Introduction historique à la physique expérimentale

Pourquoi est-il intéressant et important de faire des mesures ?

Trois types d'expériences:

a) Nouvelles observations qui ont produit des développements théoriques.
b) Tests de prédictions théoriques
c) Mesures de constantes fondamentales

Introduction historique à la physique expérimentale

- L'interféromètre de Michelson (1887) et
  mesure de l'isotropie de la vitesse de la lumière (1980)

- Expériences qui ont validé les prédictions de la relativité
  - Déviation des rayons de lumière par le soleil (mesures du 1920 et mesure 1980)
  - La mesure de la relativité du temps.

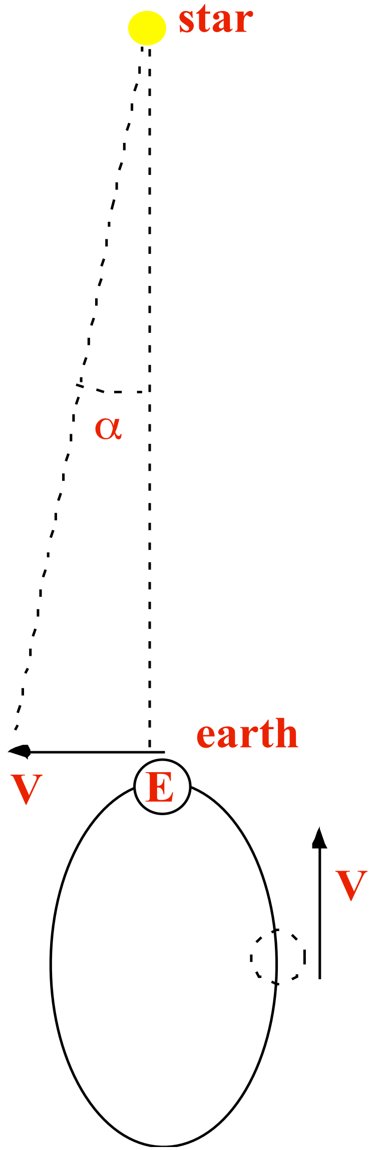
- Mesure de la constante de gravitation par la méthode de Cavendish (1796) et
  par une méthode moderne (1980)
  - Équivalence entre masse inertielle et masse gravitationnelle (1990)
  - Hypothèse de la cinquième force (1980)

- Histoire du nombre d'Avogadro et mesure de la constante de Boltzmann par Perrin et par des méthodes plus récentes.

Michelson experiment history

- 1725 - Star aberration (Bradley)
- 1851 - Experiment on the velocity of light in a moving medium (Fizeau)
- 1886 - Same experiment (Michelson and Morley)
- 1887 - Experiment on the relative speed between the earth and the Ether (Michelson and Morley)
- 1921 - Mount Wilson experiment (Miller)
- 1922 - Experiment with a modified Michelson interferometer (Kennedy).
- 1955 - New analysis of Mount Wilson data.
- 1979 - New experiment on the isotropy of the speed of light. (Brillet)

Star aberration (Bradley, 1725)



$$\alpha = V/C$$

Measurements

$$\alpha \simeq 20'' = 9.6\ 10^{-5} rad$$

$V_E \simeq 3\ 10^4 m/s$ and $C \simeq 3.1\ 10^8 m/s$

The Ether theory

- Maxwell equation are not invariant for a Galilean transformation

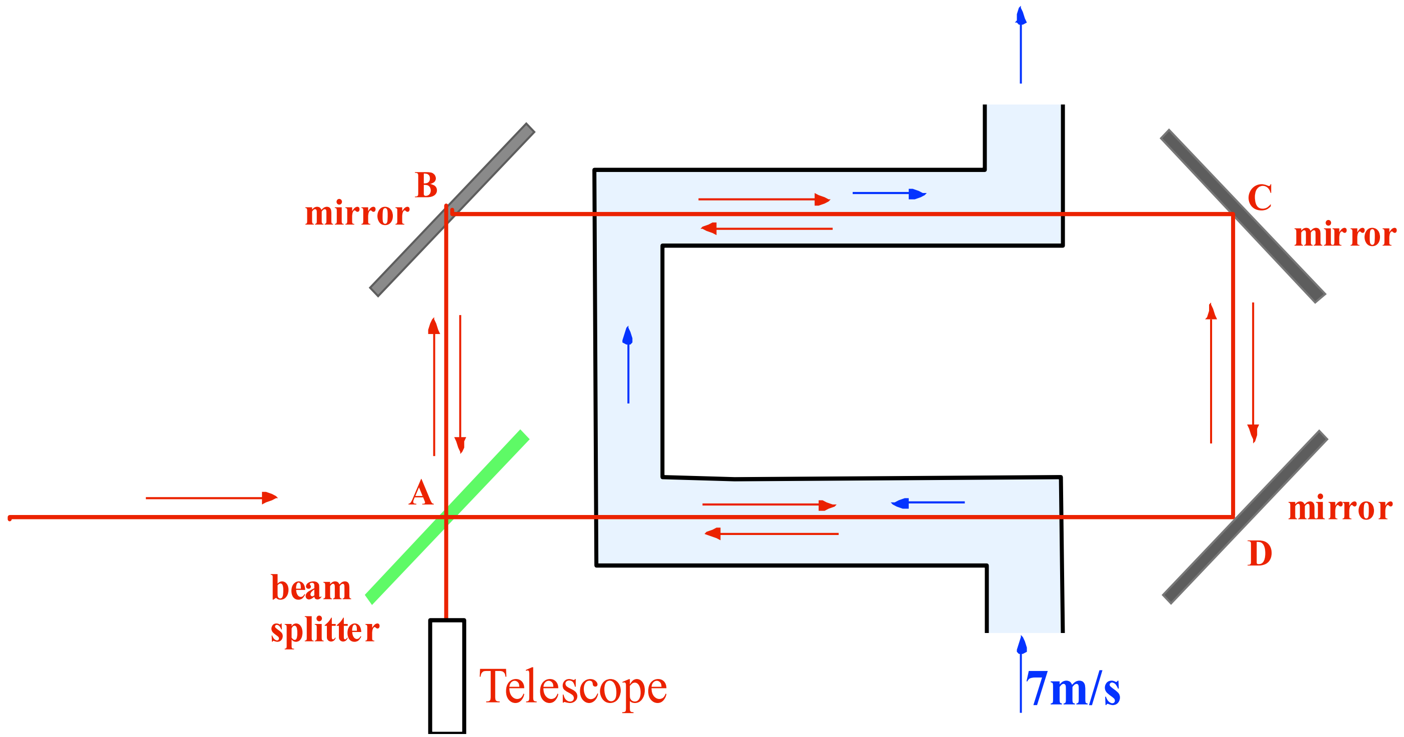
• Hp: Electrodynamics is valid only in one system which is at rest relative to the so called world ether.

• Hp: The ether was imagined as a medium which penetrated through all matter and empty space and was the carrier of all optical and electromagntic phenomena.

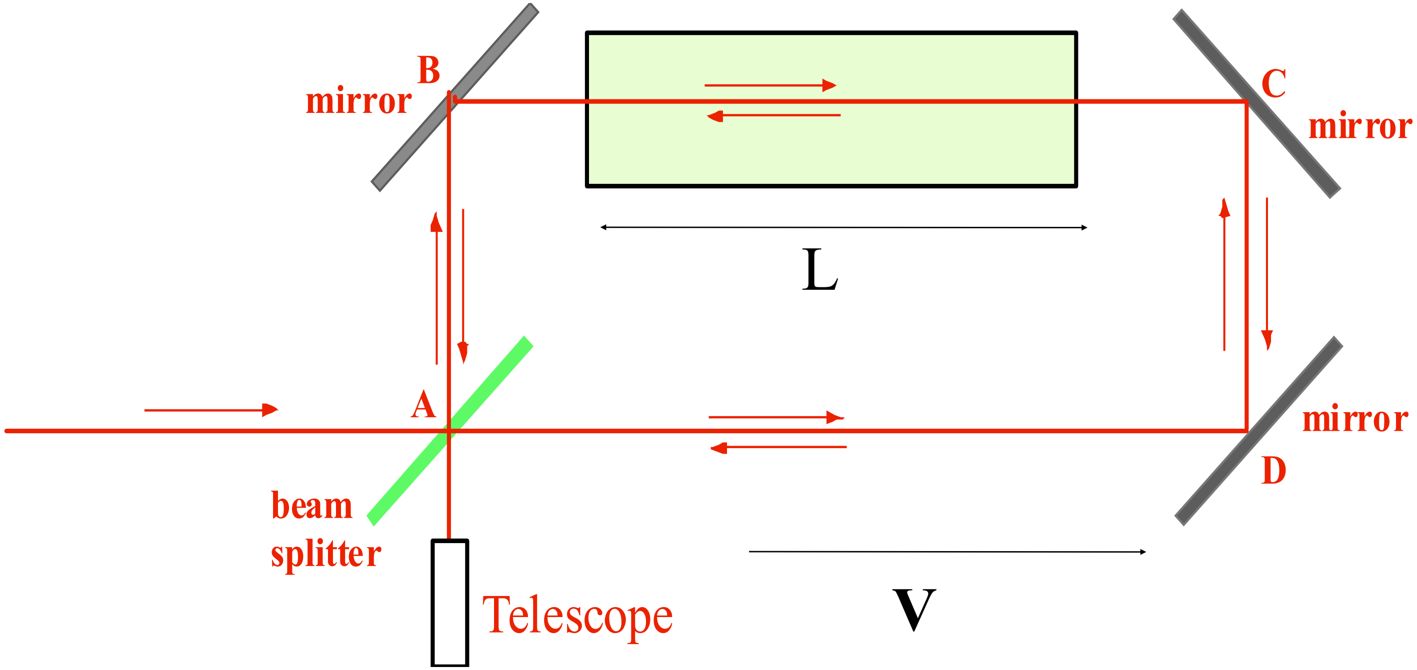
The questions at those times was :
What are the consequences of this point view for the optical phenomena in a system moving relative to the other ?

Lorentz : ‘’ On fera bien, à mon avis, de ne pas se laisser guider dans une question ainsi importante par des considérations sur le degré de probabilité ou de simplicité de l’une ou de l’autre hypothèse, mais s’adresser à l’expérience pour apprendre à connaître l’état de repos ou de mouvement dans lequel se trouve l’éther à la surface de la terre’’

Experiment on the velocity of light in a moving medium
(Fizeau – 1851),Michelson (1886)



Hoek's experiment (1868)

