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PHYSICAL OPTICS

Quadratic Sagnac Effect Recorded by an Observer in the Laboratory Frame

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Abstract—The quadratic Sagnac effect, recorded by an observer in the laboratory frame of reference (inertial frame), relative to which the Michelson interferometer moves, has been considered. The quadratic Sagnac effect was previously calculated in a rotating frame of reference, where it occurs as a consequence of the influence of the gravitational potential of the Coriolis force in the rotating frame of reference and leads to a phase difference in the rotating Michelson interferometer. It has been shown that the quadratic Sagnac effect values calculated in the inertial frame and rotating frame of reference are practically the same. It has also been shown that, in various cases, the calculation of the quadratic Sagnac effect is most rational to carry out either in the inertial frame or in the rotating frame of reference. The numerical estimates performed have shown that the experiments on recording the quadratic Sagnac effect are quite possible. The concept of effective lengths of the arms of a Michelson interferometer moving relative to a stationary observer: the light paths lengths during its propagation in the forward and backward directions, has been introduced. These effective arm lengths coincide with neither Michelson interferometer proper arm length L nor its relativistic length L/γ. The introduction of this concept is due to the fact that the moving Michelson interferometer mirrors move during the light propagation. In some calculations, it is advisable to take into account the Michelson interferometer effective arm lengths.

Keywords: quadratic Sagnac effect, Michelson interferometer, Michelson–Morley experiment

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1. INTRODUCTION

In our work [1], we considered the quadratic Sagnac effect, which occurs because of the influence of the gravitational potential of the Coriolis force, recorded by an observer who is in the reference system moving with the rotation of the Michelson interferometer or, in other words, in the rotating frame of reference. The quadratic Sagnac effect results in a phase difference in the arms of the rotating Michelson interferometer. As shown in [1], in the case when the platform in the plane of which the Michelson interferometer is located is oriented orthogonally to the plane of rotation and one of the Michelson interferometer arms is rotated by a ψ angle relative to some straight line lying in the plane of rotation, the optical phase difference in the Michelson interferometer arms is

$$\Delta\Phi(\psi) = -\frac{L}{\lambda}\frac{\Omega^2 R^2}{c^2}\cos 2\psi. \qquad (1)$$

Therefore, the value of the quadratic Sagnac effect is proportional to the length L of the arm Michelson interferometer, the square of the rotation angular frequency Ω, the squared distance from the center of rotation R, and inversely proportional to the light wavelength λ. Since in this paper as in [1], the Michelson interferometer considered is located on the surface of the Earth, making an orbital rotation around the Sun, R is the radius of the earth's orbit ($R \sim 1.5\times 10^8$ km) and Ω is the angular velocity of the Earth's orbital rotation ($\Omega \sim 2\pi$ rad/year). If the platform in the plane of which the Michelson interferometer is located is oriented not orthogonally, but at some angle to the plane of rotation (to the plane of the earth's orbit), the expression (1) becomes more complicated (see Eq. (9) in [1]).

The purpose of this work is to find the physical causes of the occurrence of the quadratic Sagnac effect, which is registered by an observer located in the laboratory (inertial) frame of reference (inertial frame), where the special theory of relativity is obviously valid. If the observer is in the inertial frame, they can consider not only straight and uniform motion, but also a curvilinear motion [2]. Note also that, as shown in [2–4], under certain conditions, a fairly wide class of physical phenomena can be considered in noninertial coordinate systems within the special theory of relativity.

Another goal of the work is to consider the quadratic Sagnac effect not only in terms of the changes in the time of passage of the arms of Michelson interferometer by the light, but in terms of the number of wavelengths of light that fall on the lengths of the Michelson interferometer arms at the light passages of the Michelson interferometer arms in direct and back directions, when a Lorentzian change occurs not only in the Michelson interferometer arm lengths, but also in the light wavelength. It will be shown that both approaches lead to the same result.

