goal of this article is to show that the rotation gives rise to an additional phase difference not only in the RI, but also in the MI, if its arms are oriented differently with respect to the rotation plane. Therefore, the change in the phase difference that arises at the output of the MI under its rotation, which was observed in the Michelson–Morley (M – M) experiments [12, 13] and many other reproductions, has nothing to do with the hypothetical 'luminiferous ether'.

It is well known that in 1881 A A Michelson (1852–1931) developed the MI in order to solve a problem which was very topical at that time: observation of the translational motion of Earth relative to the hypothetical motionless 'luminiferous ether' [12]. The experiments with MI were repeated by many scientists, as well as by Michelson himself together with E W Morley (1838–1923) in 1887 [13]. Every time, these experiments revealed the appearance of some change in the phase difference for orthogonal arms of the MI after its rotation, but this effect was significantly smaller than the magnitude predicted by the 'luminiferous ether' theory. Negative results of M–M experiments [12, 13] may account for rejecting the hypothesis for the luminiferous ether and this eventually led to the development of the STR [14–16]. Small changes in the phase difference in the MI arms came to be treated as the experimental error.

M–M experiments [12, 13] were repeated over and over again. One such experiment was performed in 1921–1926 in the astronomical Mount Wilson Observatory by D C Miller (1866–1941) and showed quite a significant change in the phase difference at the output of the MI, while it was slowly rotating [17–20]. At the time, still numerous supporters of the luminiferous ether theory and Miller himself treated this fact as a final refutation of the STR. One of Miller's articles [18] was translated into Russian and published in the USSR in the *Uspekhi Fizicheskikh Nauk* (*UFN*) journal [21]. In turn, S I Vavilov published a series of studies [22–25] in *UFN* and a monograph [2] where he claimed the validity of the STO and doubted that the Miller results were interpreted correctly.

A number of researchers in the USA and Western Europe have repeated [26–34][2] the M–M experiments, and the results showed the existence of some change in the phase difference in the output of the MI, but the effect was significantly smaller than in the Miller experiments [17–20]. D C Miller's results were discussed at the special conference held on 4–5 February 1927 at the Mount Wilson Observatory [36], attended by many famous physicists, including A A Michelson and G A Lorentz.

Even today, the results of D C Miller's experiments are exciting for some STR opponents. Therefore, another goal of this article is to show that the results of experiments [17–20] can easily be explained in the framework of the STO.

2. D C Miller's experiments and the physical community response to the results obtained. Review

The Morley and Miller families were neighbors in Cleveland (Ohio, USA) and were good friends [37]. In 1900, E W Morley and D C Miller went together to an International Scientific Congress in Paris, where they met lord Kelvin (W Thomson) [38]. Kelvin presented a talk about the main ether theories and the significance of the M–M experiments [12, 13]. Later, in a private talk, he convinced E W Morley and D C Miller to repeat these experiments, but with a higher precision [38].

This shows how the friendship with E W Morley and meeting with lord Kelvin greatly increased the scope of the scientific interests of D C Miller. By that time, Miller was already a well-known highly qualified specialist in acoustics; he was developing devices for harmonic analysis, synthesis, and recording sound (on motion picture film) and was a consultant to music instrument manufacturers.

E W Morley and D C Miller repeated the M–M experiments in 1902–1905 using a larger MI with an arm length of 32 meters[3] (the results were published in article [26] in 1905). The experiments [26] revealed that the measured phase difference for the light waves at the output of the MI appeared to be significantly smaller than the one predicted by the ether theory. The STR had already been developed by that time [14–16], and it predicted zero results for the M–M experiments. It seemed that there was no need to repeat these experiments.

However, during the first decades of the 20th century, the STR still had not a few serious opponents — well-known and highly qualified scientists that received their education in the 19th century. Among them was D C Miller. For his new experiments (1921–1926), he utilized an interferometer which partially remained after the joint measurements with

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[1] The indicated values for the Galaxy are only approximate, because the rate of a star rotation around the Galaxy center does not decrease as a square root of the distance to the Galaxy center (as follows from Newton's mechanics), but adheres to a more complex law: first it increases proportionally to the distance to the center, and then it becomes constant. The reason for this can be both the presence of distributed dark matter and dark energy in the Galaxy and the errors in the astronomical measurements for the velocities of stars and galaxies, which arise due to the relativistic aberration effect [3].

[2] The Russian translation of article [34] was published in *UFN* [35].

[3] In experiments [12], the length of the MI arm was 1.2 m, and in experiments [13] it was 11 m.

E W Morley [26], but he made a number of modifications, such as using various materials for the interferometer frame in order to eliminate the influence of Earth's magnetic field, temperature, and other interfering factors [17–20]. Preliminary measurements were performed in Cleveland, while the main ones were carried out at the Mount Wilson Observatory, situated on Mount Wilson in California [17–20].

