Bibnum

Founding texts of science

Physics
2018
Optics

Sagnac and experience against the grain

PiErrE SPagnoU
https://doi.org/10.4000/bibnum.737

Reference(s) :
Georges Sagnac (1869-1928). "*L'éther lumineux démontré par l'effet du vent relatif d'éther dans un interféromètre en rotation uniforme*", Comptes Rendus des Séances de l'Académie des Sciences, 157 (1913, t. 2), pp. 708-710 and *"Sur la preuve de la réalité de l'éther lumineux par l'expérience de l'interférographe tournant*", Comptes Rendus. des Séances de l'Académie des Sciences, d°, p. 1410

Summary

In the two notes he published in 1913, French physicist Georges Sagnac interpreted the positive result of his rotating interferometer experiment as proof of the existence of the ether and confirmation of Fresnel's wave theory. Little did he know that he had just uncovered a purely relativistic phenomenon (*i.e.* one that cannot be explained in classical physics, like the "Einstein effect" on frequency shift, the third test of general relativity): today, this phenomenon is perfectly understood within the framework of special relativity, even if it continues to be the subject of countless errors of reasoning.

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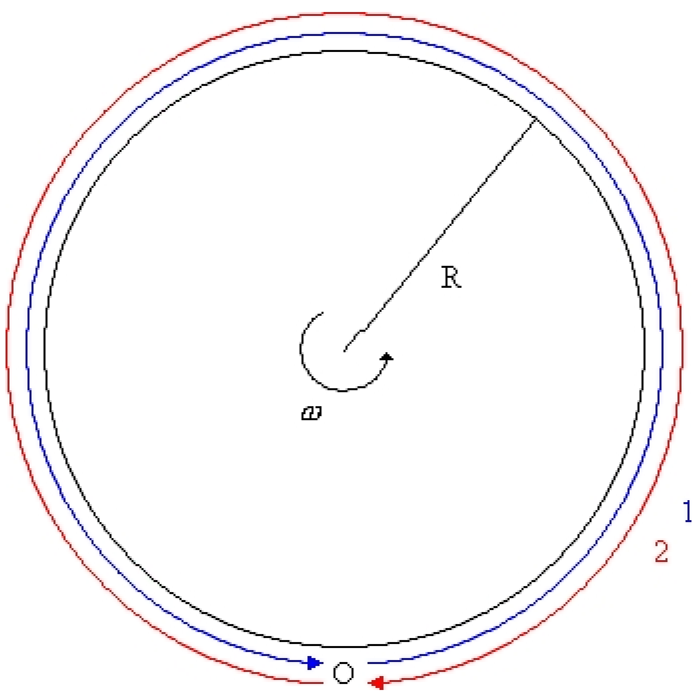
Full text

1 Document analyzed

Source of digitization: BNF / Gallica URL:

https://archive.org/details/121Sagnac

Figure 1



Schematic diagram of an experiment demonstrating the Sagnac effect (two light signals emanating from point O at the same instant and travelling in opposite directions at the same speed around a rotating disk).

Image WikiCommons Didier Lauwaert

The Sagnac experiment: the ether's last trick

2 In contrast to all previous attempts to demonstrate variations in the speed of light due to the Earth's motion relative to the ether (the most famous being that of Michelson and Morley at the end of the 19th century), the 1913 experiment by French physicist Georges Sagnac (1869-1928) stands out for its (finally!) positive result, confirming a prediction of Fresnel's ether theory. The two notes by Sagnac published in 1913 referred to here appear to consecrate this important result as solid proof of the existence of the ether, against Einstein's relativity, whose founding paper dates back to 1905. And yet, beyond appearances, this experiment was to reveal a typically relativistic effect, with unexpected practical applications. Contrary to its author's intentions, Sagnac's experiment, taken in all its generality, is today one of the most emblematic of special relativity, of which it constitutes a dazzling confirmation.

Light, a strange business

3 The history of the study of the properties of light is littered with surprises and often baffling twists and turns. Although light is omnipresent in our daily lives, where it appears to us as a matter of course, it is one of the most extraordinary and richest phenomena ever to have been offered to the sagacity of physicists.

4 As early as antiquity, two hypotheses emerged: one - corpuscular (or ballistic) - imagined light to be made up of tiny projectiles endowed with characteristic velocities; the other - undulatory - interpreted light (by analogy with sound for air) as a wave propagating through a medium filling the entire space between the stars, the ether. The first scientist of the modern era (beginning with Galileo) to propose a rational explanation was Huygens in the 17th century, with his remarkable wave theory. However, his concept was soon superseded by Newton's corpuscular theory, which was to remain the authority until the early 19th century. Newton imagined low-mass particles subject to the influence of gravitation: as a result, the speed of light was expected to vary according to the size of stars and their own motion in space.

5 The trouble begins with the discovery of the annual **aberration** of stars by James Bradley in 1728. Searching for parallax (the apparent shift in the position of stars depending on the angle of observation from the Earth, which varies with its motion around the Sun), Bradley came across an unexpected phenomenon that would prove to be a key discovery in more ways than one[1]. All stars have an apparent motion relative to the Earth (they describe an ellipse) that we'll call an aberration[2], because it's a discrepancy between the real position and the observed position; it's a combined effect of the speed of light and the Earth's speed, depending only on the ratio V/c (with V = 30 km/s). Bradley found that the motion of light was identical at all distances, and that the aberration of all stars could be calculated **with the same constant**.

6 This conclusion was not unanimously accepted, as the data available at the time did not rule out small variations in the speed of light. In 1810, French physicist François Arago set up an experiment designed to clarify the question: is it possible to detect, in accordance with corpuscular theory, small variations in the speed of light emitted by stars, originating either from the motion of the stars themselves, or from the specific characteristics of these stars (size, density...), or finally from the motion of the light itself?

Terre3 ? Arago had the ingenious idea of using prisms to amplify the effect and make it measurable. He exploited a property predicted by Newtonian corpuscular theory, namely that the greater the entry velocity, the greater the deflection of the incident light beam through the prism. This is because the normal component of the incident velocity will be increased by the gravitational force exerted by the refractive medium.

7 What did Arago measure in these experiments? The result was clearly negative: no significant deviation in the prism was observed. Arago tried to detect variations in two ways: either by examining different stars, or by capturing the light of certain stars in the morning (from which the Earth, in its movement around the Sun, is approaching) and other stars in the evening (from which the Earth is moving away). Let's listen to Arago himself recount his ingenious experiment[4] :

> We know, moreover, that its *[the Earth's]* motion is directed towards the stars that pass the meridian at 6 a.m. and towards those that pass at 6 p.m., in such a way that it approaches the former and moves away from the latter. The deviation, in the first case, must therefore correspond to the speed of emission increased by 1/10000 part, and, in the second, to this same speed decreased by 1/10000; so that the rays of a star passing the meridian at 6 a.m. must be less strongly deviated than those of a star passing at 6 p.m., by an amount equal to that caused by 1/5000 change in the total speed.

8 The above figure of 1/10,000th is, of course, the ratio of the speed of the Earth to the speed of light. Although a negative result (the non-observation of an expected effect) is frustrating for the experimenter, it is often rich in lessons. Arago was initially a firm believer in corpuscular theory, but how could his results be reconciled with this theory? We'd expect to see variations in the characteristics (diameter, density, speed, etc.) of the source stars, as well as in the Earth's motion. Initially, Arago had no choice but to safeguard the corpuscular theory by assuming that we do indeed receive light particles at various speeds, but that the human eye would only be sensitive to a small range of speeds. This ad hoc hypothesis couldn't hold water for long, and in 1818 Arago turned to his protégé Augustin Fresnel, the undisputed champion of the wave theory of light. Fresnel's theory easily explained the independence of the speed of light in relation to the emitting source (the case is similar for sound waves), assuming that the space between the stars is bathed in a stationary ether. But can it explain why the speed of light does not depend at all on the speed of the observer (the Earth)?

