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Lloyd Mirror Interferometer Experiments on the Speed of Light from a Moving Source.

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Summary. — The Lloyd mirror interferometric experiments, by Tolman in 1910 and by Beckmann and Mandics in 1964, on the speed of light from a moving source are shown to be unproductive of conclusive results. The related Rotz experiment in 1963 with moving slits is inconclusive since no experimental knowledge of the effect of slits on the speed of light is known. The inherently *avoidable* null results of certain other related closed-path interferometric experiments, on the speed of light from a moving source, are also inconclusive for reasons closely similar to those involved in the inherently *unavoidable* null results in the Lloyd mirror work.

1. – Tolman's experiment.

The possibility that a mirror acts as a « new » source of reflected light led TOLMAN (1), in 1910, to use a Lloyd mirror in an experimental check on Einstein's second postulate on the absolute speed of light from a moving source. By means of a lens he focused the image first of one limb, and then of the other limb of the Sun upon a slit, behind which was mounted a Lloyd mirror. It was Tolman's assumption that the speed of a ray of light reflected, at grazing incidence, from the mirror would be altered to c if its relative speed before reflection was $c \pm v$, where v is the tangential speed of the limb of the Sun. TOLMAN did not find his predicted relative shift of two fringes in the interference pattern formed by the direct and reflected light from the slit illuminated by the image of each

(1) R. C. TOLMAN: *Phys. Rev.*, **31**, 33 (1910).

limb of the Sun. He interpreted this result as proof that the speed of light was not relative, but was *absolute* in the sense of Einstein's second postulate that the speed of light is independent of the relative motion of its source.

There is the tacit assumption that the slit, which diffracts the incident solar light, would not alter the relative speed of light $c \pm v$ from a moving source to c from a stationary source. There is no experimental evidence (indeed, the point has hardly been considered) on the effect that a slit might have, acting as a « new » source, on the speed of light from a moving source. Afterwards, TOLMAN indicated in a footnote in 1912 the problems involved in a comprehensive approach to various propagation phenomena: « Optical theories in which the velocity of light is assumed to change during the path are not considered in this article. It might be very difficult to test theories in which the velocity of light is assumed to change on passing through narrow slits or near large masses in motion, or to suffer permanent change in velocity on passing through a lense » (2). FOX (3) has indicated that it can be supposed on theoretical grounds that a slit behaves like a new source. This theoretical indication is the basis of his conclusion that the Rotz (4) experiment is inconclusive. This experiment involves the diffraction pattern produced by three co-moving slits, the central one of which was covered by glass. Experimentally, nothing is known of the effect of an open (uncovered) moving slit on the speed of light emergent from it. The experimental investigation of the effect of « open » slits undertaken by ROTZ (4) in 1963 has not, as yet, been published. The behavior of a slit either as a moving light source or as a stationary re-emitter of light from a moving source is a matter of complete experimental ignorance at this time. The null results of experiments involving slits on the absolute or relative speed of light are therefore ambiguous and inconclusive.

The destruction of the relative speed of light from a moving source (limb of the Sun) by the intervening media of the solar atmosphere, the « stationary » Earth's atmosphere, and the lens predetermined a null result in Tolman's experiment, apart from considerations on the effects of the slit. TOLMAN incorrectly argued that these intervening media did not obliterate the possible relative speed of light. He did this by the circular logic of applying the Einstein « addition » theorem of speeds, based on the absolute speed of light, to the case for the relative speed of light. TOLMAN claimed that, relative to the source, the speed of light in the moving lens is $(c/\mu) \mp v\theta$, where μ is the index of refraction of the stationary medium of the glass lens and $\theta = (\mu^2 - 1)/\mu^2$.

This Fresnel expression for the convected speed of light (in the moving lens) relative to the source follows as a first-order approximation from the Einstein « addition » theorem in which the relative lens speed v is « added »

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(2) R. C. TOLMAN: *Phys. Rev.*, **35**, 136 (1912).
(3) J. G. FOX: *Am. Journ. Phys.*, **33**, 15 (1965).
(4) R. B. ROTZ: *Phys. Lett.*, **7**, 252 (1963).

algebraically to the speed of the light c/μ propagating relative to the lens. TOLMAN makes the perplexing error of asserting, according to the classical addition of speeds, that « with respect to the medium it [the speed of the light relative to the lens] will be $(c/\mu) \pm v(1-\theta)$ » (1) rather than the correct value which is simply c/μ, as pointed out by PAULI (5). By circular and inappropriate logic supported by a wrong calculation, TOLMAN justified a predicted fringe shift that was physically prevented to begin with.

