Foucault and Measuring the Speed of Light in Water and in Air

Jean-Jacques Samueli
Docteur d'État en physique

Jean Bernard Léon Foucault was born on 18th September, 1819 in Paris where his father was a publisher. His family settled in Nantes when he was very young but, after the death of his father in 1829, Foucault returned to Paris where he lived for the rest of his life with his mother in a house located at the corner of streets Assas and Vaugirard[1]. He did his first years of study at the Collège Stanislas in Paris where he met two future physicists, Lissajous and Fizeau.

He then began to study medicine, under the direction of Alfred Donné (1801-1878), an independent professor of microscopy at the Faculty of Medicine of Paris and discoverer of leukæmia, who took on Foucault as his assistant. Foucault invented a *microscope-daguerreotype* which he used to make onscreen projections of microscope slides (and later daguerreotypes) which would serve as a basis to the Atlas added in *Cours de microscopie complémentaire des études médicales*..., which he published with Professor Donné in 1845. Foucault, however, soon abandoned his studies in medicine because he could not stand the sight of blood and so he turned to physics.

The same professor Donné summarises in the *Journal des Débats* meetings of the *Académie des sciences*; he abandons this position in 1845 and proposes that Foucault succeed him.

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Foucault is best known for his pendulum, thanks to which he showed in 1851 the daily rotation of Earth. We are also indebted to him for his many other contributions to physics such as the invention of the *gyroscope* and the discovery of *Eddy currents* (or *Foucault currents*) induced in a metal by a variable field. In 1857, Foucault invented the polarizer which bears his name and in the following year he designed a method to give reflecting telescopes the shape of a spheroid or a paraboloid of revolution. The property of a spheroid or elliptical mirror is that it has two focal points and that it reflects on one both rays from the other.

1. The first experiments of "Foucault's pendulum", before taking place in the Panthéon, took place in the basement of this apartment, where the oscillation amplitude was not very large - given the height. Nonetheless this basement let Foucault prepare his experiment in full size.

With regard to the parabolic mirror[2], the rays that leave the focus (or lens) are reflected so in a parallel manner to the axis of the paraboloid and also vice versa.

Overall his work can be classified into several areas of physics:

- Mechanics, with the pendulum and gyroscope.
- Electricity and magnetism, with Eddy currents.
- Optics, with his polarizer and telescope inventions[3], and of course his "crucial" experiment on the speed of light (which will be discussed in this analysis).
- And not mention his popular scientific activity, which he cared a lot about, in particular by way of his column in the *Journal des Débats*.

In 1862, Foucault was named a member of the Bureau des longitudes. In 1864, he was admitted as a foreign member of the *Royal Society* in London and, in the following year, he entered the mechanical section of the *Académie des sciences* in Paris. He died in Paris in 1868 at the age of forty-nine.

THE NATURE OF LIGHT

The exact nature of light has been the subject of various hypotheses since Antiquity, the Pythagoreans supporting the theory of particle emissions and the Aristotelians the theory of waves. It was not until 1925 that the answer came from the works of Bohr and de Broglie on wave-corpuscle duality: both of these theories have been found, at least in part, to be correct.

In the emission theory, developed by Newton, light is composed of particles of different masses according to their colour. When they come to the surface of a medium, these particles undergo the action of a refractive force incited by them, perpendicular to this surface, proportional to the density of the collided body and which works at a short distance of the latter. This force, by deflecting the trajectory of corpuscles, causes at the same time reflection, refraction, dispersion and diffraction. A consequence is that the speed of light, in the corpuscular theory, is weaker in vacuum or in air, than in a denser medium: indeed, the gravitational pull on light corpuscles, due to the denser medium, and being directed perpendicularly to the surface of separation of two media, modified only the normal component of the velocity of light corpuscles via

2. On parabolic mirrors, see *BibNum* analysis by Vincent Guigueno of Fresnel's 1822 text (November 2008).
3. This microscope, using quite recent daguerreotypes, invented in 1836, and designed by Foucault during his studies in medicine, may also be related to his works in optics (such as this one mentioned here), confirming his pioneering nature in his devices for light representation, either in medicine or in physics.

