Experimenting from a distance - determination of speed of light by a Remotely Controlled Laboratory (RCL)

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Abstract. The speed of light is an essential topic in the teaching of physics at school and at university: either with respect to the type of experiment or of course with respect to its genuine inherent importance. In reality, the various available experiments are hardly performed in class because of many reasons. Therefore, we offer this experiment as a Remotely Controlled Laboratory (RCL). An RCL is a real experiment setup at location A which can be controlled via Internet by a user at a remote location B. It allows several actions like in the real experiment and delivers convincing results. Finally, we describe the added value of the experiment as an RCL and give hints to implement the RCL in class.

1. Introduction

The speed of light *c* in vacuum and/or in matter is taught at school or university level in different ways and depths:

- Treating by means of the history of astronomical and terrestrial methods of measurement,
- *c* as a constant with defined value in the context of SI units (definition of the meter),
- *c* as a fundamental constant in all types of lectures on electrodynamics, optics and quantum mechanics (e. g. deceleration of light),
- in combination with modern technical applications such as electronic devices (e. g. Global Positioning System, GPS).

Table 1

Figure 1

Table 1 provides an overview of some historical methods of the determination of the speed of light. The decreasing error in determining the speed of light is shown by figure 1. It can be recognized that the results for the speed of light *c* converges to certain value which was then taken as an exact value for the definition of the meter in 1983 [3].
It is a “must” to perform at least one real experiment in teaching. Several methods are offered by the respective industry (e. g. LD Didactic [4], PHYWE [5], PASCO [6]). Common to most of them are disadvantages, why such an experiment is not presented in real class or why several measurements are not feasible: the experimental setup is too expensive, the existing one is not working properly, it takes hours to obtain sufficient alignment of optics (e. g. rotating mirror method) or the applied method is not obvious to be understood by students, since it is not a direct measurement of speed (e. g. phase modulation method).
Therefore, we offer the determination of the speed of light as a Remotely Controlled Laboratory (RCL). The RCL is a real experimental setup at location A being controlled via the Internet by a user at a distant location B. Details on this were already published in basic articles [7, 8] in which we describe the technical realization, the didactical objectives of the Internet as an educational mean, our experience of the usage during the last years and the additional costs to setup an RCL.

2. RCL variant and principle of measurement

For our purposes we used and adapted an experimental setup provided by LD Didactic [9], because it is an obvious determination of a velocity according to the time-of-flight method. This recently developed technique uses a modern optoelectronic high power LED which emits light pulses of ca. 20 ns duration at a repetition rate of 40 kHz (wavelength 615 nm). The principle of measurement is shown by figures 2 and 3.

Figure 2

Figure 3

The light pulses of the LED are divided by a beam splitter into two parts. One part is reflected by a fixed mirror at short distance (~ 2 cm) and registered by a detector. The electrical signal is displayed on an oscilloscope screen and defines the zero of the time scale ($t_1 = 0$), it therefore serves as reference signal. The other part of light travels the distance s (around 10 m) to a movable mirror, is reflected back and then detected too. Since this signal travels with finite speed of light c it is time delayed with respect to the first signal at t_1: $\Delta t = t - t_1 = 2s/c \sim 10^{-8}$ s.
The RCL variant can be viewed partially in figure 3. Figure 3a) shows the core electronic unit which generates the light pulses and contains the detector for the reflected ones. These pulses are recorded and displayed by means of an oscilloscope (voltage as a function of time). The signals on the oscilloscope screen are transmitted to the user in real time by a web camera. The lens provides for parallel beam of light travelling to the distant mirror and focuses the back reflected light onto the detector.
The movable mirror (retro-reflector) is mounted on a wagon pulled by a toy train allowing the user to vary the distance s by remote control. In order to measure the distance s the movement of the toy train is transferred by a thread to a wheel with light barrier which enables to read out the actual position of the reflecting mirror (figure 3b). The movement of the toy train can be observed in real time by a second web camera.

Figure 4

Figure 4 presents the laboratory website [10] when the user chooses the item "Laboratory" in the navigation bar of the RCL (left). In the control panel (right) the user can vary the distance s by means of the buttons "Decrease/Increase distance s of reflector". Simultaneously, in the streaming video images of the web cameras (middle) the user can follow the motion of the toy train, register roughly the distance s indicated on a scale at the wall and observe the decreasing or increasing distance between reference and travelling signal on the oscilloscope screen. When the user is pushing the button "Stop train – measure distance s of reflector" the actual distance s of movable mirror is displayed in the control panel.
Generally, the height of the travelling signal is smaller than the height of the reference signal. The processing electronics introduces errors in the time interval Δt in that case. To avoid this systematic error in determining the speed of light both signals have to be made equal in height [9]. Therefore, we equipped the setup with two motorized diaphragms for each light path which make possible to reduce the intensity of each beam of light independently.