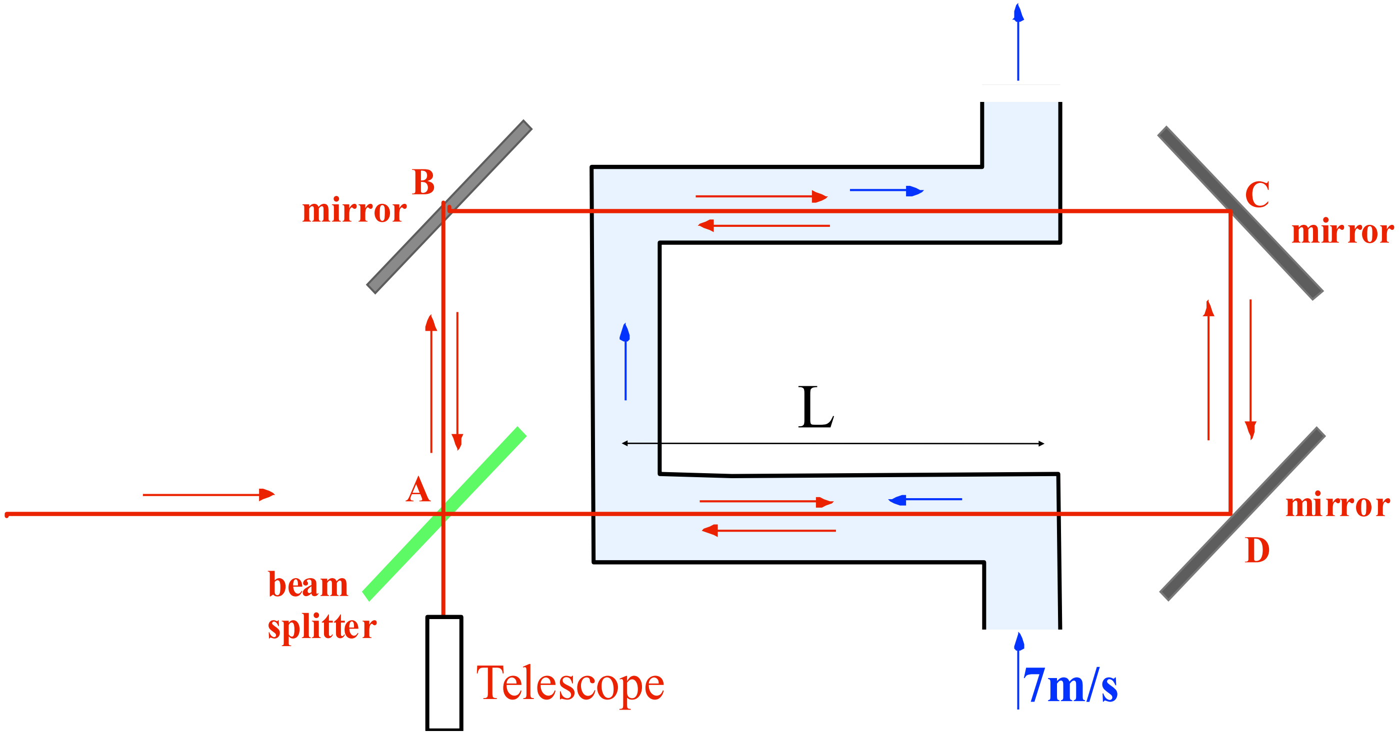


The dephasing if ether is not dragged by the transparent object is:

$$\Delta\phi = \frac{2\ L\ V}{\lambda\ C}(n^2 - 1)\left[1 + (1 + n^2)\frac{V^2}{C^2}\right]$$

Rotation of the apparatus of 180. The result of the experiment was of course $\Delta\phi = 0$.

Experiment on the velocity of light in a moving medium (Fizeau – 1851),Michelson (1886)



Because of the Hoek experiment one has to assume that ether is partially dragged by the moving medium, i.e. $C' = C/n - \alpha \vec{V} \cdot \vec{n}$

Fresnel proposes $\alpha = (1 - 1/n^2)$ and $\Delta\phi = \frac{2\ L\ V\ n^2}{\lambda C}(1 - \frac{1}{n^2})$

$V \simeq 10m/s$, $\lambda = 570nm$, $L = 10m$ and $n^2 = 1.78$ then $\Delta\phi \simeq 2$

Experimental problems

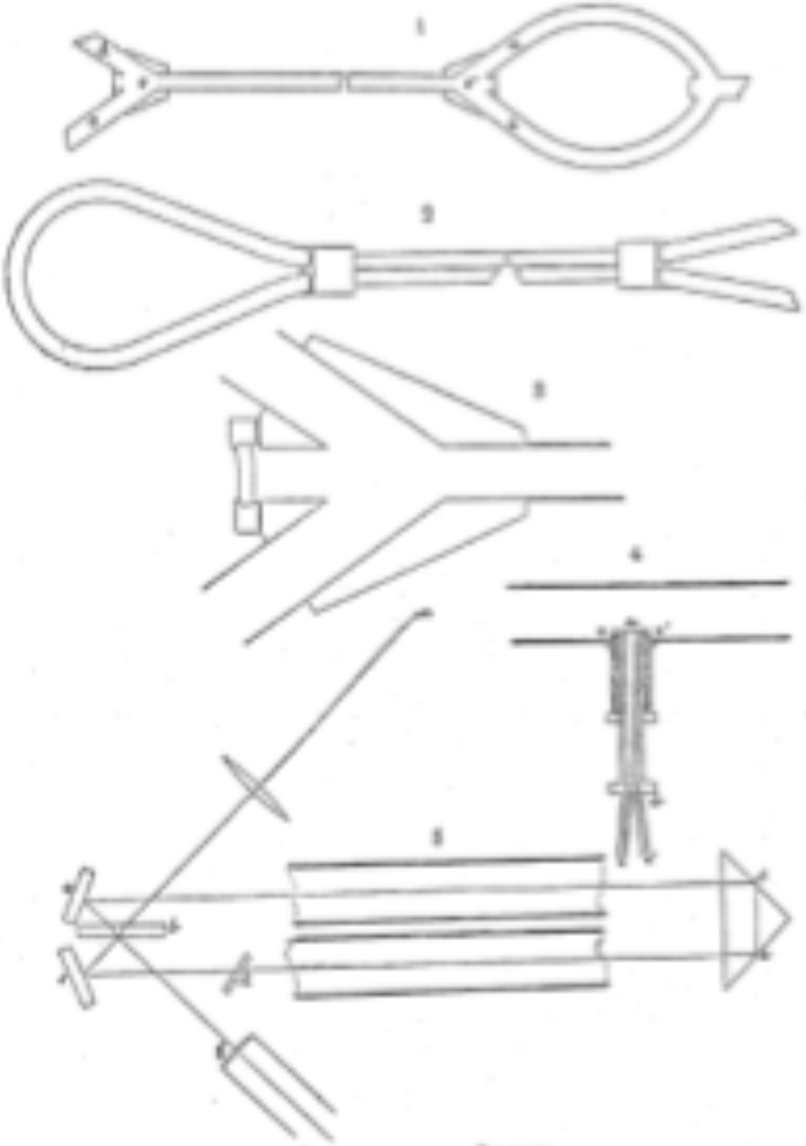
1st. The elimination of accidental displacement of the fringes by deformation of the glass ends of the tubes, or unsymmetrical variations of density of the liquid, etc., depends on the assumption that the two pencils have traveled over identical (not merely equivalent) paths. That this is not the case was proven by experiment; for when a piece of plate glass was placed in front of one of the pencils and slightly inclined, the fringes were displaced.

2d. The arrangement for producing the motion of the medium necessitated very rapid observation—for the maximum velocity lasted but an instant.

3d. The tubes being of necessity of small diameter and only their central portion being available (since the velocity diminishes rapidly toward the walls) involved considerable loss of light—which, having to pass through a slit was already faint.

4th. The maximum velocity (in the center of the tube) should be found in terms of the mean velocity. (Fizeau confessedly but guesses at this ratio.)

Michelson experiment



EXPLANATION OF FIGURES.

FIG. 1.—Vertical section through tubes. FIG. 2.—Plan of tubes. FIG. 3.—One end of tubes, showing glass plate inclined to axis. FIG. 4.—Gauge for velocity at different points. FIG. 5.—Plan of refractometer.

Observations of the double displacement Δ.

1st Series. l = 3·022 meters.
v = 6·73 meters per second.
Δ = double displacement; w = weight of observation.

Δ.	w.	Δ.	w.	Δ.	w.	Δ.	w.
·518	1·9	·531	0·9	·520	0·6	·511	2·5
·568	1·6	·515	·9	·474	2·0	·533	2·1
·504	1·7	·535	·6	·503	1·4	·480	·9
·473	1·4	·538	2·1	·521	·8	·435	10·6
·557	·4	·577	·6	·500	·3	·548	2·8
·425	·6	·494	1·7	·478	·6	·506	3·7
·500	2·9	·518	1·3	·495	1·0	·492	2·1
·544	·1	·490	·6	·558	·6	·472	2·8
·521	·1	·510	·5	·509	2·0	·498	·6
·515	·1	·504	·5	·470	2·1		

2d Series. l = 6·151, v = 7·65.

Δ.	w.	Δ.	w.	Δ.	w.	Δ.	w.
·799	4·9	·891	1·7	·900	1·6	·882	0·6
·790	2·6	·881	2·5	·899	1·7	·908	2·9
·940	4·6	·852	11·1	·925	4·3	·960	2·6
·633	1·1	·883	1·8	·827	2·1	·907	2·5
·876	7·9	·843	1·1	·848	1·9		
·956	3·6	·820	3·4	·877	4·7		

3d Series. l = 6·151, v = 5·67.

Δ.	w.	Δ.	w.	Δ.	w.	Δ.	w.
·640	4·6	·626	11·0	·636	2·1	·613	6·6

If these results be reduced to what they would be if the tube were 10ᵐ long and the velocity 1ᵐ per second, they would be as follows:

Series.	Δ.
1	·1858
2	·1838
3	·1800

Results of measurements

Measured Δ	N_m	V (m/s)	L (m)	Δ for L=10m and V=1m/s	computed n^2
0.486 ± 0.05	60	8.72	3 .02	1.86	1.81
0.867 ± 0.05	86	7.65	6.15	1.84	1.79
0.627 ± 0.008	26	5.67	6.15	1.80	1.76

N_m is the number of measurements

$$\Delta = \frac{4\ L\ V\ n^2}{\lambda C} x \qquad \text{and} \qquad x = \frac{\Delta\ \lambda\ C}{4\ L\ V\ n^2}$$

The parameter L,V,C,$\lambda = 570nm$ and $n = 1.335$ (index of refraction of water) are known.

If the Fresnel hypothesis is correct then one has to find

$$n^2 = 1/(1 - x)$$

Article Michelson

THE

AMERICAN JOURNAL OF SCIENCE.

[THIRD SERIES.]

ART. XXXVI.—*On the Relative Motion of the Earth and the Luminiferous Ether*; by ALBERT A. MICHELSON and EDWARD W. MORLEY.*

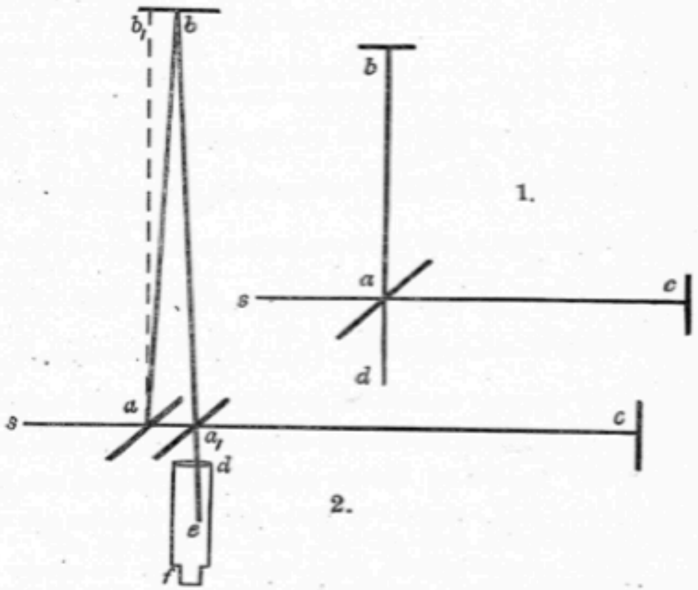
THE discovery of the aberration of light was soon followed by an explanation according to the emission theory. The effect was attributed to a simple composition of the velocity of light with the velocity of the earth in its orbit. The difficulties in this apparently sufficient explanation were overlooked until after an explanation on the undulatory theory of light was proposed. This new explanation was at first almost as simple as the former. But it failed to account for the fact proved by experiment that the aberration was unchanged when observations were made with a telescope filled with water. For if the tangent of the angle of aberration is the ratio of the velocity of the earth to the velocity of light, then, since the latter velocity in water is three-fourths its velocity in a vacuum, the aberration observed with a water telescope should be four-thirds of its true value.†

* This research was carried out with the aid of the Bache Fund.

† It may be noticed that most writers admit the sufficiency of the explanation according to the emission theory of light; while in fact the difficulty is even greater than according to the undulatory theory. For on the emission theory the velocity of light must be greater in the water telescope, and therefore the angle of aberration should be less; hence, in order to reduce it to its true value, we must make the absurd hypothesis that the motion of the water in the telescope carries the ray of light in the opposite direction!