augmentation; the tangential component does not change. The refractive index is in this emission theory

$$n = \frac{V_{water}}{V_{air}} = \frac{\sin i}{\sin r}$$

i = angle of incidence = angle formed by the incident ray and the normal
r = angle of refraction = angle formed by the refracted ray and the normal,

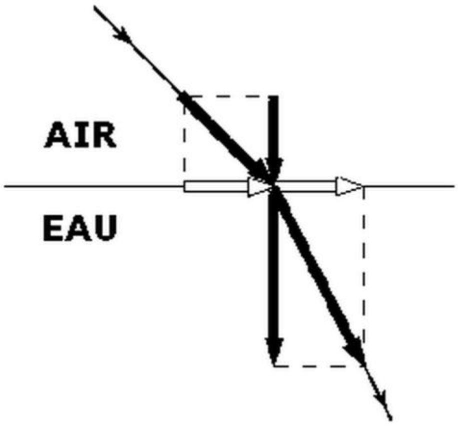

Figure 1: *In Newton's corpuscular theory, light was supposed to be accelerated at the shift towards a denser medium (in its normal component).*

With regard to the wave theory, both Huygens and another author, Pierre Ango (1640-1694), a professor of mathematics at Rouen, had studied the experiments of Jesuit Ignace-Gaston Pardies (1633-1673), described in a manuscript which was never published. These experiments seem to have suggested to Ango and Huygens their wave and light theory. Ango published in 1682 a work[4] which was actually the first hypothesis that stated the wave nature of light, and Huygens had a copy of this treatise in his library[5]. In this theory, an omnipresent fluid, ether, is the medium needed to transport light. The ether of the seventeenth century physicists (Newton, Huygens, Hooke, Pardies, Ango) fills every pore of all material bodies; it is an elastic medium capable of propagating vibrations. It is also responsible for the cohesion of materials and its density varies from one body to another. In this theory, the speed of light is more elevated in vacuum or in air, than in denser materials. In this theory, in effect,

$$n = \frac{V_{water}}{V_{air}} = \frac{\sin i}{\sin r}$$

4. *L'Optique*, by P. Pierre Ango, Paris, Michallet, 1682 (on line in *Google Books*).
5. Catalog of the Huygens sale, Moetjens, La Hague, 1695, page 13.

In 1838, Arago proposed an experiment he claimed as crucial for validating both theories[6]. Foucault's thesis, which was defended in 1853, is the realisation of *the crucial experiment* proposed by Arago and which involves the measuring of the speed of light in air and in water in order to validate either of the theories.

Figure 2: from left to right: Foucault (1819-1868), Arago (1784-1853), Fizeau (1819-1896). *The first and the third would compete to carry out the experiment devised by the second.*

Let's note, however, that Foucault's experiment is not actually crucial. It starts from the hypotheses which are not as such that the confirmation of one of the two theories implies the negation of the other – and that the nullification of one implies the validity of the other. Indeed, the hypothesis of Arago and Foucault is that all corpuscular theory is false if the speed of light in vacuum is greater than the speed in a denser medium: in fact, this result invalidates only the modelling of refraction in the corpuscular theory.

REMINDER OF THE HISTORY BY FOUCAULT

Foucault's thesis begins with *Historical preliminaries*, in which the author recalls the three methods, used previously, to measure the speed of light. His text is based on a certain popularisation on these experiments - Foucault was also a populariser of science.

He firstly refers to the technique of Roemer[7] which

> *is, as we know, in the apparent inequality of successive returns of the satellite eclipses that accompany Jupiter.*

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6. « Sur un système d'expériences à l'aide duquel la théorie de l'émission et celle des ondes seront soumises à des épreuves décisives » *CRAS*,7, pp.954-965, 1838; also: *Annal. Chim.* LXXI, pp.49-65, 1839.
7. *Journal des Savants*, 7 December 1676, pp. 233-236 (see BibNum analysis of this text by F. Beaubois, October 2009).

