

LETTERS TO THE EDITORS

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On the possibility of experimental verifying the second postulate of special relativity

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The equality of the speed of light for the forward and backward directions of propagation (hereinafter we are dealing with the physical velocity of light in vacuum, which can be measured [1]) is one of the consequences of the second postulate of the special theory of relativity (STR). This is how Albert Einstein formulated the second postulate of the STR in his basic work [2]: "...light in free space always propagates with a specific velocity V independent of the state of motion of the radiating body". Therefore, the second postulate of the STR actually constitutes two statements: (i) the speed of light is constant for an arbitrary direction of propagation, and (ii) the speed of light is independent of the velocity of the radiation source.

Immediately after the advent of the STR, W Ritz raised objections to the second statement [3, 4] by putting forward the so-called ballistic (emissive) theory of radiation, which assumes that the speed of light is algebraically added to the velocity of the radiation source relative to the observer. Experiments performed by Q Majorana [5], R Tomaschek [6], and A M Bonch-Bruevich [7] at different times demonstrated the fallacy in Ritz's ballistic hypothesis. Similar experiments carried out with γ-rays also showed that the speed of light is independent of the velocity of the radiation source, to within the experimental error [8]. It should be mentioned that an effort to experimentally prove the validity of Ritz's ballistic hypothesis was mounted by W Kantor [9] (see also Refs [10 – 12]) [2].

No experimental verification of the first statement has been performed so far, because the method of timing the clock at two different points of the same frame of reference with the aid of light signals, accepted in the STR [3], makes it impossible to compare the speed of light for the forward and backward directions. As shown in Refs [15 – 17], the problem of time synchronization is impossible to solve by way of either clock transportation or simultaneous triggering the clock at points A and B with some mechanical device. This is what H Poincaré wrote on this subject [14]: "...the velocity of light is [assumed] constant and, in particular, the same in all directions. That is a postulate without which any measurement of this velocity would be impossible to undertake. The postulate can never be verified in experiment directly. It might be in contradiction to experiment in the event that the results of different measurements were mutually inconsistent. We should feel happy about the absence of this contradiction..." Einstein stated [18] that the equality of the speeds of light in opposite directions "...in actual truth is not a premise or hypothesis about the physical nature of light but [is] a statement which can be made on the basis of free choice to arrive at the definition of simultaneity".

The definition of any physical quantity, including the speed of light, is always associated with the method of its experimental determination. This is how Einstein defines the speed of light [1]: "In accord with experiment we also assume that the quantity

$$\frac{2\overline{AB}}{t'_A - t_A} = V \qquad (*)$$

is a universal constant (the velocity of light in vacuum) [4]. It is significant that we have defined the time with the aid of an immobile clock in a rest frame..." The definition $(*)$ relies on the method used to measure the speed of light to the present day. [5] It involves measuring the time interval between the emission of the light and its return to the initial point upon reflection from the mirror located at a known distance.

It is sometimes stated that the experiments of Michelson – Morley [21 – 23] and Kennedy – Thorndike [24] [6] confirm that

[1] It is pertinent to note that there exists the concept of a coordinate velocity of light, which depends on the selection of a coordinate system, i.e., on the spacetime metric, and also depends, in going from one coordinate system to another, on the form of spatiotemporal transformations involved (see, for instance, Ref. [1]).

[2] Kantor's experiment and its subsequent refutation were considered in detail in the monograph [13].

[3] This method of time synchronization in the STR was introduced by Einstein [2] and had previously been considered by H Poincaré [14].

[4] Here, $\overline{AB}$ is the distance between point A, which is the location of the source of light, the receiver, and the clock, and point B, which is the location of the light reflector (mirror); t_A and t'_A are the emission time and the time for the light to return to point A, and V is the symbol which Einstein employed to denote the speed of light.

[5] This approach was first realized by H Fizeau [19, 20].

[6] The Michelson – Morley experiments were repeated many times. The majority of these works were cited in the collection [25] and they were discussed in detail in the well-known monograph by S I Vavilov [26] and in the book by U I Frankfurt and A M Frank [13]. After the development of lasers with a nonlinear absorption cell — quantum frequency standards — J Hall and co-workers (National Bureau of Standards, Boulder, CO, USA) repeated the Michelson – Morley [27] and Kennedy – Thorndike [28] experiments at a very high level of accuracy. German researchers recently repeated the Kennedy – Thorndike experiments with a Fabry – Perot resonator made of crystalline sapphire cooled to liquid helium temperatures [29, 30].

