

IU3

Modul Universal constants

Speed of Light

The speed of light in vacuum is approximately $c \approx 3.0 \times 10^8$ m/s. It is a fundamental physical constant and the purpose of this experiment is to determine the value of this fundamental constant. Further, we want to examine the influence of a medium on the propagation speed of light.

Versuch IU3 - Speed of Light

The speed of light in vacuum is approximately $c \approx 3.0 \times 10^8$ m/s. It is a fundamental physical constant and the purpose of this experiment is to determine the value of this fundamental constant. Further, we want to examine the influence of a medium on the propagation speed of light.

1.1 Preliminary Questions

- What is the electromagnetic spectrum, and how does it relate to light?
- Explain the concepts of transverse and longitudinal waves and connect these notions to light waves, sound waves, and water waves.
- Calculate the time it requires for a light wave to travel a 2 m long distance. Explain the limitations that arise when attempting to measure this time delay using a 20 MHz bandwidth oscilloscope. Propose solutions to address this issue.
- What happens when the light crosses the surface between two media of different distinct atomic densities.
- How does the wavelength and frequency of light change upon entering a different optical medium??
- Which colour of light is bent stronger when refracted into a denser medium?

1.2 Theory

1.2.1 Basics

The speed of light in a vacuum, denoted as "c," is a fundamental constant in physics with a value of approximately $c \approx 3.0 \times 10^8$ m/s. This universal constant shapes our understanding of the cosmos and plays a crucial role in theories such as Einstein's theory of relativity. Over the centuries, scientists have employed various methods, from Galileo's early attempts to modern interferometry and laser technology, to measure and refine our knowledge of this constant. The speed of light not only defines the ultimate speed limit for anything with mass but also assist key principles shaping our understanding of space, time, and the nature of the universe.

The speed of light c_n in a medium depends on the refractive index n of that medium. This refractive index is influenced by the material's effective dielectric permittivity (ϵ_r) and magnetic permeability (μ_r) which can vary between different materials. Essentially, the refractive index tells us how much light slows down when it travels through a specific substance, and this depends on the material's electrical and magnetic properties. The speed of light c_n in a medium can be directly expressed as

$$c_n = \frac{c_0}{n} \quad (1.1)$$

where $c_0 = 2.998 \cdot 10^8$ m/s is the propagation speed of light in vacuum. Different velocities of light correspond to different propagation times along a given path length d . The propagation time (see Fig. 1.1) of light in a medium is

$$t_n = \frac{d}{c_n} \quad (1.2)$$

whereas in vacuum, the propagation time is

$$t_0 = \frac{d}{c_0} \quad (1.3)$$

With the definition of a time delay

$$\Delta t = t_n - t_0 \quad (1.4)$$

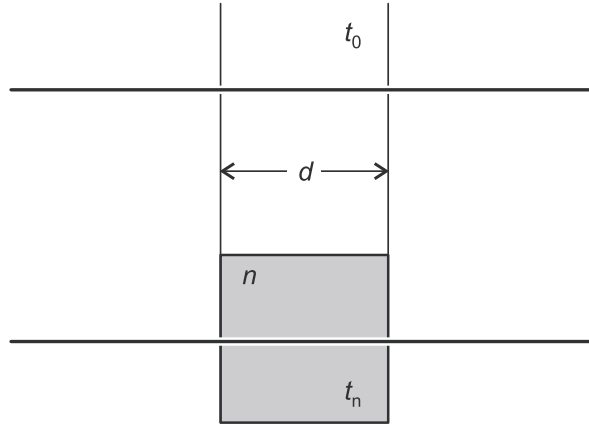


Figure 1.1: In a medium with refractive index n , light propagates slower than in a vacuum. This results in different transition times for a distance d .

and equations (1.2) and (1.3), the speed of light in the medium is determined by the equation

$$c_n = \frac{c_0}{1 + \frac{\Delta t}{d}c_0} \quad (1.5)$$

By comparison with (1.1)

$$n = 1 + \frac{\Delta t}{d}c_0 \quad (1.6)$$

is obtained.

