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MEASUREMENT OF THE VELOCITY OF LIGHT IN A PARTIAL VACUUM

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ABSTRACT

The observations were made by the rotating-mirror method, the light passing through a steel tube 1 mile long, evacuated to pressures which ranged from 0.5 to 5.5 mm mercury. By multiple reflections the path length was increased to 8 or 10 miles.

The distance was obtained by reference to a carefully measured base line adjoining the tube.

The time was measured stroboscopically through successive steps by use of a tuning fork synchronized with the rotating mirror, a free swinging pendulum, a chronometer, and wireless signals from Arlington.

There were made 2885.5 determinations of the velocity, the simple mean value of which is 299,774 km/sec., with an average deviation of 11 km/sec. from the mean.

INTRODUCTION

The following is a report on the measurements of the velocity of light made at the Irvine Ranch near Santa Ana, California, during the period September, 1929, to March, 1933. The undertaking was proposed and planned by A. A. Michelson, professor of physics at the University of Chicago and research associate of the Carnegie Institution. Professor Michelson also obtained the funds for the project and lived to see the apparatus installed but was unable to take part in the measurements, which were carried out by F. G. Pease, of the Mount Wilson Observatory, and F. Pearson, of the University of Chicago.

It will be recalled that a series of measurements of the velocity of light had been made between Mount Wilson and Mount San Antonio in 1924–1926 which gave a value of 299,796 km/sec.[2] Since the internal agreement of these measures was good, some explanation is desirable as to why it was thought necessary to repeat the experiment at the Irvine Ranch. The measurements involve two distinct

[1] Dr. Michelson died on May 9, 1931, when 36 of the 54 series of 1931 observations had been completed.

[2] *Mt. W. Contr.*, No. 329; *Ap. J.*, 65, 1, 1927.

elements: first, the time; and, second, the distance. It was estimated that with a rated tuning fork and stroboscopic methods the time of rotation of the mirror could be measured to one part in a million. The time element could therefore be determined with sufficient accuracy.

In the 1924–1926 experiments the determination of the distance required the measurement of a long base line and an extended triangulation from this base into the mountains. Since the Observatory was not prepared to carry out this part of the work, the United States Coast and Geodetic Survey kindly consented to undertake it. Although the splendid work of the Survey in the resulting investigation[3] had never been excelled, it was felt that the direct measurement of a short base line, without subsequent triangulation, might yield an even higher order of accuracy. Moreover, there was the fact that the results for the velocity of light depend upon the refractive index of the air between the stations, about which little is known except that the total effect is small. The use of a vacuum tube a mile long would eliminate this factor and have the added advantage of giving a small, well-defined image, unaffected by atmospheric disturbances. By allowing the beam of light to traverse the tube eight or ten times, the length of path would be such that the speed of the rotating mirror need not be excessive.

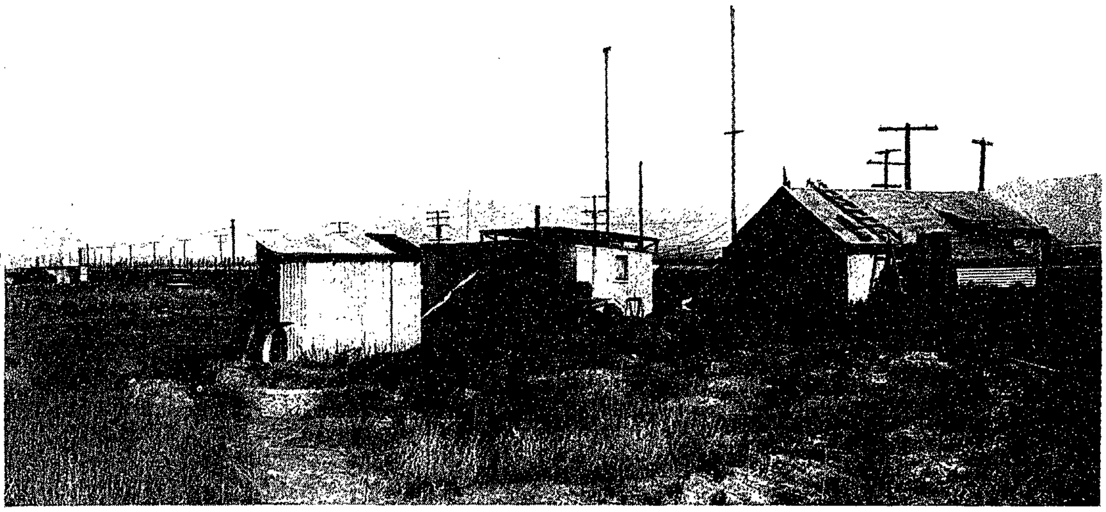
Funds for repeating the investigation with these improvements were generously supplied to the University of Chicago and the Mount Wilson Observatory by the Rockefeller Foundation and the Carnegie Corporation. Through the courtesy of Mr. James Irvine, Jr., a level, unobstructed site on the Irvine Ranch near the city of Santa Ana, California, was selected for the location of the vacuum tube. Preliminary experiments late in 1929, on a tube 1100 feet long, gave results which were so promising that the construction of the mile-long tube was begun in the winter of 1929–1930 (Pl. VI*a*).

The United States Coast and Geodetic Survey was again called upon for three successive years to determine the length of the new base line, this time a simple distance between two points about a mile apart. The mean result obtained in these measurements by

[3] A detailed account by William Bowie is given in the *U.S.C. and G.S. Report of Geodetic Observations*, 1923.

