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Instruction Sheet **476 30/34/35**

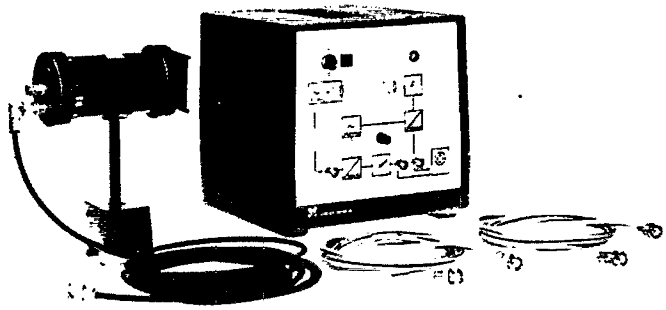


Fig. 1 Light transmitter and receiver (and saddle base 300 11)

Light Transmitter and Receiver
Plastic Body
Tube with Glass Ends

Important: Please observe all notes on electromagnetic compatibility given on page 6!

Light transmitter and Receiver (476 30) serves to determine the velocity of light by an electronic method of modulation. Therefor a short light path of eg. 1,5 m is sufficient to achieve result with graeter accuracy (± 1%) in comparison to the classical Foucalt-Michelson method.

An acrylic glass block (476 34) or a tube with two end-windows (476 35) filoled with a clear liquid is required in the light path between transmitter and receiver for the determination of refractive indicies.

Literature: Physics Experiments, Volume 3 (599 942)

1 Technical Data

1.1 Light transmitter and Receiver (476 30)

1.1.1 Light transmitter

Transmitter:	Light-emitting diode (red, 670 nm) with condenser
Modulation frequency:	60.0 MHz ± 5 kHz
Reference signal:	Transmission via tuned coaxial cable (BNC), 6 m
Power supply:	(via the above cable) from power supply of the receiver
Dimensions:	Lamp house: approx. 60 mm dia., approx. 110 mm length (not extended) Rod: 10 mm dia., 115 mm length
Weight:	0.8 kg incl. coaxial cable (6 m)

1.1.2 Receiver and power supply unit

Sensor:	Silicon PIN photodiode
Mixer:	Receiver signal + auxiliary frequency
Auxiliary frequency:	59.9 MHz
Difference frequency:	100 kHz ± 10 kHz
Mixer:	Reference signal x auxiliary frequency
Phase relation:	adjustable between 0 and nearly 2 π via rotary knob
Outputs:	2 x approx. 100 kHz via BNC sockets
Output voltage:	Reference channel approx. 2 V_{pp} Working channel approx. 2 V_{pp} with good illumination
Signal-to-noise ratio:	46 dB (0.5 % of well illuminated working channel)
Load resistor:	higher than 2 kΩ, outputs are short-circuit proof
Mains supply:	110/125/150/220 and 240 V 50/60 Hz
Power consumption:	15 VA
Fuses:	for 220 V and 240 V: T 0.125 B (Ref. No. 698 06) for 110/125/150 V: T 0.2 B (Ref. No. 698 08)
Dimensions:	185 mm x 190 mm x 230 mm
Weight:	3.5 kg

1.2 Plastic body (476 34)

Material:	Acrylic glass
Refractive index:	approx. 1.5
Dimensions:	70 mm dia., 50 mm length polished end faces

1.3 Tube with glass ends (476 35)

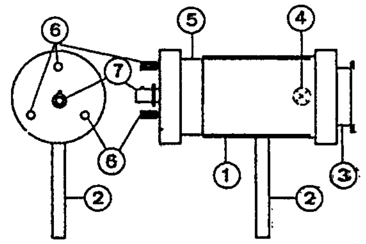
Length:	1000 mm (incl. glass panes)
Glass panes:	3 mm thick
Inside length:	994 mm
Inside diameter:	72 mm
Outside diameter:	approx. 76 mm, with two holding rods (12 mm dia.) for mounting into saddle bases (300 11) or stand bases (e. g. 300 02)
In/outlet ports:	2, with hose nozzle and tap
Filling quantity:	approx. 4 ltr. water
Weight:	empty: 2.3 kg filled: 6.3 kg