The results of Miller's experiments [17–20] (which were discussed in detail in his article [38] in 1933, summarizing years of work) turned out to be sensational: Miller obtained the value of the ether wind velocity of ≈ 10 km s^{-1}, which was quite close by order of magnitude to the value predicted by the luminiferous ether theory, being ~ 30 km s^{-1} and equal to Earth's orbital velocity. For D C Miller and other supporters of the luminiferous ether theory, this was a definitive disproof of the STR. Miller assumed that Earth executes not only orbital motion relative to the motionless ether, but also takes part in translational motion of the whole Solar System with respect to ether, and that the rate of this motion is around 200 km s^{-1} [38]. Moreover, he believed that the ether wind velocity significantly decreases near the surface of Earth and one should perform the measurements high in the mountains. Finally, the MI should be placed in a lightweight building, since the main walls, made of bricks, in his opinion, weakly transmit the ether wind.

The reaction in the USSR to the results were quite interesting [17–20]. As mentioned before, Miller's article [18] was translated into Russian and published in the *UFN* journal [21]. S I Vavilov published articles [22–25] in *UFN* and monograph [2], where he convincingly defended the validity of the STR and reasonably doubted that D C Miller correctly treated his results. Particularly, S I Vavilov published in *UFN* [25] an abridged Russian translation of the R J Kennedy article [27], where the M–M experiments were repeated with a higher precision of the interference fringe shift measurements. The review by G Joos [39], where, in particular, the Miller experimental results were also criticized, was translated into Russian and published in *UFN* [40] as well.

At the same time, shortly after the first Miller publication in April 1922 [17], some highly qualified Soviet physicists doubted the validity of the STR. Particularly, Ya I Grdina [41] and L Ya Shtrum [42] suggested different modifications to the composition law for relativistic velocities. In order to explain the results of paper [17], physics theorist L Kordysh [43] assumed that the solutions of the Maxwell equations allow the existence of velocities higher than the speed of light.

The physicist and Marxist philosopher A K Timiryazev, who was well known for his uncompromising struggle with the STR, accepted Miller's experimental results with great enthusiasm. He translated Miller's works [19, 20] into Russian and published them in the journal *Pod Znamenem Marksizma* (*PZM*) [44, 45]. Moreover, these translations were preceded by his enthusiastic foreword [46] and a Russian translation [47] of an article by L Silberstein in *Nature* [48], which favored Miller's conclusions. A K Timiryazev even published an article in the *Izvestiya* newspaper about the D C Miller results [49].

The reaction to the unexpected results obtained by Miller [17–20] was much more pragmatic in the USA and Western Europe — the results were not only discussed, but also double checked: in the USA by R J Kennedy [27], K K Illingworth [28], and A A Michelson and co-authors [31, 32]; in Belgium by A Piccard and E Stahel [29, 30], and in Germany by G Joos [33, 34]. A discussion concerning Miller's results [17–20, 27] took place at the specially organized conference on 4–5 February 1927 at the Mount Wilson Observatory [36], where many famous physicists and astronomers, including D C Miller himself, A A Michelson, R J Kennedy, H A Lorentz, P Epstein, and a well-known American astronomer G Stromberg, who helped D C Miller in the processing of the results gathered [18, 38].

The discussion at the conference [36] did not make the problem clearer. D C Miller held his ground; R J Kennedy noted that his experiments [27] did not confirm the Miller results; P Epstein reported on the results obtained by A Piccard and E Stahel [29, 30], which, like the results in Ref. [27], showed a significantly smaller shift of the interference fringes at the output of the MI than in the D C Miller experiments [17–20]; A A Michelson was diplomatic and neither sad 'no' nor 'yes', but only expressed joy that the work of D C Miller and R J Kennedy had once again aroused interest in his old experiments; H A Lorentz only recalled his old idea [50] that the M–M experiments and their repetitions can be explained using the hypothesis about the contraction of the real length of the MI arms as they move relative to the ether: "If one would ask me if I consider this contraction as reality, I would say 'yes'. It is as real as everything we observe" [50].

It is interesting to note that Albert Einstein did not consider it necessary to discuss the D C Miller results in scientific publications, but instead made an ironic comment on them in a newspaper article[4] [1].

Further attempts to repeat the M–M experiments [28, 31–34] did not confirm the Miller results [17–20, 38], either, which remained a scientific artifact.

In review [52] published 30 years after the conference [36], Miller's results [17–20, 38] were explained by the inhomogeneous heating of the MI arms.

In Section 3, we will discuss the influence of Earth's orbital motion on the phase difference in the MI arms in the framework of the special theory of relativity.

3. Michelson interferometer rotation in the theory of relativity

Earlier, it was assumed that the phase difference in counterpropagating beams appears as a result of rotation only in the case of such interferometers which comprise some closed area. Among such interferometers are, for example, Sagnac and Mach–Zehnder interferometers. In this case, the phase difference of counterpropagating beams is proportional to the area inside the interferometer. Since the area in each orthogonal arm of the MI is zero, it was earlier believed that the rotation does not give rise to the emergence of a phase difference in MI arms.

