

Pogany 1926

F. Harress, in his dissertation published in 1911, presented the results of his investigations concerning the propagation of light in a rotating glass body. An analogous experiment was conducted two years later by Sagnac with the difference that the light propagated not in glass, but in air. The theory of the experiment published by Harress was corrected by P. Harzer and A. Einstein, and the theory of both experiments was summarized in connection with the Fizeau and Zeeman experiments by Id. von Laue. Based on the corrected theory, Harress's results were reworked by O. Knopf.

The theoretical result is quite simple. On the periphery of a closed polygon at rest in a coordinate system connected with the Earth, two coherent light beams travel, one in one direction and the other in the opposite direction, through any medium. After both beams have traversed 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.

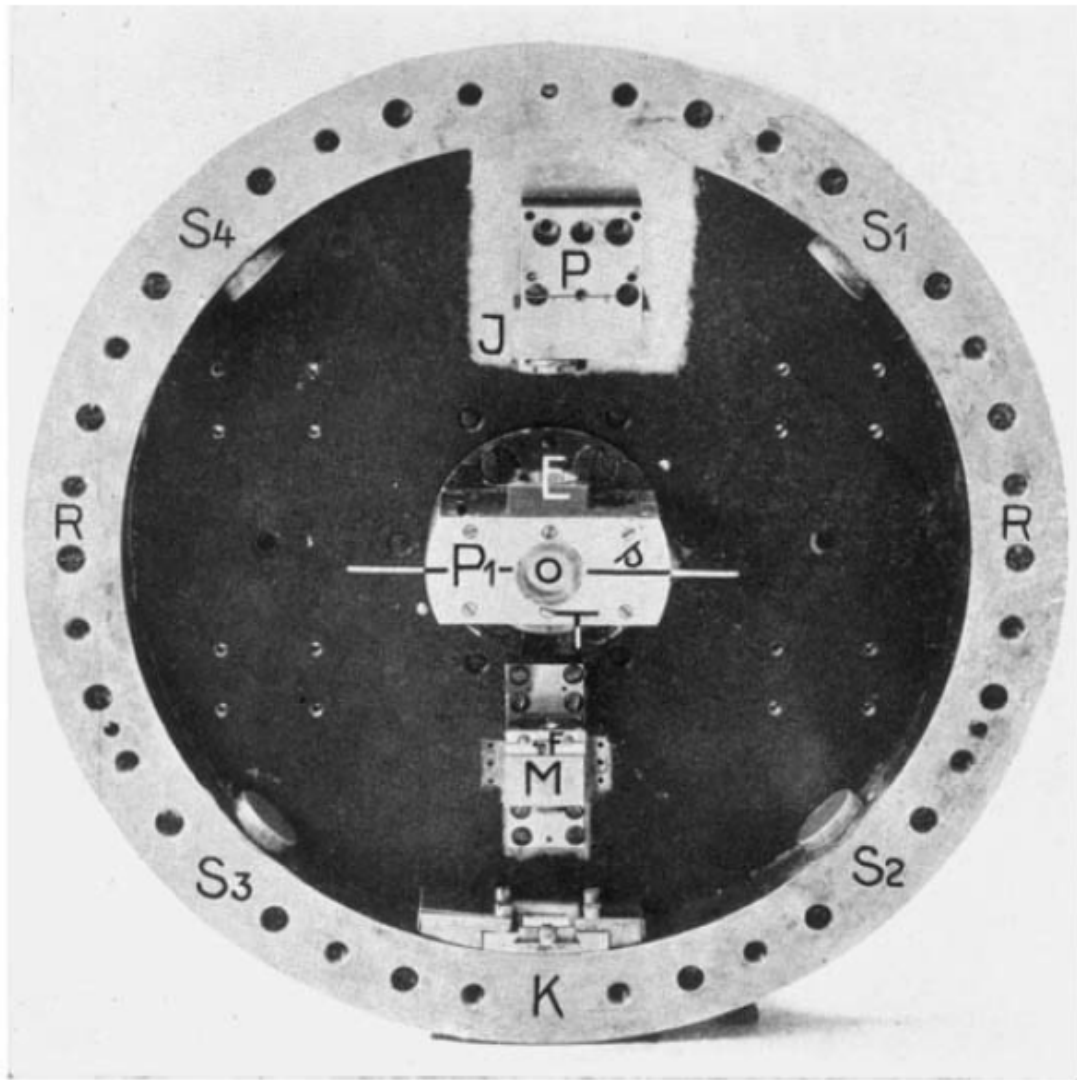


Fig. 4

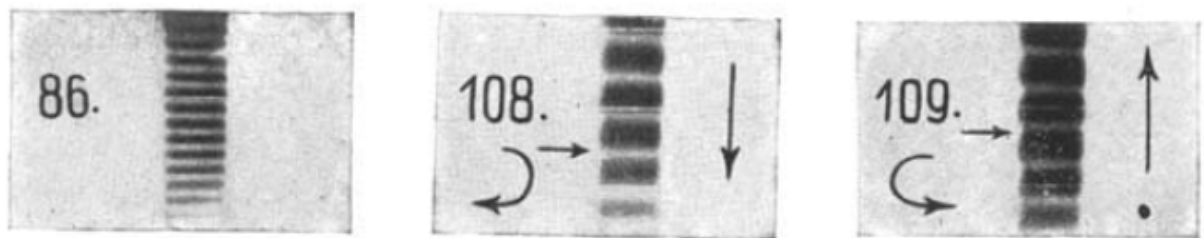


Fig. 6

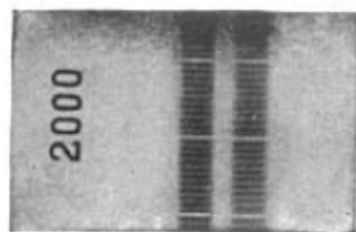


Fig. 7

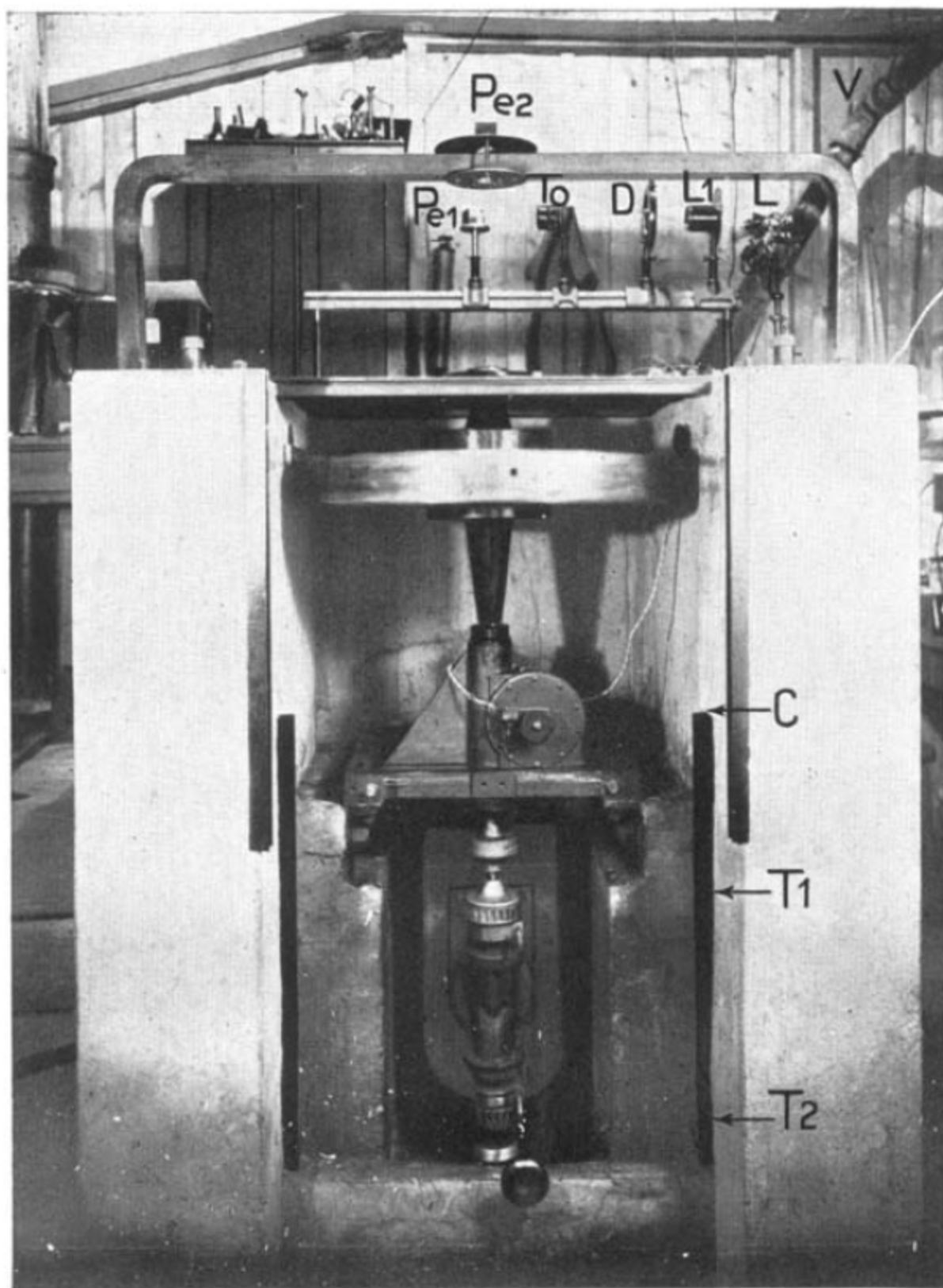


Fig. 5

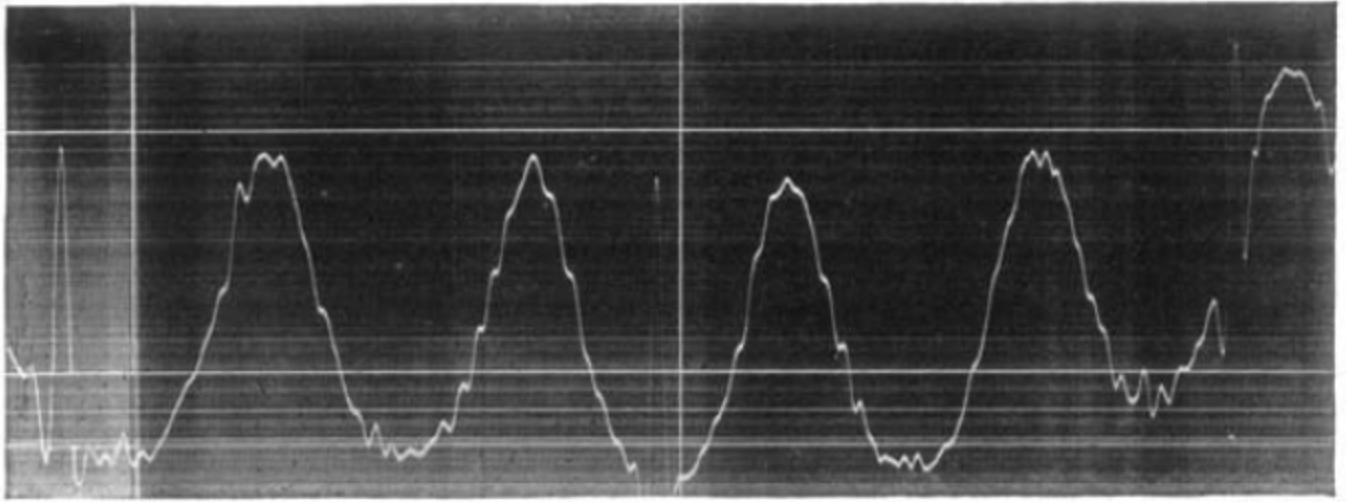


Fig. 8

B. Pogány

