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OLD AND NEW ETHER-DRIFT EXPERIMENTS: A SHARP TEST FOR A PREFERRED FRAME

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M. CONSOLI

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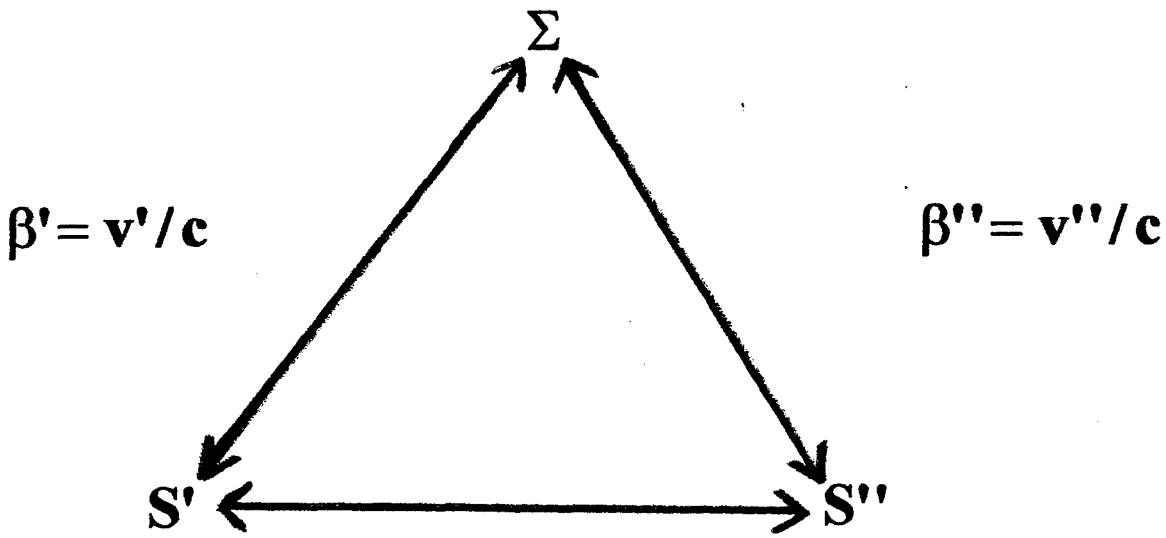
References:

[1] M.Consoli and E.Costanzo, gr-qc/0406065, to appear in Il Nuovo Cimento B.

[2] M. Consoli, A. Pagano and L. Pappalardo, Phys. Lett. A318 (2003) 292.

Relativity with a preferred frame Σ



$$\beta_{rel} = \frac{\beta' - \beta''}{1 - \beta'\beta''}$$

Can β' and β'' be experimentally determined ?

Answer from ether-drift experiments.

Bell's derivation of Lorentz transformations

Let us consider a reference frame

Σ with coordinates (X,Y,Z,T)

For Σ, time is homogeneous and space is homogeneous and isotropical.

Σ is a preferred frame since the relative motion with respect to it produces physical modification of all time and length measuring devices. Namely, the basic atomic parameters are changed by the Larmor time dilation and by the Fitzgerald – Lorentz contraction along the direction of motion.

One can introduce, however, another reference frame

S' with coordinates (x',y',z',t')

such that the description of the moving atoms for S' is exactly the same as the description of the stationary atoms in Σ. The transformation

$$(X,Y,Z,T) \Rightarrow (x',y',z',t')$$

is precisely the standard Lorentz transformation. In this way, time and space, as measured through the clocks and rods of S', have the same homogeneity and isotropy properties as in Σ.

ON THE ELECTRODYNAMICS OF MOVING BODIES

By A. EINSTEIN

IT is known that Maxwell's electrodynamics—as usually understood at the present time—when applied to moving bodies, leads to asymmetries which do not appear to be inherent in the phenomena. Take, for example, the reciprocal electrodynamic action of a magnet and a conductor. The observable phenomenon here depends only on the relative motion of the conductor and the magnet, whereas the customary view draws a sharp distinction between the two cases in which either the one or the other of these bodies is in motion. For if the magnet is in motion and the conductor at rest, there arises in the neighbourhood of the magnet an electric field with a certain definite energy, producing a current at the places where parts of the conductor are situated. But if the magnet is stationary and the conductor in motion, no electric field arises in the neighbourhood of the magnet. In the conductor, however, we find an electromotive force, to which in itself there is no corresponding energy, but which gives rise—assuming equality of relative motion in the two cases discussed—to electric currents of the same path and intensity as those produced by the electric forces in the former case.

Examples of this sort, together with the unsuccessful attempts to discover any motion of the earth relatively to the "light medium," suggest that the phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest. They suggest rather that, as has already been shown to the first order of small quantities, the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of

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AND

WILLIAM FRANCIS, PH.D. F.L.S. F.R.A.S. F.C.S.

"Nec aranearum sane textus ideo melior quia ex se fila gignunt, nec noster vilior quia ex alienis libamus ut apes." JUST. LIPS. *Polit.* lib. i. cap. 1. Not.

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tributed in some places than in others, of infinitely small average density through the whole of infinite space. In regions where the density was then greater than in neighbouring regions, the density would become greater still; in places of less density, the density would become less; and large regions would quickly become void or nearly void of atoms. These large void regions would extend so as to completely surround regions of greater density. In some part or parts of each cluster of atoms thus isolated, condensation would go on by motions in all directions not generally convergent to points, and with no perceptible mutual influence between the atoms until the density becomes something like 10^{-6} of our ordinary atmospheric density, when mutual influence by collisions would begin to become practically effective. Each collision would give rise to a train of waves in ether. These waves would carry away energy, spreading it out through the void ether of infinite space. The loss of energy, thus taken away from the atoms, would reduce large condensing clusters to the condition of gas in equilibrium * under the influence of its own gravity only, or rotating like our sun or moving at moderate speeds as in spiral nebulas, &c. Gravitational condensation would at first produce rise of temperature, followed later by cooling and ultimately freezing, giving solid bodies; collisions between which will produce meteoric stones such as we see them. We cannot regard as probable that these lumps of broken-looking solid matter (something like the broken stones used on our macadamised roads) are primitive forms in which matter was created. Hence we are forced, in this twentieth century, to views regarding the atomic origin of all things closely resembling those presented by Democritus, Epicurus, and their majestic Roman poetic expositor, Lucretius.

II. *On the Michelson-Morley Experiment relating to the Drift of the Æther.* *By* W. M. Hicks, *F.R.S.*†

[Plate I.]

IN the following pages it is proposed to consider in detail the general theory of the experiment by which Messrs. Michelson & Morley ‡ attempted to decide the question of the rest or motion of the æther when a material body moves through it. The theory is not so simple as it may appear at

* Homer Lane, American Journal of Science, 1870, p. 57; Sir W Thomson, Phil. Mag. March 1887, p. 287.

† Communicated by the Author.

‡ Phil. Mag. Dec. 1887.

The maximals for different small strips of the flame are therefore differently inclined. It has been seen that these intersections with the plane of the first mirror coincide. Hence they coincide nowhere else. Consequently a fringe will be seen if the telescope is focussed on the first mirror, which will gradually become more and more indistinct as the plane on which it is focussed recedes more and more from it.

If γ denote the angular breadth of the flame as seen from the point on the plate where the datum line meets it, the maximals for the various points of the flame will form a system of pencils of angular breadth γ, whose vertices pass through the maximal points on the first mirror which have just been shown to be the same for every point on the flame. The fringe on a screen parallel to the first mirror will then completely fade into white light when its distance from the first mirror is such that the pencils intersect, each, the succeeding one. This takes place at a distance y such that $y\gamma$ = breadth of a band. At distances greater than y no fringes can be seen at all. At distances nearly as great as y we should expect dark lines on a more or less uniformly bright background.

Discussion of the Displacement of Fringe.

17. The position of the central band is given by

$$x = \frac{b}{\sin(B-A) - \frac{1}{2}\xi^2 \cos 2\alpha}.$$

If then $B>A$, b must be positive, that is the plane of the second mirror must lie to the right of the intersection of the first mirror and the plate. If on the other hand $A>B$, b must be negative, or the second plane must lie to the left of the same intersection. It will be convenient to distinguish these two cases as the B and the A type respectively.

Suppose an experiment to start with the drift in the same direction as the incident light. Then as the drift alters from this position in either direction, the central band is displaced to the right in the B type and to the left in the A type. As $A-B$ is exceedingly small—of order 10^{-5} (or 2 sec.) at most—the adjustment of the mirrors can easily change from one type to the other on consecutive days. It follows that averaging the results of different days in the usual manner is not allowable unless the types are all the same. If this is not attended to the average displacement may be expected to come out zero—at least if a large number are averaged.

If D denote the distance of the central band from the intersection of the plate and mirrors, when there is no drift—or when the drift is parallel to the plate—

$$D = \frac{b}{\sin(B-A)}$$

$$x = \frac{D\sin(B-A)}{\sin(B-A) - \frac{1}{2}\xi^2\cos 2\alpha}.$$

$$\left.\begin{array}{r}\text{Displacement to}\\ \text{left of this position}\end{array}\right\} = x - D = \frac{\frac{1}{2}\xi^2 D\cos 2\alpha}{\sin(B-A) - \frac{1}{2}\xi^2\cos 2\alpha}.$$

In any given case suppose $\sin(B-A) = \frac{1}{2}k\xi^2$, then

$$\text{Displacement} = \frac{D\cos 2\alpha}{k - \cos 2\alpha}.$$

Fig. 6.