2 Description

2.1 Light transmitter and Receiver (476 30)

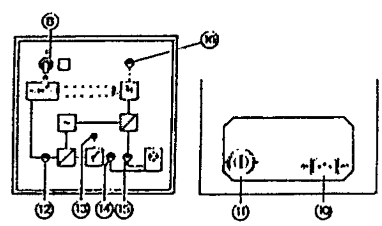
Including: Light transmitter
receiver and power supply unit
Screened cable (BNC), approx. 6 m
Screened cable (BNC), approx. 1,5 m

2.1.1 Light transmitter



① Lamp house
② Holding rod
③ Condenser
④ Light-emitting diode installed in insert ⑤
⑤ Sliding insert with transmitter and light-emitting diode
⑥ Knurled adjustment nuts
⑦ BNC socket (with green band over flange) to connect the tuned coaxial cable (approx. 6 m to the power supply in the receiver

2.1.2 Receiver and power supply section (Fig. 3)



⑧ Power switch
⑨ pilot lamp of power supply
⑩ Socket for power cable (included in standard equipment)
⑪ Voltage selector and fuse holder
⑫ Input (BNC) for reference signal from transmitter and at the same time output for power supply
⑬ Phase shifter
⑭ Output (BNC) reference channel (100 kHz) to connect an oscilloscope. This channel is used for triggering. With a two-channel oscilloscope the signal can also be shown on the screen.
⑮ Output (BNC) working channel (100 kHz) to connect an oscilloscope
⑯ Input for optical signal, behind (approx. 13 mm) photodiode and preamplifier

2.2 Plastic body (476 34); see fig. 4

⑰ Base (e. g. for placing on the prism table, Cat. No. 460 25)
⑱ Polished end faces, spacing 50 mm

2.3 Tube with glass ends (476 35); see fig. 5

⑲ Tube
⑳ Inlet and outlet port with tap and hose nozzle
㉑ Vent nozzle with tap
㉒ End windows
㉓ Holding rods for mounting into saddle bases (300 11) or into stand bases (300 02)

When supplied, the tube might still contain some water (residue from leak test).

3 Principle

Transmitter (red LED modulated with 60 MHz) and receiver (photodiode, amplifier, mixer and power supply) are accommodated in two separate housings which are connected only by a coaxial cable of 6 m length via which the transmitter is powered from the power supply section of the receiver while at the same time a reference signal running synchronously with the transmit signal is returned.

To determine the velocity of light from the ratio of a distance traveled by the light to the time required to travel this distance, transmitter and receiver are directly placed opposite each other with at first small and then larger spacing. For adjustment of the optical path see 4.2.

To enable determination of the short time required for a short distance of e. g. 10 cm to an accuracy of approx. 2×10^{-11} s, using a school-type oscilloscope (time base up to 10^{-8} s/mm), a time extension by a factor of approx. 600 for transmit and receive signal is made in the receiver housing.

By mixing (multiplying) a 59.9 MHz signal (ω_2) with the 60 MHz signals (ω_1) of transmitter and receiver (Fig. 6) one obtains low-frequency signals of approx. 100 kHz each (difference frequency: $\omega_1 - \omega_2$) with the same phase information as transmit and receive signal, due to the addition theorem

$$2 \cos a \cos \beta = \cos (a + \beta) + \cos (a - \beta)$$

When selecting the modulation of the transmitter e. g. proportional to $\cos \omega_1 t$ it follows for the modulation of the receiver signal that the modulation is proportional to $\cos (\omega_1 t - \varphi)$, with phase shift φ caused e. g. by a more or less long distance. After mixing these two signals each with ω_2, i. e.