If the polygon now rotates around an axis enclosed by the light path with the angular velocity ω , and we denote the area of the projection of the polygon onto the plane perpendicular to the axis of rotation by P , then during the rotation, the interference fringes shift relative to the zero position by an amount measured in fringe widths.

(1)

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

where λ is the wavelength of light measured in a vacuum, and c is the speed of light. Regarding formula (1), it should be noted that:

1. The influence of accelerations was neglected in its derivation. W. Wien has shown through simple reasoning that, based on the general theory of relativity, this is justified.
2. As can be seen, the fringe shift is independent of the substance through which the light propagates.

In his measuring experiments, Harress was able to achieve an angular velocity of about 750 revolutions per minute with his apparatus; this resulted in approximately $\Delta = 0.2$, meaning the fringes shifted by about $2\Delta = 0.4$ when rotating to the left compared to their position when rotating to the right. Sagnac worked with a maximum speed of 120 revolutions per minute, where Δ was about 0.07. Judging Sagnac's measurement accuracy is difficult because only the results of four measurements are reported. In any case, the apparatus rotated so slowly that the effect itself was small. He used the white light from a small incandescent lamp. The determination of the wavelength entering formula (1) was done by comparing the fringe widths obtained with the stationary apparatus using the incandescent lamp and a mercury line. Sagnac comments on the stability of his apparatus in the section "Précautions à prendre" as follows: "This orientation (of the moving interference fringes) is relative to the orientation at rest, and it was found useful to slightly misalign in advance, so that the fringes are slightly inclined in the suitable direction when the platform is at rest. The fringes straighten when the platform rotates and become vertical at an appropriate frequency."

The individual measurements of Harress regarding Δ show discrepancies among themselves ranging from 10 to 18%. Consequently, M. von Laue and M. Wien suggested a repetition of the experiment. The funds for this were provided partly by the Emergency Association, but mainly by the Zeiss company. The apparatus was built at the Zeiss works in Jena, and the experiment was carried out there.

