

Determining the velocity of light in the air from the path and transit time of a short light pulse

Objects of the experiment

- Relatively measuring the transit time t of a short light pulse with an oscilloscope as a function of the position s of the reflecting mirror.
- Determining the velocity of light in the air from the slope of the graph $s = f(t)$.
- Absolutely measuring the transit time t of a short light pulse with an oscilloscope for a given path $2s$ by marking the zero point with a reference mirror.
- Determining the velocity of light in the air as the quotient of the path and the transit time.
- Calibrating the time measurement using a quartz-controlled oscillator signal.
- Absolutely measuring the transit time t of a short light pulse for a given path $2s$ by marking the zero point with a reference mirror.
- Determining the velocity of light in the air as the quotient of the path and the calibrated transit time.

Principles

The light velocity measuring instrument emits extremely short pulses of red light with a pulse width of about 20 ns via a high-performance LED. After traversing a known measuring distance in both directions, the light pulses are converted into voltage pulses for observation on the oscilloscope.

Path of the light:

The light source, a bright red ($\lambda = 615 \text{ nm}$) LED, is focused through the window F_1 of the light velocity measuring instrument on infinity by the lens L . The large triple mirror T_1 reflects the beam path on itself, so that the LED is imaged on itself (see Fig. 1).

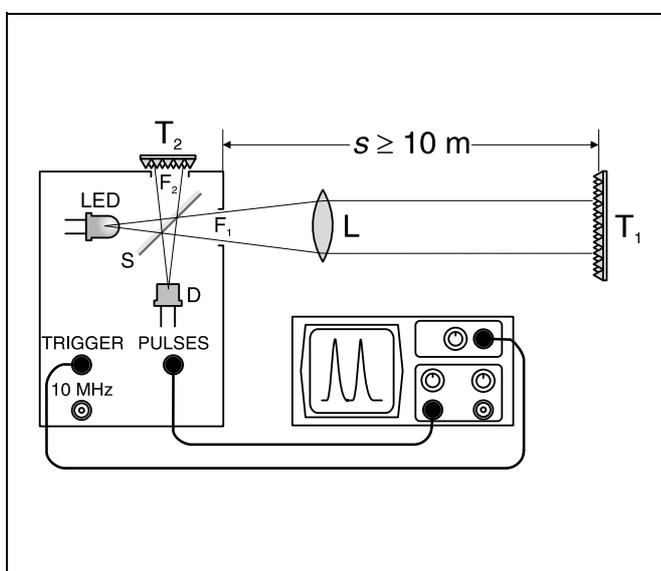
The beam divider S in the light velocity measuring instrument reflects the returning light downward onto the photodiode D . At the same time, it reflects half of the light coming from the LED upward, where it emerges through window F_2 . This upward beam path is equivalent to the horizontal path.

The small triple mirror T_2 directly above F_2 generates a reference pulse with negligible transit-time delay and has no effect on the measuring beam.

Measuring method:

A measuring distance of 10 m corresponds to a transit time of the light pulse of around 60 ns for the outgoing and return distances. The pulse width of approx. 20 ns is matched to this transit time. The special design of the light velocity measuring instrument permits the use of a relatively simple oscilloscope.

Fig. 1: Schematic diagram showing the principle of measurement of the velocity of light with short light pulses



Apparatus

1 Light velocity measuring instrument	476 50
1 Plug-in unit 230 V/12 V AC	562 791
1 Lens in holder, $f = 200$ mm	460 10
1 Optical bench with standard cross-section e.g.	460 32
2 Optics riders, height: 90 mm, width: 50 mm	460 352
1 Two-channel oscilloscope 303	575 211
3 BNC cables, 1 m	501 02
1 Wooden ruler, 1 m long	311 03
1 Large stand base, V-shape	300 01
1 Stand rod, 100 cm	300 44
1 Leybold multiclamp	301 01

The light pulses are emitted with a high repetition frequency of 40 kHz. This ensures sufficient brightness of the signal on the oscilloscope screen, even when using the maximum deflection speed of the oscilloscope.

