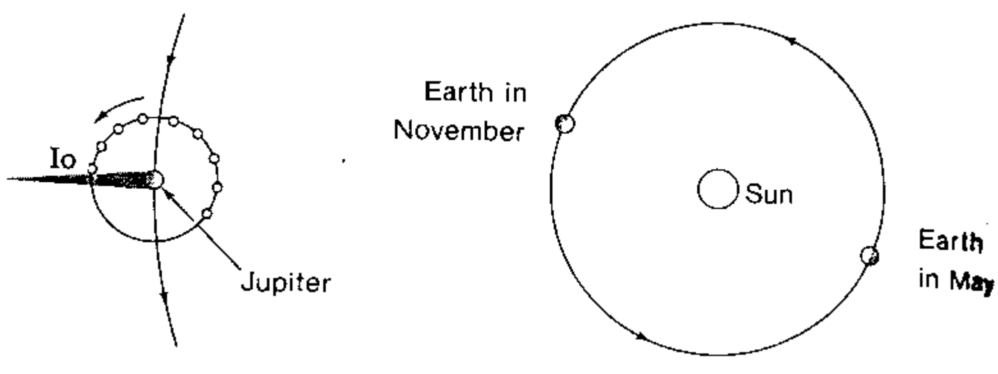
OPTICAL ENGINEERING NOTE #43: COMPARISON OF SPEED OF LIGHT KITS

The kits available from Arbor Scientific[1], CENCO[2], Metrologic[3] and PASCO[4] either use the rotating mirror technology of the nineteenth century experiments of Foucault* and Michelson, or the more contemporary method of looking for the time delay in arrival between two laser beams that started simultaneously but with one taking the long road whilst the other takes a shorter path.

In 1638 Galileo reported on experiments trying to find the speed of light by signalling with lanterns across great distances, but came to no numerical result. He had hoped to determine whether or not the speed of light was infinite, but only realized that the measurement was impossible with the instrumentation available then.

Olaf Roemer, a Danish astronomer, calculated that the speed of light was about 214,000 km/sec, using purely astronomical observations in 1676. He measured the discrepancy in time between actual and predicted eclipses of one of Jupiter's moons (which Galileo had discovered 60 years earlier,) with the Earth nearer and farther from the giant planet by the diameter of our orbit. Although only 2/3 of the speed we know nowadays, he proved that light did have a finite speed.



Römer's discovery
(Adapted from Henry Crew, *General Physics*, 3rd ed., rev., New York: Macmillan, 1916, p. 521)
Observations of the eclipse of Jupiter's satellite Io, at six-month intervals, gave the data needed to determine the speed of light across the diameter of the earth's orbit.

*foo-koe

It wasn't until the nineteenth century that devices were built expressly to measure the speed of light. The first was that of Armand Hippolyte Fizeau's* 1849 device, as illustrated below. Light from the source A passes through a gap in the toothed wheel, is collimated by a lens to travel a long distance without spreading out too wide, is focussed by a similar lens onto a mirror, which retroreflects the light back to the sending unit. If the timing is right, the returned beam can slip through the next slit in the toothed wheel, otherwise it will be blocked by a tooth. (Some returning light is reflected back to the light source by the semitransparent mirror m_1, but the rest is passed through, to the observing eyepiece or ocular at O_4.)

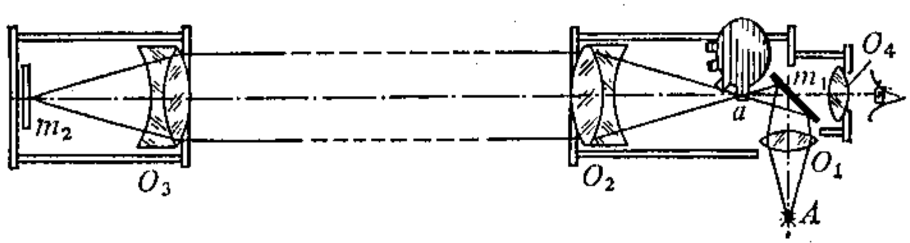


Fig. 12. The scheme of Fizeau's experiment, A is the source of light, m_1 is a semitransparent mirror, m_2 is a flat mirror, a is a toothed wheel, O_1-O_3 are objectives, and O_4 is the ocular.

Fizeau cranked up the speed of the gear until he saw the first darkening of the light in the eyepiece. This meant that light went and came back in the time it took for the toothed wheel to move one half the angular dimension of a tooth. Measuring the path length and the rate of rotation of the mechanism, he calculated the speed of light to be 314,000 km/sec, not too far off for clockwork-powered mechanisms, and much better than astronomical observations, using disances which in themselves may not have been too accurate.

Greater accuracy was afforded in 1862 by Leon Foucault, with a rotating mirror device. There was no possibility of subjective error in determining when the return beam was truly darkened; all that needed to be measured was the difference in position of the returned beam with the mirror spinning or at rest, as the **Speed of Light Apparatus** from PASCO asserts. (The following two pages.) Notice that they use a micrometer in the **Measuring Microscope** for accuracy. Foucault used sunlight for his experiment, but nowadays the experiment wouldn't be sexy without a laser.

