How to measure the speed of light at your university with a dinner budget

Article *in* Revista Brasileira de Ensino de Física · March 2015

DOI: 10.1590/S1806-11173711649

2 authors:

Manuel Ortiz
Pontificia Universidad Católica de Valparaíso

Alicia Montecinos
Texas State University

Revista Brasileira de Ensino de Física, v. 37, n. 1, 1502 (2015)
www.sbfisica.org.br
DOI: http://dx.doi.org/10.1590/S1806-11173711649

How to measure the speed of light at your university with a dinner budget

(Como medir a velocidade da luz com um equipamento de baixo custo)

Manuel Ortiz, Alicia Muriel Montecinos[1]

Facultad de Ciencia, Instituto de Física, Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile

Recebido em 8/8/14; Aceito em 13/10/14; Publicado em 31/3/2015

Although the idea of using a modulated laser signal to measure the speed of light is not new, most methods found in international literature are still expensive, as a result of either the instruments or the circuits used. In the present approach, we provide an alternative that requires equipment that most universities own for their undergraduate programs, plus some inexpensive circuitry, allowing the students of any undergraduate physics laboratory course to obtain an eight-point graph using relatively small distances (such as corridors), combining a low budget with an accurate result that is equally as good as those achieved by kits available on the market.
Keywords: speed of light, low budget equipment.

Embora a ideia de utilizar um sinal modulado de laser para medir a velocidade da luz não seja nova, a maioria dos métodos encontrados na literatura internacional ainda são caros, devido aos instrumentos ou circuitos utilizados. Na presente abordagem, oferecemos uma alternativa que requer equipamentos que a maioria das universidades possuem para os seus cursos de graduação, além de alguns circuitos de baixo custo, permitindo que os alunos de qualquer curso de laboratório de física de graduação obtenham um gráfico de oito pontos com distâncias relativamente pequenas, combinando um baixo orçamento com um resultado preciso, que é tão bom quanto os resultados obtidos com kits disponíveis no mercado.
Palavras-chave: velocidade da luz, equipamento de baixo orçamento.

1. Introduction

For undergraduate science students, the experience of measuring the speed of light gives the opportunity to develop different abilities, in addition to having an intrinsic value *per se*. But the experience of measuring the speed of light risks becoming overshadowed by the effort involved when using apparatus that requires too much calibration time. An example of this is any version of the classic experiment based on a rotating mirror, such as that described by DiCurcio [1] or built versions such as Leybold Didactics's rotating-mirror method (according to Foucault and Michelson) [2] and Pasco's speed of light apparatus [3].

When the professor has a short period of time to achieve this goal, a much simpler implementation is desirable. She or he may consider modulated laser signal-based implementations. In these cases, there are expensive didactic sets such as those offered by Leybold Didactics [4, 5], Pasco [6] and Phywe [7-9], which are mostly based on short laser pulses. In the case of physics departments that may buy one or more of these devices, they will not be able to provide one set for every other student. This may work for a lecture class, especially if the professor uses an active learning session, but there would be an insufficient number of devices for a laboratory session. This means that the experimental class session transforms into a professor demonstration, instead of a truly experimental practice class for the students, which is not to be disregarded. Literature abundantly shows us that traditional methods will not necessarily help students to increase their understanding of physics concepts, unless they engage in active learning (see for example, a review of this issue in Prince [10]).

Therefore, if we accept "active learning" in a laboratory course as a method that requires *all* our students to *think* about *what* they are *doing* (and therefore, promote engagement), what does the professor do next? He or she considers a "homemade" version of a light speed measuring apparatus that may be fully manipulated by the students. There are several good arrange-

[1]E-mail: montecinos.alicia@gmail.com.

ments, such as those proposed by Brody [11] or Carlson [12], but again there is the need of expensive oscilloscopes, frequency generators and photo detectors. Perhaps the only inexpensive method found in the literature is the classic microwave oven marshmallow burning, as it is explained by Stauffer [13], which deals with the standing wave phenomenon.

