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# The Sagnac effect and its interpretation by Paul Langevin

## *L'effet Sagnac et son interpretation by Paul Langevin*

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A B S T R A C T

The French physicist Georges Sagnac is nowdays frequently cited by the engineers who work on devices such as ring-laser gyroscopes. These systems operate on the principle of the Sagnac effect. It is less known that Sagnac was a strong opponent to the theory of special relativity proposed by Albert Einstein. He set up his experiment to prove the existence of the aether discarded by the Einsteinian relativity. An accurate explanation of the phenomenon was provided by Paul Langevin in 1921.


R É S U M É

Le nom de Georges Sagnac est aujourd'hui très connu des ingénieurs travaillant sur les systèmes de navigation, tant maritime qu'aérienne, qui exploitent sa découverte de 1913. Ce que l'on sait moins est que ce physicien était un farouche opposant à la relativité, théorie révolutionnaire qui avait été élaborée par Albert Einstein quelques années auparavant, en 1905. L'expérience de Sagnac a été pensée pour prouver l'existence de l'éther luminifère. Son interprétation correcte (relativiste) a été fournie par Paul Langevin en 1921.


## 1. Historical development

It would seem useful to recall the context of the discovery of the Sagnac effect. Around 1910, a very strong conservatism reigned concerning the paradigm of absolute space and its counterpart, the aether, the hypothetical medium of propagation of light. To this statement, we must add the presence of a very large number of skeptics, both physicists and philosophers, who opposed a non-sequitur to the new vision of space and time that was implied by the very recent Einsteinian theory of relativity. Some key points should also be highlighted.

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### 1.1. Newton and the absolute space (end of the 17th century)

For Isaac Newton, the concept of absolute space (or pure extension) exists, regardless of the presence or not of any material. In Newton's worldview, absolute space was a pre-existing frame, empty and immutable, a fundamental background to any moving body. But its undefined nature made it a kind of metaphysical entity, close to transcendence. In the Scholium, at the beginning of the *Principia* (Definitiones), Newton expatiated on time, absolute or relative space and motion [1]. He suggested that an absolute motion can be distinguished from a relative motion. To justify his argument, he introduces a thought experiment that is still famous. A bucket filled with water is subjected to a fast rotation. There are two phases. (*i*) The bucket rotates, but the surface of the water remains flat. (*ii*) The movement is finally transmitted to the water. It is then observed that the latter leaks from the center and ascends towards the walls, the free surface taking the form of a paraboloid. During the first phase, there is indeed a relative movement water/bucket, but no centrifugal force appears. It is only in the second phase, when the movement of rotation is communicated to the water, that these forces develop. For Newton, the conclusion was that these forces are not correlated with the relative movement of the water/bucket, but are generated by the movement of water in relation to absolute space. A second thought experiment was also devised by Newton. Two spheres are connected by a rope and the assembly is rotated. The rope tightens and one can measure the tension that develops there. Newton's conclusion is the same.

### 1.2. Ernst Mach and the relativity of motion (end of the 19th century)

The concept of absolute space as introduced by Newton was strongly criticized by Ernst Mach in his book published in 1893 [2]. Mach assumed a positivist vision from the outset. He noted that Newton's experiment simply demonstrates that the shape of the water surface (a paraboloid) is not induced by the relative movement of water in relation to the immediate environment (the bucket in particular). But Newton did not extend his thought sufficiently far. It did not consider the distant masses (represented by the stars). According to Mach, it is legitimate to attribute the deformation of the surface of the water to a rotation, but not relative to an absolute space as Newton had suggested, but to a relative rotation of the water and massive distant bodies. Suppose that the bucket is fixed and that the whole Universe is put in rotation. Would the surface of the water take the form of a paraboloid? For Mach, the answer is yes.

We know that Mach's ideas had a considerable influence on the development of Albert Einstein's reasoning, especially during the first five years of the 20th century. But most physicists did not share Mach's point of view, and were very opposed to getting rid of the concepts of absolute space and aether.