He refers to the experiment of Bradley[8] on the aberration of stars:

> *The two speeds* [that of light and that of Earth around the sun] *are as 10200 is to 1; consequently, when a telescope is directed towards a star located in the circle of maximum aberration, it is led in a direction perpendicular to the direction of its axis, by the motion of Earth; and during the time that light takes to travel the distance from the optical centre of the lens to its origin, the eye of the instrument advances in a parallel fashion to the focal plane, of approximately the ten-thousandth part of this distance.*

Foucault indicates that this is the proposed experiment, formulated by Arago in 1389, which is the source of his own work. Arago's goal, as we have already said, was to imagine a crucial experiment on the speed of light in refracting environments such as water, in order to decide if the emission or wave theories should ultimately be adopted.

MOST RECENT EXPERIMENTS: WHEATSTONE & ELECTRICITY, FIZEAU & LIGHT.

Foucault then describes the method of the rotating mirror invented by Charles Wheatstone who had imagined a technique for measuring the time interval between two events by converting this time interval into amplitude of an angular deviation. He is, one might say, the first time-amplitude converter in history; current time-amplitude converters use electronic techniques and can measure intervals of a few picoseconds [9].

Wheatstone (1802-1875) and the Measuring of the Velocity of Propagation of Electric Power

The goal of Wheatstone's experiment was to measure the speed of propagation of an electric current on a conductive wire[10].
Wheatstone believed in the two-fluid theory of electricity. These fluids propagating in the opposite direction from both ends of an electrical circuit should (in this theory) reach the middle of the circuit after a certain delay due to the time of propagation. Wheatstone thus incorporated in series in a wire three spark gaps and applied to the circuit the voltage difference obtained in a Leyden jar. A spark gap[11] is an item comprising of two metal spheres separated by a small air

8. *Phil. Trans*. London, vol. 35, pp 637-660, 1729.
9. Cf. J.J. Samueli et al. *Instrumentation électronique en physique nucléaire.* Masson, 1968.
10. C. Wheatstone. "An account of some experiments to measure the velocity of electricity and the duration of electric light" *Phil. Trans*. vol. 124, pp. 583-591, 1834.
11. The reciprocating engine spark plugs are simple spark gaps. Modern spark gaps used in electronics are encapsulated, containing a neutral gas and a third trigger electrode. A radioactive alpha source is sometimes included to pre-ionize the gas and reduce the delay and the temporal fluctuation when triggered. These devices can transfer thousands of amperes.

gap: when the voltage difference across both spheres exceeds the breakdown voltage of air, a spark is produced and the spark gap becomes conductive by emitting a flash of light as well as a pop. Wheatstone examined the reflection on a rotating mirror of three pulses of light that appeared in the spark gap during the passage of the current; no deflection of light rays intervened in return if the three light pulses were synchronous. Conversely, any time interval of the emission of light signals corresponded to an angular deviation.
The method of measuring the time interval of the light pulses was excellent, but the modelling of the transmission of the electric current was false and the evaluation with spark gaps was doomed to fail. The current in the circuit with three spark gaps in series could not, for example, show that when the three spark gaps were all conductors and the light flashes were thus all synchronised on the conduction of the last spark gap. Moreover, the functioning of a spark gap is connected to the initial ionization of the gas separating the electrodes, and the three spark gaps that were in direct view, exchanging a flux of photons, ionising each other during their sparking. Wheatstone thus obtained insignificant results. He even found a speed of propagation of the electric current greater than the speed of light in vacuum. Yet his experiment made him famous.