Just before the light pulse is emitted in the light velocity measuring instrument, a trigger signal is output for externally triggering the oscilloscope. Therefore, the complete voltage pulse appears on the oscilloscope screen even when the transit time of the light pulse is negligibly short, i.e. when the triple mirror is at a minimum distance in front of F_1 or above F_2 . It is thus not necessary to use an oscilloscope with built-in delay line.

When we increase the distance between the large triple mirror and the outlet window, the pulse signal on the oscilloscope is shifted farther to the right in response to the longer transit time. We can calculate the velocity of light as the quotient of the change in the distance and the change in the transit time. When using the reference pulse via the small triple mirror, the total transit time can be determined on the oscilloscope in absolute terms. The light velocity is then calculated as the quotient of the distance and the transit time.

To calibrate the time measurement, a quartz-controlled oscillator signal can be displayed simultaneously on the oscilloscope. As the oscillator signal can be shifted by more than one period with respect to the measuring pulse, its edges are most suitable for use as a measuring benchmark. In this case, the time measurement is independent of the time base of the oscilloscope.

Setup

Set up the experiment as shown in Fig. 2.

Mechanical and optical setup:

- Place the optical bench on a table of suitable height and mount the light velocity measuring instrument on the optical bench so that window F_1 is facing the lens (see Fig. 2).

- Mount the lens on the optical bench about 20 cm from the light velocity measuring instrument, with its midpoint at the same height as window F_1 .
- Attach the large triple mirror to stand material (see Fig. 2) and set it up several meters from the light velocity measuring instrument. Align the midpoint in the same height as the optical axis and the mirror surface approximately perpendicular to this axis.
- Switch on the light velocity measuring instrument by plugging in the plug-in unit.

If, when looking past the lens from a vantage point just above the light velocity measuring instrument, the triple mirror does not appear red or is red only at the edges:

- Vary the beam direction by tilting and swiveling the optical bench, and change the height of the lens if necessary, so that the beam strikes the triple mirror in the center.

Connecting the oscilloscope:

- Connect the “pulse” output with oscilloscope channel I and the “trigger” output to the external triggering input using BNC cables.

Table 1: Oscilloscope settings, e.g. for the two-channel oscilloscope 303 (Cat. No. 575 211).

Operating mode:	channel I only
Channel I:	DC, 5–100 mV/cm
Zero line:	bottom edge of screen
Triggering:	external, AC, + (rising edge)
Triggerlevel:	automatic
Time-base sweep:	0,2 μ s/cm, cal.
X-magnification:	1 \times
Intensity:	maximum

- Using the oscilloscope settings from table 1, find a voltage pulse.
- Set up the large triple mirror at the maximum distance anticipated for this experiment and optimize the pulse amplitude by slightly varying the optical adjustment, particularly by moving the lens on the optical bench.
- Switch the x-magnification of the oscilloscope to 10 \times .

Carrying out the experiment

a) Measuring the transit time as a function of the position of the triple mirror:

- Set up the large triple mirror close to the optical bench and mark its position.
- Shift the maximum of the voltage pulse to a vertical grid line on the left side of the oscilloscope screen by varying the x-position (see Fig. 3, top).
- Move the large triple mirror in the beam path, measure the change in distance s and write this value in your experiment log.
- Read the shift in the time t of the voltage pulse from the oscilloscope (see Fig. 3, top) and write this value in your experiment log.
- Repeat your measurements for further shifts in s (see table 2).

