[3] Kirk-Othmer, *Encyclopedia of Chemical Technology* (Interscience, New York, 1965), Vol. 8, 2nd ed., pp. 891.

[4] In our experiment as we have determined the resonant frequency to a better accuracy than the area of the coil "A," expression (8) is used in preference to expression (3). Also the values of K and other correction terms due to the finite radius of the wire and the pitch of the winding (see Ref. 5, pp. 429–432) can be avoided for the determination of μ_r as described in this paper.

[5] F. Langford-Smith, *Radio Designer's Handbook* (Iliffe Book Ltd., London, 1967), 4th ed., pp. 430.

Measurement of the Speed of Light

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Measurement of the speed of light by the rotating mirror method of Foucault using a laser source and photodiode detector is described. With a path length of 38 m and rotation rates up to 500 Hz, the result $c = 3.00 \pm 0.02 \times 10^8$ m/sec is obtained.

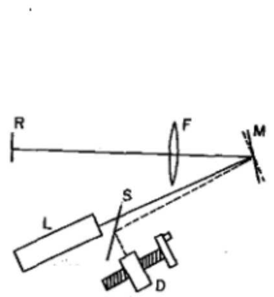

Fig. 1. Arrangement of components in the rotating mirror method of Foucault. L, laser source; M, rotating mirror; R, plane reflector; F, lens; focal length 4.75 m; S, partially silvered mirror; D, moveable photodiode detector.

The measurement of the speed of light by the rotating mirror method of Foucault is at once beautiful in its simplicity, significant in its content, and impressive in its outcome. With a light source and detector, three mirrors, and a lens students can, in effect, measure transit times for light of 10^{-7} sec over a path within a classroom and, with the simple equipment we will describe, to a precision of better than 1%.

The arrangement of these components, identical to the original arrangement of Foucault, is shown in Fig. 1. In 1850 Foucault obtained the result $c = 298\,000 \pm 500$ km/sec. He and others, including Michelson, subsequently refined the technique, principally through the introduction of longer paths. Michelson's first result, given in 1879 was $c = 299\,910 \pm 50$ km/sec, his last from the measurements from Mt. Wilson in 1926 was $299\,798 \pm 4$ km/sec.[1]

Light from the source L is reflected from the rotating mirror M so that the beam is swept through a large arc. Within that arc it strikes normally a plane reflector R, returning from it to the mirror M. Because M has rotated through an angle θ during the light's transit of MRM the beam returns to the partially reflecting mirror S along a path deviating 2θ from the incident path. At S it is reflected to the detector D which is moveable perpendicular to the reflected beam. The lens F having a focal length one-fourth the distance between L and R is placed midway between them producing a sharp image of the source at R and at D. The procedure is to set the rotational frequency f of the mirror to various values and for each to locate the position p of the return beam. (In his original experiment Foucault used $f=800$ Hz and $MR=4m$ producing a beam displacement $\delta p=0.7$ mm.) The speed of light c is computed from the measured quantities using

$$p=p_0+8\pi(MR)(MSD)f/c. \quad (1)$$

For the source L we use a Spectra–Physics Model 130 He–Ne laser with nominal output power of 1 mW. The mirror M is square, 1 cm on a side. It is Epoxy glued into a slot milled in the top of an aluminum rotor of diameter 12.5 mm. Centering and alignment is accomplished while rotating the assembly in a lathe as the Epoxy sets. The rotor is mounted on the shaft of a small high-speed drill motor[2] and covered by a guard with a small opening for passage of the laser beam. The motor is in turn mounted on a sturdy base and powered through an autotransformer for speed control. The reflector R is held by rubber bands against three leveling screws for adjustment to normal incidence in the fashion of the PSSC Michelson inferometer, with the assembly mounted on a wall.

The detector is a Hewlett–Packard PIN photodiode, type 5082-4220. It is incorporated in a circuit recommended by the manufacturer,[3] as shown in Fig. 2. With no special effort at miniaturization the diode and amplifier are housed in a cylindrical brass can of diameter 3.8 cm and length 12 cm, making the detector simple to hold and translate. It is battery powered. The detector output pulses, at the frequency f, are viewed with an oscilloscope. The pulse amplitudes at

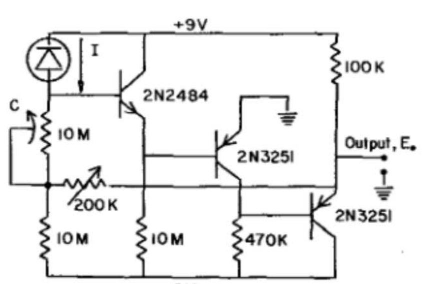

FIG. 2. Photodiode-amplifier schematic diagram. $Z_0=30\ \Omega$, $\Delta E_0/\Delta I=10^7\ \Omega$, $T_r=19\ \mu$sec, $C\approx 0.5$ pf to prevent overshoot.