The discusssion of this oversight and of the entire experiment forms the subject of a very searching analysis by H. A. Lorentz,* who finds that this effect can by no means be disregarded. In consequence, the quantity to be measured had in fact but one-half the value supposed, and as it was already barely beyond the limits of errors of experiment, the conclusion drawn from the result of the experiment might well be questioned; since, however, the main portion of the theory remains unquestioned, it was decided to repeat the experiment with such modifications as would insure a theoretical result much too large to be masked by experimental errors. The theory of the method may be briefly stated as follows:

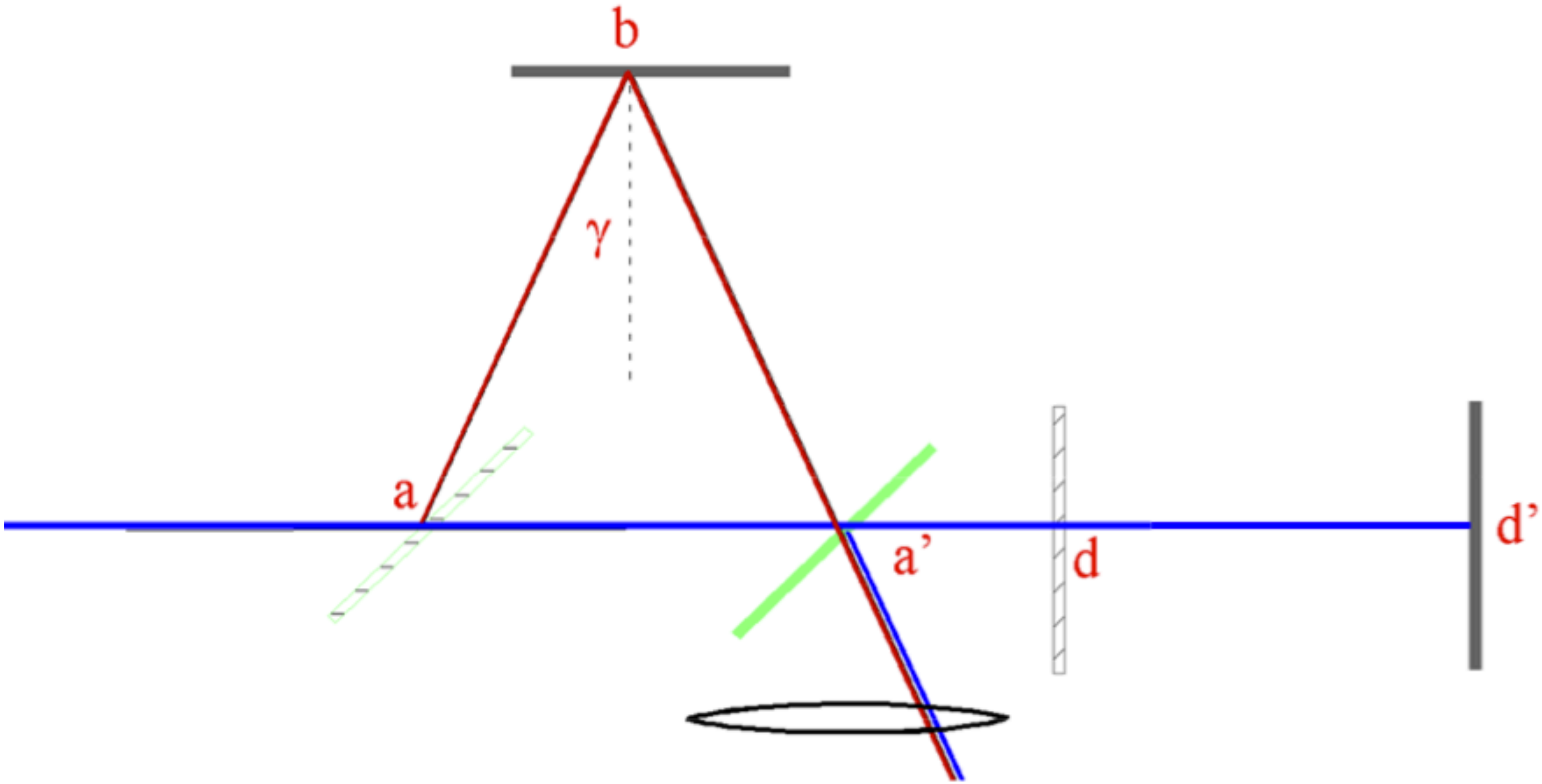
Let *sa*, fig. 1, be a ray of light which is partly reflected in *ab*, and partly transmitted in *ac*, being returned by the mirrors *b* and *c*, along *ba* and *ca*. *ba* is partly transmitted along *ad*,



and *ca* is partly reflected along *ad*. If then the paths *ab* and *ac* are equal, the two rays interfere along *ad*. Suppose now, the ether being at rest, that the whole apparatus moves in the direction *sc*, with the velocity of the earth in its orbit, the direc-

* De l'Influence du Mouvement de la Terre sur les Phen. Lum. Archives Néerlandaises, xxi, 2^me livr., 1886.

Path difference in the Ether

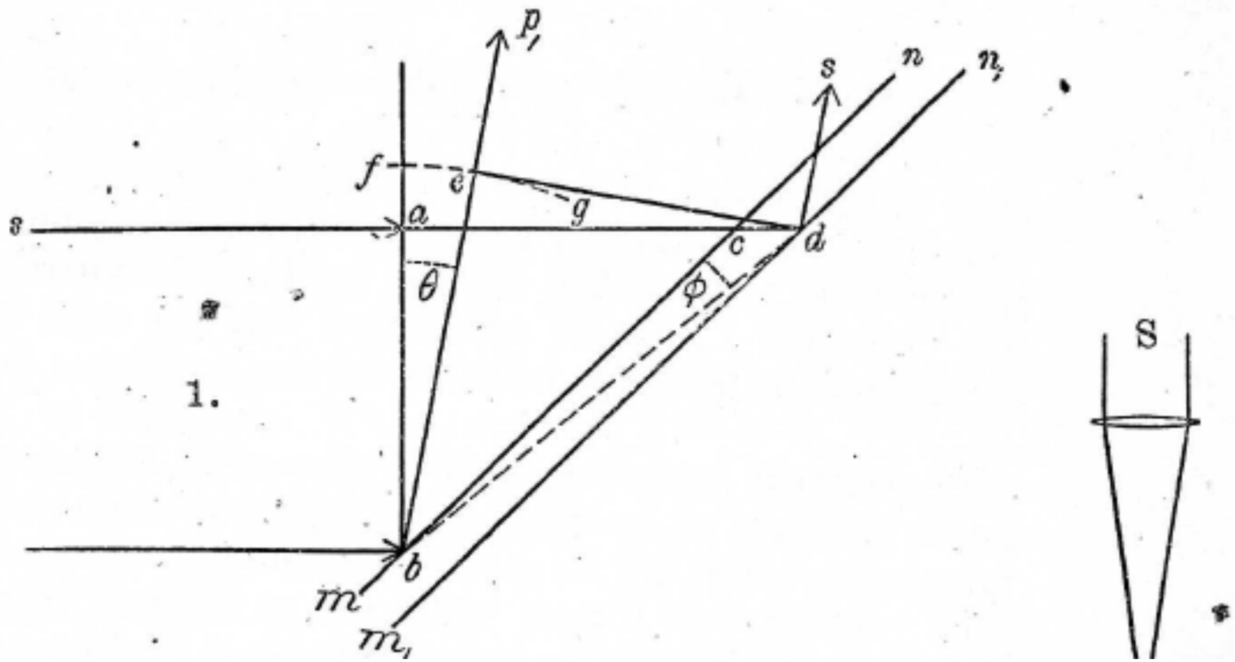


$aa' = dd' = Vt$ and $\gamma = V/C$

Dephasing after the rotation of the apparatus of 90 is $\Delta\phi = \frac{2D}{\lambda}\frac{V^2}{C^2}$

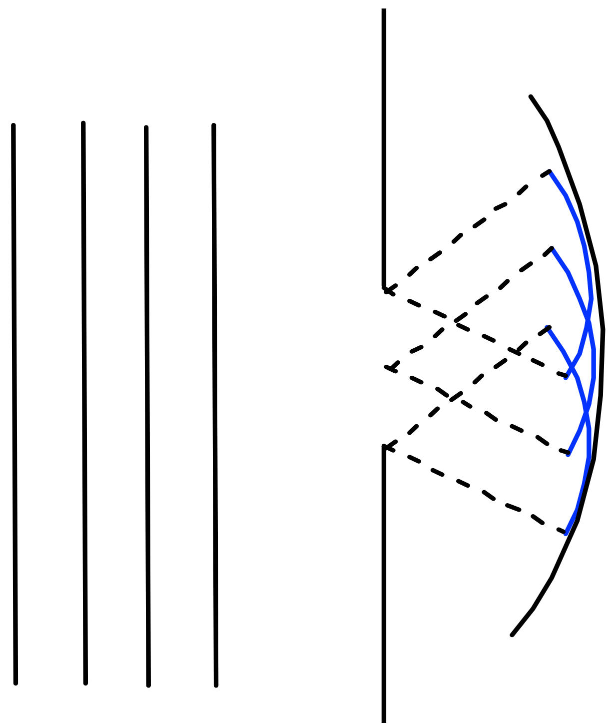
if $V \simeq 3\ 10^4 m/s$, $\lambda = 500nm$, $D = 10m$ then $\Delta\phi = 0.4$

Annexe

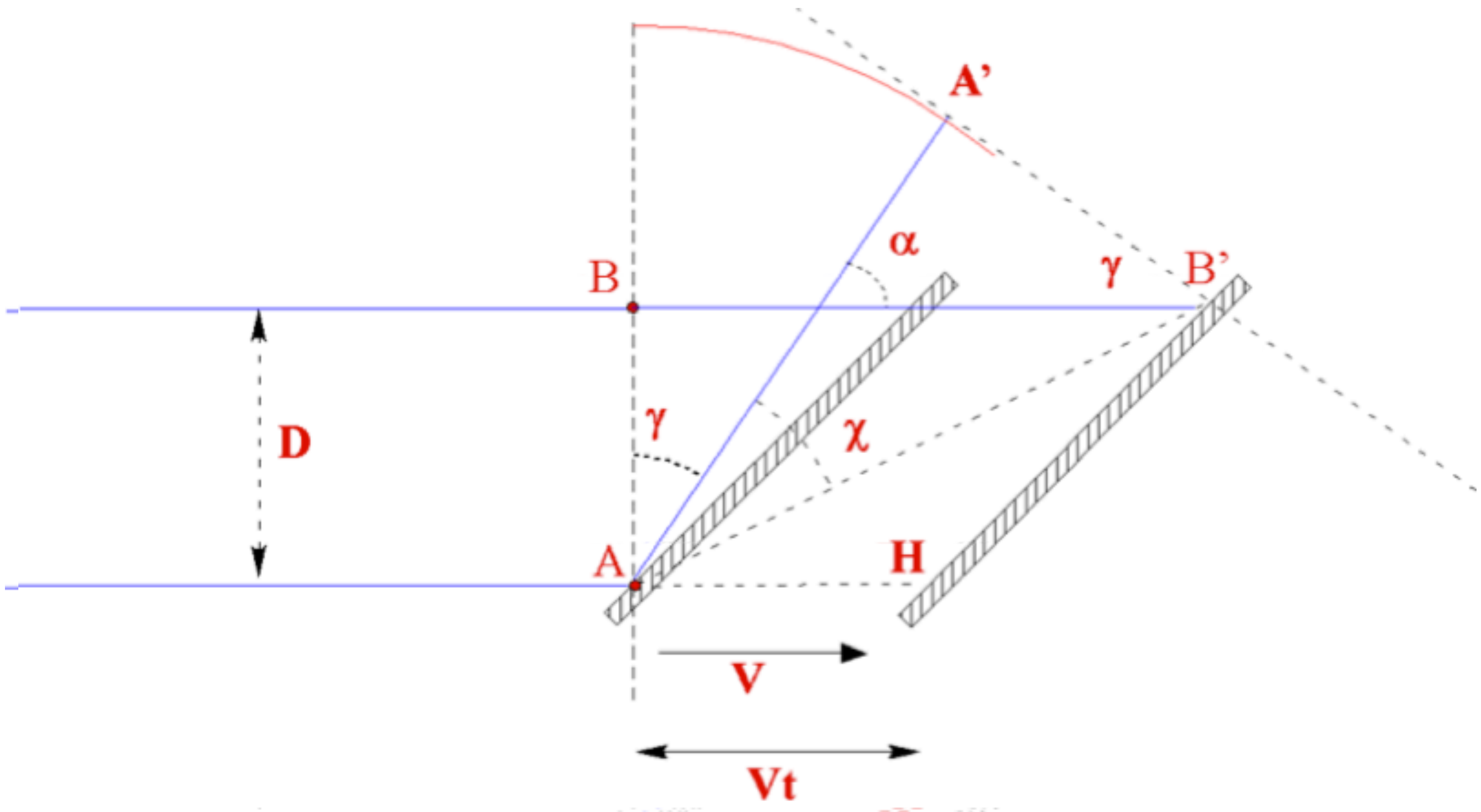


Huygens principle

Consecutive wave surfaces are obtained as the envelopes of elementary waves starting from each point of a wave surfaces.