1.2.2 Experimental measurements

In this experiment, the propagation time of light is measured by modulating the intensity of a light beam. The modulation frequency is given as

$$\Delta\phi = 2\pi\nu\Delta t = 2\pi\frac{\Delta t}{T}, \quad (1.7)$$

where T is its time period. The phase shift is measured with a receiver, which converts the light signal into an alternating voltage that exhibits temporal behavior, given as

$$U = a \cdot \cos(2\pi\nu t - \Delta\phi). \quad (1.8)$$

In this setup, a reference signal, synchronized with the light transmitter's intensity, aligns with the receiver signal using an electronic phase shifter, establishing a time reference for a fixed distance s between the transmitter and receiver. When a medium is inserted on the ray path, covering the partial path length d , this causes a change Δt in the propagation time of the light signal. This change can be measured as a phase shift $\Delta\phi$ between the reference and the receiver signal. This system enables the detection and analysis of changes in the propagation time caused by the insertion of a medium in the light path.

As a basic oscilloscope is used for determining the phase shift that involves electronically combining (multiplying) the two signals with a frequency of $\nu' = 59.9\text{MHz}$, followed by the suppression of the high-frequency component in the mixed signal. The receiver signal can be expressed as

$$U_1 = \frac{1}{2}a \cdot \cos(2\pi\nu_1 t - \Delta\phi) \quad (1.9)$$

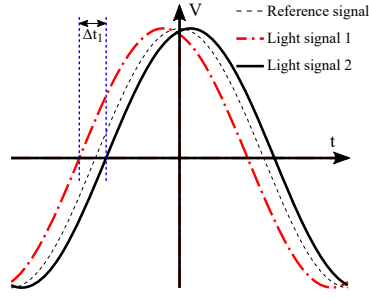


Figure 1.2: Principle of the delay measurement: a reference signal (dotted line) provides the time reference of the modulated light intensity. The detected light signals correspond to the two signals 1, dotted dashed, (resp. 2, full line) observed without (resp. with) a medium inserted on the light path. The apparent time delay Δt_1 induced by the medium corresponds to the delay between the zero crossings of the two signals.

with $\nu_1 = \nu - \nu'$. This signal illustrated in Figure 1.2 can be presented using a standard oscilloscope because the frequency ν_1 is 100 kHz falling below the oscilloscope's bandwidth. While the mixing doesn't alter the phase shift $\Delta\phi$, it does translate into an *apparent change* Δt_1 in the lower frequency signal, which has a period T_1 . From

$$\Delta\phi = 2\pi \frac{\Delta t_1}{T_1} \quad (1.10)$$

one gets

$$\Delta t = \Delta t_1 \frac{T}{T_1} = \frac{\Delta t_1}{T_1 \nu}. \quad (1.11)$$

Combined with Eq. (1.5) and Eq. (1.6), one can finally express the speed of light in the medium

$$c_n = \frac{c_0}{1 + \frac{c_0}{d\nu} \frac{\Delta t_1}{T_1}} \quad (1.12)$$

and the refractive index

$$n = 1 + \frac{c_0}{d\nu} \frac{\Delta t_1}{T_1} \quad (1.13)$$

1.3 Experiment

1.3.1 Accessories

Component	Quantity
light transmitter and receiver	1
Lens $f = +150$ mm	1
Coaxial cable	2
saddle bases	3
Two channel oscilloscope	1
metal scale, 1 m	1
tube with 2 end windows	1
Acrylic glass block	1
prism table	1

