A New Test of the Second Postulate of Special Relativity Sensitive to First-Order Effects (*).

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After the famous 1887 experiment by MICHELSON and MORLEY (1) and its interpretation by EINSTEIN in his 1905 celebrated paper (2), a large number of optical experiments have confirmed the second postulate of special relativity on the constancy of the speed of light (3). All these experiments are sensitive to second-order effects in the ratio $u/c = \beta$ between the velocity u of the laboratory with reference to a hypothetical absolute frame and the light velocity in empty space. This is because the first-order effects are cancelled in the «closed optical circuits» employed, where the light beam from the point—the source—is first split into two beams, which follow different paths and then are brought together at the same point to observe their interference effects (4).

The purpose of this letter is to illustrate a new method sensitive to first-order effects in β and to report an experiment based on this method, by which a new upper limit is obtained for the absolute velocity u. This limit is about one-hundred times smaller than the lowest value obtained thus far by conventional optical methods. Needless to say, the new method would give not only the value but also the sign of the velocity u.

In order to observe some possible first-order effects in β, one has first to abandon the idea of using closed optical circuits. The development of highly monochromatic and stable sources, based on the laser process, makes it feasible to observe possible first-order effects in β by using two independent such sources. The continuous gas lasers are certainly ideal sources for this type of experiments. Unfortunately, however, the wave trains of two lasers, altough very long, can present differences in phase, thus giving rise to an interference pattern which may change in time in a random way. Of course it would be possible to maintain constant the phase difference by some electronic circuit, coupling one laser to the other. But such a circuit (5) would necessarily require

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(1) A. A. MICHELSON: *Amer. Journ. Sci.*, **22**, 20 (1881); A. A. MICHELSON and E. W. MORLEY: *Amer. Journ. Sci.*, **34**, 333 (1887).

(2) A. EINSTEIN: *Ann. d. Phys.*, **17**, 549 (1905).

(3) For a general review: E. WHITTAKER: *A History of the Theories of Aether and Electricity* (New York, 1960); W. PAULI: *Teoria della relatività* (Torino, 1958).

(4) H. A. LORENTZ: *The Theory of Electrons* (Leipzig, 1916).

(5) L. H. ENLOE and J. L. RODDA: *Proc. of the IEEE*, **53**, 165 (1965).

the transmission of some signal travelling in a given direction, say from the first to the second source. Under the hypothesis of the influence of the laboratory movement on the propagation velocity of the electromagnetic waves, there would be a delay, which might cancel the possible first-order effects.

In the new method adopted in the present experiment, two equal completely independent lasers are used. The measurements are limited only to the time intervals during which a given phase difference between the two trains gives rise to a stable interference pattern. Figure 1 shows a schematic view of the apparatus. The two lasers L_1 and L_2 are placed on an optical bench, which can rotate around a vertical axis normal to the plane of the Figure. The two light beams overlap at S_1 and reach a fast photodiode Ph, whose signal, amplified by A, is observed on a fast oscilloscope O.