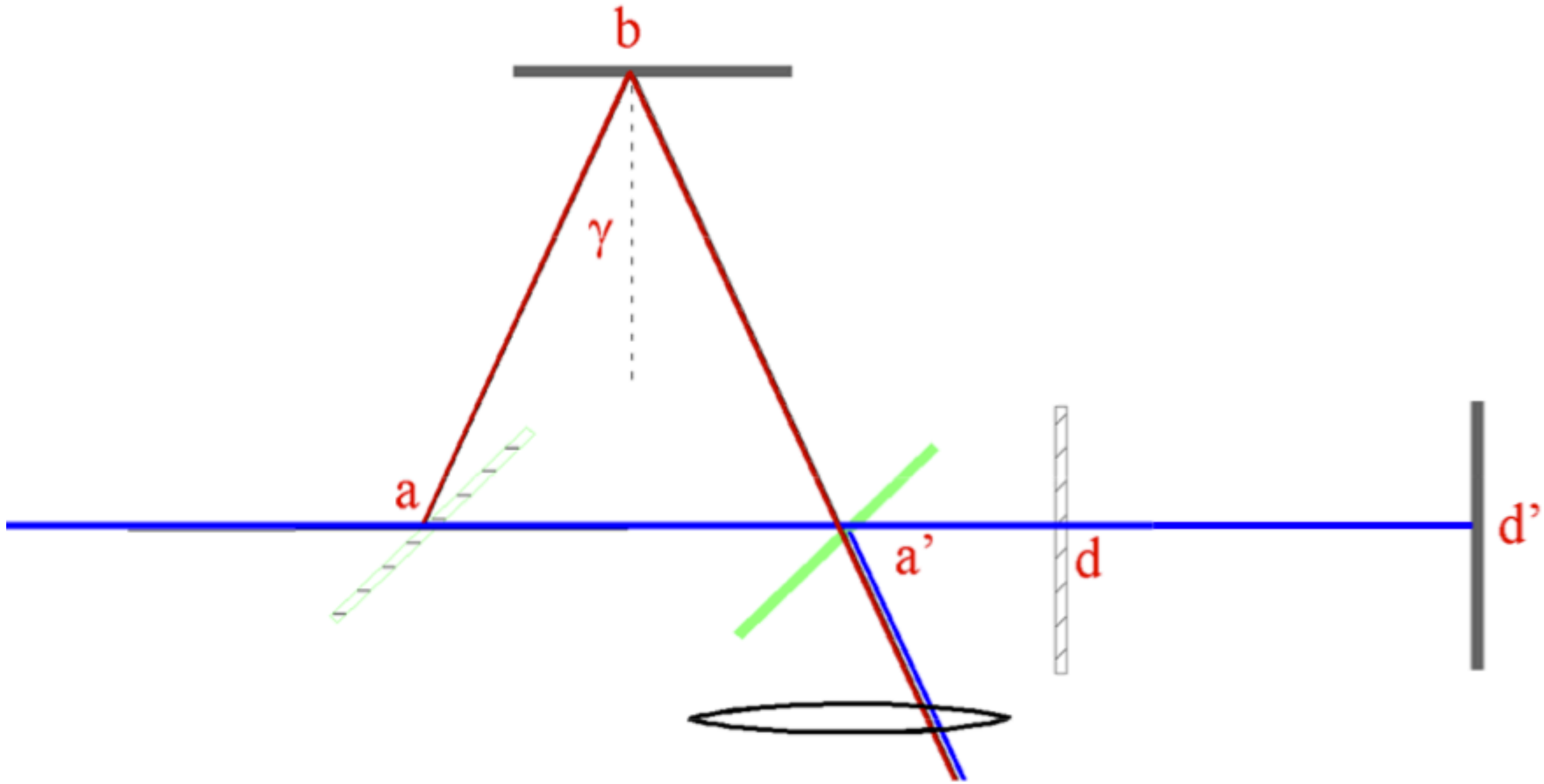


Déviation d'un rayon réfléchi



$$\gamma = V/C$$

Path difference in the Ether



$aa' = dd' = Vt$ and $\gamma = V/C$

Dephasing after the rotation of the apparatus of 90° is $\Delta\phi = \frac{2D}{\lambda}\frac{V^2}{C^2}$

if $V \simeq 3\ 10^4 m/s$, $\lambda = 500nm$, $D = 10m$ then $\Delta\phi = 0.4$

In the ether reference frame

For the first branch $D_1 + Vt_{ad'} = Ct_{ad'}$ and $D_1 - Vt_{d'a'} = Ct_{d'a'}$

$$t_{ad'a'} = \frac{D_1}{C-V} + \frac{D_1}{C+V} = \frac{2\ C\ D_1}{C^2-V^2} \simeq 2\ \frac{D_1}{C}(1 + \frac{V^2}{C^2})$$

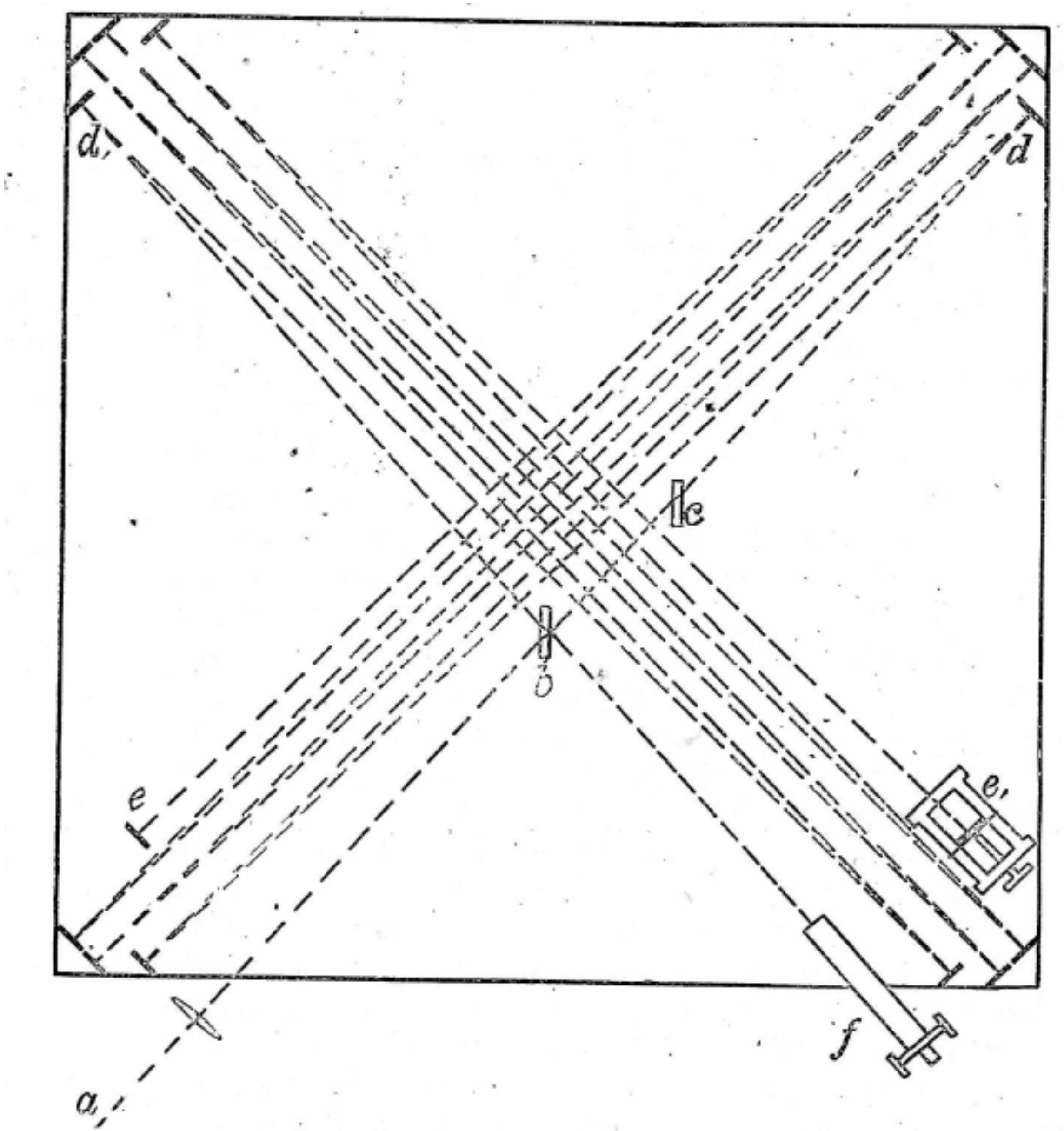
For the second branch $t_{aba'} = \frac{2\ D_2}{C\sqrt{1-\frac{V^2}{C^2}}} \simeq 2\frac{D_2}{C}(1 + \frac{1}{2}\frac{V^2}{C^2})$

Finally $\quad \delta_0 = \nu(t_{aba'} - t_{ad'a'}) = \frac{(D_2-D_1)}{\lambda} + \frac{(D_2-2D_1)}{\lambda}\frac{V^2}{C^2}$

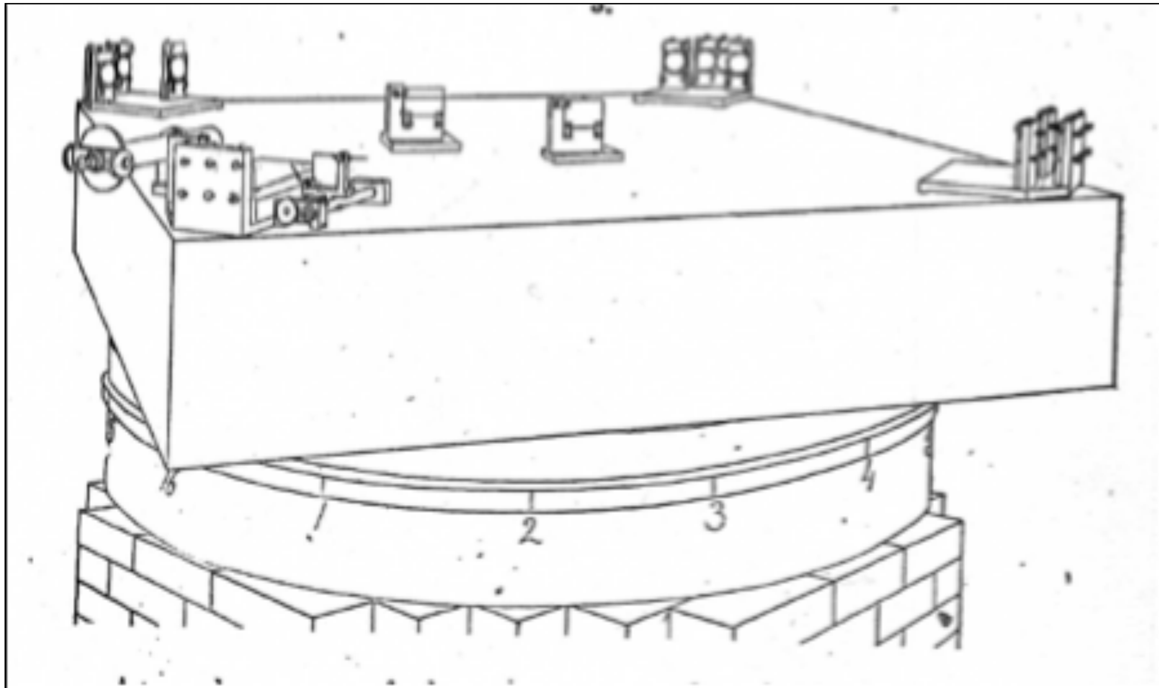
$$\delta_{90} = \frac{(D_2-D_1)}{\lambda} + \frac{(2D_2-D_1)}{\lambda}\frac{V^2}{C^2}$$

$$\Delta\Phi = \delta_{90} - \delta_0 = \frac{(D_2+D_1)}{\lambda}\frac{V^2}{C^2}$$