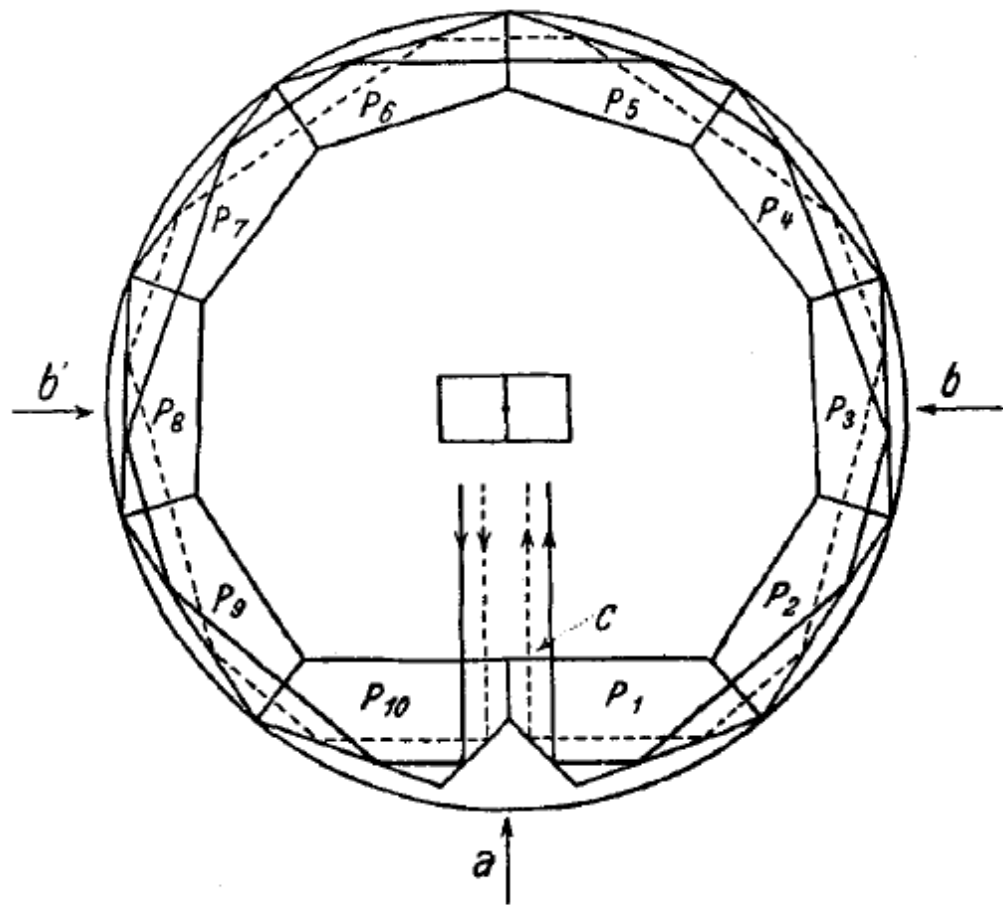


Fig. 1

To clearly highlight the considerations taken into account during the reconstruction of the Harress apparatus, I will briefly discuss the original apparatus of Harress. The horizontal layout of the apparatus is shown in Fig. 1. The light traveled through the prisms P1-P10. The entry of the light and its separation into two coherent beams occurred in the central prism body, which, viewed in the direction of arrows a and b, can be seen in Figs. 2a and 2b. The adjustment of the interferences, or the regulation of their width and orientation, was done using the adjustment prism, which could be rotated around a point with the help of three screws.

The light entered the apparatus horizontally in two azimuths, in the direction of arrows b and b', during one rotation. After the two coherent beams had traversed the path in the prism ring once, they were reunited at the semi-transparent silver layer in the apparatus and then exited in the direction of the rotation axis to reach the photographic camera. The aperture of the apparatus was about $1/4$ degree. During a rotation lasting Tsek., light fell through the apparatus onto the photographic camera only during a brief interval of approximately $1/720$ second.

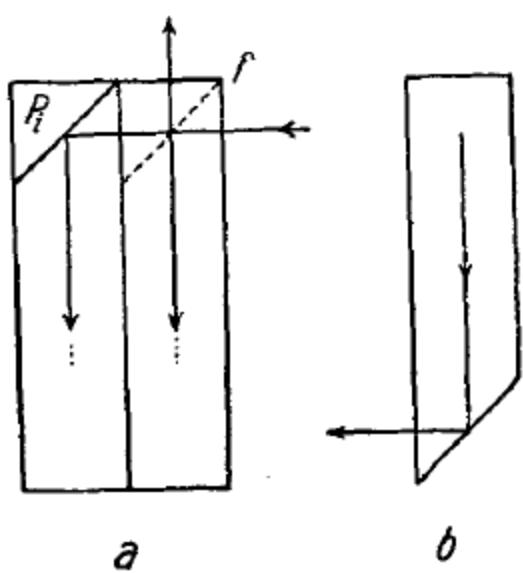


Fig. 2

The interference phenomenon was so faint that only arc light, filtered through colored glass, could be used. As already mentioned, Harress achieved a rotational speed of 750 revolutions per minute. At higher speeds, the interferences became blurred.

In Sagnac's arrangement, both the light source, a small light bulb, and the camera participated in the rotation.

When repeating Harress's experiment, I aimed to increase the rotational speed while keeping the interferometer setup unchanged so that 2Δ would be nearly 1. For this, the Harress apparatus needs to achieve about 1600 revolutions per minute. However, according to Harress's observation, the interferences disappeared above 750 revolutions per minute. Two reasons could be responsible for this: first, the vibrations of the apparatus at higher speeds, in which the photographic camera did not participate, and second, the displacements of the light-reflecting prisms caused by centrifugal force. To eliminate these reasons, it was proposed to build the apparatus with a "flying wave" and to fill the interior with a liquid whose density is identical to that of the prisms, thereby counteracting the centrifugal forces. The critical speed of the flying wave must, of course, be well below the target speed of 1600 revolutions per minute.