from $\cos \omega_1 t \cdot \cos \omega_2 t$ and
$\cos (\omega_1 t - \varphi) \cdot \cos \omega_2 t$

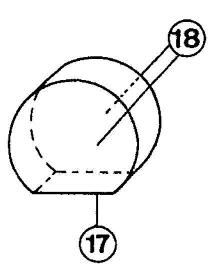


Fig. 4

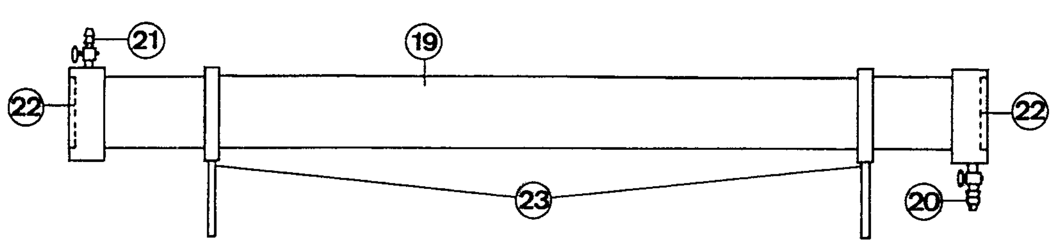


Fig. 5

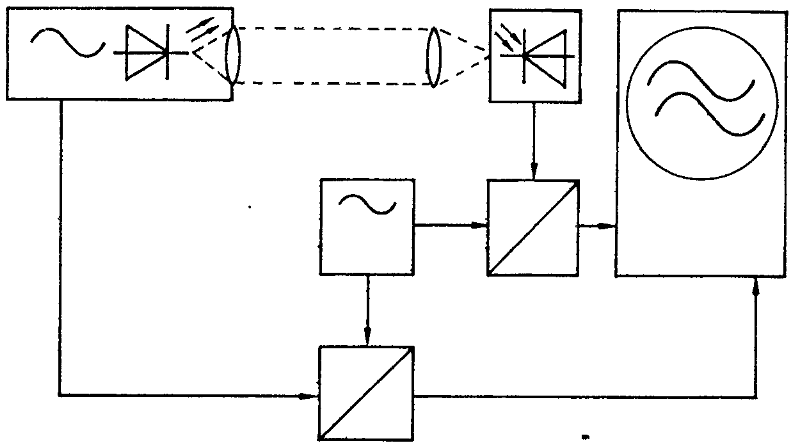


Fig. 6 Block diagram

and after separating the high-frequency components $(\omega_1 + \omega_2)$ by suitable filters, one obtains two proportional low-frequency signals $(\omega_1 - \omega_2)$

$$\cos(\omega_1 - \omega_2)\,t \text{ and } \cos[(\omega_1 - \omega_2)\,t - \varphi]$$

During mixing the phase shift φ has remained unchanged. But now the time corresponding to this phase shift is different from that of the original modulation frequency of 60 MHz. This time has increased by the factor $\omega_1/(\omega_1 - \omega_2)$.

For exact determination of this time shift (approx. 600) the difference frequency can be measured with a digital counter (eg. 575 40)

By phase comparison on an oscilloscope of the two low-frequency signals resultant by mixing one obtains their time shift and therefrom, by division by the factor of the time extension, the change of the real travel time of the light (light modulation) between transmitter and receiver.

For notes on experiments see Section 5.

4 Operation and Adjustment

4.1 General

Check voltage selector ⑪ on rear of receiver; the local voltage rating should appear near the white mark ㉔ (see also Section 4.5 "Exchanging the Fuse").

Mount the light transmitter (Fig. 2) in saddle base (300 11) or in rider to an optical bench (e. g. in 301 01 on 460 43). Connect BNC socket ⑦ of the transmitter to BNC socket ⑫ of the receiver (Fig. 3) using the screened coaxial cable of 6 m length supplied with the equipment.