PLATE VI

a



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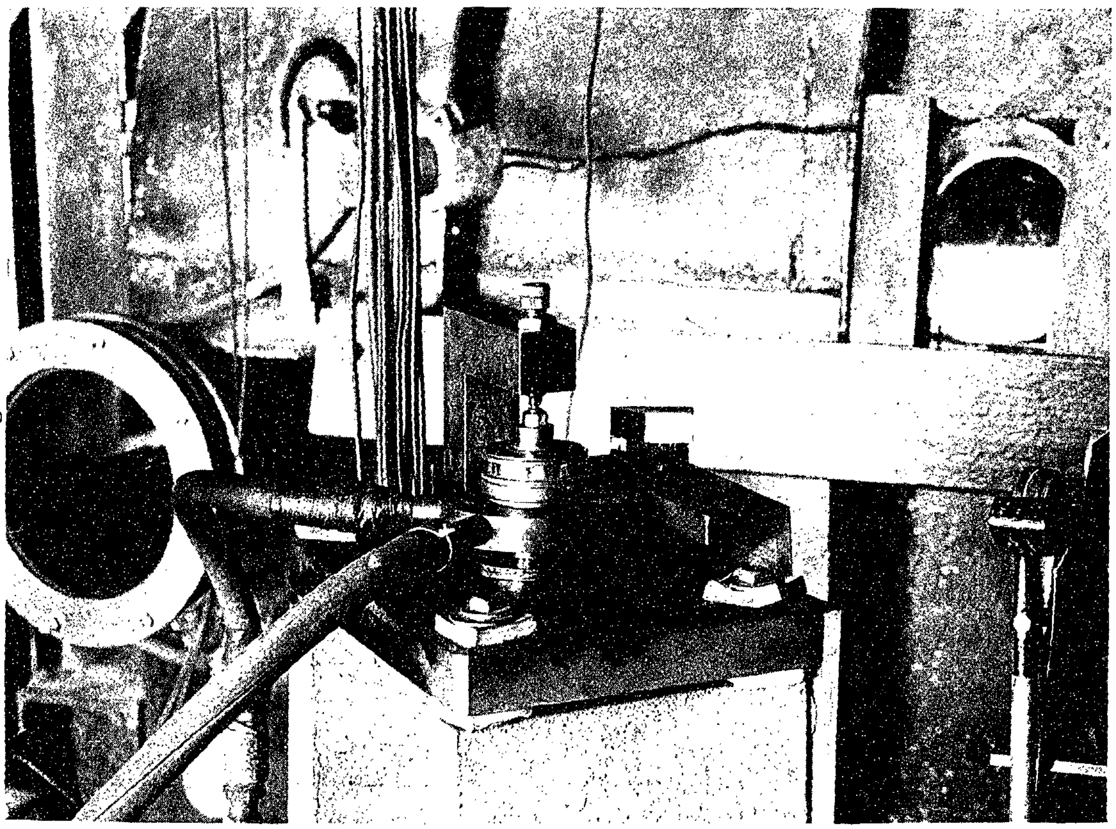


a) Vacuum Pipe Line and Observing Room
b) The Rotating Mirror

Commander Garner and Lieutenant Latham, as furnished by the Coast Survey, is 1594.2658 m.

The simple mean of all the readings for the velocity of light is 299,774 km/sec. *in vacuo*. Since the values fluctuate somewhat with the time, this mean may differ slightly from what would be obtained if observations were made continuously over an extended period. Series of measures 1–13 and 26–54, made from February 20 to July 14, 1931, gave 299,775 km/sec. Series 14–25, made from March 25 to April 3, 1931, gave 299,746 km/sec. The fact that these mean results differed from each other and from the value 299,796 km/sec. obtained on Mount Wilson necessitated additional readings.

Further readings made from March 3 to August 4, 1932, gave a mean value of 299,775 km/sec. If, however, the readings be divided into two groups with an equal number of individual determinations of the velocity, series 55–110 give a value of 299,780 km/sec., while series 111–158 give 299,771 km/sec.

Readings were resumed in December, 1932, giving a mean high value of 299,785 km/sec., which dropped to a mean of 299,765 km/sec. on January 15 and rose again to the earlier value on February 28. The mean velocity for the 75 series was 299,775 km/sec.

Attempts to explain these variations in velocity as a result of instrumental effects have not thus far been successful.

DESCRIPTION OF APPARATUS

Optical layout.—A diagram of the optical arrangement of the apparatus is shown in Figure 1. Light from an arc lamp *A* was imaged on the slit *C* by the condensing lens *B*. For the first 46 series of the 1931 observations it passed above the right-angle prism *I* to the upper half of the rotating mirror, *D*, thence through the plane-parallel glass window *L* into the tube to the diagonal flat *E* and the concave mirror *F*. It next passed above the flat mirror *H* and then, by means of repeated reflections at the flat mirrors *G* and *H* until the desired distance had been traversed, formed on the surface of *G* or *H* a magnified conjugate image of the slit *C*. The beam then retraced its path directly below the incoming path and emerged from the tube, striking the lower half of the rotating mirror *D;* it then passed through the reflecting prism *I* onto the crosswires *J* and was observed in the eyepiece *K*.