With physically conducive conditions, a negative result, as STEWART (6) noted, could be regarded as merely showing that the specific assumption that $c \pm v$ is changed to c on grazing reflection is not correct. At *normal* incidence the specific inelastic ballistic hypothesis that $c \pm v$ is changed to c is based on the supposition that the incident photon is re-emitted with speed c from the stationary mirror acting at the point of incidence as a « new » source. At *grazing* incidence the inelastic ballistic hypothesis must not be uncritically accepted to be the same phenomenon as at *normal* incidence. Phenomenologically, the speed on reflection could be angle-dependent in some manner analogous to the angle dependence of the intensity and polarization of light reflected from a plane glass surface. STEWART championed what is in effect equivalent to an elastic ballistic hypothesis whereby the reflected speed of the light is equal to the incident speed of the light $c \pm v$ from a moving source. On the basis of such an elastic rebound (or Fermat's principle of least time) the angle of reflection from a fixed mirror would equal the angle of incidence with the consequent null result of the Lloyd mirror experiment to be expected (when $v/c \ll 1$). Einstein's second postulate that the speed of light is absolute also leads to the prediction of a null result since there is no speed or angle change on reflection of the light from a stationary mirror. Rather than speculate on other interesting ballistic hypotheses, a new experiment will be suggested later which may provide an experimental indication of the possible nature of an angle-dependent ballistic behavior of light from a moving source, when that light is reflected from a stationary mirror. In a corpuscular ballistic model for the behavior of light, the two factors that can be experimentally examined are the speed and angle of the reflected light for a specific source speed and a specific angle for the incident light.

Tolman's experiment is of doubtful value even if it is uncritically assumed that reflection at grazing incidence will change $c \pm v$ into c. The first-order fringe shift effect to be expected with a Lloyd mirror from such an assumption is relatively negligible and undetectable as will shortly be shown. This will prove quite relevant to other interferometric experiments on the relative speed of light.

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(5) W. PAULI: *Theory of Relativity* (New York, 1958), p. 17.
(6) O. M. STEWART: *Phys. Rev.*, **32**, 421 (1911).

Tomaschek's repetition (7) of the Michelson-Morley experiment used sunlight and starlight which were first reflected from heliostats into a telescope and then passed through a laboratory window to finally enter the interferometer. Naturally, the intervening glass predetermined a null result just as in Tolman's experiment.

2. – The Beckmann-Mandics experiment.

The same assumption for the change of speed for the reflection of light at grazing incidence was made by BECKMANN in the experiment by BECKMANN and MANDICS (8). A contradiction with Fermat's principle of least time is also explicitly made in that the angle of reflection r, shown in Figure 1, is equal to

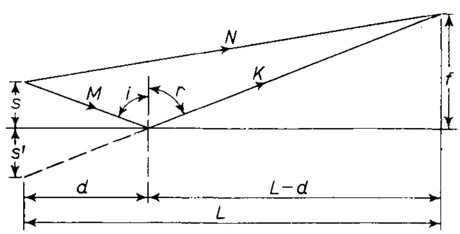

Fig. 1. – Lloyd's mirror.

the angle of grazing incidence i, even though the speeds of the incident and reflected light are assumed unequal. BECKMANN and MANDICS repeated the Tolman experiment in air and in vacuum fifty-four years later in 1964. Their moving light source, without the presence of a slit, was established by means of the reflection of light incident at 15° on a tiny mirror mounted on a rotor at 12.8 cm from the axis of rotation. For the reasons already given, their other null result experiments with a stationary-slit light source are inconclusive, and need not be discussed.

In Figure 1, f is the perpendicular distance of a particular fringe from the plane of the mirror. The integer number or order of a fringe increases (or decreases) directly with f. The perpendicular distance of the source from the plane of the Lloyd mirror is s, and s' is the equidistant mirror image of s. The plane of observation of the fringe field is at distance L normal to the line ss', and d is the perpendicular distance of the point of reflection, on the Lloyd mirror, from ss'. When the light source is stationary $i = r$, so that

$$\operatorname{ctg} i = s/d = f/(L-d) = (f+s)/L \ll 1, \qquad (1a)$$

(7) R. TOMASCHEK: *Ann. der Phys.*, **73**, 105 (1924).