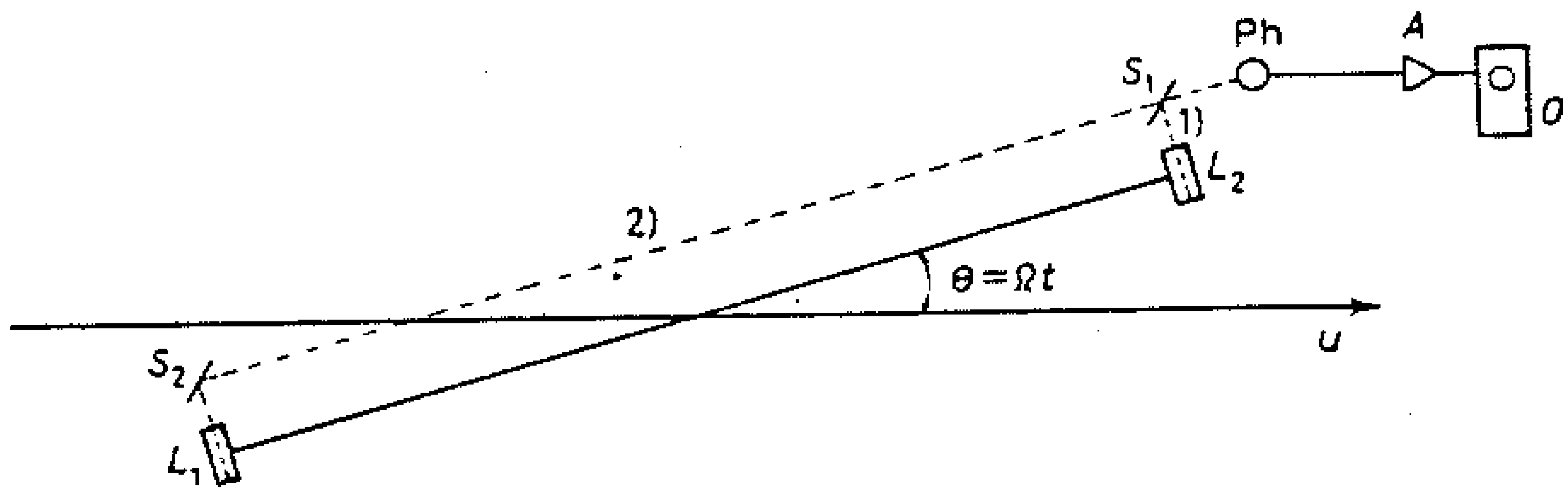

Fig. 1. – S_1 is a partially reflecting mirror. S_2 is a totally reflecting mirror, parallel to S_1. Ph is the photodiode. A and O are the amplifier and the oscilloscope.

The experiment is performed in the following way. Once the beats appear on the oscilloscope screen, one turns the whole optical bench around the vertical axis, keeping the interference pattern under constant observation in order to see any possible displacement of its maxima and minima. Of course, if the prerelativistic classical theory were true, the interference pattern would change as soon as the bench begins to rotate; and during this rotation there should be a regular passage of maxima and minima on the oscilloscope screen. On the contrary, an interference pattern which remains unchanged during the bench rotation indicates that the light velocity is constant and independent of the laboratory speed, that is of the Earth speed. The mode of operation outlined above is repeated till when the beat pattern disappears or moves away; that is expected to occur when one of the waves trains ends and is replaced by another one with a phase generally different. We shall now evaluate the sensitivity of the apparatus assuming that

1) the emitted wave trains are sinusoidal and polarized with their polarization planes parallel to each other,

2) the paths L_1S_1 and L_2S_2 are negligible with respect to the other paths involved,

3) the rotation of the optical bench occurs with a constant angular velocity Ω,

4) there is a reference system absolutely at rest, as in the prerelativistic theories.

At the point S_1 the two wave trains overlap; then the electric field at S_1 is given by

$$E = E_1 \cos \alpha_1 + E_2 \cos \alpha_2 ,$$

where E_1 and E_2 are the amplitudes of the electric-field vibrations of the two beams and

$$\alpha_1 = \int_0^t \omega_1' \, \mathrm{d}t + \varphi_0 , \qquad \alpha_2 = \int_0^{t-\tau} \omega_2' \, \mathrm{d}t . \tag{1}$$

Here $\omega_1'/2\pi$ and $\omega_2'/2\pi$ are the frequencies of the two lasers, φ_0 is the phase difference between the two trains at the laser exits at $t=0$, τ is the time necessary for the beam 2 to arrive at the point S_1. Taking into account that because of assumption 4) the frequency of the laser radiation depends on the orientation of the cavity, we find from eq. (1)

$$\left\{\begin{aligned} \alpha_1 &= \omega_1 t + \omega_1 \frac{\beta L}{c} F(\theta) + \varphi_0 , \\ \alpha_2 &= \omega_2 t - \omega_2 \frac{\beta L}{c} F(\theta) - \omega_2 \tau , \end{aligned}\right. \tag{2}$$

where

$$F(\theta) = \frac{5 - 6\cos\theta + \cos^3\theta}{6} \quad \text{and} \quad \theta = \Omega t .$$

The photodiode gives a signal proportional to the square of the electric field. If we consider that the continuous component and the higher frequencies are filtered by the electronic circuits, the signal amplitude is then proportional to

$$2E_1E_2 \cos\left[(\omega_1 - \omega_2)t + \omega_2\tau + (\omega_1 + \omega_2)\frac{\beta L}{c} F(\theta) + \varphi_0\right].$$