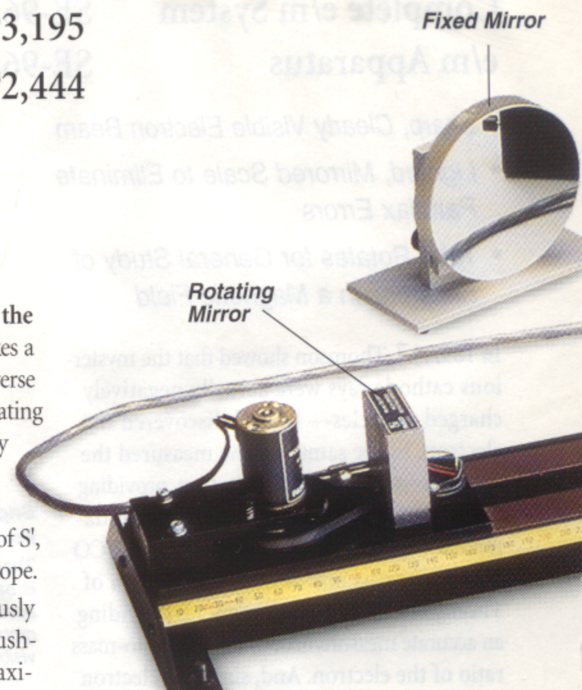
*fee-zoe

FUNDAMENTAL CONSTANTS

Speed of Light Apparatus

Complete Speed of Light Apparatus	OS-9261	$3,195
Basic Speed of Light Apparatus	OS-9262	$2,444

- *Classic Foucault Method*
- *1 - 15 Meter Path Length*
- *Tabletop or Hallway Experiment*



The speed of light in free space is an intriguing and very important fundamental constant. One of Albert Einstein's most perplexing postulates is that the speed of light is independent of the relative speeds of the light source and the observer. Furthermore, as he presented in his Special Theory of Relativity, objects moving near the speed of light follow a set of physical laws radically different not only from Newton's Laws but from the basic assumptions of human intuition. Throughout history, most of those who speculated about the speed of light supposed it to be infinite. In 1667 Galileo suggested and carried out an experiment to calculate the speed of light. Although his method failed, others were inspired to make the measurement, and in 1862 Foucault succeeded in measuring the speed of light quite accurately.

This Speed of Light Apparatus reproduces Foucault's measurement, but with some significant improvements such as a laser light source and a high-speed, servo-stabilized, rotating mirror with a digital readout of angular velocity.

How It Works

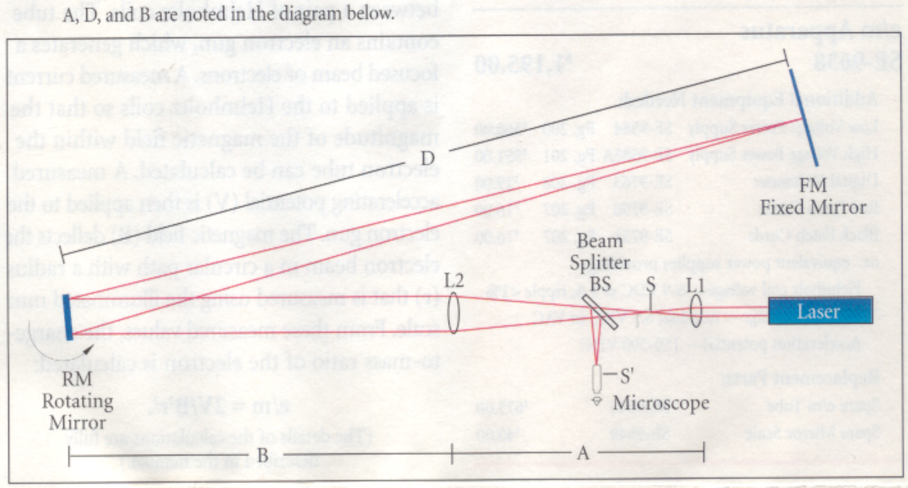
The method is basically the same as that used by Foucault in 1862.

1. **The first observation is made when the rotating mirror (RM) is not rotating**— Light from a He-Ne laser is focused to a point at S by lens L1. Lens L2 is positioned so that the image of S is reflected from the rotating mirror (RM) and focused onto the fixed mirror (FM). The fixed mirror reflects the image back onto the rotating mirror, which in turn reflects the light back through the lenses, to reform the point image at S. However, the light also passes through a beam splitter (BS), which forms a mirror image at S', where it can be observed with the microscope.
2. **The second observation is made when the rotating mirror is rotating**— Since it takes a finite amount of time for the light to traverse the distance D, between the fixed and rotating mirrors, the rotating mirror is in a slightly different position when the light returns after reflecting off the fixed mirror. This produces a displacement in the position of S', which can be measured with the microscope.