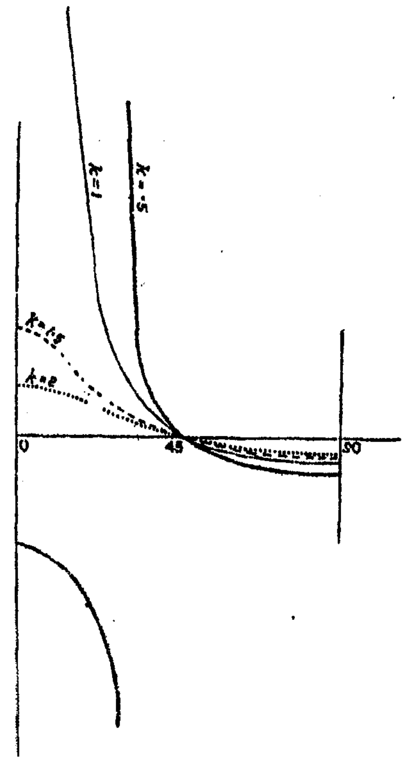

Fig. 6 shows how the displacement changes with α, for the shorten until when k is large the curves become the ordinary harmonic curve $y = k \cos 2\alpha$. In Michelson and Morley's experiment k was apparently always large.

Discussion of Michelson and Morley's Observations.

18. The result of §17, that it is not allowable to average the results of different sets of observations until the type of each has been determined, naturally leads us to a reconsideration of the numerical data obtained by Michelson and Morley, who did lump together the observations taken on different days. I propose to show that, instead of giving a null result, the numerical data published in their paper show distinct evidence of an effect of the kind to be expected.

It may here be recalled that in taking an observation, the apparatus was rotated in its mercury bath and readings taken at 16 equidistant points as the reading-telescope passed them. On each occasion this was repeated six times, and the means of the six readings in each position taken. These means are the numbers printed in their paper. They are given for noon on July 8, 9, and 11, and for 6 P.M. on July 8, 9, and 12. The means of these three days are taken and then the means of the first eight and of the second eight, thus eliminating any effect depending on $\cos \alpha$ alone. The result is that there is no apparent displacement of the fringe.

In looking at the sets of readings, one is struck at once with the fact that all the readings continuously increase or decrease. This is evidently the effect of temperature changes. For short intervals, it is extremely likely that the temperature disturbances will be a linear function of the time. If this is exactly so, and if the readings were taken at equal intervals of time, it is possible to eliminate the disturbances due to this. For the readings at the beginning and at the end of a complete revolution ought (in absence of temperature effects) to be the same, whilst on the supposition made above there would be a temperature error altering by equal steps for each successive reading—in a way to be indicated immediately. The readings for each set of complete revolutions should first be corrected in this way and then the average of the six taken to eliminate accidental and personal

The Ether-Drift Experiment and the Determination of the Absolute Motion of the Earth

DAYTON C. MILLER, *Case School of Applied Science*

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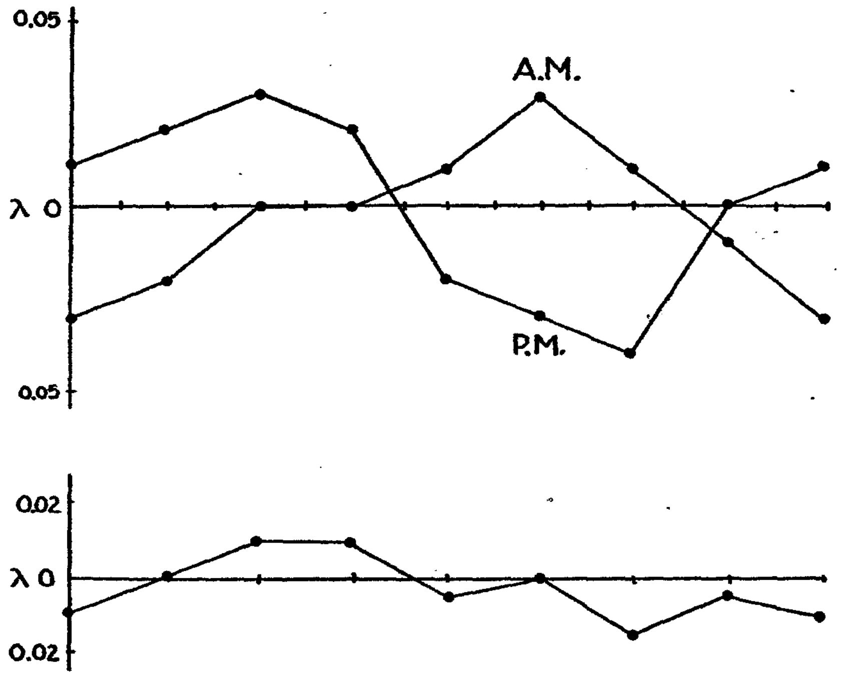

FIG. 11. Method of combining the ether-drift observations of July, 1904, now considered erroneous.

Morley-Miller experiment

being based upon an erroneous hypothesis as to the resultant absolute motion of the earth. The morning and evening observations each indicate a velocity of ether drift of about 7.5 kilometers per second; these values are charted in Fig. 4 in relation to the magnitudes predicted by the new hypothesis of a much larger predominating cosmic motion of the solar system and show reasonable consistency.

Observations by Morley and Miller in 1905

In 1905, the interferometer was mounted in a temporary hut on a site in Cleveland Heights, free from obstruction by buildings and at an altitude of about 285 meters. The house was provided with glass windows at the level of the interferometer so that there should be no opaque screens in the plane of drift. The test of the contraction hypothesis was continued; the wooden rods which determined the length of the optical path in the experiments of 1904 were omitted and all the mirror frames were fastened

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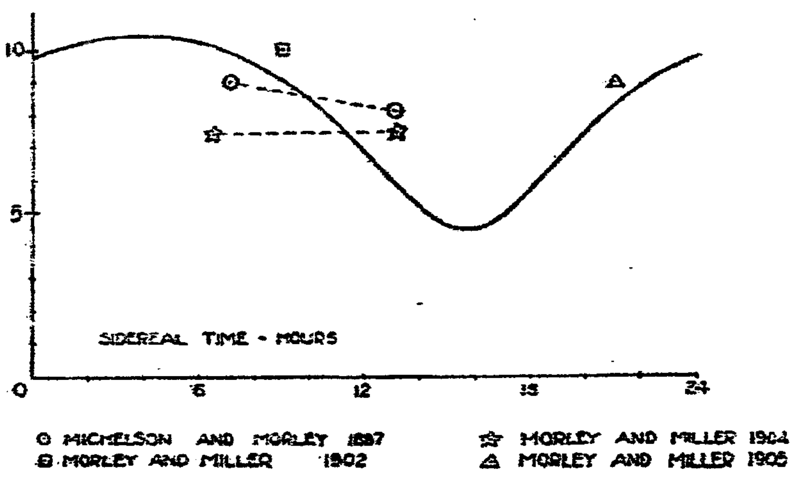
D.C. Miller 1933

cancels the full-period effect and all odd harmonics, giving the shorter curve which is the desired half-period effect (together with any higher even harmonics which may be present). Inspection shows clearly that these curves are not of zero value, nor are the observed points scattered at random; there is a positive, systematic effect. These full-period curves have been analyzed by the mechanical harmonic analyzer, which determines the true value of the half-period effect; this, being converted into its corresponding value for the velocity of relative motion of the earth and ether, gives a velocity of 8.8 kilometers per second for the noon observations, and 8.0 kilometers per second for the evening observations. In Fig. 4, the smooth



$\left(\frac{8.4}{30}\right)^2 \sim \frac{1}{13}$

FIG. 4. Velocity of ether drift observed by Michelson and Morley in 1887, and by Morley and Miller in 1902, 1904 and 1905, compared with the velocity obtained by Miller in 1925.

curve shows the value of the ether-drift throughout the day for the latitude of Cleveland, as

THE LORENT

The Michelso indicated that th incomplete or ir attention becaus and because the Professor FitzGer an explanation hypothesis that t of a solid might b solid through the dimension of the s would be shorten and that this con neutralize the o Michelson-Morley not publish this th he expounded it i was given publicit address on *Aberra Experiments*, prese March 31, 1892, w the *Philosophical* 1893.[5] Lodge has historical fact in ography.[6] In 1895 developed the theo the supposition tha held together by motion of the body upon the electrostat magnetic effect due

L. S. Swenson Jr — 'Physics Today', May 1987

their report begins by stating the rationale for testing the hypothesis of a stationary ether through which the Earth moves. Seeking only Earth's orbital velocity (its speed and direction), they designed the apparatus to increase the path length of the cross of light to about ten times its 1881 value. The influences of Potier and Lorentz were here evident. Null results, once again presented in tabular and graphic form, reinforced the fame of their failure, within significant figures. They had expected a change corresponding to about 0.4 wavelength. They observed a change of less than 0.04 wavelength. Less than 10% of their expectation meant a *conclusive* null result. Yet in their supplement to that classic paper, Michelson and Morley offered at least seven ideas—four possibilities for laboratories and three for observatories—for attacking all over again the problem of the motion of the whole Solar System through space!

In his final Lowell Lecture, "The ether," Michelson confessed:

> The experiment is to me historically interesting, because it was for the solution of this problem that the interferometer was devised. I think it will be admitted that the problem, by leading to the invention of the interferometer, more than compensated for the fact that this particular experiment gave a negative result.