In addition, the numerical estimates that show that conducting experiments on recording the quadratic Sagnac effect is quite possible were made.

2. CIRCULAR MOTION OF THE MICHELSON INTERFEROMETER

Let us consider the simplest corresponding to Eq. (1) case, in which an equal-arm Michelson interferometer (arm lengths are $L_A = L_B$) is located in a plane perpendicular (in general, at an arbitrary angle) to the plane of rotation of the disk of radius R. In other words, the Michelson interferometer plane is defined by two vectors: the **N** vector parallel to the rotational rate $\mathbf{\Omega}$ of the disk and the linear velocity vector **v** tangent to the disk of rotation (Fig. 1). The linear velocity of the circular motion at an angular rate Ω is $v = R\Omega$. Here we can consider the rotation of the Earth around its axis (R = 6300 km, v_{earth} = 0.458 km/s is the velocity at the equator), the orbital rotation of the Earth around the Sun ($R = 150 \times 10^6$ km, $v_{\text{orbit}} \simeq 30$ km/s), or the rotation of the Earth together with the Solar system around the center of the Galaxy (The Milky Way) ($R \sim 2.6 \times 10^{17}$ km, $v_{\text{Gal}} \sim 230$ km/s). Thus, just as in [1], we consider circular motion at large but not relativistic linear velocities. Let there be the ψ angle between the Michelson interferometer arm A and the **N** vector lying in the plane of the Michelson interferometer and parallel to $\mathbf{\Omega}$. The Michelson interferometer is located on a round-shaped turntable that allows you to change the ψ angle and the Michelson interferometer center (the dividing mirror M_1) coincides with the table center.

It can be seen in Fig. 1 that various optical elements of the Michelson interferometer (the M_1, M_2 and M_3 mirrors) move at different linear velocities in the course of orbital motion. As will be shown below in the third and fourth sections, this circumstance allows us to find out the physical causes of the quadratic Sagnac effect.

Note that, as shown in [1], some changes of the phase difference in the Michelson interferometer arms observed in the experiments by Michelson–Morley [5,

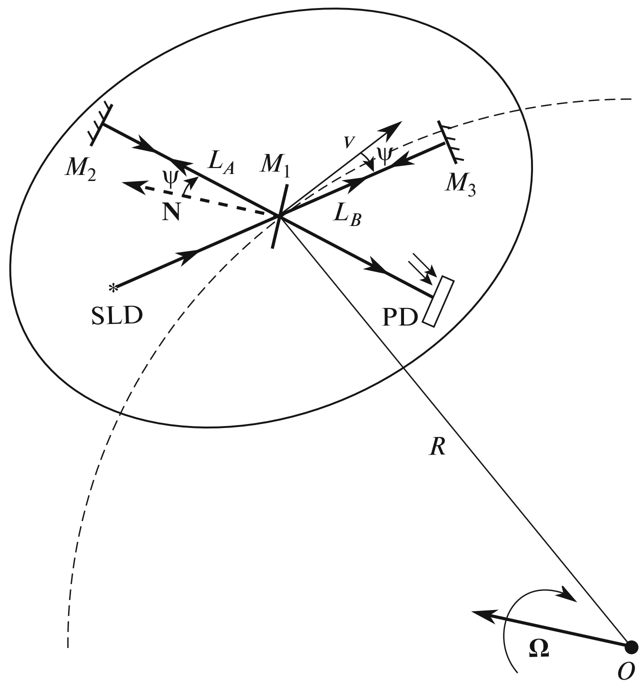

Fig. 1. O is the center of rotation, R is radius of rotation, $\mathbf{\Omega}$ is the angular velocity vector (the arrow indicates the direction of rotation), **N** is the vector parallel to $\mathbf{\Omega}$, $L_A = L_B$ are the Michelson interferometer arm lengths, M_1 is the Michelson interferometer beam-splitting mirror, M_2 and M_3 reflective mirrors in the Michelson interferometer arms, ψ is the angle between the vector **N** and the Michelson interferometer A arm, SLD is a superluminescent diode, and PD is a photodiode.