Connect BNC socket ⑭ of the receiver with e. g. channel I of a two-channel oscilloscope (e. g. 575 27) using one of the coaxial cables of 1.5 m length. Trigger on this channel during all experiments. If no two-channel oscilloscope is available, connect socket ⑭ with ext. trigger input of the oscilloscope (e. g. 575 17). Connect BNC socket ⑮ of the receiver with channel II of the two-channel oscilloscope or, in case of a one-channel oscilloscope, with the Y-channel.

Connect the receiver to the mains and switch on the power switch ⑨. Pilot lamp on receiver and LED ④ of transmitter light up.

Connect the oscilloscope (e. g. 575 27) to the mains and switch on. An oscillation of approx. 2 V_{pp} and approx. 100 kHz (reference signal) appears on channel I on the screen of the two-channel oscilloscope.

4.2 Adjustment

For adjustment and further experiments the following equipment is required in addition:

	Cat. No.
1 Lens, f = 150 mm	460 08
1 Saddle base	300 11
or	
1 Rider for optical bench	e. g. 301 01
For adjustment over distances > 3 m:	
1 Lamp house	450 60
1 Lamp	450 51
1 Transformer, e. g. 6 V/12 V, 30 VA	562 73

4.2.1 Adjustment at close range, up to approx. 3 m

Adjustment can be made in a non-darkened room.

Place transmitter (Fig. 2) in saddle base (300 11) or in rider (460 80) on an optical bench (460 75) at the desired distance. Input photodiode, lens and transmitter should be at the same level and in line.

For easy preadjustment, place a piece of paper over input ⑯. Make the red beam of the LED of the transmitter as parallel as possible to the condenser and focus it to input ⑯ using lens f = 150 mm.

Move the lens by approx. 13 mm toward the input as the receiver photodiode is positioned approx. 13 mm behind input ⑯. Remove the paper. A sinusoidal signal of likewise 100 kHz appears on the oscilloscope screen (575 27) on channel II (possibly still with very small amplitude).

During further adjustment observe this signal whose amplitude and phase are proportional to the amplitude and phase of the optical signal transmitted between transmitter and receiver.

Move the lens slightly until the amplitude of the working signal on the oscilloscope reaches a maximum. Find the optimum position of the LED in the transmitter, using knurled nuts ⑥, so that the amplitude on the oscilloscope continues to increase. With good adjustment a signal of approx. 2 V_{pp} is obtained.

4.2.2 Adjustment at very long distance (> 3 m)

Place lens f = 150 mm (460 08) in saddle base (300 11) before the input ⑱ for optical signal at approx. 150 mm distance.

Replace the adjustable insert ⑤ of the transmitter by the corresponding insert of lamp house (450 60) with screewed-in lamp (450 51). Because of its higher luminous intensity, this lamp is used for preadjustment of height and direction (focus the beam sharply on covered (!) input for photodiode). Then replace the lamp again by insert ⑤ of the transmitter and make fine adjustment via knurled nut ⑥. For this adjustment observe oscilloscope screen and adjust maximum amplitude.

4.3 Limitation by cross-interference

Cross-interference was kept to a minimum by constructional measures (transmitter and receiver in two separate housings and screened accordingly) and by electronic measures (e.g. the reference signal runs from transmitter to receiver via cable with 30 MHz only). A typical value is approx. 0.2 % (0.5 % max.) of the fully excited working signal. However, for the experiments described in Section 5, the fault caused by cross-interference is insignificant. But if the accuracy shall be increased by increasing the path difference (e.g. 5 m or 10 m), the attainable accuracy is limited at last by cross-interference.

4.4 Exchanging the fuse of the receiver

Disconnect mains plug before exchanging the fuse.

