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A one-way speed of light experiment

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A recently proposed experiment that demonstrates the feasibility of carrying out a one-way measurement of the speed of light was performed using a time of flight technique. A single oscillator amplitude modulates a He–Ne laser beam, which transverses a distance to a sensor. The output signal returns via a coaxial cable to a digital oscilloscope where the phase difference between the reference and the sensor signals is measured as a function of the distance traveled by the light. The results, within 0.4% of the accepted value of c, prove the feasibility of measuring the speed of light moving in one direction. © *2009 American Association of Physics Teachers.*
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I. INTRODUCTION

There has been a very long controversy on whether it is feasible to measure the speed of light on a one-way fashion.[1–4] An argument in a letter written by Einstein to Sommerfeld[5] in 1908 makes a characteristic reference to the problem. Questioning of the feasibility of one-way speed measurements has been fostered by the fact that the second postulate of special relativity[6,7] states that the speed of light is a universal constant. The quest of testing relativity or the old concept of the luminiferous ether by proposing that one should look for spatial anisotropy of the speed of light has fuelled the controversy.[8] The Michelson–Morley experiment[9] used an interferometer where light beams are compared in a two-way fashion. Critics of this important experiment have argued that the two-way nature of the measurement may be the cause of its negative outcome. Simple distance and time measurements are questioned by arguments of clock synchronization.[10] Einstein's synchronization procedure for two clocks A and B is to send a simultaneous light signal from the midway point to the two clocks.[11] However, this operational definition of simultaneity presumes that light travels at the same speed in both directions. Hence, clock synchronization has been used to claim that the one-way speed of light is a quantity that cannot be measured,[8,12] leading to unphysical statements in the literature.[13] Measurements of the speed of light designed to test for possible space anisotropies[14] have been performed and criticized when they involve two-way measurements. Clearly they lack a logical foundation if they rely on Einstein's synchronization procedure. Reports claiming sensitivity to the isotropy of the one-way speed of light to $\Delta c/c \leq 3\times10^{-9}$ paradoxically use a counter-running laser beam.[15] Any measurement of the speed of light in one direction, from A to B, which uses only one clock to avoid the problem of synchronization, requires the return back to A of the time information of the arrival at B. A mechanical, coupled, spinning, slotted-disks, Fizeau-type one-way speed of light experiment was performed by Marinov[16] and reputedly showed evidence of space anisotropy. More recent is a reputedly successful detection of the ether-drift by DeWitte.[17] Further attempts at measurements of the one-way speed of light are being planned.[18,19]

In this paper we do not address the problem of space anisotropy or its detection. We report on a simple student-experiment recently proposed[20] that demonstrates the feasibility of performing one-way measurements of the speed of light. It is a variation of an equally simple tabletop experiment recently reported by Aoki and Mitsui.[21] It differs in that the latter is a two-way measurement of the speed of light.

II. DESCRIPTION OF THE EXPERIMENT

We review the proposal in Ref. 20. The experiment is a variation in the procedure with which contemporary surveyors[22] measure distances. An instrument transmits a light beam of visible wavelength from a He–Ne laser (modulable laser, Metrologic, model ML869) to which is applied a modulation signal of approximately 1 MHz. The beam is amplitude-modulated. In a geodimeter (without the variation) the light beam is directed onto a mirror at a distant point from which it is reflected back to the instrument. The incoming light is received by a photosensor and converted to an electrical signal, and the difference in phase between the reference transmitted and the received signals is measured in a digital oscilloscope (Tektronix, model TDS 210). The oscilloscope can average 128 sweeps so that fluctuations in the light path can be largely smoothed. The timing of the light

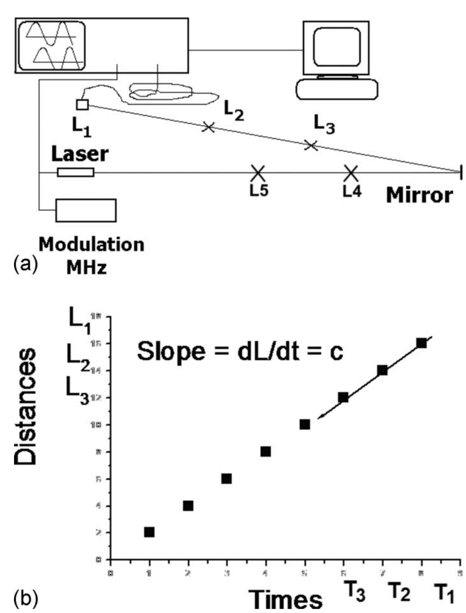

Fig. 1. (a) Schematic diagram of the experiment to determine the one-way speed of light. (b) Sketch of the expected results if the one-way speed of light measurement is possible (from Ref. 20).