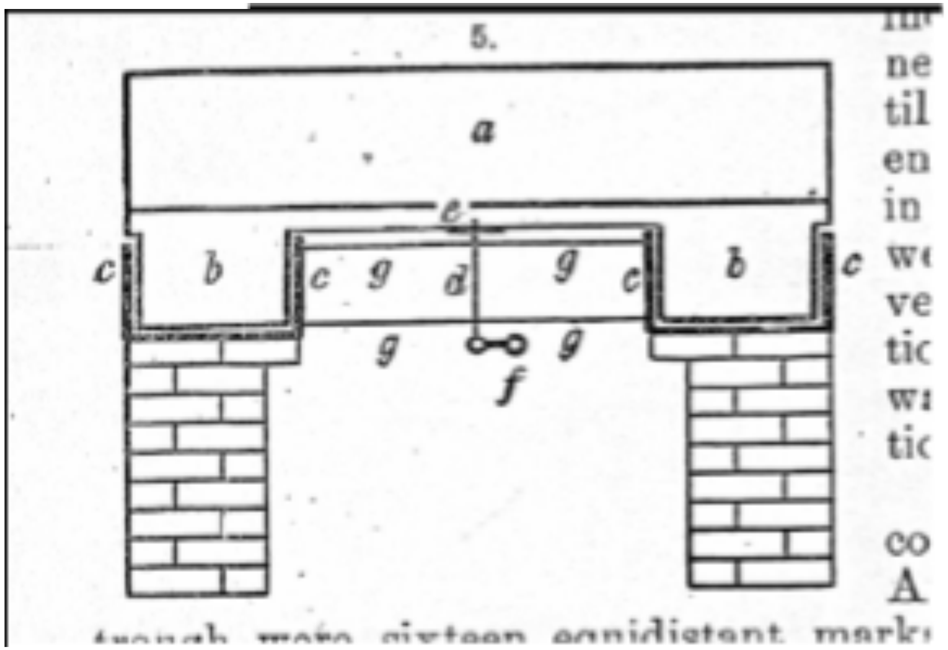
Optical allignement



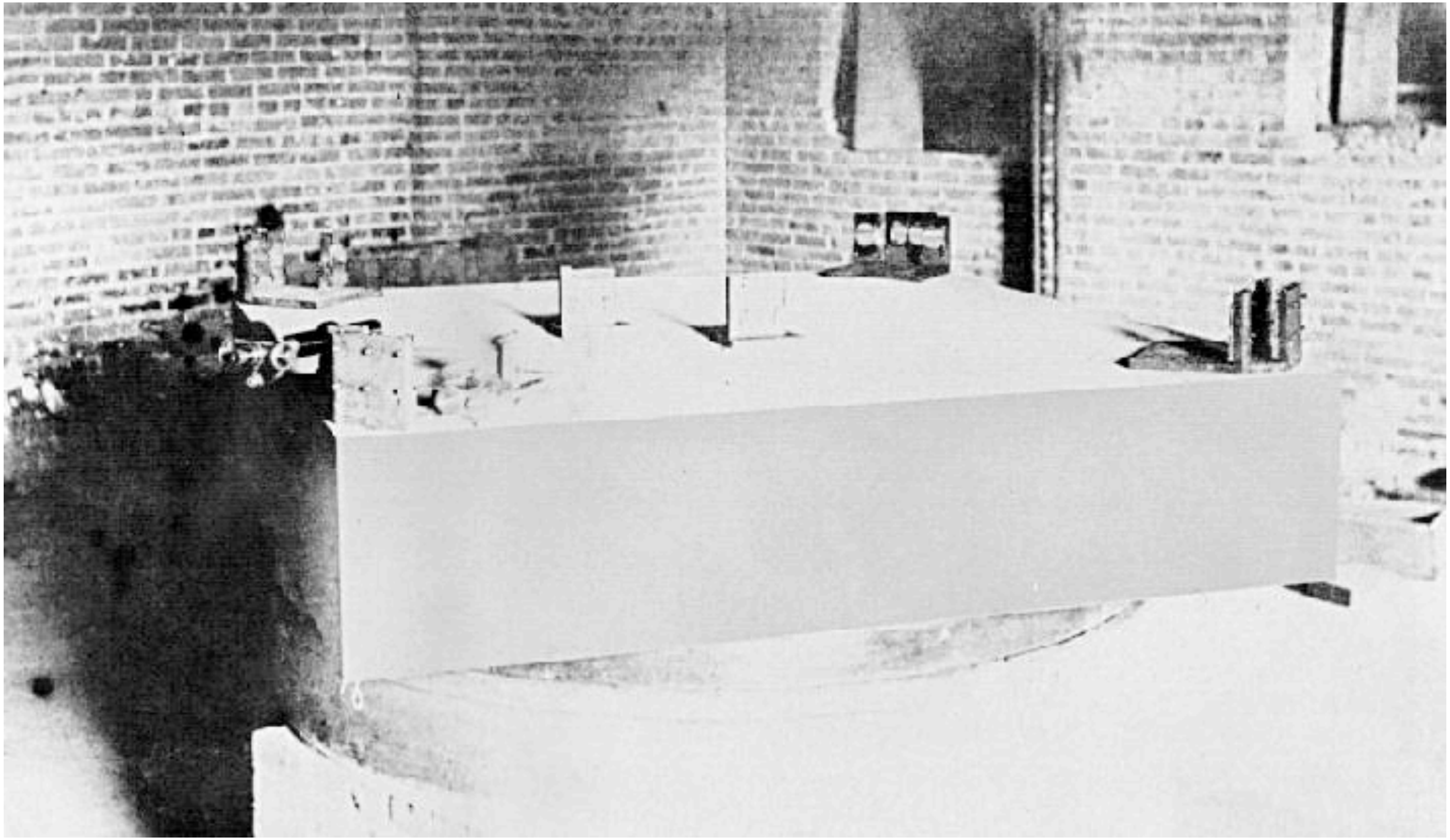
Set-up



Vibration insulation



Michelson interferometer



Experimental procedure

- Two sets of measurement per day one at noon the second at 6pm

- The apparatus was turned (6min/turn)

  once counter clockwise (noon) and clockwise in the evining

  Six revolutions are done at each measurement

- The rotation is mantained for a few minutes before starting the measure.

- Dephasing was set to zero at the beginning of the measurement

- The width of the fringes is 50 divisions of the cross wire micrometer.

- At each of the 16 positions the fringes displacement has been measured.

- The apparatus was mantained in rotation during the measurments.

Table of data

means 0·02 wave-length. The rotation in the observations at noon was contrary to, and in the evening observations, with, that of the hands of a watch.

NOON OBSERVATIONS.

	16.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.
July 8	44·7	44·0	43·5	39·7	35·2	34·7	34·3	32·5	28·2	26·2	23·8	23·2	20·3	18·7	17·5	16·8	13·7
July 9	57·4	57·3	58·2	59·2	58·7	60·2	60·8	62·0	61·5	63·3	65·8	67·3	69·7	70·7	73·0	70·2	72·2
July 11	27·3	23·5	22·0	19·3	19·2	19·3	18·7	18·8	16·2	14·3	13·3	12·8	13·3	12·3	10·2	7·3	6·5
Mean.........	43·1	41·6	41·2	39·4	37·7	38·1	37·9	37·8	35·3	34·6	34·3	34·4	34·4	33·9	33·6	31·4	30·8
Mean in w. l.	·862	·832	·824	·788	·754	·762	·758	·756	·706	·692	·686	·688	·688	·678	·672	·628	·616
	·706	·692	·686	·688	·688	·678	·672	·628	·616								
Final mean.	·784	·762	·755	·738	·721	·720	·715	·692	·661								

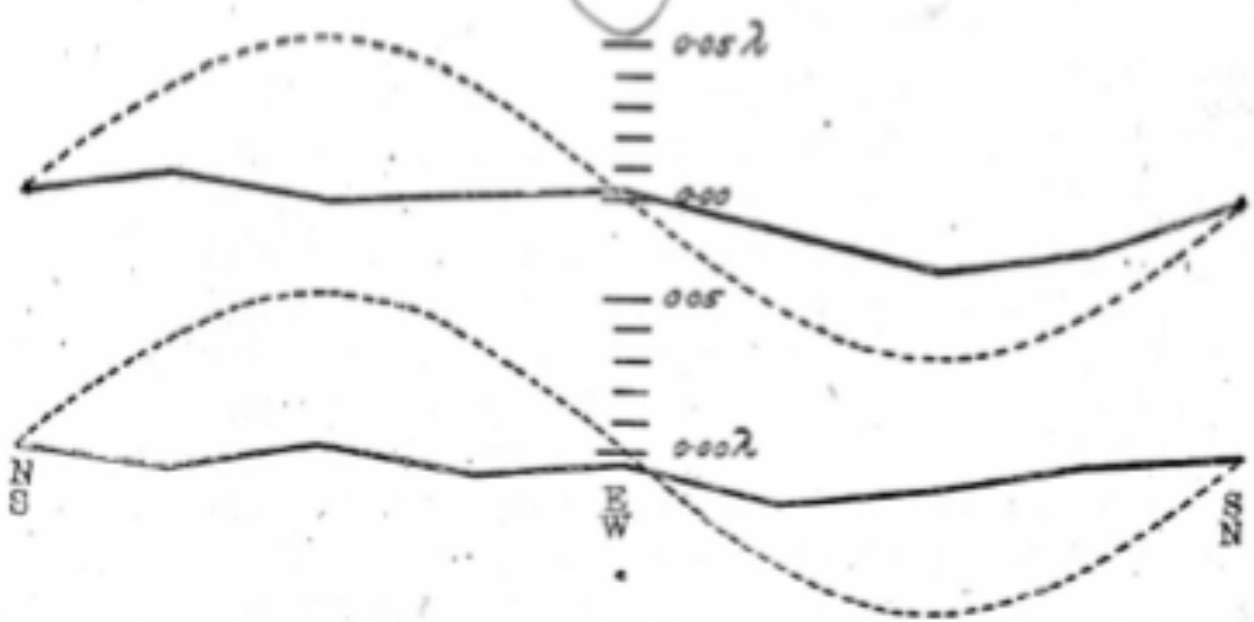
P. M. OBSERVATIONS.

July 8	61·2	63·3	63·3	68·2	67·7	69·3	70·3	69·8	69·0	71·3	71·3	70·5	71·2	71·2	70·5	72·5	75·7
July 9	26·0	26·0	28·2	29·2	31·5	32·0	31·3	31·7	33·0	35·8	36·5	37·3	38·8	41·0	42·7	43·7	44·0
July 12	66·8	66·5	66·0	64·3	62·2	61·0	61·3	59·7	58·2	55·7	53·7	54·7	55·0	58·2	58·5	57·0	56·0
Mean	51·3	51·9	52·5	53·9	53·8	54·1	54·3	53·7	53·4	54·3	53·8	54·2	55·0	56·8	57·2	57·7	58·6
Mean in w. l.	1·026	1·038	1·050	1·078	1·076	1·082	1·086	1·074	1·068	1·086	1·076	1·084	1·100	1·136	1·144	1·154	1·172
	1·068	1·086	1·076	1·084	1·100	1·136	1·144	1·154	1·172								
Final mean.	1·047	1·062	1·063	1·081	1·088	1·109	1·115	1·114	1·120								

Michelson plot

The results of the observations are expressed graphically in fig. 6. The upper is the curve for the observations at noon, and the lower that for the evening observations. The dotted curves represent *one-eighth* of the theoretical displacements. It seems fair to conclude from the figure that if there is any dis-