For exchanging the primary fuse, put a coin into slot ㉖ of the voltage selector and fuse holder ⑪ and turn switch until the white mark ㉔ is near to position "0" as shown in Fig. 7. The fuse pushed out in this position by a spring is caught by hand. Insert new fuse into opening ㉕ and press down by means of a pointed object (ball pen or screw-driver) at the same time turning and pressing down the coin in the slot ㉖.

Set voltage selector so that the local voltage rating appears near the white mark ㉔.

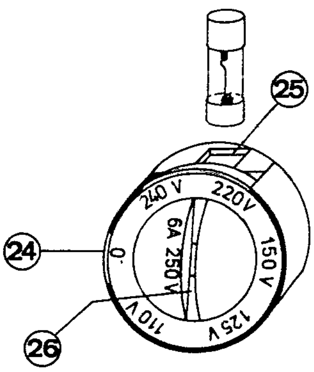


Fig. 7

5 Notes on Experiments

5.1 Preliminary experiment (Fig. 8)

Mount the transmitter e.g. in rider (460 80) on optical bench (460 75). Select time base of 1 µs/cm on the oscilloscope (575 26).

When continuously displacing the transmitter, a continuous shift of the optical signal is obtained (preferably watch a zero passage). Hence, the velocity of light is finite and the travel time proportional to the travel distance.

5.2 Velocity of light with small differences in travel distance

Set-up according to Fig. 8.

With a travel distance (Δs) of 0.1 m, a displacement of 2 mm is obtained on the oscilloscope (1 µs/cm). This is difficult to observe. To increase the velocity, choose another time base on the oscilloscope, e.g. 0.1 µs/cm.

Increase the slope of the working signal (if too flat), e.g. 0.1 V/cm.

Now the shift on the oscilloscope for Δs = 0.1 m is approx. 20 mm giving

$$\Delta t = 0.2\ \mu s/600$$

and for the velocity of light (± 5 %)

$$c = \frac{\Delta s}{\Delta t} = \frac{0.1\ \mathrm{m} \cdot 600}{0.2 \cdot 10^{-6}\ \mathrm{s}} = 3 \times 10^8 \mathrm{m/s}$$

The factor of approx. 600 results from the ratio of the two frequencies 60 MHz and 100 kHz (see Section 3) and should be determined precisely by measuring the two frequencies if a result with an accuracy of better than ± 5 % is to be attained.

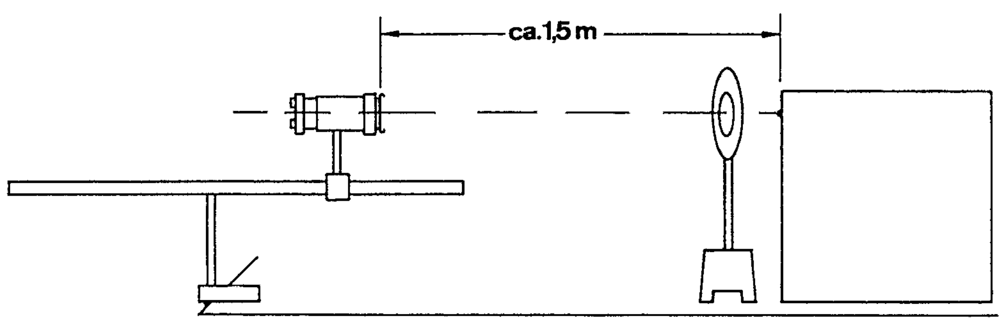


Fig. 8

5.3 Velocity of light with large differences in travel distance

e. g. $\Delta s = \lambda_M/2$ (half modulation wavelength)

For this experiment mount the transmitter e. g. into the saddle base (300 11). Set up the transmitter approx. 3 m before the receiver (for adjustment see Section 4.2.2). Select time base of oscilloscope, e. g. 0.5 µs/cm, i. e. half an oscillation (100 kHz) on the screen.

With greater distance, adjust (phase shifter ⑬) so that the phases of reference and working signal are shifted by 180° (Fig. 9a). Then place the transmitter near the receiver and displace it until the two signals are in equiphase (Fig. 9b).