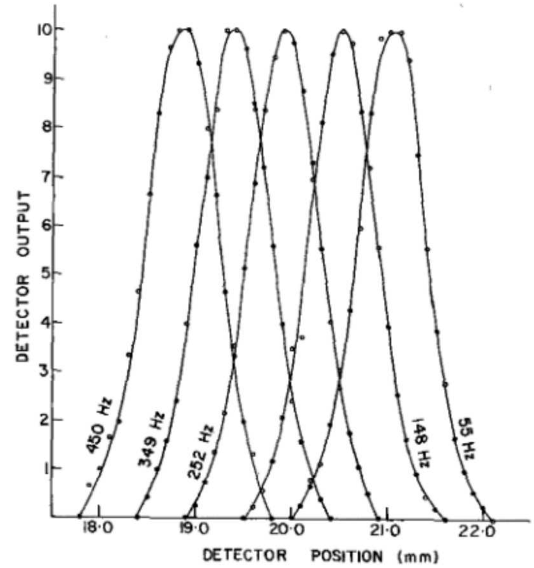

FIG. 3. The relative detector output versus position for various rotational frequencies of mirror M. The paths are $MR=1429.9$ and $MSD=464.5$ cm.

the center of the reflected beam range from 2.2 V at low f down to 60 mV at $f=500$ Hz. (The amplifier rise time is nominally 19 μsec.) This method of detection[4] thus yields both the position p and the frequency f.

Some results of measurements with this apparatus are shown in Fig. 3 in which are plotted the relative amplitudes of output pulses versus the position of the detector for the five frequencies noted. The measured width of the return beam is noteworthy, being 0.8 mm FWHM roughly 38 m from the source. The detector photosurface has a width of 0.5 mm, contributing somewhat to this measured width. With these data the center of the return beam may be located with a precision of ± 0.01 mm. The path lengths may be surveyed to ± 1 cm with ease. We have observed fluctuation in the rotation rate of ± 2 Hz during the measurements but the net effect of this fluctuation tends to zero. Regulation of the line voltage should reduce it.

The final results are shown in Table I. Fitting a curve $p=af+p_0$ to these results by the method of least squares yields the estimators $a=-5.57\times 10^{-3}$ mm/Hz and $p_0=21.34$ mm. The values of p computed with these estimators at the frequencies

TABLE I. Center of the reflected beam.

f (Hz)	Measured p (mm)	Best fit p (mm)
55	21.04	21.03
148	20.52	20.52
252	19.92	19.94
349	19.40	19.40
450	18.84	18.83

tabulated are shown for comparison. Using this value of a with the measurements $MR=1429.9$ cm and $MSD=464.5$ cm yields from Eq. (1) $c=3.00\pm0.02\times10^8$ m/sec, to be compared with the presently accepted value of $2.9979250(10)\times10^8$ m/sec.

Except for the laser, frequency measuring equipment, and oscilloscope, the total cost of the apparatus is less than $100. For frequency measurements we used an audio oscillator to sweep the oscilloscope in synchronism with the pulses and counted its frequency. If such equipment is not on hand, the oscilloscope may be swept by the line voltage and f set to multiples of that with no loss of precision. Almost any oscilloscope will do since the signal has amplitude greater than 60 mV and frequency less than 500 Hz. The oscilloscope presentation allows several students to view the results simultaneously. Compared to detection with the eye, the photodiode offers a significant improvement in the precision with which the return beam may be located. The pulse nature of the results helps clarify the phenomenon.

Recently, Edmonds and Smith[5] have described a modernized version of the Galileo time-of-flight measurement, using a laser, photodiode, and oscilloscope. Their technique is to register the departure of a light pulse using one detector and its return following reflection with a second, measuring the clapsed time between them. While the students may grasp the simpler principle of this measurement more easily, in practice it may be somewhat more difficult. A path of 200 m, roughly five times ours overall, is required to produce an elapsed time of 0.64 ± 0.01 μsec. A fast oscilloscope is required for the timing with dual trace to present the two events. Their final value was $c=2.96\pm0.05\times10^8$ m/sec.

ACKNOWLEDGMENTS

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[1] These geodimeter measurements are described in Bernard Jaffee, *Michelson and the Speed of Light* (Doubleday, Garden City, N. Y., 1960). A review of all methods and results is given in E. Bergstrand, Handbuch Physik **24,** 1 (1956).

[2] Dremel Moto-Tool Model 280. Available from Newark Electronics, 500 N. Pulaski Rd., Chicago, Ill. 60624. The motor is available with a clamping ring and ball-joint mounting which are convenient in aligning the apparatus.

[3] Application Note 915 (Hewlett–Packard Associates, Palo Alto, Calif. 1967).

[4] The method is identical to that reported by L. Thomas Dillman, Amer. J. Phys. **32,** 567 (1964).

[5] D. S. Edmonds, Jr. and R. V. Smith, Amer. J. Phys. **39,** 1145 (1971).