However, recently an Italian researcher P Maraner [53] called attention to the fact that the rotation leads to some phase difference for light in the orthogonal arms of the MI. Article [53] considers a special case, when both arms of the MI lie in the rotation plane, so both arms are orthogonal to the rotation axis. Under this condition, as the MI rotates, its

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[4] An interesting fact was mentioned in Ref. [51]. In his article, Einstein writes "Herr Miller", while, according to the scientific ethics of that time, a university lecturer should be called "Professor Miller". This means that Einstein explicitly expressed no confidence in Miller's results. It is fair to note that D C Miller writes simply "Einstein" in his articles [18-20] without using any initials or the word "Mr.".

optical elements move relative to the laboratory inertial frame of reference (IFR) and the light in every arm describes some small closed area. Then, due to the Sagnac effect [4–11] and under the condition that the MI arms be oriented in such a way that the distances from the ends of the first and second arms to the rotation center are different, a quite small phase difference arises. This phase difference is proportional to the length squared of the MI arm, to the angular velocity of rotation, and to the distance from the rotation center [53]. According to Ref. [53], Earth's rotation causes in a significantly large MI, which was studied in Ref. [13] (arm length $L = 11$ m), a phase difference of $\Delta\Phi \sim 10^{-8}$ rad, which cannot really be measured. But, as was shown in Ref. [53], for a long-baseline MI [for example, an interferometer used at LIGO (Laser Interferometer Gravitational Wave Observatory) physics experiment with $L = 4$ km] with multiple reflection of light (due to the Fabry–Perot resonators installed in the interferometer arms), the effect can be significant.

In this article, we will consider a stronger effect which takes place when the MI arms are oriented differently with respect to the rotation plane. As shown in our previous work [7, 9–11], it is convenient to calculate phase incursions for the rotating ring interferometer in a corotating reference frame, using the value of the Newtonian (nonrelativistic) scalar gravitational potential of the Coriolis forces, which induce time dilations. The interferometer is motionless in this frame of reference, and there is no need to calculate the offsets and rotations of its optical elements.

Here, we will adopt the method elaborated in Refs [7, 9–11] for the case of a rotating MI. It is obvious that for the case described in Ref. [53] the values of the scalar gravitational potential of the Coriolis forces, acting on different arms of the MI, are practically the same. The slight difference arises from the different distances between various points in the interferometer arms and the rotation center and from the difference in the orientation of the arms.

In general, the MI arms can be oriented differently in the rotation plane. We will first consider the simplest case, when the plane on Earth's surface, where the MI is located, is orthogonal to the rotation plane, and one of the MI arms is orthogonal (subscript $\perp$) to the rotation axis, while the other one is parallel to it (subscript $\|$). Then, in the corotating reference frame the propagation times for the light traveling in the MI arms forwards (superscript plus) and backwards (superscript minus) will be expressed for the circular motion in the following way [7, 9–11]:

$$t_{\perp}^{\pm} = t\sqrt{1 - \frac{\Omega^2 R^2}{2c^2} \mp \frac{2\Omega R}{c}}\,, \qquad t_{\|}^{\pm} = t\sqrt{1 - \frac{\Omega^2 R^2}{2c^2}}\,, \quad (1)$$

where $t = L/c$, Ω is the angular velocity of rotation, and R is the rotation radius. Expressions (1) are approximate and they hold true under the condition $2\Omega R/c \ll 1$ [7, 9–11]. In this case, $\Omega^2 R^2/c^2 \ll 2\Omega R/c$.

The second term of the radicands in expressions (1) emerges due to the influence of the scalar gravitational potential of the centrifugal force, and the third term of the radicands in the expression for $t_{\perp}^{\pm}$ emerges due to the influence of the scalar gravitational potential of the Coriolis forces.

Expressions (1) are derived for the circular motion [7, 9–11] in the absence of gravitational fields. In the case considered of Earth's orbital motion, the gravitational force of the Sun is present and it compensates for the centrifugal force, which simplifies the expressions (1):[5]

$$t_{\perp}^{\pm} \approx t\sqrt{1 \mp \frac{2\Omega R}{c}} \approx t\left(1 \mp \frac{\Omega R}{c} - \frac{1}{2}\frac{\Omega^2 R^2}{c^2} - \ldots\right), \quad t_{\|}^{\pm} \approx t\,. \quad (2)$$

Here, we have left only the terms of the first and second orders of smallness in the series expansion of the radicand in the expression for $t_{\perp}^{\pm}$. Now, the difference in the propagation times for light in the MI arms can be written out as

$$\Delta t \approx \left(t_{\|}^{+} + t_{\|}^{-}\right) - \left(t_{\perp}^{+} + t_{\perp}^{-}\right) = -\frac{L}{c}\frac{\Omega^2 R^2}{c^2}\,, \quad (3)$$

and the optical phase difference in the MI arms, expressed in units of the interference fridge width (2π rad), is given by

$$\Delta\Phi = \Delta t\,\frac{c}{\lambda} = -\frac{L}{\lambda}\frac{\Omega^2 R^2}{c^2}\,, \quad (4)$$

where λ is the radiation wavelength.

