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Earlier studies of the Sagnac effect

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Contents

Abstract. Studies of the Sagnac effect carried out during the latter part of the nineteenth and the first half of the twentieth century are reviewed. A discussion of the chronology issue shows, in particular, that O Lodge was the first to recognize the possibility of the effect. It is also shown that, apart from detecting rotation, in most studies the improvement of the Fresnel – Fizeau drag coefficient in rotating reference frames was the primary concern. As possible directions for the development of Sagnac interferometry, a wider operational range for electromagnetic waves, the interference of material de Broglie waves, and the interference of acoustic and magnetic surface waves are considered.

1. Introduction

The Sagnac effect [1 – 3], a term used to describe that in a rotating circular interferometer, interfering waves gain a phase shift which is directly proportional to the angular rotation rate and the interferometer area, and inversely proportional to the emission wavelength, has now been well studied. Besides in the optical range, this effect is found in the radiowave [4] and X-ray ranges [5]. It also occurs in the case of interference of de Broglie waves of particles (electrons [6], neutrons [7], and calcium atoms [8]) as well as in the case of surface acoustic and electromagnetic waves [9]. Circular lasers and wave guide circular interferometers based on the Sagnac effect have found wide application in navigation [10].

Earlier studies of the Sagnac effect were considered in a number of papers [5, 6, 11 – 19] but none of them presented a thorough historical review of the problem. There is also much obscurity in the chronology, since the effect concerned was, prior to G Sagnac, noted by F Harress [20], while the experimental design was suggested earlier by A Michelson [21] and, as recently became known, by O Lodge [22, 23]. Therefore one can sometimes find in literature such terms as the Sagnac – Michelson effect [12] or the Michelson – Sagnac interferometer [14].

It should be noted that the paper by S I Vavilov [11] provides a detailed description of experiments on the measurement of the Sagnac effect performed before 1928. The paper emphasizes a very important point: the Sagnac effect is a first order effect with respect to v/c, where v is the rotation rate of the circular interferometer mirrors, c is the speed of light. The idea of the experimental design arose after second order effects with respect to v/c had failed to be observed. However, Vavilov was probably not familiar with the papers by Lodge [22, 23] since he wrote (see Ref. [11]) that the statement of the problem was due to Michelson [21].

Note also, that as the Sagnac effect takes place in a rotating reference frame (noninertial), it results from the general theory of relativity. This implication can be found, for example, in Ref. [13].

This paper is intended to present in a consistent and systematic way the early experiments on the Sagnac effect performed in the first half of the 20th century when they were of purely academic interest; i.e. before the construction of circular lasers [24] and wave guide circular interferometers. We also consider some papers concerned with the statement of the problem on measurement of the effect which cover a somewhat wider historical period. The papers of each author are given in chronological order, starting with the first.

2. Papers by Oliver Lodge (1851 – 1940)

To our knowledge the possibility of detecting the Earth's rotation from the interference band shifts in a circular interferometer was first suggested by Oliver Lodge [22] (1893). It is interesting to understand how he arrived at this

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idea. In Ref. [22] Lodge carried out experiments to detect ether dragging by heavy bodies. In an immobile circular Fizeau interferometer [26]† light passed through a slit between two interconnected rotating disks of total weight 3/4 t. In order to enhance the sensitivity, each interfering beam thrice transversed the interferometer of 1 m^2 area. If the ether had been dragged by heavy bodies, this would have caused an interference band shift (in the same manner as water did in Fizeau's experiments [26]). But since no shift of the bands was observed, Lodge concluded that the ether was not dragged by the Earth's rotation either and therefore this rotation could be measured with respect to the immobile ether.

For this purpose Lodge suggested the construction of an interferometer of 1 km^2 area. Therefore, Lodge proposed a way to measure the Earth's rotation with the use of a circular interferometer of large area 11 years earlier than Michelson [21].

In his next paper [23] Lodge wrote that "if the system as a whole, i.e. a lamp, an optical system‡, a telescope§ and an observer had been set upon a rotating table and put into rotation, then a relative shift of interfering bands could have been observed at different directions of the rotation". Lodge saw the main problem in the centrifugal forces acting on the observer. As we shall see subsequently, Harress [20] and Sagnac [1 – 3] found a way to avoid placing the observer on the rotating table.