Into the 20th century

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Simplified Theory of the Michelson-Morley Experiment

ROY J. KENNEDY, *University of Washington*

(Received March 22, 1935)

It is shown that a correct application of Huygens' principle in the theory of the experiment leads to the same expression for the expected result as is derived in the simple classical theory. The effect due to path difference is shown to be the same as the effect derivable from the relative rotation of the interfering beams. Critics of the classical theory have mistakenly regarded the latter value as a compensating factor almost exactly offsetting the first.

THE usually accepted theory of the Michelson-Morley experiment has been adversely criticized in a number of papers, the first of which apparently was that of Hicks.[1] Since then Righi[2] and Hedrick[3] have concluded that the effect is not the accepted one, at least not for the so-called "ideal" adjustment of the mirrors, while Woempner[4] and Cartmel[5] derive a third-order expression for the fringe-shift. (By the order of the effect is meant the degree of the ratio β of the velocity of the system through the ether to the velocity of light.) The formulas derived by all these writers involve factors which depend on the adjustment of the apparatus. Righi, Hedrick and Woempner suppose that the fringe-shift to be expected in view of the difference in the times required to traverse the two paths in the interferometer is compensated for by the relative rotation of the two recombining beams, at least in special cases. Their procedure seems to be essentially that of computing the same quantity approximately in two different ways, and then mistakenly subtracting one result from the other. They find that the position of the central fringe is practically unaffected by rotation of the apparatus, but wrongly infer from this fact a null (or very small) effect for the experiment. Oddly enough the third-order effects derived by Woempner and by Cartmel seem to be in good agreement with Miller's experimental data if the linear velocity of the solar system due to rotation of the galaxy is used in evaluating the ratio β.

It was long ago demonstrated by Lorentz[6] that a rotation of the interfering beams of the magnitude actually occurring could not offset the phase difference produced by the relative lengthening of one path as compared to the other. Contrary results have been reached by so many other investigators, however, that it has seemed worth while to attack the problem by a variation of their detailed method with a view to reconciling it with Lorentz's beautifully simple treatment. The present discussion is based almost entirely on the careful application of Huygens' principle to the reflection from the moving mirrors. By this means the directions of the rays in a reference system supposed fixed in the ether are computed; from these directions it is a simple matter to infer the courses of the two beams with respect to the apparatus, and the fringe-shift (or relative phase change) which would result from rotation of the apparatus. It turns out to be unnecessary to compute the lengths of the actual paths in the ether.

In the first place a simple demonstration will be given of the relation of the angle of reflection ϕ to the angle of incidence θ (glancing angles) of a beam of light falling on a mirror moving with velocity v in a direction at an angle α with the normal to the back of the mirror. In Fig. 1 is represented an element of the mirror of length $\delta s(=\overline{op})$. During the time δt between the arrival of the wave front at o and its arrival at p the point p of the mirror will have moved a distance $v\delta t=\overline{pp'}$ to the position p'. Hence by the usual argument it is evident that the reflected wave front will be along $\overline{gp'}$, which is tangent to the

---

[1] Hicks, Phil. Mag. 6, 3, 32, 555 (1902).

[2] Righi, Comptes rendus, 1917, several papers. These are summarized in English by Stein, Memori della Societa Astronomica Italiana I, 283 (1920).

[3] Hedrick, Conference on the Michelson-Morley Expt., Astrophys. J. 68 (1928).

[4] Woempner, unpublished manuscript.

[5] Cartmel, paper presented at the Pittsburgh Meeting of the Am. Phys. Soc., Dec. 27–29, 1934. Phys. Rev. 47, 333A (1935).

[6] Lorentz, demonstration restated at Conference, reference 3.

fringe-widths simply the ratio of x to this width, i.e.,

$$\frac{l\beta^2 \cos 2\psi/\tan 2(\omega_2-\omega_1)}{\lambda/\tan 2(\omega_2-\omega_1)}=\frac{l}{\lambda}\beta^2 \cos 2\psi. \quad (3)$$

Now the wave fronts from mirror M_2 are indistinguishable from those from M_2' except as to phase, and from the elementary theory of the experiment it turns out that the variable part of this difference of phase is the distance between M_2 and M_2' multiplied by $(\beta^2/\lambda) \cos 2\psi$. The distance is $l \tan \omega_2$ so the fringe-shift due to this path-difference is $(l/\lambda)\beta^2 \cos 2\psi \tan \omega_2$; because of the factor $\tan \omega_2$ this is evidently ignorable in comparison with the shift expressed in Eq. (3).

The errors of the writers referred to are of two kinds: they either confuse the central fringe defined above with the axial fringe, and so infer a null effect from the fact that the former is practically stationary, or else regard the effect computed above from the angular deviations of the rays as but one component of the whole effect, the other being the shift due to the difference in the lengths of the two paths. By computing the latter approximately (to the second order) and the former to the third order, one erroneously derives a third-order effect. It is readily shown, however, that the *total* effect is expressed in Eq. (3) which we have derived. For the wavefronts in each beam are parallel planes at fixed distances apart, two of which intersect in a line (the central fringe established by a hypothetical case) which is practically fixed in the axes moving with the apparatus. Hence their intersections, and the fringes formed at them, are completely determined in position by the angles between the wave fronts.

Hence the total effect to be expected in the experiment is expressed in Eq. (3), which is the same as results from the simple approximate theory.

The same variation in phase exists in the "ideal" case, i.e., that in which the end-[illegible] are exactly perpendicular to the axes, al[illegible] then the approximate expression in te[illegible] fringe-width would not be valid and the [illegible] would become indefinitely broad. Never[illegible] the method employed by the writer [illegible] Illingworth,[8] in which the phase-shift [illegible] exhibit itself by unbalancing a split photo[illegible] field, would still be applicable. In other [illegible] the "ideal" case is special only in that the [illegible] produced are too broad to permit direct [illegible] estimation of their positions.

The actual experiment, of course, deal[illegible] cones of rays brought finally to a focu[illegible] telescope, instead of plane waves interferi[illegible] a screen. The latter have been considere[illegible] only because they have given rise to the [illegible] confusion. It is much simpler, paraph[illegible] Lorentz, to treat the general case. The [illegible] differences may be computed by the eleme[illegible] method in which the second-order differen[illegible] direction discussed above are ignored fo[illegible] reason that such directional differences ca[illegible] produce errors of order higher than the s[illegible] in the result. For, if the approximate val[illegible] the length of either path be l_0 while the [illegible] length is a function $l(\epsilon_1, \epsilon_2, \epsilon_3)$ where the [illegible] ments are the small angles (of the order [illegible] between corresponding segments of the [illegible] and approximate paths, then on expansi[illegible] the function we find for the error

$$l(\epsilon_1, \epsilon_2, \epsilon_3)-l_0=\epsilon_1\frac{\partial l}{\partial \epsilon_1}+\epsilon_2\frac{\partial l}{\partial \epsilon_2}+\epsilon_3\frac{\partial l}{\partial \epsilon_3}$$

+terms involving higher powers of t[illegible]

But Fermat's principle requires that the pa[illegible] a minimum; hence the first derivatives va[illegible] showing that the error involves only powe[illegible] β higher than the third, and therefore igno[illegible]

[7] Kennedy, Proc. Nat. Acad. Sci. 12, 621 (1926).
[8] Illingworth, Phys. Rev. 30, 692 (1927).