Notice that in the case of rotating RI, the phase difference for counterpropagating light waves emerges (Sagnac effect) due to the influence of the scalar gravitational potential of the Coriolis forces on the time dilation [7, 9–11], and it is proportional to $\Omega R/c$. However, in the case of a rotating MI, the phase difference between light waves in its two arms is proportional to $\Omega^2 R^2/c^2$, because after summing up the phase incursions of counterpropagating waves in the arm of the MI, which is orthogonal to the rotation axis, terms of the first order in $\Omega R/c$ cancel each other. This means that if the Sagnac effect is of the first order in $\Omega R/c$, then the effect considered in this article is of the second order in $\Omega R/c$. Therefore, we suggest that this phenomenon be named the quadratic Sagnac effect. The quadratic Sagnac effect, unlike the conventional one, can be observed even in interferometers which do not describe a closed area.

Because the velocity of the circular motion of the MI is $v_{\text{circ}} = \Omega R$, then one obtains

$$\Delta\Phi = -\frac{L}{\lambda}\frac{v_{\text{circ}}^2}{c^2}\,. \quad (5)$$

It is interesting to note that expression (5), derived in the framework of the theory of relativity, up to the sign coincides with the expression

$$\Delta\Phi = \frac{L}{\lambda}\frac{v^2}{c^2}\,, \quad (6)$$

which can be obtained by performing classical kinematic calculations with an assumption that the luminiferous ether exists. The derivation of expression (6) can be found in papers [12, 13] and in a number of textbooks (see, for example, book [54]). However, despite the fact that expressions (5) and (6) formally coincide, there are significant physics disparities between them.

(1) Expression (6) for the ether holds true in the case of the linear motion of the MI, but expression (5) describes only the

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[5] Actually, full compensation takes place only for points resided in the orbit. Since the MI is deployed on Earth's surface, it slightly changes its position relative to the orbit due to the rotation of the Earth, and an incomplete compensation takes place.

circular motion of the MI — that is, in the presence of the Coriolis force.

(2) In order for expression (6) to hold true, it is enough for the first arm of the MI to be parallel to the velocity of its motion, while the orientation of the second arm in space does not matter, since it is always orthogonal to the first one. In order for expression (5) to hold true, the first arm of the MI should be orthogonal to the rotation axis, while the second one should be parallel to it.

(3) As shown in Refs [12, 13, 54], during the calculation by formula (6) in the framework of the 'luminiferous ether' theory, a phase incursion due to the effect considered arises in the first MI arm which is parallel to its velocity of motion and this phase change is twice the value of the one described by formula (6). A phase incursion appearing in the second arm has the same value with that from Eqn (6) but the opposite sign. The algebraic sum of these phase incursions is described by expression (6). On the other hand, in the case of STR calculations, a whole phase incursion caused by the effect considered arises in the first arm of the MI, which is orthogonal to the rotation axis.

(4) In formulas (5) and (6), only the terms on the order of v^2/c^2 are taken into account. If one added higher-order terms in v^2/c^2 to Eqns (5) and (6), these expressions would have not only different signs, but also different values. However, since $v^2/c^2 \ll 1$ for the orbital motion of Earth, this difference would be small.

Let us now consider a more general case, when the plane where the MI is deployed is still orthogonal to the rotation plane, but the arms of the interferometer are rotated through the angle ψ with respect to the straight line lying in the rotation plane [for the case considered above, which leads to expression (2), $\psi = 0$]. This will allow us to find out how the optical phase difference in the arms of the MI changes as it is rotated — that is, when the angle ψ is changed. In this case, one has

$$\begin{aligned} t^{\pm}_{\pi/2+\psi} &\approx t\sqrt{1 \mp \frac{2\Omega R}{c}\cos\psi} \\ &\approx t\left(1 \mp \frac{\Omega R}{c}\cos\psi - \frac{1}{2}\,\frac{\Omega^2 R^2}{c^2}\cos^2\psi - \ldots\right), \\ t^{\pm}_{\psi} &\approx t\left(1 \mp \frac{\Omega R}{c}\sin\psi - \frac{1}{2}\,\frac{\Omega^2 R^2}{c^2}\sin^2\psi - \ldots\right), \end{aligned} \tag{7}$$

and the optical phase difference in the MI arms takes the following form

$$\Delta\Phi(\psi) = -\frac{L}{\lambda}\,\frac{\Omega^2 R^2}{c^2}\cos(2\psi)\,. \tag{8}$$

We will now consider the most general case, when the plane in which the MI is deployed is tilted at the angle of $\pi/2 - \phi$ with respect to the rotation plane, and one of the MI arms is rotated through the angle ψ with respect to the line which is situated in the interferometer base plane and is parallel to the rotation plane. Then, after quite cumbersome trigonometric calculations, one can arrive at

$$\Delta\Phi(\psi, \phi) = -\frac{L}{\lambda}\,\frac{\Omega^2 R^2}{c^2}\left(\cos^2\phi\cos(2\psi) - \sin^2\phi\right). \tag{9}$$