9 This was the challenging question posed to Fresnel. He succeeded in solving
brilliantly tackles the problem by assuming that the result can be explained by compensation effects due to the use of refractive media (in this case, prisms). To do this, he argues that the ether contained in the prism is partially entrained by the Earth's motion. More precisely, the movement of the prism would carry with it a quantity of ether corresponding to the excess of ether contained in the prism relative to the vacuum. Fresnel assumes that the speed at which the ether in the prism is dragged along is neither zero nor equal to the Earth's speed V, but equal to :

$$\left(1 - \frac{1}{n2}\right)v$$

where *n* is the refractive index and *V* the speed of the Earth.

10 Fresnel was thus able to explain why all optical phenomena observed on Earth by refraction experiments are independent of terrestrial motion if we

is limited to first-order terms in *V/c* (i.e. neglecting higher-order terms in *V/c*). He also predicted similar results for the propagation of light through water. In 1851, Hippolyte Fizeau was the first to perform an experiment using terrestrial light sources propagating through two columns of water, one of which was in motion. The results confirmed the "partial entrainment" of ether proposed by Fresnel. In 1850, Léon Foucault repeated Arago's experiment, comparing the propagation of light through water and air: the speed of light is slower in liquids than in air or vacuum. This result[5] invalidated Newton's corpuscular theory, which had predicted the opposite.

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11 Let's stop for a moment in 1860: Fresnel's aether theory was by then the most complete and coherent explanation of all known optical phenomena. There had been a minor scare with aberration, but everything seemed to be back to normal.

12 But the story is far from over. In the 1860s, James Maxwell published his theory of electromagnetism, in which light appears as a special case of an electromagnetic wave always traveling at speed *c* in the ether, its supposed propagation medium. In 1879, Maxwell planned to detect variations in the speed of light using a terrestrial interferometer. However, he judged the effects to be too small to measure (in *V2/c2*). The idea was to abandon the use of refractive media such as prisms for measurements, in order to avoid the compensating effects produced by the partial entrainment of the ether. The American physicist Michelson (1852 - 1931), who was awarded the Nobel Prize in Physics in 1907, decided to take up the challenge with his colleague Morley. If a light beam is split into two signals, each traveling the same length along an arm perpendicular to the other, classical physics predicts that the speed of light along each arm must vary according to the direction of the Earth's speed as it moves around the Sun, with the two signals arriving at the receiver offset accordingly. Despite numerous reproductions of this experiment, which continued into the early 20th century, the results were always negative. Was it still possible to save Fresnel's wave theory?

13 In 1889, the Irish physicist Fitzgerald was the first to propose a solution within the framework of aether theory: the idea of compensation made a comeback. He hypothesized that all objects are contracted in the direction of motion through the aether: thanks to this trick, variations in velocity are compensated for by shortening the interferometer arms in the direction of motion. However, it was Lorentz who, a few years later, achieved the first synthesis of this idea (which he proposed independently of Fitzgerald) with his own microscopic theory of electromagnetism (in which he described the behavior of electrons in coherence with Maxwell's theory). Lorentz didn't stop there, however, and developed the coordinate transformations (which Poincaré would call "Lorentz transformations") that guaranteed the invariance of the laws of electromagnetism in all inertial reference frames. Poincaré strove to clarify certain aspects of Lorentz's theory, giving it a form he believed to be complete. Poincaré's famous Palermo Memoir (the full version of which was submitted to the publisher a few weeks after Einstein's groundbreaking paper) was in fact the ultimate extension of his attempts to reconcile classical physics (based on the notions of absolute space and time) with the whole range of known phenomena, even if the mathematical formalism that Poincaré explored so skilfully anticipated in many respects that of future special relativity.

14 This is what Poincaré wrote in 1909 about his own work[6] :

> I have published an article in *Rendiconti* in which I set out Lorentz's theory of Electron Dynamics, and in which I believe I have succeeded in removing the last difficulties and giving it perfect coherence.

15 All the leading physicists of the time (Poincaré included) reasoned in terms of dynamics, and thus sought to explain the contraction of lengths as the effect of special kinds of forces exerted by the ether on bodies in the direction of their motion. No physicist before Einstein ever wrote a line about time dilation as a physical phenomenon. Time t' in the Lorentz transformation has never been understood in terms of time dilation. Lorentz didn't attribute any physical meaning to it.

16 In 1915, with salutary hindsight, he wrote with great [lucidity7] :

> The main reason for my failure [in the discovery of special relativity] was that I clung to the idea that only the variable t could be considered as real time, and that my local time t' should be regarded as a mere auxiliary mathematical quantity. In Einstein's theory, on the other hand, t' plays the same role as t. If we want to describe a phenomenon using x', y', z', t', we have to work with these variables as we would with x, y, z, t.

Figure 2

Albert Einstein (1879-1955) and Hendrik Lorentz (1853-1928). Although the latter was on the threshold of relativity, he never took the decisive step, unlike the former.

1921 photograph taken by physicist Ehrenfest in front of his house in Leiden, WikiCommons image.

17 As for Poincaré, he certainly endeavoured to define the local time introduced by Lorentz as a measurable physical quantity, but it completely ignores the factor $\frac{1}{\sqrt{1-V^2/c^2}}$ from time dilation, so that this local time $t - vx/c^2$ has nothing to do[8] with relativity of time. It's true that explaining the contraction of lengths in terms of dynamics was possible - but doing the same for the dilation of durations was another story: within the framework of ether theory, how could we understand that all clocks in motion relative to the ether could be slowed down by a mechanical effect? This aspect must have played a part in the mental block of the time: but it's a fact that neither Lorentz nor Poincaré ever envisaged this concept. The only one who touched on it was Larmor, but he never mentioned the effect in its generality or as applicable to moving clocks.

18 Despite this factual data, some physicists, after Einstein's publications and relying excessively on secondary sources, constructed an *a posteriori* physical theory, a kind of scientific *uchrony*, a parallel history of physics that never existed. This theory, sometimes called the Larmor-Lorentz theory or the Lorentz-Poincaré theory, is said to be based on two fundamental hypotheses: the contraction of lengths and the dilation of durations, while preserving the classical framework of the ether. And yet, as we have already pointed out, nothing was written about the second hypothesis[9] until Einstein's seminal 1905 paper *"On the electrodynamics of moving bodies"*.

19 In this landmark paper, the brilliant physicist completely reverses the perspective, proposing a solution that is both simpler and more radical, capable of accounting for all known phenomena by virtue of its universal character: it "suffices" to change the kinematic framework that was taken for granted, i.e. the way in which space and time coordinates transform from one frame of reference to another. This new kinematics is born of the fusion of two apparently incompatible axioms: the constancy of the speed of light in all inertial reference frames and the principle of relativity. In this new framework, applicable to all present and future physical theories, the most astonishing aspect is no longer the contraction of lengths but the relativity of time, since it is accompanied by an absolute effect: the **desynchronization of perfect** clocks[10]. This unprecedented and revolutionary consequence was predicted by Einstein as early as his first paper in 1905, with an ease that stands in stark contrast to the hesitations of his predecessors. Another novelty: Einstein simply got rid of the ether as a superfluous hypothesis.