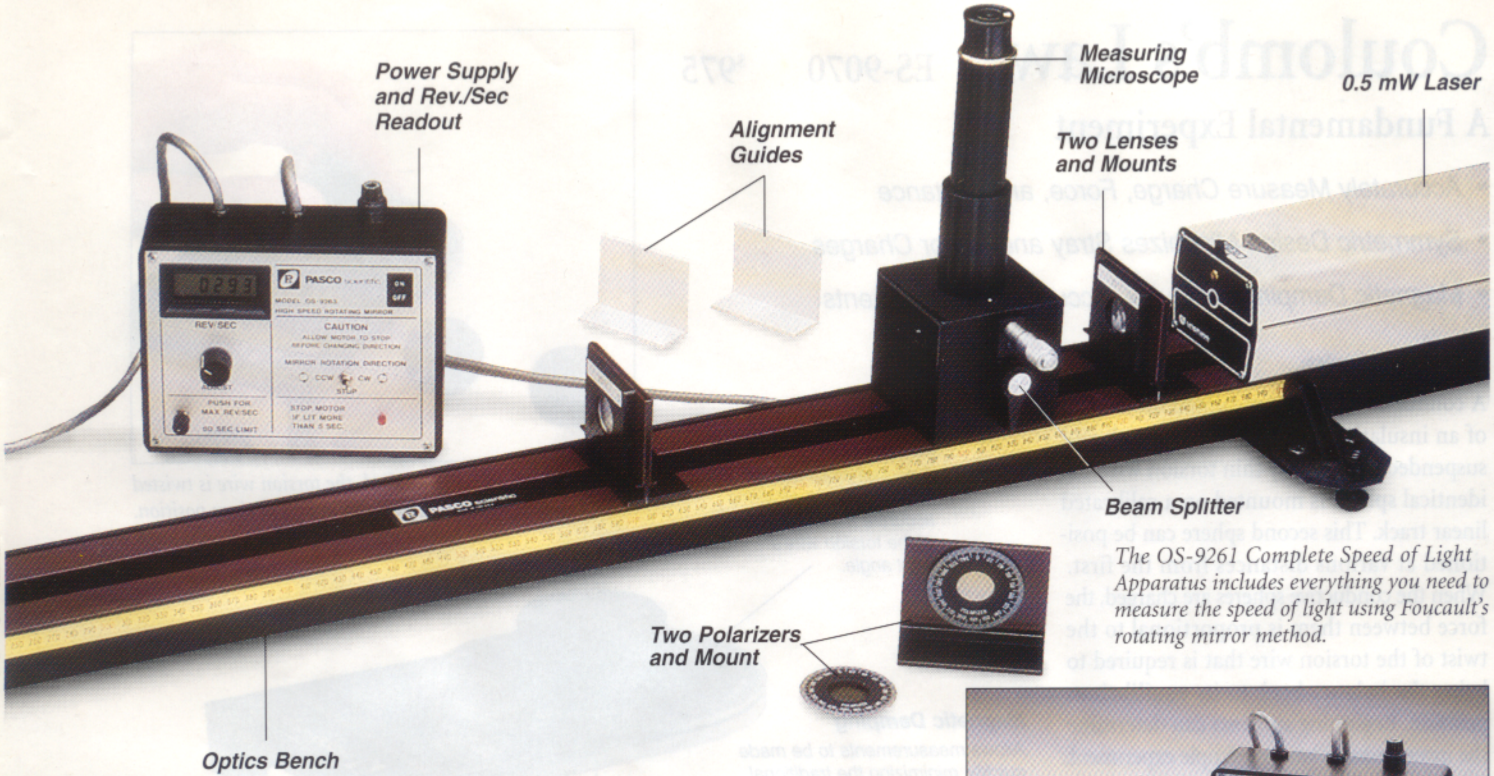
   The angular velocity can be continously varied from 100 to 1,000 rev/sec. A push-button switch brings the mirror to maximum speed at approximately 1,500 rev/sec. Since the direction of rotation is reversible, the effective speed is 3,000 rev/sec, producing a significantly large ΔS'.
3. **The displacement**— of S' between the first and second observations (ΔS') is proportional to the transit time of the light over the distance D, and to the angular velocity of the rotating mirror. With a very straight forward calculation, the speed of light (c) can be calculated:

$$c = \frac{4AD^2\omega}{(D+B)\Delta S'}$$

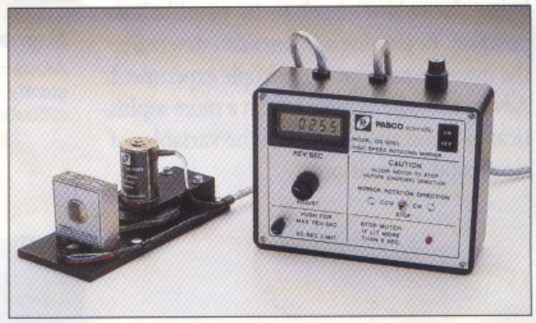
ω = Rotational speed of the rotating mirror.
A, D, and B are noted in the diagram below.



The optimum distance for performing the experiment is 10 to 15 meters between the two mirrors. Over this range, accuracy within 5% is readily obtainable. However, if space is a problem, the space between the mirrors can be reduced to as little as 1 meter and a proportional reduction in accuracy will result. Either way, your students will be measuring one of the most fundamental constants in physics.