It is obvious that expression (9) turns into (8) at $\phi = 0$. When $\phi = 90°$, both MI arms lie in the same (rotation) plane and, consequently, although the time dilation effect still takes place, its magnitude in both arms of the interferometer is the same and does not depend on the rotation angle ψ. However, as was mentioned above, both expression (1) and expression (9) are approximate. Actually, there is another very weak effect, which is not taken into account in expression (9). This effect was considered by Maraner [53] and its magnitude is numerically equal to that of the effect described here multiplied by the coefficient $2\sqrt{2}L/R$. In the classical M–M experiments and their reproductions [12, 13, 26–34], the MI arm length $L \approx 1-30$ m, and $R \approx 1.5 \times 10^{11}$ m for the orbital motion of Earth; therefore, the effect considered in Ref. [53] is obviously very small.

As expression (9) implies, in a uniform rotation of the MI around its axis (i.e., the angle ψ changes linearly, $\psi = at$, where a is a constant value), the intensity of the interference signal changes at the second harmonic of the frequency $a/(2\pi)$ — that is, at the frequency a/π. Let us note that expression (9) has no direct analogue in the 'luminiferous ether' theory.

4. Rotation of the Michelson interferometer, deployed on Earth's surface, with respect to the ecliptic plane

Let us consider the orbital motion of Earth in the ecliptic plane. Since the angle of Earth's equator inclination to the ecliptic plane is 23°26′13″, the site on Earth's surface, located at the geographic latitude of φ, constantly changes its angular orientation with respect to the ecliptic plane as Earth rotates around its axis. If the site is located in the equatorial area — that is, between the parallels of 23°26′13″ north latitude (n.l.) and 23°26′13″ south latitude (s.l.) ($-23°26'13'' \leqslant \varphi \leqslant 23°26'13''$), then it becomes orthogonal to the ecliptic plane two times per day. If $|\varphi| > 23°26'13''$, the site will never take up the position orthogonal to the ecliptic plane. It is not hard to show that in this case the site would reach maximal and minimal angular deflections from the orthogonal orientation with respect to the ecliptic plane when $\phi^+ = \varphi + 23°26'13''$ and $\phi^- = \varphi - 23°26'13''$, respectively. Figure 1 depicts a schematic of the MI deployed on the surface of Earth which orbits the Sun and rotates around its own axis.

For numerical estimations of the phase difference in the interferometer arms, one should substitute values of ϕ^+ and ϕ^- into expression (9). It is obvious that in the Northern

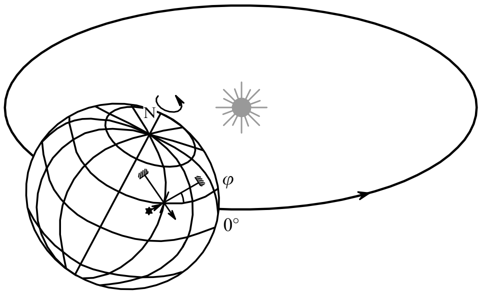

Figure 1. Earth rotates about its axis and executes orbital motion around the Sun. Point N marks the North Pole. Arrows show the rotation directions. The equator latitude is 0°. The equator plane is tilted with respect to the ecliptic plane (orbital plane). MI is deployed on Earth's surface at the latitude φ in the Northern Hemisphere, and it is oriented under some angle with respect to the direction of the parallel. The asterisk indicates the light source; the straight arrows indicate the input and output directions for the light beam.

Hemisphere during the rotation of the MI at the angle ψ the amplitude of the change in the phase difference would be maximal for ϕ^- and minimal for ϕ^+, because in the first case the angle between the site of the interferometer and the ecliptic plane is closer to a right angle than in the second case.

5. Analysis of Miller's experimental data

The astronomical Mount Wilson Observatory, where D C Miller performed his main experiments [17–20, 38], is located at the latitude of $\varphi = 34°13'28''$ s.l. Therefore, $\phi^+ = 34°13'28''+23°26'13'' = 57°39'41''$, and $\phi^- = 34°13'28'' - 23°26'13'' = 10°47'15''$ for most informative Miller's experiments[6] [18–20, 38].

The MI in experiments [18–20, 38] had the following parameters: arm length $L = 32.03$ m, and radiation wavelength $\lambda = 0.57$ μm [38]. Despite the fact that Miller and all researchers at that time evaluated measurements in the fractions of the interference fridge width, he almost never cited the primary results in his work, but marked the results obtained in units of the ether wind velocity (km s^{-1}). In order to obtain the Miller data in a dimension of the interference fridge width, one must perform an inverse transformation to expression (6). In Miller's experiments [18–20, 38], the maximal change in the phase difference for the MI arms was observed as the interferometer was rotated at the angle of $\psi = 90°$ from some other angle ψ [which indirectly confirms the validity of expression (9)], and this change corresponded to the experimental ether wind velocity of about 10 km s^{-1}. This means that the amplitude of the periodical shift of the interference fringe was $A(\Delta\Phi) = 6.25 \times 10^{-2}$ (the shift by one interference fridge corresponds to the change in the phase difference in the MI arms by 2π).