20 Einstein himself summed up the importance of his contribution shortly before his death[11] :

> What was new in this dissertation was the discovery that the scope of the Lorentz transformation transcended its connection with Maxwell's equations and called into question the nature of space and time in general. What was also new was that Lorentz invariance is a general condition for all physical theory. This was of particular importance to me, as I had already discovered earlier that Maxwell's theory did not account for the microstructure of (electromagnetic) radiation and therefore could not claim universal validity.

What is desynchronization of perfect clocks?

Let's consider two clocks, initially stationary H and H_0 at point O in an inertial reference frame, and perfectly synchronized. Let's suppose that we make the clock go through

H a closed curve of any kind that starts from O and returns to O, and on its return to point O we find that clock H is running behind clock H_0 . What could be the cause of this?

The classical physicist with his absolute time has only one solution to propose: the displaced clock (or each of the two clocks) has gone out of adjustment, and therefore has not correctly measured the elapsed time, hence the discrepancy at the finish. For the relativistic physicist, on the other hand, there's another solution: each of the clocks has continued to work perfectly (beating the second imperturbably), but the times actually elapsed are different in each of their reference frames.

A key consequence of relativity is that each line of the universe[12] has its **own specific time**. By *proper time*, we mean the time measured by a perfect clock attached to a given observer. The notion of proper time is essential[13] in relativity, as it corresponds to the space-time distance element that is invariant from one inertial frame of reference to another. In relativity, neither lengths nor durations are conserved from one inertial frame of reference to the next, but a mixture of the two (formally introduced by Minkowski in his famous article[14] of 1908). To those who are put off by these new concepts, we can turn the question around: why should we live in a universe in which lengths and durations don't change from one frame of reference to another? It's perfectly possible to imagine universes with a geometric structure such that these quantities are no longer conserved: as it happens, we live in one of these logically possible universes.

And the light turned

21 Such was the context when, in 1913, Georges Sagnac set about carrying out his experiment. He was not the first physicist to have anticipated the effect he was seeking to measure, i.e. the **time lag in the reception of light signals** travelling in opposite directions through a closed circuit.

22 Sir Oliver Lodge (1851-1940) envisaged in 1893, within the framework of ether theory, the detection of the Earth's rotation around its axis using a hypothetical interferometer measuring one square kilometer; then, in 1897, he anticipated the result of Sagnac's experiment by reasoning with a small interferometer set in rotation. In 1904, Michelson also studied the possibility of demonstrating the Earth's rotation using an interferometer. In 1925, Michelson and Gale actually succeeded in measuring the predicted effect using an optical interferometer of impressive dimensions.

Figure 3

Sir Oliver Lodge (cartoon by Leslie Ward, published in Vanity Fair, February 4, 1904, WikiCommons). An example of length dilation in this cartoon?

23 During his thesis work in 1911, German student Frank Haress stumbled across the phenomenon while studying the effects of light refraction through prisms, again within the framework of Fresnel's theory. For the sake of convenience, he had arranged the prisms in a ring and rotated them. He observed, but could not explain, the displacement of the interference bangs. Unintentionally, Haress helped to demonstrate that the Sagnac effect was observed even in the presence of refractive media (through which light travels at a speed lower than c).

24 Finally, Georges Sagnac himself predicted the effect in 1911 with the ether theory. That same year, Max Von Laue pointed out that special relativity also accounted for the phenomenon, having demonstrated as early as 1907[15] that this theory allowed Fresnel's predictions for the partial entrainment of the ether to be recovered to a first approximation.

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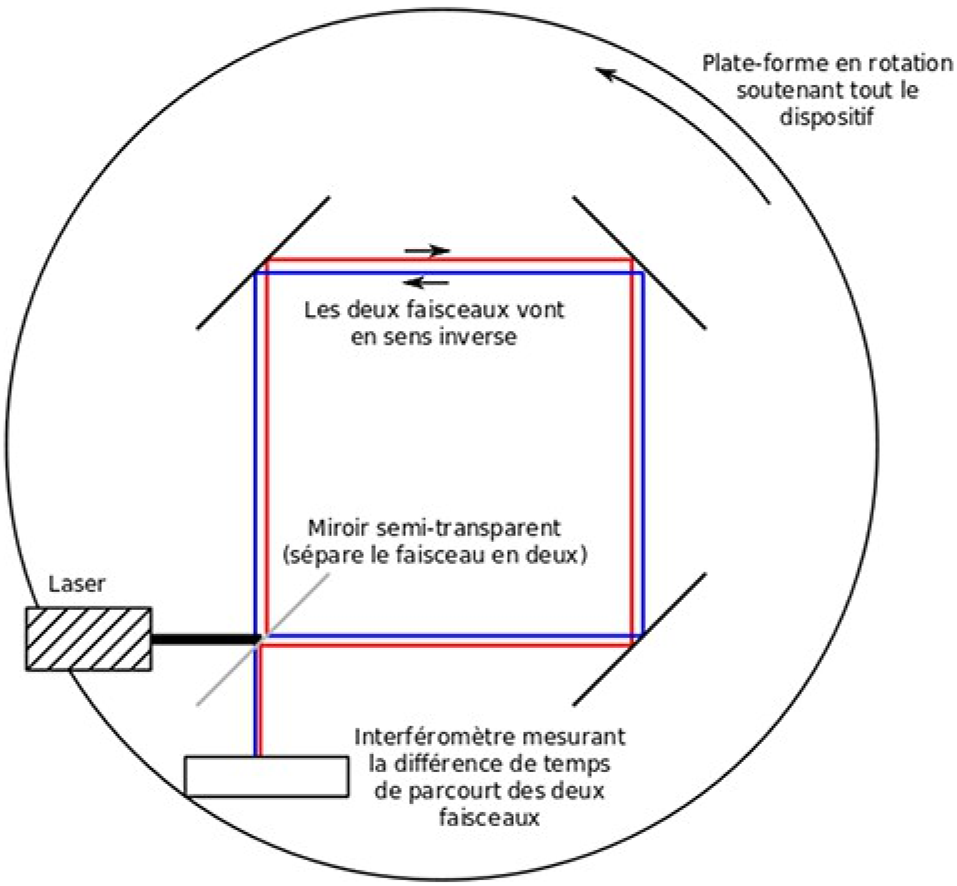
25 We are now ready to analyze the two notes published by Sagnac in 1913 as an account of his successful experiment. We will focus mainly on the first note, which contains the essential aspects for discussion.

26 Sagnac's first note, entitled "L'éther lumineux démontré par l'effet de vent relatif d'éther dans un interféromètre en rotation uniforme" (The luminous aether demonstrated by the effect of relative aether wind in a uniformly rotating interferometer), logically begins by explaining the principle of the method used:

> The two interfering beams, reflected by four mirrors placed at the edge of the turntable, are superimposed in opposite directions on the same horizontal circuit surrounding a certain area S.

27 The conditions are clearly set here: two light signals are made to travel through an identical closed circuit in opposite directions, and the interference is observed at the point where they meet (the receiver being a photographic plate which records the interference bangs). A detailed diagram of this closed circuit is provided in the second note.