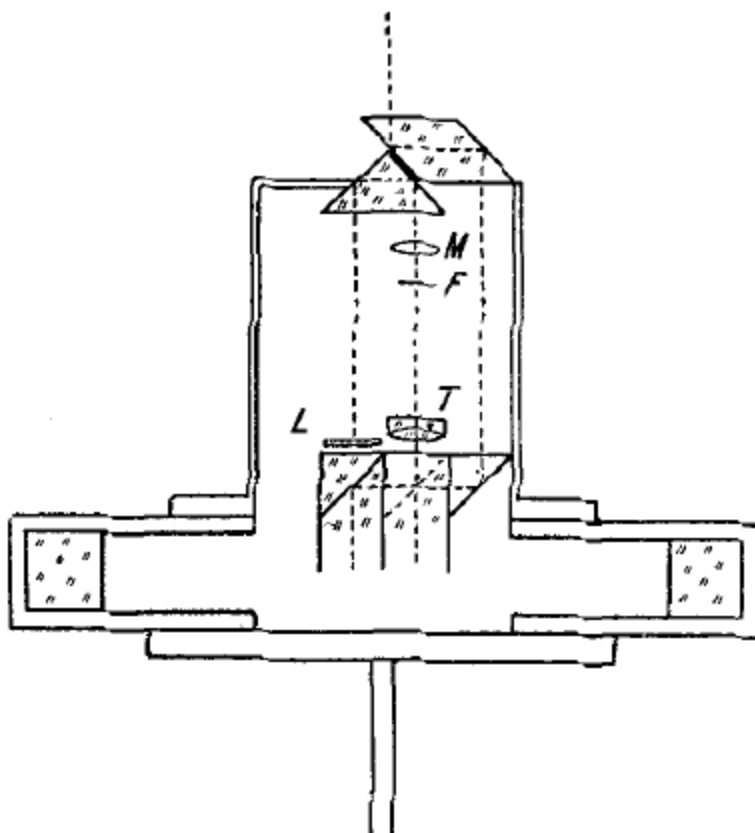


Fig. 3

At the same time, I wanted to use monochromatic light. Since a quartz-Hg arc lamp could be easily incorporated into the apparatus, I chose an arrangement where the light source remained stationary and the light continuously entered the apparatus along the axis of rotation. The photographic camera, similar to Sagnac's setup, participated in the rotation. Initially, the interferometer optics were identical to those of the Harress apparatus. The photographic camera was mounted on top (Fig. 3). The parallel light entered the apparatus along the projected line. The interferences were created in the focal plane F of the Tessar lens T. A glass plate with inscribed measurement marks was placed there. The interferences, along with the measurement marks, were then imaged onto the photographic plate L using the Mikroplanar lens (focal length 2 cm). Due to the liquid filling, total internal reflection at the outer surfaces of prisms P1-P10 (Fig. 1) was eliminated, necessitating silvering of these surfaces. The liquid used for filling had to neither damage this silvering nor the inner walls of the Siemens-Martin steel apparatus nor the internal aluminum parts. It had to be transparent and have a density of 3.2. Chemically, an aqueous solution of cadmium-boro-tungstate was recommended to me. However, it proved unsuitable as it immediately oozed out through the filling hole after being filled. Apparently, gases developed inside the apparatus, pushing the liquid out. Therefore, the liquid had to be removed. The prisms were then pressed against the outer wall using rubber stoppers and strong screws, and the apparatus was used in this manner. The apparatus weighed about 80 kg and was mounted on a 16 mm thick vertical axis, which extended approximately 50 cm above the top guide. The turbine was attached to the lower end of the shaft. The entire apparatus was embedded in a concrete block weighing about 4 tons and housed in the basement of the "skyscraper" of the Zeiss works. The water tank was located on the top floor. The water pressure in the basement was about 4.5 atmospheres. To measure the rotational speed, every hundredth rotation of the apparatus and the second signals from the Zeiss observatory's sidereal clock were recorded on a chronograph strip. The critical speed of the apparatus was about 600 revolutions per minute. The apparatus rotated flawlessly at 1600 revolutions per minute, but while passing through the critical speed, it experienced such strong vibrations that the optics were damaged. To prevent this, I tried to replace the glass prisms with steel mirrors. At that time, the Krupsche special steel, particularly suitable for mirrors, was not available. So, attempts were made to make the mirrors from Siemens-Martin steel. Unfortunately, it was not possible to produce perfectly flat mirrors of at least 1600 mm focal length in the 4 x 12 cm format. The mirrors had varying and significantly smaller focal lengths in different azimuths, making the interferences blurred and indistinct at larger angles of incidence. Therefore, I had to revert to using glass prisms and equip the apparatus with a rigid axis of rotation at the top and bottom. The upper axis was drilled to allow light entry. At the same time, the photographic camera was given a flatter form by wrapping the light path around the upper axis using prisms. Another improvement concerned the adjustment mechanism of the interferometer. Previously, the interference adjustment was done using the prism P1. Securing the position of this prism with three screws seemed unreliable. Therefore, the prism P1 was permanently assembled with the central 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 30°. The arrangement was inserted into the light path at point C (see Fig. 1) and mounted so that each wedge could rotate around the light beam as its axis and be fixed in any position. The wedge angle could be continuously varied from 0 to 60°, and the thickest part of the wedge could be brought to any azimuth around the beam. This allowed for adjusting the width and orientation of the interferences as desired. Since the beam direction at point C is parallel to the centrifugal force, the rotational movement for adjusting the fringe width and orientation occurs in a plane perpendicular to the centrifugal force. Thus, the centrifugal force does not exert any torque in this direction. A hole about 1 cm in diameter was drilled in the wall of the photographic camera; through this hole, the light that otherwise fell on the plate could be directed out of the apparatus using a prism placed between the Tessar lens 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 lens during the rotation.