D C Miller changed the rotation angle ψ of the MI during measurements. Therefore, the theoretical value for the amplitude of the phase difference change $\Delta\Phi(\psi)$ at the output of the MI can be obtained from expression (9):

$$A\big(\Delta\Phi(\phi^{\pm})\big) = \frac{L}{\lambda}\,\frac{\Omega^2 R^2}{c^2}\cos^2\phi^{\pm}\,. \qquad (10)$$

Then, $A(\Delta\Phi(\phi^+)) = 1.6\times10^{-1}$ and $A(\Delta\Phi(\phi^-)) = 5.4\times10^{-1}$. This means that the value of $A(\Delta\Phi)$, measured in experiments [18–20, 38], should fall within the bounds of $1.6 \times 10^{-1} - 5.4 \times 10^{-1}$ interference fringe shifts. The experimental result obtained by D C Miller is 2.5 times less than the lower theoretical limit (1.6×10^{-1}) for the fringe shift. Such a deviation should not be surprising: in Refs [18–20, 38], one can see in figures an averaged dependence for $\Delta\Phi(\psi)$ and the dispersion of the experimental points, which exceeds the average value by a factor of more than unity. D C Miller explained these deviations as the 'ether wind variations'. In reality, some additional factor was present in experiments [18–20, 38], which led to the random change in the shift of the interference fringes, as the interferometer slowly rotated. One can assume that the cross-like base (4 × 4 m) of the MI in Refs [18–20, 38] was not properly balanced with respect to the rotation center and its ends (where the MI mirrors were mounted) slightly bent under their own weight during the slow rotation. Since the accuracy of the measurements in Refs [18–20, 38], as well as in other interferometric experiments of that time, was rather small, one can say that experimental results [19, 20, 38] agree quite well with the theoretical predictions.

It should be noted that if we had used an angular velocity of rotation around the Galaxy center for the linear velocity of an MI rotation instead of Earth's orbital rotation in our numerical estimations, using expression (9), we would have obtained the value for $A(\Delta\Phi)$, which is by two–three orders of magnitude larger than the one measured in the M–M [12, 13], Morley–Miller [26], Miller [17–20, 38] experiments, and other repeated experiments [27–34]. Moreover, the angle of inclination of Earth's equator with respect to the Galaxy plane is around 62.4°, and the rotation direction is opposite to Earth's orbiting around the Sun. This means that if the galactic rotation of Earth influences to some extent the MI, the phase shift induced by this influence should be subtracted from the phase shift induced by Earth's orbital revolution.

Expression (9) also explains the fact why in Cleveland D C Miller observed a slightly smaller shift of the interference fringes than at the Mount Wilson Observatory. Cleveland's latitude is $\varphi = 41°29'58''$ and, correspondingly, for the MI used in experiments [18–20, 38], the amplitude of the fringe shift should lie within the bounds of $9.8 \times 10^{-2} - 4.9 \times 10^{-1}$, which is smaller than at Mount Wilson. Miller himself assumed that this difference arises due to the fact that the Mount Wilson Observatory is 1.5 km higher than Cleveland and the ether wind velocity is higher there [38].

The calculated results following from equation (9) for experiments [12, 13, 26–34] show that for measurements [12, 30, 31] the amplitude $A(\Delta\Phi)$ of the interference fringe shift is found within the bounds determined by expression (10), while in the other studies $A(\Delta\Phi)$ is several-fold smaller than the lower theoretical limit.

A detailed analysis of experiments [27–34], which is a topic of separated research, will be performed by the authors of this article in the forthcoming publication [55].[7] Here, we will only note that experiments [27–30, 33, 34] were carried out at latitudes higher than the latitude of the Mount Wilson Observatory, where D C Miller conducted his main experiments [18–20, 38]. And, according to expression (9), the value for the amplitude $A(\Delta\Phi)$ of the interference fringe shift, normalized to the MI arm length L, is smaller in Refs [27–30, 33, 34] than in Refs [18–20, 38].

6. Further investigations of possible light speed anisotropy

Classical M–M experiments and their reproductions [12, 13, 26–34] were performed for almost 50 years (1881–1930). Later on, a number of tests concerning the light speed anisotropy were conducted, but the technique of these measurements always differed from the one used in classical M–M experiments [12, 13]. We will briefly discuss some of these examinations in this section.

Already at the very beginning of the 20th century some researchers were starting to doubt the validity of the M–M

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[6] Due to unknown reasons, the value of the latitude of Mount Wilson, which Miller indicated in Ref. [20], was $\varphi = 31°14'$ s.l. The point with such a latitude is located more than 330 km to the south of the Mount Wilson Observatory in Mexico, Baja California state. It is even stranger, because the observatory's location is determined with less than one angular second error in order to perform astronomical observations. In his other work, D C Miller does not mention Mount Wilson's latitude at all.