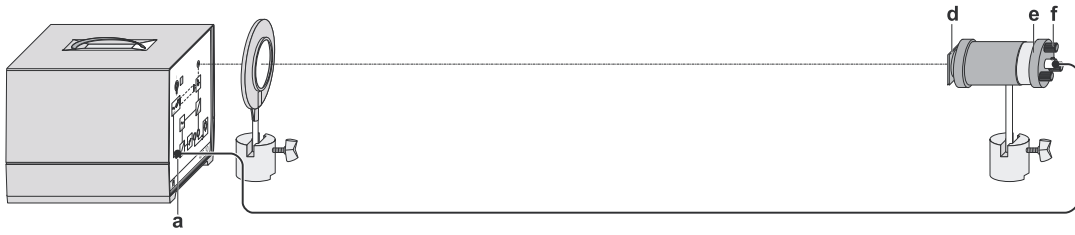


Figure 1.3: Set-up for the measurement for the propagation speed of light in air.

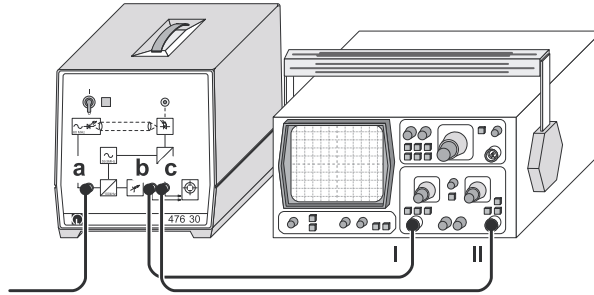


Figure 1.4: Connection of the oscilloscope for measuring the phase of the periodic light signal.

1.3.2 Experimental Set-up

The experimental set-up is illustrated in Figs. 1.3 and 1.4.

- Set the light transmitter up at a distance of approx. 1.5 m from the receiver, connect the transmitter to output (a) of the receiver and turn on the receiver.
- Observe the red light patch of the light transmitter on the front plate of the receiver and displace the insert (e) relative to the condenser (d) such that the red light patch maintains approximately the same size for different distance between the transmitter and the receiver (collimation of the source).
- Place the lens on the ray path and centre it with respect to the light beam.
- Align the light transmitter and the lens so that the red light patch focuses on the entrance aperture of the receiver. If necessary, optimize the alignment of the light transmitter with the knurled screws (f).
- Connect the output (c) of the receiver to channel II of the oscilloscope. (Coupling channel II: AC, Trigger: channel II).
- Observe the receiver signal on the oscilloscope and optimize the alignment of the light transmitter and the lens so that the amplitude of the detected signal is maximal. Adjust the vertical position such that it is symmetric to the horizontal center line. And also adjust the two signals using phase shifter such that they are in phase.

Speed of Light in Air

- Set-up as seen in Fig. 1.3.

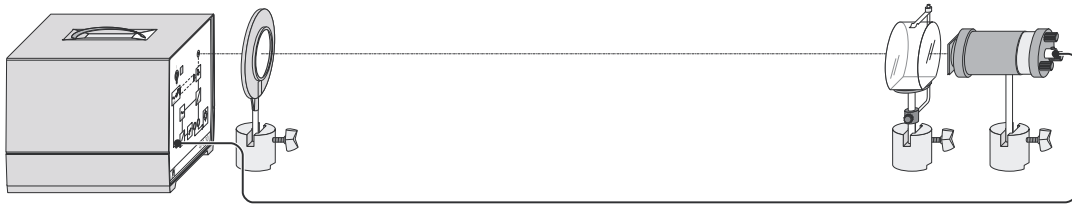


Figure 1.5: Set-up for the measurement of the speed of light in acrylic glass.

Speed of Light in Acrylic Glass

- Mount the prism table in a saddle base, and clamp the acrylic glass block on the prism table with the metal holder. (see Fig. 1.5).