Foucault does not discuss, in his thesis, the validity of Wheatstone's experiment in electrical terms, but rightly emphasises the value of the method of the rotating mirror for transforming a time interval between light signals and an angular shift. He writes:

> *Mr. Wheatstone deduced from these kinds of experiments a value of the speed of electricity that is not consistent with the results of more recent measurements. Perhaps he has been misled by incidental phenomena that complicate the main phenomenon, but which are independent of the optical method that he has used. If so his work still offers material for discussion; it does not appear that the objections may relate to the valuable property of the rotating mirror to separate, by the angular displacement of certain images, the very close moments that correspond to the appearances of instant phenomena.*

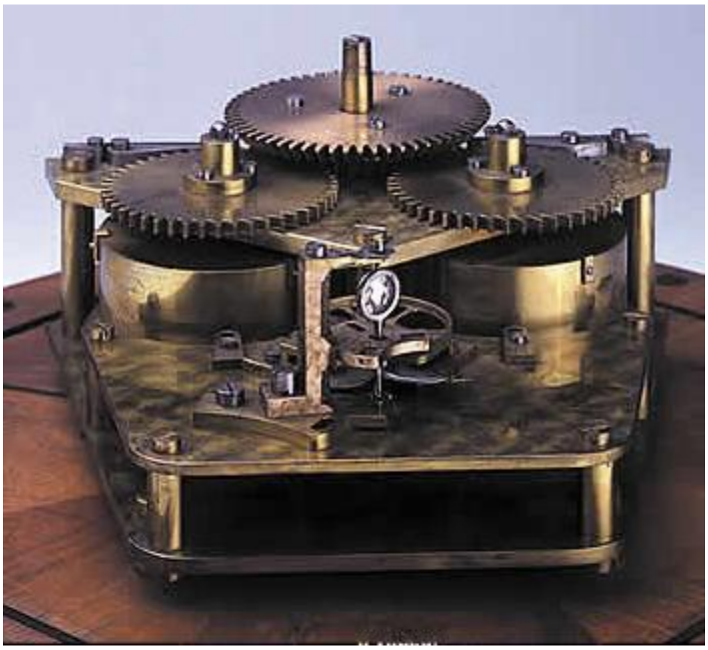

Figure 3: The rotating mirror device developed by Bréguet. *At the centre of the image is the small mirror that must be rotated at a high speed (500 to 800 rpm/s). Louis Bréguet[12] (1803-1883) was both a physicist and engineer and he designed this horologic device for this type of experiment (here is the device used by Fizeau). As Foucault indicates: "the most important and the newest part of this apparatus was the machine which had to communicate to the mirrors the movement of rotation. The construction was entrusted to Mr. Bréguet, whose talent ensured a complete success".*
(image: Observatoire de Paris, site www.foucault.science.gouv.fr)

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Foucault also describes the method used by Fizeau in 1849 for measuring the speed of light in air directly and absolutely, with the aid of a light ray passing through Paris and going from Suresnes to Montmartre, on a distance of 8630 metres. The essential element of the apparatus is a rotating toothed wheel which cuts into pulses a continuous ray incident. A telescope sends the chopped ray starting from Suresnes on an identical telescope located in Montmartre which focuses it on a mirror, then the ray is sent by means of the telescope towards Suresnes. The latter then focuses light of the other side of the toothed wheel. The observation of the reflected ray depends on the speed of rotation of the toothed wheel, the light being transmitted or stopped by this wheel following aforesaid speed and the number of teeth. On 23rd July 1849, Fizeau informed the *Académie des sciences* that, after a series of 28 measurements, he had obtained the value of 315300 km/s for the speed of light in air.

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12. The grandfather of aircraft manufacturer Louis Bréguet (1880-1955), founder of *Bréguet Aviation*.