When the interferences were visually observed through this hole, it was possible to observe the disappearance of the interferences at 650-700 rotations per minute. During such visual observation, the interferences naturally also disappeared when they were rotated out of their horizontal position due to the displacement of a reflecting prism surface.

Photographs taken with the rotating camera showed that this initial disappearance of the interferences was actually due to the stripes being rotated out of their horizontal position, while their width also increased. At even higher speeds, between 800 and 850 rotations per minute, the interferences became blurry on the rotating plates and eventually disappeared completely. It was notable, however, that their orientation and width remained almost unchanged during this blurring process.

This indicated that the final disappearance of the interferences was not due to the displacement of a reflecting prism surface. Because if the position of such a surface is changed, or equivalently, if the adjustment wedge at C is rotated to make the interferences disappear, the stripe width necessarily changes, either becoming zero or so large that no stripes are visible in the field of view.

The images of the blurry interferences looked exactly like the photographs I obtained with the stationary apparatus using the astigmatically reflecting steel mirrors. This suggested that the final disappearance of the interferences was due to the prisms being bent by the centrifugal force, despite the most careful preparation of the contact surfaces, and thus reflecting astigmatically.

It should be noted that a prism weighing around 0.6 kg was subjected to a load of about 200 kg by the centrifugal force. To prevent this bending of the prisms, the space between the prisms and their contact surfaces was filled with a cement that could withstand a high load. The prism surfaces were coated with a very thin layer of lead-glass-glycerin cement and then pressed against the outer wall. This cement fulfilled the expectations placed on it. After the prisms were fixed in the manner described above with the cement, I obtained perfectly sharp interferences even at 2000 rotations per minute.

However, final measurements were not yet made with this apparatus either, because the stripe width during movement differed from that at rest by several percent of the stripe width. Therefore, based on all previous experiences, it was decided to construct a third apparatus. When viewed from above with the cover plate removed, the apparatus is shown in Fig. 4. The number of reflecting surfaces was reduced to a minimum. Only four mirrors were used, and their mounting was carried out with the greatest care.

The light entered along the axis of rotation, coming from above, through the opening O into the middle prism body P of the apparatus. On a semi-transparent silver layer, it was split into two coherent beams, which, emerging from P, fell onto the prism P. From there, one beam was reflected to the right onto the mirror S₁, the other to the left onto the mirror S₂. The area enclosed by the light in the interferometer was, apart from the parallelogram between P and P to be subtracted, a square with a side length of about 353 mm, with the mirrors reflecting at 45° placed at the corners. After the two coherent beams had traveled around the square once, they were recombined on the semi-transparent silver layer in P and brought to interference. The interferences were formed in the focal plane F of the Tessar lens T.

At that location, a thin glass plate with engraved measurement marks was placed. The interferences, along with these measurement marks, were imaged onto the photographic plate of the camera K through the Microplanar lens M (focal length 8 mm). The two adjustment wedges were placed at J. The circular glass mirrors were 14 mm thick and had a diameter of 5 cm. A pin was ground onto their backside in the center. The front side was flat, while the backside, except for the pin, was a spherical surface with a radius of 26 cm. The inner surface of the massive ring RR, made of Siemens-Martin steel with a cross-section of 5 x 6 cm, was also a spherical surface with a radius of 26 cm. At four corresponding points, holes were drilled in the ring RR for the mirror pins. By inserting the pins into these holes, the spherical back surfaces of the mirrors fit perfectly against the spherical inner surface of the ring RR. The mirrors were then adjusted, cemented to the ring, and finally silver-plated on the surface.

Since part of the interferometer, namely the four mirrors, was attached to the ring RR, while the other part, namely the semi-transparent silver layer or the prism P, was attached to the base and cover plates of the apparatus, it was necessary to ensure an extremely rigid connection of the ring with the plates. The reinforcement was achieved through 18 pairs of ground and screw-tightened cones. Additionally, there were 18 pairs of strong screws beneath the cones. The rigidity achieved was so perfect that if the apparatus was disassembled and reassembled after adjustment, the interferences would appear immediately without any further adjustment.

Securing the mount of the prism P properly posed quite a challenge. It had to withstand a centrifugal force of around 500 kg at 1500 rotations. After numerous attempts, I succeeded using very strong, ground cones.