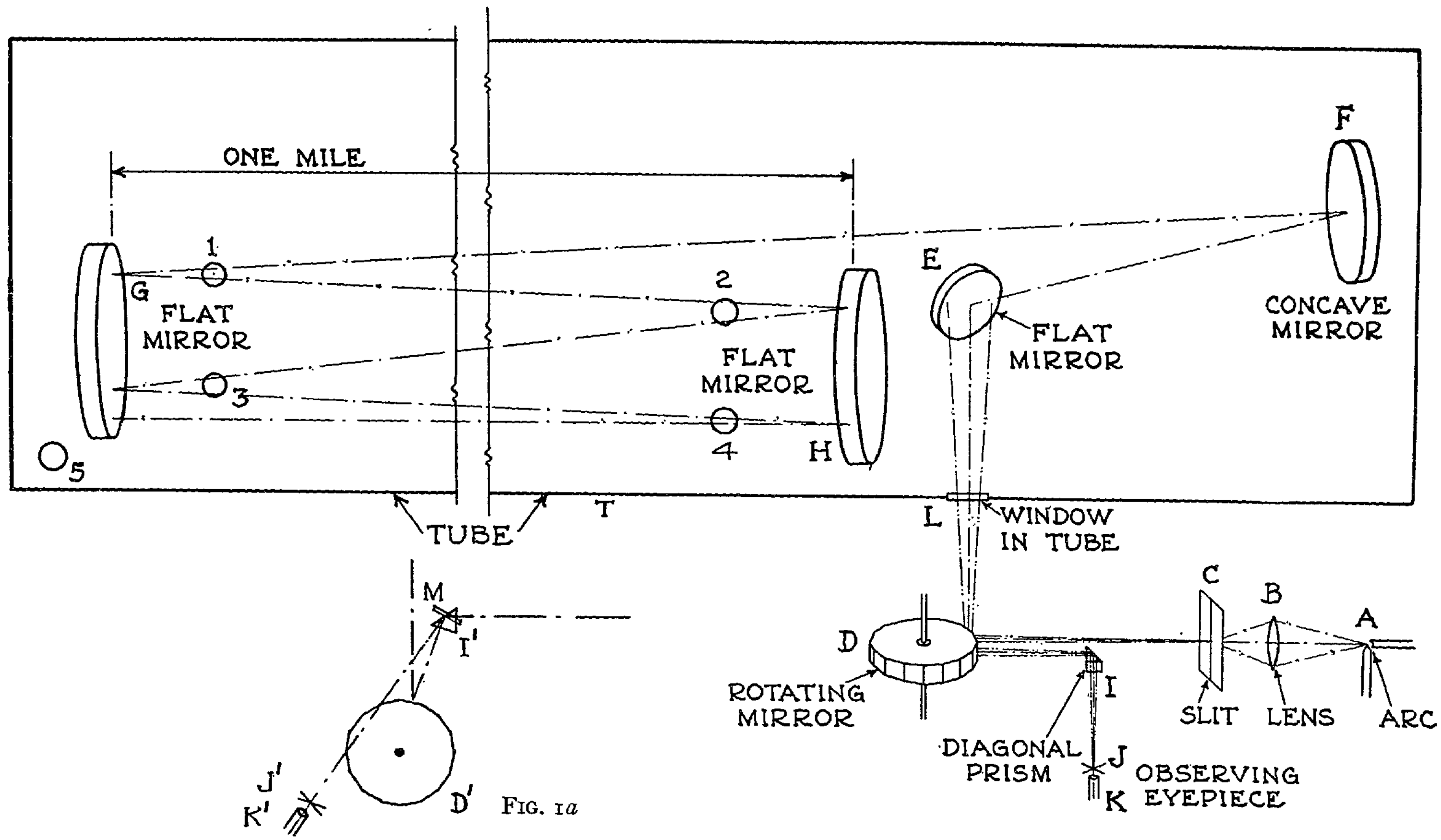
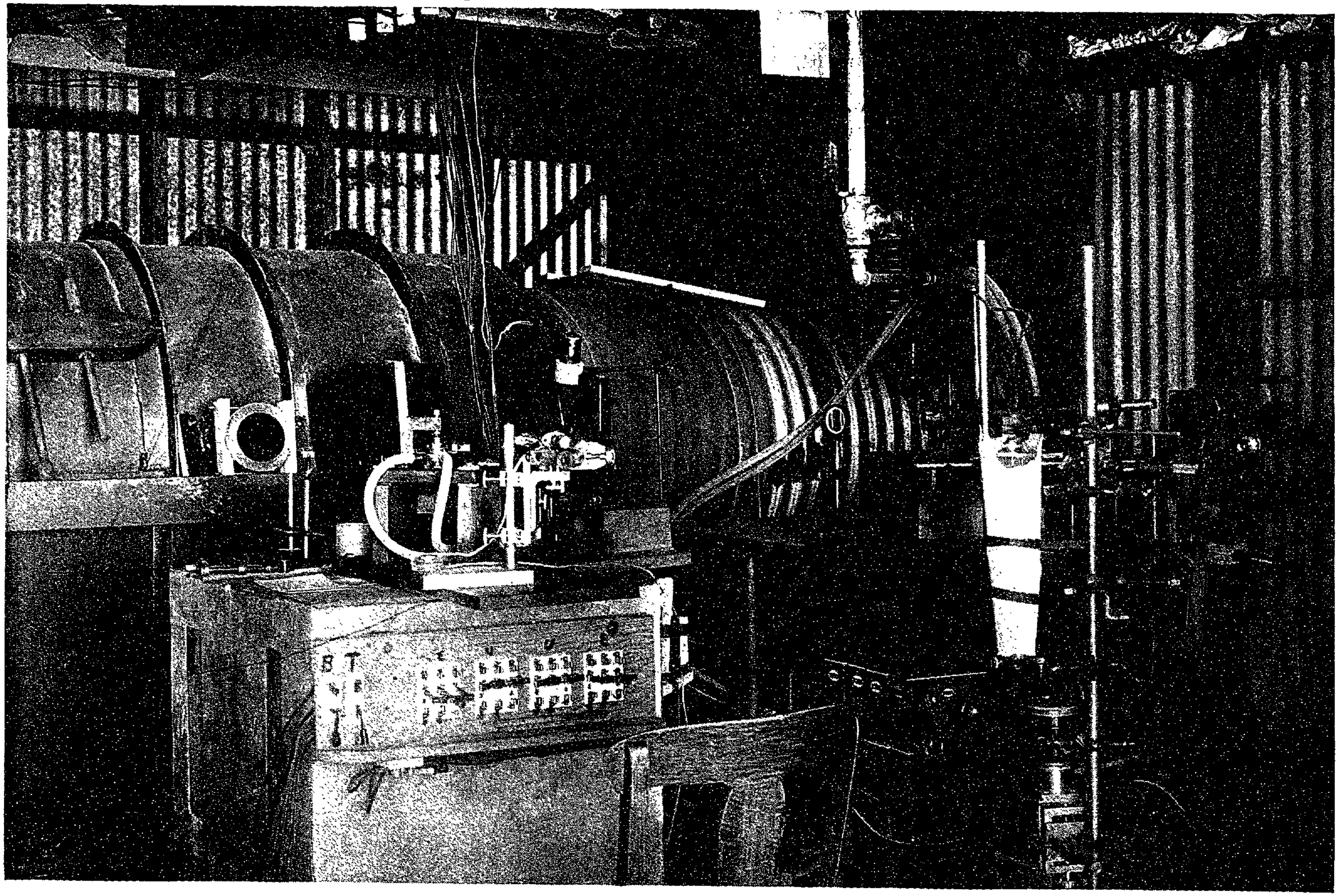