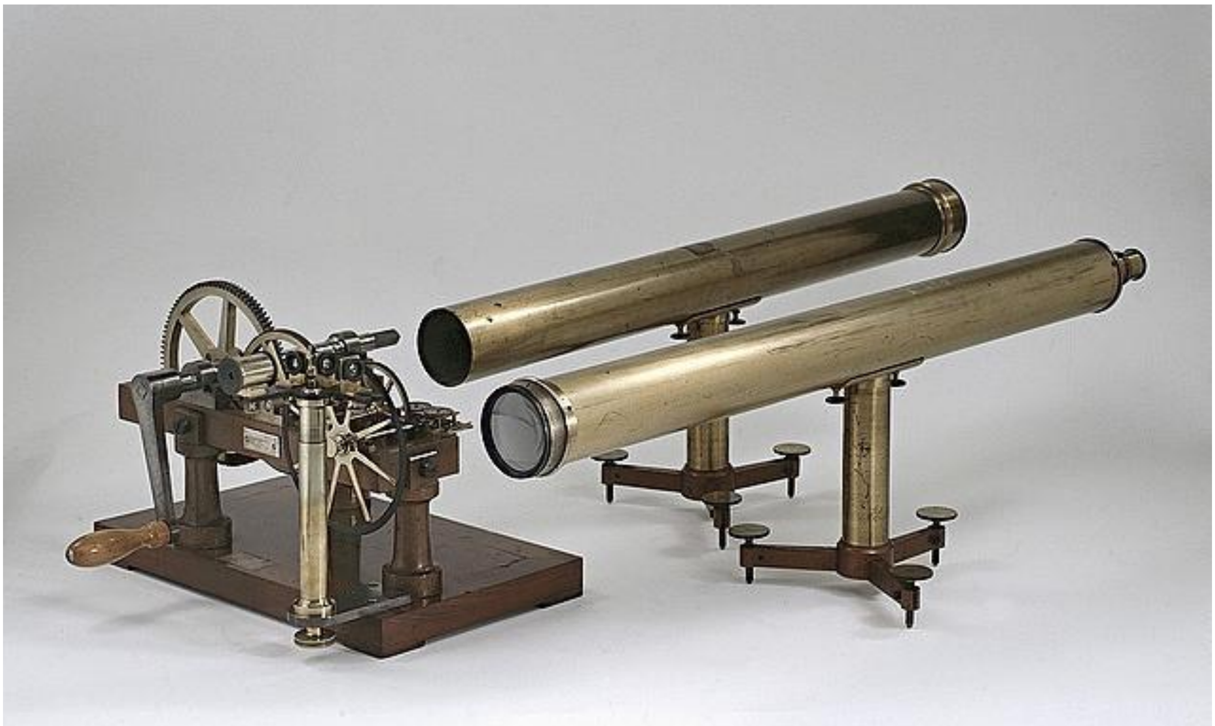

*__Figure 4__**: The device from Fizeau's experiment, 1849.*** *To resume the description made by Foucault: "Mr. Fizeau had placed the telescope eyepiece* [at the right of the photo] *overlooking a house located in Suresnes, and the telescope reflection* [at the top of the previous page] *on the height of Montmartre, at a distance approximately 8633 metres. The disc* [at the left of the photo]*, bearing seven hundred and twenty teeth, was mounted on a wheel driven by weight"*
(Image: Bibliothèque de l'École polytechnique, inventaire général ministère de la Culture)

FOUCAULT'S EXPERIMENT

Even if the thesis was supported in 1853, the experiment dates back in fact to April 1850. Fizeau himself only pulled off this experiment six weeks later, which led to a pronounced dispute between the two men.

From page 15 of his paper, Foucault describes his own experiment in which the essential character, he writes, consists of *the observation of the still image of a moving image*, in order to assess "the time employed by light to cross an interval of a <u>few</u> metres". He writes (see figure below):

> *Indeed, ab, fig.1 is an object* [figure below to the left]*, and a'b' its image* [to the right, on the concave mirror M], *formed by lens L* [under the indication fig.1, to the right] *and falling to the reflecting surface of concave mirror M; c is the point in the space where later on the figure centre of a turning mirror is placed* [mirror m, under the indication fig.1, to the left]; *if the concave mirror has its centre of curvature at point c, the reflected ray on its surface will return majorly by the objective to reform on the object ab an image, straight and of natural size.*
>
> *…when it* [mirror m] *is rotated, the image moves in the space on a*

circumference whose radius can take as much a wide range as desired. Thus obtained is the moving image in which the trace can be received and distinguished on a screen. To get the still image, it is necessary to place on the circumference described by the moving image [the circumference in M, to the left]*, the reflecting surface of a concave spherical mirror oriented so much that its centre f curvature coincides with the centre of figure of the rotating mirror…*

