Pogany 1927

O. Knopf reported here a few years ago (Naturwissenschaften 8, 815, 1920) on F. HARRESS's experiments concerning the speed of light in moving bodies. The experiment from 1911 by HARRESS is closely related to that of SAGNAC (1914). The difference between the two experiments is that in HARRESS's experiment, light propagates in glass, while in SAGNAC's, it propagates in air. Both setups share the rotating interferometer, which in HARRESS's experiment consists of a prism polygon, and in SAGNAC's, of a mirror polygon. The theory behind both experiments was presented based on a note by EINSTEIN, by V. LAV~ in connection with the well-known FIZEAU and ZEEMAN experiments.

The theoretical result is extremely simple. On the periphery of a closed polygon, which is at rest in a coordinate system connected to the Earth, two coherent beams of light travel in any medium, one in one direction, the other in the opposite direction. After both beams have traveled this closed light path once, they are brought to interference. The resulting position of the interference fringes with respect to a crosshair is called the zero position. If the polygon rotates around an axis enclosed by the light path, with an angular velocity ω, and we denote the area of the projection of the polygon onto the plane perpendicular to the axis of rotation with A, then during rotation, the interference fringes shift relative to the zero position by an amount measured in fringe widths:

$$\Delta = 4\omega F/\lambda c$$

where λ_0 is the wavelength of light in vacuum, and c is the speed of light.

Regarding the connection with the FIZEAU and ZEEMAN experiments, it should be noted briefly as follows: if we denote the propagation speed of light in a medium with a refractive index n, which is at rest in a coordinate system K with V, and now the medium moves with respect to K with the velocity v, then generally the propagation speed of light in the moving medium relative to K is:

$$V + q \times \alpha$$

where a represents the FRESNEL drag coefficient. This coefficient differs depending on how the light enters the moving medium. In the FIZEAU experiment with the flowing liquid, where light enters through a stationary surface perpendicular to the direction of motion of the medium:

$$\alpha = I - I/n^2 - \lambda/n^2 \times dn/d\lambda$$

where λ represents the wavelength of light. In the ZEEMAN experiment with the straight, uniformly moving prism, light enters the body through a surface moving with it, perpendicular to the direction of motion:

$$\alpha = I - I/n^2 - \lambda/n^2 \times dn/d\lambda$$

and finally, in the HARRESS-SAGNAC experiment, where light enters through a surface moving with it, parallel to the direction of motion:

$$\alpha = I - I/n^2$$

Since in the latter experiment, the medium does not move in a straight line but rotates, there is no significant difference because the accelerations considered, as W. WIEN showed through a simple reasoning based on the principle of equivalence, must have no influence on the speed of light in the moving body. What is remarkable about formula (1) is that the refractive index does not appear in it, so the fringe shift must be the same under otherwise identical conditions in both the HARRESS setup, where light travels in glass, and in the SAGNAC setup, where it travels in air.

In the measurement experiments, HARRESS was able to achieve an angular velocity of about 75 ° rotations per minute with his apparatus; this resulted in approximately A = 0.2, so the fringes shifted by about 2A = 0.4 when rotating to the left compared to their position when rotating to the right. At higher rotation speeds, the interferences became blurry and eventually disappeared completely. The individual measurements of A showed deviations from 10 to 18% among each other. HARRESS used arc light filtered through colored glasses. He could not use strictly monochromatic light—such as that of the quartz-Hg arc lamp—because the interference phenomenon would then become too weak. To explain this and to highlight the perspectives considered during the redesign of the HARRESS apparatus later, I must briefly describe the original HARRESS apparatus. The horizontal layout of the apparatus can be seen in Fig. 1.

The horizontal layout of the apparatus is shown in Fig. i. Light traveled through prisms P_1 - P_10. The introduction of light and the separation into two coherent beams occurred in the middle prism body, which, viewed in the direction of arrows a and b, can be seen in Figs. 2a and 2b.