Interestingly, the paper by Lodge [22] is often cited in books on the history of science (see, for example, Refs [27 – 31]) as being one of the most important works on the special theory of relativity. It is well known that one of the originators of special theory of relativity, D Fitzgerald did not publish his results on relativistic transformations himself but communicated them to Lodge, who presented them (of course, with reference to Fitzgerald) in Ref. [32] and somewhat later, in Ref. [22]. In 1985 A G Lorentz (see Ref. [33]) pointed out that he learned about Fitzgerald's results from Ref. [22]. Despite the fame of Ref. [22], the problem of the measurement of the angular rotation rate with a circular interferometer has been thought so far to have been stated by Michelson [21]. Only very recently the authors of Refs [6, 17, 19] admit the priority of Lodge in this problem.

To explain the expected effect Lodge [22, 23], followed by Michelson [21] and Sagnac, used the theory of the immobile ether, assuming the speed of light to be different for interfering waves in a rotating circular interferometer. However, as is shown in Ref. [34], this assumption, though being fundamentally wrong in terms of relativity theory, leads to an appropriate result when the rotation rate of the platform edge is small with respect to the speed of light.

As indicated above, the Sagnac effect results from general theory of relativity [13]. Nevertheless, calculations performed on the basis of the special theory of relativity yield the same expression for the phase shift of the interfering waves in a circular interferometer [34]. This is rarely the case: at nonrelativistic velocities of motion of circular interferometer mirrors the theories of an immobile luminiferous ether and of general relativity predict similar results. As Vavilov [11] noted, "If the Sagnac phenomenon had been revealed earlier than the first results of the second order experiments were obtained, it would certainly have been considered a brilliant proof of the existence of the ether". Conceivably, a deep conviction of the existence of the luminiferous ether made Lodge sure of the positive results of the proposed experiment.

Why did Lodge not conduct an experiment to measure the interference band shifts upon rotation of a circular interferometer? A bulky rotating platform with standing several thousand rpm [22, 23] made such an experiment readily devised. However, Lodge undoubtedly meant to measure the Earth's rotation with a circular interferometer of large area, as described in his correspondence with J Larmor in 1897 [35] (some extracts from the correspondence are given in Ref. [19]). Most likely, he did not realize this project because of its high cost. Nevertheless the statement of the problem of the measurement of the rotation of a reference frame with a circular interferometer is due to Lodge.

3. Papers by Albert Michelson (1852 – 1931)

In Ref. [21] (1904) Albert Michelson suggested the construction of a large-sized circular interferometer in one of two variants 1 × 1 km — to measure the angular rate of the Earth's rotation about its axis and 10 × 10 km — to measure the angular rate of the Earth's rotation about the Sun. The latter project was not implemented, while the first was postponed for 20 years, probably because of financial problems. Originally [36] (1923), the mirrors of the circular interferometer were installed outdoors and airflows blurred the interference bands. Subsequently [37] (1925, devised in collaboration with H Gale and F Pearson) an interferometer of size 630 × 340 m was placed in a system of 305 mm steel tubes, in a vacuum (the pressure was 12 mmHg). A very peculiar approach taken to calibrate the interference band shifts. For this purpose the interferometer was provided with an additional frame of considerably less area. As a result of these experiments, Michelson and his co-authors succeeded for the first time to measure the angular rate of the Earth's rotation with the use of a circular interferometer.

It should be noted that Michelson never referred to either Lodge, or Sagnac, or Harress. The question of whether he was acquainted with the papers by Lodge [22, 23] remains open. However it is known from Lodge's letter to Larmor that Lodge and Michelson met (presumably at a conference held in Toronto on 19 – 25 August1897) where they discussed methods of measuring the Zeeman effect [38]. Michelson's co-author H Cale also wrote regarding the measurement of the Earth's angular rate [39]: "A similar experiment was suggested by O Lodge".

4. Dissertation by Francis Harress (died in 1915)

Francis Harress's dissertation [20] was concerned with the experimental determination of the Fresnel – Fizeau drag coefficient. In the classical case this coefficient is $\alpha = 1 - 1/n^2$, and with the Lorentz correction it takes the form $\alpha = 1 - 1/n^2 - (\lambda/n)(\mathrm{d}n/\mathrm{d}\lambda)$ (where n is the medium refractive index, λ is the light wavelength). Thus Harress dealt with the experimental verification of relativity theory. Notice that interest in the experimental determination of the Fresnel – Fizeau drag coefficient continues even now (see, for example, Refs [40, 41]) since for optical dispersive materials the Lorentz correction, or so called dispersion term makes up as much as 1 – 2% of the value of $1 - 1/n^2$.