(8) P. BECKMANN and P. MANDICS: *Radio Sci.*, **69** D, 623 (1965).

because of the physical condition of grazing incidence and reflection. From (1*a*) find

$$s/f = d/(L-d)\,, \tag{1b}$$

$$d = Ls/(f+s)\,, \tag{1c}$$

and

$$L-d = Lf/(f+s). \tag{1d}$$

The geometrical path length difference $(M+K-N)$ for a stationary light source $(i=r)$ is equal to some multiple m of the wavelength λ, which can also be expressed in terms of the transit time difference δt_0 of the direct and reflected light rays as

$$c\delta t_0 = M + K - N = m\lambda\,; \tag{2a}$$

$$M + K = L\sqrt{(1 + (f+s')^2/L^2)} \simeq L(1 + (f+s)^2/2L^2)\,, \tag{2b}$$

and

$$N = L\sqrt{(1 + (f-s)^2/L^2)} \simeq L(1 + (f-s)^2/2L^2)\,, \tag{2c}$$

since $(f \pm s)/L \ll 1$ due to grazing incidence as noted in (1*a*). From (2*a*)-(2*c*), find

$$f = m\lambda L/2s \tag{2d}$$

or

$$m = f/\delta f\,, \tag{2e}$$

where $\delta f = \lambda L/2s$ and is the distance between fringes or the fringe width. From (2*d*) and (1*b*) it follows that

$$m = (2s^2/Ld)(L-d)/\lambda\,. \tag{2f}$$

Assume that light, from a source moving with speed v, travels in vacuum along M and N with speed $c(1\pm\beta)$; $\beta = v/c$. It was uncritically assumed that the light traveled along K after *grazing* reflection with the speed c, together with the assumption, contradicting Fermat's principle, that $r = i$. Based on these challengeable assumptions, the difference in the time of flight δt of the direct and reflected light rays is expressed as

$$\delta t = [M/c(1\pm\beta)] + [K/c] - [N/c(1\pm\beta)] = m'\lambda/c\,, \tag{3a}$$

where $m'\lambda$ is the equivalent path difference for light traveling from a stationary source at speed c. To first-order in β the multiple m' can be found from (3*a*) and (2a) as

$$m' = c\delta t/\lambda = m(1 \mp \beta) \pm \beta K/\lambda \,. \tag{3b}$$

With $K^2 = f^2 + (L-d)^2$ it follows that

$$K \simeq L - d \,, \tag{3c}$$

since $f^2/(L-d)^2 \ll 1$, as previously noted, at grazing incidence in (1a). From (3b) and (3c) it follows, since $\beta \ll 1$, that

$$m' \simeq m \pm \beta(L-d)/\lambda \,. \tag{4}$$

The phase change in the transit time difference $\beta K/c \simeq \beta(L-d)/c$ between the direct and reflected light rays is due to the (particular assumed) change in the relative speed of light on reflection. The effective optical-path change $\pm\beta(L-d)$ due to the time phase change modifies the geometrical path difference $m\lambda$ inherent in the Lloyd interferometer. The transit time phase change attendant on the first-order effect for the change of the speed of light due to reflection would be misleadingly interpreted, on the basis of the questionable assumptions, as an apparent shift in the fringe position f.

The angle of reflection r may *not*, as is uncritically assumed, equal the angle of incidence i. The angle r may change due to the change in the relative speed of light on reflection. There would be a change in the geometrical paths K and N because the angle r differs from the angle i, so that there would be a real (geometrical) shift of the fringe position f. The geometrical path changes attendant on the first-order angular-aberration effect (change in r) would be manifest as an actual geometrical shift modifying the inherent fringe position f that corresponded to m. The geometrical fringe shift due to angular aberration could actually diminish the optical phase fringe shift depending on the reflection behavior of the relative speed of light. This would render the experiment inconclusive since the absolute speed of light also leads, as already noted, to a null result because there is no speed or angle change on the reflection of light from a stationary mirror. This suggests a new first-order experiment which for various angles of incidence is sensitive only to a change in the angle of reflection for the relative or absolute speed of light. The optical lever technique as refined by JONES (9) is as sensitive as interferometry and could prove quite effective.

The Beckmann-Mandics experiment, under vacuum conditions, was done with the parameters $L = 425$ cm, $\lambda = 6328$ Å and $\beta = 2.41 \cdot 10^{-7}$. The fringe width δf and therefore s is not given, nor is the measured position f and therefore m. The value of d is not given. It is therefore not possible to fully evaluate this inconclusive experiment.