### 1.3. The luminiferous aether

The idea of a medium for the propagation of light waves goes back to Christian Huygens (1690). Unfortunately, owing to Newton's great aura, Newton's corpuscular theory, exposed in his treatise Opticks (1704), completely dominated for more than 100 years and took precedence over Huygens' wave description. But Huyghens' hypothesis enjoyed a sudden revival at the very beginning of the 19th century, thanks to Augustin Fresnel and Thomas Young. Since then, the aether was considered as the absolute frame of reference, especially in relation to which Maxwell's equations (dating from 1862) had to be written and the celerity of the light was the constant $c$. This aether was automatically identified with the absolute space of Newton. But the Earth moves in this absolute space. Does it carry the aether with it as it moves? To answer this question considered as fundamental by the physicists at that time, a number of experiments were carried out in the first half [3,4] and at the end of the 19th century [5,6]. In spite of the fact that all these experiments, taken together, showed that the aether was an illusive medium, it must be remarked that as late as 1910, Hendrick Lorentz and Henri Poincaré had still not adopted a very clear position concerning the status of the aether [7]. For a more complete analysis of the debate on the light-bearing aether, see [8–11].

## 2. The experiment of Sagnac

In 1899, Georges Sagnac[1] had developed a theory of the existence of a motionless mechanical aether [12]. His aim was to explain within this theoretical framework all the optics phenomena, and especially the Fresnel–Fizeau experiment for the drag of light in a moving medium [4]. In 1910, he conceived a rotating interferometer for testing his ideas and to see the optical whirlwind effect, as he called it (Fig. 1).

The effect discovered by Sagnac, and published in the *Comptes rendus de l'Académie des sciences* in 1913 [13,14],[2] has led to many applications in positioning technologies (Global Positioning System, Galileo, etc.). The sensors (gyrolasers and gyrometers) that measure angular velocities with respect to an inertial frame of reference, exploit the physics of the Sagnac effect. Generally numbering three, these sensors form a part of the inertial stations, in particular those used to determine the orientation of all types of vehicles: aircraft, boats, submarines, space probes, etc. These devices have also been applied

[1] This author is also known as the first in France to work on X-rays, following the German scientist W.C. Röntgen.

[2] A more extended version has also been published by Sagnac in the *Journal of Physics* the following year in 1914 [15].

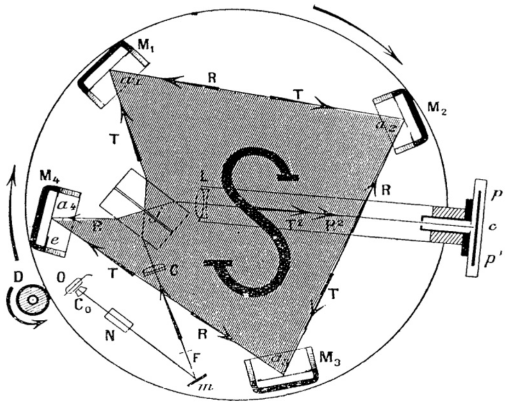


**Fig. 1.** Sagnac interferometer mounted on a turntable (reproduced from his paper of 1913).

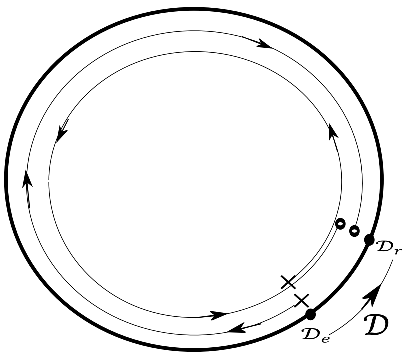


**Fig. 2.** Propagation of the light beams seen from the laboratory.

to geodesy and seismology [16–18]. Since the 1960s, a large number of studies have been devoted to the narrative of the discovery of this effect, its interpretation and to its practical consequences [19–22]. On 10 October 2013, a symposium held at the *Fondation Simone-et-Cino-del-Duca* (Paris) was organized to celebrate the centenary of the Sagnac effect [23]. Even more and ironically enough, the Sagnac device was initially conceived to prove that the special relativity is wrong, is today used for testing the general relativity. For instance, in the GINGER (Gyroscopes IN GEneral Relativity) project a three-dimensional array of large-size ring-lasers will be conceived for measuring in a ground-based laboratory the de Sitter and Lense–Thirring effects [24].