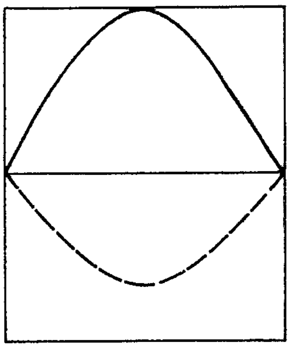


Fig. 9a

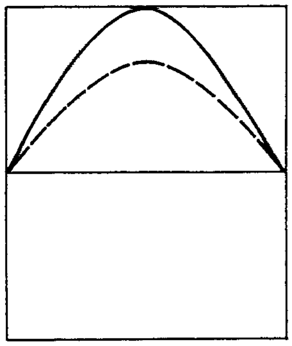


Fig. 9b

The resultant difference in travel distance is approx. 2.50 m ± 0.03 m. From this it follows:

$$c = \lambda_M \cdot f_M = 2 \times 2.5\ \text{m} \times 60 \times 10^6\ \text{Hz} = 3 \times 10^8\ \text{m/s} \pm 1\ \%$$

The error can still be slightly reduced if

$$\Delta s = \lambda_M \text{ (approx. 5 m)}$$

It cannot be reduced to any minimum (see Section 4.4).

5.4 Velocity of light in water

Fit the tube (476 35) in two saddle bases (300 11). Connect flex tubing to lower hose nozzle and let water rise slowly without bubbles (applies also to Section 5.5.3).

Place transmitter in saddle base (300 11) approx. 30 cm before the receiver. Select time base of oscilloscope of 0.5 µs/cm and amplification of working channel of 0.1 V.

Trigger oscilloscope so that the working signal passes through the zero line approx. 1 cm from the left-hand edge of the screen. Displace the transmitter exactly by Δs = 1 m and place the water-filled tube (476 35) in the newly obtained spacing.

The shift obtained on the oscilloscope will be 54 mm. It follows:

$$\Delta t = 2.7\ \mu\text{s}/600$$

For the velocity of light in water

$$c_W = \frac{\Delta s}{\Delta t} = \frac{1\ \text{m} \cdot 600}{2.7 \cdot 10^{-6}\ \text{s}} = 2.22 \times 10^8\ \text{m/s} \pm 2\ \%$$

is obtained.

Actually there are only 994 mm of water and 6 mm glass (refractive index 1.6). But this error is below 0.2 % and can be neglected.

When bringing the water-filled tube into the light beam, the amplitude of the optical signal decreases by approx. 50 %. If the amplitude reduction is greater, this may be due to the additions contained in the tap water. In that case use distilled water (applies also to Section 5.5.3).

After every experiment, empty the tube completely.

5.5 Determination of refractive index

For this experiment the spacing transmitter/receiver is maintained, only a part of this air space is filled with another medium, e. g. with the plastic body (476 34), plate glass cell (e. g. 477 03) filled with water, benzene or benzol, or tube (467 35), 1 m length, e. g. filled with water. The increase in travel time Δt is measured.

With $t_1 = \frac{d}{c}$ as travel time of the light in air or vacuum of thickness d

and $t_2 = \frac{d}{c_M}$ as travel time of the light in the medium of thickness d

it follows for the increase in travel time

$$\Delta t = d\left(\frac{1}{c_M} - \frac{1}{c}\right) = \frac{d}{c}\left(\frac{c}{c_M} - 1\right)$$

and hence for the refractive index $n = \frac{c}{c_n} = 1 + \frac{c}{d}\,\Delta t$

5.5.1 Determination of the refractive index on plastic body of thickness d = 0.05 m

Mount plastic body (476 34) in saddle base (300 11) on prism table (460 25).

Select time base of 0.1 µs/cm on oscilloscope and slightly increase the slope of the working signal (if too flat).