The final assembled arrangement is shown in Fig. 5. L is the Heraeus quartz mercury lamp, whose light was concentrated through the lens A onto the diaphragm B. The diameter of the latter was 0.5 mm. Behind D was a light filter made of about 1 cm thick didymium glass and thin green glass, which only allowed the green mercury line from the Hg spectrum to pass through. The light made parallel by the Tessar T₀ was deflected vertically to the rotation axis by the pentaprism P_{e1}. At the intersection of the axis of this beam with the rotation axis, the pentaprism P_{e2} was placed, which directed the light vertically downwards into the apparatus. C is the rotation counter, from which a cable led to the chronograph. T₁ is one turbine, T₂ is the other turbine rotating in the opposite direction, both of which were mounted on the axis. Simple switching allowed changing the direction of rotation. P is the pipe for the water supply.

Measurements were taken with this apparatus during the summer of 1925. Such recordings in original size can be seen in Fig. 6. The exposure time was 6 minutes. Recordings 108 and 109 were made with the right and left turbine, respectively, at about 1200 rotations per minute. Recording 86 corresponds to 1500, and the one in Fig. 7 to 2000 rotations per minute. In recordings 108 and 109, the vertical arrows indicate the direction of the shift of the interferences. The short, horizontal arrows on the left point to the same interference stripe in both recordings.

Since the displacement to be measured is proportional to the stripe width under otherwise identical conditions, it is advantageous to use wide interferences if it is possible to determine the position of the wide interferences with the same accuracy as that of the narrow stripes. For this purpose, the fringe curve of the wide interferences was registered photometrically. Unfortunately, as shown in Fig. 8, the curves obtained were jagged. These jagged lines resulted from fine dust particles that were constantly centrifuged from the air onto the measurement marker plate and imaged together with the interferences onto the photographic plate. This meant that the accuracy of these recordings did not even reach that of the narrow interferences. Therefore, I intend to repeat these recordings next summer using spider threads as measurement markers. I have already confirmed through experiments that the spider threads - only about 1 mm in length - can withstand the rotation.

After making various minor improvements, the recordings were made, and the results are presented in the following tables. Recordings 82 to 98 were measured directly with a comparator, while recordings 117 to 128 were evaluated based on the fringe curves using the method of G. Hansen.

Tabelle 1.

Platten- nummer	T_{sec}	\bar{T}_{sec}	b_{mm}	\bar{b}_{mm}	X_0	$\frac{X_{01} - X_{02}}{\bar{b}} = \Delta \bar{T}$	Δ	$\Delta - \Delta_m$
82	0,04002	0,03994	1,304	1,306	- 0,010	$\frac{1,198}{1,306} = 0,917$	0,916	- 0,001
83	0,03987	0,04001	1,309	1,310	- 1,208	$\frac{1,189}{1,310} = 0,908$	0,908	- 0,009
84	0,03994	0,03990	1,316	1,309	- 0,033	$\frac{1,198}{1,309} = 0,915$	0,913	- 0,004
85	0,04009	0,03971	1,305	1,312	- 1,222	$\frac{1,192}{1,312} = 0,908$	0,901	- 0,016
86	0,03971	0,03969	1,313	1,316	- 0,024	$\frac{1,199}{1,316} = 0,911$	0,908	- 0,009
87	0,03971	0,03989	1,311	1,316	- 1,216	$\frac{1,211}{1,320} = 0,917$	0,917	-
88	0,03968	0,04011	1,311	1,320	- 0,017	$\frac{1,240}{1,320} = 0,939$	0,939	+ 0,022
89	0,04011	0,04002	1,321	1,322	- 1,228	$\frac{1,227}{1,322} = 0,928$	0,931	+ 0,014
90	0,03993	0,04002	1,319	1,320	- 1,228	$\frac{1,224}{1,334} = 0,917$	0,911	- 0,006
90	0,04011	0,04014	1,319	1,322	+ 0,012	$\frac{1,192}{1,274} = 0,935$	0,935	+ 0,018
91	0,04017	0,03973	1,322	1,334	+ 0,012	$\frac{1,175}{1,276} = 0,921$	0,898	- 0,019
93	0,03986	0,03998	1,327	1,274	- 1,179	$\frac{1,204}{1,274} = 0,945$	0,922	+ 0,005
94	0,03961	0,03900	1,341	1,276	+ 0,041			
95	0,03976	0,03903	1,268	1,274	- 1,179			
96	0,04021	0,03900	1,279	1,276	+ 0,013			
96	0,04021	0,03900	1,279	1,276	+ 0,013			
97	0,03780	0,03903	1,273	1,274	- 1,162			
97	0,03780	0,03903	1,273	1,274	- 1,162			
98	0,04026	0,03903	1,275	1,274	+ 0,042			