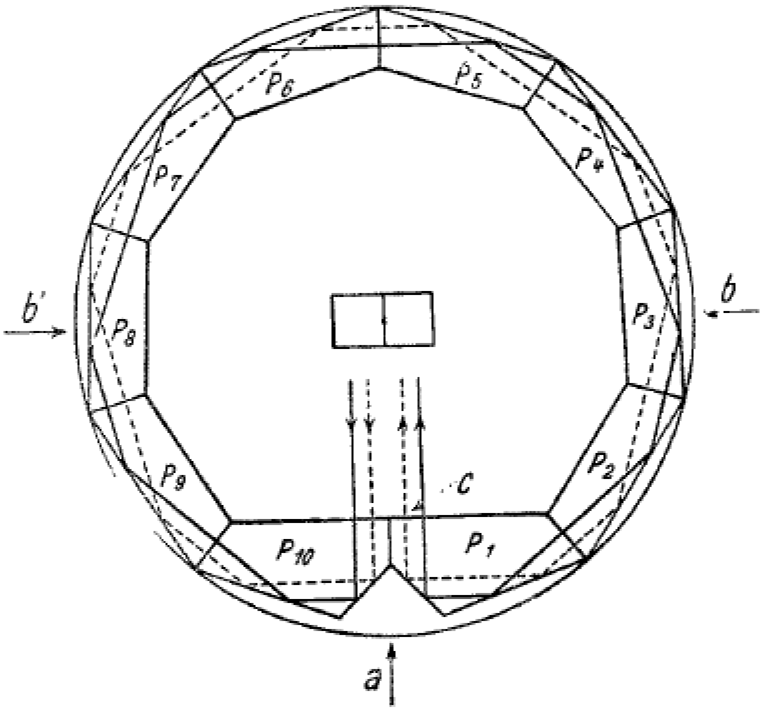

Fig. 1. Grundriß des ursprünglichen Harressschen Apparates.

The adjustment of the interferences or the regulation of their width and orientation was done through the alignment prism P_1 (Fig. 2a), which was rotatable around a point with the help of three screws. The light entered the apparatus horizontally in two azimuths during one revolution, in the direction of arrows b and b" (Fig. i). After both coherent beams completed the path in the prism ring, they were reunited at the semi-transparent silver layer J (Fig. 2a), then directed towards the axis of rotation of the apparatus, to enter the photographic camera. The aperture of the apparatus was about 1/4 degree. So, during one revolution of duration T seconds, light fell on the photographic camera through the apparatus for only 1/7T seconds. This led to the dimming of the interferences.

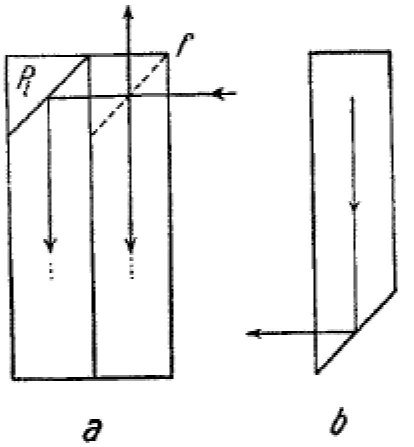

Fig. 2. Aufriß des mittleren Prismenkörpers im Harressschen Apparat.

SAGNAC worked with a maximum speed of x20 rotations per minute, with about 2A = 0.07. Evaluating the measurement accuracy of SAGNAC is difficult because only the results of four measurements are reported. In any case, the apparatus rotated slowly enough that the effect itself was small. He used the white light of a small incandescent lamp. Determination of the wavelength entering formula (i) was done by comparing the fringe widths obtained with the stationary apparatus using the incandescent lamp and with a mercury line.

Regarding the stability of his apparatus, SAGNAC expressed in the section "Precautions à prendre" as follows: "This orientation (of the moving interference fringes) differs from the orientation relative to rest and it was found useful to slightly adjust it in advance so that the fringes are slightly inclined in the appropriate direction when the plate is at rest. The fringes straighten up when the plate rotates and become vertical for a suitable frequency."

In the SAGNAC arrangement, both the light source, a small incandescent bulb, and the camera participated in the rotation. Since both the accuracy of HARRESS's and SAGNAC's measurements left something to be desired, and there was hope that it could be improved, the repetition of the experiment was suggested by M. von LAVE and M. WIEN. The means for this were provided partly by the emergency association, but essentially by the Zeiss company. The apparatus was built at the Zeiss works in Jena, and the experiment was carried out there.

In repeating HARRESS's experiment, I aimed to increase the rotational speed while keeping the interferometer surface unchanged so that 2A would be nearly 1. For this, about 1600 rotations per minute were required for the HARRESS apparatus. However, according to HARRESS's observations, the interferences disappeared above 750 rotations per minute. Two reasons could initially be responsible for this: firstly, the vibrations of the apparatus at higher rotation speeds, in which the photographic camera did not participate, and secondly, displacements of the prisms reflecting the light caused by centrifugal force. To eliminate these factors, it was proposed to build the apparatus with a "flying cell" and to fill it with a liquid whose density is identical to that of the prisms, thereby neutralizing the centrifugal forces. The critical rotation speed of the flying cell must, of course, be well below the speed of 1600 rotations per minute to be achieved. At the same time, I wanted to use monochromatic light. Since a quartz-mercury arc lamp cannot be easily installed in the apparatus, I chose the arrangement such that the light source remained stationary and the light entered the apparatus continuously along the axis of rotation, while the photographic camera, like in SAGNAC's setup, participated in the rotation.