Let us consider a rotating disk on whose rim two light beams circulate in opposite directions relative to each other.[3] Both beams initially start from the same point, located on the rim of the disk. In order to simplify the reasoning but without loss of generality, it will be assumed that the source and the receiver are combined and both attached to the disk. Let $R$ be the radius of the disk and $\omega$ its angular velocity. This velocity is assumed to be constant and the disk rotates in the counterclockwise sense for the inertial observer, $\mathcal{L}$ linked to the laboratory. For this observer, the receiver travels the distance $\Delta l$ (circular arc) at the speed $v = R\omega$. The beam in the sense $(+)$ must therefore travel the distance $l + \Delta l$ before reaching the receiver. The duration of the path of the light ray, $t_+$, is deduced from the equality (Fig. 2):

$$t_+ = \frac{l + \Delta l}{c} = \frac{\Delta l}{v} \tag{1}$$

or $t_+ = \frac{l}{c-v}$. The same reasoning applies to the other ray, moving in the opposite sense $(-)$, and the traveled distance is $l - \Delta l$. The journey time is $t_- = \frac{l}{c+v}$. The difference in the journey times is therefore:

$$\Delta t_{\mathcal{L}} = t_+ - t_- = \frac{2lv}{c^2 - v^2} = \frac{4\pi R^2\omega}{c^2}(1 - \frac{R^2\omega^2}{c^2})^{-1} \simeq \frac{4A\omega}{c^2} \tag{2}$$

[3] The generalization to any closed (non-circular) loop is immediate.

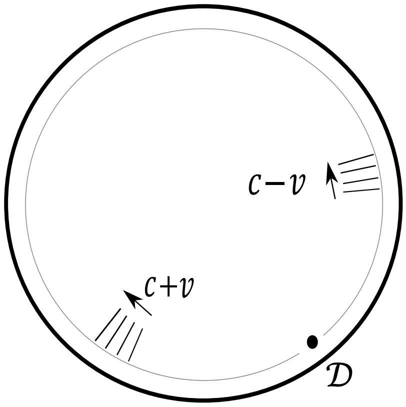


**Fig. 3.** Propagation of the light beams from the point of view of a newtonian aether supporter linked to the disk.

where $A = \pi R^2$ denotes the area of the disk. The difference in the duration of travel induces a phase shift between the two waves, hence the appearance of interference fringes (Sagnac made a differential measurement by rotating the disk in one direction and then in the other). The phase shift (expressed in wavelength) is given by the Sagnac formula:

$$\Delta\varphi = \frac{8\pi A\omega}{\lambda c} \tag{3}$$

What is the reasoning of a non-inertial observer ($\mathcal{D}$) related to the disk? According to Georges Sagnac, the light has a medium of propagation which is the aether. In the reference frame linked to the laboratory (observer $\mathcal{L}$) the propagation velocity (celerity) is $c$. On the other hand, for an observer linked to the rotating disk the light speed propagates differently, according to whether the beam propagates counterclockwise (the direction of rotation of the disk by convention), or in reverse. It is then respectively $c - v$ and $c + v$ (Fig. 3). For the observer $\mathcal{D}$, we have for the difference in time of course:

$$\Delta t_{\mathcal{D}} = \frac{l}{c-v} - \frac{l}{c+v} \simeq \frac{4A\,\omega}{c^2} \tag{4}$$

which is in perfect agreement with the result found by the observer $\mathcal{L}$. Numerically, the area of the polygonal interferometer was 0.0860 $m^2$, the rotation rate of order 2 Hz and the resulting fringe shift $\delta\varphi = 0.07 \pm 0.01$. In his paper, Sagnac also predicts that a similar effect would be observed from the diurnal Earth rotation (the Earth taken as a rotating turntable) using a very large interferometer.[4]