The OS-9261 Complete Speed of Light Apparatus includes everything you need to measure the speed of light using Foucault's rotating mirror method.



The OS-9263A High Speed Rotating Mirror.

Selecting a System

The PASCO Speed of Light Apparatus is available in two systems. One is complete and ready to operate. The other requires certain PASCO optics components which you may already have.

To perform the experiment, you will need all the items included in the Complete Speed of Light Apparatus.	OS-9261 Complete System	OS-9262 Basic System
OS-9263A High Speed Rotating Mirror with built-in power supply, digital rev/sec readout, and case	√	√
Measuring microscope with beam splitter and cross-hair micrometer	√	√
X-Y alignable fixed mirror	√	√
Optics components from PASCO's Advanced Optics Systems		
- OS-9103 Optics Bench	√	
- OS-9172 Laser Alignment Bench	√	
- OS-9171 0.5 mW He-Ne Laser	√	
- OS-9133 Lens (48 mm F.L.)	√	
- OS-9135 Lens (252 mm F.L.)	√	
- OS-9109 Calibrated Polarizers (2)	√	
- OS-9107 Component Carriers (3)	√	

Note: Those with a flare for do-it-yourself experiments may prefer the OS-9263A High Speed Rotating Mirror, which includes just the high speed rotating mirror with a built-in power supply and a digital revolution/sec readout. With this system, all other components must be supplied by the user.

TO ORDER:

Complete Speed of Light Apparatus
OS-9261 — $3,195.00

Basic Speed of Light Apparatus
OS-9262 — $2,444.00

Additional Equipment Needed:

Optics Bench	OS-9103	Pg. 146	$133.00
Laser Alignment Bench	OS-9172	Pg. 146	$89.00
0.5 m W He-Ne Laser	OS-9171	Pg. 146	$415.00
Lens, 48 mm F.L.	OS-9133	Pg. 147	$22.00
Lens, 252 mm F.L.	OS-9135	Pg. 147	$22.00
Calibrated Polarizers (2 needed)	OS-9109	Pg. 147	$17.00
Component Carriers (2 needed)	OS-9107	Pg. 147	$18.00

High Speed Rotating Mirror
OS-9263A — $1,292.00

Additional Equipment Needed:
See Note under Selecting a System chart.

The heart of this experiment is the rotating mirror. Notice in the woodcut that Foucault used a steam turbine to rotate his mirror; Pasco utilizes a permanent magnet DC motor, well-controlled. CENCO's Speed of Light Lab uses a Bosch tool motor to reflect white light instead of a laser beam, which doesn't matter as far as the measurement is concerned.

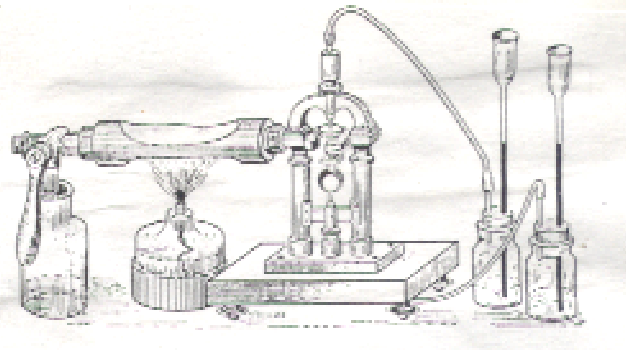


Fig. 15. A general view of Foucault's apparatus.

Speed of Light Lab

This convincing apparatus has students believing that light really is fast, and that they can measure its speed for themselves. It makes use of the classic Foucault-Michelson method for measuring the velocity of light. The quality components produce results accurate to within 5%. You can measure a time interval of 10^{-7}s without electronic assistance.

The concept behind this method is simple. Light bounces off the rotating mirror and travels to a distant mirror where it is reflected back. Because the mirror moves a little, the beam returns slightly to one side of its original path. The sophistication lies in the optical method of setting up the distance between the mirrors (about 15m) accurately, in producing an image good enough to detect a slight shift over this distance, and in determining the speed of the motor.

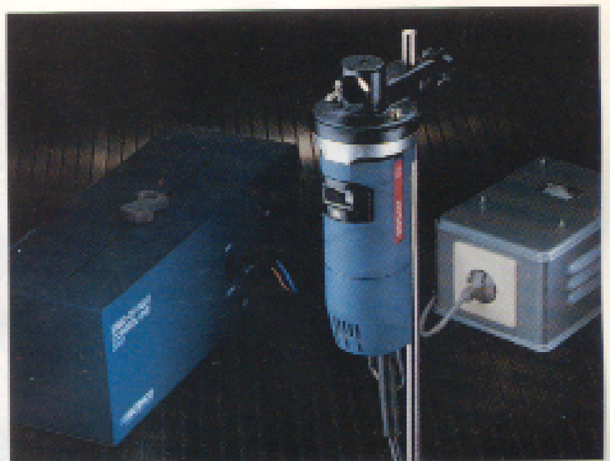
The rotary mirror that makes measurement of the shift possible is made of optically ground glass. It is front-silvered and coated with a thin layer of evaporated quartz for protection. The mirror is mounted on top of a sturdy casing, 185mm long and 55mm in diameter. This casing holds the motor that rotates the mirror at speeds up to 28,000 rpm.