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† Since this interferometer was used in Harress's [20], Sagnac's [1 – 3], and subsequent experiments, the widely-used term *Sagnac interferometer* is not correct.

‡ Interferometer.

§ A set up to observe interference band shift.

Harress performed his studies in Jena in 1909 – 1911. The equipment included a table rotating at up to 3000 rpm (actually most measurements were made at 500 – 600 rpm lest the considerable centrifugal forces should deform the interferometer). At the edge of the table were 10 adjacent prisms of total internal reflection which made up a ring of diameter 40 cm. Thus light propagated inside the prisms in a broken line approximating a circle. A very peculiar arrangement was used for the position of the light source and the observer (recorder). They were outside the rotating table and light came in from above through a set of prisms, then propagated along the rotation axis and traveled from the center of the table to its edge along the radius. There it was split into two equal components, bypassed the ring in opposite directions, and came out in a similar way. The arrangement was provided with a special camera to detect the interference band shifts and a telescope to view the experiment. In order to determine the interference band shifts, the rotation of the table was reversed, thereby doubling the effect. The experiments encountered severe difficulties; as a result of an accident the carefully adjusted arrangement was destroyed [19].

It is generally known [12, 13] that Harress made a mistake in handling the experimental data, thinking that interference band shifts were solely associated with the dragging of light by the rotating glass inside the interferometer rather than with the rotation of the interferometer as a whole. In other words he believed that if there had not been any medium inside the interferometer, the rotation would not have caused an interference band shift. In 1914 Harress's calculation error was corrected by a German astronomer Harzer [42] who derived the Fresnel – Fizeau drag coefficient as $\alpha = 1 - 1/n^2$. Thence Harzer concluded that the general theory of relativity was wrong. In the same year Einstein [43] showed that if a light source and a recorder were placed on a rotating table, then $\alpha = 1 - 1/n^2$. If they were outside the table, but the light propagated as in Harress's arrangement, i.e. along the rotation axis, then the drag coefficient was the same with an accuracy v^2/c^2.Thus a slow rotation of a circular interferometer filled with a medium can neither validate nor disprove the special theory of relativity.

It appears that Harress was not familiar with the papers by Lodge or Michelson.

Harress's dissertation was long considered lost and only very recently found by F Hasselbach and M Nicklaus [6] in the library of Tubingen University. As Harress did not publish his results, his scientific supervisor, the German astronomer and the director of the Jena observatory, O Knopf [44, 45] did it after the First World War.

5. Papers by George Mark Mary Sagnac (1869 – 1928)

George Sagnac conceived his famous experiments on the measurement of the angular rate with a circular interferometer [1 – 3] (1913) well before they were actually carried out. In 1909 he discussed the possibility of such measurements with a member of the Paris Academy of Sciences, Nobel laureate G Lippman [3] who presented most of Sagnac's papers in the journal *Comptes Rendus* (Reports of the French Academy of Sciences). Moreover, he came up with an idea for the possible measurement of the speed of light in a rotating reference frame as early as in 1905 [46]. In 1910 Sagnac published a paper [4] where he analyzed a three-mirror circular interferometer of perimeter 30m. (He reported the same results at a congress in Brussels in 1910 [48]). Since the first experiments were conducted with white light it was difficult to observe the interference bands. During the period 1910 – 1913 Sagnac published a lot of papers on the problem (for a detailed bibliography the reader is referred to review [14]).