Place plastic body in light beam. The shift of the optical signal on the oscilloscope is approx. 5 mm ± 0.5 mm. It follows:

$$\Delta t = 0.05\ \mu\text{s}/600$$

$$n = 1 + \frac{3 \times 10^8\ \text{m/s}}{0.05\ \text{m}} \cdot \frac{0.05 \cdot 10^{-6}\ \text{s}}{600} = 1.5 \pm 3\ \%$$

5.5.2 Determination of refractive index of water, benzene or benzol

Set-up as in Section 5.5.1 but mount plate glass cell (477 03) instead of plastic body on the prism table (460 25).

The inside dimension of the cell is 0.05 m, the double wall thickness is 0.005 m, so that

$$d = 0.055\ \text{m}$$

Fill the cell with water and place it into the light beam.

The shift of the optical signal on the oscilloscope is approx. 4 mm ± 0.05 mm (with 0.1 µs/cm). If follows:

$$\Delta t = 0.04\ \mu\text{s}/600$$

$$n_w = 1.36 \pm 3\ \%$$

Fill the cell with benzene or benzol and place it into the beam of light.

> *Caution:*
>
> Benzol is poisonous. The benzol vapour concentration at the work place must be zero. This experiment must not be performed by the students.

The shift of the working signal on the oscilloscope is approx. 5.5 mm ± 0.5 mm. It follows:

$$\Delta t = 0.055\ \mu s/cm$$

$$n_B = 1.5 \pm 3\ \%$$

In this experiment, particularly in case of the water-filled cell, the influence of the glass (refractive index 1.6) can be taken into account. Then

$$n_w = 1.34 \pm 3\ \%$$

is obtained as the refractive index for water.

5.5.3 Determination of refractive index of water in tube with glass ends (476 35), d = 1 m

For handling and filling the tube see Section 5.4. Select time base of 0.1 µs/cm on oscilloscope and slightly increase the slope of the working signal (if too flat).

Place the tube between transmitter and receiver.

The shift of the optical signal on the oscilloscope is 68 mm ± 2 mm. It follows:

$$\Delta t = 0.68\ \mu s/600$$

$$n_w = 1.34 \pm 1\ \%$$

5.6 Measuring error

Distance measurement: error ± 1 mm, i. e. at distances of 1 m e. g. ± 0.1 %. The error can also be neglected for smaller distances since then larger errors in time measurement are unavoidable.

Shift of working signal on oscilloscope: error ± 1 mm, i. e. with a time base of 0.1 µs/cm the resultant error in time is approx. ± 0.01 µs/600.

Time base of oscilloscope: error mostly ± 5 %. With good calibration (see 4.3) an error of only ± 0.5 % can be achieved.

Factor of time extension: error mostly 5 %. But the factor can be determined more precisely, e. g. for short times ± 0.05 %, by measuring the two frequencies 60 MHz and approx. 100 kHz.

Time shift factor: Error 5%. The factor can be measured by measurement of the difference frequency of approx. 100 kHz (Digital counter 575 40) and, more exactly, from the modulation frequency of 60 MHz, eg. briefly ± 0,5 %

Electromagnetic cross-interference from the transmitter to the receiver: error ± 0.5 % of the fully excited working channel.

Information regarding electromagnetic compatibility (EMC)

The experiment setup for determining the velocity of light does not conform to the limit values of class A (group 2 of European standard EN55011).

This assembly can cause interference with electronic devices within the EMC-zone, i.e. within the laboratory or classroom. Outside of the laboratory, radio interference can occur up to a distance of several hundred meters. In this case, the operator may be obligated to undertake appropriate measures at his/her own cost.

Measures:

- Do not switch on the apparatus at the mains switch ⑧ until you have completely assembled the arrangement.
- Only operate the apparatus for as long as is absolutely necessary for carrying out the experiment.

This device may only be operated under the instructor's supervision and may not be operated outside of educational institutions.