The speed of the motor can be set to the right level with a 440 Hz tuning fork that you supply; when the acoustic beats disappear, the motor speed is 440 Hz ±1 Hz. This apparatus comes with its own three-wire grounded cord, and is used on 110 VAC with the rheostat and transformer we supply.

31911U **$2,330.00**

Optional Accessories:

84562-08U	Concert Pitch Tuning Fork, 440 Hz	**$11.35**
85264U	Universal Light Source	**$252.45**
46014U	Precision Adjustable Rotatable Vertical Slit	**$550.00**
85645-02U	Double Convex Lens (f = 10cm)	**$3.95**
30118U	Engraved Glass Rule	**$77.50**
87050U	Plate and Grating Holder	**$60.00**



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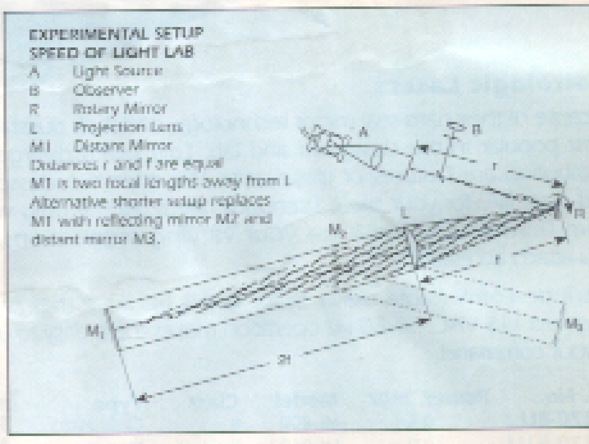
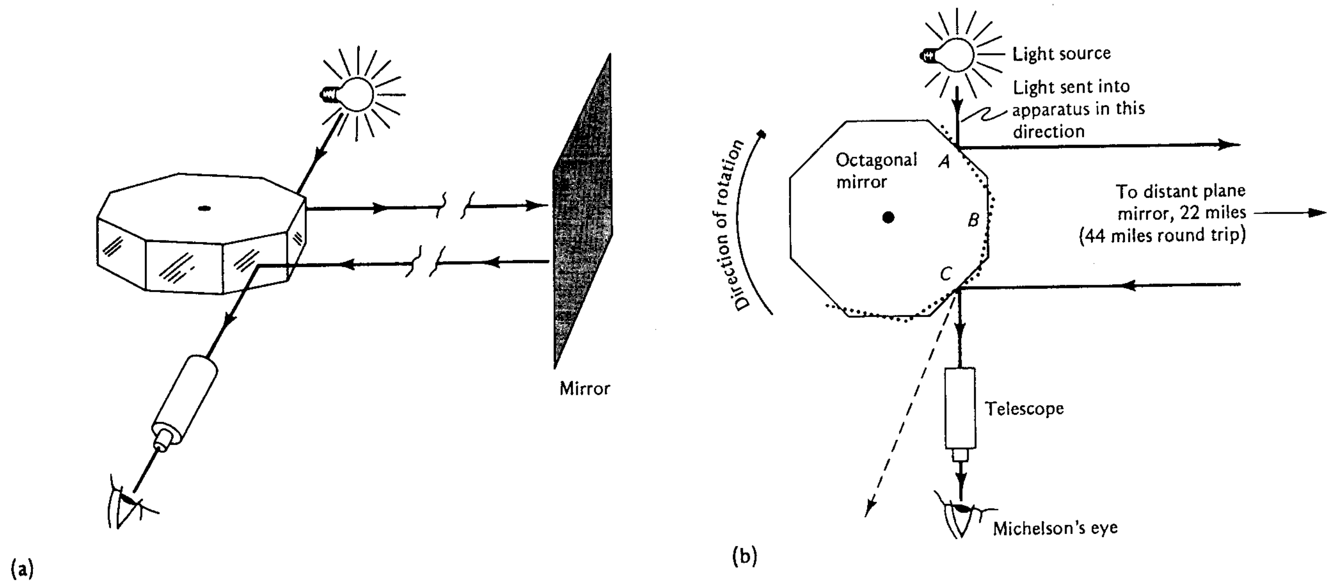