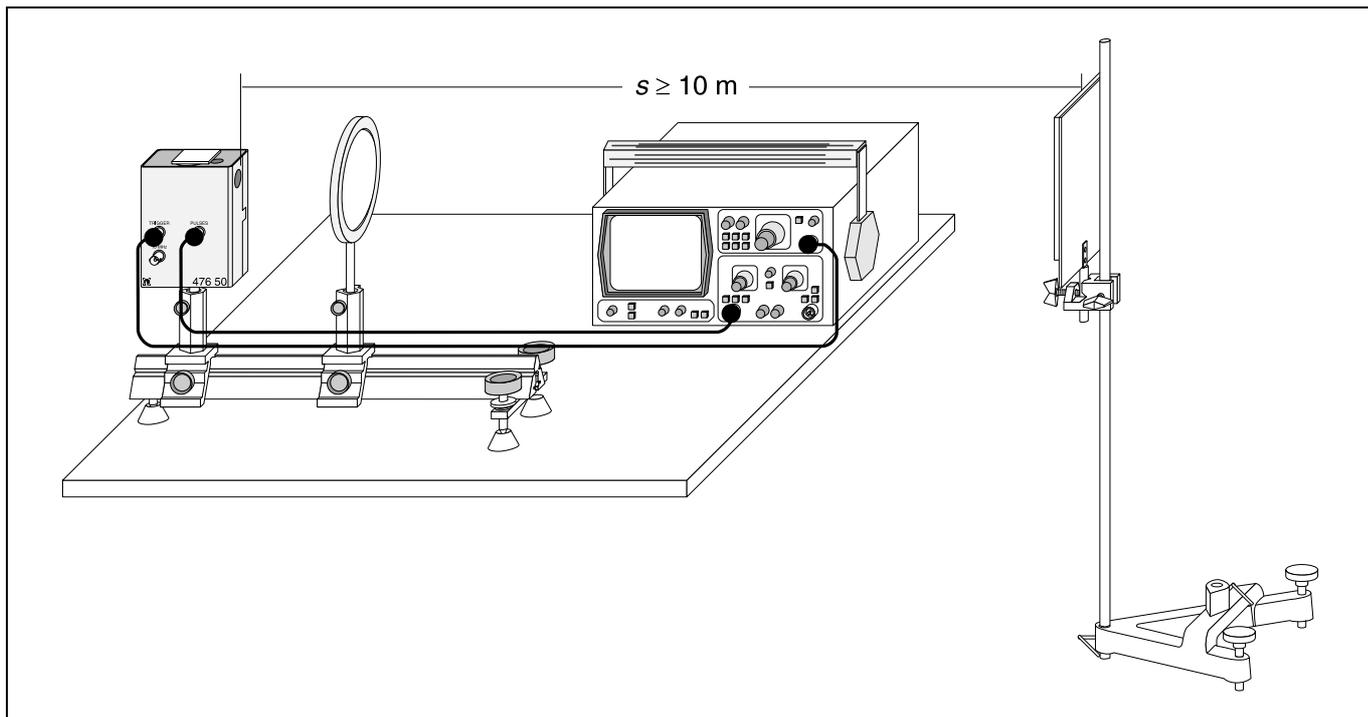


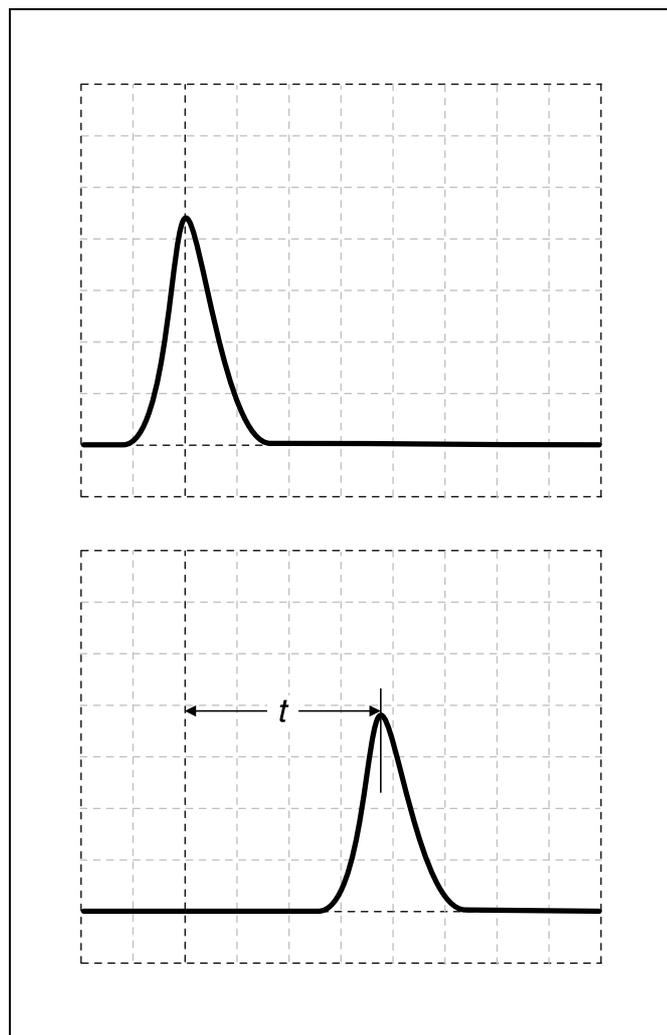
Fig. 2: Experiment setup for measuring the velocity of light

b) Measuring the transit time with a reference mirror:

- Push the assembly to the left-hand edge of the table, sight downward along the vertical edge of the light velocity measuring instrument and mark the position on the floor (see Fig. 4).
- Hold the small triple mirror directly in front of F_1 and shift the maximum of the voltage pulse to a vertical grid line on the left side of the oscilloscope screen by varying the x-position.
- Then, lay the small triple mirror on F_2 and make sure that the position of the reference pulse on the oscilloscope has not changed (equal light paths).
- Place the large triple mirror in the beam path at a distance of at least 10 meters so that the measurement pulse appears on the oscilloscope screen as a second signal at a clear distance from the reference pulse.
- By carefully moving the small triple mirror on the window opening, adjust the two signals to exactly the same amplitude. Shift the rising edge of the reference pulse so that it crosses the center line where this intersects with a vertical grid line (see Fig. 5).
- Read off the transit time t at the intersection of the second pulse with the center line (see Fig. 5) and write this value in your experiment log.

Note: the time interval between the reference pulse and the measuring pulse can only agree with the spacing between the two rising edges on the oscilloscope when both pulses have the same amplitude and the distance is significantly greater than the pulse width.

- Mark the position of the large triple mirror on the floor, measure the distance s to window F_1 and write this value in your experiment log (see Fig. 4).

Fig. 3: Relative measurement of the transit time t of the light pulse

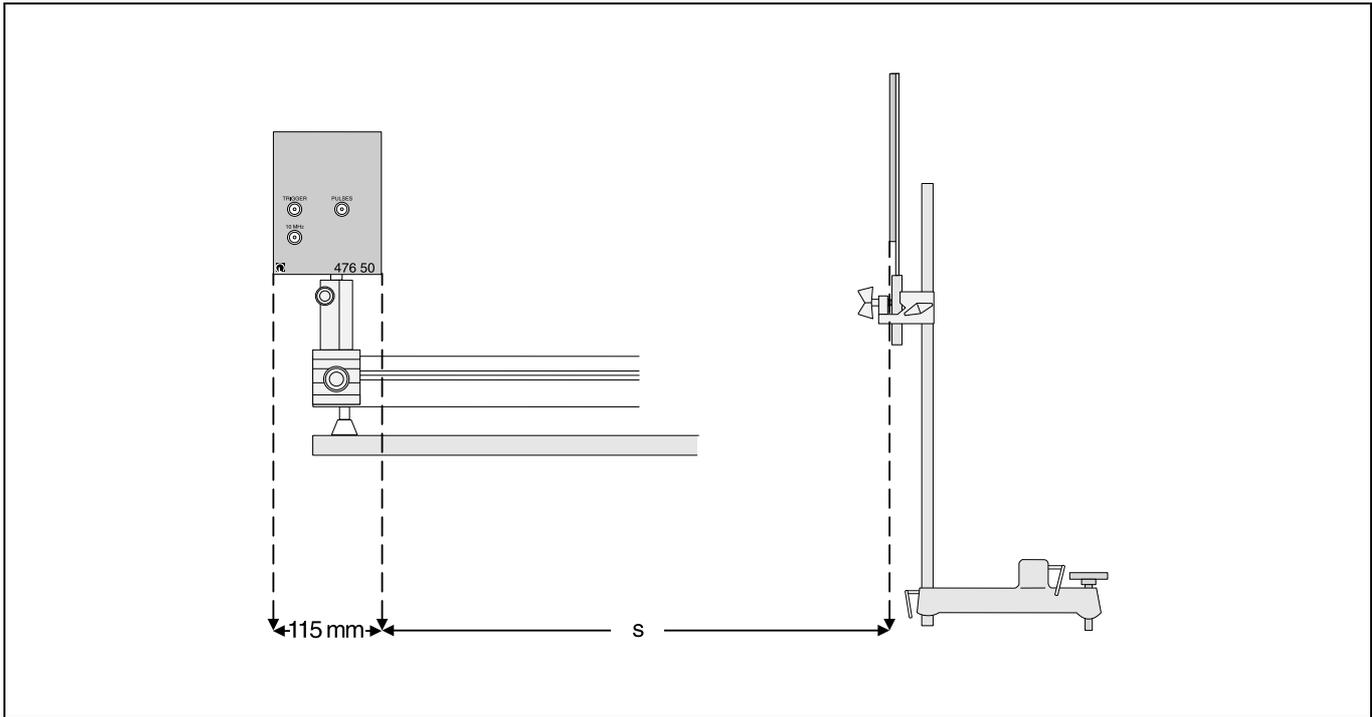


Fig. 4: Measuring the position of the light velocity measuring instrument and the large triple mirror

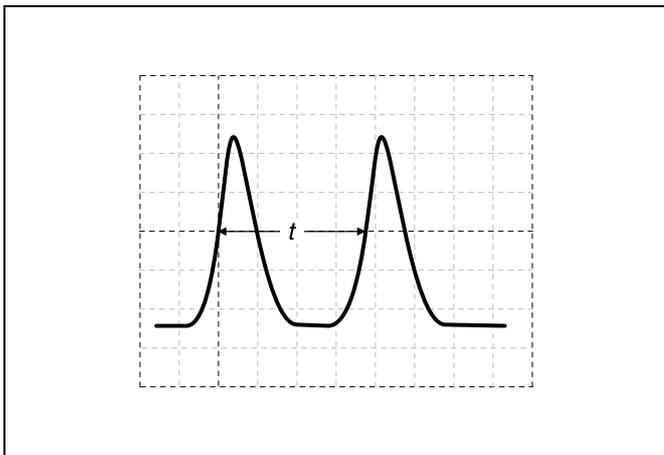