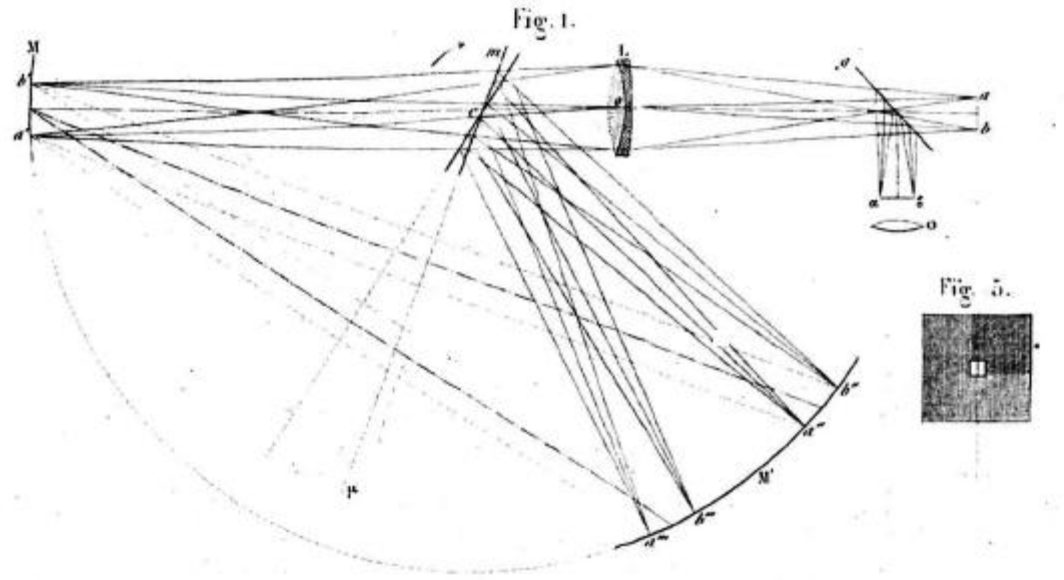

***Figure 5**: The device of Foucault's experiment, 1851* *(figures 1 & 5 from the board of figures at the end of Foucault's document). Mirror* m *turns in the direction indicated by the diagram's arrow.*

The description of the optical path of the light ray may be summarised in fact as follows. Sunlight reflected by a heliostat enters a diaphragm provided with a vertical wire (the sight, above αζ to the right, and shown in Foucault's fig.5 below); it is focused by a lens *L* onto a rotating mirror *m.* A 45° blade allows for examination the ray and two concave mirrors belonging to the same sphere having its centre in *c* are placed at the end of an optical path in the air on the one hand, and in water, on the other hand. During a round trip between *m* and *M*, the rotating mirror *m* turns a certain angle and the lateral displacement of the image in *a* or *a'* is proportional to this angle which depends on the speed of rotation of the mirror and of the travel time of light between *m* and *M*:

…to get the image on point a' *on any normal part of the surface of the concave mirror M. Reflected on itself, this ray find the plane mirror, but it has already turned, and the ray, by reflecting for a second time under a new incidence, takes a new direction too, which no longer lets it form an image at its starting point, but which requires it to give in* a *an image that is deflected in the direction of the movement of rotation…*

The first important result obtained by the device is thus the measuring of a light's travel time, obtained by the interval of the source image on the focus when the mirror turns sufficiently fast, which Foucault summarises as:

Also, when the number of the mirror's turns is less than 30 per second, the image only shines intermittently; by higher speeds (...), the image αζ then appears permanent (...) But when the mirror turns sufficiently fast another effect occurs, and we see appear the important phenomenon of deviation. The image αζ moves below the line of the ocular micrometre (...) this displacement shows that the propagation time of light between the two mirrors is not zero, and that it can be measured by the size of the deviation itself.