This represents an oscillation of frequency $(\omega_1 - \omega_2)/2\pi$ with a phase which depends on θ. A rotation of 180° of the optical bench gives rise to a change δ of this phase, given by

$$\delta = \frac{8\pi}{3}\frac{L}{\lambda}\beta , \tag{3}$$

where $\omega_1 \simeq \omega_2 \simeq 2\pi c/\lambda$. This is the first-order effect expected in this experiment on the basis of the hypothesis 4). All the other classical effects due to the hypothetical « ether wind » (apparent rotation of the mirrors and of the wave fronts, delay of the signal transmission, etc.) are second-order effects in β, which can be neglected with respect to the above first-order effect.

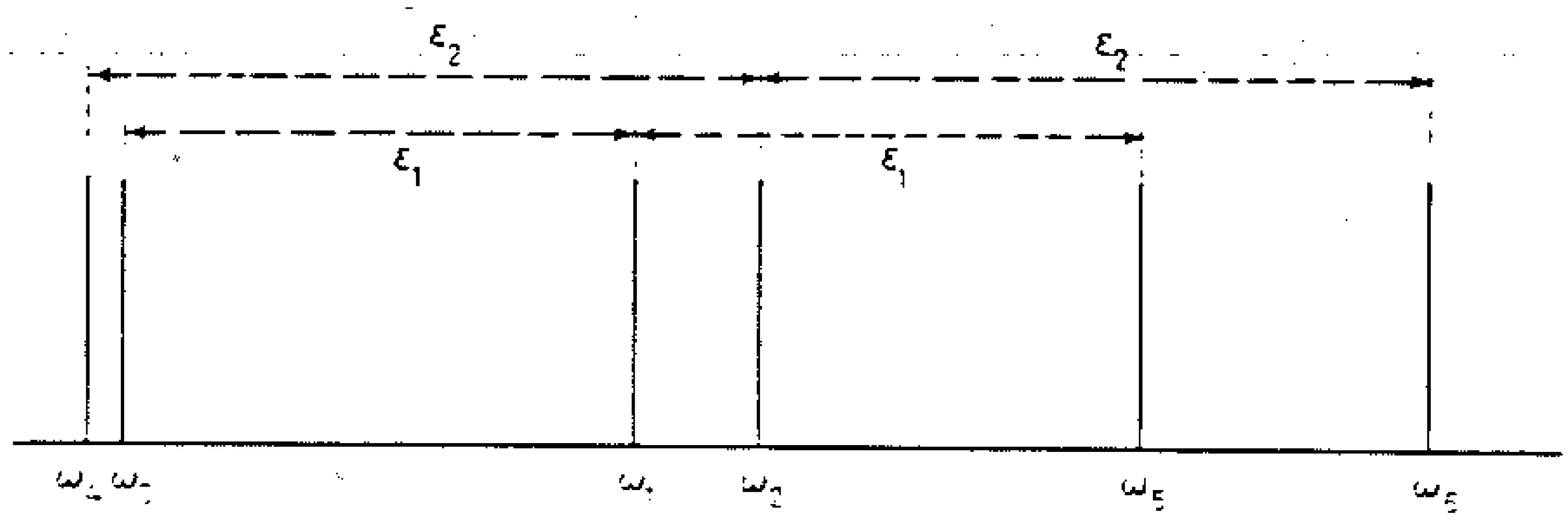

Fig. 2. – The frequencies of the laser L_1 are $\omega_3 = \omega_1 - \varepsilon_1, \omega_1, \omega_5 = \omega_1 + \varepsilon_1$ and the frequencies of the laser L_2 are $\omega_4 = \omega_2 - \varepsilon_2, \omega_2, \omega_6 = \omega_2 + \varepsilon_2$.