Fig. 5: Absolute measurement of the transit time t of the light pulse

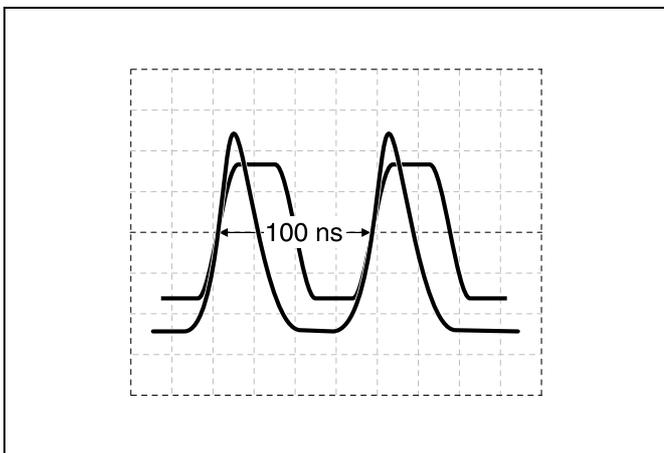


Fig. 6: Absolute measurement of the transit time t of the light pulse with externally calibrated time base

c) Measuring the transit time with an externally calibrated time base:

- Place the small triple mirror on F_2 and the large triple mirror in the beam path about 15 m away so that you can see two pulses on the oscilloscope screen.
- If necessary, maximize the distance between the two pulse signals on the oscilloscope screen by varying the time-base sweep.
- By carefully moving the small triple mirror on window opening F_2 , adjust the two signals to exactly the same amplitude.
- Connect the 10-MHz output of the light velocity measuring instrument to oscilloscope channel II via a third BNC cable.
- Select dual-channel mode ("dual" button) and activate oscilloscope channel II (AC, 0.1 V/cm), so that the measuring pulses and the oscillator signal are visible simultaneously.
- Using the phase adjuster on the light velocity measuring instrument, shift the 10 MHz signal so that the rising edge of the first voltage pulse is exactly coincident with a rising edge of the 10 MHz signal (see Fig. 6).
- Adjust the distance of the large triple mirror so that the rising edge of the second voltage pulse is exactly coincident with the next rising edge of the 10 MHz signal (see Fig. 6).
- If necessary, adjust the optical assembly or vary the triple mirrors until the voltage pulses of both triple mirrors are the same amplitude, and then readjust the positions of the rising edges.
- Mark the position of the light velocity measuring instrument and the large triple mirror on the floor (sight downward with one eye along the vertical edge of the device), measure the distance s to window F_1 and write this value in your experiment log (see Fig. 4).