Let's go over this stage: there is a still image (object ab) transformed into a multiplicity of moving images (by rotating the mirror m), these images being all reconstructed in a still image to the original source ab (or through the focus αζ for observation): but this still image in turn is shifted in relation to the original image, this interval allowing for measuring the speed of light.

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Once his general device is in place, Foucault involves two different environments, air and water:

While the lengths cM and cM' are kept equal, as circles, traversed on both sides, remain identical, the acceleration of the rotational movement, producing on the two images the same deviation, not able to make them different from each other. But the interposition of a refractive medium on one of the two directions cM or cM', altering the perfect symmetry of the system, must, by modifying the speed of light in one of the two paths, produce duplication α'α" of the imageα. This is actually what happens when, in front of the mirror M' the pipe filled with water and closed at both ends is placed, by parallel mirrors.

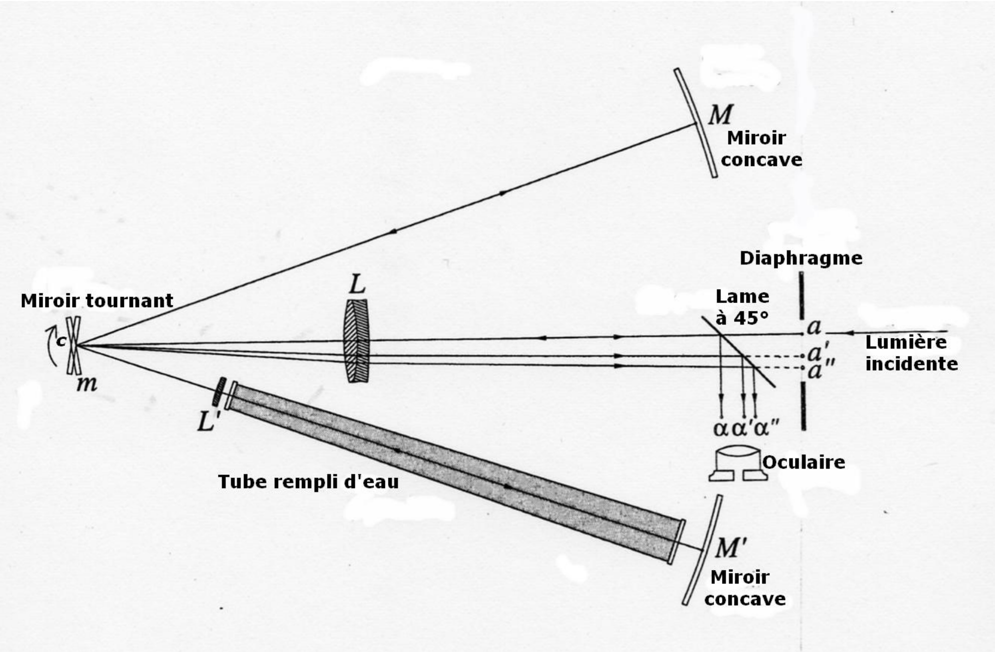

***Figure 6*: Same device as figure 5 above, stylised.** *This diagram corresponds to Fig. 3 of the Foucault board. We see in addition to the previous figure the journey in the air mM above, and the journey in the water mM' below. The rays of the concave mirrors M and M' is around l = 4 metres.*

The temporal resolution of Foucault's assembly which converts into an amplitude of angular deviation a time interval is, of course, even better when the speed of rotation of the mirror is high. Foucault was able to achieve a mirror turning 14 mm driven by a small steam engine that he describes in detail and which is drawn on the board included in his thesis. He indicates:

> *I considered obtaining obtain speed, strength and regularity by adapting a small machine that uses the flow of gases through narrow orifices.....The small steam engine acquired easily, by pressure of 1/2 atmosphere, a speed of 6 to 800 turns per second.*