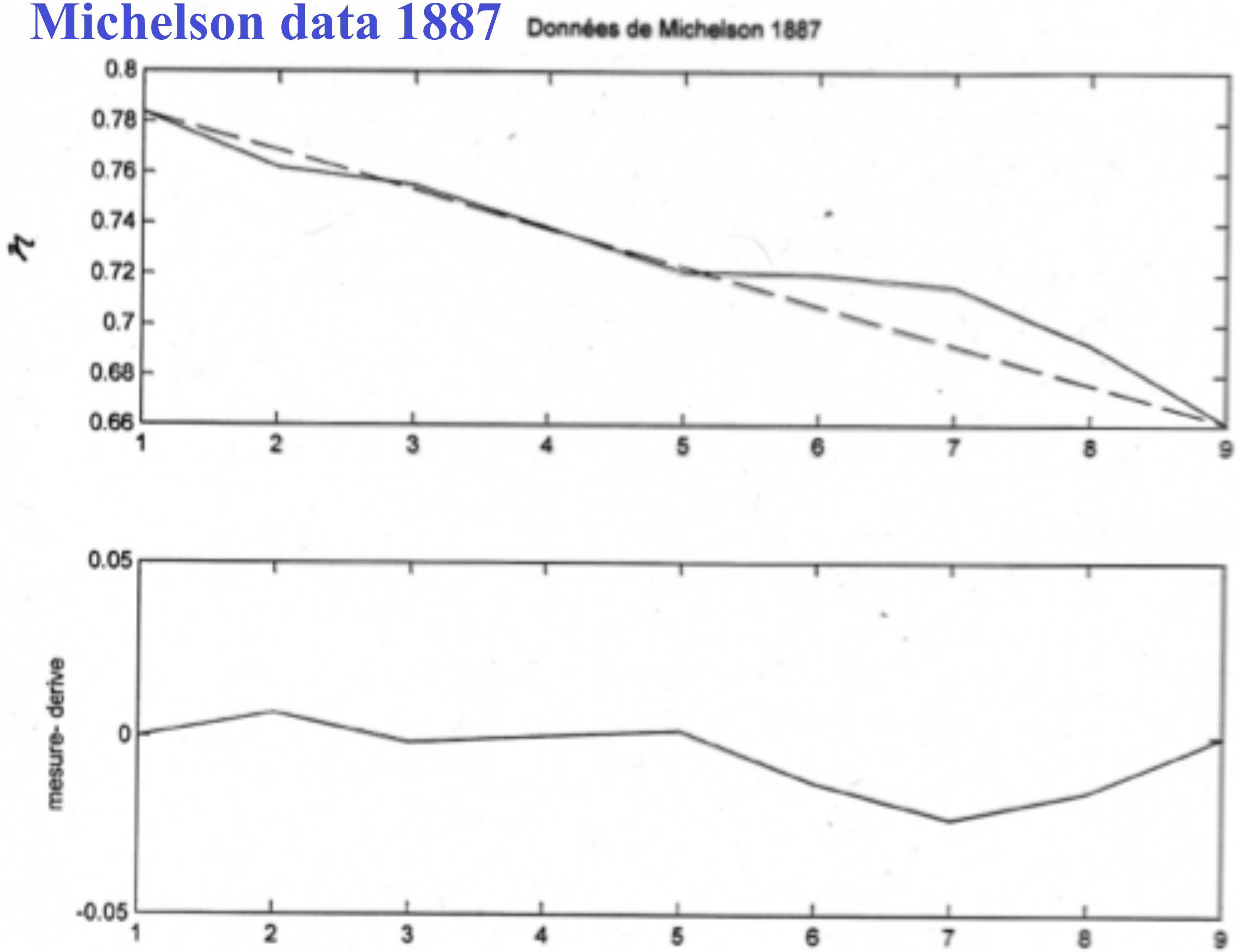
6.



placement due to the relative motion of the earth and the luminiferous ether, this cannot be much greater than 0·01 of the distance between the fringes.

Considering the motion of the earth in its orbit only, this

Michelson data 1887



The length contraction
Lorentz (1892) & Fitzgerald (1893)

In the motion direction $L \quad \to L' = L\sqrt{1 - \frac{V^2}{C^2}}$

thus

$$t_{ada'} = 2\frac{D_1\sqrt{1-\frac{V^2}{C^2}}}{C}(1 + \frac{V^2}{C^2}) \simeq 2\frac{D_1}{C}(1 + \frac{1}{2}\frac{V^2}{C^2})$$

and $\delta_0 = \delta_{90} = \frac{2(D_2-D_1)}{\lambda}(1 + \frac{1}{2}\frac{V^2}{C^2})$

and $\Delta\Phi = 0$ if $D_1 = D_2$

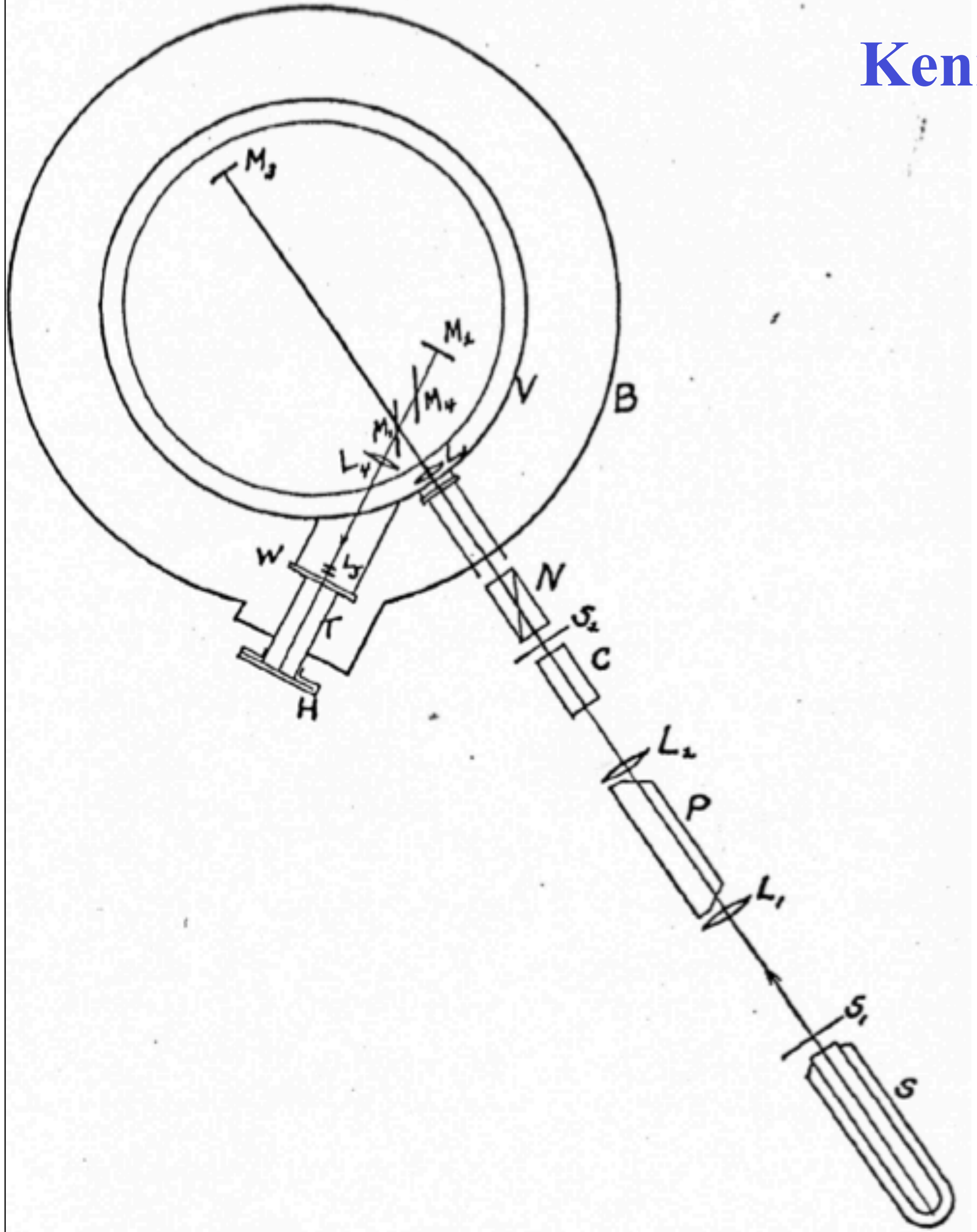
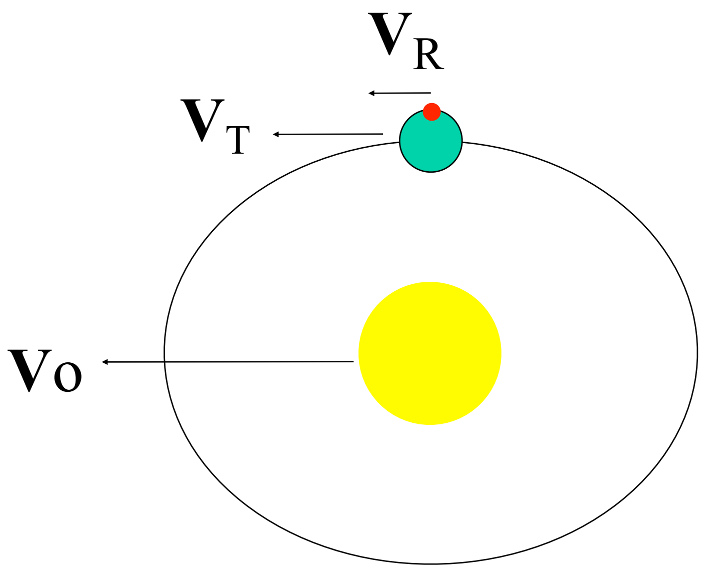


Fig. 2.

Kennedy and Thorndike

- Experiment mounted on a fused quartz base. (28cm diameter and 4 cm thick)
- The apparatus was in vacuum and temperature stabilized
- Photographic plates recorded every 12 hours. In one year
- Claimed resolution 10^{-3} fringes

Kennedy and Thorndike (1932)

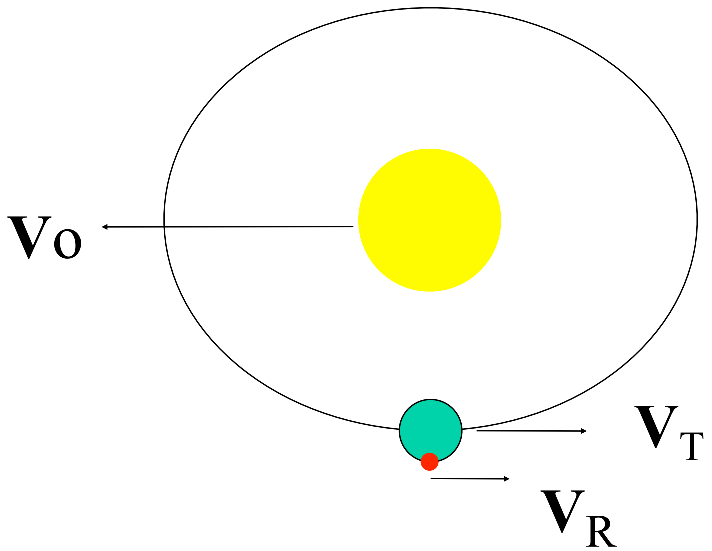


At 0h

$$V_1 = V_0 + V_T + V_R$$

after 12h

$$V_2 = V_0 + V_T - V_R$$



after 6 months and 0h

$$V_2 = V_0 - V_T - V_R$$

after 6 months and 12h

$$V_2 = V_0 - V_T + V_R$$

Features of the experiment

Thermal expansion coefficient

- Granite $5\ 10^{-6}\ K^{-1}$
- Invar $3\ 10^{-6}\ K^{-1}$
- Acier $10^{-5} K^{-1}$
- Quartz $5\ 10^{-7}\ K^{-1}$

Temperature stability 10^{-3} K

Length stability = $1.5\ 10^{-10}$ m = $3\ 10^{-4}$ fringes

Quantitative analysis of the experiment

$\delta = \frac{2(D_2 - D_1)}{\lambda}(1 + \frac{1}{2}\frac{V^2}{C^2})$

We are interested in the difference $\Delta\ V^2 = V_2^2 - V_1^2$

After 12h: $\Delta\ V^2 = 4(V_0 + V_T)\ V_R$

After 6 months at 0h: $\Delta\ V^2 \simeq 4\ V_0\ (V_T + V_R)$

$V_T = 30 Km/s$, $V_R = 0.4 Km/s$

V_0 not very well known in 1932 but certainly $V_0 >> V_T$

(Today $V_O \simeq 200\ Km/s$)