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(9) R. V. JONES: *Proc. Roy. Soc.*, A **260**, 47 (1961).

BECKMANN claimed that the distance f « may be measured on the photograph of the fringes (by utilizing the diffraction fringes due to the edge of the Lloyd mirror); .... » [8]. No diffraction pattern is visible in the published photographs of the uniformly spaced interference fringes. His unsupported assertion that s/f « was of the order of 10^{-4} » [8] is contradicted by the physical facts. It would mean according to (1b) that d was of the order of $L \cdot 10^{-4}$ or about 0.425 mm. This is comparable to or less than any physically reasonable value for s, and contradicts grazing incidence (1a) and the need for clearance between the small rotating mirror source and the Lloyd mirror. It would also mean an f in excess of the 1.5 m diameter of the vacuum chamber; the fringe at f could not be seen. The consequent value of m in (2e) and (2f) would be so huge compared to the fringe change $\beta(L-d)/\lambda$ (of the order of unity) in (4) that the effect would be undetectable even if it were visible; *i.e.* $m' \simeq m$.

The Lloyd interferometer is most sensitive to change in the relative speed of light on reflection when d in (4) is as small as is consistent with grazing incidence. Ignoring angular aberration, this means large m values in (2d)-(2f) for large K so that in agreement with (1b) $f \gg s$; *i.e.* high-order fringes. BECKMANN correctly asserts that for best sensitivity $s \ll f$ (in his notation $x \ll y$). This is oddly contradicted by the subsequent comment, « *i.e.*, for low-order fringes » [8]. Apart from aberration effects, sensitivity has to be compromised for resolvability or detectability in the Lloyd mirror when $\beta(L-d)/\lambda$ is of the order of m, which in turn depends on the unspecified quantities s and d in (2f). Erroneous predictions follow from ignoring the effect of aberration due to possible changes in the angle r. The fact that the source is of small but distinct transverse dimension leads to the superposition of fringe patterns from different lateral points of the source. At moderate to large fringe orders the problems of resolvability become formidable even with microdensitometer techniques.

In the absence of critical parameters (d, f, s) the Beckmann-Mandics experiments are altogether of doubtful value. Lloyd interferometer experiments on the relative or absolute speed of light lead to null results and are therefore inconclusive to begin with. *The inherent geometrical path difference* $m\lambda$ *at high-order fringes renders the sought for fringe shift a negligibly small and undetectable modification.* This provides significant insight on the merits of other interferometric experiments on the relative or absolute speed of light from a moving source.

The ring interferometers in all but one of these experiments [10-14], either were not initially adjusted to a zero or near-zero fringe condition or did not

(10) A. A. MICHELSON: *Astrophys. Journ.*, **37**, 190 (1913).
(11) W. KANTOR: *Journ. Opt. Soc. Am.*, **52**, 978 (1962).
(12) G. C. BABCOCK and T. G. BERGMAN: *Journ. Opt. Soc. Am.*, **54**, 147 (1964).
(13) P. BECKMANN and P. MANDICS: *Radio Sci.*, **68** D, 1265 (1964).
(14) R. O. WADDOUPS, W. F. EDWARDS and J. J. MERRILL: *Journ. Opt. Soc. Am.*, **55**, 142 (1965).

maintain such a condition when the light source was in motion. The effective result was that an unnecessary geometrical path difference $m\lambda$ for the counter propagating light rays was very large compared to the very small change in the optical-path difference due to the effect of the relative speed of light. The modification of the avoidable $m\lambda$ path difference by the optical fringe shift effect was too small to be detected. The wrong conclusion, in all but one ([11]) of these experiments, that the apparent null results supported the absolute speed of light hypothesis, while seemingly reasonable, has been too hastily embraced.

● RIASSUNTO (*)

Si mostra che gli esperimenti interferometrici con lo specchio di Lloyd, di Tolman nel 1910 e di Beckmann e Mandics nel 1964, sulla velocità della luce proveniente da una sorgente in movimento non possono produrre risultati conclusivi. L'esperimento di Rotz nel 1963, in relazione con essi, con fessure in movimento non è conclusivo perché non si ha alcuna conoscenza sperimentale dell'effetto delle fessure sulla velocità della luce.

(*) *Traduzione a cura della Redazione.*

Резюме автором не представлено.