This phase change is difficult to observe with the oscilloscope because one can see on the oscilloscope screen few beat oscillations, corresponding to a small rotation angle θ. This is because the sweep triggering cancels all the phase differences. In order to surmount this difficulty we make more laser frequencies to overlap. In fact in this experiment we have two He-Ne lasers with a resonant cavity 30 cm long. Each laser emits three frequencies separated by about 580 MHz, as shown Fig. 2. The lasers are mounted on an optical rotating bench two metres long. The photodiode is a PIN-type diode with a response of less than 1 ns. The preamplifier is mounted with the photodiode in a

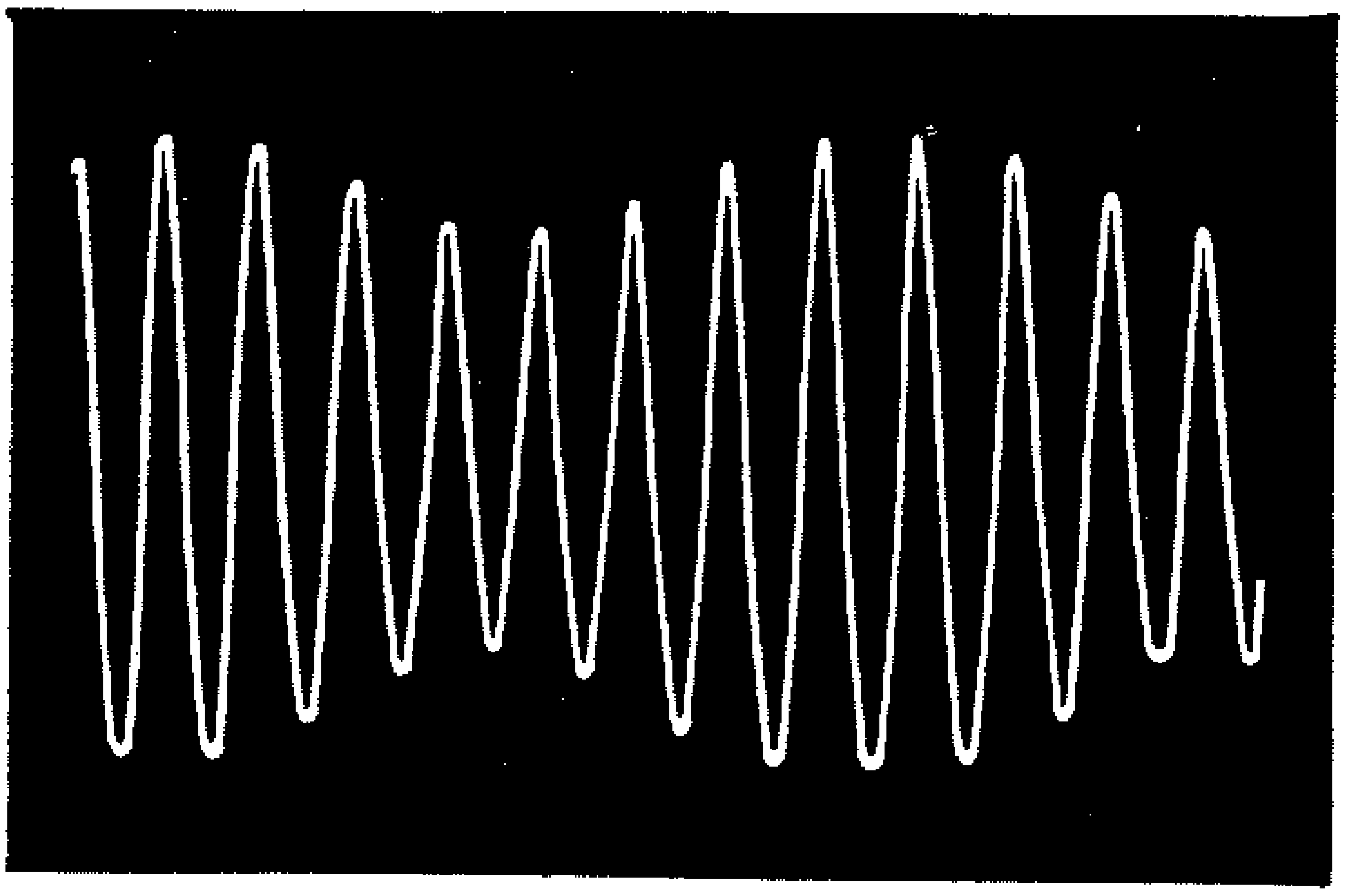

Fig. 3. – Typical oscillographic record obtained in these experiments; in the record we have $\Delta\omega/2\pi = 1.4\cdot10^7$ Hz and $\Delta\varepsilon/2\pi = 2.4\cdot10^6$ Hz.