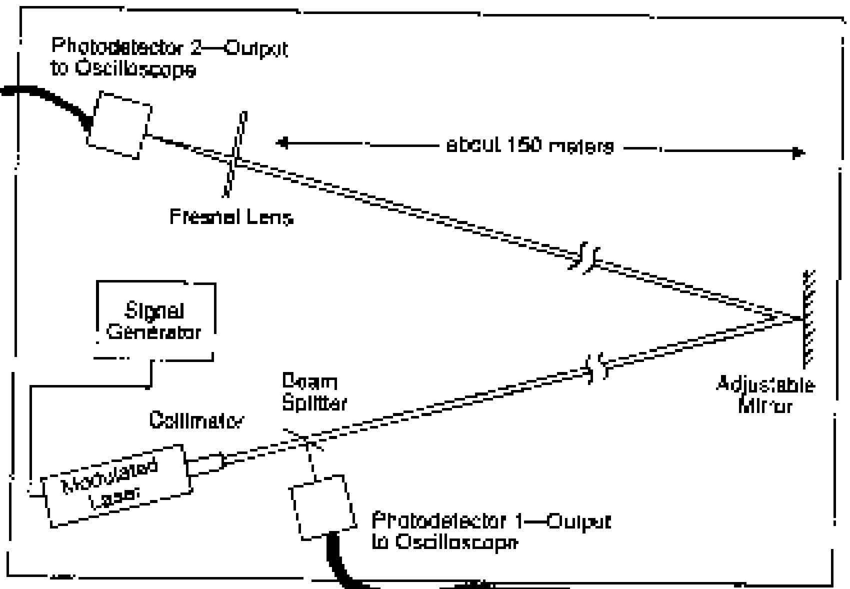
CENTRAL SCIENTIFIC COMPANY

The Master of Light, Albert Michelson, also used a rotating mirror to find the speed of light in 1879. With his usual persnicketiness in measurement, he found that light was travellng at 299,910 +- 50 km/sec, which is within 3% of what we know it to be nowadays.



When the octagonal mirror is at rest, the telescope is aligned to view the light source, although in the same room, via another mirror placed 22 miles away. Once the mirror is spinning, no light is seem through the telescope, since the light returning from the distant mirror hits a facet of the octagon and upon reflection will probably miss the entrance pupil of the telescope, unless the rate of rotation is such that the return beam impinges upon a face of the spinning mirror at just the right time so that it is reflected into the telescope's objective. If the rate of revolution is known along with the distance travelled, the speed of light can be determined.

The other, more contemporary **Speed of Light Kits** use no moving mechanical parts. The trick is to use a modulated light source. An electronic circuit varies the output power of a laser or LED at a fixed high frequency, like around 1 MHz for the Metrologic laser or 60MHz for the LED in the CENCO set. (By going with a higher frequency, the beam path length can be shorter.) An oscilloscope trace of what a photocell sees in the path of one of these beams would show the sine-wave shape of the modulation of the intensity of the laser.



Apparatus arrangement for measuring the speed of light using a modulated laser and the Metrologic Speed of Light/Laser Video Kit 45-720.

The optical layout splits the modulated beam, into long and short paths which fall onto their own photodetectors. The detectors are hooked into the A and B channels of a dual-trace oscilloscope. When the modulated waves are traced on the 'scope's screen, the short path's shape is to the left of the long's, as it arrived earlier. Measuring the distance between them in the horizontal or Time Base axis will give the length of time of flight in the longer path. See the trace on the 'scope in the CENCO Velocity of Light from Signal Phase Shift description. Dividing this time into the longer path's length gives the speed of light.

Velocity of Light from Signal Phase Shift

For accurate results when determining the velocity of light, this apparatus uses sophisticated electronic techniques. The module provides reliability because it eliminates many of the sources of error that arise from visual readings of an image shift.

The apparatus uses a precisely modulated LED as a light source. It produces light at a wavelength of 670nm, and is modulated at 60MHz. The light travels to a special receptor-demodulator unit that prepares the signal for readout on an oscilloscope. It covers an optical path of about 1m, whose exact length you predetermine. Two lenses ensure that most of the light falls on the receptor. The signal is electronically compared with a reference signal generated in the receiver and synchronized precisely with the light source. The phase shift between the two signals is measured and displayed on the oscilloscope.

Special consideration is given in the design of this module, so accurate determinations of the phase shift can be made from a standard dual-trace oscilloscope. Both the incoming and the receptor signals are heterodyned with a 59.9MHz signal. Two 100kHz signals are produced, which can be read on a standard oscilloscope, while preserving the phase information. A built-in phase shifter lets the reference signal be synchronized with the incoming signal at this 100kHz level. Velocity of light determinations are now made by moving the receptor unit through a predetermined distance and measuring the resulting phase shift. The transmitter also has a BNC output that carries a signal of exactly 1/10 the modulating frequency. You can use this signal with a frequency counter to check the precise frequency being generated.

This velocity of light set comes with a transmitter, mounted in an optical housing, a receptor and heterodyning unit, a mounted plano-convex lens; cables and support bases, and a complete instruction sheet. Also supplied is a 50mm thick acrylic block. The instructions describe the use of the block and other optically clear substances in index of refraction experiments. You'll need to supply a dual-channel oscilloscope with a sweep of at least 2 ns/cm, and you may wish to add a frequency counter with a 10 MHz range. Using the oscilloscope, you can determine the speed of light to better than 1% with a separation of just 2.5m. This apparatus is easy to arrange in any lab, for highly reliable results.