For Sagnac, this result proves the existence of the aether. The argument of this author appears *a priori* quite convincing. The existence of a propagation medium for light waves seems to be confirmed by his experiment. But in science, an hypothesis cannot be validated only if it allows one to explain all the experiments, not one in particular. Other experiments definitively invalidate the hypothesis of the aether. Perhaps most famous is the crucial experiment of Michelson and Morley [5]. The aim of this experiment was to measure the displacement of the Earth with respect to the aether. Using an interferometric device, they showed that the velocity of the aether wind, if any, was less than 5 km/s (we should remember that the velocity of the Earth in the solar system is 30 km/s, and therefore much greater). The procedure has obviously been repeated several times within a year (in case at a given time, and by an extraordinary coincidence, the Earth's velocity at the time of measurement had been zero with respect to the aether), but no seasonal effects have been found. The Michelson–Morley experiment has been repeated with ever-increasing accuracy. The Michelson-type experiment carried out by Georg Joos in 1930 allowed him to give a bound to the velocity of the aether wind of less than 1.5 km/s [27]. More recently, experiments have been carried out using various sophisticated devices, such as lasers and masers, optical resonators and microwaves, etc. [28]. The conclusion is always the same: no measurable aether wind. We can thus conclude that the relative velocity of the Earth with respect to the aether is experimentally found to be very close to zero, with high precision. But if we only focus on the Michelson–Morley experiment, it is still perfectly legitimate to imagine that the Earth completely drags the aether in its translatory motion (Fresnel had already suggested in 1818 the hypothesis of a partial dragging of the aether with moving substances [29]). In this case, the negative result of the Michelson experiment has a trivial explanation. Unfortunately, however, such an assumption cannot be maintained. There are two immediate reasons for this. First of all, it is inconsistent with the aberration of fixed stars (as we know, during a year the stars describe a small ellipse on the background of the sky. This effect cannot occur if the aether is fully dragged by the Earth). Secondly, the experiment of Sagnac was repeated by Michelson and Gale in 1925 [30], but this time taking the Earth as a rotating disk (as already suggested by Sagnac himself). These authors observed a displacement of the fringes of interferences, as had Sagnac

[4] Let us note that the so-called Sagnac effect had been approached by Sir Oliver Lodge as early as 1893 [25]. This effect had also been glimpsed by Harres in 1911 [26], but this author does not seem to have paid much attention to it. When Sagnac realized his experiment, the idea was therefore in the air.

in his own experiment. This positive result undoubtedly confirms that the Earth does not drag the hypothetical aether in its rotation (it is therefore illogical to admit that it drags this medium in its translation). The only acceptable conclusion that can be drawn from these two experiments, Michelson–Morley, on the one hand, and Michelson–Gale, on the other hand, is that the hypothesis of the existence of a medium of propagation for light is not tenable (unlike sound, the light can spread in the vacuum). In the classical context, it is clear that the Sagnac effect cannot at all be explained.

## 3. The relativistic interpretation

Special relativity has successfully passed tests of thousands of experiments of all types (for example, the experiments of Kennedy–Thorndike [31] and Ives–Stilwell [32]). If it is clearly no longer questionable today, the situation was quite different at the beginning of the twentieth century.[5]

An experiment such as Sagnac's was still used as a strong argument by the opponents of the theory of relativity, who were still quite numerous at the time, including Sagnac himself. The scientific community as a whole only accepted relativity after some time. So a lot of pseudoparadoxes issued from relativity, which seemed to arise here and there, were solved rather slowly. The first convincing explanation of the Sagnac effect, in the framework of relativity, was provided by Paul Langevin in 1921 [36].[6]

It appears rather amazing that the correct relativistic interpretation of the Sagnac effect took eight years. A seemingly obvious reason is that Sagnac's experiment was not very much discussed in the scientific literature, even in France after the discovery of 1913.[7] Conscious of this situation, in 1919, Sagnac published five papers on his work in the *Comptes rendus* [37]. The paradox is that his ideas were nevertheless borne by a French group of strong antirelativists. In 1919, Sagnac was even rewarded with the Pierson–Perrin Prize for his achievements on this topic (first for the experiment, seen as a rebuttal of the relativity principle, the constancy of light, and also for having proven the reality of absolute space and time) [38]. Eventually, in 1921, the mathematician (and relativist skeptic) Émile Picard asked Paul Langevin to demonstrate the effect in the framework of the relativity, perhaps guessing it was impossible [39]. Again any such expectations and within a couple of months, Langevin derived the effect from the General relativity [36]. Let us specify however that the Sagnac effect was already derived from special relativity by Von Laue one year before Langevin [40]. Many derivations were in fact proposed all along the 20th century, issued from both special relativity and general relativity [41,42], even though the Sagnac effect is usually deemed to be a special relativistic effect [43].