FIG. 1*a*

FIG. 1.—Diagram of optical system

PLATE VII



INTERIOR OF OBSERVING ROOM

For series 47–54, to eliminate the effect of any lateral shift of the rotating mirror, the light after passing through the slit entered the 90° prism *I′* (Fig. 1*a*) and was reflected to the lower half of the rotating mirror at nearly perpendicular incidence, thence into the tube to the flat mirror at an equivalent distance of 4 or 5 miles. The returning beam struck the upper half of the rotating mirror and was then reflected by the silvered surface *M*, which stands directly above the 90° prism, onto the crosswires *J′* and into the eyepiece *K′*. Since the advantages of this setup were found to be negligible, the original arrangement of the prism (Fig. 1) was used in the 1932 and 1933 measures. It was originally intended to pass parallel light from *F* to *G* and *H*, thence under *G* to a concave mirror about 51 feet beyond it, which would converge the light onto a small concave mirror and thus form a system similar to that used in the Mount Wilson–San Antonio experiments. This auto-collimating system was used in the earlier work because it requires no delicate adjustment, whereas, without the auxiliary mirrors, the flat must be kept accurately aligned.

Actual observations showed, however, that the light returned from the conjugate image was brighter than that given by the auto-collimating system; the former arrangement was therefore used throughout the experiments.

The vacuum tube *T* (Figs. 1 and 2) is 3 feet in diameter and approximately a mile long. The pipe is interrupted at *H* and *G* (Fig. 2) by steel tanks which house the 22-inch flats and ended at *R* and *N* by tanks containing the concave mirrors.

All operations were conducted from the observing room at *H* (Fig. 2 and Pl. VII). Here the optical axis was located about 5 feet above the floor, and in the 1931 experiment the slit, condensing lens, rotating mirror, air controls, etc., were mounted outside the tube on a metal table bolted to the cement floor. In the 1932–1933 experiments the slit, prism, rotating mirror, and observing eyepiece were mounted on a heavy cast-iron base, fastened to a solid concrete pier. The pier, together with the metal table and the pendulum case, was fastened to a single massive concrete pier 3 feet thick, whose top lay flush with the floor. The arc lamp, which stood outside the observing room, was surrounded by a metal shield, provided with a red-glass window for observing the arc itself. A blackened tube extended from the wall to the condensing lens, and the use of a small aperture, about 0.5 inch square, at the inner end of the tube eliminated much of the undesirable light.

To assist in lining up the mirrors, small 6-volt lamps were inserted at *1*, *2*, *3*, *4*, and *5* (Fig. 1). Lamps 1 and 3 were placed 100 feet in front of the *N* 22-inch flat and opposite the centers of the upper and

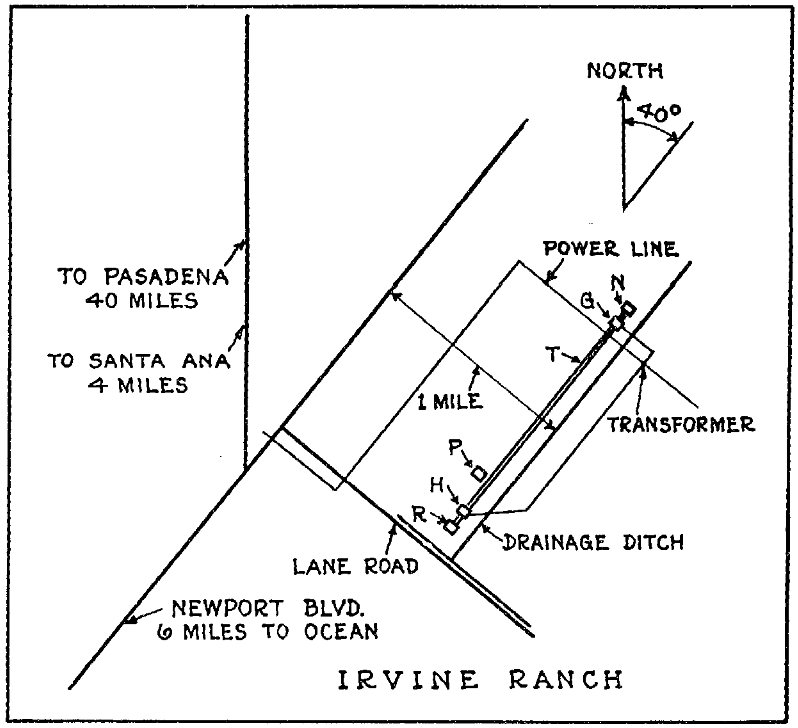


FIG. 2.—Plan of experiment

lower halves, respectively, of the mirror. Lamps 2 and 4 were similarly placed in front of the *S* 22-inch flat. Lamp 5 was opposite the center of the *N* concave. Lamps 1 and 3 and 2 and 4 were mounted on semaphore arms (electric windshield-wipers) which could be swung into position when needed for aligning. The arc lamp *A* (Fig. 1) was a Mole-Richardson semi-automatic projection lamp, using National cored carbons. It operated on 110 volts and 40 amperes. The arc ran steadily over long periods of time, needing only occasional adjustments by the attendant. The slit *C* (Fig. 1) was adjustable horizontally and vertically and racked for focus. The slit aperture was limited vertically by occulting bars; the slit width was about 0.003 inch.

The rotating mirror *D* (Fig. 1 and Pl. VI*b*) used in these experiments is of well-annealed optical glass and has 32 faces. It is 0.25 inch thick and 1.5 inches across its diagonals and has a central hole to define its position on the axis. Its angles are correct to 1″.0 and its surfaces flat to 0.1 wave. The operating aperture in each direction is 9/64 inch wide and 1/8 inch high. The mounting is one of those used in the Mount Wilson–San Antonio experiments having compressed-air turbine drive capable of rotation in either direction. A slight amount of oil suffices to lubricate the plain journal bearings and the single-ball step-bearing below.