Speed of Light in Water

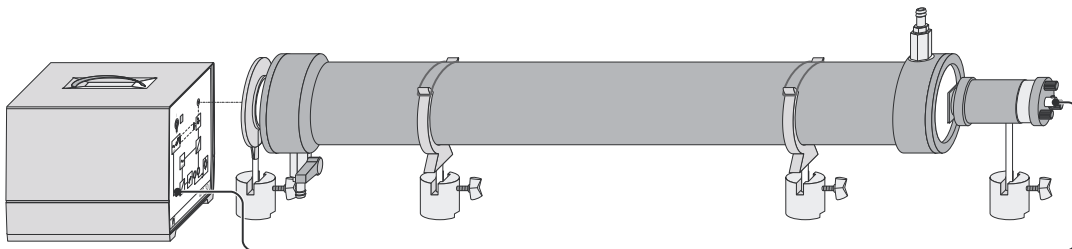


Figure 1.6: Set-up for the measurement of the speed of light in water.

- Place the tube between the transmitter and the lens (see Fig. 1.6). Ensure that the tube is horizontal and fill it carefully with water.

1.3.3 Measurements

A satisfactory accuracy of the result can only be obtained with thermal stability of the light transmitter and the receiver. Start the measurement only after the light transmitter and the receiver have been switched on for 15 minutes.

Synchronizing the Phases of the Reference and the Receiver Signal

- Connect the output (b) of the receiver to channel *I* of the oscilloscope and look at channel *I* (reference signal) and channel *II* (receiver signal) simultaneously. (Oscilloscope settings: Coupling channel *I* and *II*: AC, trigger: channel *I*).
- Adjust the vertical positions of channels *I* and *II* so that they are as symmetric as possible with respect to the horizontal centre line of the screen.
- For the sake of control adjust the vertical deflections with the fine adjustment control so that the maxima of both signals touch the same horizontal line.
- Adjust the two signals with the phase shifter ϕ such that they are in phase.
- Choose a suitable horizontal scale of the signals, and measure the period T_1 .

Speed of Light in Air

- While changing the distance between the transmitter and receiver, carefully observe the oscilloscope for any change in the phase of the incoming wave. The phase should only exhibit a unidirectional shift. If this is not the case, repeat the alignment procedure, ensuring that the light beam remains both horizontal and centered with respect to the lens throughout the entire course of transmitter.
- Measure the time delay between the reference signal and the light signal for different distances. Estimate the statistical uncertainty and systematic uncertainty for each measurement. Initiate the experiment with the maximum distance achievable between the transmitter and receiver, gradually reducing the distance in 5 cm increments for a total of 15 measurements.

Speed of Light in Acrylic Glass

- Choose an arbitrary distance between transmitter and receiver. Match both signals at the zero crossing. Use a suitable time-scale.
- Mount the acrylic glass block directly in front of the transmitter (see Fig. 1.5)
- Measure the delay between the zero crossings and the *apparent change* Δt_1 (note: the delay in the time axis is tiny!).
- Repeat these measurements for 10 arbitrary distances and note their mean value of Δt_1 . Discuss why those values are all close to each other and why the absolute distance does not matter.

Speed of Light in Water

- Put the tube into the ray path immediately in front of the light transmitter. Match both signals at the zero crossing. Use a suitable time-scale.
- Fill the tube with water.
- Measure the delay between the zero crossings and the *apparent change* Δt_1 .
- Repeat these measurements five times and compute the mean value of Δt_1 .

1.3.4 Tasks for Evaluation

- Convert all measurements of the apparent time changes into real time changes. First, determine the conversion factor with the period to the modulation frequency (1.11).

Air

- Plot the measured propagation distances s as a function of the calculated real time delays, incorporating statistical error into the data points. Perform a linear fit through all the data points on the graph. The slope of the fit corresponds to the speed of light in the given medium.
- Compare the measured value of speed of light in the air to the literature value (refractive index under typical condition of 1.003 ± 0.001). Precisely evaluate the different sources of error in your measurement.