Figure 5

Figure 6

Finally, the time axis of the oscilloscope screen has to be calibrated by the user. A square wave signal (frequency f = 10 MHz, oscillation period T = 100 ns) serves as a calibration signal (figure 5). By means of simple image processing software the calibration can be easily performed. After taking a screenshot of the oscilloscope screen a row of pixels along the middle of the square wave signal and parallel to the time axis is evaluated (figure 6). The result here is 0.9804 ns/pixel [11].

Figure 7

In figure 5 two screenshots of the oscilloscope screen are shown for two different distances s of the movable reflector after the signal heights were carefully adjusted by means of the motorized diaphragms. It can be clearly recognized that the time of flight, Δt, increases with rising distance s and that the signal height of the long distance reflected light decreases. The time interval Δt between reference signal and long distance travelling signal can be obtained by a procedure similar to the calibration. The result of a series of measurements with $N = 13$ data points are shown in figure 7. A linear fit of the data delivers the slope, that is the speed of light in air, $2s/\Delta t = c = 2.99 \cdot 10^8$ m/s here. The error from linear regression of the data is below ± 2 %. The uncertainty $\Delta c/c$ due to the experimental parameters time, $t - t_1$, and total distance, $2s$, can be estimated up to about 6 % and is mainly caused by the inaccuracy of calibrating the time scale as well as determining the time interval Δt between both signals (~ 5 %). The error in determining the total distance, $2s$, is comparatively small (order of about 1 %). Although the measurement took less than half an hour including adjustment of the signal heights, the result is pretty good.

3. Added value

As an example, the RCL “Speed of Light” represents our philosophy to develop remotely controlled experiments, which allow users to perform an experiment with a maximum of interactivity combined with an intuitive use. The added value of this RCL is according to us:

- The principle of this experiment is a direct determination of a velocity (time-of-flight method). Therefore, the experiment is even useful for students at the age of 15.
- The used technique applies modern optoelectronics.
- The necessary space (up to around 15 m) is not everywhere available.
- Each user can choose different distances from the full range and produce his or her own set of data.
- A series of measurements with different positions of the movable reflector is feasible on a short time scale.

We suggest elaborating in class the working principle and the technique of measurement, for example in the course of discussing the failure of early trials (Galilei). Each student then has to perform measurements with the RCL at home according to a useful time schedule. In order to minimize statistical error groups of students may collect their data via the Internet prior to analysis of the whole set of data.
Summing up, with the RCL “Speed of Light” we have added a further essential experiment to our project [10]. Currently, we provide 18 experiments like “Photoelectric Effect”, “Electron Diffraction”, “Diffraction and Interference”, for example.

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References

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[2] Vyskocil M and Jodl H-J 1979 Lichtgeschwindigkeitsmessungen – eine Übersicht für den Physiklehrer *Physik und Didaktik* **7** 116-128.
[3] Giacomo P 1983 The new definition of the metre *Eur. J. Phys.* **4** 190-197.
[4] LD Didactic, online at http://www.lddidactic.de/
[5] PHYWE, online at http://www.phywe-systeme.com/
[6] PASCO, online at http://www.pasco.com/
[7] Gröber S, Vetter M, Eckert B and Jodl H-J 2007 Experimenting from a distance - remotely controlled laboratory (RCL) *Eur. J. Phys.* **28** S127-S41
[8] Gröber S, Vetter M, Eckert B and Jodl H-J 2008 Remotely controlled laboratories: aims, examples, and experience *Am. J. Phys.* **76** 374-8
[9] LD Didactic: Instruction Sheet „Light Velocity Measuring Instrument" No. 47650, online available at http://www.lddidactic.de/ga/4/476/47650/47650de.pdf
[10] The web site is at http://rcl.physik.uni-kl.de
[11] Of course, the time calibration should be performed parallel to each time-of-flight measurement since drifts of the electronics may cause deviations from the true time scale. Each oscilloscope screenshot, therefore, contains two important quantities simultaneously: the signal for calibration of time scale *and* the signals to determine time of flight, Δt.