Mittel = 0,917 = Δ_m

Tabelle 2

T_{sec}	\bar{T}_{sec}	b_{mm}	\bar{b}_{mm}	X_0	$\frac{X_{01} - X_{02}}{\bar{b}} = \Delta \bar{T}$	Δ	$\Delta - \Delta_m$
0,03998	0,04003	28,245	28,369	- 79,585	$\frac{26,193}{28,369} = 0,923$	0,924	-
0,04013	0,04006	28,494	28,520	- 53,342	$\frac{26,541}{28,520} = 0,928$	0,929	+ 0,005
0,04013	0,04006	28,494	28,545	- 53,342	$\frac{26,541}{28,520} = 0,928$	0,929	+ 0,005
0,03998	0,04000	28,545	28,574	- 79,883	$\frac{25,905}{28,574} = 0,907$	0,907	- 0,017
0,04002	0,04000	28,603	28,574	- 79,883	$\frac{25,905}{28,574} = 0,907$	0,907	- 0,017
0,04003	0,03999	28,088	28,008	- 52,706	$\frac{25,393}{28,008} = 0,905$	0,905	- 0,019
0,03994	0,03999	27,938	28,008	- 78,099	$\frac{25,393}{28,008} = 0,905$	0,905	- 0,019
0,03994	0,04001	27,933	28,048	- 78,099	$\frac{26,113}{28,048} = 0,931$	0,931	+ 0,007
0,04007	0,04001	28,163	28,048	- 51,986	$\frac{26,113}{28,048} = 0,931$	0,931	+ 0,007
0,04007	0,03997	28,163	28,206	- 51,986	$\frac{25,333}{28,206} = 0,898$	0,897	- 0,027
0,03986	0,03997	28,249	28,206	- 77,319	$\frac{25,333}{28,206} = 0,898$	0,897	- 0,027
0,03986	0,03989	28,249	28,254	- 77,319	$\frac{26,157}{28,254} = 0,926$	0,923	- 0,001
0,03992	0,03989	28,259	28,254	- 51,162	$\frac{26,157}{28,254} = 0,926$	0,923	- 0,001
0,03992	0,04003	28,259	28,348	- 51,162	$\frac{26,714}{28,348} = 0,942$	0,943	+ 0,019
0,04013	0,04003	28,436	28,348	- 77,876	$\frac{26,714}{28,348} = 0,942$	0,943	+ 0,019
0,04013	0,04025	28,436	28,326	- 77,876	$\frac{26,964}{28,326} = 0,952$	0,958	+ 0,084
0,04036	0,04025	28,215	28,326	- 50,912	$\frac{26,964}{28,326} = 0,952$	0,958	+ 0,084

Mittel = 0,924 = Δ_m

Platten-
nummer

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During the measurements with the comparator, each stripe as well as the measurement mark was set 10 times. This gives the position X_k of the k -th stripe with respect to the measurement mark. By introducing the position X_0 of the 0-th stripe and the stripe width b , one obtains equations of the form:

$$X_k = X_0 + kb$$

where X_0 and b are unknowns. These were determined by the method of least squares. The results are compiled in the two tables.

T is the rotation period in sidereal seconds, and b is the stripe width in millimeters. T' and b' are the mean values for two combined recordings of opposite rotation. Where two consecutive recordings were not combined, it indicates that either the reticle setting, orientation, or the width of the interferences was corrected between the two recordings. In recordings where either the adjustment of the crosshairs, or the orientation, or the width of the interferences was corrected, the resulting value $\Delta T'$ from the measurements corresponds to the rotation period T' ,

$$\Delta = \Delta T' = T'/0.04$$

belongs to the rotation time $T = 0.04$ sidereal seconds. Δ_m is the average of the observed Δ values. Δ_m thus belongs to the rotation time $T = 0.04$ sidereal seconds, or $T = 0.003989$ seconds.

In the case of narrow interferences, $\Delta - \Delta_m$ is consistently less than 2%, whereas with the wide interferences it exceeds 3% at one point.

In the tables, Δ denotes twice the shift given by formula (1), as two recordings of opposite rotation were always combined. The theoretical value for Δ corresponding to the table is obtained from:

$$\Delta = 8\omega F/\lambda c$$

The area traversed by the light is, for the mean path,

$$F = 1178 \text{ cm}^2$$

The angular velocity corresponding to $T=0.03989$ sek seconds is:

$$\omega = 157.431/\text{sec}$$

Substituting further,

$$\lambda = 546 \times 10^{-7} \text{ cm}$$

and $c = 3 \times 10^{10} \text{ cm/sec}$,

$$c = 3 \times 10^{10} \text{ cm/sec}$$

then one obtains,

$$\Delta = 0.906$$

The observed mean values are about 1.2% to not quite 2% larger. According to a letter from Mr. von Laue, with which I fully agree, the deviation between the calculated and observed (mean) stripe displacement appears rather large for the good agreement between individual observations.

The investigation is not yet complete. In addition to recordings with the green Hg line, recordings with other wavelengths are to be made. Furthermore, I intend to place a liquid chamber between the mirrors S_1 and S_2 or S_3 and S_4, which should not affect the magnitude of the displacement.

I would like to express my sincere thanks to the Notgemeinschaft and especially to the gentlemen of the Zeiss company, who made the implementation of the investigation at the Zeiss works possible and supported it in the most courteous manner, particularly Dr. W. Bauersfeld and Prof. Straubel from the management, and Mr. Chief Engineer Meyer, Engineer Büchele, and Koppen from the design office.

Special thanks are due to Mr. Geheimrat M. Wien for his extremely kind and supportive interest in my work, and to my superior authority, the Royal Hungarian Ministry of Education, which graciously enabled me to carry out the work in Jena.