Experimental Proposal for Determination of One-Way Velocity of Light with One Single Clock

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Abstract: In 1898 Henri Poincaré stated the physical impossibility of measuring the one-way velocity of light. In the present note, we present a proposal for two experimental processes that may overcome the so-called Poincaré's curse.

KEY WORDS: Special relativity, one-way velocity of light, clock calibration.

1. Introduction

At a first sight, it would seem that the experimental determination of the one-way velocity of light is a single task. So, in order to do that it is only necessary to have a source of light emitting from point A and let the light travel the path of length L to arrive at point B. Then, by measuring the time the light takes to travel from point A to B it seems possible to obtain the one-way velocity of light simply by dividing the length L by the time difference measured by the two clocks. Still this appearance of simplicity is only an illusion[1]. To measure the initial time, the time of departure of the pulse of light from point A we need a clock placed at that point. To determinate the arriving time, the final time, another clock must be placed at point B. The transit time will then be the time difference of the two readings, if and only if the two clocks are synchronized. Now arises the magnum problem how to synchronize two separated clocks[2].

We could synchronize the two clocks at the same position A then, by slowly moving the clock B to the final position we would get them calibrated at different positions. Nevertheless it was shown[3] that whether this displacement is done in slow motion or in fast motion there is always an indeterminate amount of time necessary to calibrate the clock B. This time, needed to synchronize the two separated clocks, depends on the theory. The usual way to synchronize two clocks is given by special theory of relativity[4]. Nevertheless as shown by Reichenbach[5] and by Selleri[6] there are many other open possibilities compatible with the two-way velocity of light invariance. Since the synchronization of the two separated clocks depend on the theory it follows immediately that the one-way velocity of light, being the relation between the travel path length L and the measured difference in the two times readings, depends also on the assumed theory. It was precisely because of being aware of these basic facts that, back in 1898, Henri Poincaré[7] arrived at the conclusion that it was impossible to measure the one-way velocity of light. Since then, this impossibility statement is known as Poincaré's curse.

In the present note, we present two concrete proposals of experiments that may overcome Poincaré's curse. The basic idea is that both experiments are done with one single clock.

2. Experimental determination of the one-way velocity of light with one single clock

The process is sketched in Fig.1, where the pulse of light from the source S is divided into two beams, one going by air, the other through an optical medium. After, both beams return to the initial point through air. The relative one-way refractive index *n*, between the two mediums is assumed to be known. The two beams went from the initial point and return to the same point after traveling precisely the same distance.

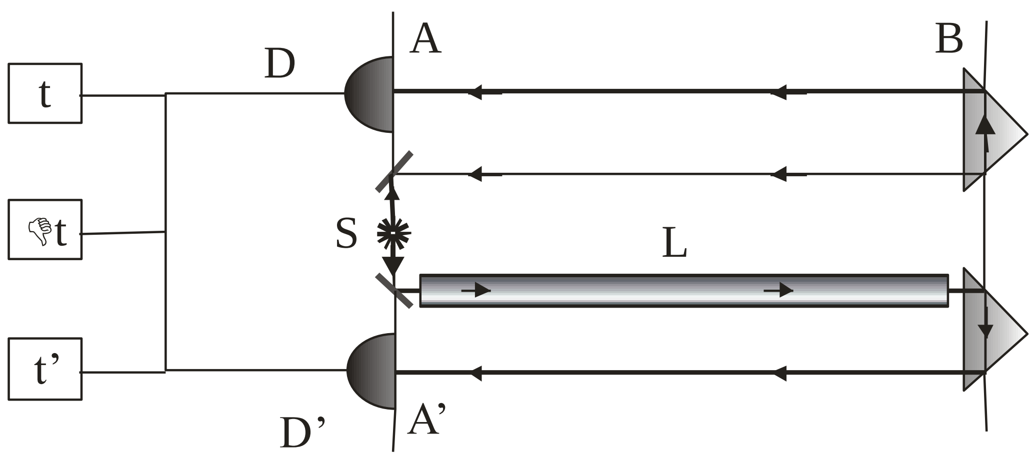

Fig.1 – Single-clock-one-way velocity of light

The upper beam travels through the air, while the lower beam goes through an adequate optical medium like glass, water or so, of length L. In the drawing, due to the lack of perspective, points A and A' were represented as separated, nevertheless in the real experiment they are very close so that one is allowed to make A ≈ A'.

If in the lower beam the optical medium were removed the two arriving times, measured at detectors D and D' placed at point A, would read precisely the same since the optical paths are equal. Nevertheless, in our case the total traveling times of the pulses, by air and through the optical medium, are:

$$\begin{cases} t = t_{AB} + t_{BA} \\ t' = t'_{AB} + t'_{BA} \end{cases} \qquad (2.1)$$

were

$$t'_{AB} = t_a + t_m , \tag{2.2}$$

with t_a standing for the time in the air and t_m the time through the medium. These being given by

$$t_a = \frac{\ell - L}{c_{AB}}, \quad t_m = \frac{L}{c'_{AB}} , \tag{2.3}$$

were ℓ is the distance from A to B, c_{AB} is the one-way velocity of light from point A to B, and c'_{AB} is the one-way velocity of light through the optical medium. The time the pulse of light takes to go from A to B through air is given by

$$t_{AB} = \frac{\ell}{c_{AB}} . \tag{2.4}$$

Since the return paths are both of the same length and done in the same medium, the air, the return transit times are equal

$$t'_{BA} = t_{BA} , \tag{2.5}$$

consequently, the time difference between the two readings, at the two clocks placed at point A, is given by

$$\Delta t = t'_{ABA} - t_{ABA} = t'_{AB} - t_{AB} , \tag{2.6}$$

that is, by substitution

$$\Delta t = \left(\frac{\ell - L}{c_{AB}} + \frac{L}{c'_{AB}} \right) - \frac{\ell}{c_{AB}} ,$$

or

$$\Delta t = \frac{L}{c'_{AB}} - \frac{L}{c_{AB}} . \tag{2.7}$$

Multiplying the last expression by c_{AB} we get

$$\Delta t \, c_{AB} = L \left(\frac{c_{AB}}{c^1_{AB}} - 1 \right),$$

recalling that the definition of relative index of refraction is

$$n = \frac{c_{AB}}{c_{AB}^{'}}, \qquad (2.8)$$

we finally get

$$c_{AB} = (n-1)\frac{L}{\Delta t} \qquad (2.9)$$

the expression for the one-way velocity of light in term of known measured quantities.