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the speed of light is the same for an arbitrary direction of propagation, but this does not represent the facts. This is what A S Eddington wrote on this issue [31]: "Strictly speaking, the Michelson – Morley experiment did not prove directly that the velocity of light was constant in all directions, but that the average to-and-fro velocity was constant in all directions". Therefore, the Michelson – Morley type experiments are, in the rigorous sense, void of conclusive evidence regarding the problem of measurement of the isotropy of the velocity of light but testify to it indirectly. This circumstance was perfectly recognized by A A Michelson and E W Morley themselves, who wrote as follows: "If it were possible to measure with sufficient accuracy the velocity of light without returning the ray to its starting point, the problem of measuring the first power of the relative velocity of the Earth with respect to the ether would be solved" [22, 23]. Furthermore, the authors of Refs [22, 23] proposed two different optical schemes for these measurements, whose principle of operation involves the use of two widely separated mirrors rotating with equal velocities. Interestingly, to record the time difference of the arrival of oppositely directed light signals in one of the schemes they proposed the use of selenium photocells — the precursors of modern photodiodes.

It is noteworthy that as far back as 1868, i.e., 13 years before the first Michelson experiments [21], M Hoek [32, 33] endeavored to discover the translational motion of the Earth relative to the 'luminiferous ether' (or, which is the same, to discover the anisotropy of the speed of light) with the aid of an immobile ring interferometer of rectangular form. [7] One of the four sides of the rectangle was filled with an optical medium — glass or water. If the interferometer arm filled with the optical medium is aligned with the direction of terrestrial motion relative to the ether, the velocity differences of the counterpropagating light waves in this arm and the opposite ('empty') arm will be distinct, which may give rise to the phase difference of the counterpropagating waves. Should the interferometer be rotated by 180 degrees, this phase difference would change sign. However, on rotating the interferometer Hoek discovered no change in the phase difference of the counterpropagating waves. Similar experiments were recently repeated by S Marinov [35] and, with a substantially higher accuracy of measurement, by V V Ragul'skiĭ [36 – 38], the results of Refs [36 – 38] also being negative. To further improve the accuracy of the experiments under discussion, Kravtsov and Ragul'skiĭ [39] came up with the idea of placing the optical medium in one of the arms of a ring laser [39]. Another possibility for improving the measurement accuracy consists in the use of the modulation technique, which was proposed by G S Gorelik [40] and I L Bershteĭn [41] more than half a century ago and is presently enjoying wide application in precise interferometry.

However, as shown in monographs [13, 34], the negative results of Hoek's experiments [32, 33] (and, naturally, of Ragul'skiĭ's [36 – 38]) can be explained in the context of the Fresnel theory of partially entrained ether [42]. [8] This comes as no surprise, for Fresnel's theory was specially elaborated to explain the results of F D Arago's experiments [43] (performed and reported to the French Academy in 1810, but published only 43 years later) which showed that the refractive index of a prism is independent of the velocity of the radiation source. A perplexity may arise: since Fresnel's theory of partially entrained ether has long been refuted by the STR, the explanation of the negative results of the Hoek – Ragul'skiĭ type experiments in the framework of the Fresnel theory, as is outlined in Refs [13, 34], makes no sense. However, in accordance with the first statement of the second postulate of the STR, the speed of light is isotropic and, hence, the Hoek – Ragul'skiĭ type experiments, like of the Michelson – Morley type, are *a priori* bound to yield a zero result in the context of the STR. Even the very arrangement of such experiments is a test of the validity of the STR and therefore allows for their interpretation from the standpoint of other theories, the Fresnel theory in particular. The Hoek – Ragul'skiĭ type experiments demonstrate the isotropy of the refractive index of the optical medium but cannot serve as a rigorous refutation of the 'luminiferous ether' theory. Therefore, the Hoek – Ragul'skiĭ type experiments, like the Michelson – Morley ones, cannot, strictly speaking, serve as convincing evidence concerning the issue of measurement of the isotropy of the speed of light but testify to it indirectly. The experiments discussed in the foregoing, like any other experiments relying on the interference effect, cannot substitute for a direct measurement of the speeds of light for the forward and backward directions of its propagation, because recording the interference pattern inevitably implies measurement at one point in space.