Measuring example

a) Measuring the transit time as a function of the position of the triple mirror:

Table 2: Change in distance s of the large triple mirror and the transit time t of the light pulse

$\frac{s}{m}$	$\frac{t}{ns}$
0.0	0
3.0	20
6.0	41
9.0	60
12.0	81
15.0	101
18.0	122

b) Measuring the transit time with a reference mirror:

$$s = 15.00 \text{ m}, t = 99 \text{ ns}$$

c) Measuring the transit time with an externally calibrated time base:

$$s = 15.05 \text{ m}$$

Evaluation

a) Measuring the transit time as a function of the position of the triple mirror:

Fig. 6 shows the graph of the measured values for s as a function of t . From the slope a of the straight line through the measuring points, we obtain the following value for the velocity of light through air:

$$c = 2 \cdot a = 2.98 \cdot 10^8 \frac{\text{m}}{\text{s}}$$

b) Measuring the transit time with a reference mirror:

From the quotient of the distance s and the transit time t , we obtain the following value for the velocity of light through air:

$$c = 2 \cdot \frac{s}{t} = 3.03 \cdot 10^8 \frac{\text{m}}{\text{s}}$$

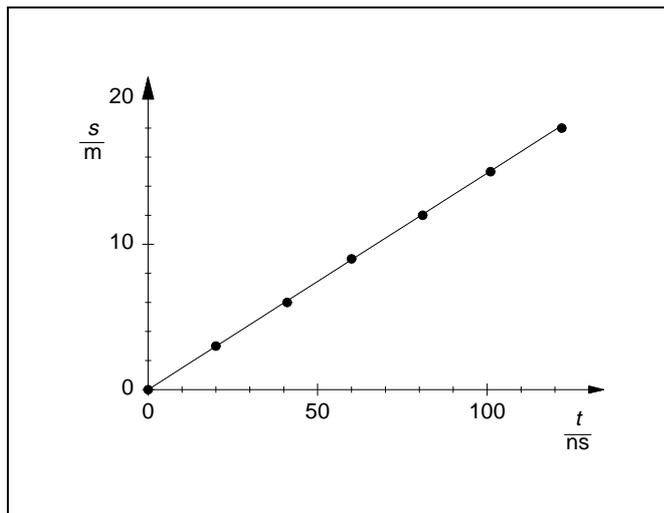


Fig. 7: Change in distance s of the large triple mirror as a function of the transit time t of the light pulse

c) Measuring the transit time with an externally calibrated time base:

The distance s was selected so that the total transit time t of the light pulse is 100 ns.

$$c = 2 \cdot \frac{s}{100 \text{ ns}} = 3.01 \cdot 10^8 \frac{\text{m}}{\text{s}}$$

d) Comparing the measuring methods:

In addition to the reading errors occurring for the time value in all measurements, we need to take the accuracy of the calibrated positions for the time-base sweep of the oscilloscope into consideration for measurements a) and b). For the oscilloscope used here, this value is 3 %.

e) Literature values

Velocity of light in a vacuum:

$$c_0 = 2.998 \cdot 10^8 \frac{\text{m}}{\text{s}}$$

Velocity of light through the air (phase velocity):

$$c = \frac{c_0}{n} = 2.997 \cdot 10^8 \frac{\text{m}}{\text{s}}$$

(Refractive index $n = 1.003$ at standard temperature and pressure)

Strictly speaking, the propagation velocity of the short light pulses in air corresponds to the group velocity of a wave packet. However, given the measuring accuracy attained here, there is no need to go into the difference between phase velocity and group velocity.