$D_1 - D_2 \simeq 0.3m$, $\lambda = 500\ nm$

Sensitivity $\delta_{min} = 10^{-3}$ fringe

After 6 months one may estimate

the minimun speed of the sun that we can measure

$$V_{0_{min}} = \frac{\delta_{min}\ \lambda\ c^2}{(D_1 - D_2) 4\ V_T} \simeq 1200 m/s$$

Conclusions on Michelson experiments

• The Michelson experiment imposes the existance of the length contraction

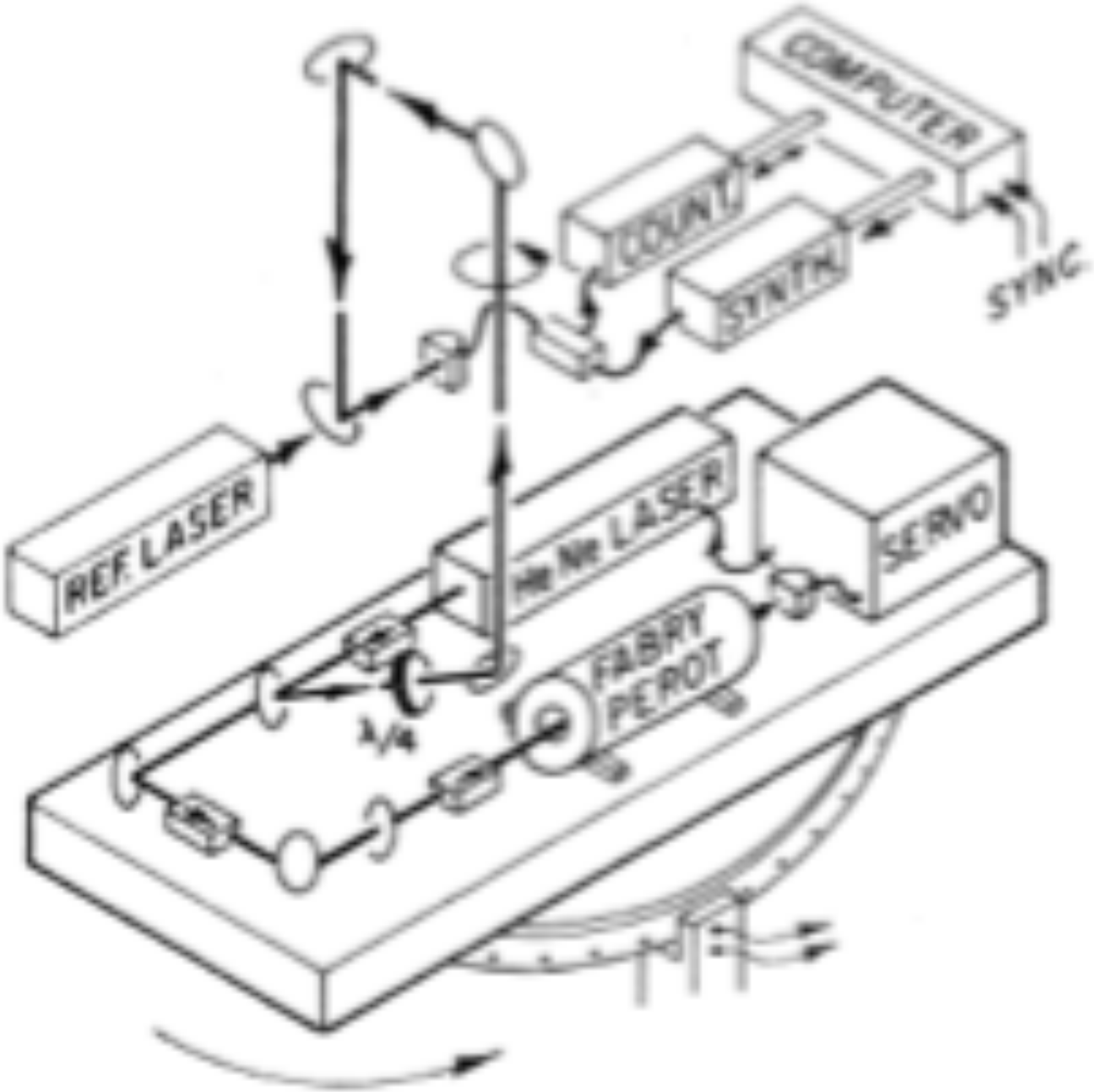
• The 1932 experiment indicates that this contraction is not enough to explain the nul result

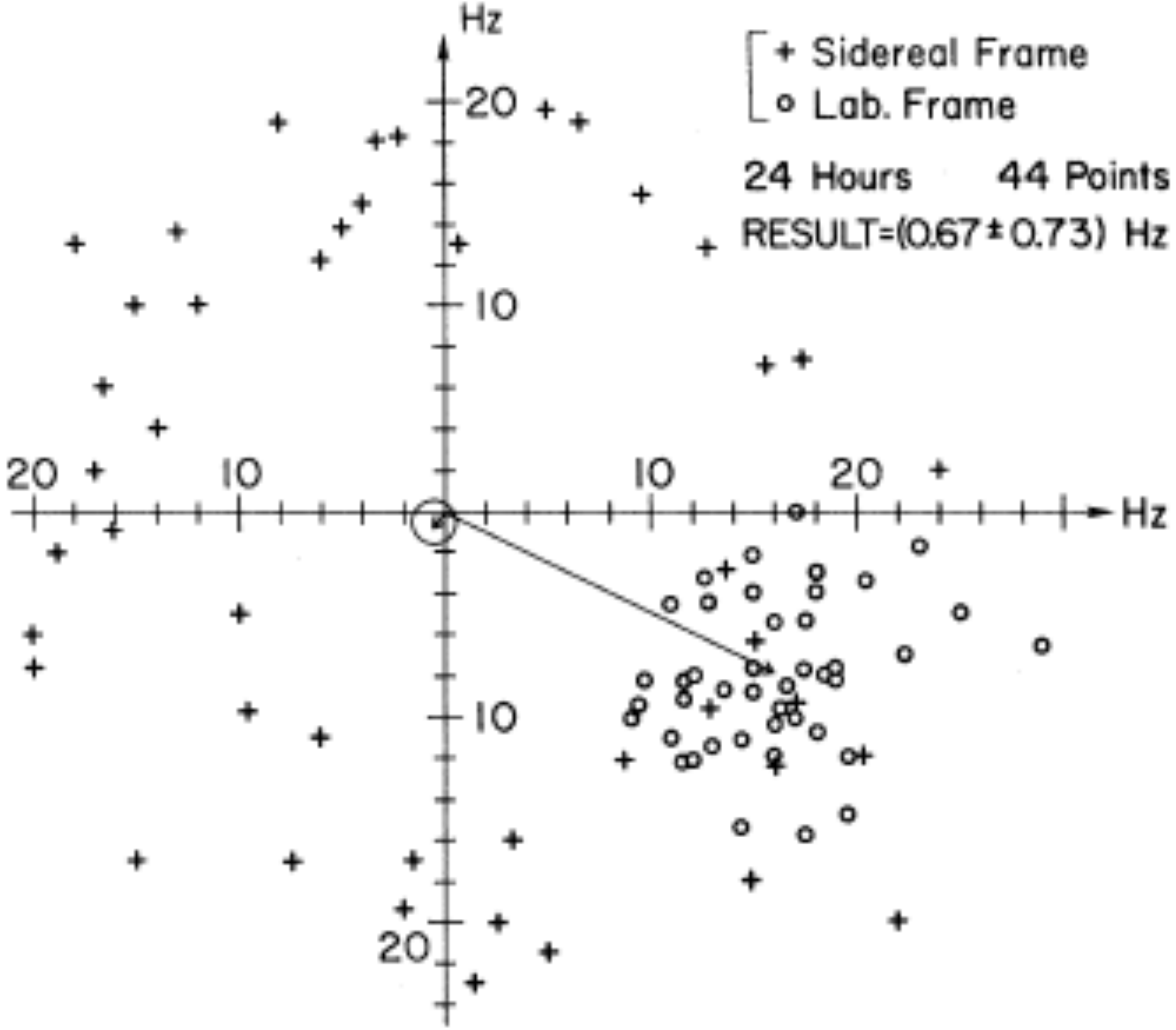
$$\delta = \frac{2\ (D_1 - D_2)}{\lambda\sqrt{1-(\frac{V}{C})^2}} = \frac{2\omega\ (D_1 - D_2)}{C\ \sqrt{1-(\frac{V}{C})^2}}$$

The independence of δ on V implies that the mobile observeur must see something different:

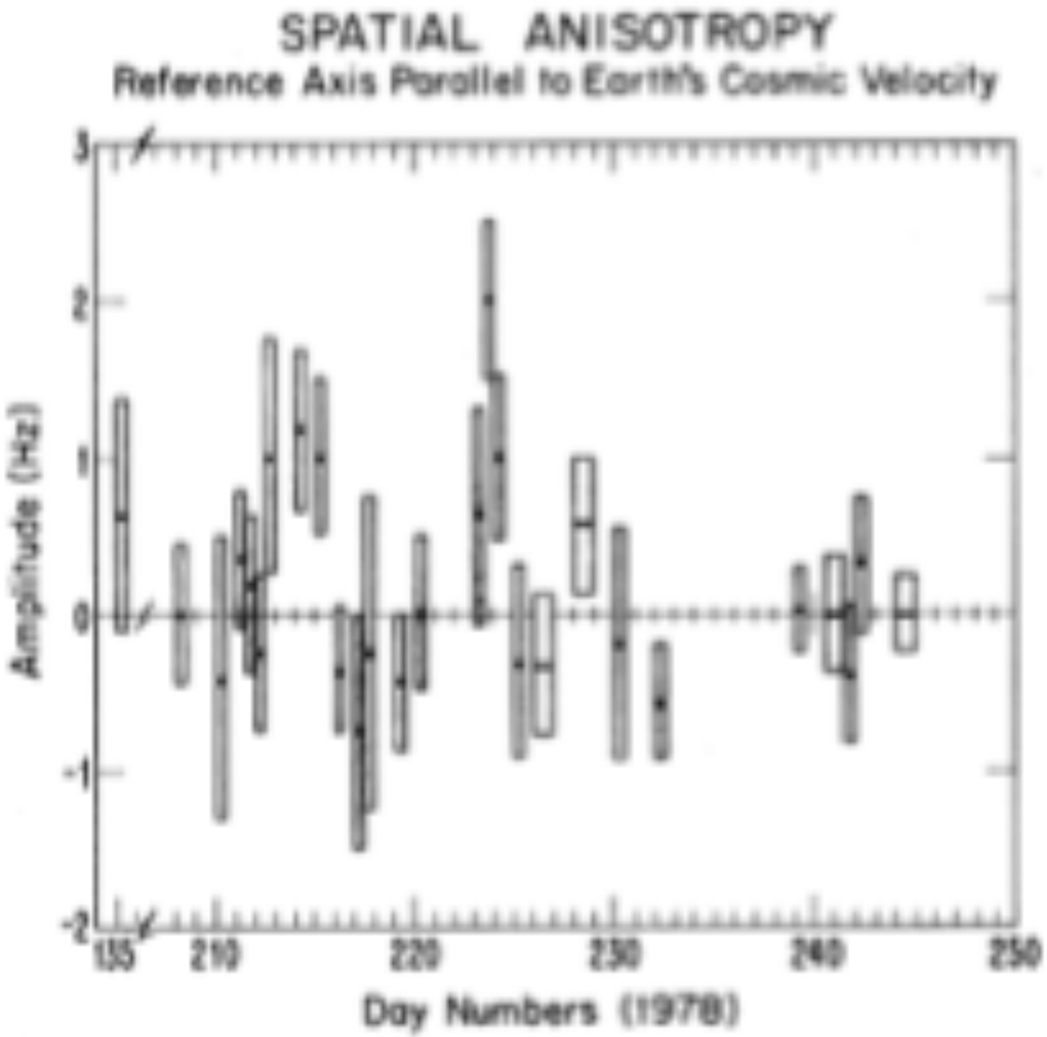
$$\omega' = \frac{\omega}{\sqrt{1-(\frac{V}{C})^2}}$$

Rotating Laser experiment (Brillet 1979)