[7] Note that the Russian translations of articles [1, 12, 13, 19, 20, 26–32, 36, 38, 46, 56, 57] may be acquainted in the collection of work [51].

experiments [12, 13]. Many various objections were voiced, but the most serious of them was the fact that, according to the FitzGerald–Lorentz hypothesis [50, 58], the moving object experiences a real length contraction in the direction of its motion by a factor of γ. In this case, despite the predictions of the STR, various inertial frames of reference (IFRs) are no longer equivalent and the IFR related to the luminiferous ether becomes determinant.

Unfortunately, an MI cannot, in principle, distinguish between STR predictions [14–16] and the FitzGerald–Lorentz hypothesis [50, 58]. Researcher needed to repeat the M–M experiments with an MI having unequal arm lengths. In this case, during a yearly change in the absolute value of Earth's velocity relative to the hypothetical luminiferous ether (which has to take place due to the vector addition of Earth's velocity relative to the Sun and the Sun's velocity relative to the IFR connected with the ether) the lengths of the interferometer arms would change to different values. In order to perform such experiments, however, one needs a sufficiently bright monochromatic radiation source with a large correlation length. The light from sources which were used in these days, after passing a monochromator, was not bright enough, and lasers had not been invented yet. Only in 1932 did R J Kennedy and E M Thorndike [59] perform nine-month-long experiments (named subsequently K–T ones) using an MI with one arm 7.5 times longer than the other. The experiments demonstrated the practically complete absence of the interference fringe shift, predicted by the FitzGerald–Lorentz hypothesis, and, therefore, confirmed the validity of the STR.

One should emphasize that the main difference between the K–T [59] and M–M [12, 13] experiments is not even the unequal arm lengths of the MI, but the fact that during the K – T experiments [59] an MI with unequal arm lengths was not rotated around its axis at all — that is, the angle ψ in expressions (7)–(9) did not change: $\psi = \text{const}$. In this case, a slow change in the phase difference in the MI arms takes place due to the change in the angle ϕ [see expression (9)] with a day period (because of Earth's rotation). Therefore, K–T type experiments need a special theoretical analysis. Particularly, if Earth's equator were not tilted with respect to the ecliptic plane, the time dilation effect considered in this article due to the presence of the scalar gravitational potential of the Coriolis forces would not lead to any change in the phase difference in the MI arms for K–T type experiments.

K–T experiments were repeated by D Hills and J L Hall [60] using an He – Ne laser with an iodine nonlinear absorption cell ($\lambda = 0.63$ μm) at a quite high precision level. Recently, German researchers have repeated the K–T experiments using two orthogonally oriented Fabry–Perot resonators made of crystalline sapphire, cooled to liquid-helium temperatures [61–63]. As in the K–T experiment [59], the plate on which the optical setup was mounted did not rotate in experiments [60–63], but instead Earth's rotation around its axis was taken into consideration.

In the experiment performed by A Brillet and J Hall [64], the MI was not tapped at all. The radiation from the rotating He – Ne laser, frequency-coupled to the motionless quantum frequency standard (an He – Ne laser with a methane nonlinear absorption cell, $\lambda = 3.39$ μm) was passed through a stabilized Fabry–Perot resonator which was rotating together with the laser, and the laser optical axis was perpendicular to the rotation axis. In this case, it was not possible to perform a simultaneous comparison of the phase difference for the optical beams in orthogonal directions. Moreover, since the Fabry–Perot resonator length was stabilized on the frequency of the rotating He – Ne laser, any effect that causes a change in its resonant frequencies would automatically lead to a change in the resonant frequencies of the Fabry–Perot resonator.

Already at the end of the 1950s, J P Cedarholm et al. [56, 57] performed a measurement using two ammonia masers (generation frequency 23.870 Hz), whose resonators were oriented parallel but had opposite directions of the excited ammonia molecule emissions. The authors' idea [56, 57] was that the existence of the ether wind would lead to a difference in the generation frequencies of two masers, and this difference would change its sign under the simultaneous turning of the masers through 180°. However, this effect was not observed in the experiments [56, 57]. Since in the latter the rates of the electromagnetic radiation in orthogonal directions were not compared, these measurements are not directly related to the M–M experiments and their reproductions and, consequently, can neither confirm nor refute expressions (7)–(9). The results of work [56, 57] can only indicate the absence of the influence of the ether wind on the maser generation frequency.

Apparently, the experiment which is closest to the M – M measurements is the one performed by Ch Eisele, A Yu Nevsky, and S Schiller [65], where the resonance frequencies of a vacuum high-Q glass resonator with a square cross section were compared for the mutually orthogonal directions. The axis of one of the Fabry–Perot resonators was directed horizontally, while the other one was directed vertically. The length of the square side was 8.4 cm, and the resonance FWHW was around 10 kHz. The whole system rotated around the vertical axis with an angular velocity of ≈ 0.3 revolutions per minute. The resonators were excited by Nd:YAG laser radiation ($\lambda = 1.06$ μm), and the locking of the radiation frequency to the resonance frequencies of the orthogonal sides of the resonator was performed by means of acousto-optical modulators.