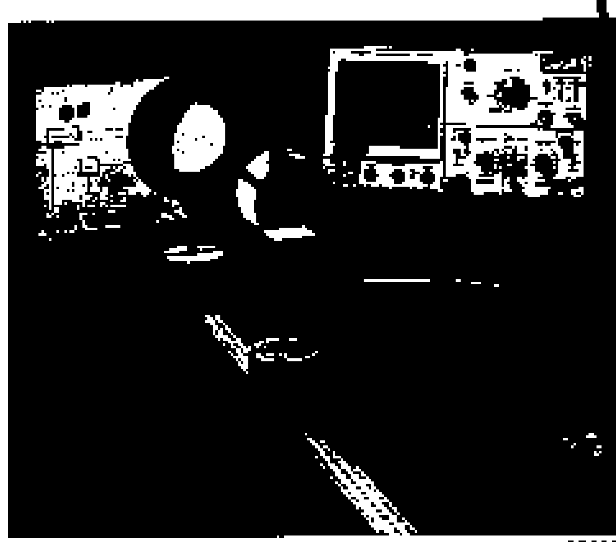
32012U **$3,650.00**

You Need to Supply:

An oscilloscope, such as our 32046? Dual-Trace 20MHz Oscilloscope

Optional Accessory:

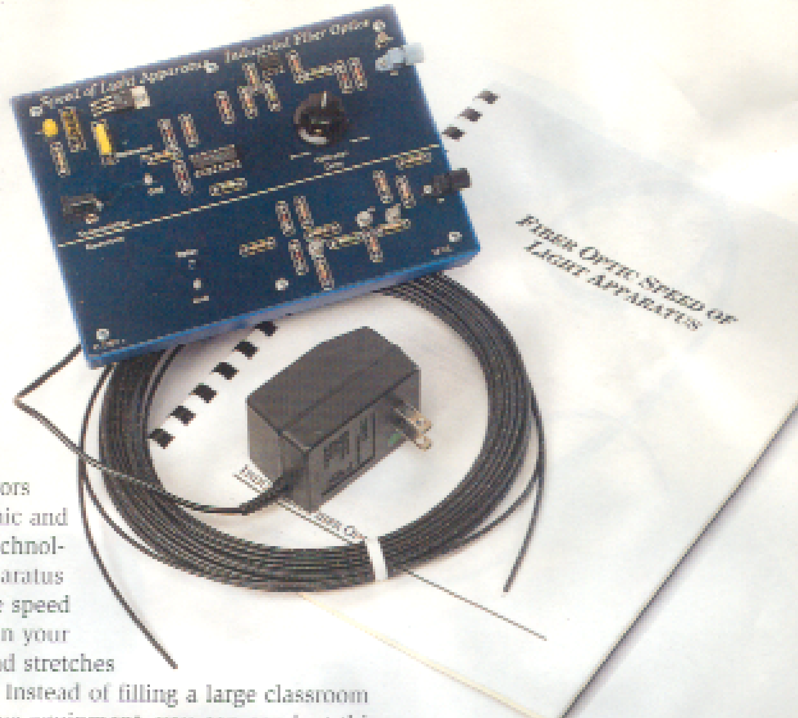
31577U Portable Frequency Counter $197.00



32012

ONE OF MANY!

Some of the kits rely on large path length differences in air, which may not be practical in some classroom situations. Using a coiled fiber optic can make the demonstration more compact, although what is found is the speed of light as measured in the glass of the fiber. Note that LED's are used instead of lasers in both the Arbor Scientific and CENCO units.

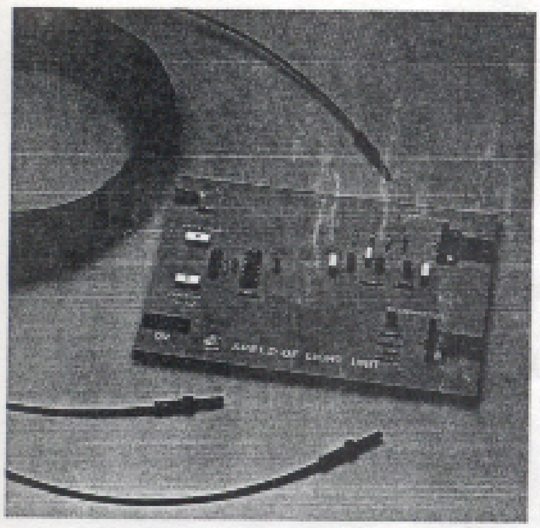


Speed of Light Apparatus

By replacing traditional rotating mirrors with electronic and fiber optic technology, this apparatus measures the speed of light within your classroom and stretches your budget. Instead of filling a large classroom with expensive equipment, you can conduct this measurement with the 20 meter fiber optics coil and apparatus sitting on your desk. Pulse signals generated by a protected, slim circuit board are monitored directly on one channel of a dual-track oscilloscope. The light then travels the length of the cable, where it is attached to a special receiver. The second channel of the oscilloscope records the results from this receiver and displays the two signals with their phase difference. You then calculate the speed of light from the length of the cable and the phase difference. Please note that users must supply the dual-track oscilloscope.

Included in the guidebook which accompanies the apparatus are instructions, as well as a history of the study of the speed of light, detailing past investigations which were possible only when using huge rooms, mirrors, lasers, and other costly, difficult equipment.