Hz
Sidereal Frame
Lab. Frame
24 Hours 44 Points
RESULT=(0.67 ± 0.73) Hz
20
10
10
20
20
10
10
20
Hz


SPATIAL ANISOTROPY
Reference Axis Parallel to Earth's Cosmic Velocity
Amplitude (Hz)
3
2
1
0
-1
-2
135
210
220
230
240
250
Day Numbers (1978)

Laser stabilization (Hansch 1980)

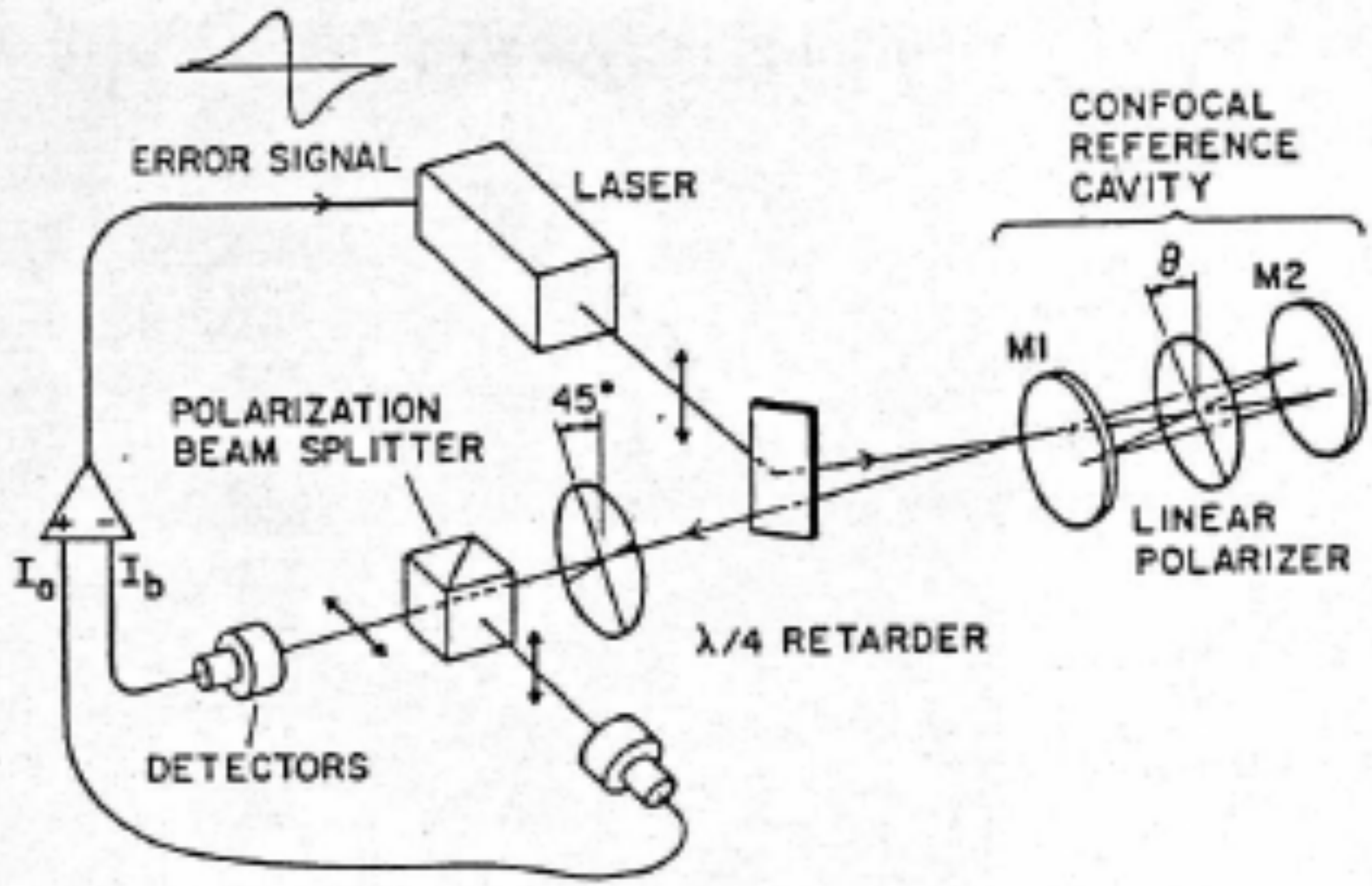


Fig. 2. Scheme for laser frequency stabilization.

Fabry Perot response.

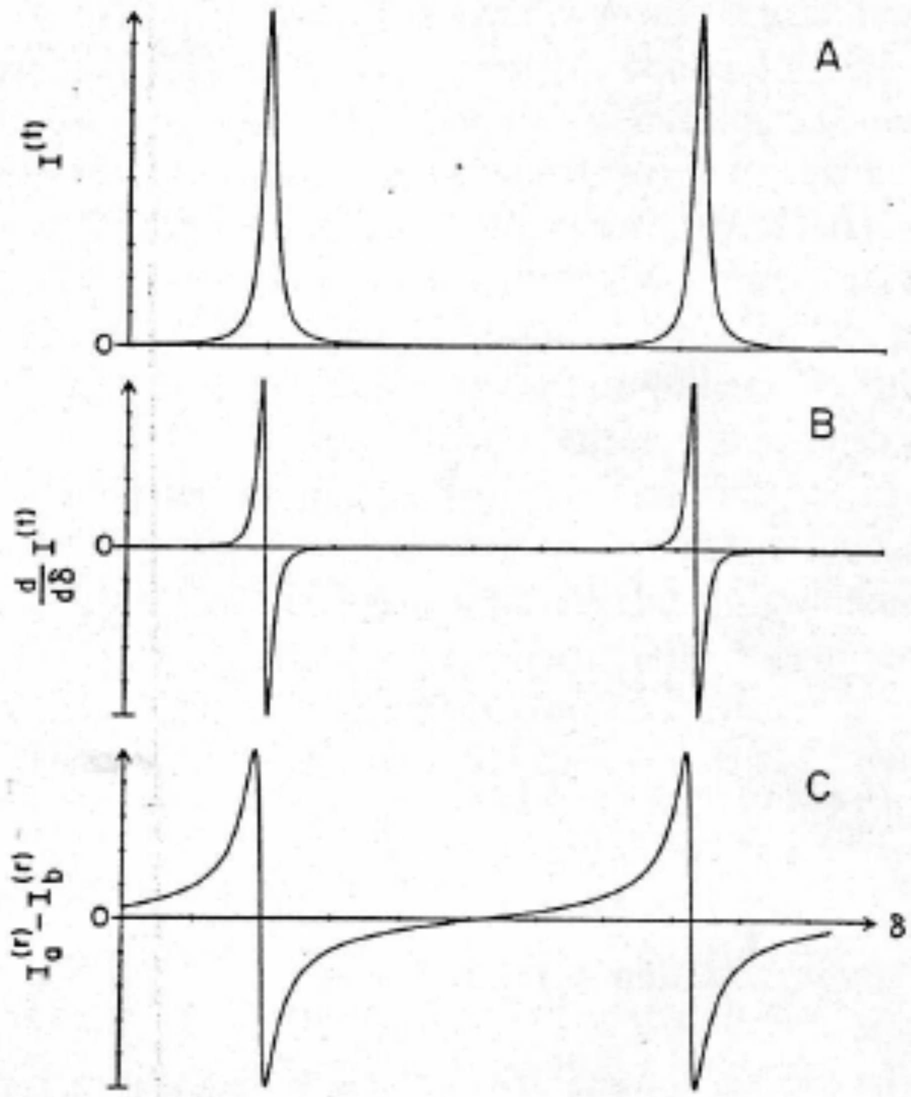
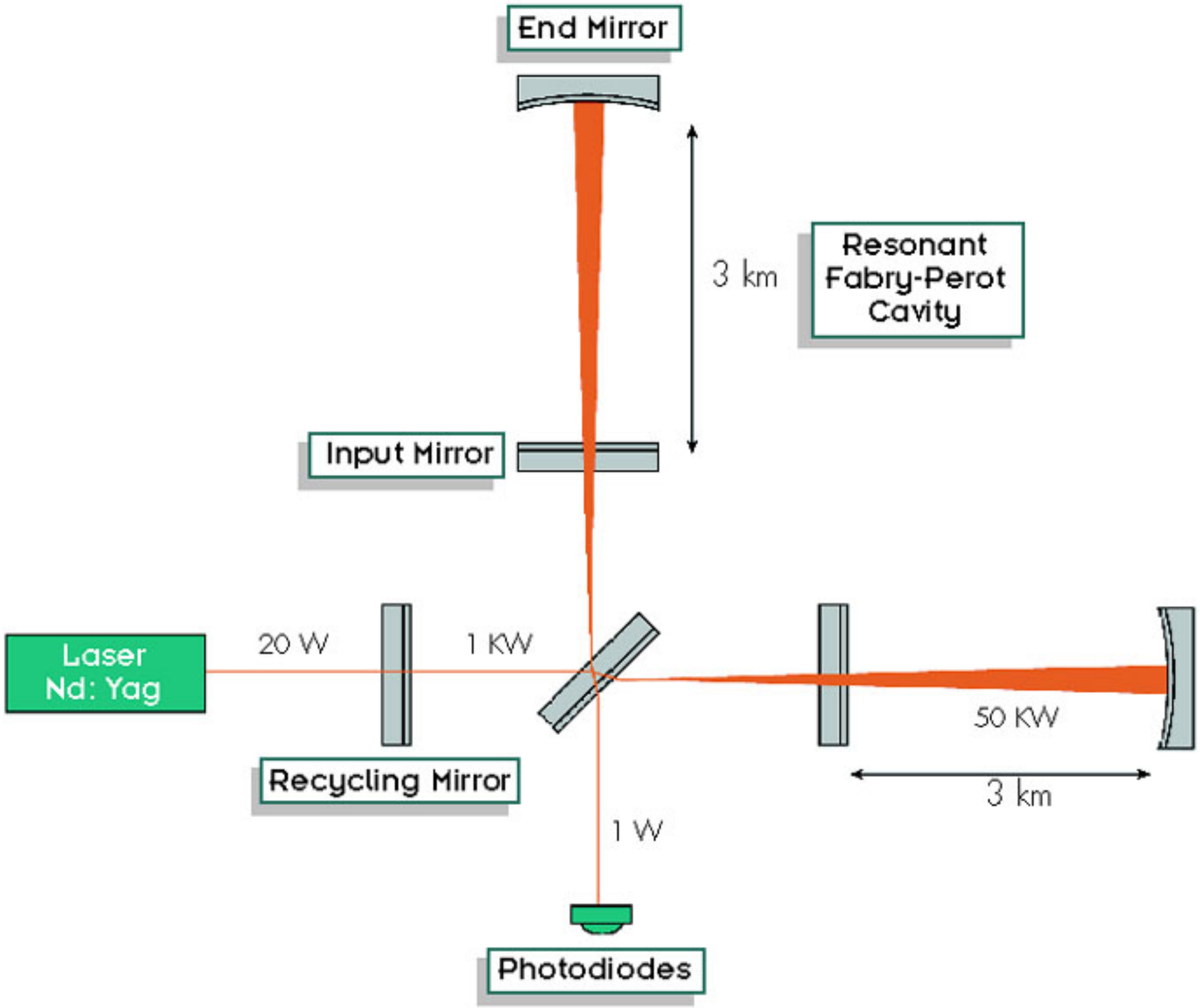


Fig. 1. A: spectrum of the intensity transmitted by a passive cavity. B: first derivative of the transmission spectrum. C: dispersive resonances obtained by polarization spectroscopy.

Virgo Interferometer



Introduction historique à la physique expérimentale

- L'interféromètre de Michelson (1887) et
  mesure de l'isotropie de la vitesse de la lumière (1980)

- Expériences qui ont validé les prédictions de la relativité
  - Déviation des rayons de lumière par le soleil (mesures du 1920 et mesure 1980)
  - La mesure de la relativité du temps.

- Mesure de la constante de gravitation par la méthode de Cavendish (1796) et
  par une méthode moderne (1980)
  - Équivalence entre masse inertielle et masse gravitationnelle (1990)
  - Hypothèse de la cinquième force (1980)

- Histoire du nombre d'Avogadro et mesure de la constante de Boltzmann par Perrin et par des méthodes plus récentes.