- Calculate the refractive index of air.
- Calculate a full error estimation of the systematic error. The statistical error can be obtained from your fit program.

Glass and Water

- Calculate the speed of light from the mean values of the propagation time difference and the refractive index. Use the literature value for the speed of light in vacuum.
- Repeat the same calculations, this time by using the determined value for the speed of light in air. What is your observation?
- Perform a complete error estimation.

1.4 Literature

- D. Meschede, "*Gerthsen Physik*", Springer Verlag
- Details about Oscilloscope (<https://download.tek.com/manual/071219901web.pdf>)

A.1 Oscilloscope

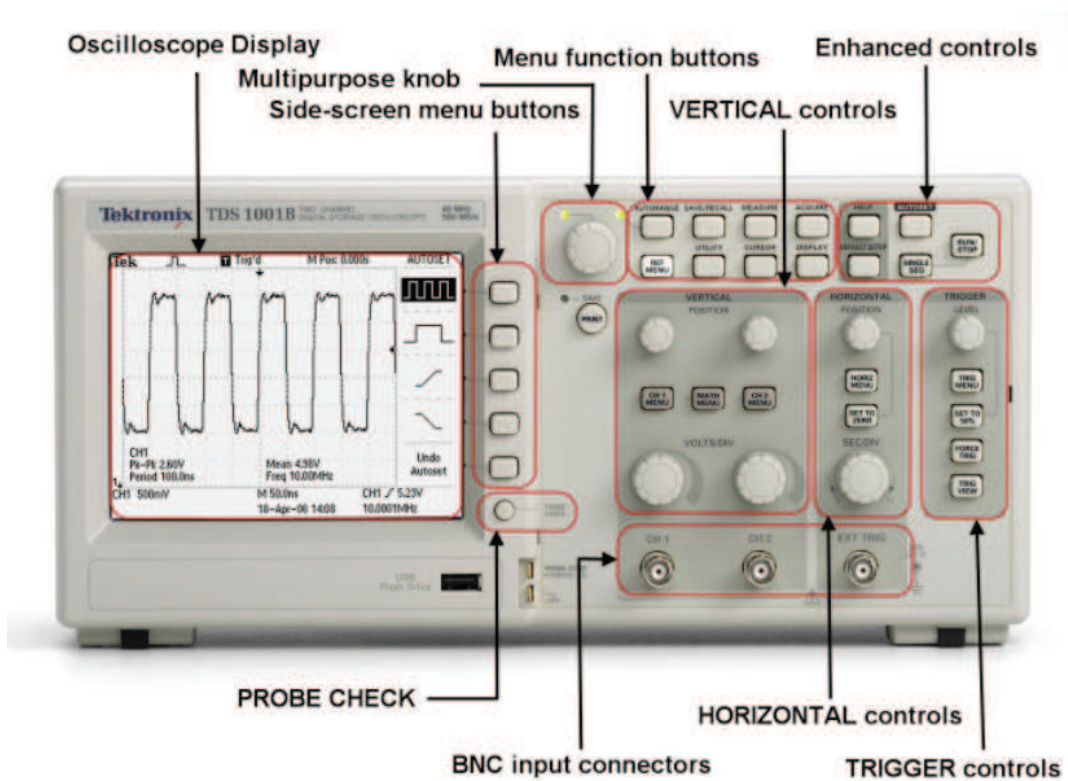


Figure A.7: The TDS1001B digital storage oscilloscope.