Figure 4



Schematic diagram of an optical Sagnac interferometer

Image WikiCommons author Didier Lauwaert

Figure 4bis

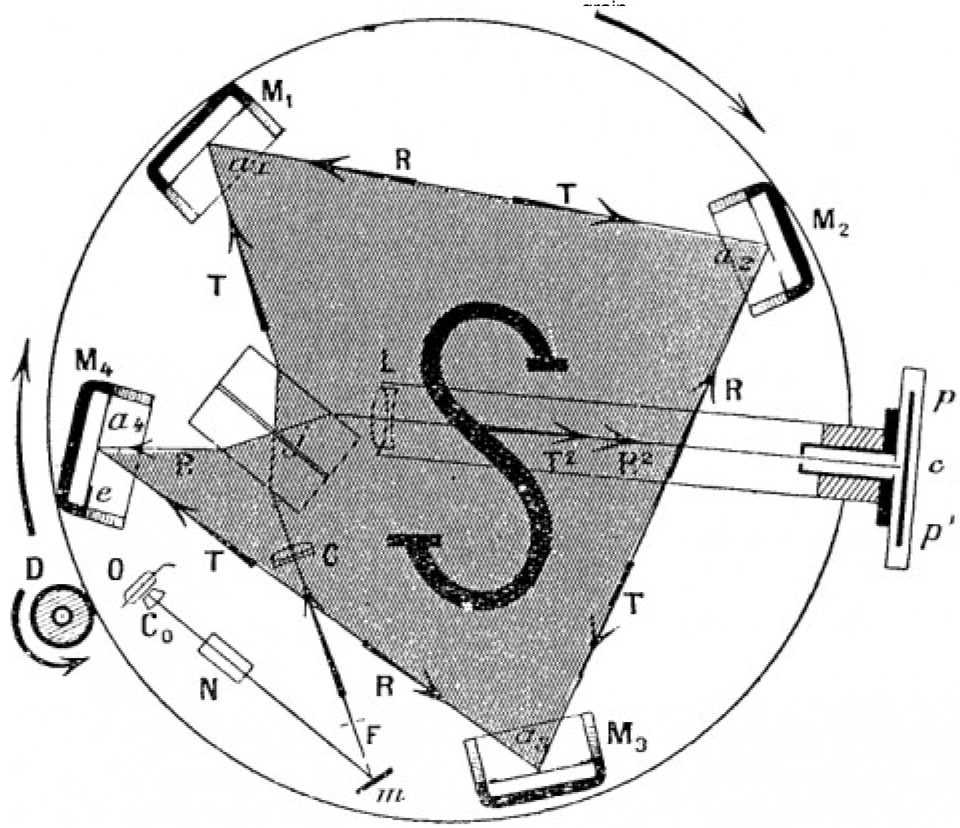


Diagram as shown in G. Sagnac's article.

28 The **displacement of the interference center** (i.e. the center of the median fringe corresponding to maximum light intensity) is measured by comparing two separate photographs, each corresponding to a uniform rotation of the plate at the same speed in one of two possible directions.

29 Sagnac then describes the predicted effect from a theoretical point of view. What assumptions does he base it on? What does he mean by the *optical vortex effect*?

> In a system in overall motion relative to the ether, the propagation time between any two points in the system must be altered as if the system were stationary and subject to the action of an ether wind, whose relative speed at each point in the system would be equal to and directly opposite to that of that point, and which would carry away light waves in the manner of the atmospheric wind carrying away sound waves.

30 Sagnac's reasoning is based on Fresnel's ether theory. The light wave, like sound in air, propagates through the ether (a mysterious medium whose composition remains unknown, unlike air), independently of the motion of the emitting source. The analogy with the sound wave is constant and guides the argument. The speed at which a light wave propagates should depend on the observer's speed relative to the ether, just as it does for sound relative to air. If the observer moves towards the source at speed Rω, he will measure the equivalent for light of a wind for air (i.e. c + Rω), whereas if he moves away from it, he will measure c - Rω, hence the name *ether wind*. This terminology was already in use for Michelson and Morley's experiment.

> Observing the optical effect of such a relative wind of aether will constitute proof of the aether, just as observing the influence of the relative wind of the atmosphere on the speed of sound in a moving system would, in the absence of any other sensible effect, prove the existence of the atmosphere surrounding the moving system.

31 Sagnac insists here on the analogy with air: if light propagates in the same way as a sound wave in air, the detection of the relative aether wind should confirm the existence of light's own propagation medium. We'll come back to the detailed calculation a little later.

32 He then mentions another experiment he had carried out, involving a vertical optical circuit: the effect measured was zero to within the precision of the measurements, and allowed ether entrainment to be ruled out.

> I have shown interferentially [...] with an optical circuit of 20m² vertical projection, that ether entrainment in the vicinity of the ground does not produce even an ether vortex density b of 1/1000 radian per second.

33 He predicted the existence of an effect due to the Earth's rotation that could be detected using a horizontal circuit.

> I hope to be able to determine whether the corresponding small optical vortex effect exists or not.

34 But Sagnac died in 1928, and it was Michelson and Gale in 1925 who first succeeded in measuring this effect using a "giant" interferometer. Sagnac returned to the main subject, which concerned the result obtained with a smaller optical circuit set in rotation:

> It was easier for me to find proof of the ether first by running a small optical circuit.

35 It recalls the theoretical value predicted for the *z* parameter, which corresponds to the shift already mentioned in the interference center between two photographs:

$$z = \frac{16\pi NS}{\lambda c}$$

36 Where *N is* the number of revolutions per second of the turntable, *S* the surface area of the closed circuit, λ the wavelength used, *c* the speed of light (Sagnac's notation is v_0 , still common at the time - we've replaced it with *c*).

Sagnac's interference formula

How do we obtain this formula using ether theory?

To simplify, let's derive the above formula from a rotating disk (the one shown in figure 1), a case that can easily be generalized to a closed circuit encompassing any surface S. We thus have two light signals emitted at the same instant from point O (fixed on the rotating disk) which travel around the circumference via a set of mirrors to return to O, each in a different direction. Although emitted from the rotating disk, the signals propagate at speed *c* relative to the ether (laboratory), in accordance with Fresnel's theory. On the other hand, in relation to the rotating disk, the speed of each of the signals is increased or decreased by that of the disk, depending on the direction of travel (this is the speed additivity law usual in classical physics). The time difference between the arrival of the signals at O is therefore given by :

$$\Delta t = \frac{2\pi R}{c-R\omega} - \frac{2\pi R}{c+R\omega} = \frac{4\pi R^2 \omega}{c2-R^2 \omega 2}$$

Noting that the rotational speed of the disc is small compared to *c* and that S = π R², we obtain :

$$\Delta t = \frac{4\omega}{c^2}$$

The phase shift Δφ between the two light beams is ω ×Δt :

$$\Delta\varphi = \frac{2\pi c}{\lambda} \times \frac{4S\omega}{c2} = \frac{8\pi S \omega}{\lambda c}$$

The theoretical value given by Sagnac is double the previous one (which is the usual known value) because, remember, the displacement of the interference center is measured by comparing two photographs corresponding to two opposite rotations of the rotating interferometer.

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37 A final precaution is pointed out by Sagnac: he explains how he ensured that fringe displacements could not be attributed to instability of the optical parts during rotation.

> This shows that the observed effect is indeed due to a phase difference linked to the system's rotational movement.

38 With the results confirming the value predicted by Fresnel's ether theory, Sagnac can triumphantly announce that the existence of the ether has been proven.

> The observed interferential effect is indeed the optical vortex effect due to the motion of the system relative to the aether, and directly manifests the existence of the aether, the necessary support for Huygens' and Fresnel's light waves.