The main difference between this last experiment and the M–M experiments [12, 13] lies in the fact that the authors of work [65] did not exploit the MI, but took advantage of two orthogonally oriented resonators instead. The effect considered in this article [see expressions (2), (3)] implies that the optical lengths of the resonator for counter directions are different in the case of the optical axis being orthogonal to the rotation axis, and this difference shows itself already in the first order in $\Omega R/c$. Therefore, a frequency nonreciprocity of the counterpropagating waves takes place for Fabry–Perot resonators [65]. However, the problem of calculating the eigenfrequencies of the Fabry–Perot resonators in the presence of a nonreciprocity (for example, generation frequencies of the laser, which has a cell with a moving liquid inside the resonator) still does not have a correct solution. In this connection, one should note that the results of Ref. [65] need additional analysis.

7. Conclusions

Let us make a list of the main results of the present article:

(1) It was shown that if an MI with equal arms rotates and its arms are oriented differently with respect to the rotation plane, a phase difference arises for the light beams traveling in the two arms, caused by the different values of the Newtonian (nonrelativistic) scalar gravitational potential

of the Coriolis forces, which act on different arms of the interferometer.

(2) Since the phase difference for counterpropagating light waves, induced by the Sagnac effect [4–11], is proportional to $\Omega R/c$ in a rotating RI, and is proportional to $\Omega^2 R^2/c^2$ in the rotating MI, we propose naming the latter phenomenon the quadratic Sagnac effect. Both normal and quadratic Sagnac effects are caused by the influence of the scalar gravitational potential of the Coriolis forces on the time dilation in a rotating reference frame [7, 9–11]. Unlike the normal Sagnac effect, the quadratic one can be observed even in interferometers which do not describe a closed area.

(3) It was shown that the results of the experiments performed by D C Miller [17–20, 38] have a simple explanation in the framework of the STR.

(4) We believe that this is a very unusual situation for physics, when the scientists that follow different concepts are all right at the same time — that is, not only A Einstein and S I Vavilov, but also D C Miller in some sense. Einstein was absolutely correct when he claimed that Miller's results have nothing to do with the ether wind [1]. Vavilov was absolutely right when saying the Miller interpretation was "inconsistent with his own observations, which remain bare facts needing to be explained" [2]. There was no such explanation in 1920, but it is given in the present article. Miller had registered a systematic change in the phase shift in the rotating MI arms, and the order of magnitude of this change is close to the one that follows from expression (9). Of course, Miller's interpretation of his own results [17–20, 38] leaning upon the luminiferous ether theory is wrong.

(5) Since the M–M experiments have not been repeated in the classical form for 75 years and the sensitivity of the interferometric measurements has increased by many orders of magnitude during this time, it is advisable to repeat them using modern optical elements. More than 60 years ago, I Ya Brusin et al. [66] and I L Bershtein [67] used a modulation method of phase measurements in optics, which for a sufficiently large light intensity allowed periodic changes in the phase difference to be observed with an accuracy of about $10^{-6} - 10^{-7}$ rad.

In a sense, D C Miller was lucky: he performed the main measurements [17–20, 38] at the Mount Wilson Observatory, located at the closest latitude to the equator, compared to the latitudes of locations where other similar experiments were conducted (except for experiments [31, 32], which were also held at the Mount Wilson Observatory). Moreover, the length L of the MI arms in Refs [17–20, 38] was larger than in other similar experiments.

A question can arise: why did Einstein not explain the Miller results [17–20] by himself using the Newtonian scalar gravitational potential of the Coriolis forces in a rotating reference frame? It is even more surprising if we take into account the fact that nobody else but Einstein discovered the influence of the scalar gravitational potential on time dilation [68] and light propagation [69]. The reason is probably connected with the dismissive attitude of A Einstein with respect to D C Miller himself, as well as to his results [17–20] discussed in Section 2. Miller treated his results [17–20] as a refutation of the STR and Einstein was absolutely confident in the STR's validity, did not believe the Miller results, and did not bother himself finding a rational explanation for them.

When this article was already accepted for publication, an experimental study was reported [70] which demonstrates the absence of the light speed anisotropy, at least up to the eighteenth significant digit. However, the authors of this study did not use an optical MI, but instead used so-called qubits — memory cells of a quantum computer — in the presence of a strong magnetic field. If light speed anisotropy were present, the daily and orbital rotation of Earth would lead to a change in the coupling between two qubits, which was not observed. In experiment [70], however, there is no light propagation (or De Broglie waves for material particles or waves of other natures), particularly, no light propagation in the forward and backward directions, as in the MI arms. Consequently, there is no Coriolis force acting on photons and, correspondingly, the quadratic Sagnac effect is absent. The results [70], as well as the analysis of the experiments [56, 57, 59–65] performed in Section 6, show that not all the methods for the observation of possible light speed anisotropy suggest the emergence of the Coriolis force and its influence on the measurement results.†

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† For some addendums and amendments to this article, see *Uspekhi Fizicheskikh Nauk* **185** (8) 895 (2015) [*Physics–Uspekhi* **58** (8) (2015)]. (*Author's note to English proofs.*)

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