The present proposal comprises an implementation that re-uses equipment that any science faculty will own, plus some circuits costing a total amount below a dinner budget, in other words, below 15USD. This proposal has a different data analysis approach to any other version found of "homemade" circuits and apparatus, and it can be achieved in a reasonable timeframe. One of the differences between the present method and those found in the literature is that our proposal leads the students to obtain an eight-point graph, the slope of which gives the value of the speed of light, requiring them apply what they have learned in waves mechanics (which is a common topic in general classical mechanics courses), using laboratory and corridor distances. In addition, the proposed method needs just one single, cheap photodetector. The most significant difference, however, is that we use a periodic signal instead of a pulse. This crucial detail allows the implementation to overcome the problem of the time delay of the circuits.

The educational value of the proposal compared with homemade kits is discussed further after the results have been presented below.

2. Outline of the implementation

The experiment consists of comparing a modulated laser beam of known period travelling different distances along with a reference signal in order to obtain the time delay between them and then plot these time differences against displacement. The slope of the resulting graph (straight line) will give the speed of light.

Our aim was to re-use anything found in the laboratory. The first apparatus is a common laser pointer connected to the circuit shown in Fig. 1. The purpose of the circuit is to pulse the laser at a desired frequency using a common function generator.

As can be seen in the previous image, this circuit is extremely simple compared to those proposed by Kenichiro and Takahisa [14] in a similar experiment, or Carlson [12]. This characteristic allows undergraduate students to build the circuits themselves, with some basic electronic instruction.

Secondly, we used a frequency generator of up to 2 MHz and a 35 MHz oscilloscope which most Science Faculties have in their Physics laboratories. As we can see, we can give a new use to old analog equipment sometimes kept in the storage. There is no need of any other more expensive equipment. The modulated laser signal must travel back and forth, and so we re-used a hard drive disk as a reflecting surface (a quarter piece will do just fine).

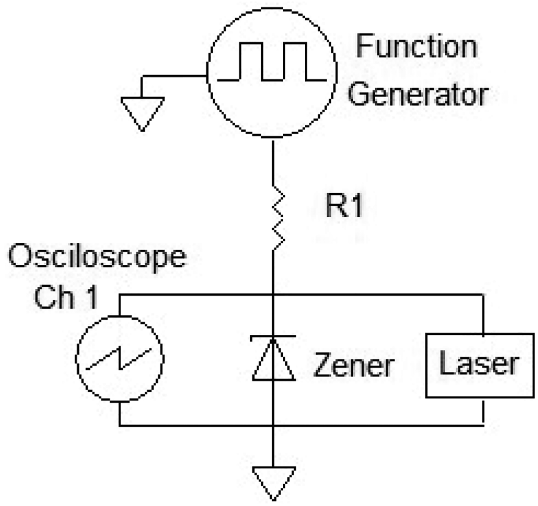

Figura 1 - Emitter Circuit. In order to feed the emitter laser, we used a Zener diode (1N4729A) connected in reverse polarity in series with a resistor, R_1 (1 kΩ), thus, when the frequency generator output is at a maximum, the laser pointer will not be harmed. The function generator worked nearly at it's maximum output, while the Zener provided a constant 4,3 V to the laser (which was a 4,5 V laser).

Finally, we used an inexpensive photo detector, inserted in the circuit shown in Fig. 2.

The laser emitter and photo detector, plus their respective circuits, and the reflective surface, stand on small platforms above low pressure bicycle tire innertubes, which act as a very effective and low budget vibration control device. It is evident that re-cycling old inner tubes is desirable. This feature allows the experiment to be carried on most floors in your faculty building, providing an advantage to class work. If the photodiode is properly set inside a box, this implementation can be used with daylight, avoiding the necessity to work in the dark.

The signal that is fed into the laser along with the signal from the photo detector are fed into the oscilloscope, whose screen is recorded with a common webcam, enabling us to save the data without the need of a digital oscilloscope, for the purpose of determining the time delay between the reference and travel signals. The reference signal will be fed into the laser.

Before explaining how to proceed with the data collection and subsequent analysis, we wish to explore the following implementation flowchart (Fig. 3).