(web sites accessed as of October 13, 2009)

Tables

Table 1: Selected values of the speed of light from some historically important experiments [1 - 3].

Year	Experimenter / author	Method	*c* in km/s
Astronomical			
1676	Rømer	Motion of Jovian satellite Io	214 000 ± ?
1726	Bradley	Aberration of light from stars	301 000 ± ?
Terrestrial			
1849	Fizeau	Rotating cogwheel	315 000 ± ?
1862	Foucault	Rotating mirror	298 000 ± 500
1882	Newcomb	Rotating mirror	299 810 ± 30
1926	Michelson	Rotating prism	299 796 ± 4
1940	Hüttel	Kerr cell	299 768 ± 10
1947	Essen and Gordon-Smith	Microwave cavity resonance	299 792 ± 3
1951	Aslakson	Radar technique	299 794.2 ± 1,4
1951	Bergstrand	Modulated light	299 793.1 ± 0,4
1951	Froome	Microwave interferometer	299 729.6 ± 0,7
1956	Rank et al.	Optical spectroscopy	299 791.9 ± 2
1972	Evenson et al., National Bureau of Standards (NBS)	'Cat hair' diode, He-Ne laser	299 792.4562 ± 0.0011
Since 1983	Conférence Générale des Poids et Mesures (CGPM)	Definition of the meter	299 792.458 exact

Figure Captions

Figure 1. Improvement of accuracy in determining the speed of light between 1880 and 1980 (selection of experimental results) [1-3].

Figure 2. Simplified sketch of the experimental setup (see text).

Figure 3. Components of the experimental setup as an RCL. a) Emitter and detector unit containing the light source (LED), the detector as well as the fixed mirror, see figure 2. b) A toy train, movable on a track by remote control, carries the reflector of the long distance light path.

Figure 4. Laboratory site of the RCL "Speed of Light". Menu bar (left), view of live video streams (middle) and control panel to vary technical parameters (right) are shown.

Figure 5. Screenshots of the oscilloscope screen during measurement, two examples are presented. a) s = 6.986 m, Δt = 45.42 ns, the red line marks those pixels of the image which will be used for calibration of the time scale (see figure 6). b) s = 11.265 m, Δt = 74.51 ns.

Figure 6. Evaluation of the calibration signal: intensity value (brightness) of pixels as a function of the time axis (given in pixel) reflecting the cut through the square wave calibration signal (red line shown in figure 5 a)). The distance between peaks represents half of the oscillation period, $T/2$ = 50 ns, corresponding with 51 pixels.

Figure 7. Evaluation of a series of quick measurements (N = 13). The statistical error of fitting the slope is ± 0.0049 m/ns and the regression coefficient is r = 0.9986 due to rough adjustment of the signal height.