6] and their numerous repetitions (the most notable effect was observed by D.K. Miller [7]) found an approximate explanation using the quadratic Sagnac effect, given the fact that the sites in the plane of which the Michelson interferometers were located were at different terrestrial latitudes during these measurements and, accordingly, were oriented at certain angles to the plane of the earth orbit. This issue is discussed in detail in [1].

It follows from Eq. (1) that if we consider not the orbital linear velocity of the Earth when it rotates around the Sun (~30 km/s), but the rotation of the Earth together with the Sun around the center of the Milky Way (~220 km/s), the optical phase difference in the Michelson interferometer arms that is due to the quadratic Sagnac effect should be approximately by 50 times greater. However, this estimate does not coincide at all with the results of these experiments by Michelson–Morley [5, 6] and D.K. Miller [7]. The reason for this significant discrepancy has not yet been found. We can assume that it is related to the rotation features of various sections of the Milky Way. The rotational rate of stars is a rather complex dependence on the distance to the center of our galaxy and not a constant value. The Milky Way is a complex distributed system and this can affect the dependencies of the centrifugal forces and Coriolis forces on the distance to the center of our galaxy. This issue was discussed in [1].

We note that S.I. Vavilov not only translated into Russian [7], but also wrote a detailed commentary to this work [8].

3. TIME DELAYS IN THE MICHELSON INTERFEROMETER ARMS DURING ITS RECTILINEAR AND CURVILINEAR MOTIONS

First, let us consider the straight-line uniform motion of the Michelson interferometer. In the literature, training courses, and monographs, as a rule [9], the consideration of rectilinear motion of the Michelson interferometer is given only from the point of view of the long-outdated theory of the light-bearing ether. The authors of these works show that, within the framework of this theory, there should have been a certain phase shift in the Michelson interferometer arms, which is not observed in reality, refuting the theory of the light-bearing ether. Sometimes this makes a conclusion, rather dubious from the point of view of logic, that since the theory of the light-bearing ether is erroneous, the special theory of relativity is correct. In fact, as shown in [10], to confirm the validity of special theory of relativity, it is necessary to involve not only the results of Michelson–Morley experiments, but also other classical optical experiments: the experiments of I. Fizo, in particular [11], on the checking of the Fresnel dragging coefficient in a moving optical medium [12] and the experiments of G. Ives and J. Stilwell [13, 14] on the detection of the transverse Doppler effect.

The author found the consideration of the rectilinear motion of the Michelson interferometer within the framework of special theory of relativity only in the lectures of L.I. Mandelstam [15] and R. Feynman [16]. Let the Michelson interferometer arm $L_B = L$ coincide with the direction of linear velocity **u** and the Michelson interferometer arm $L_A = L$ is orthogonal to **u**. The velocity **u** is directed along the X axis in a positive direction. The stationary observer is located to the left of the radiation source. During the time that the light travels from the M_1 mirror to the point on the axis where the M_3 mirror is located when the light exits the M_1 mirror, the M_3 mirror will have time to move some distance in the positive direction of the X axis. Let $x_l = ct$, where c is the velocity of light in a vacuum, be the coordinate of the light front at the t moment: the light left the mirror M_1 at the moment $t = 0$ and $x_{M_3} = L + ut$ is the coordinate of the M_3 mirror at the t moment. The light reaches the M_3 mirror at $x_l = x_{M_3} = L_1^{\text{eff}}$, where $L_1^{\text{eff}} = L/(1 - u/c)$ is the effective length of the Michelson interferometer arm, i.e., the passage of light from M_1 to M_3 from the point of view of a stationary observer. However, the given expression for L_1^{eff} was obtained in the framework of classical physics without taking into account the Lorentzian reduction of the lengths of moving objects for a stationary observer by γ times, where $\gamma = 1/\sqrt{1-\beta^2}$ and $\beta = u/c$. As a result, we get