The plane-parallel window *L* is of crown glass 6 inches in diameter and 0.75 inch thick. At first cemented to the tank flange, it was later held by clamps and atmospheric pressure against a rubber gasket. The diagonal flat mirror *E* is 5 inches in diameter and 0.5 inch thick. It has motor-driven slow motions about vertical and horizontal axes. The concave mirror *F* is of glass, 40 inches in diameter and 3.9 inches thick, and has a focal length of 49.28 feet. It is covered with a cardboard screen having an elliptical aperture 12×15 inches. The mirror and its mounting were built for the Mount Wilson–San Antonio experiment. The mounting is of cast-iron, in two sections. The lower ribbed base frame rests on three legs, the front one of which is adjustable by motor, which tilts the mirror about a horizontal axis at right angles to the tube axis. The base stands on three cylindrical steel plugs, set in a pier separate from that holding the tank and projecting through three holes in the bottom of the steel tank. Rubber sleeves connecting the tank and the cylinders form a flexible, air-tight joint, thus leaving the mirrors free from any motion the tank itself might have. The upper section of the mounting rests on three balls and has a slow motion in rotation about a vertical axis directly under the face of the mirror. The mirror is held in its cell by three pivoted edge-arcs, the top one having spring contact to prevent excessive loading. Three tangential grooves in the edge of the mirror fit corresponding lugs in the edge-arcs.

The flat mirrors *G* and *H* are $22\frac{3}{8}$ inches in diameter and 4 and 5 inches thick, respectively, and are adjustable about horizontal and vertical axes. The details of the mountings are similar to those of the concave mirrors already described. It was found that the silver coatings of the mirrors deteriorated rapidly; Dalton, of the Observatory optical shop, succeeded in coating them with a very thin silver lacquer in such a manner that their optical properties were not impaired. The 90° prism *I* is blackened on its top surface and silvered and blackened on its diagonal face to prevent any unnecessary illumination in the field of view. For series 1–25 it was mounted directly on the rotating-mirror support, but for the remaining work it was mounted on a shelf attached to the table, thus eliminating displacements due to any possible turbine reaction. Later experiments showed that these displacements were negligible. The micrometer is a simple slide with a single vertical crosswire, moved by a screw of 40 threads per inch, the head of which is divided into 25 parts, making each division equal to 0.001 inch. An eyepiece of 2.5-inch focus was used. A 6-volt lamp with push-button control illuminated the head.

Vacuum pump.—For exhausting the 1100-foot tube, and for preliminary work with the 1-mile tube, a small Kinney rotating-plunger vacuum pump was used. This pump performed so well that in the final work a Kinney rotating-plunger pump of 350 cubic feet of free-air capacity driven by a 15-hp motor was used. These pumps have no internal packing, are oil sealed, and on a closed system produce a vacuum of 0.05 mm. The pump was connected with the tube by a 6-inch steel pipe and was fitted with an automatically controlled check valve to prevent oil from passing into the tube when the pump accidentally stopped. A gate valve, placed at the outer end of the pipe, allowed air to enter the tube when it was necessary to let down the vacuum.

The compressed-air system.—To drive the turbines of the rotating mirror, compressed air at a pressure of 100 lb. was supplied by an ordinary motor-driven compressor. The air was piped to a tank outside the operating room, thence to the valve on the operating table.

The regulating valve *V* (Fig. 3) is an escape valve, consisting of a chamber with an open top fitted with a flat plate with ground surface. A *V*-socket in the top of the plate holds a $\frac{1}{4}$-inch ball, across which extends a lever held in compression by a spring. The least upward lift by the operator changes the nearly balanced pressures and allows a slight escape of air. After passage through the valve and regulator, the air stream branches, running to the *R* and *L* turbines in the rotating mirror.

Electrical system.—Power is obtained from a high-tension A.C. line which crosses the tube about 4000 feet from the *S* end, where it is stepped down to 110–220 volts and feeds a line paralleling the tube. The power plant located at *P* (Fig. 2) houses the vacuum pump, the air compressor, and the 6-kw motor-generator set supply-

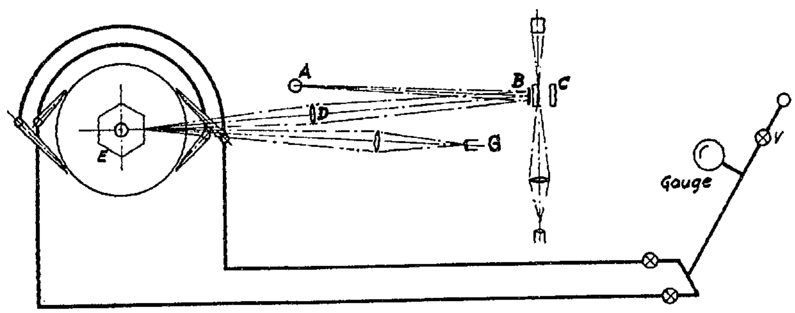


FIG. 3.—Diagram showing mirror speed control

ing current to the arc. All the mirror slow motions are operated by the observer at the micrometer. Those at the *S* end are handled by direct switches. Those at the *N* end are worked by a common push-button line, the proper contact being made through a selector operated by a Selsyn motor.

Pipe.—The pipe is of 14-gauge galvanized Armco steel sheets, 26 inches wide, rolled and corrugated and then formed into sections 60 feet long. The longitudinal seams are double riveted, the circumferential seams single riveted, and all of them soldered. The sections are mounted on wooden trestles shown in Plate I*a* and make contact on shoes at the bottom, at 45°, and at the sides.

The pipe sections, *A–A*, are separated about an inch, each joint being treated as shown in Figure 4. Over each junction was placed a rolled sheet of 12-gauge galvanized iron 8 inches wide, forming a sleeve *B* whose overlapping ends are bolted to the two ends of the pipes with loosely fitting stove bolts.