In experiments [1 – 3] the angular rotation rate of the platform was in the range 50 to 140 rpm. The interferometer of about 0.5 m in size (square 866 cm^2) consisted of 5 mirrors, four of which were opaque and one (splitting) semitransparent.The interferometer, a quasichromatic light source, and a recorder (camera) were placed on a rotating platform. (Sagnac called this set up an interferograph). After photographing the interference bands upon rotation, the platform was brought to rest, the photoplate was displaced, and rotation was resumed in the opposite direction. After that the interference bands were photorecorded again. This enabled Sagnac to exclude a random initial shift of the bands in handling the experimental data, while the measuring accuracy was doubled. To make the interference bands sharper, Sagnac used plane polarized light produced with a Nickol prism. Note that Sagnac did not refer to either Lodge or Harress's experiments, which he was not familiar with, but twice quoted Michelson. In Ref. [47] Sagnac wrote: "To split a beam into two interfering beams I initially used a silvered semitransparent mirror following Michelson who did it for the first time". Thus Sagnac admitted Michelson's priority only in the use of a semitransparent silvered mirror as a beam splitter in a circular interferometer, but not in the statement of the problem on the detection of rotation with a circular interferometer. In Ref. [3] Sagnac referred to the well-known experiments by Michelson and Morley [49] which dealt with the detection of translational motion of the Earth with respect to an immobile ether, having no relation to the detection of the rotation of a reference frame or, as it was thought at that time, the rotation of the Earth with respect to an immobile ether. Sagnac conducted experiments with a special goal of detecting interference band shifts in a rotating interferometer, and the effect revealed was named after him with good reason. Sagnac proposed the use of this effect in navigation [3].

6. Papers by Bel Pogany (1887 – 1943)

In 1925 – 1928 Hungarian physicist Bel Pogany reconstructed and improved the set up used by Harress in Jena [50 – 52]. The rotation rate of the platform was increased to 1000 – 2000 rpm, vibrations were considerably reduced and all the interferometer components were fixed lest the centrifugal forces should displace them. The interferometer had the form of a square with 35 cm sides and consisted of 4 mirrors and a prism of total internal reflection. The prism split the incoming light beam into two equal components which transversed the interferometer in opposite directions. Light came onto the rotating table (and came out) in the same way as in Harress's experiments. Besides the verification and improvement of Harress's and Sagnac's results, Pogany had another problem to solve. He set himself a task to check if the effect depends on the refractive index of the medium inside the interferometer. For this purpose he put two massive glass bars, each of length 32 cm along the beam runs in order to enlarge the optical length of the interferometer. Pogany's experiments demonstrated with high precision that the Sagnac effect was independent of the refractive index of the medium filling a circular interferometer. This can be explained as follows: the increase in the optical length of a circular interferometer produced by increasing refractive index of the medium is exactly compensated for by the decrease in the Frensel – Fizeau drag coefficient. This problem was fully considered in a number of papers (see, for example, I L Berstain [4]). Interestingly, in the late 70s, when Pogany's papers [50, 52] were largely forgotten, and Berstain's paper [4] was little-known in optics, this problem became the subject of new discussions [53, 54] due to the development of wave guide circular interferometers [25].

7. Papers by Alexander Dufour and Fernand Prunier

Alexander Dufour's and Fernand Prunier's first papers [55, 56] were devoted to the experimental verification of the dependence of the Sagnac effect on whether or not the light source occurs on a rotation platform. As could be expected from the results of Ref. [43], at nonrelativistic rotation rates of the platform edge there is no such dependence.

In their subsequent work [57] (1942) these authors described a very interesting experiment: they rotated only the interferometer while the medium inside (glass) remained immobile. The rotation rate went up to 300 rpm. Dufour and Prunier found that in this case the interference band shift is larger that in the case when the interferometer and the medium rotate as a single whole. A theoretical explanation of this phenomenon was given by E Post [13] who showed that the interference band shift Δz is different for the following cases:

1. The interferometer and the medium rotate as a single whole (experiments by Harress [20, 44, 45] and Pogany [50 – 52]:

$$\Delta z \sim n^2(1-\alpha)\,, \quad \text{where} \quad \alpha = 1 - \frac{1}{n^2}\ [43]\,,$$

note that $n^2(1-\alpha) = 1$ only in this case and Δz is independent of n.

2. The interferometer rotates while the medium is immobile (experiments by Dufour and Prunier [57]):

$$\Delta z \sim n^2\,.$$

3. The interferometer is immobile while the medium rotates (Fizeau's experiments [26]):

$$\Delta z \sim n^2\alpha\,, \quad \text{where} \quad \alpha = 1 - \frac{1}{n^2} - \frac{\lambda}{n}\frac{\mathrm{d}n}{\mathrm{d}\lambda}\ [43]\,.$$

Thus, the experiments by Dufour and Prunier completed the study of these three cases.