small box and is followed by a high-pass filter. The oscilloscope has a band width of 150 MHz. Thus we have at S_1 the overlapping of the six laser frequencies. Taking into account the filtering of the electronics we find that the signal amplitude is proportional to

$$E_1E_2\cos[\Delta\omega t + \psi] + E_3E_4\cos[(\Delta\omega + \Delta\varepsilon)t + \psi'] + E_5E_6\cos[(\Delta\omega - \Delta\varepsilon)t + \psi''] , \tag{4}$$

where the E_i are the amplitudes of the electric-field vibrations of the six frequencies, $\Delta\omega = \omega_1 - \omega_2$, $\Delta\varepsilon = \varepsilon_1 - \varepsilon_2$ and

$$\psi = \omega_2\tau + (\omega_1 + \omega_2)\frac{\beta L}{c}F(\theta) + \varphi ,$$

$$\psi' = (\omega_2 + \varepsilon_2)\tau + (\omega_1 + \omega_2 + \varepsilon_1 + \varepsilon_2)\frac{\beta L}{c}F(\theta) + \varphi' ,$$

$$\psi'' = (\omega_2 - \varepsilon_2)\tau + (\omega_1 + \omega_2 - \varepsilon_1 - \varepsilon_2)\frac{\beta L}{c}F(\theta) + \varphi'' .$$

The phases φ, φ', φ'' depend on the phases of these six waves at the laser exits, at $t = 0$. It can be shown that, if the interference pattern remains unchanged on the oscilloscope screen, even with the optical bench in a fixed direction, then expression (4) becomes

$$E_1E_2\left[1 - 2\frac{E_3E_4}{E_1E_2}\cos\Delta\varepsilon t\right]\cos(\Delta\omega t + \phi) , \tag{5}$$

where

$$\phi = \frac{\Delta\omega}{\Delta\varepsilon}(\varphi' - \varphi) - \varphi - \omega_2\tau - (\omega_1 + \omega_2)\frac{\beta L}{c}F(\theta) . \tag{6}$$

The signal amplitude (5) represents an oscillation of frequency $\Delta\omega$ modulated with the frequency $\Delta\varepsilon$. We point out that there is the phase difference (6) between the carrier frequency oscillation $\Delta\omega$ and the modulation one, which depends on θ. A rotation of 180° of the optical bench gives rise to a change of ϕ given by $8\pi/3(L/\lambda)\beta$, coincident with that given by eq. (2). It is easy to observe any change of ϕ on the oscilloscope screen.

In this experiment we have $L = 160$ cm, $\lambda = 6328$ Å. Therefore a change of a maximum into a minimum, very easy to observe, corresponds to a velocity $u = 45$ m/s. The displays indeed are so sharp that one can estimate the fiftieth part of this displacement, that is a velocity $u = 0.9$ m/s. In this experiment we used only the beats giving rise to a stable interference pattern. This occurred with an average time interval of about five minutes. The length of the beats were at most one or two seconds. The observations were repeated several times during the years 1970 and 1971, at the Monte Porzio Observatory (Italy). No displacement was observed in any rotation of the optical bench. Thus we conclude that the hypothetical « ether wind » on the Earth cannot have a speed greater than 0.9 m/s. The horizontal component of the translation velocity of the Earth during these observations was on the average greater than 30 km/s. In terms of the hypothesis of a partial drag of the « ether » by the Earth, characterized by a drag coefficient k ($v = c + ku$, where v is the light velocity measured in the laboratory and u is the absolute laboratory velocity) this experiment yields $k < 3\cdot10^{-5}$. In the last experiment by Joos [6] an upper limit of 80 m/s was reported for the speed of the « ether wind », corresponding to $k < 2.6\cdot10^{-3}$. From the observations on the double stars DE SITTER [7] derived a similar limit: $k < 2\cdot10^{-3}$. The optical experiment described in this letter yields, in conclusion, a further, far more precise confirmation of the second postulate of special relativity.

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(6) G. JOOS: *Phys. Zeits.*, **31**, 801 (1930).
(7) W. DE SITTER: *Phys. Zeits.*, **14**, 429, 1267 (1913).