M.C.
E. Costanzo
2003

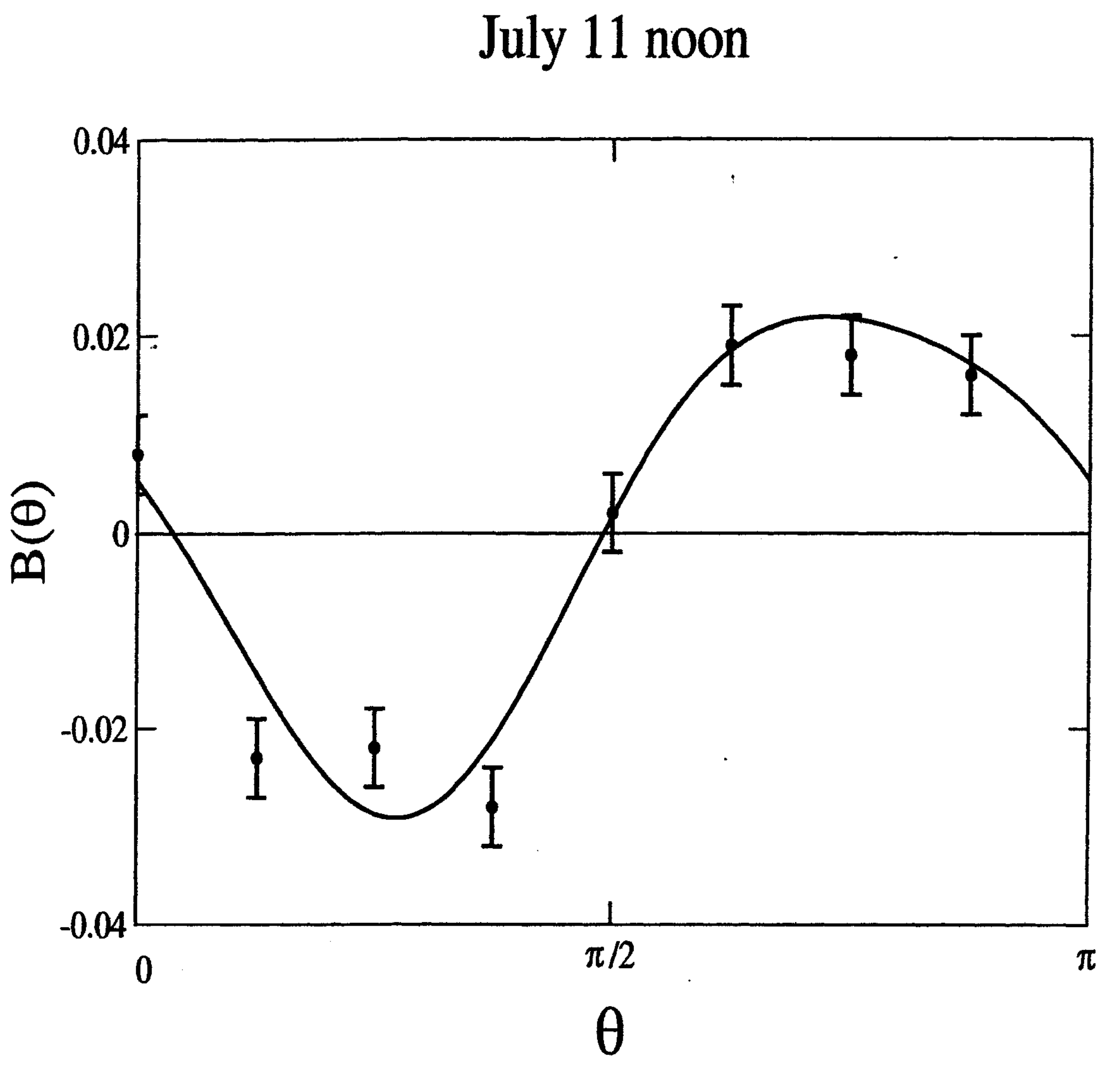


Figure 2: A typical fit Eq.(4) to the even combination of fringe shifts $B(\theta) = \frac{\Delta\lambda(\theta)+\Delta\lambda(\pi+\theta)}{2\lambda}$ obtained from the data reported in Table 1. The fitted amplitudes are $\bar{A}_2 = 0.025 \pm 0.004$ and $\bar{A}_4 = 0.004 \pm 0.004$.

M.C.
E. Costanzo 2003

$$\frac{\Delta\lambda(\theta)}{\lambda} \simeq \underbrace{\frac{D}{\lambda}\frac{V_{obs}^2}{c^2}}_{\bar{A}_2} \cos(2\theta)$$

SESSION	$\bar{A}_2$
July 8 (noon)	0.010 ± 0.005
July 9 (noon)	0.015 ± 0.005
July 11 (noon)	0.025 ± 0.005
July 8 (evening)	0.014 ± 0.005
July 9 (evening)	0.011 ± 0.005
July 12 (evening)	0.018 ± 0.005

Table 2: We report the amplitude of the second-harmonic component $\bar{A}_2$ obtained from the fit Eq.(4) to the various samples of data.

$$\langle \bar{A}_2 \rangle \simeq 0.0155 \pm 0.0020$$

$$V_{obs} \simeq 8.4 \pm 0.5 \quad km/s$$

The interferometer is being set up again on the campus of Case School of Applied Science in Cleveland, near the place where the original Michelson-Morley experiment was performed in 1887. It is proposed to make a series of observations for four epochs of the year, comparable in every way with the Mount Wilson series. This will give information as to the possible effects of local conditions; it is hoped that it will show more definitely whether there is any effect due to altitude, and whether the orbital motion is appreciable.

IV. DR. ROY J. KENNEDY (CALIFORNIA INSTITUTE OF TECHNOLOGY)

When Professor Miller published the conclusions that he presented to us yesterday, it became necessary, or at least very desirable, that the experiment be repeated independently. It is such a performance of the experiment that I shall discuss this morning.

In this experiment the light-paths were reduced to about 4 m, and the required sensitiveness was obtained by an arrangement capable of detecting a very slight displacement of the interference pattern. The whole optical system was inclosed in a sealed metal case containing helium at atmospheric pressure. Because of its small size, the apparatus could be effectively insulated, and circulation and variations in density of the gas in the light-paths nearly eliminated. Furthermore, since the value of $\mu-1$ for helium is only about one-tenth that for air at the same pressure, it will be seen that the disturbing effects of changes in density of the gas correspond to those in air at only a tenth of an atmosphere of pressure. Actually it was found that any wavering of the interference pattern was imperceptible, and when temperature equilibrium had been reached there was no steady shift.

The plan of the apparatus is sketched in Figure 8. The optical parts are mounted on a marble slab 122 cm square by 10.5 cm thick, which rests on an annular float in a pan of mercury 77 cm in diameter. This is simply a reduced copy of Michelson's original mounting. The mirrors M_1, M_4, and M_5 are fixed in position; such adjustments of the compensating plate C and mirror M_2 as are necessary after the cover is in place can be made from the observer's position at the telescope. The green light λ 5461 is separated by the lens and prism system from the radiation of a small mercury arc lamp that a should not be much less than 0.025 λ, which was the value finally used. Substituting these values in the last equation, we get

$$\delta x = 5 \times 10^{-5} \lambda$$

as the least detectable change in position of one of the mirrors. This corresponds to a change of optical length of path

$$\delta l = 2\delta x = 10^{-4} \lambda .$$

To take full advantage of the possibilities of the arrangement would have required perfect mirrors and an intenser and, therefore, hotter source of light than would have been desirable near the sensitive apparatus, as well as lengthening the interval between observations, thus allowing greater chance for any steady temperature shift to show itself. No attempt was made in the experiment, therefore, to go below values of δl equal to $2 \times 10^{-3} \lambda$; such variations were detectable without the least uncertainty.

With this apparatus the velocity of 10 km/sec. found by Professor Miller would produce a shift corresponding to 8×10^{-3} wavelengths of green light, which is four times the least detectable value.

The experiment was performed in a constant-temperature room in the Norman Bridge Laboratory at various times of day, but oftenest at the time when Miller's conclusions require the greatest effect. The sensitiveness of the eye was tested for each trial by the placing or removal of a small weight on the slab before and after rotating it. There being no fluctuations in the field of view, it was unnecessary to take the average of a number of readings. As has been shown, a shift as small as one-fourth that corresponding to Miller's would have been perceived. The result was perfectly definite. There was no sign of a shift depending on the orientation.

Because an ether drift might conceivably depend on altitude, the experiment was repeated on Mount Wilson, in the 100-inch telescope building. Here again the effect was null.

[*Note added April, 1928.*—Illingworth at the California Institute of Technology has continued the work with Kennedy's apparatus, using improved optical surfaces and a method of averaging. He concludes[1] that no ether drift as great as 1 km/sec. exists.]

[1] *Physical Review*, 30, 692, 1927.

H. Múnera
1998

Since N is small, we have calculated the error bounds using a two-tailed Student's test at the 95% C.L., rather than a normal distribution. As shown in Table 3, the low bound is higher than zero in over half the cases.

TABLE 4. Intra-session variability of velocity

	Miller's session at 03:02, Sept. 23, 1925				Illingworth's session 2A, July 9, 1927		
Turn, j	y_j	$\|y_j\|$	V_A, km/s		y_j^*	$\|y_j\|$	V_A, km/s
1	-1.17	1.17	9.62		-0.50	0.50	3.54
2	-0.83	0.83	8.13		+0.33	0.33	2.89
3	-0.83	0.83	8.13		-0.33	0.33	2.89
4	-0.33	0.33	5.14		-0.33	0.33	2.89
5	-3.00	3.00	15.42	adjust	-0.83	0.83	4.57
6	+0.50	0.50	6.30		+1.17	1.17	5.41
7	-1.67	1.67	11.50		+0.50	0.50	3.54
8	-0.50	0.50	6.30		+0.17	0.17	2.04
9	-1.67	1.67	11.50	adjust	0.00	0.00	0.00
10	-0.17	0.17	3.64		-0.50	0.50	3.54
11	-1.50	1.50	10.91				
12	-0.33	0.33	5.14				
13	+0.83	0.83	8.13				
14	+0.67	0.67	7.27				
15	-2.00	2.00	12.59				
16	-1.00	1.00	8.90				
17	+0.33	0.33	5.14				
18	-0.83	0.83	8.13				
19	-0.50	0.50	6.30	adjust			
20	-0.50	0.50	6.30				
Average	|-0.72|	0.96	8.22		|-0.03|	0.47	3.13
U.B. ** 95% CL	1.17	1.29	9.61		0.45	0.71	4.17
L.B. ** 95% CL	0.28	0.63	6.83		0	0.23	2.09
Results in km/s							
Average	7.58	8.72	8.22		0.91	3.42	3.13
U.B. ** 95% CL	9.63	10.10	9.61		3.36	4.21	4.17
L.B. ** 95% CL	4.70	7.06	6.83		0	2.42	2.09

* Illingworth's y has reversed sign relative to eq. (11)

** U.B.= upper bound, L.B.= lower bound, CL= confidence level

Miller 8.2 ± 1.4 km/s
95% C.L.