If we assume that the refractive index of water is equal to 1.33, the light travels a metre of air in around 3.3 nanoseconds and a metre of water in 4.4 nanoseconds. At the speed of 500 turns per second (respectively 2 times), the mirror turns 360° in 2 milliseconds or 2×10^6 nanoseconds. A nanosecond time interval corresponds thus to a deviation of the mirror of $360/(2\times10^6) = 1{,}8\times10^{-4}$ degrees (respectively 2 times more). With this value we find, for the dimensions of the assembly given by Foucault on page 25, an image deviation observed in the eyepiece of a few tenths of a millimetre[13], therefore perfectly measureable:

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13. The deviation is proportional to *l* distance of travel in water and to *r* distance between the lens and the focus (in fact, if the mirror is shifted by an angle θ, the focus is shifted by $r\theta$), as confirmed by Foucault's page 20 approximate formula, where the deviation *d* of the focus is proportional to $r \times l$: $d = 8\pi lnr/V$. This formula

… we have for the white image [image in air] *a deviation of 0mm,375, and for the green image* [image in water] *a deviation of 0mm,469*[14]*; their difference can obviously not escape observation.*

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Foucault adds, after a simple calculation, a remark that justifies the title of his thesis "On the Relative Speeds of Light in Air and in Water":

Moreover, to decide the question that interests to such a high point the theory, it is not necessary to measure the speed of light in water, not to worry about the means of achieving it; it is enough to state in what sense the deviation that occurs in operating solely in air, it changes when we interpose a column of water long enough to produce a significant effect; better yet to have in the apparatus two lines of experiments, one for air only, the other for air and water, and to observe simultaneously the two corresponding deviations. The comparison becomes then so easy, that it is unnecessary to make any measurement.

Foucault concludes in the following manner, which sums up well his whole experiment:

By bringing together a concave mirror and a rotating mirror, the latter can give to the observer the still image of a moving image; still image for a uniform rotation, but which deviates directly because of the angular speed of the mirror and of the duration of the double route of the light between two very close together stations; a very simple calculation shows that we obtain a noticeable and measurable indication of the duration of propagation of the principle light between two distant points of a small number of metres. Consequently it becomes possible to interpose either air or water and to judge relative speeds by corresponding deviations. An experimental artifice allows also obtaining simultaneously the two deviations, to superimpose them in the field of the same instrument, and to make direct comparisons without relating them to a common unit, without the need to take any measurement.

That we modify the speed of the mirror or the distance of the stations or that of the difference parts of the device, the deviations change in size without a doubt; but always that which corresponds to the journey in water seems larger than the other, always the light is delayed in its passage through the most refractive medium.

The final conclusion of this work consists thus in declaring the emission system incompatible with the reality of the facts.

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gives in air (V = 300 000 000, l =4m, r = 3m, n=500) a gap of 0.5 mm, and in water (V= 300 000 000/1.33) a gap of 0.67 mm: the difference between the two is approximately 1/10^{e} mm.

14. The values given by Foucault are obviously correct; with respect to the calculation of note 14 above, they are slightly lower, as well as the gap between the two values, for various reasons that Foucault details: exact calculation of the travel time in water (the ray which goes into water is also in the air at a part of its path) + not a precise coincidence of the rotating mirror and the centre of the concave mirror. But the order of size given in note 14 above is valid.

Let's add that the exact theory of the refraction of light was only established as part of electromagnetism. J.C. Maxwell showed, in 1868, that light is a type of electromagnetic radiation; seven years later, H.A. Lorentz formulated the theory of reflection and of the refraction of light within this electromagnetic theory[15].

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(September 2009)

(Translated in English by John Moran, published September 2014)

The author wishes to thank Alexandre Moatti for his participation in the writing of this commentary.

15. *Over de theorie der terugkaatsing en breking van het licht*, (On the Theory of the Reflection and Refraction of Light) Academisch proefschrift, H. A. Lorentz, Arnhem: K. van der Zande, 1875