Even if from the conceptual point of view this is a solid and consistent process for determination of the one-way velocity of light, the concrete experiment need to be done in a large laboratory. This conclusion follows from the fact that the resolution times of the light detectors and of the associated electronics is of about ten nano seconds. In such conditions a pulse of light of for instance one pico second of duration would travel in that time about three meters. So, in order to have some reasonable resolution, the length of the optical medium need to be at least of about one hundred meters long. In order to overcome this experimental necessity it is possible to devise a shorter device to determinate the hypothetical one-way velocity of light variation.

3. Experimental determination of the variation one-way velocity of light with one single clock and with a time precision of fentosecond order.

Consider Fig. 2 where it is shown a kind of reversed Mach-Zehnder interferometer with the input and output ports placed practically at the same point, A' ≈ A.

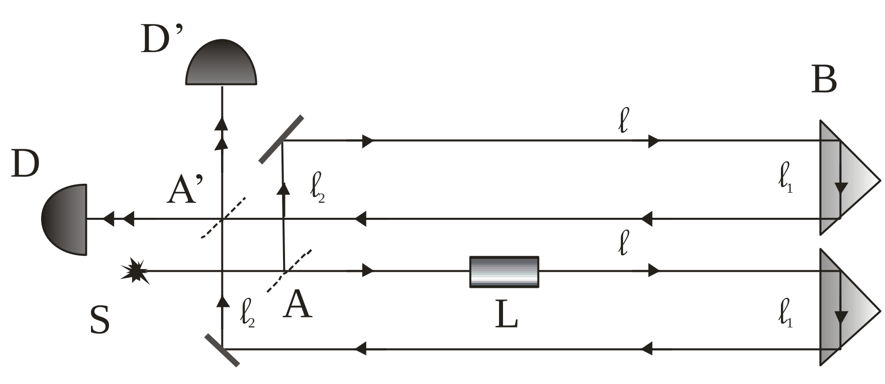

Fig.2 – Reversed mac-Zehnder interferometer

From the sketch one see that point A behaves like the initial clock A and point A' like the final arriving clock A'. Since A and A' are placed practically at the same physical point of space there is no need for clock calibration due to the relative motion. In such circumstances one is allowed to assume that for all practical purposes clock A and A' are the same single clock.

The time difference, measured at A', for the light traveling through two different and independent optical paths of precisely the same length can be found easily.

The waves arriving at the return beamsplitter localized at point A' in the plane wave approximation can be written

$$\begin{cases} \psi_1 = A\, e^{i[k(2\ell+\ell_1+\ell_2)-\omega t]} \\ \psi_2 = A\, e^{i[k(\ell+(\ell-L)+\ell_1+\ell_2)+k'L-\omega t]} = \psi_1 e^{i(k'-k)L} = \psi_1 e^{i\delta} \end{cases} \tag{3.1}$$

with

$$\delta = (k'-k)L\,. \tag{3.2}$$

The intensity measured at output port D is given, for 50% beamsplitters, by the usual formula

$$I = 2I_0(1+\cos\delta)\,. \tag{3.3}$$

From the value of the measured intensity one gets the value of the phase δ. This phase given by expression (3.2) can also be expressed in terms of time giving

$$\delta = \omega\,\Delta t \tag{3.4}$$

assuming, as the experimental evidence tells us, that the frequency of the light does not change. This time interval is, for the optical range, given by

$$\Delta t \approx \frac{\delta}{2\pi}\times 10^{-15} s\,. \tag{3.4'}$$

Recalling the setup of the experiments and formula (2.9) we can write immediately

$$c_{AB} = (n-1)\frac{L}{\Delta t}$$

Since in this case the value measured experimentally is the phase difference the one-way velocity of light can be expressed taking in consideration (3.4) in terms of known values

$$c_{AB} = (n-1)\frac{\omega L}{\delta}\,. \tag{3.5}$$

Still in this interferometric experiment it is very difficult to know the value of the length L of the piece of the optical medium with great precision. On the other hand the phase difference is calculated form the value of the measured intensity. This intensity is the same for a multiplicity of phase differences given by

$$\theta = 2n\pi + \delta, \quad \text{with} \quad 0 \le \delta \le 2\pi \,. \tag{3.6}$$

As a consequence from expression (3.5) it is in general not possible to arrive at the experimental value for the one-way velocity of light. The difference between two one-way velocities, if any, must be very small, therefore the ratio for two different directions it is given by

$$\frac{c_{AB}^{1}}{c_{AB}^{2}} = \frac{\delta_2}{\delta_1} \tag{3.7}$$

or

$$\delta_1 \, c_{AB}^{1} = \delta_2 \, c_{AB}^{2} \,.$$

4. Conclusion

It was shown, under reasonable experimental requirements, that it is in principle possible to determinate the value of one-way velocity of light or at least its hypothetical variation with the direction can be measured with great precision.

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