3.1 ± 1.0 km/s
95% C.L.
Illingworth

Lichtweg Verschiebungen bis zu $^1/_{10}$ Streifenbreite beobachtet wurden, auf störende Einflüsse zurückgeführt sein. Zum Vergleich, welche Genauigkeitsforderungen man stellt, wenn man $^1/_{1000}$ Streifen als obere Grenze setzt, sei folgendes angeführt: Bei einem Lichtweg von 21 m und einer Wellenlänge von 5461 Å.-E. bedeutet eine Änderung von $^1/_{1000}\,\lambda$ eine relative Änderung von $2{,}6 \cdot 10^{-11}$. Setzen wir die Entfernung Erde—Mond mit rund $3{,}6 \cdot 10^{10}$ cm in Rechnung, so entspricht diese relative Genauigkeit der Forderung, daß eine Änderung dieser Entfernung um 1 cm noch nachweisbar sein soll. Damit ist auch ein von Strömberg[1]) berechneter Effekt von $^{17}/_{1000}$ Streifenbreiten Verschiebung für 16 m Lichtweg, den Michelson erwähnt, als sicher nicht vorhanden erwiesen.

Weniger in die Augen springend ist der Fortschritt an Genauigkeit, wenn man aus der Streifenverschiebung *gegen die Mittellage* nach der bekannten Formel

$$\Delta Z = \frac{l}{\lambda}\left(\frac{v}{c}\right)^2 \tag{1}$$

die Grenze der Geschwindigkeit v des Ätherwinds berechnet. Wegen des quadratischen Eingehens von v bedingt $^1/_{1000}$ Streifen Genauigkeit als obere Grenze für v den Betrag 1,5 km/sec.

Einen Vergleich mit einem „erwarteten Effekt“ zu ziehen, ist ziemlich müßig, da man heute weiß, daß der Hauptanteil der Erdbewegung durch die gemeinsame Geschwindigkeit des Milchstraßensystems (Größenordnung 300 km/sec) gegeben ist, die jedoch nach Richtung und Betrag noch reichlich unsicher ist. Der volle Effekt dieser Bewegung würde eine Verschiebung um rund 38 Streifen verursachen, wie man durch Einsetzen in (1) sofort sieht.

Es war nun ursprünglich geplant, den Apparat auf das Jungfraujoch zu schaffen. Herr Direktor Lichti von der Jungfraubahngesellschaft unterstützte die Vorbereitungen aufs wärmste, wofür ihm der Dank ausgesprochen sei. Inzwischen hat sich aber durch den Widerruf der ursprünglich angegebenen Höhenabhängigkeit des Effekts durch D. C. Miller die Situation

1) Erwähnt in der oben zitierten Arbeit von Michelson, Pease und Pearson. Näheres konnte darüber nicht in Erfahrung gebracht werden.

wesentlich verändert und man kann mit Recht fragen, ob angesichts dieser Änderung, ferner angesichts des völlig negativen Ausfalls aller in der Höhe unternommenen Wiederholungen des Trouton-Noble-Versuchs[1]) und angesichts der finanziellen Notlage der deutschen Wissenschaft die Kosten einer derartigen Expedition noch zu rechtfertigen wären.

Zusammenfassung

Es wird ein registrierendes Michelson-Interferometer von 21 m Lichtweg beschrieben. Die mikrophotometrische Ausmessung der damit gemachten Aufnahmen ergibt, daß ein etwa vorhandener Ätherwindeffekt hleiner als $^1/_{1000}$ *Streifenbreite, der Betrag des Ätherwinds kleiner als 1,5 km/sec sein müßte.*

Zum Schluß möchte ich dem Vorstand des Physikalischen Instituts der Universität Jena, Herrn Geh. Rat M. Wien noch besonders dafür danken, daß er für die zahlreichen Hilfsarbeiten (Untersuchung der Materialien, Photometrierung der Platten usw.) die Institutsmittel unbeschränkt zur Verfügung stellte.

1) R. Tomaschek, Ann. d. Phys. **78**. S. 743. 1925; **80**. S. 509. 1926; **84**. S. 161. 1927. C. T. Chase, Phys. Rev. **30**. S. 516. 1927.

Jena, September 1930.

(Eingegangen 27. September 1930.)

Summary of the classical ether-drift experiments:

1) Michelson-Morley , Morley-Miller, Miller **(air)**

$$v_{obs} \approx 8.5 \pm 1.5 \quad \text{km/s}$$

anisotropy of the speed of light : $(v_{obs}/c)^2 \approx 10^{-9}$

2) Kennedy, Illingworth **(helium)**

$$v_{obs} \approx 3.1 \pm 1.0 \quad \text{km/s}$$

anisotropy of the speed of light : $(v_{obs}/c)^2 \approx 10^{-10}$

3) Joos **(vacuum)**

$$v_{obs} < 1.5 \quad \text{km/s}$$

anisotropy of the speed of light : $(v_{obs}/c)^2 \approx 10^{-11}$

$v_{obs} \neq 0 \Rightarrow$ **the two-way speed of light is anisotropical for an observer S' placed on the Earth**

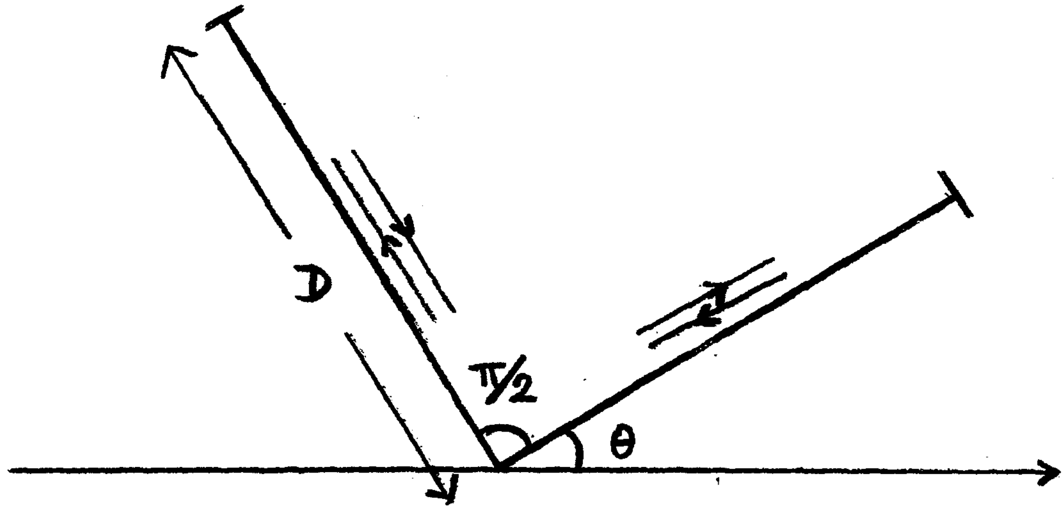
Standard approach: isotropy in a preferred frame Σ

Σ		S'
c	**Galilei's transformation**	c ± v
$u = \frac{c}{N_{medium}}$	**Lorentz transformation**	$\frac{u - \gamma v + v(\gamma - 1)\frac{v \cdot u}{v^2}}{\gamma\left(1 - \frac{v \cdot u}{c^2}\right)}$

Two-way speed of light in S'

$$\frac{\overline{u}'(\theta)}{u} = 1 - (A + B \sin^2\theta)\frac{v^2}{c^2}$$

$$A \approx N^2_{medium} - 1 \qquad B \approx -\frac{3}{2}(N^2_{medium} - 1)$$



$$\frac{\Delta\lambda(\theta)}{\lambda} = \frac{u}{\lambda}\left[\frac{2D}{\overline{u}'(\theta)} - \frac{2D}{\overline{u}'(\pi/2+\theta)}\right] \approx \frac{D}{\lambda}\,\frac{v^2}{c^2}\,(-2B)\,\cos(2\theta)$$

$$v^2{}_{obs} \approx v^2(-2B) \qquad\qquad B \approx -3(N_{medium} - 1)$$

Michelson-Morley
Morley-Miller $v_{obs} \approx (8.5 \pm 1.5)$ **km/s** $\Rightarrow$ $v_{earth} \approx (204 \pm 36)$ **km/s**
Miller

$$N_{air} - 1 \approx 2.9 \cdot 10^{-4}$$

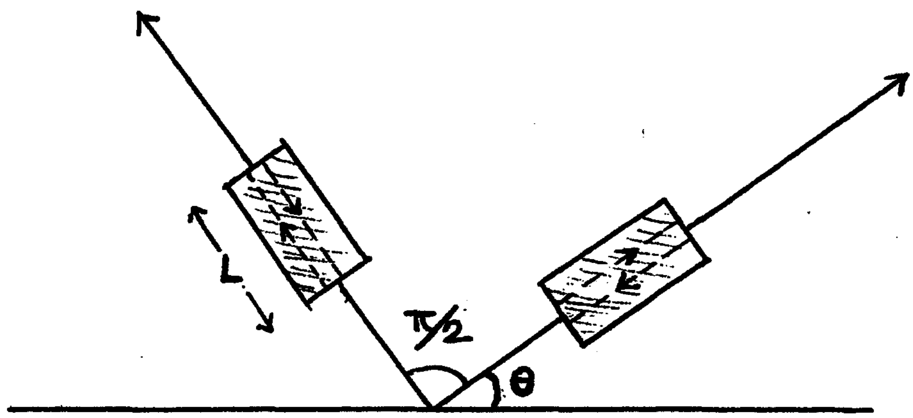
Kennedy
Illingworth $v_{obs} \approx (3.1 \pm 1.0)$ **km/s** $\Rightarrow$ $v_{earth} \approx (213 \pm 72)$ **km/s**

$$N_{helium} - 1 \approx 3.6 \cdot 10^{-5}$$

Joos $v_{obs} \approx 1$ **km/s** $\Rightarrow$ $v_{earth} \approx 150 \div 400$ **km/s**

$$N_{vacuum} - 1 = O(10^{-6})$$

Modern ether-drift experiments



$$\nu(\theta) = \frac{\bar{u}'(\theta)}{2L} n \qquad\qquad n = \text{integer}$$

$$\frac{\Delta\nu(\theta)}{\nu} = \frac{\bar{u}'(\theta) - \bar{u}'(\pi/2+\theta)}{u} \approx \frac{v^2}{c^2}(-2B_{medium})\cos(2\theta)$$