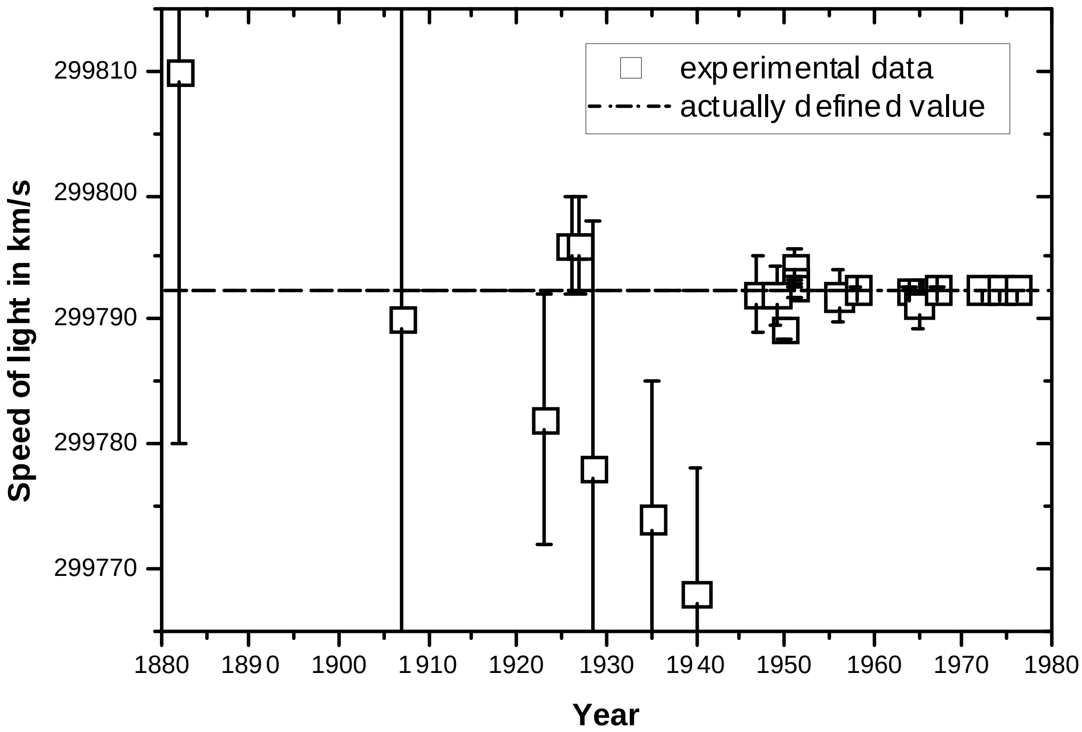

experimental data
actually defined value
Speed of light in km/s
299810
299800
299790
299780
299770
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
Year