The reasoning, both simple and elegant, of Langevin can be shown in a few lines. This illustrious physicist begins by noting that this is an experiment of the first order in $\frac{v}{c}$ (more precisely in $\frac{R\omega}{c}$, if $R$ denotes the radius of the disk and $\omega$ the angular velocity, assumed to be constant), contrarily to the experiment of Michelson–Morley, which involves a second-order effect. We start from the Minkowskian metric associated with the central observer, denoted by $O$, located at the center of the rotating disk. In his article, Langevin used the cartesian coordinates, we modernize the presentation a little by choosing the cylindrical coordinates, which are better suited to the analysis of the problem (by eliminating the third coordinate $z$ which is superfluous). We write the Minkowskian $\mathrm{d}s^2$, expressed in these coordinates

$$\mathrm{d}s^2 = c^2\mathrm{d}t^2 - \mathrm{d}r^2 - r^2\mathrm{d}\theta^2 \tag{5}$$

The observer $O$ then performs the global transformation of the coordinates ($\theta \in [0, 2\pi]$)

$$(t,\ r,\ \theta) \longrightarrow (t,\ r,\ \theta + \omega t) \tag{6}$$

imposing the constraint $r < R < \frac{c}{\omega}$.

This transformation means that the observer $O$ (inertial) now uses a coordinate system that accompanies the disk in its rotation. From the inertial observer $O$ point of view, the source, the detector and the non-inertial observer $\mathcal{D}$ (assumed to be at the same place) are located on a radius with a fixed orientation, for instance $\theta = 0$. Neglecting a small second-order term in $\frac{R\omega}{c}$, the $\mathrm{d}s^2$ (relativistic invariant) takes the form

$$\mathrm{d}s^2 = c^2\mathrm{d}t^2 - \mathrm{d}r^2 - r^2\mathrm{d}\theta^2 - 2r^2\omega\,\mathrm{d}\theta\,\mathrm{d}t \tag{7}$$

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[5] Remember that Einstein was not awarded the Nobel Prize for the relativity, but for the photoelectric effect in 1921! The Nobel Committee has never given this prestigious award to anybody in recognition of the discovery of the relativity. The name of the eminent mathematician Henri Poincaré, the other important contributor to this theory, had been suggested (by a committee led by Georges Darboux in 1905 [33]); but Poincaré did not receive this prestigious award either. If he had, would Albert Einstein have jointly received the award? It is a remarkable fact that Poincaré presented the great trails of his work on special relativity in the *Comptes Rendus* in 1905 [34]. In the same year, a lesser known physicist, Albert Einstein, independently presented in *Annalen der Physik* similar results, but more complete [35]. It should be noted that Poincaré, too conservative, never totally got rid of the aether, whereas Einstein considered this concept superfluous.

[6] Also let us note that Paul Langevin is recognized as one of the first physicists to have defended the relativistic conceptions in France in numerous seminars; in particular the contributions of Einstein in the field, better known as they had been eclipsed in this country by the work of Poincaré on the same topic.

[7] The quotations were very scarce between this date and the 1960s, where the effect became well known for its applications in gyrolasers (first built in 1963). The first significant paper in English related to the Sagnac effect is the study of Post published in 1967, which contained also some historical information [19].

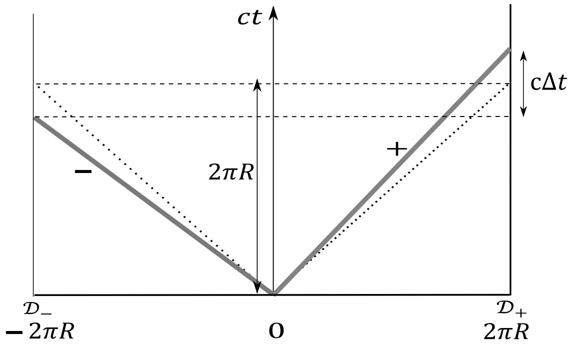


**Fig. 4.** Effect of no-synchronization of the clocks in a rotating frame.

Following Langevin, this expression is called the metric of the rotating disk. It will be noted the presence of a cross term in $\mathrm{d}\theta\,\mathrm{d}t$, source of the impossibility of synchronizing clocks, uniformly distributed around the periphery of the disk and connected thereto (a relativistic phenomenon which is the essence of the Sagnac effect).