$$L_1^{\text{eff}} = \frac{L}{\gamma(1-\beta)}. \tag{2}$$

Then the time of light propagation from M_1 to M_3 for a stationary observer is

$$t_1 = \frac{L/c}{\gamma(1-\beta)}. \tag{3}$$

Similar calculations for the opposite direction of light in the Michelson interferometer B arm show that

$$L_2^{\text{eff}} = \frac{L}{\gamma(1+\beta)}, \tag{4}$$

$$t_2 = \frac{L/c}{\gamma(1+\beta)}. \tag{5}$$

The total time of light propagation in the Michelson interferometer arm L_B from the M_1 to M_3 mirrors and back is

$$t_1 + t_2 = \frac{2L/c}{\gamma(1-\beta^2)} = \frac{2L/c}{\sqrt{1-\beta^2}} = 2L\gamma/c.$$

The M_2 mirror in the Michelson interferometer A arm for a stationary observer moves at a u velocity orthogonally to the light propagation direction in this arm. As shown in [16] (see Fig. 15.2 in [16]), the directions and trajectories of light propagation in the forward (from M_1 to M_2) and reverse (from M_2 to M_1) directions do not coincide, but the effective A arm lengths in the forward and reverse directions are equal and is

$$L_3^{\text{eff}} = \frac{L}{\sqrt{1-\beta^2}} = L\gamma, \tag{6}$$

$$t_3 = L\gamma/c. \tag{7}$$

Then, as shown in [16],

$$t_1 + t_2 = 2t_3. \tag{8}$$

This is the proof of R. Feynman [16] that there is no difference in the time of light propagation in the Michelson interferometer arms at a straight-line uniform motion of the Michelson interferometer regardless of the linear velocity u within the special theory of relativity.

Now let us consider the Michelson interferometer motion along a circular trajectory. If $\psi = 0$, the direction of the B arm coincides with the direction of linear velocity $\mathbf{v}$ of the circular motion and, therefore, in accordance with the Lorentz transformations, its length will decrease by γ times relative to a stationary observer, who does not participate in the rotation ($\gamma = (1 - v^2/c^2)^{-1/2}$ is the so-called "Lorentz factor" and c is the velocity of light in vacuum). The Michelson interferometer A arm is parallel to the N straight line and correspondingly orthogonal to $\mathbf{v}$ and, therefore, does not experience a Lorentzian contraction. Since the condition $R\Omega \ll c$ is met even for rotation around the center of the Galaxy, it is obvious that there is a difference in the optical radiation phases in the Michelson interferometer arms proportional to v^2/c^2. In general, for an arbitrary ψ, we can write expressions for the lengths of the Michelson interferometer arms, taking into account the Lorentz contraction:

$$L_A = L\sqrt{\left(1 - \frac{v^2}{c^2}\right)\sin^2\psi + \cos^2\psi},$$
$$L_B = L\sqrt{\left(1 - \frac{v^2}{c^2}\right)\cos^2\psi + \sin^2\psi}. \tag{9}$$

Then, taking into account that the light passes each of the Michelson interferometer arms twice: in the forward and reverse directions, the difference in the optical paths in the arms $\Delta L = 2(L_A - L_B) \simeq -L(R^2\Omega^2/c^2)\cos 2\psi$ and the optical phase difference in the Michelson interferometer arms is

$$\Delta\Phi(\psi) = -2\pi \frac{L}{\lambda}\frac{\Omega^2 R^2}{c^2}\cos 2\psi, \tag{10}$$