A.2 Speed of light measurements

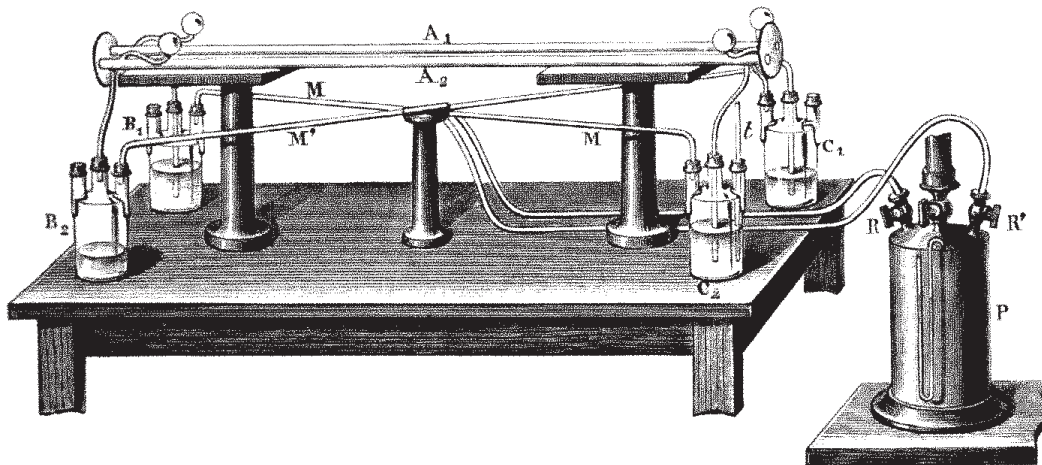


Figure A.8: Fizeau method (1851).

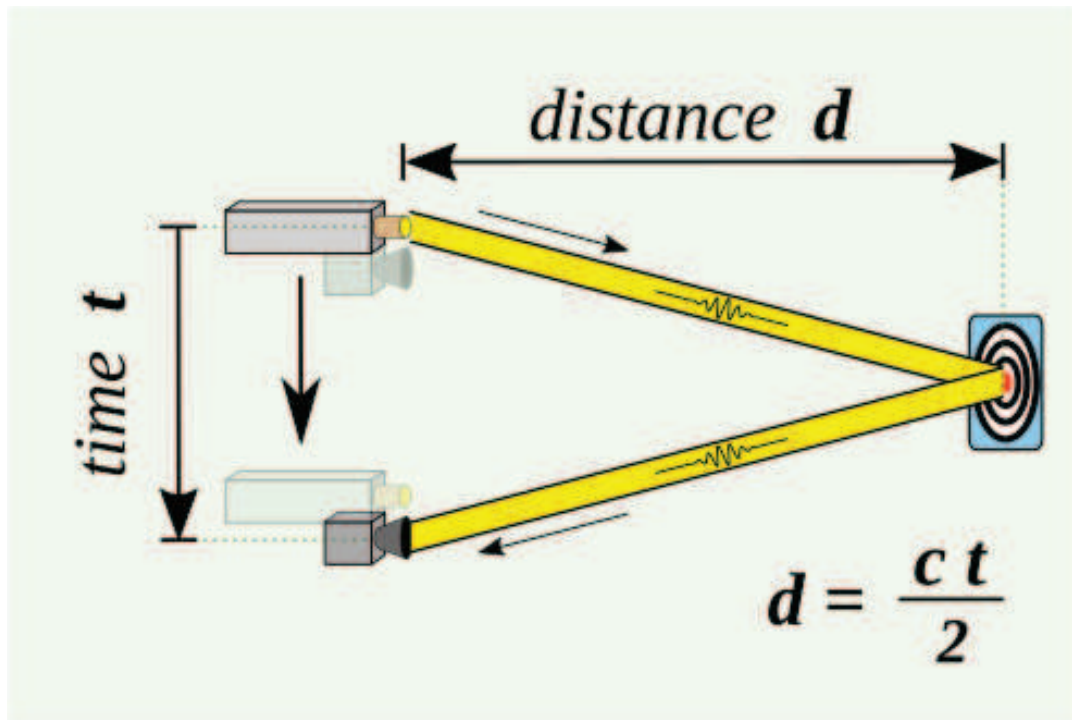


Figure A.9: Time-of-Flight method involves measuring the time it takes for a light pulse to travel a known distance.