Figure 1

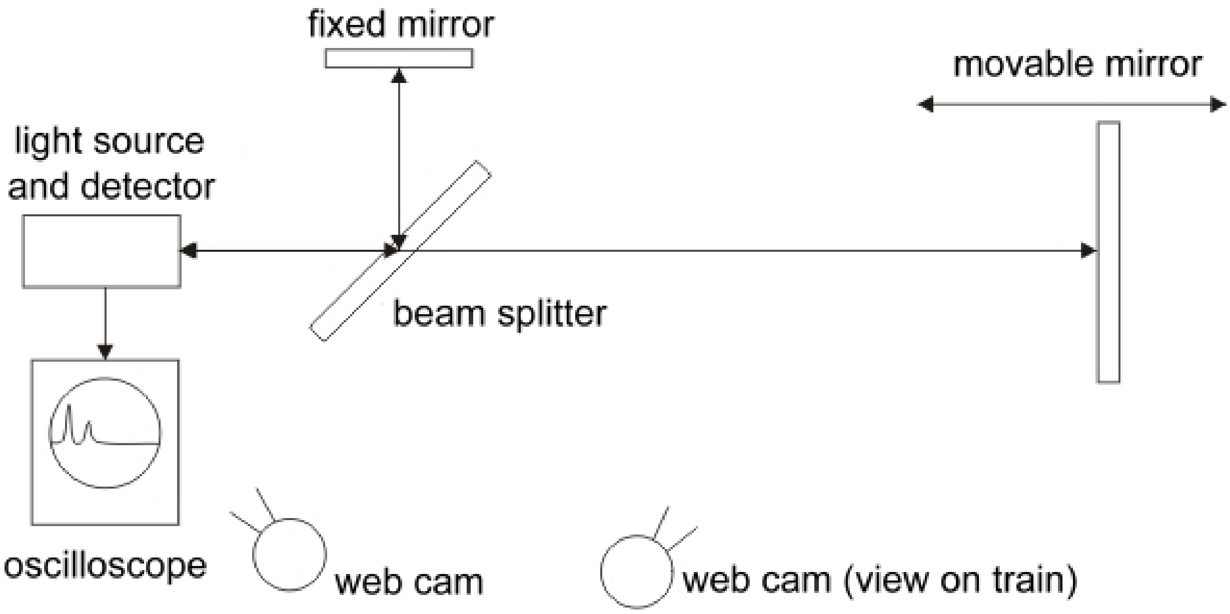
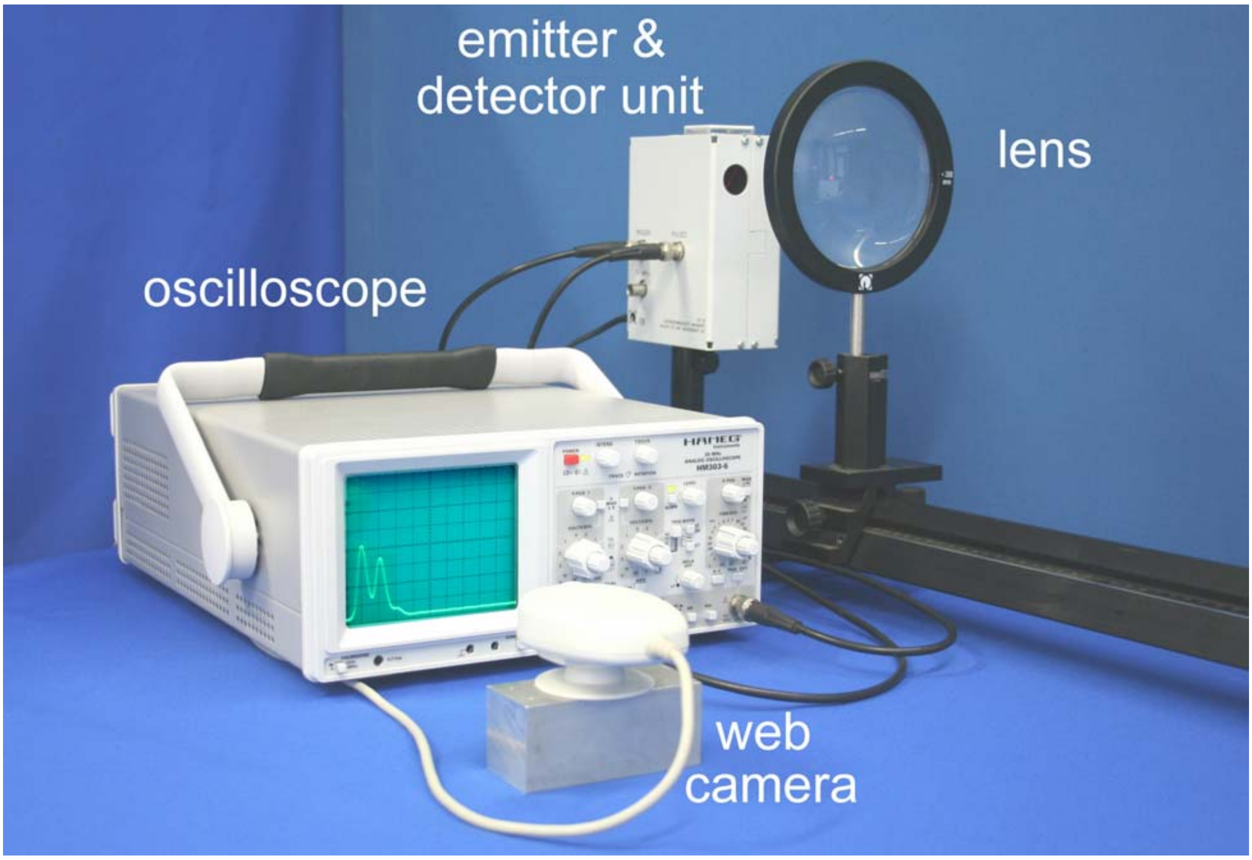
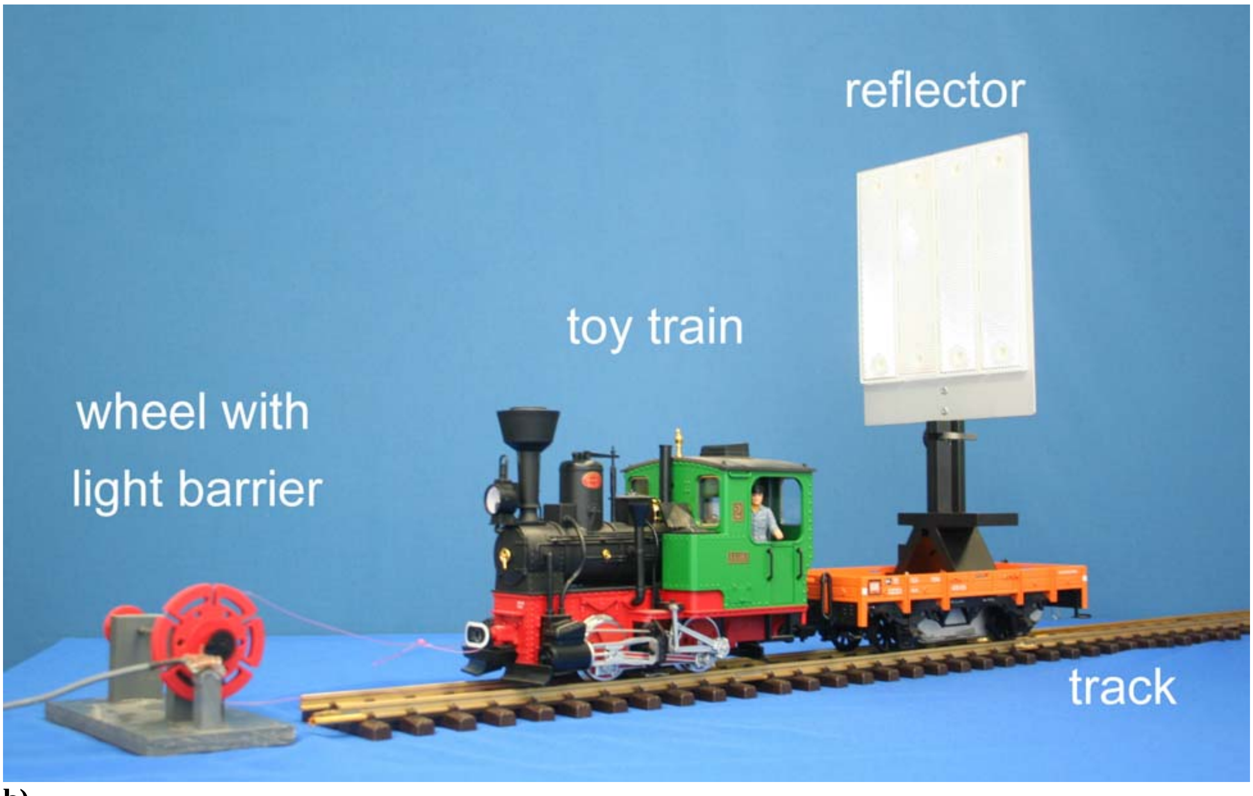