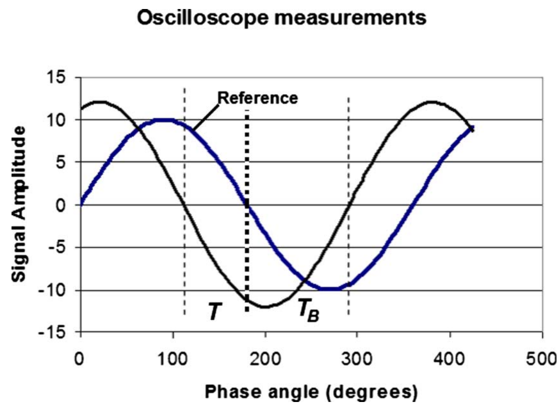

Fig. 2. Waveforms showing the measurement cursors (dashed lines) in the oscilloscope. Phase angle changes were deduced from the values of the intervals $\boldsymbol{T}$ and $\boldsymbol{T}_{\mathrm{B}}$.

path is done by a measurement of the phase difference between the transmitted modulated signal in the instrument and the signal received by the light sensor.

Our experiment shown in Fig. 1 consists of adding a long coaxial cable (23.73 m, 50 Ω) to the light sensor so that it can be moved toward the mirror. The mirror was used in order to perform the experiment in a laboratory of limited size. The distance is then shortened to values $\boldsymbol{L}_1, \boldsymbol{L}_2, \boldsymbol{L}_3, \ldots$ to the point of reaching the mirror position, and then moved toward the laser at positions $\boldsymbol{L}_4, \boldsymbol{L}_5, \ldots$. The coaxial cable introduces a fixed time delay of $\boldsymbol{T}_c = 79$ ns. Hence, the measured phase difference will be due to the time delay (time of flight) in traversing the light path from the source to the sensor, plus the fixed delay in the long cable and detection electronics. Let the total time delays corresponding to such phase differences be $\boldsymbol{T}_1, \boldsymbol{T}_2, \boldsymbol{T}_3, \ldots$. What does a graph of the total distances $\boldsymbol{L}_i$ as a function of the measured times $\boldsymbol{T}_i$ look like? Are the times $\boldsymbol{T}_1, \boldsymbol{T}_2, \boldsymbol{T}_3, \ldots$ all equal, or do they decrease due to a reduction in the path traversed by the light?

A graph of the measured times as a function of the total distance traveled by the light beam should be a straight line with slope equal to the speed of light. When the sensor reaches the position of the mirror, the light has traveled a one-way distance toward the sensor. The measurements of these delay times and the distances traveled should give the one-way speed of light.

The phase changes corresponding to different distances $\boldsymbol{L}_1, \boldsymbol{L}_2, \boldsymbol{L}_3, \ldots$ were measured in the oscilloscope by placing a reference cursor at a point where the reference oscillator signal cuts the $y=0$ axis. The oscilloscope was triggered by this signal so that this cursor position was stable. The shift in the time delays corresponding to phase differences $\boldsymbol{T}_1, \boldsymbol{T}_2, \boldsymbol{T}_3, \ldots$ was measured in the oscilloscope at two points where the sensor signal crosses the $y=0$ axis, $\boldsymbol{T}$ and $\boldsymbol{T}_{\mathrm{B}}$ on either side of the reference cursor (see Fig. 2).