8. Paper by I L Berstain (born in 1908)

The Sagnac effect was studied in the radiowave range (see Ref. [4]) in Physical and Technical Institute (Gor'kiĭ) in 1950, the study being supported by Academician A Andronov and Professor G Gorelik. The circular interferometer presented a RK-3 cable coiled round a cylinder of diameter 2 m. The angular rotation rate of the cylinder was in the range 60 to 78 rpm. The emission wavelength was 10 m. The generator and the electronic unit for processing the output signal were placed on the cylinder. This multiloop interferometer was a prototype of modern wave guide interferometers (as was noted in Ref. [5]).

The aim of the work was formulated in Ref. [4] as follows: "We see the interest of the experiment in that: 1) to our knowledge, it is the first radiophysical experiment† on the electrodynamics of moving bodies; and 2) in our experiment waves propagate in a medium strongly different from a vacuum (the cable filling has dielectric constant $\varepsilon = 2.44$). Owing to this, in our experiment, as in Fizeau's optical experiment with flowing liquid, Fresnel's drag effect (in terms of Newtonian physics) becomes of significance"‡.

To evaluate the technical difficulty of the experiment, it should be borne in mind that the Sagnac effect is inversely proportional to an emission wavelength. Thus, due to long wavelength the sensitivity of the set up was over seven orders of magnitude lower than those described above. The difference in phase between two interfering waves was only 10^{-5} rad. However by that time Berstain had developed a sensitive method for measuring small phase fluctuations [58]§ which enabled him to record such a phase with high accuracy.

To measure the phase difference of interfering waves a very peculiar method of signal processing was applied. Instead of being superposed on each other, the interfering waves were superposed on a carrying signal coming directly from a generator. Commutation was realized with a special relay of 12.5 Hz frequency. Then the signal at this frequency was amplified and entered a synchronous detector.

As a result, Berstain [4] succeeded in revealing the Sagnac effect in radiowaves and in showing that its value was independent of the dielectric constant (i.e. the refractive index) of the medium.

9. Patent by Aaron Wallace

Aaron Wallace's patent [59], which he transferred to the Maxon Electronic Corporation, was submitted for consideration on the 7th of July 1958. However it took the patent five years to be registered, finally on the 3rd of September 1963.The patent is interesting in that the scheme of a guide circular interferometer which was actually constructed 18 years later [25] was proposed for the first time. Moreover, this document was the first to present the schemes of Sagnac's rotation detectors using X-ray (realized 36 years later [5]), γ-ray (have not been realized to date), and electrons (realized 35 years later [6]). However, the engineering solutions were so naive (at least in the current view) that it is doubtful whether the Maxon Electronic Corporation could gain any commercial benefit from the patent.

By the time Wallace's patent was published, circular lasers had already appeared [24] and interest in circular interferometers had been lost. This is probably the reason why in literature there are practically no references to the patent, the only exception, as far as we know, being H Arditty's bibliography [60].

10. Conclusions

The main conclusions of the paper are as follows:

1. The statement of the problem of the detection of the rotation of a reference frame with a circular interferometer is due to Lodge (1893).

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† Here we deal with the radiowave region.

‡ It should be mentioned that Berstain was not familiar with the Pogany papers.

§ He was awarded the Mandelstam prize by the Presidium of the USSR Academy of Sciences in 1949.

2. The first experiments with the specific goal of understanding this phenomenon were designed by Sagnac (1913) and the effect revealed was justly named after him.

3. Harress meant to study the Fresnel–Fizeau drag coefficient in rotating glass (1909–1911) and it was not until 1914 that it became clear from Harzer's and Einstein's works that in Harress's experiment the rotation of a reference frame was detected. Nevertheless, Harress was the first to demonstrate experimentally that the rotation of a reference frame influences the interference band shifts in a circular interferometer. He also showed that the dispersion term is absent in the Fresnel Fizeau drag coefficient when the interferometer, the optical medium and the light source rotate as a single whole.

4. Michelson (1925) was the first to detect the Earth's rotation with the use of the Sagnac effect.

5. Pogany (1928) for the first time provided experimental evidence for the independence of the Sagnac effect on the refractive index of a medium filling a circular interferometer.

6. The fact that the Sagnac effect is practically independent of the position of the light source was first experimentally shown by Dufour and Prunier (1937).

7. The first measurements of the Sagnac effect in radiowaves were made by Berstain (1950). He also pioneered the use of the electronic unit for processing the output signal.

8. A scheme of a wave guide circular interferometer was first suggested by Wallace.

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