fixed mirror
movable mirror
light source
and detector
beam splitter
oscilloscope
web cam
web cam (view on train)

Figure 2

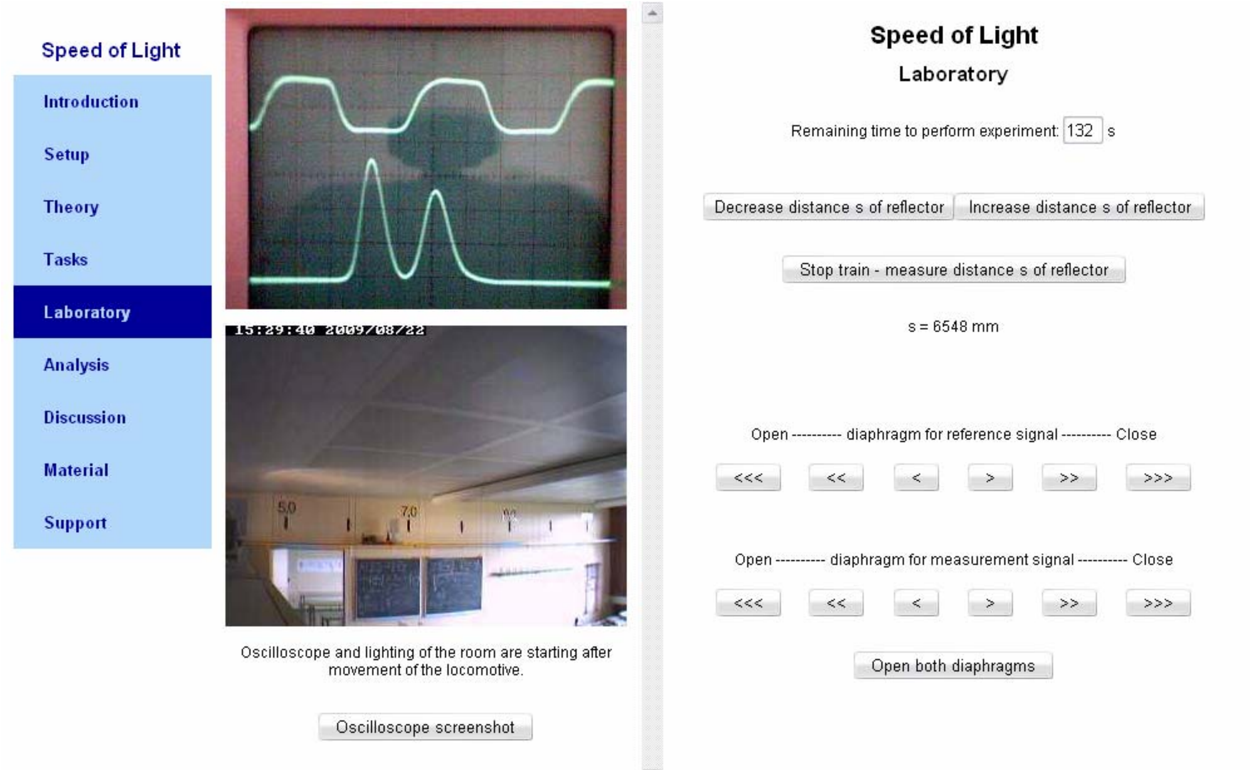

emitter &
detector unit
lens
oscilloscope
web
camera

a)