39 He drives the point home in the conclusion of his second note, entitled "On the proof of the reality of the luminous ether by the rotating interferogram experiment":

> The results of our measurements show that, in ambient space, light propagates with a velocity V_0, independent of the overall motion of the light source O and the optical system. This property of space experimentally characterizes the luminous ether.

40 Sagnac's result was evidence in favor of Fresnel's theory of the ether (or that of Lorentz and Poincaré, who extended it with electromagnetism): but was it the only possible explanation? Sagnac was well aware that special relativity, already 8 years old, could not be left out of the discussion. One of Sagnac's closest colleagues was Langevin, one of the few French physicists who resolutely supported Einstein's theory. Honesty would have dictated that we at least leave open the question of whether this effect could be interpreted within the relativistic framework. However, Sagnac's strong conviction (that of the experimental physicist all too happy to confirm his familiar concepts in direct relation to sensitive data) undoubtedly precipitated him towards his preferred conclusion, to the detriment of a more innovative approach.

41 In any case, at this stage, we can list a few undoubted properties of the Sagnac effect:

- It conforms to the formula demonstrated by Sagnac using ether theory. It does not
- depend on the shape of the closed surface.
- It does not depend on the position of the center of rotation.
- It does not depend on the presence of a co-turning refractive medium in the signal path.

In fact, special relativity predicts the Sagnac effect...

42 What is special relativity's prediction for the Sagnac effect? The answer is important, since Sagnac claimed to demonstrate the existence of the ether, which relativity has put to rest.

43 First of all, the reasoning is identical to that of the ether theory, if we place ourselves in the context of the ether. laboratory reference frame (which can be considered inertial): in both cases, the speed of the signals is equal to *c* (the difference is that relativity does not presuppose the existence of a propagation medium for light). It's easy to reproduce the prediction obtained with aether theory in the reference frame of the laboratory, where the disk rotates. In the laboratory, the signal emitted in the same direction as the disk rotation must travel a greater distance, as the disk rotates slightly while the signal is propagating. The signal transmitted in the opposite direction, on the other hand, has a shorter distance to travel, but at the same speed, hence the time lag in signal reception. Let's demonstrate this in detail, using relativity.

44 Let t_+ and t- be the path lengths of each of the signals measured in the laboratory reference frame (noting + the signal emitted in the same direction as the disk rotation). The lengths traveled relative to the laboratory are :

$$ct_+ = 2\pi R + R\omega t \; ct_+ \; {}_- = 2\pi R - R\omega t_-$$

45 Hence

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

46 The two theories (ether and relativity) are in agreement when viewed from the laboratory frame of reference. But how does relativity describe the situation from the point of view of the rotating disk?

47 The Sagnac delay measured by the observer at O is given by :

$$\Delta t' = \Delta t \sqrt{1 - \frac{R^2 \omega^2}{c^2}} = \frac{4\pi R^2 \omega}{c^2 \sqrt{1 - \frac{R^2 \omega^2}{c^2}}}$$

48 It is this time interval that corresponds to the result of Sagnac's measurement, since the phase shift is measured in relation to the rotating disk. The value predicted by relativity is **slightly different** from that provided by aether theory: there is a time dilation factor to take into account. Nevertheless, this term is negligible in practice and the two predictions can be considered to coincide. This is not to say that the explanations are of the same nature.

49 Contrary to popular belief, the relativistic origin of the Sagnac delay is not the anisotropy[16] of the speed of light in the rotating frame of reference (this misinterpretation stems from the fact that we believe we are allowed to admit anisotropy in the rotating frame of reference because it is not inertial), but the particular structure of our space-time. In the rotating frame of reference[17] , lengths **depend on the direction of** travel and the speed of light remains constant, unlike in classical physics.

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50 In the 1990s, Italian physicist Franco Selleri thought he had detected a paradox[18] (and therefore a logical contradiction) in special relativity: according to him, in the relativistic framework, the two signals did not propagate at the same speed relative to the rotating disk (he assumed anisotropy, as was done in classical physics), which seemed admissible since the reference frame was not inertial. The ratio between the two velocities in opposite directions was different from 1 and depended only on the quantity $R\omega/c$, since he assumed that the lengths travelled were identical. By tending the disk radius towards infinity and the angular velocity ω towards zero, while keeping the tangential velocity $R\omega$ constant, the rotating disk became an inertial reference frame in which the isotropy condition of the speed of light was violated, hence the paradox. This reasoning is invalid, since in reality, signals in the Minkowskian relativistic framework have the same velocity relative to the rotating disk; and we will now see that the originality of the Sagnac effect lies in the fact that it is also observed for any perfectly isotropic signals or objects. As a result, the term $c2$ in the Sagnac delay $4\pi R^2\omega/c^2$ will no longer appear as the square of the particular velocity of a signal, but as a **structural constant** of our universe.

The universality of the Sagnac effect

51 Where do we stand? We found that both aether theory and special relativity were capable of predicting the effect observed with light signals, but differed radically in the explanation given. Is there any way to tell them apart? Physicists love to vary the parameters of experiments to titillate their theories, and this case is no exception. What would happen if, instead of light signals, in Sagnac's experiment we used particles or even macroscopic objects travelling around the circumference of the disc rotating at any (but identical) speed in both directions?

52 Let's do a thought experiment that will be very useful to us and that we'll call the **turtle paradox**.

Figure 5

The "turtle-watch", a key element in understanding the universal Sagnac effect

53 Back to our spinning disc. This time, we're going to use two turtles instead of light signals. Why two turtles? Because we want to minimize any relativistic effect linked to their speed. These two turtles are equipped with perfect watches, both set to noon. They set off in opposite directions at the same instant from the fixed point O on the rotating disk, and make a complete revolution at the same speed V_0 .

54 What can we say? First of all, each of our turtles can measure its speed V_0 throughout its journey and ensure that its speed is constant and equal to V_0 . It can also regularly measure the distance covered and ensure that at the finish line

that it is indeed equal to that obtained by its counterpart. We deduce that the duration of the journey for each of the turtles will be identical, e.g. 1 hour. The time shown on each watch on arrival at point O will therefore be 13:00.

55 Let's assume that our two turtles don't arrive at point O at the same time, which means that an observer at point O will see one turtle arrive and wait for the other for (say) 10 minutes. This simply amounts to assuming that the Sagnac effect demonstrated for light signals would also be observed for any object.

56 What conclusion can we draw? When the second turtle joins its fellow turtle at point O, what are the times displayed by their respective watches?

57 The watch of the first turtle to arrive will show **13:10** (since it has been waiting for its fellow turtle for 10 minutes), while the other will show **13:00**. The two watches will be 10 minutes apart: this is the phenomenon of desynchronization of perfect clocks. We deduce that the Sagnac delay necessarily implies the desynchronization of perfect clocks. Conversely, if this desynchronization phenomenon didn't exist, we wouldn't be able to observe a delay in the arrival of our two turtles (or any two objects).

58 We can conclude from this that any physical theory capable of explaining **the Universal Sagnac** (i.e. the offset in arrival at the origin observed independently of the speed and nature of the signals used) must also take into account the desynchronization of perfect clocks.

59 By extending Sagnac's initial experiment to any objects or signals with the same velocity relative to the disk, we have a means of determining which of the two theories (Fresnel ether or relativity) correctly accounts for the general phenomenon.

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60 Let's now compare the two theories quantitatively.

61 In Fresnel's theory, time is absolute, so the travel times of each of the objects traveling in the opposite direction at speed V_0 relative to the disk will be identical in all reference frames: that of the laboratory in which the disk rotates, that of the rotating disk (transceiver) and that of the objects traveling along the disk.