Basically, the present implementation begins by making a fixed axis on the floor with position marks every 3 m. We recommend 24 m in total, which means 9 points where the reflective surface shall be located, including the origin of the fixed axis which we located at 0.3 m from the laser in order to have enough room to work. In comparison, other implementations such as Leybold's Light Velocity Measuring Instrument [4] needs 10 m as a starting point.

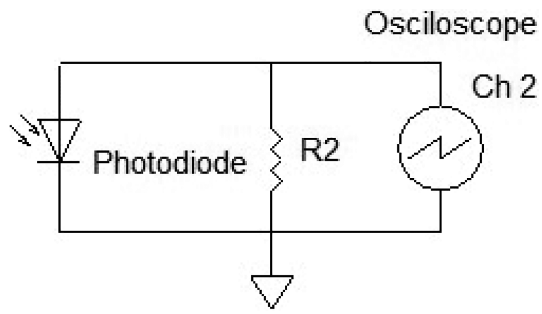

Figura 2 - Receptor Circuit. This circuit consists ofa photodiode (Vishay BPW34) working as a photoelectric cell connected in parallel to a resistor, R_2 (1 kΩ), in order to avoid noise being induced by the osciloscope and the photodiode itself.

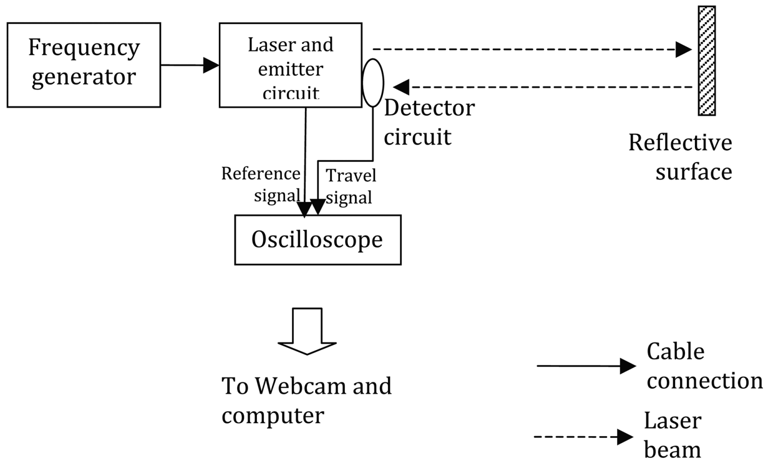

Figura 3 - Implementation's flowchart, showing the equipment, circuits and laser beam paths.

During the development of this work, specifically after our first measurements, we realized that it was not necessary to use a focus lens over the detector circuit, because the photodiode (receiver) was able to provide a good signal response by a direct beam.

Calibration of this experimental arrangement consists of making sure the reflected laser beam fully falls into the photo detector. This cell must be located next to the laser emitter. This ensures a strong detected signal and a negligible path difference between the departing signal and returning signal distances.

3. Data collection procedure

Once the implementation is set up and the equipment has been switched on, we have to make sure we are watching real information on the oscilloscope screen instead of noise. This is achieved by comparing the average of the two signals fed into the oscilloscope (see Fig. 3) with the nominative period value shown on the frequency generator. After this we can begin our data collection. This consists of placing the reflective surface on the positions marked on the fixed axis on the floor. A safety warning must be noted at this point: laser safety glasses must be provided to all participants, as in any laser related experiment.

The webcam must be oriented in such way that no parallax effect is noticeable. We used a simple video and photograph analysis software which are very common in mechanics laboratories courses for undergraduate students. We recorded a short video of approximately 5 s for each of the 9 measurement points. Once the software had converted these videos to photographs, we were able to obtain the phase shift between the reference signal and the photo detector signal (or travel signal). For every measurement point, we checked that the original signal actually stayed in place on the oscilloscope screen, and that the returned signal presented a phase shift. Thus, we gathered data for a time versus position graph, through the period shift and displacement of the reflective surface (mirror). As we can see in Fig. 4, in each photograph the upper curve is solely used as a reference to ensure that the original frequency delivered by the generator is the same as that fed to the laser. The displacement of the bottom curve compared the first photograph shows the time delay resulting from the increased distance.