The path in space–time of the light rays is determined by the cancellation of the $\mathrm{d}s^2$ and by putting $\mathrm{d}r = 0$ and $r = R$ (the spatial trajectory of the light rays is circular and follows the periphery of the disk). We obtain an equation of the second degree in $\mathrm{d}t$. The solutions ($R\omega \ll c$) are written

$$\mathrm{d}t_\pm = \frac{R^2\mathrm{d}\theta}{c^2}\left[\omega \pm \sqrt{\frac{c^2}{R^2} + \omega^2}\right] \simeq \frac{R^2\mathrm{d}\theta}{c^2}\left[\omega \pm \frac{c}{R}\right] \tag{8}$$

It is then integrated on the periphery of the disk (noting that $\mathrm{d}t_\pm > 0$, that is $\mathrm{d}\theta > 0$ for $\mathrm{d}t_+$ and $\mathrm{d}\theta < 0$ for $\mathrm{d}t_-$). It yields

$$\Delta t = t_+ - t_- = \frac{4\pi R^2\omega}{c^2} \tag{9}$$

We find again the relationship given by eq. (4).

Fig. 4 illustrates this situation. When the disk is in rotation, the light beams are represented in thick gray lines, labeled respectively $+$ for the beams traveling in the trigonometric direction, $-$ for the ray moving in the opposite direction (in dashed lines are the beams for the disk at rest). For the fixed observer $\mathcal{L}$, the difference in velocities between the light beam $+$ (resp. $-$) and the observer $\mathcal{D}$ is $c - v$ (resp. $c + v$). If the speed of the light beams with respect to this observer is $c$, the same value is definitely measured by the observer $\mathcal{D}$ linked to the disk, whatever the direction of travel of the considered beam. The points $\mathcal{D}_+$ and $\mathcal{D}_-$ shown in Fig. 4 are identified.[8]

## 4. The universality of the Sagnac effect

The Sagnac effect appears universal. More specifically speaking, one can cite the experiment carried out by Hafele and Keating in 1971 [44]. It consisted of the following. Two planes each equipped with an atomic clock flew around the Earth, one in the direction of the Earth's rotation and the other in the opposite direction (the two clocks are synchronized at the start). On arrival, it is observed that the two clocks indicate different times (in fact it is simply a revisited Sagnac experiment). A practical conclusion is that one cannot synchronize a collection of clocks distributed all along the Earth equator. The effect in question is taken into account in the GPS calculations.

The phase shift of the Sagnac experiment was also measured in the case of coherent beams of relativistic neutrons traveling in opposite directions along the circumference (closed path) of a rotating disk [45,46].

More generally, since the first atom interferometry experiment in 1991, measurements of rotation using the Sagnac effect have been currently performed with atoms [47].

Finally, the quantum mechanical phenomenon predicted by Y. Aharonov and D. Bohm [48] can also be perceived as some kind of Sagnac effect (by replacing the light beams by charged particle beams (charge $q$) in the experiment, formally substituting the rotation $\omega$ by a magnetic field $B$ and doing $\frac{8\pi}{\lambda c} \longrightarrow \frac{q}{\hbar}$ in the relationship (3)) [49].

[8] But then we may wonder why, since the waves have the same speed in a direction and in the other for the observer $\mathcal{D}$, is there a difference in the travel times measured by this observer. The subtlety is that the points $\mathcal{D}_+$ and $\mathcal{D}_-$ reported in Fig. 4 are actually distinct and are identified only by abuse. A close analogy can be made with the screw dislocations seen in material sciences. A more mathematical approach can be envisioned with help of the complex function $Lnz$. This function is continuous and differentiable throughout $\mathbb{C}$, but a cut must be created along any line joining 0 and infinity. The cut is made necessary because when the $z$ phase jumps to $\pm 2\pi$, the $Lnz$ function does not return to its initial value. From a topological (and not merely geometrical) point of view, we must therefore see the two regions represented in Fig. 4, $]-2\pi R, 0[\,\times\, t$ and $[0, 2\pi R[\,\times\, t$ as a two-leaf foliation of the space–time of the rotating disk.

## 5. Conclusion

In Sagnac's view, his experiment had been initially designed to prove the existence of the aether, the assumed medium of propagation of light waves. It is now known that this hypothetical medium, with its clearly very contradictory physical properties, does not exist. In 1921, Langevin gives the appropriate (relativistic) explanation in a very short note to the *Comptes rendus*. The Sagnac effect is today at the basis of virtually all of our terrestrial and satellite inertial guidance systems. These technological developments were far from being imaginable when this famous experiment was conducted.

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