62 Here are the durations as predicted by classical physics (i.e. Fresnel theory) in the various reference frames to be considered :

Reference	Durations measured for a complete lap	
	In the direction of rotation	In the opposite direction
Labo	**$2\pi R / V_0$**	**$2\pi R / V_0$**
Rotating disc	**$2\pi R / V_0$**	**$2\pi R / V_0$**
Turtle on rotating disc	**$2\pi R / V_0$**	**$2\pi R / V_0$**

63 In classical physics, the Sagnac delay (the difference between the two durations above with respect to the rotating disk) is zero for our turtles (or any other objects): they return to their starting point at the same instant. What happens to these durations in special relativity? Here are the new predictions[19] :

Reference	Durations measured for a complete lap	
	In the direction of rotation	In the opposite direction

Labo	$\frac{2\pi R}{v_0(1-\frac{R^2\omega^2}{c^2})}\left(1+\frac{v_0 R\omega}{c^2}\right)$	$\frac{2\pi R}{v_0(1-\frac{R^2\omega^2}{c^2})}\left(1-\frac{v_0 R\omega}{c^2}\right)$
Rotating disc	$\frac{2\pi R}{v_0\sqrt{1-\frac{R^2\omega^2}{c^2}}}\left(1+\frac{v_0 R\omega}{c^2}\right)$	$\frac{2\pi R}{v_0\sqrt{1-\frac{R^2\omega^2}{c^2}}}\left(1-\frac{v_0 R\omega}{c^2}\right)$
Turtle on rotating disc	$\frac{2\pi R}{v_0\sqrt{1-\frac{R^2\omega^2}{c^2}}}\sqrt{1-\frac{v_0^2}{c^2}}$	$\frac{2\pi R}{v_0\sqrt{1-\frac{R^2\omega^2}{c^2}}}\sqrt{1-\frac{v_0^2}{c^2}}$

Table taken from Pierre Spagnou's book, *De la relativité au GPS*, Ellipses, 2012

64 The difference between the times measured relative to the rotating disk (shown in the table above) is the Sagnac delay, $4\pi R^2\omega/c^2$ to a first approximation, independent of the speed V_0 relative to the disk **which disappears from the formula**. However, the

The clocks attached to the turtles measure an identical duration (last line of the table above) and are therefore out of sync when compared at point O. If we replace our turtles with twins, this gives us a **variant of the famous twin paradox**: when they meet at point O, the two twins do indeed end up with different ages. This should come as no surprise: in relativity, the plurality of proper times is the rule, not the exception.

65 Beyond these theoretical predictions, what can we learn from observation? The Sagnac effect has it been measured? The possibility of repeating Sagnac's experiment with electrons was first envisaged in 1935[20] by Fernand Prunier (a staunch anti-relativist), in order to distinguish between classical and relativistic theories (the effect must be zero in non-relativistic physics). The first measurement using a matter-wave interferometer (particles behaving quantum-like) was made in 1965 by Zimmerman and Mercereau with superconducting electrons. Since then, the effect has also been observed with neutrons and atoms.

66 The universal Sagnac effect is therefore a natural phenomenon that has been clearly established with elementary particles or atoms.

67 Up to now, it has not been possible to measure the shift in arrival at the origin point directly with macroscopic objects, as it would be necessary to be able to measure extremely small time intervals (wave behavior being no longer exploitable). Nevertheless, we were able to measure the desynchronization of perfect clocks by means of a rather similar experiment, carried out by **Hafele and Keating** in 1971. In this experiment, two airliners were flown around the Earth at the equator, one to the east, the other to the west, carrying four high-precision atomic clocks. The time indicated by the clocks on their return to the point of departure was compared with that provided by reference clocks on the Earth's surface. The differences measured showed good agreement with relativistic predictions. If a perfect equatorial journey had been made, the eastbound clock would have been 207 nanoseconds later than the terrestrial clocks on arrival, while the westbound clock would have been 207 nanoseconds earlier. The measured values were slightly lower due to deviations from the ideal equatorial trajectory.

Figure 6

Physicists Joseph Hafele (b. 1933) and Richard Keating on board an airliner, with their cesium atomic clocks.

Photo from *Popular Mechanics* magazine, January 1972

68 The desynchronization of perfect clocks is now a clearly established phenomenon (in circumstances similar to those of the Sagnac experiment), as is the universal Sagnac effect. The twins paradox was therefore no fanciful fantasy. Georges Sagnac, who died in 1928, never perceived the close connection between his own observations and one of the most extraordinary consequences of special relativity, which his colleague Paul Langevin had helped to make known from 1911 onwards.

An experiment of no practical interest?

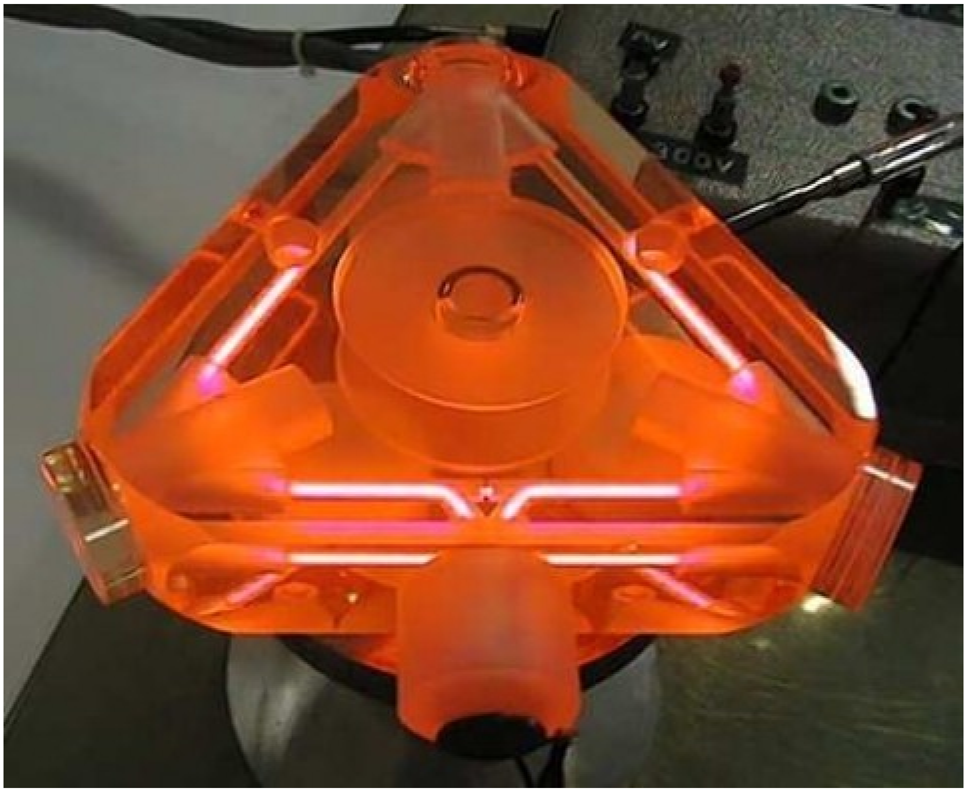
69 The foregoing ideas were not condemned to remain abstract; on the contrary, they have given rise to technological tools of the utmost importance.

70 The strangeness of the Sagnac effect lies in the fact that it depends neither on the nature of the signals or objects used, nor on their speed relative to the rotating reference frame (provided it is the same in both directions and not zero). This means that the desynchronization of clocks moving even very slowly across the Earth's surface is inevitable, unless they are made to follow a meridian or a curve such as a figure-of-eight[21].