The lack of direct experimental verification of the first statement of the second STR postulate is one of the main arguments of the opponents of this theory [9] and gives rise to much of speculation (see, for instance, Refs [44 – 48]). In particular, Kupryaev [47] and Obukhov and Zakharchenko [48] believe that the speed of light c' in the frame of reference moving relative to some "absolute frame of reference which is at rest relative to the outer space" [47] or 'ether' [48] is anisotropic and equal to $c'_{\pm} = c/(1 \pm \beta)$ (where $\beta = v/c$) for the opposite directions. In this case, the total time of light propagation in the forward and backward directions is independent of the velocity relative to the 'ether', making it possible to account for the results of the Michelson – Morley and Hoek – Ragul'skiĭ experiments. S Marinov [46] believed that he had managed to discover the earth's motion relative to the 'luminiferous ether' with a velocity of 362 ± 40 km s^{-1} by measuring the speeds of light in the opposite directions with the aid of two optical choppers (disks with circularly arranged openings). The optical choppers were spaced at 1.2 m and were mounted on the shaft of an electric motor rotating with an angular velocity of 400 rps. [10] The radiation of two independent lasers was allowed to pass through both optical choppers in the opposite directions. The first optical chopper formed a sequence of light pulses. The second one, which had time to slightly turn during the pulse transit time, would

[7] A description of these experiments is given in Refs [13, 34].

[8] According to A Fresnel [42], it will be remembered that the speed of light in an optical medium with a refractive index n, moving with a velocity $\pm v$ relative to the 'ether', is equal to $c/n \pm (1 - 1/n^2)v$, where $1 - 1/n^2$ is the Fresnel drag coefficient, and c is the speed of light in vacuum.

[9] It is worth bearing in mind that the fact that Ritz's ballistic hypothesis is inconsistent cannot serve as a refutation of the 'luminiferous ether' theory because the speed of light in the 'ether' in the context of this theory is independent of the velocity of the radiation source, like the velocity of acoustic waves in a gas or a liquid.

[10] In Marinov's earlier works [44, 45], use was made of a scheme with two rotating mirrors, proposed by Michelson and Morley as far back as 1887 [22, 23]. The scheme with optical choppers constitutes its modification and is much easier to fabricate but ranks significantly lower than the scheme of Refs [22, 23] in the accuracy of measuring the speed of light.

somewhat shorten or lengthen each pulse, depending on the initial angular position of its openings. However, the circuit for processing the signals from the photodetectors located behind the optical choppers [46] was so imperfect that the results of this work on the discovery of the 'luminiferous ether' cannot be treated as being trustworthy.

It is worth noting the works of Michelson and Morley [22, 23] and accordingly Marinov [44–46] contain a positive proposal: two mirrors or optical choppers rotating at a constant angular velocity and separated by some distance can be treated in a sense as a pair of 'clocks' synchronized due to the rigid connection to the shaft. However, the mechanical devices under discussion cannot in reality provide a measurement accuracy of the speed of light anywhere near the acceptable one. Nevertheless, from the fundamental standpoint experiments of the Michelson–Morley–Marinov type possess a conclusiveness regarding the issue of measuring the anisotropy of the speed of light.

It is worth mentioning that even the noted specialist on the STR, O Costa de Beauregard [49], did not rule out the possibility that the speed of light in its passage in one direction depends on the ether wind direction (see also Ref. [50]; this issue was considered at length in Ref. [15]).

All the aforementioned statements that contradict the foundations of the STR are related to the fact that there exists a kind of vicious circle: to measure the velocities of light in the opposite directions requires synchronizing specially separated clocks, for which purpose in the STR it is conventional to harness light signals. It is therefore necessary to suggest a clock synchronization procedure such that the quantity being measured (in this case, the velocity of light) has no bearing on the time synchronization.

To synchronize spatially separated clocks, in our opinion, it is appropriate to take advantage of the so-called 'light spot' proposed in V L Ginzburg's work [51] more than 30 years ago and considered at greater length by B M Bolotovskiĭ and Ginzburg [52].[11] The light spot can have a supraluminal phase velocity. Considered in Refs [51, 52] was the on-screen motion of the ray of a projector rotating with an angular velocity Ω. When points A and B are equally remote from the projector and their distance r to the projector is long enough, the linear velocity v of the light spot obeys the condition $v = r\Omega \gg c$. Naturally, the light spot cannot transfer information from point A to point B with a supraluminal speed: the photons arriving at point A would never find themselves at point B, and therefore the causality principle is not violated.