The interferometer optics initially were identical to those of the HARRESS apparatus. The photographic camera was mounted on top (Fig. 3). The parallel light entered parallel to the axis of rotation along the dashed line into the apparatus. The interferences occurred in the focal plane F of the Tessar T. There, a glass plate with engraved measuring marks was attached. The interferences, along with the measuring marks, were then imaged onto the photographic plate L through the Microplanar M (focal length 2 cm). Due to the liquid filling, total reflection at the outer surfaces of prisms P_1 - P_10 (fig 1) was eliminated, and therefore, these surfaces had to be silvered. The liquid used for filling should not affect this silvering or the inner wall of the apparatus made of Siemens-Martin steel, as well as the aluminum parts inside, it had to be transparent and have a density of 3.2. From a chemical standpoint, I was recommended an aqueous solution of cadmium boron tungstate. However, it turned out to be unusable because it swelled out of the filling hole immediately after insertion. Apparently, gases developed in the apparatus that pushed the liquid back out. Therefore, the liquid had to be removed. The prisms were then pressed against the outer wall through rubber stoppers with strong screws, and the apparatus was put into operation. The apparatus weighed about 80 kg and was placed on a 16 mm thick vertical axis, which protruded about 5 cm above the top guide. The turbine was attached to the lower end of the shaft. The whole apparatus was installed in a concrete block of about 4 tons and was housed in the basement of the "Wolkenkratzer" of the Zeiss works. The water tank was located on the top floor. The water pressure in the basement was about 41/8 atmospheres. To measure the rotational speed, every hundredth rotation of the apparatus was recorded on a chronograph strip, and the second signals of the clock of the Zeiss Observatory were registered. The critical rotation speed of the apparatus was about 600 per minute. With 1600 rotations per minute, the apparatus rotated flawlessly, but when passing through the critical speed, it experienced vibrations, causing the optics to fail. To avoid this, I attempted to install steel mirrors instead of the glass prisms. The Krupp special steel suitable for mirrors could not be obtained at that time. Therefore, attempts were made to manufacture the mirrors from Siemens-Martin steel. Unfortunately, it was not possible to produce truly flat mirrors with a minimum focal length of 1500 mm in size 4 × 12 cm. The mirrors had significantly different and smaller focal lengths in different azimuths, and the interferences were blurry and fuzzy at large angles of incidence. Therefore, I had to revert to using the glass prisms and provide the apparatus with a rigid axis of rotation at the bottom and top. The upper axis was pierced for the introduction of light. At the same time, the photographic camera received a flatter form by wrapping its light path around the upper axis with the help of prisms. Another improvement concerned the adjustment arrangement of the interferometer. So far, the interference adjustment had been done through prism P~. The fixation of the position of this prism using three screws seemed unreliable. Therefore, prism P~ was permanently assembled with the middle prism body, and a different arrangement was introduced into the light path to adjust the interferences. This arrangement consisted of two circular glass wedges with a diameter of 4 cm and a wedge angle of 3°. The arrangement was inserted into the light path at U (see Fig. 1) and mounted so that each wedge could be rotated around the light beam's axis and fixed in any position. Thus, the wedge angle could be continuously adjusted from 0 to 6°, and the thickest part of the wedge could be brought into any azimuth around the beam, allowing for the width and orientation of the interferences to be changed as desired. Since the beam direction at point 6* is parallel to the centrifugal force, the rotational movement, through which the fringe width and direction are adjusted, occurs in a plane perpendicular to the centrifugal force. A hole of about 1 cm in diameter was drilled in the wall of the photographic camera; through this hole, the light that would otherwise fall on the plate could be led out of the apparatus using a prism placed between the Tessar and its focal plane. If the interferences were oriented parallel to the plane of rotation, they could be observed through this hole with a telescope adjusted to the focal plane of the Tessar even during rotation. When the interferences were visually observed through this hole, the disappearance of the interferences could be observed at 650 to 700 rotations per minute. In such visual observation, the interferences naturally disappear when they are rotated out of their horizontal position due to the displacement of a reflecting prism surface. Images of the blurred interferences obtained with the camera rotating with the apparatus showed that this initial disappearance of the interferences indeed resulted from the rotation of the fringes out of their horizontal position, accompanied by an increase in their width. At even higher speeds, at 800 to 850 rotations per minute, the interferences also became blurry on the rotating plates and eventually disappeared completely. However, it was noteworthy that their orientation and width remained almost unchanged during this blurring. It was therefore concluded that this disappearance of the interferences did not result from a displacement of a reflecting prism surface. Because if the position of such a surface is changed, or what amounts to the same thing, if the adjustment wedge at C is rotated and the interferences are made to disappear thereby, the