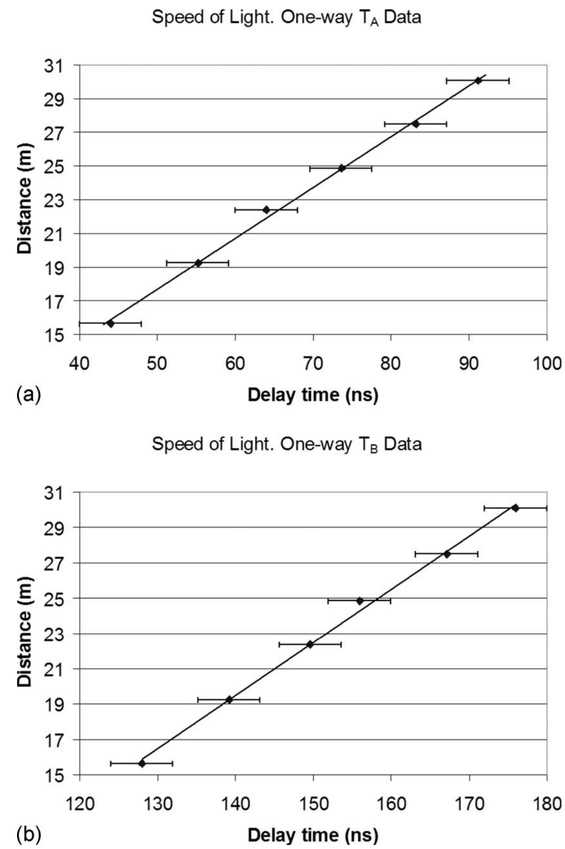

Fig. 3. The laser-to-sensor distances as a function of the delay time between the reference and the sensor signals. The distance error bars of 0.005 m are not visible. The slope of the linear fit yields the speed of light. (a) $\boldsymbol{T}_{\mathrm{A}}$ data. (b) $\boldsymbol{T}_{\mathrm{B}}$ data.

Five independent measurements were taken over 5 min periods at each $\boldsymbol{L}_i$ position and averaged. The phase differences have a time resolution of 4 ns. Due to the decreasing phase difference, one of the measurements ($\boldsymbol{T}$ in Fig. 2) is monotonically increasing and the other ($\boldsymbol{T}_{\mathrm{B}}$ in Fig. 2) is monotonically decreasing. Data reduction included the subtraction of the increasing values from an arbitrary value of 400 ns ($\boldsymbol{T}_{\mathrm{A}} = 400 - \boldsymbol{T}$ in Table I). The distances $\boldsymbol{L}_i$ were determined with a 30 m plastic tape measure, have ±5 mm estimation error, and are probably systematically larger due to slight tape sag.

III. RESULTS

The measured values of the phase changes are shown in Table I and plotted in Fig. 3. The linear fit to both sets of data gave similar slopes, which are measurements of the speed of light. The fits were quite good with the correlation coefficient R equal to 0.998 in both sets of data. The slopes of the curves

Table I. Laser-sensor distances, phase differences, and fitted slopes.

	Measurements						Fitted slope	Error
Distance (m)	30.071	27.508	24.868	22.380	19.236	15.660	$\times 10^8$ (m/s)	
$\boldsymbol{T}_{\mathrm{A}}$ (ns)	91.2	83.2	73.6	64.0	55.2	44.0	3.016	0.071
$\boldsymbol{T}_{\mathrm{B}}$ (ns)	176.0	167.2	156.0	149.6	139.2	128.0	3.004	0.085

have errors of 2.4% and 2.8% for data sets A and B, respectively. Hence the values of c obtained agree with the accepted value within the experimental error. The average value of the two measures, 3.009×10^8 m/s, differs from the accepted value of $c=2.9979\times10^8$ m/s by 0.4%, which is surprisingly accurate, considering the crude distance measurements.

IV. DISCUSSION AND CONCLUSIONS

All timing measurements were performed at one end of the distance that light transverses. Although we used two clocks (the oscillator modulating the laser beam and the oscillator defining the sweep frequency of the oscilloscope), they are located at the same place at one end of the distance that light transverses. Hence there is no reason to prevent them from being synchronized or using a single clock.

The experiment demonstrates that it is possible to perform a one-way measurement of the speed of light in a teaching laboratory. The accuracy of the experiment can be improved substantially with a higher frequency oscillator and careful distance determination. A frequency of 30 MHz is used in accurate geodimeter instrumentation with milimetric accuracy for km distances,[22] and 60 MHz is used in a commercially available teaching experiment.[23]

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