reflector
toy train
wheel with
light barrier
track

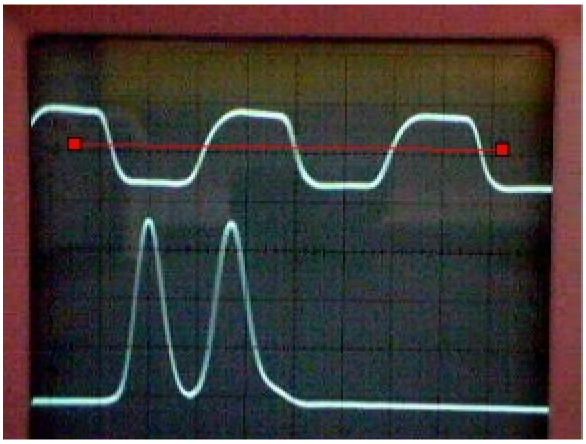
b)

Figure 3

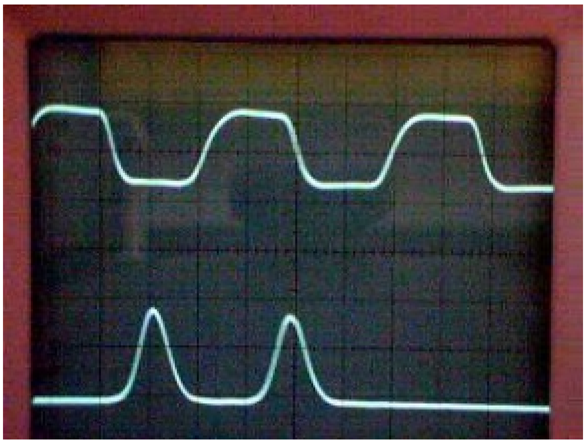


Speed of Light
Introduction
Setup
Theory
Tasks
Laboratory
Analysis
Discussion
Material
Support
15:29:40 2009/08/22
Oscilloscope and lighting of the room are starting after movement of the locomotive.
Oscilloscope screenshot
Speed of Light
Laboratory
Remaining time to perform experiment: 132 s
Decrease distance s of reflector
Increase distance s of reflector
Stop train - measure distance s of reflector
s = 6548 mm
Open ---------- diaphragm for reference signal ---------- Close
<<< << < > >> >>>
Open ---------- diaphragm for measurement signal ---------- Close
<<< << < > >> >>>
Open both diaphragms

Figure 4



a)



b)