brought. The circular glass mirrors are 14 mm thick and have a diameter of 5 cm. On their backside in the middle, a pin was ground out. The front side was flat, while the backside, apart from the pin, was a spherical surface with a radius of 26 cm. The inner surface of the solid ring BB, made of Siemens-Martin steel, with a cross-section of 5 × 6 cm, was also such a spherical surface with a radius of 26 cm. At corresponding four points, four holes were made in the ring RR for the mirror pins. By sinking the pins into these holes, the spherical back surfaces of the mirrors fit perfectly against the spherical inner surface of the ring BB. The mirrors were then adjusted, cemented to the ring, and finally received a surface silvering. Since part of the interferometer, namely the four mirrors, was attached to the ring BB, and the other part, namely the semi-transparent silver layer or the prism P, was attached to the base and cover plate of the apparatus, extreme care had to be taken for a very rigid connection of the ring with the plates. The stiffening was achieved by 18 pairs of ground and screw-tightenable cones. In addition to the cones, there were also 18 pairs of strong screws. The stiffening achieved in this way was so complete that if the apparatus was disassembled and reassembled after adjustment, the interferences appeared immediately without any further adjustment. The corresponding attachment of the mounting of the prism P caused quite a bit of trouble. At 1500 rotations per minute, it had to withstand a centrifugal force of about 500 kg. After various attempts, I succeeded with very strong, ground cones. The fully assembled arrangement can be seen in Fig. 5. B is the HARRESS quartz mercury lamp, whose light was focused on the diaphragm D by the lens 151. The diameter of the latter was 0.5 cm. Behind D, a light filter made of approximately 1 cm thick Didym glass and thin green glass was installed, which only allowed the green mercury line from the Hg spectrum to pass through. The light made parallel by the Tessar T 0 was thrown forward vertically to the axis of rotation by the penta-prism Pe t. At the intersection of the axis of this bundle with the axis of rotation, the penta-prism Pe~ was attached, Fig. 6. Interferences at 1200 rotations per minute, which throws the light vertically downwards into the apparatus. On the tachometer, a cable leads to the chronograph. T 1 is one, T 2 the other, turbine rotating in opposite directions, which were both mounted on the axis. Simple switching allowed the direction of rotation to be changed. V is the pipe of the water supply. With this apparatus, measuring recordings were made during the summer of 1925. Such recordings are shown in their original size in Figs. 6 to 8. The exposure time was 6 minutes. Recording 108 and 109 were made with the right and left turbines at about 1200 rotations per minute. Recording 86 refers to 1500, and the one in Fig. 8 to 2000 rotations per minute. In recordings 108 and 109, the vertical parts denote the direction of displacement of the interferences. The short horizontal arrows on the left indicate the same interference strip on both recordings. One series of measurements - with a stripe width of about 1.3 mm - was measured directly with the comparator, the other - with a stripe width of about 3 mm - the registered darkening curves according to G. HANSEN's method. The first series of measurements resulted in a rotation time T = 0.03989 sec. for 2d, the mean was 2 d~ = 0.917, with the largest deviation of the individual value from the mean being about 2%; the second series of measurements yielded at the same rotation time 2 A~ = 0.924, with the largest deviation of the individual value from the mean being a little over 3%. From the angular velocity, interferometer area, and wavelength of the fine Hg line, one calculates based on (i) 2 d = 0.906. The observed mean values are about 1.2% and almost 2% larger. According to a written remark from Mr. v. LAUE, with which I fully agree, the deviation between the calculated and observed (mean) stripe displacement appears somewhat large for the good agreement between the individual observations. The investigation is not yet completed. In addition to the fine Hg line, recordings with other wavelengths are planned. Furthermore, it was intended to install a liquid chamber between the mirrors S~ and S~ or S~ and S 4, respectively, whereby the magnitude of the displacement must not be affected. However, the attempts with the liquid chambers did not lead to any results. Liquids of different viscosities from benzene to glycerine were tested; however, due to the streaks, the interferences lost their sharpness and straightness, and depending on the viscosity, the sharpness, straightness, width, and orientation of the interference fringes changed slower or faster over time, so that measuring was out of the question. Glass prisms about 24 cm long will now be installed instead of the liquid chambers. In contrast to the HARRESS arrangement, these prisms will only be used for the passage of light, and no reflection of the interfering bundle will occur on any prism surface. Therefore, if there should be a slight deflection despite the measures taken, it will not be able to affect astigmatic reflection. I hope to be able to report on the results soon.