71 The most spectacular application is the gyrometer (angular velocity sensor): if two signals at the same speed are made to travel in both directions in a closed circuit, the measured phase shift gives us an estimate of the device's rotation speed. Today, one of the most common components of an inertial measurement system[22] (used on commercial airliners) is the gyrolaser: the signals are two beams of coherent light whose phase shift is measured. Coupled with accelerometers, gyrolasers can be used to determine all aircraft movements and changes in orientation. Their advantages over conventional gyrometers

(course conservers) is that they use no moving mechanical parts, which means less wear; they are also less sensitive to shocks or jolts.

Figure 7



Example of a gyrolaser manufactured by Thales Source

Thales Aerospace

72 There are also fiber-optic gyrometers. Signal velocity is no longer *c*, but is slightly lower due to refraction: this has no impact on the Sagnac effect, as already indicated.

73 Research is underway into future gyrometers using matter waves: the phase shift between the two wave packets associated with atoms or particles is measured (according to the laws of quantum physics).

A unique case of a phenomenon with multiple... and false interpretations

74 Since the initial experiment in 1913, the Sagnac effect has given rise to a considerable number of publications proposing very different interpretations of the same phenomenon. Many papers, even recent ones, claim to provide, on the basis of independent hypotheses, a result identical (at least to a first approximation) to that obtained in a relativistic framework. What is the value of these interpretations?

75 One source of confusion lies in the belief that the relativity of time is only involved in the Sagnac effect through the factor $\gamma = \frac{1}{\sqrt{1-V^2/c^2}}$ which is negligible in first approximation and that the residual effect can therefore be obtained by classical physics. In other words, we think we're entitled to use post-Newtonian reasoning, which amounts to treating the relativistic prediction as **a simple corrective to an** already existing **classical effect.** The practice of post-Newtonian reasoning in relativity has a long history[23], but exposes us to serious risks of error, as it can

lead to ignoring purely relativistic effects **that have no equivalent in classical physics**, and thus to failing to understand essential aspects of relativity. The Sagnac effect is a kind of concentrate of these errors. In the case of matter waves, it is sometimes interpreted as the effect of a Coriolis force applied to a particle of fictitious mass *hv/c2*, the observed phase shift being explained by the encounter of two atomic waves of different speeds (relative to the laboratory) arriving at the same instant (contrary to the relativistic point of view, which describes two waves of the same frequency arriving at different instants).

76 It is interesting to note that another typically relativistic effect suffers from errors of analogous reasoning: the **Einstein effect**. This is the frequency shift (as measured on Earth) in the emission spectrum of a distant atom placed in a different gravitational field. A common interpretation in popular literature is to attribute an inertial (i.e. gravitational) mass *hv/c2* to the photon, and to deduce that the photon's frequency is altered because its potential energy varies with distance. This explanation cannot be correct, since we know that, according to general relativity, it is a "contraction" effect of time that is at the origin of the phenomenon, **the natural frequencies being unchanged**. If the non-relativistic explanation were correct, we should in fact observe a double effect[24]. The relativistic origin, on the other hand, has been validated by experiments such as those of Hafele and Keating, already mentioned.

77 To return to the Sagnac effect, not all interpretations are equally valid, as the phase shift observed is typically relativistic and should therefore not be treated as an approximation. Here again, if the alleged causes of the phenomenon have nothing to do with the relativistic desynchronization of the clocks, the effect should be cumulative with that predicted by relativity, which is not the case.

78 Any non-relativistic interpretation is consequently false[25] and the use of such reasoning should be abandoned, as it does not allow a correct understanding of the Sagnac effect in all its generality.

79 In the course of time, the Sagnac effect has been a formidable revealer of the profound misunderstandings that relativity still suffers from today, and its elucidation will have made a major contribution to reaffirming some sometimes forgotten truths:

- The Sagnac effect generates no paradox (logical contradiction) in special relativity.
- The Sagnac effect is by no means proof of anisotropy in the velocity of the that would conflict with special relativity.
- The real originality of the effect lies in the fact that it is observed *despite* the perfect isotropy in velocity of any signals or objects (relative to the disc).
- General relativity is not useful in explaining the Sagnac effect: it is a purely kinematic effect (only motion is involved) predicted by special relativity.
- The relativity of time (more precisely, the desynchronization of perfect clocks) lies at the heart of the phenomenon.
- Any explanation of the Sagnac effect that does not involve the kinematics of the relativity is **necessarily** erroneous[26].

80 And we can add the following important elements:

- The plurality of proper times is certainly the most important concept in relativity (special and general).
- Special relativity allows us to study any type of motion, including rotations.
- The speed of light is constant even in accelerated reference frames, provided it is measured at the observer's location.

***

81 In a tender irony of the history of science and a spectacular final twist, Sagnac's most famous contribution to physics was to prove the opposite of what had motivated his initial experiment: he brought *to light* a **purely relativistic** phenomenon that can be fully explained within the framework of special relativity, the concept of the ether as a medium for the propagation of light being obsolete.

82 Contresens is certainly the most appropriate term here: Firstly, literally, because it involves two signals travelling in opposite directions; secondly, because instead of revealing an anisotropy of the speed of light in relation to the rotating disk, the phenomenon is observed identically for any signals or objects that are rigorously isotropic (in speed); lastly, because the Sagnac effect, far from signifying a return to classical conceptions, is ultimately a **signature of the relativity of time**, since the delay in signal reception corresponds exactly to the Einsteinian desynchronization of two perfect clocks moving in opposite directions across the disk.

83 Unbeknownst to him, in 1913 Georges Sagnac carried out a superb **counter-experiment** of unsuspected conceptual richness, which today ranks among the most representative of special relativity.

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Articles for further reading

For a detailed explanation of the Sagnac effect within the framework of special relativity and the resolution of physicist Selleri's "pseudo-paradox":

G. Rizzi and A. Tartzaglia, "Speed of Light on Rotating Platforms", *Foundations of Physics* 28, 1663 (1998) (Arxiv PDF link)

For a comprehensive summary of the various (and often false) interpretations of the Sagnac effect: Malykin, "The Sagnac effect: correct and incorrect explanations", *Physics* 43 (12) 1229 - 1252 (2000) (online presentation)

On another purely relativistic phenomenon, the Einstein effect, subject to misinterpretations similar to those of the Sagnac effect: Okun, Selivanov and Telegdi, "Gravitation, photons, clocks", *Physics* 42 (10) 1045 - 1050 (1999) (available online).

On Einstein as the unique "discoverer" of time relativity: W. Rindler, "Einstein's Priority in Recognizing Time Dilation Physically", *American Journal of Physics* 38 (1970) (PDF available online).

Notes

1 The annual aberration of stars is a magnificent triple proof: 1°) It confirms the finite nature of the speed of light established in 1676 by Römer (cf. *BibNum* text and analysis by Francis Beaubois) while providing the first reliable estimate of this speed (Bradley provides a value for the v/c ratio); 2°) It provides the first solid proof of the Earth's motion around the Sun (which Galileo had missed), thus validating heliocentrism; 3°) It shows that the

The speed of light is independent not only of the motion of the source, but also of that of the observer, a finding that would prove crucial for special relativity.

2 The aberration reflects the fact that the apparent direction of a light source depends on the observer's speed, just as rain, when we're running, seems to come at us from a direction towards the front of our umbrella rather than vertically.