Two pieces of canvas *C*, 11 inches wide, were placed over the sleeve, the inner one tied with a large rope *D* to fill the groove and the outer one with string. A 32×6-inch circular molded inner tube *G*, previously slit along its inside circumference and stretched over the end of one of the pipe sections away from the canvas, was then drawn over the canvas so that it extended about 2 inches beyond either edge. The edges of the rubber tube were rolled back a few inches and the steel pipe and the inner side of the rubber smeared with rubber cement. The rubber was then rolled flat, smeared for an inch or two with cement, and the joint then wound with several laps of friction tape *H* and coated with glyptal. In the earlier trials the rubber tube

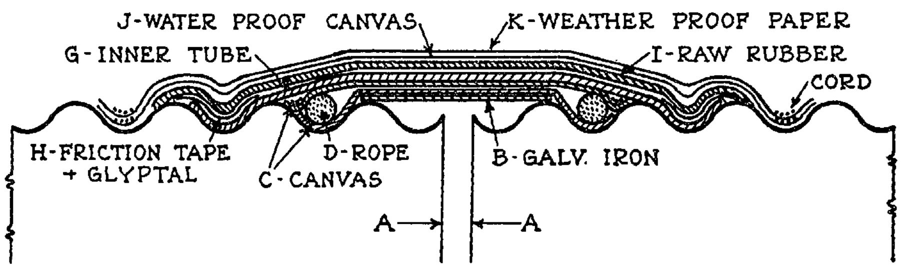


FIG. 4.—Cross-section of pipe joint

was then directly covered with canvas, but later it was smeared with cement and then covered with a sheet of raw rubber *I*, 15 inches wide, which becomes tacky with heat and closes any cracks occurring in the inner tube. Waterproof canvas *J* and a sheet of weatherproof paper *K* form the outer covering, each tied with stout cord. After completion the seams and joints were painted with glyptal to seal any leaks which might occur in them.

Four manholes give access to the tube, one at each end between the 22-inch flats and the concaves, and two others in the main section of the tube.

Tanks.—The four tanks housing the mirrors and their mountings within the vacuum tube are constructed of $\frac{3}{8}$-inch steel plate, reinforced with appropriate steel sections welded on. The tanks consist of a flat base plate and a removable upper box section, fitting into a groove in the base, which is sealed only with a strip of solder serving as gasket and with Hydroseal. No bolts are used to tie the sections together. The base is a $\frac{5}{16}$-inch flat steel sheet, reinforced with 8-

inch *I*-beams and stands on four small concrete piers. The upper sections are rectangular in shape up to the optical axis and semicylindrical above that. Openings in the ends, with flanges 3 feet in diameter and 1 foot long, make the standard flexible connection with the pipe.

The concave mirror tanks *R* and *N* (Fig. 2) are 4 feet and 4 inches long, 5 feet and $\frac{1}{2}$ inch high, and 4 feet and 6 inches wide, inside measure. The outer ends are fitted with steel drumheads, 3 feet in diameter and 9 inches long, which are joined to the tank with the standard wrapping and supported by a steel frame on two separate piers. Two $\frac{7}{8}$-inch diameter rods about 15 feet long tie these heads to plates sunk about 4 feet underground. Turnbuckles adjust the heads when the 7-ton air pressure is removed from the tube.

The flat mirror tanks *H* (Pl. VII) and *G* (Fig. 2) are 6 feet long, 3 feet and 8 inches wide, and 5 feet and 7 inches high inside. A porthole 8 inches in diameter, at a point opposite the face of the 22-inch flat mirror, permits a transfer of measures from the mirror systems inside the tube to the measured-mile piers outside. Tank *H* has an additional port through which the light passes to and from the rotating mirror. A 4.5-inch i.d. sleeve with a turned outer flange is welded to the tank, the outer end being inclined 10° so that multiple reflections from the window do not interfere with the working beams.

The mirrors and their mountings are those used in the previous velocity experiments, altered to fit the new arrangement and equipped with motor mechanisms for adjustment, all of which are controlled by the observer at the micrometer eyepiece.

SYSTEMS OF MEASUREMENT

Measurement of time.—In velocity-of-light measures made previous to the Mount Wilson–San Antonio experiment the outgoing and return beams were reflected from the same face of the rotating mirror. The return image could always be observed by shifting the eyepiece sideways. In the null method used in the Mount Wilson–San Antonio, and in the Irvine Ranch experiments, the light emerges from one face and is received on some other face—the adjacent face in the Irvine experiment. As the mirror starts rotating, the image gradually passes from the field of view and reappears in the other side of the field only when the rotating mirror is approaching its proper speed.

While several methods are available for measuring the velocity of light with this arrangement, the one chosen is as follows: The rotating mirror is brought into synchronism with a tuning fork whose period of vibration is determined; the position of the image is then read with a micrometer for the right- and left-hand rotations of the mirror. The distance remains fixed. The time interval to be measured is therefore that during which the rotating mirror turns 1/32 revolution, plus or minus a small angle derived from the readings of the micrometer. The period of the fork is determined by stroboscopic methods in terms of free-pendulum beats. Since the period of the tuning fork varies with temperature, comparisons between the fork and the pendulum are made before and after each set of readings. The true time of the pendulum beats was determined before and after each annual series of experiments.

Mirror-speed control.—The light from a 6-volt lamp A (Fig. 3), after striking the small mirror B on the tuning fork C, was imaged by the small achromatic lens D on the one polished face of the nut E, which clamps the rotating mirror to its shaft. Since the fork stood vertically, the image vibrated up and down on the nut. The focal length of the lens D was such as to give sufficient amplitude to the motion of the image. Since the nut rotated in a horizontal plane, the image, as the mirror speeded up, passed through a series of vibrating and stationary states and finally reached a permanent stationary state when the beats heard between the fork and the rotating mirror ceased. At this point a second observer made a setting on the return image and a reading of the micrometer. A reversal of the direction of motion of the mirror eliminated any necessity for making a zero reading.