As we can see in Fig. 5, for the purposes of data analysis it is necessary to choose a point on the waveform that is easy to follow. In our case, we worked with the points marked in Fig. 5.

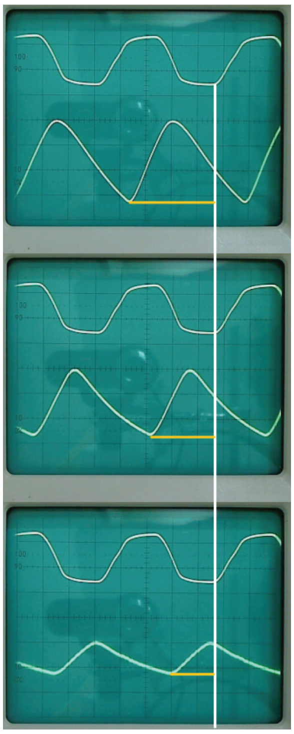

Figura 4 - Different frames showing the time delay produced by the increase of the travelled distance. Also, we can appreciate the decrease in the amplitude of the received signal, due to the increment in distance. Horizontal axis showing time, vertical axis showing voltage induced in the photo diode (receptor).

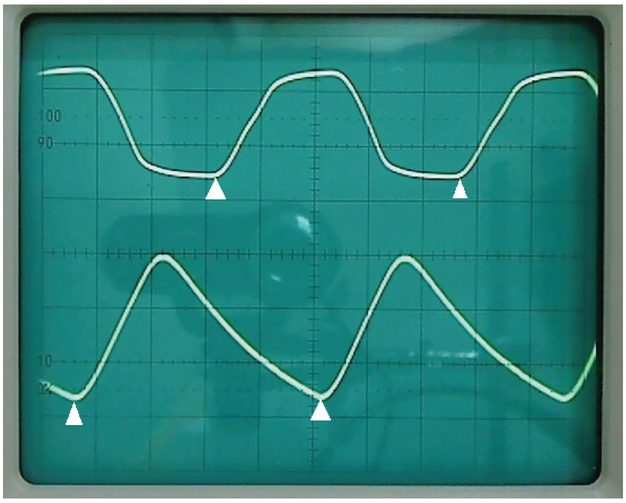

Figura 5 - Comparing the periods of both signals with each other, and with the frequency generator, allows us to be sure about the actual frequency. Horizontal axis showing time, vertical axis showing voltage induced in the photo diode (receptor).

The period of both signals was therefore calculated. We verified that the period calculated was consistent with that of the frequency generator, and also that it was consistent with the subsequent photographs. It was seen that the reference signal stayed in place, while the travel signal moved, producing a time delay in line with the movement of the reflecting mirror.

The measurements were taken only with the lower curve and its displacement on the oscilloscope screen.

It is important to establish that with every measurement, checks were constantly made of the period of both signals in comparison with the function generator. It is also important to state that the main purpose of the software analysis was providing a series of frames taken from single video related to one measurement point, and therefore, working with an average value.

We zoomed in on the photographs until the image on the oscilloscope screen filled the PC monitor, in order to attain the lowest appreciation error and justify an uncertainty of ± 1 pixel in the measurements.

In order to convert from pixels to centimetres, we obtained a conversion factor using the width of the oscilloscope screen. Measuring the horizontal axis values and using the base time of the oscilloscope, it was then possible to obtain the time delay in seconds.

4. Results

Table 1 was graphed using Origin. The obtained graph is in Fig. 6.

Tabela 1 - Time delay between the original and travel signals versus the position distance of the reflective surface. The latter variable does not have an uncertainty, as it is so low that it was not noticeable with the error flags in the subsequent graph.

(Time delay ± 0.2) x 10^{-8} s	Position distance m
00.0	0.00
01.9	6.00
03.7	12.00
05.6	18.00
07.9	24.00
09.8	30.00
11.6	36.00
13.5	42.00
15.8	48.00

Considering that c is a constant defined as 299,792,458 m/s in a vacuum [15], the result attained has a percentage difference close to 2%. We may add that the trend line falls into the error bars of each point.