where λ is the light wavelength. The expression (10) coincides with Eq. (8) in [1] and, therefore, the quadratic Sagnac effect for an observer located in both the rotating frame of reference and inertial frame of reference is described by the same expression (in [1], the expression (10) and other expressions for the phase difference in the Michelson interferometer arms are written in the number of interference bands and in this work—in radians). Note that the usual Sagnac effect in rotating frame of reference [3] and inertial frame of reference [2, 17] is also described by the same expression. There is another effect associated with the displacement and rotation of the mirrors, which occurs when the Michelson interferometer is rotated in the inertial frame of reference, which also affects the phase difference in the Michelson interferometer arms. This effect is considered in [18]. Its dependence on the ψ angle is described by Eq. (10) multiplied by the coefficient $2L/R$. Since $L = 1$–30 m $\ll R$ for the Michelson interferometers used in the Michelson–Morley experiments and their repetitions, this effect can be neglected in the first approximation.

It should be noted that the calculation of the quadratic Sagnac effect in the inertial frame of reference for the case when the Michelson interferometer is not located in the plane of rotation is more difficult than that in the rotating frame of reference [1]. However, for the simple case discussed above, the interpretation of the quadratic Sagnac effect in inertial frame of reference is physically more visible and transparent, since it is a consequence of the Fitzgerald–Lorentz reduction effect for the size of a moving object and the calculation of the quadratic Sagnac effect value in inertial frame of reference requires only the use of the Lorentz transformations, as all calculations are carried out within the special theory of relativity.

4. THE NUMBER OF LIGHT WAVELENGTHS FIT INTO THE MICHELSON INTERFEROMETER ARMS AT ITS RECTILINEAR AND CURVILINEAR MOTIONS

Calculating the number of light wavelengths that fit into the interferometer arms of one type or another is a clear and very productive way to consider the influence of various effects on the shift of interference bands. While the consideration of the time delays in the Michelson interferometer arms gives us the integral representation of the optical effects in the Michelson interferometer arms, the number of light wavelengths that fit in the Michelson interferometer arms gives us a local insight into of the optical effects in the Michelson interferometer arms on the scale of the light wavelength. However, with this approach, even for the case of rectilinear and uniform movement of the Michelson interferometer, there are some subtle points, which we will consider below.

Let us give a simple example of the straight and uniform motion of the Michelson interferometer at the u velocity. At $\psi = 0$, the Michelson interferometer arm L_B will be reduced for a stationary observer by γ times because of the Lorentz transformations. But the light wavelength should also be reduced by γ times because of the Lorentz transformations and no interference effects should be observed. However, in reality, everything is much more complicated, since the reduction of the wavelength for a stationary observer occurs as a result of the relativistic Doppler effect, predicted by A. Einstein in 1905 [19] and confirmed by the experiments of G. Ives and J. D. Stilwell [13] in 1938. The literature usually provides the relevant formula not for the wavelength of light, but for the light frequency ν [9]:

$$\nu = \nu_0 \frac{\sqrt{1-\beta^2}}{1+\beta\cos\psi}, \tag{11}$$

where ν_0 is the light frequency in the inertial frame of reference where the Michelson interferometer moving with the u velocity is located; ν is the light frequency in the inertial frame of reference in which the stationary observer is located; and $\beta = u/c$. Then, for the light wavelength $\lambda = c/\nu$, the following expression takes place

$$\lambda = \lambda_0 \frac{1+\beta\cos\psi}{\sqrt{1-\beta^2}}, \quad (12)$$

where λ_0 is the light wavelength in the inertial frame of reference in which the Michelson interferometer is moving at the u velocity and λ is the light wavelength in the inertial frame of reference in which the stationary observer is located. It follows from Eq. (12) that the light wavelength is different at the propagation of light in opposite directions even for the same Michelson interferometer arm. The exception is the case $\psi = \pi/2$, when there is a transverse (quadratic) Doppler effect.