The observer at the eyepiece G (Fig. 3) controlled the air supply to the mirror turbines by means of the regulator V already described. The tuning-fork period was adjusted as follows: The light-path was first measured with an ordinary tape. The best available value of the velocity of light divided by thirty-two times this distance gave the whole number of vibrations of the fork per second (N). A fork having a slightly greater period of vibration was selected and filed off until it was very close to the desired pitch. The fork was then mounted in its frame and, while the mirror was rotating in synchronism with it, micrometer readings were made for right and left rotations. This procedure was repeated until the pitch of the fork, as indicated by the small difference between the right and left readings, was a trifle high. The final correction was made by adding a small lump of universal wax to each prong.

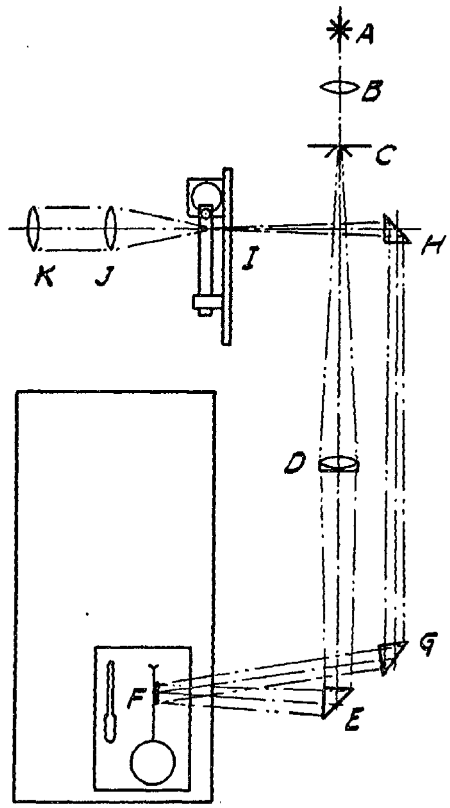


FIG. 5.—Stroboscopic timing system showing pendulum and fork.

Fractional number of beats of the tuning fork.—Light from a filament lamp A (Fig. 5) was focused on a narrow slit C and reflected into the pendulum case, whence it was returned by the mirror F on the pendulum and focused by the achromatic lens D on an edge of tuning fork I. When the fork was vibrating, the flashes of light from the pendulum illuminated the fork in various positions and showed to an observer at the telescope J a series of sawtooth images. When the period of the fork was an exact multiple of that of the pendulum, the images as seen against a pointer in the field of view appeared stationary. When the period differed from an exact multiple, the teeth appeared to travel across the field of view. Cognizance was taken of the flashes in one direction only; when the images traveled in the same direction as the flash, the fork was losing on the pendulum and the sign of the fractional correction was minus. If the image traveled against the flashes, the sign was plus. If n denotes the number of flashes occurring during the passage from one tooth to the next, the fraction $\pm 1/n$ added to the whole number N gave the period of the fork in terms of the free pendulum.

True period of free pendulum.—The determination of the period of the free pendulum in terms of mean solar time was made in two steps: first, a comparison of beats between the pendulum and a flash box operated each second by a contact-making chronometer; second, a comparison of the chronograph records of second marks from the chronometer with signals (1931 by hand, 1932–1933 by self-recording wireless) recording true time sent by long-wave wireless from Arlington four times each day. This determination was made several times during 1931 and before and after each experiment in 1932–1933, temperatures of the pendulum box and the time intervals being recorded. Since the period of the pendulum varies slightly with the length of swing, readings were taken for several lengths of swing and interpolations made for other swings. The pendulum is one of those formerly used by the United States Coast and Geodetic Survey in the determination of gravity. It is set in motion by an outside lever, swings in a vacuum chamber, and beats half-seconds. Its knife-edges are of agate, rocking on a flat agate plate. When not in operation it rests on auxiliary edges. On the pendulum near its point of suspension and on the shelf which carries it are mounted small speculum-metal mirrors. A dummy bob hangs inside the case carrying a thermometer. The box is of heavy bronze and is provided with adjusting screws and levels. Windows permit observation of the graduated arc and the thermometer and allow the passage of light to and from the mirrors. Consistent readings could not be obtained with the pendulum in 1931, but its inclosure in a constant-temperature case in 1932–1933 eliminated this difficulty. Throughout the experiment the pendulum case was connected with the main vacuum tube.

The flash box used for comparing beats of the pendulum with those of the chronometer consists of a rectangular box and a laboratory telescope mounted on a stand. In the forward end of the box is a 6-volt lamp, a slit, and a shutter, operated by relay with the 6-volt contact circuits of the clocks and controlled by a trigger mechanism which works with great rapidity, giving flashes of very short duration. The images of the slit reflected from the two small mirrors in the pendulum case are seen in the telescope together with a scale on glass placed at the focus. The flash box is usually placed at a given distance from the pendulum box, and the stationary pendulum mirror is adjusted to bring the two images close to one another in the eyepiece field.

The object of the flash box is to determine the times of coincidence between the beats of the pendulum and the chronometer. When the pendulum is started, the chances are that only the fixed-mirror flash will be seen. In a few moments the second image will appear flashing, say in the bottom of the field, and gradually approach the center. When the images are in coincidence, the time indicated by the chronometer is noted. At approximately half the period the moving image appears at the top of the field, and when the down coincidence occurs, the time is noted. The comparisons are continued until coincidences have been obtained over the whole range of temperatures covered by the experiment.

Since the time of vibration depends upon the length of arc of the swing, readings are taken both for the maximum swing and for about one-half the maximum.

If n be the number of seconds between coincidences, then $n/(n \pm 1)$ is the time of one vibration of the pendulum in chronometer seconds, the plus sign being used if the flash travels in a direction opposite to that in which the pendulum swings, and minus if the two travel together. With the apparatus used the pendulum beat faster than the chronometer, and the period of coincidence was roughly 18 minutes.

Two timepieces were used, one a Bond ship's chronometer beating seconds on the relay and missing every fifty-ninth second. The rate was quite constant for a period of 24 hours following its winding. The other was a Constant Frequency Assembly of General Radio make (used late in 1931 only), controlled by an oscillating quartz crystal whose period 50,000∼ was reduced through two multivibrators to 1,000∼. A unipolar motor of 1,000∼ drives a shaft at 10 r.p.s., operating a seconds relay and a synchro-clock. (The rate of this clock was distinctly more constant than that of the chronometer.) The chronograph was a small one of Henson make, driven by a phonograph synchronous motor at a paper speed of 1 inch per second. In 1931 two ink pens were supplied, one operated by the clock circuit beating seconds and the other by hand. In 1932–1933 the records were traced on paraffined paper by self-recording styli.