Conclusions

The data obtained allowed us to validate the precision of the set-up employed to take the measurements, with a percentage difference close to 2% with regard to the standard value. The present proposal has lower cost than other methods that also use photodiodes. Furthermore, the experiment requires an easy implementation and it can be calibrated very quickly in comparison to more classical methods (*i.e.* Fizeau's rotating mirror).

Thanks to these characteristics, a student is able to conduct the entire experiment during one class period (typically 2 h), obtaining a very good value of the speed of light. In addition, due to the simplicity of the experimental set-up required for this proposal, a class may be divided into several groups that can work simultaneously during class time taking measurements, selecting experimental conditions and choosing different measurement increments.

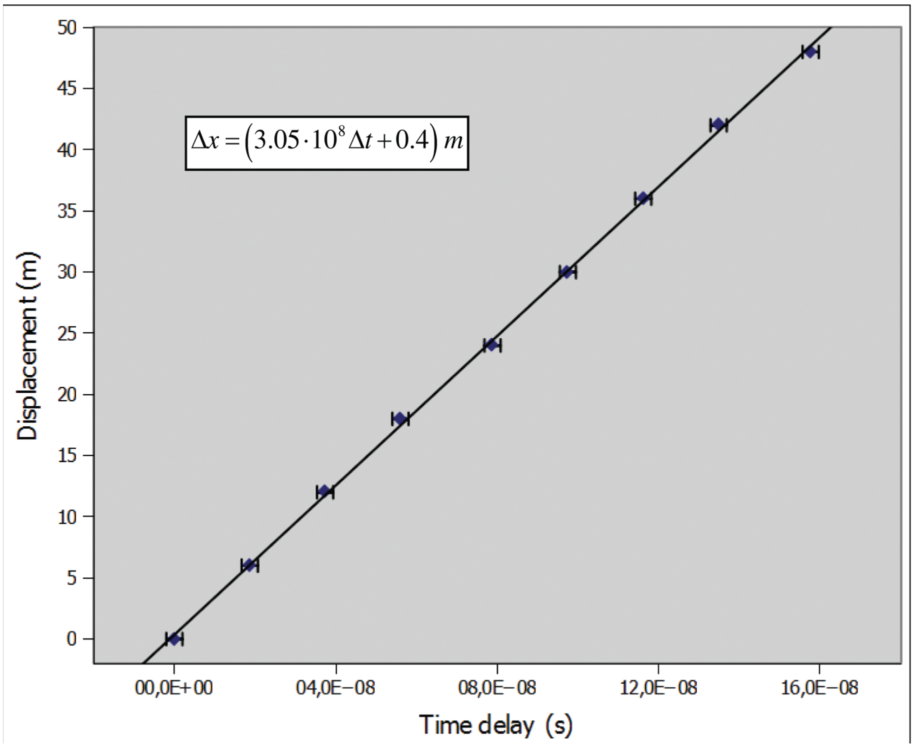

Figura 6 - The software gave the best linear adjustment shown in the equation above, were the slope gives the speed of light, and the 0,4 m is a consequence of the small measurement's errors and the best adjustment done. Thus, the linear adjustment shows a speed of light value of (3.05 ± 0.03). 10^8 m/s.

5. Discussion

First of all, this proposal shows us that it is not necessary to depend upon expensive ready-made kits to achieve an excellent experimental result for the value of the speed of light. Using inexpensive equipment together with what we already own in our laboratories, we can equal the results of the best kits currently available on the market.

Thus, this proposal shows that it is possible to obtain low cost, active learning activities not only in mechanics, but also in a slightly more sophisticated topic such light speed measurement, avoiding a traditional approach and expensive kits. In other words, this proposal can helps with any budget and/or a time limitation.

However, what is of the uttermost importance in our discussion is that we are translating what has been proven and reported by physics education research over the years, from a physics lecture class to a physics laboratory class: the educational value of the session is undeniably higher when the students build the equipment set-up from scratch, instead of turning a ready-made machine on and off, as they will need to constantly evaluate *what* are they doing, and *why*, permanently debating among themselves.