In very high vacuum

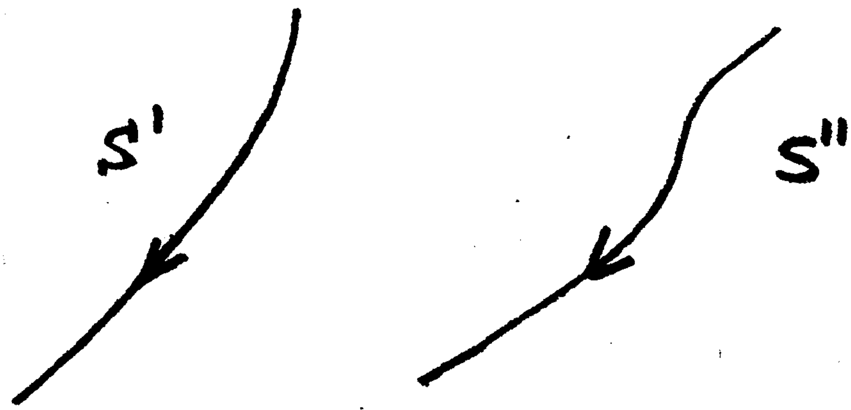
$$\left\langle \frac{\Delta\nu}{\nu} \right\rangle_{exp} = (2.6 \pm 1.7) \cdot 10^{-15}$$

Mueller et al. 2003

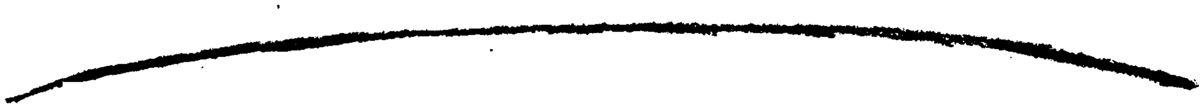
Theoretical interpretation $B_{vacuum} \approx -3(N_{vacuum} - 1)$

$$N_{vacuum} = ?$$

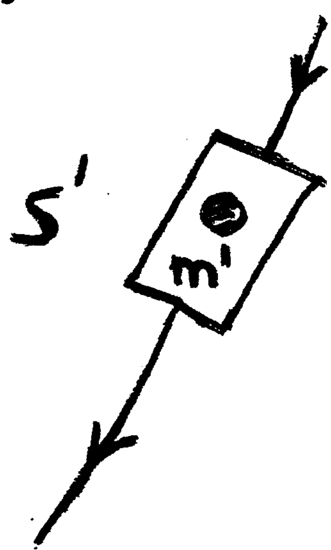
Freely falling frames



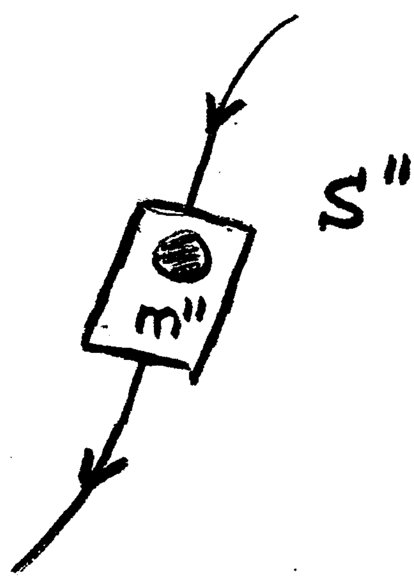
Locally $c' \approx c'' \approx c$ **Equivalence Principle**



However, if S' and S'' carry on board two different heavy objects with mass m' and m''



$c' \neq c'' \neq c$



How to compute c' and c'' ? Use General Relativity

To first order the isotropic form of the Schwarzschild metric is

$$ds^2 \approx (1+2\varphi)dt^2 - (1-2\varphi)(dx^2+dy^2+dz^2)$$

so that $$N_{vacuum} \approx 1-2\varphi$$

For an observer S' placed on the Earth

$$\varphi = -\frac{G_N M_{earth}}{c^2 R_{earth}} \approx -0.7 \cdot 10^{-9}$$ **so that**

$$|B_{vacuum}| \approx 3(N_{vacuum}-1) \approx 4 \cdot 10^{-9}$$

From the classical experiments one gets $v_{earth} \approx (204 \pm 36)$ **km/s, thus**

$$\left\langle \frac{\Delta\nu}{\nu} \right\rangle_{theor} \approx \frac{v^2{}_{earth}}{c^2} |B_{vacuum}| \approx (1.9 \pm 0.7) \cdot 10^{-15}$$

consistent with the experimental result

$$\left\langle \frac{\Delta\nu}{\nu} \right\rangle_{exp} = (2.6 \pm 1.7) \cdot 10^{-15}$$ **Mueller et al. 2003**

What the classical ether-drift experiments say:

- To exclude (or confirm) the existence of a preferred frame, one should replace the high vacuum in the resonating cavities with a gaseous dielectric medium

- If the small deviations found in the classical experiments were not mere instrumental artifacts, the typically measured frequency shift

$$\Delta\nu \approx 1 \text{ Hz} \qquad (\text{in the vacuum where } B_{vacuum} \approx 10^{-9})$$

should increase by orders of magnitude. For instance, one should find

$$\Delta\nu \approx 100 \text{ kHz} \qquad (\text{in the air where } B_{air} \approx 10^{-4})$$

$$\Delta\nu \approx 10 \text{ kHz} \qquad (\text{in the helium where } B_{helium} \approx 10^{-5})$$

- Check with the experiment performed by Jaseja et al. in 1963 using He-Ne masers. In this case, the result is equivalent to an experiment with cavities filled with a He-Ne mixture ($\approx$90% He and $\approx$10% Ne). Taking into account the various refractive indices, we obtain $B_{He\text{-}Ne} \approx 1.2 \cdot 10^{-4}$.

Both values, however, give a critical half thickness below 500 Å. Thus, we see that a film somewhat thinner than 1000 Å *could* break up into a mixed state. Whether it does, however, depends on whether it is energetically favorable to do so. There is, though, one further piece of information. Even though κ is greater than 0.707 in a thin film, the order will probably be constant across the film thickness d, for we can show that $L>d$ for $d<d_{\text{critical}}$. From (35)

$$a/L=\frac{A}{0.91}\left[\frac{H_c(t)}{H_0}\frac{\lambda_L(t)}{\lambda_L(0)}\right](a/\xi_0)^{1/2}. \qquad (42)$$

For diffuse scattering, which gives the slightly larger estimate, we obtain from (42) the result

$$a/L=0.45, \quad \text{at } T=0^{\circ}\text{K}, \quad a=a_{\text{critical}}. \qquad (43)$$

For thinner films, higher temperatures, or specular scattering, a/L is even smaller. Thus we see that the order probably does not vary across the film thickness in a thin film.

To summarize our results, we have shown that a simple nonlocal model previously used with some success to calculate the critical fields of superconducting films can also be used to calculate the Ginzburg-Landau-Abrikosov-Gor'kov parameters such as the weak field penetration depth δ_0, the dimensionless parameter κ, and the range of order parameter $L=\delta_0/\kappa$. We have calculated these quantities in the local limit and have shown that the results are in good agreement with those obtained by other techniques. We have also obtained simple expressions for these parameters which are valid in the thin limit. From these limiting formulas, we show that κ can get large in a thin film and estimate that κ exceeds the critical value of $1/\sqrt{2}$ in indium films somewhat thinner than 1000 Å. We also conclude that in the thin limit, one would expect the order parameter to be constant across the film thickness.

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Test of Special Relativity or of the Isotropy of Space by Use of Infrared Masers*

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(Received 26 July 1963; revised manuscript received 30 October 1963)

The highly monochromatic frequencies of optical or infrared masers allow very sensitive detection of any change in the round-trip optical distance between two reflecting surfaces. Hence, comparison of the frequencies of two masers with axes perpendicular to each other allows an improved experiment of the Michelson-Morley type, or a very precise examination of the isotropy of space with respect to light propagation. Two He-Ne masers were mounted with axes perpendicular on a rotating table carefully isolated from acoustical vibrations. Their frequency difference was found to be constant to within 30 cps over times as short as about one second, or to one part in 10^{13} of the maser frequency, which is near 3×10^{14} cps. Rotation of the table through 90° produced repeatable variations in the frequency difference of about 275 kc/sec, presumably because of magnetostriction in the Invar spacers due to the earth's magnetic field. Examination of this variation over six consecutive hours shows that there was no relative variation in the maser frequencies associated with orientation of the earth in space greater than about 3 kc/sec. Hence there is no anisotropy or effect of either drift larger than 1/1000 of the small fractional term $(v/c)^2$ associated with the earth's orbital velocity. This preliminary version of the experiment is more precise by a factor of about 3 than previous Michelson-Morley experiments. There is reason to hope that improved versions will allow as much as 2 more orders of magnitude in precision, and that similar techniques will also yield considerably improved precision in an experiment of the Kennedy-Thorndike type.

OPTICAL and infrared masers make possible and attractive a number of new experiments, and refinements of old ones, where great precision in measurement of length is needed. On type is the examination of the isotropy of space for light propagation, or more specifically the examination of what effects the earth's velocity or various other fields may have on the velocity of light. We have completed the first stages of an experiment with He-Ne masers which can be regarded as equivalent to a Michelson-Morley experiment of improved precision. These preliminary tests show that the effect of "ether drift" is less than 1/1000 of that which might be produced by the earth's orbital velocity.