P2-5500 $175



32007

Speed of Light Apparatus

Electronics and fiber optics take the place of rotating mirrors, giving you an economic and simple to use apparatus. 1MHz pulses are generated and applied simultaneously to one channel of an oscilloscope and an electro-optic transmitter. The light pulses produced travel down a 20m length of fiber optic cable, and are registered by a special receiver. The second channel of the oscilloscope records the results from this receiver, displaying the two signals with the phase delay produced by the 20m light path.

The pulsed signals are generated by a slim circuit board, 15 x 11cm. Two fiber optics cables are included: a 15cm reference cable, and a 20m test cable. The fibers end in "sweet spot" connectors for efficient coupling with the circuit board. All circuit board inputs and outputs are on 2mm jacks. You'll need to supply a 9V power supply, and a dual-trace 20MHz oscilloscope. Complete instructions are provided for this apparatus.

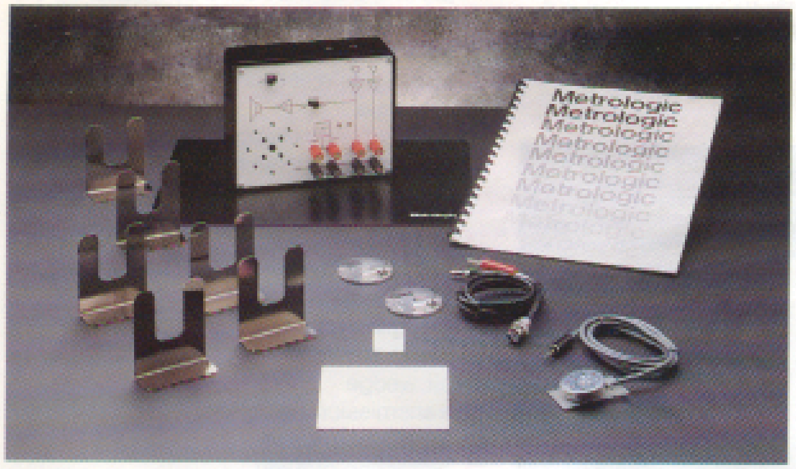
32007-01U $250.00

You Need to Supply:

An oscilloscope, such as our 32046C 20MHz Dual-Trace Oscilloscope

31383U	12 VAC/DC Power Supply	**$295.00**
32954-1U	Red 60cm Test Lead, 2mm Banana Plug	**$8.20**
32954-2U	Black 60cm Test Lead, 2mm Banana Plug	**$8.20**
32955-1U	Banana Plug Reducer, 4mm to 2mm	**$4.70**
32955-2U	Banana Plug Enlarger, 2mm to 4mm	**$4.70**

Speed of Light Kit/Laser Video Kit



Speed of Light/ Laser Video Kit
Order # 45-720
Shipping weight: 3 lbs.

Speed of Light Instruction Booklet
Order # 45-721
Shipping weight: 1 lb.

With its electronic control box, photodetectors and optical accessories, the Speed of Light Lab/Laser Video Kit:

- Receives light from a distant audio-modulated laser; detects, amplifies and reproduces voice communications or music
- Receives light from a distant video-modulated laser; detects, amplifies and furnishes an output for a video monitor to reproduce pictures
- Produces a 1 MHz signal to modulate a laser, then splits, reflects, focuses, detects and amplifies the waveforms to produce outputs for a dual channel oscilloscope. (This makes it possible for students to measure the speed of light, with an accuracy of a few percent, in the space of an average classroom over a 20 meter path.)

The Speed of Light/Laser Video Kit contains:

- high impedance microphone
- beam splitter
- two converging lenses
- front surface mirror
- six magnetic optics mounts
- large steel plate to hold optics mounts
- front surface mirror
- electronic control box containing: 1 MHz oscillator, dual channel photodetector amplifier, loud speaker, and labeled input and output terminals
- one 9-volt battery
- Speed of Light instruction booklet

Note: Not included but required for operation are a modulated laser, video camera and monitor, and a dual channel oscilloscope.

In the early part of 1994, this product will be replaced by an improved version. The new unit will enhance speed of light measurements, provide better audio transmissions, and transmit excellent color video signals.

8 CALL TOLL-FREE: 1-800-436-3876 • FAX: 609-228-6673

If you have a modulable* light source, you can then encode sound or even video onto the beam of light. This dual-purpose makes the most sense to penny-pinching administrators when ordering.

REFERENCES

Books most helpful in the preparation of this article:

The Master of Light; a Biography of Albert A. Michelson, Dorothy Michelson Livingston, Charles Scribner's Sons, New York, 1973, pp. 45-66.

The Greatest Speed, S. R. Filonovich, Mir Publishers, Moscow, 1986.

ENDNOTES

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*Able to be modulated.

ONE OF MANY!

1. Arbor Scientific, P.O. Box 2750, Ann Arbor, MI 48106-2750, 800-367-6695.

2. CENtral Scientific COmpany, 3300 CENCO Parkway, Franklin Park, IL 60131, 800-262-3626, http://www.cenconet.com.

3. Metrologic, P.O.Box 307, Bellmawr, NJ 08099-0307, 800-436-3876.

4. PASCO scientific, P.O. Box 619011, 10101 Foothills Blvd., Roseville, CA 95678-9011, 916-786-3800, sales@pasco.com