Therefore, the present proposal has a tremendous educational value because it allows every student from a whole class group to give their unique contribution to the discussion and performance of the experiment, developing their science competences, since every student will have the chance to understand the implementation by actively building it. This opportunity to engage in the activity and discuss it, is a key aspect of any active teaching-learning sequence [10].

It may be argued that there is an error in the measurement of the distance travelled by the light beam. During its geometrical propagation path an isosceles triangle is formed by the round trip of the light beam. However, though there is not true coincidence between the receptor and the emitter points, both points are very near, and for that reason this error is negligible (less than 0.01%) with regard to the first measurement (to 3 m). Therefore, this error will be reduced even more for the subsequent measurements.

In reference to the error flags for the time measurements, they arise from the double information of each plot. Therefore, we worked with the average value, which generates an error in the time measurements in the order of $(\pm 0.2) \cdot 10^{-8}$ s.

Finally, a faster photodiode would mean that the received waveform (from the voltage induced on the photodiode) would keep its original shape better.

Acknowledgements

We would like to acknowledge the Physics Institute of the Pontifical Catholic University of Valparaiso for

granting the conditions to perform our measurements.

References

[1] DiCurcio, Phys. Teach. **volume**, 326 (1978).

[2] Leybold Physics Leaflets, *Optics. Determining the velocity of light by means of the rotating-mirror method according to Foucault and Michelson. Measuring the image shift for the maximum rotational speed of the mirror P5.6.1.1*, `http://downloads.gphysics.net/leybold/EXP/HB/E/P5/P5612_E.PDF`. Retrieved 2013-03-01.

[3] Pasco, *Basic Speed of Light Apparatus OS-9262*, `http://www.pasco.com/file_downloads/product_manuals/Complete-Speed-of-Light-Apparatus-Manual-OS-9261A.pdf`. Retrieved 2013-03-01.

[4] Leybold Physics Leaflets, *Optics. Determining the velocity of light in the air from the path and transit time of a short light pulse P5.6.2.1*, `http://pec.sjtu.edu.cn/ols/P5/P5621_E.PDF`. Retrieved 2013-03-01.

[5] Leybold Physics Leaflets, *Optics. Determining the velocity of light with a periodic light signal at small distances P5.6.3.1*, `http://downloads.gphysics.net/leybold/EXP/HB/E/P5/P5631_E.PDF`. Retrieved 2013-03-01.

[6] Pasco, *Laser Speed of Light Apparatus Model No. AP-8586*, `http://www.pasco.com/file_downloads/product_manuals/Laser-Speed-of-Light-System-Manual-AP-8586.pdf`. Retrieved 2013-03-01.

[7] Phywe, *Measuring the velocity of light LEP 2.1.01*, `http://www.nikhef.nl/~h73/kn1c/praktikum/phywe/LEP/Experim/2_1_01.pdf`. Retrieved 2013-03-01.

[8] Phywe, *Measuring the velocity of light TEP 2.1.01 -01* `http://www.phywe.com/index.php/fuseaction/download/lrn_file/versuchsanleitungen/P2210101/e/P2210101.pdf`. Retrieved 2013-03-01.

[9] Phywe, *PC-based measurement of the velocity of light TEP 2.1.01-11*, `http://www.phywe-ru.com/index.php/fuseaction/download/lrn_file/versuchsanleitungen/P2210111/e/P2210111.pdf`. Retrieved 2013-03-01.

[10] M. Prince, Education **93**, 223 (2004).

[11] B. Brody, Phys. Teach. **41**, 276 (2003).

[12] J. Carlson, Phys. Teach. **34** 176 (1996).

[13] R. Stauffer, Phys. Teach. **35**, 231 (1996).

[14] A. Kenichiro, preprint arXiv:0705.3996[physics.ed-ph]. Retrieved 2013-03-01.

[15] CODATA value, Speed of Light in Vacuum. The NIST reference on Constants, Units, and Uncertainty. NIST. Retrieved 2013-03-01.