From Eq. (12) we obtain

$$\lambda_1 = \lambda(\psi = 0) = \lambda_0\sqrt{\frac{1+\beta}{1-\beta}},$$

$$\lambda_2 = \lambda(\psi = \pi) = \lambda_0\sqrt{\frac{1-\beta}{1+\beta}},$$

$$\lambda_3 = \lambda(\psi = \pi/2) = \lambda(\psi = 3\pi/2) = \lambda_0\sqrt{\frac{1}{1-\beta^2}}.$$

It should also be noted that for light that propagates in the Michelson interferometer arms in opposite directions, the calculations should take into account not the relativistic length of the arms (L/γ for the L_B arm and L for the L_A arm), but the effective arm lengths given in Eqs. (2), (4), and (6), since the Michelson interferometer mirrors move during the light propagation.

The number of the light wavelengths that fit in the Michelson interferometer arms for the observer who is in the same inertial frame of reference as the Michelson interferometer does is $m = L/\lambda_0$. In order to calculate the number of light wavelengths that fit in the arms of the Michelson interferometer moving at the velocity u relative to a stationary observer, we use Eqs. (2), (4), and (6) for the effective lengths of the Michelson interferometer arms relative to this stationary observer. Then the number of light wavelengths that fit in the Michelson interferometer arms will be

$$\begin{aligned} m_1 &= L_1^{\text{eff}}/\lambda_1 = m\gamma, \\ m_2 &= L_2^{\text{eff}}/\lambda_2 = m\gamma, \\ m_3 &= L_3^{\text{eff}}/\lambda_3 = m. \end{aligned} \quad (13)$$

Two important conclusions follow from Eq. (13).

1. Despite the fact that the effective lengths of the Michelson interferometer arms for the forward (L_1^{eff}) and backward (L_2^{eff}) directions of light propagation are different for the Michelson interferometer B arm and, moreover, the light wavelengths for the forward (λ_1) and backward (λ_2) directions are also different, the number of light wavelengths that fit in the Michelson interferometer arms for the forward (m_1) and backward (m_2) directions are the same for the stationary observer. The equality $m_1 = m_2$ does not depend on the velocity u of the Michelson interferometer. Since $\lambda_1 \neq \lambda_2$, a travelling, not stationary, light wave will be observed in the Michelson interferometer B arm for the stationary observer.

2. As for the Michelson interferometer A arm, the number of light wavelengths that fit in this arm, from the point of view of a stationary observer, does not depend on the velocity u of the Michelson interferometer movement. In the Michelson interferometer A arm, a stationary observer will also not observe stationary light waves, since, as shown in [16] (see Fig. 15.2 in [16]), the trajectories of light propagation in the forward (from M_1 to M_2) and reverse (from M_2 to M_1) directions do not coincide.

At a curvilinear motion of the Michelson interferometer, all three Michelson interferometer mirrors move at different linear velocities and, therefore, Eqs. (12) and (13) are not applicable.

5. NUMERICAL ESTIMATES OF THE EXPECTED EFFECT FOR THE CASE OF THE EARTH'S ORBITAL ROTATION AROUND THE SUN FOR THE LATITUDE OF NIZHNY NOVGOROD

Let us make numerical estimates of the expected effect for the case of the Earth's orbital rotation around the Sun when $L_A = L_B = L = 20$ cm (such a short length of the Michelson interferometer arm will significantly reduce the influence of thermal effects on the phase difference in the Michelson interferometer arms) and $\lambda = 1.31$ μm. For the estimates, we will use an expression[1] that allows us to calculate the phase difference $\Delta\Phi$ in the most general case when the platform in the plane of which the Michelson interferometer is located is tilted by an angle $\pi/2 - \phi$ to the plane of rotation:

$$\Delta\Phi(\psi,\phi) = -2\pi\frac{L}{\lambda}\frac{\Omega^2 R^2}{c^2}(\cos^2\phi\cos 2\psi - \sin^2\phi), \quad (14)$$

where ϕ is a geographical latitude. Equation (14) is valid if we assume that the Earth's axis is orthogonal to the plane of the Ecliptic (Earth's orbit). In fact, the Earth's axis is tilted by the angle 23°26′13″ with respect to the perpendicular to the plane of the Ecliptic and the value $\Delta\Phi(\psi,\phi)$ will depend on the time of day. Fig-

[1] In [1], this expression is given under number (9).