Let there be a preliminary agreement that a photocell-controlled quick-response device actuates at the instant the light-spot arrives at point A to send a short light pulse to point B, and an identical device sends the same pulse to point A at the moment the light spot arrives at point B. The clocks at points A and B are started up simultaneously with the emission of the light pulses. The time difference of the light-spot arrival at points A and B can be neglected, because it is much shorter than the time of journey of a light pulse. Measuring the speeds of light for the opposite directions in this case reduces to measuring the time intervals between the emission of its 'own' pulse and the detection of the 'foreign' pulse at points A and B for a known path length $\overline{AB}$. Therefore, the proposed method for synchronizing the spatially separated clocks is conclusive regarding the measurement problem of the isotropy of the speed of light.

Consider the question of whether the proposed clock synchronization procedure is consistent with the basics of the STR. This is what the authors of Ref. [52] write on the subject: "...it is pertinent to note that the application of the velocity of light to clock synchronization, which is commonly employed in the presentation of the relativity theory is, first, just one of possible methods rather than the only one; second, this method is indeed the most convenient and expedient one in the majority of cases not because the velocity of light is the highest possible velocity, but because this velocity is universal — the same in all inertial frames of reference..." Since points A and B in the case involved reside in a common inertial frame of reference, it cannot be doubted that the light spots can be taken advantage of to synchronize the clocks at points A and B. Processes extending in space with arbitrary velocities have been considered in other papers as well (see, for instance, Refs [51, 56–58], but only in Ref. [52] was it indicated that the conventional clock synchronization method reliant on light pulses is not the only one possible.

Different ways of realizing the supraluminal-speed 'light spots' of an arbitrary nature have been discussed in the literature: pulsar radiation [51, 52, 59]; a rotating beam [51, 52, 58]; a rotating electron beam [52]; a charged filament obliquely incident on a conducting plane [52, 56]; an electric charge moving over a conducting plane [52, 56], and the reflection of a light pulse from a cone-shaped diffraction grating [60, 61]. The highest velocity ($R\Omega = 1.2 \times 10^{19}$ m s^{-1}) is exhibited by the 'light spot' produced by the radiation of the NP 0532 pulsar in the Crab Nebula [51, 52, 59] ($\Omega = 200$ rad s^{-1}, the distance to the Earth is $R = 6 \times 10^{19}$ m). It is noteworthy that the employment of a 'spot' produced by a rotating electron beam may offer some advantages over a 'light spot', because the electron velocity is not related to the speed of light.

Therefore, Poincaré's statement [14] that the speed of light is fundamentally impossible to measure in the opposite directions is contrary to facts. There are at least two ways of synchronizing spatially separated clocks: employing two mechanical elements (mirrors [22, 23, 44, 45] or optical choppers [46]) rigidly connected together, and using 'light spots' of an arbitrary nature with supraluminal speeds [51, 52]. It is worth mentioning that Einstein never considered but at the same time never rejected the feasibility of measuring the speed of light in opposite directions.

Is there any point in carrying out this experiment? In our view, there is no need. The results of measurements [30] demonstrate that the speeds of light for orthogonally traveling directions are equal to within $2-3 \times 10^{-15}$. A different situation for the opposite directions of propagation is difficult to perceive. We emphasize that Ragul'skiĭ's experiments [36–38] demonstrate the equality of the refractive indices of the optical medium and the speeds of light for the opposite directions with respective accuracies of 5×10^{-8} and 5×10^{-10}, which is an additional indirect testimony to the isotropy of the speed of light in vacuum.

It may nevertheless be beneficial to estimate the possible accuracy of the technique proposed for measuring the unidirectional speed of light. The real measurement accuracy will be limited not by the speed of a 'light spot', which can be made arbitrarily high, but by the duration of the light pulses, as well as the response time and identity of the devices which trigger the clock and send the laser-produced pulses. When

[11] Significant for the comprehension of the STR foundations, this work was republished with some alterations [53–55].

femtosecond lasers with a pulse duration of 5 – 10 fs are employed as the source of short light pulses, and quantum standards with a relative frequency stability of $10^{-14} - 10^{-16}$ as the clock, in laboratory conditions it is possible to ensure a measurement accuracy of the speed of light up to ± 30 m s^{-1}, i.e., at a level of 10^{-7}. Despite the fact that this precision ranks below the precision of present-day Michelson – Morley [30] and Hoek – Ragul'skiĭ [36 – 38] experiments [12], the proposed type of measurements is, unlike those proposed in Ref. [30] and Refs [36 – 38], a direct instead of an indirect technique for measuring the unidirectional speed of light.

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[12] It is evident that the accuracy of interference measurements can exceed that of temporal ones by many orders of magnitude: the former allow measurements down to $10^{-7} - 10^{-8}$ of the light oscillation period, while the latter are limited in accuracy to several light oscillation periods.

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