Figure 5

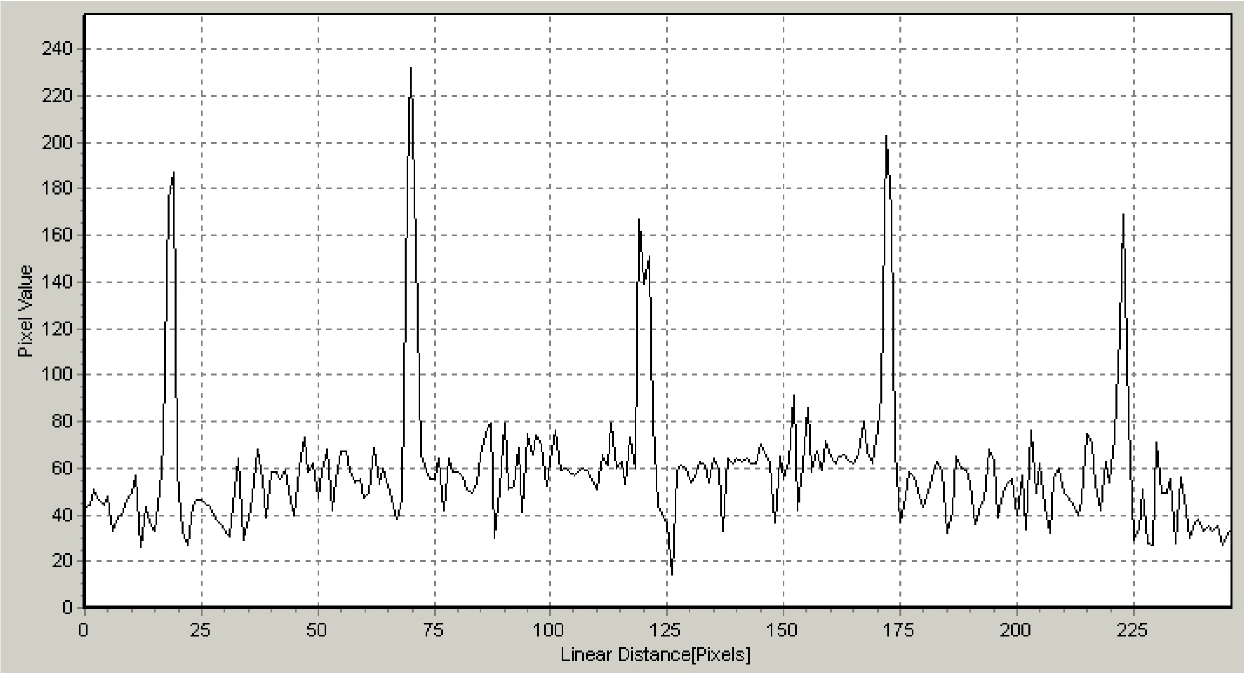

Pixel Value
240
220
200
180
160
140
120
100
80
60
40
20
0
0
25
50
75
100
125
150
175
200
225
Linear Distance[Pixels]

Figure 6

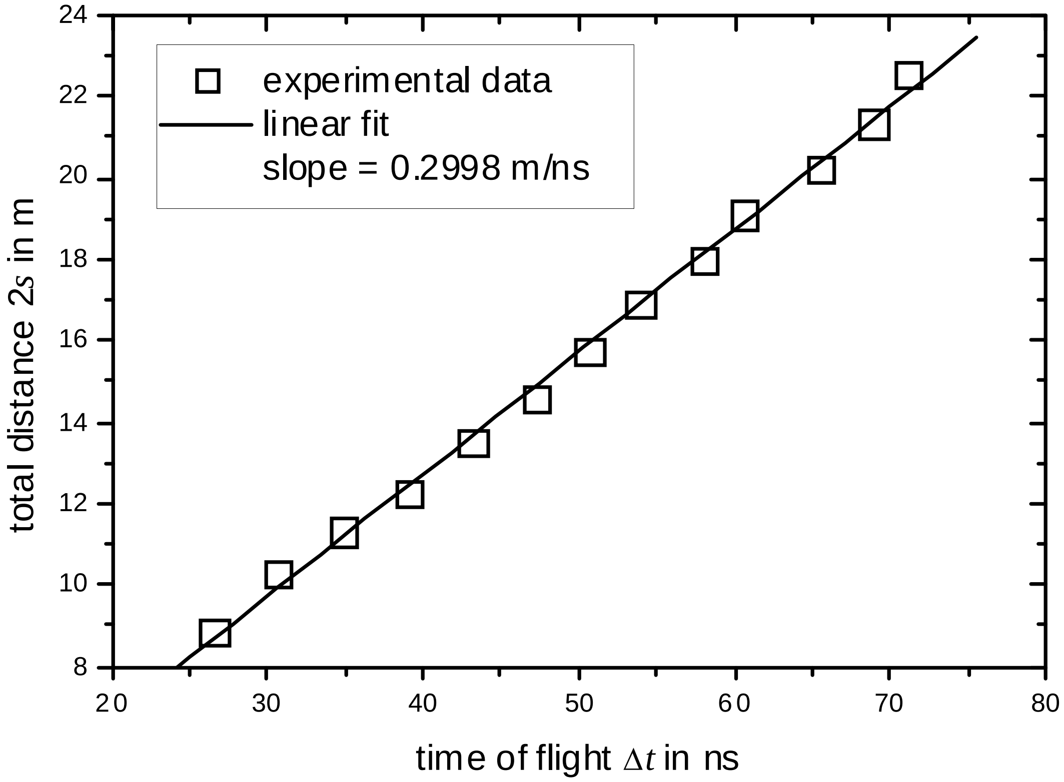

experimental data
linear fit
slope = 0.2998 m/ns
total distance 2s in m
time of flight Δt in ns
24
22
20
18
16
14
12
10
8
20
30
40
50
60
70
80

Figure 7