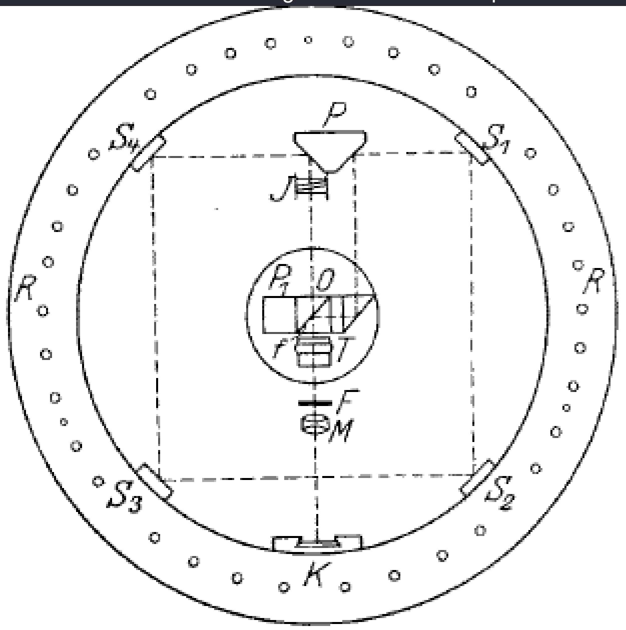

Fig. 4. Schematischer Grundriß des neuen HARRESS-schen Apparates.

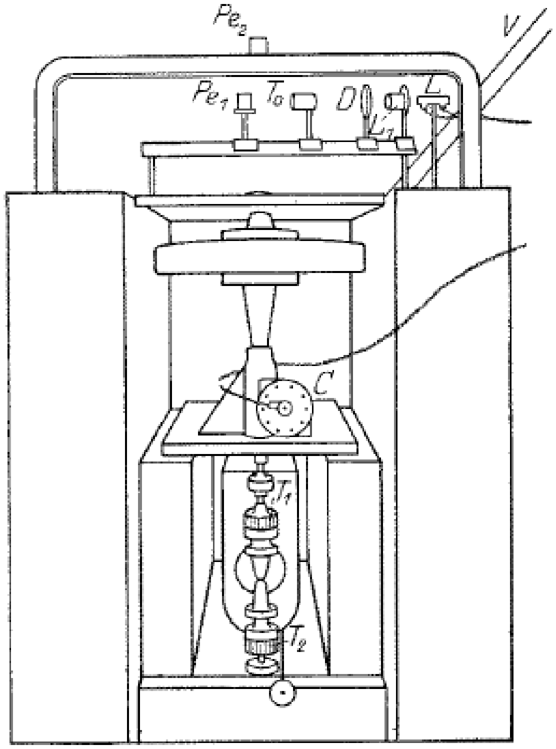

Fig. 5. Der zusammengebaute Apparat mit Turbinen und Lichtzuführung.

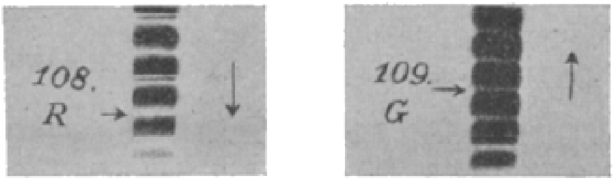

Fig. 6. Interferenzen bei 1200 Drehungen pro Minute.

das das Licht längs der Drehachse senkrecht nach unten in den Apparat wirft. C ist der Tourenzähler, von ihm führt ein Kabel zum Chronographen. T_1 ist die eine, T_2 die andere, in entgegengesetzte Richtung drehende Turbine, welche

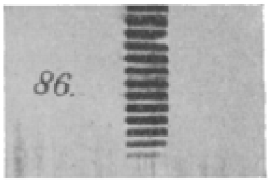

Fig. 7. Interferenzen bei 1500 Drehungen pro Minute.

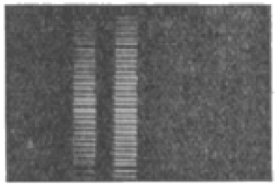

Fig. 8. Interferenzen bei 2000 Drehungen pro Minute. Positivbild.