3 Recall that, in classical physics, the law of additivity of velocities tells us that the velocity of the measured object must be decreased by that of the observer if the latter is moving away from the source, or increased in the opposite case.

4 Quoted from his 1810 memoir (published in 1853), analyzed by James Lequeux, "Les expériences d'Arago sur la vitesse de la lumière (1810*)*", *BibNum*, September 2008.

5 For an analysis of Foucault's thesis describing his 1850 experiment (described as crucial by Arago), see Jean-Jacques Samueli, "*Foucault et la mesure de la vitesse de la lumière dans l'eau et dans l'air*", *BibNum*, September 2009.

6 Quotation from Henri Poincaré's letter to Gaston Darboux, Bibliothèque de l'Institut de France, Darboux Correspondance, MS 2720 (8-9).

7 Lorentz, *Théorie des électrons* (second edition of 1915, note 72).

8 For Poincaré, local time is the time indicated by one of the clocks attached to an inertial frame of reference in motion relative to the ether. This time is erroneous in relation to true time, because it is impossible, according to Poincaré, to synchronize the clocks correctly with each other, due to the anisotropy of the speed of light. This local time explains the failure of optical experiments in V/c.

9 For a more detailed analysis of this insufficiently known historical fact, see W. Rindler's article, "Einstein's Priority in Recognizing Time Dilation Physically", *American Journal of Physics* 38, 9 (1970), which has lost none of its topicality.

10 This effect is also known as the "twin paradox", but there's no logical contradiction: if you replace the clocks with twins, the twins end up with different ages.

11 *Technische Rundschau*, Bern, No. 20, May 6, 1955.

12 Trajectory to get from point A to point B in our 4-dimensional universe.

13 For a more detailed justification of the crucial importance of proper time in relativity, see chapter 2 of Jean Eisenstaedt's book, *Einstein et la relativité générale*, CNRS Editions (reed. 2013).

14 "Die Grundgleichungen für die elektromagnetischen Vorgänge in bewegten Körpern", Königliche Gesellschaft der Wissenschaften zu Göttingen, mathematisch-physikalische Klasse, *Nachrichten*, 1908: 53-111.

15 For an analysis of Max von Laue's 1907 article, see Jean-Jacques Samueli and Alexandre Moatti, "*L'entraînement partiel de l'éther et la relativité restreinte*", *BibNum,* November 2010.

16 The anisotropy of a physical quantity is its independence from direction.

17 See the article by G. Rizzi and A. Tartaglia, 1998, "Speed of Light on Rotating Platforms", *Foundations of Physics* 28, 1663 for a detailed demonstration. In the rotating frame of reference, the lengths travelled no longer correspond to a closed curve (circumference) but to **helices**, when reasoned in Minkowski space-time.

18 See the article by G. Rizzi and A. Tartaglia, *op. cit.* for a debunking of Selleri's pseudo-paradox.

19 For a demonstration based on the relativistic velocity composition formula, see Appendix A of Pierre Spagnou's book, *De la relativité au GPS*, Ellipses (2012). For a demonstration based on direct comparison of proper times, see chapter 13 of Eric Gourgoulhon's book, *Relativité restreinte*, EDP sciences (2010).

20 Prunier's note entitled "Sur une expérience de Sagnac qui serait faite avec des flux d'électrons" was presented by Paul Langevin to the Académie des Sciences in 1935. In an additional note, Langevin confirms the difference between classical and relativistic predictions for such an experiment.

21 The Sagnac effect is non-existent when traversing a terrestrial meridian, since the speed in the direction of rotation or in the opposite direction is zero. If we travel along a figure-of-eight curve, the effect is cancelled out, since the two terms corresponding to opposite trajectories with respect to the direction of the Earth's rotation compensate each other.

22 An inertial unit is a system capable of integrating a device's movements (acceleration and angular velocity) in order to estimate its orientation, speed and position from

from a known reference point (supplied, for example, by GPS). With three accelerometers and three gyrometers arranged on three axes, the position and orientation in space of the device can be precisely determined.

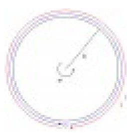
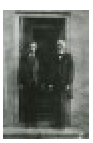
23 See Jean Eisenstadt's book (*op. cit.)* for a similar reflection on the dangers of post-Newtonian reasoning in general relativity (pages 361 - 362).

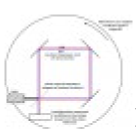
24 For a detailed analysis of this misinterpretation of the Einstein effect, see the article by Okun, Selivanov and Telegdi, "Gravitation, photons, clocks", *Physics* 42 (10) 1045 - 1050 (1999).

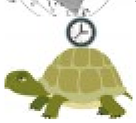
25 For a very comprehensive summary of the various interpretations of the Sagnac effect (most of them wrong), see Malykin's seminal article "The Sagnac effect: correct and incorrect explanations", *Physics* 43 (12) 1229 - 1252 (2000). Interestingly, Malykin seems to underestimate the crucial role of desynchronization of perfect clocks in the origin of the phenomenon, although he correctly regards the Sagnac effect as a purely kinematic effect of special relativity.

26 General relativity can of course be used (special relativity being a borderline case), but it doesn't add anything to the Sagnac effect, as gravitation has nothing to do with the phenomenon.

Table of illustrations





Title	Figure 1
Legend	Schematic diagram of an experiment demonstrating the Sagnac effect (two light signals leaving point O at the same instant and travelling in opposite directions at the same speed around a rotating disk).
URL	Image WikiCommons Didier Lauwaert
credits	http://journals.openedition.org/bibnum/docannexe/image/737/img-1.png
File	image/png, 7.2k
Title	Figure 2
Legend	Albert Einstein (1879-1955) and Hendrik Lorentz (1853-1928). Although the latter was on the threshold of relativity, he never took the decisive step, unlike the former.
Credits	1921 photograph taken by physicist Ehrenfest in front of his house in Leiden, WikiCommons image.
URL	http://journals.openedition.org/bibnum/docannexe/image/737/img-2.jpg
File Title	image/jpeg, 48k
	Figure 3
Legend **URL**	Sir Oliver Lodge (cartoon by Leslie Ward, published in Vanity Fair, February 4, 1904, WikiCommons). An example of length dilation in this cartoon?
File Title	http://journals.openedition.org/bibnum/docannexe/image/737/img-3.jpg
Caption	image/jpeg, 32k
Credits	Figure 4
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Caption	http://journals.openedition.org/bibnum/docannexe/image/737/img-4.png
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caption	image/png, 56k
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	The "turtle-watch", a key element in understanding the universal Sagnac effect
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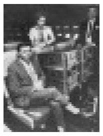

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Legend	Figure 6
URL	Physicists Joseph Hafele (b. 1933) and Richard Keating on board an airliner, with their cesium atomic clocks.
credits	Photo from *Popular Mechanics* magazine, January 1972
File Title	http://journals.openedition.org/bibnum/docannexe/image/737/img-7.jpg
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Credits	Figure 7
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File	Source Thales Aerospace
	http://journals.openedition.org/bibnum/docannexe/image/737/img-8.jpg
	image/jpeg, 24k

To cite this article

Electronic reference
Pierre Spagnou, "Sagnac et l'expérience à contresens", *Bibnum* [Online], Physics, online October 01, 2013, accessed December 22, 2023. URL : http://journals.openedition.org/bibnum/737 ; DOI : https://doi.org/10.4000/bibnum.737

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- **Einstein and the Misunderstood Article of 1911** [Full text] Appeared in *Bibnum*, Physics
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