* Work supported by the U. S. National Aeronautics and Space Administration and by a Tri-Service Contract in the Research Laboratory of Electronics.
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I. INTRODUCTION

A synoptic treatment of the connections between measurements in coordinate systems in relative motion

He-Ne maser experiment

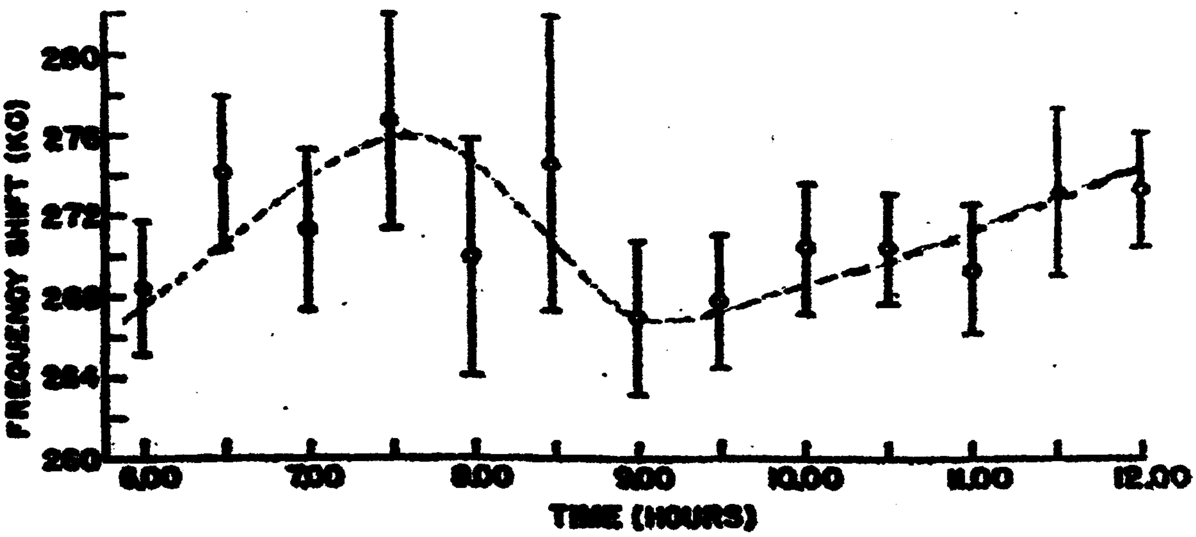


FIG. 3. Plot of relative frequency variation of two masers with 90° rotation as a function of the time of day between 6:00 a.m. and 12:00 noon on 20 January, 1963.

order of magnitude in precision of the search for any anisotropy. It appears likely that great care in this experiment may eventually allow two orders of magnitude improvement, or detection of any effects of anisotropy as large as five orders of magnitude less than the $(v/c)^2$ term associated with an "ether drift" when v is the earth's velocity.

It is clear from the introduction that the Kennedy-Thorndike experiment, or the comparison of time and length, already represents the greatest uncertainty in an experimental test of transformation of the line element in a moving coordinate system. Fortunately this too may be now redone with considerable accuracy by

$\delta_b(\Delta\nu) = (1.6 \pm 1.2)$ kHz

FIG. 3. Plot of relative frequency variation of two masers with)° rotation as a function of the time of day between 6:00 a.m. nd 12:00 noon on 20 January, 1963.

OR OF ISOTROPY OF SPACE A1225

$\delta_a(\Delta\nu) = (9 \pm 6)$ kHz

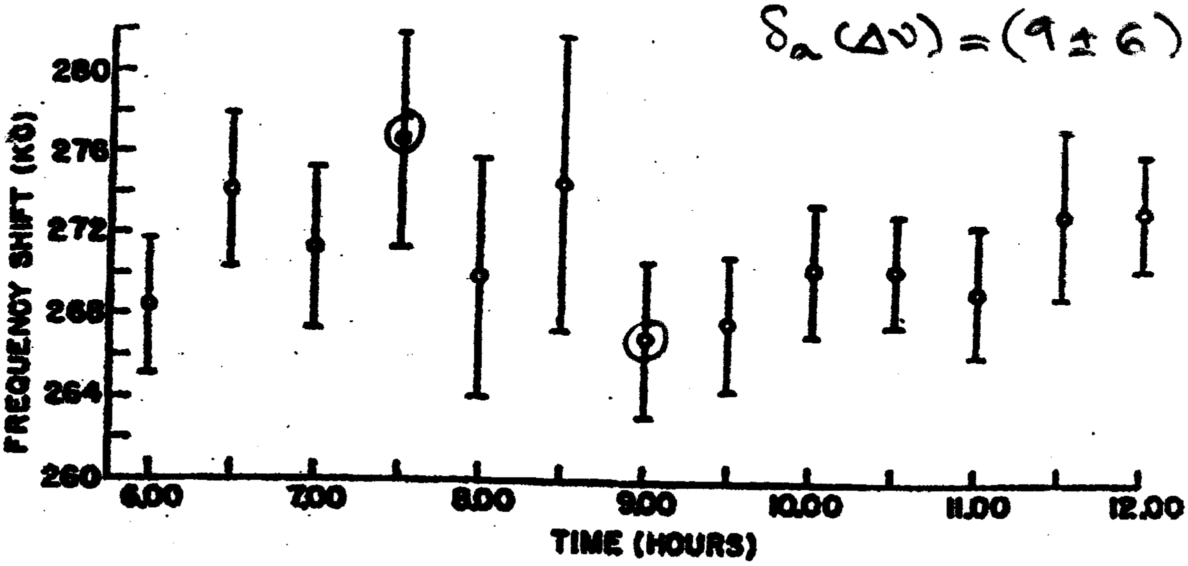


FIG. 3. Plot of relative frequency variation of two masers with)° rotation as a function of the time of day between 6:00 a.m.

Predictions for the experiment with He-Ne masers

The general formula

$$\Delta\nu = \nu \, B_{medium} \frac{v_{earth}^2}{c^2}$$

using $\nu \approx 3 \cdot 10^{14}$ Hz, $B_{He\text{-}Ne} \approx 1.2 \cdot 10^{-4}$ and the range

$v_{earth} \approx 204 \pm 36$ km/s , leads to the following reference value for the

frequency shift

$$(\Delta\nu)_{ref} \approx 16 \quad \text{kHz}$$

Look for a time modulation of $\Delta\nu$ in the data of Jaseja et al. There is a maximum at $\approx$7:30 a.m. and a minimum at $\approx$9:00 a.m..

To evaluate the difference between maximum and minimum, one can follow two different strategies:

a) just consider the two data corresponding to the maximal and minimal values. In this case, one gets

$$\delta_a(\Delta\nu) \equiv \Delta\nu_{exp}(7{:}30 \text{ a.m.}) - \Delta\nu_{exp}(9{:}00 \text{ a.m.}) \approx (9 \pm 6) \text{ kHz}$$

b) group the data in bins of five, by defining average values, $\langle\Delta\nu\rangle_{exp}(7:30$ a.m.) and $\langle\Delta\nu\rangle_{exp}(9:00$ a.m.). In this case, one gets

$$\delta_b(\Delta\nu) \equiv \langle\Delta\nu\rangle_{exp}(7:30 \text{ a.m.}) - \langle\Delta\nu\rangle_{exp}(9:00 \text{ a.m.}) \approx (1.6 \pm 1.2) \text{ kHz}$$

which is the procedure followed by Jaseja et al.

Using the reference value of 16 kHz, the theoretical prediction for the time modulation of the frequency shift can be expressed as

$$\delta(\Delta\nu)_{theor} \approx 16\,\mathrm{kHz}\,\frac{v^2{}_{earth}(7:30\,\mathrm{a.m.}) - v^2{}_{earth}(9:00\,\mathrm{a.m.})}{(200\,\mathrm{km/s})^2}$$