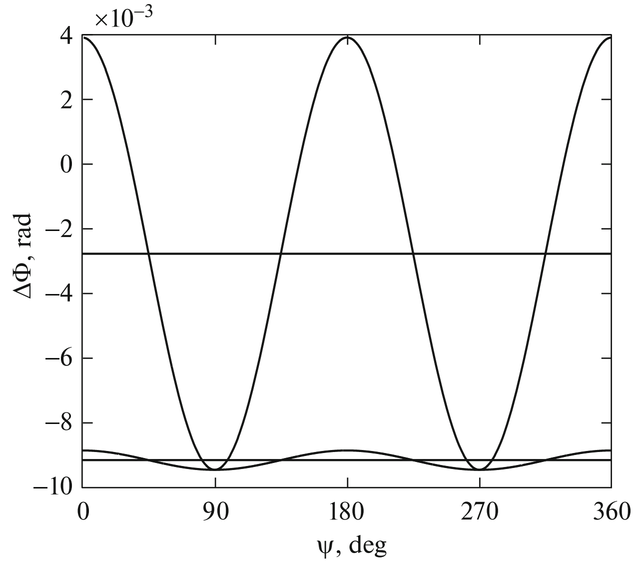

Fig. 2. Dependence $\Delta\Phi(\psi)$ for the latitude of Nizhny Novgorod at the most (the upper curve) and least favorable (the lower curve) time of day for observing the quadratic Sagnac effect. The Michelson interferometer are lengths are 20 cm.

ure 2 shows the dependence $\Delta\Phi(\psi)$ at $\phi = 56°19'24''$ (the latitude of Nizhny Novgorod). As can be seen from Fig. 2, the amplitude $\Delta\Phi$ of the harmonic change when the angle ψ changes according to the linear law will be $\simeq 6.7\times10^{-3}$ rad at the most favorable time of day for observing the quadratic Sagnac effect (the upper curve) and $\simeq 3\times10^{-4}$ rad at the least favorable time (the lower curve). For the measurements at other times of the day, the dependencies $\Delta\Phi(\psi)$ will lie between the lower and upper curves. A modulating method for measuring the phase difference in interferometers of various types, proposed by I.L. Berstein 70 years ago for the Sagnac ring interferometer in the radio range [20] and later found application in optics [21, 22], now allows detecting periodic changes in the phase difference with an error of up to 10^{-6}–10^{-7} rad at a sufficiently high light intensity. Thus, conducting experiments on recording the quadratic Sagnac effect is quite possible.

6. CONCLUSIONS

Let us list the main results of the work.

1. It was shown that the quadratic Sagnac effect can be calculated not only in the rotating frame of reference, but also in the inertial frame of reference.

2. It was shown that the experiments on recording the quadratic Sagnac effect with a compact Michelson interferometer are quite possible.

3. The concept of effective arm lengths of the Michelson interferometer moving relative to a stationary observer: the lengths of the light paths when it propagates in the forward and reverse directions. These effective arm lengths coincide neither with the proper length L of the Michelson interferometer arm or its relativistic length L/γ.

4. It was shown that since the Michelson interferometer mirrors move in the process of light propagation, it is advisable to take into account not the relativistic lengths L/γ and L of the arm that are oriented parallel and orthogonally to the Michelson interferometer velocity direction, respectively, but the proper lengths of the Michelson interferometer arms.

5. It was shown that, from the point of view of a stationary observer, for each of the Michelson interferometer arms, the number of light wavelengths that fit in the Michelson interferometer arms for the forward and reverse directions of light propagation coincide. At the same time, since the wavelengths or propagation paths for the opposite directions of light propagation in the Michelson interferometer arms differ, a stationary observer will see not stationary, but travelling light waves.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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