For a rough evaluation of the ratio of Earth's velocities

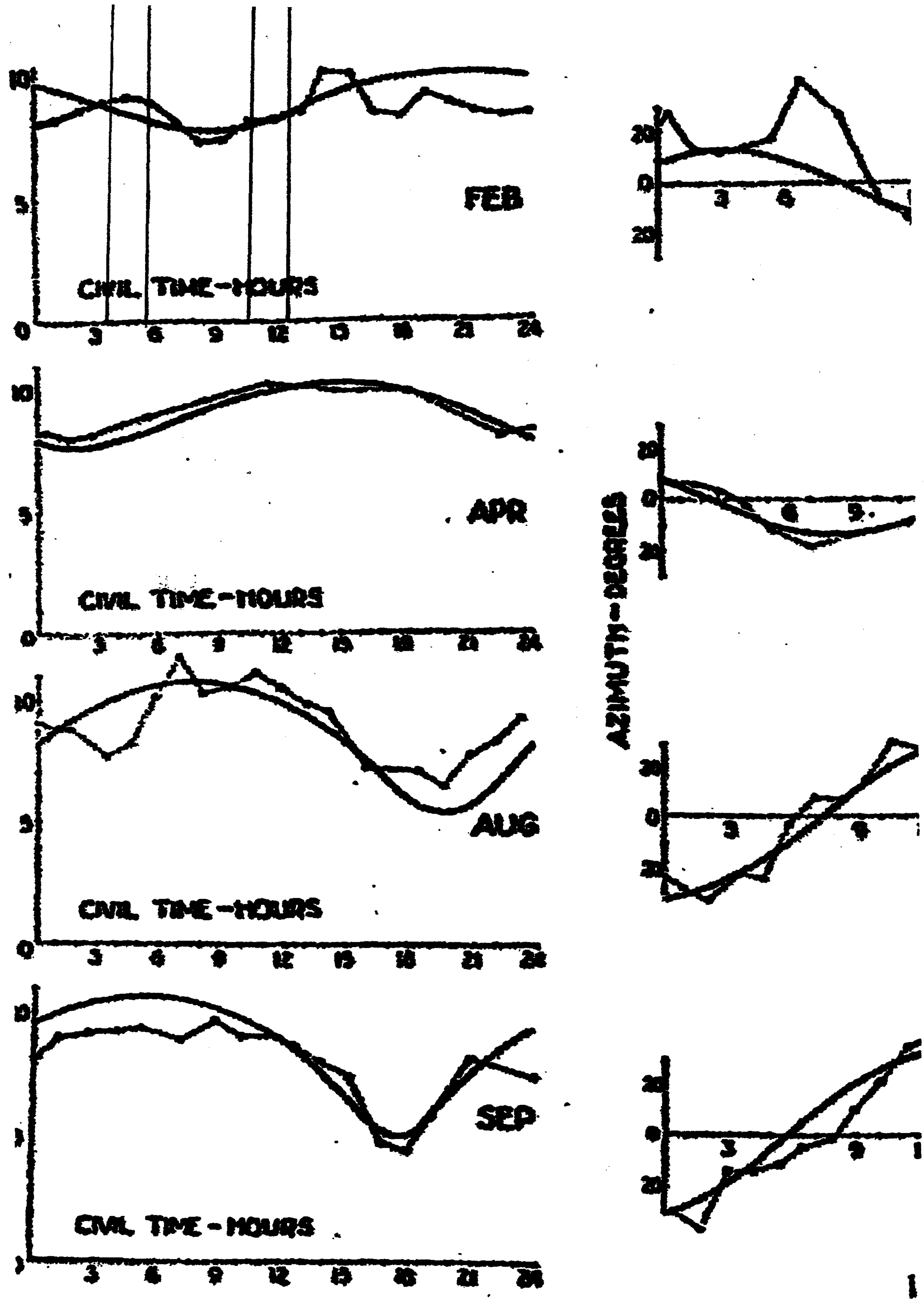
$$\frac{\delta v^2}{v^2} = \frac{v^2{}_{earth}(7:30\,\mathrm{a.m.}) - v^2{}_{earth}(9:00\,\mathrm{a.m.})}{(200\,\mathrm{km/s})^2}$$

one can compare the time modulation of the maser experiment (Fig. 3 of Jaseja et al.) with the time modulation of Miller's v_{obs}, at about the same hours of the day and epoch of the year, (Miller's Fig. 27).

Although one does not expect an exact correspondence (different locations of the laboratories, Mt.Wilson and Boston, and different periods of the year, January 20th and ≈February 8th) the two trends are surprisingly close. Therefore, one can try to use Miller's data to predict the value of $\frac{\delta v^2}{v^2}$ to be used in $\delta(\Delta\nu)_{theor}$.

Depending on the adopted experimental value, i.e.

$$\delta_a(\Delta\nu) \approx (9 \pm 6)\ \mathrm{kHz} \qquad \text{or} \qquad \delta_b(\Delta\nu) \approx (1.6 \pm 1.2)\ \mathrm{kHz}$$


FEB
CIVIL TIME—HOURS
APR
CIVIL TIME—HOURS
AUG
CIVIL TIME—HOURS
SEP
CIVIL TIME—HOURS
AZIMUTH—DEGREES

one has to choose whether to average the Miller's data or just to take the difference between maximal and minimal velocities. In the two cases, one gets corresponding values of $\frac{\delta v^2}{v^2}$

say $\frac{(\delta v^2)_a}{v^2}$ **and** $\frac{(\delta v^2)_b}{v^2}$**, that range from** ≈ 0.1 **to** ≈ 0.4 **.**

The corresponding theoretical predictions for $\delta(\Delta\nu)_{theor}$ **are found in the range from**

$$\approx 1.6\ \text{kHz} \ \text{to} \approx 6.4\ \text{kHz}$$

and completely consistent with the experimental data.

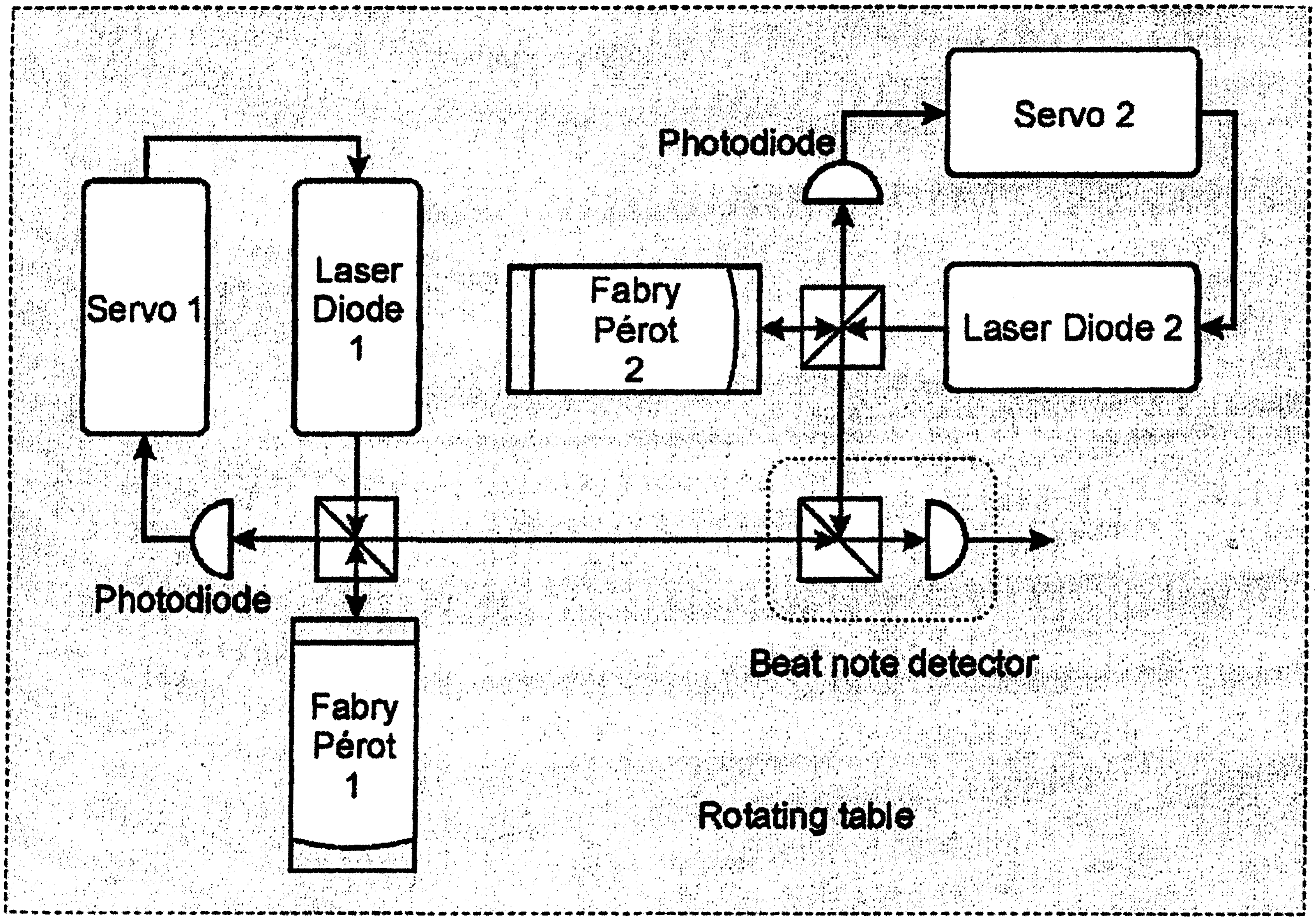


Fig. 1

L'intero
opportu
necessa
dall'am
Poiché
vuoto p
spinto
alloggia
una vol
gas, sa
delle m
specchi

Conclusions

1) Modern ether-drift experiments look for a preferred frame by measuring the relative frequency shift $\Delta\nu$ between two cavity-stabilized lasers, upon local rotations of the apparatus or under the Earth's rotation.

2) If the small deviations found in the classical experiments were not mere instrumental artifacts, by replacing the high vacuum used in the resonating cavities with a dielectric gaseous medium (e.g. air), the typical measured $\Delta\nu \approx 1\,\text{Hz}$, should increase by orders of magnitude.

3) This prediction is consistent with the characteristic modulation of a few kHz observed in the original experiment with He-Ne masers. However, the rather large experimental errors require new experimental checks. If the predicted enhancement will not be confirmed by new and more precise data, the existence of a preferred frame can be definitely ruled out.

4) On the other hand, if the huge predicted enhancement will be observed, we shall have to re-consider our interpretation of the relativistic effects for a pair S' and S'' of observers. Rather than being due to the relative motion, these effects should be interpreted in terms of the individual motion of S' and S'' relatively to a preferred frame Σ. Experiments performed on the Earth suggest a value of the Earth's velocity with respect to Σ (in the plane of the interferometer) of about 200 km/s.