Time of light-transit.—Let a_1 and a_2 be the right and left readings of the micrometer and r the distance from the mirror to the cross-wires. Then the small angle by which the rotating mirror differs in position from 1/32 revolution is

$$\frac{a_1+a_2}{4r}=\frac{\alpha}{4}.$$

If $1/n$ be the period of the optical beats between the fork and the pendulum and $1/\nu$ that of the coincidence between the pendulum and the true seconds, and if N be the nearest whole number of the fork, then the correct time elapsed during the passage of the light from the rotating mirror through the tube and back is

$$T=\frac{\frac{2\pi}{32}-\frac{\alpha}{4}\,(1-\nu)}{2\pi(N+n)}\,,$$

which reduces to

$$\frac{\left(1-\frac{4\alpha}{\pi}\right)(1-\nu)}{32N\left(1+\frac{n}{N}\right)}.$$

Putting

$$\frac{4\alpha}{\pi}=a,\qquad \frac{n}{N}=b\,,\qquad \nu=c\,,$$

the formula becomes

$$T=\frac{(1-a)(1-c)}{32N(1+b)}\,.$$

Measurement of distance.—After a conference with Commander C. L. Garner, assistant chief of the Division of Geodesy of the United States Coast and Geodetic Survey, it was decided to lay out the base line about 10 feet to the west of the pipe and place six piers along the line.

Piers *E* and *B* (Fig. 6) are opposite the flats in tanks *G* and *H*, and *A* and *F* opposite the concaves in tanks *R* and *N*. Piers

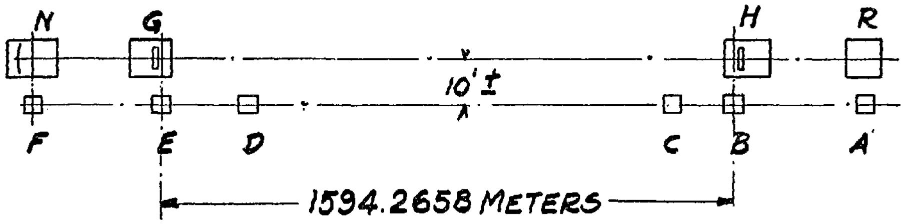


FIG. 6.—Plan of base-line piers

C and *D* were intended for use in triangulating into the tube but were not actually used. The mean length of this base line was found by the United States Coast and Geodetic Survey to be 1594.2658 m. The transfer from the base line into the tube and the measurement of the internal distances were made by ourselves in the following manner: Before and after measuring the distance the alignment of the apparatus was carefully checked optically, with the arc on and the rotating mirror stationary, and intersecting marks were drawn on the small diagonal flat at the center of the cone of light. An excellent straight edge (Fig. 7) (used to align the tracks of the 50-ft. interferometer on Mount Wilson) 12 feet long was passed through the 8-inch diameter opening and supported on frames in a horizontal position. The straight edge was carefully adjusted parallel to the face of the flat by calipering at *a*, *b*, and *c*, and the separation *a* noted. A mercury plumb bob was then dropped from its edge and its position marked on the bronze plate in the pier. The bob was rotated to determine its neutral position and allowance made for the thickness of the string. If *d* be the distance

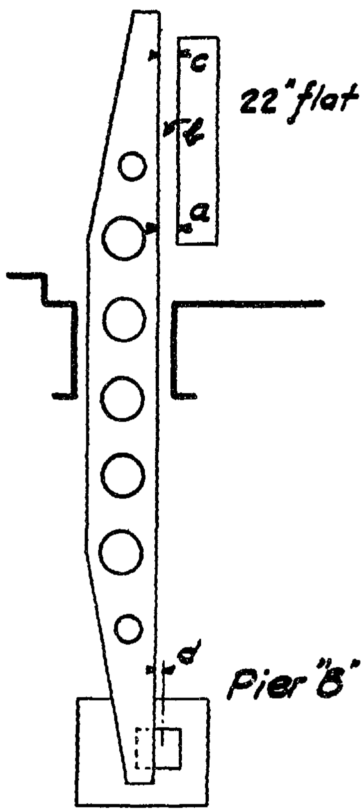


FIG. 7.—Diagram showing method of transferring mirror position to base-line pier.

of the bob from the bench mark, the simple summation $d \pm a$ gave the position of the south flat with respect to pier *B* and of the north flat with respect to pier *E*. The distance between the top of the *S* 22-inch flat and the center of the *S* concave was measured with a steel tape under 16.7-lb. tension, to which a steel scale was clamped to make contact with the concave. Temperatures were recorded and the mean of three readings taken as a correct one. This inclined distance was then corrected to give the horizontal distance between

TABLE I

LENGTH OF BASE LINE, PIERS *B–E*

Date	Observer	No. of Traverses	Distance in Millimeters
	U.S. Coast and Geodetic Survey		
1931 Feb. 27—Mar. 2	Garner	9	1594259.2
1932 Jan. 11—Jan. 14	Latham	8	1594265.8
1933 Jan. 14—Feb. 17	Latham	31	1594272.3
Mean			1594265.8
	Mount Wilson Observatory		
1933 July 17–20	Pease	8	1594263.8

the mirrors. The distance from the *S* concave to the small diagonal flat was measured with the same tape, tension, and scale. The addition of a trammel bar clamped to the tape at the end near the flat allowed its point to be adjusted to a center mark on the flat.

The distance from the small diagonal flat to the rotating mirror was taken through the window-opening by means of a trammel bar and measured on the tape. Corrections were then made for the path length through the glass 19.33 mm thick, at an inclination of 10° ($n_d = 1.52$) equivalent to a vacuum thickness of 29.39 mm. The air path outside the window was reduced to vacuum thickness by using 1.000295 as the index for air.

Table I gives the various results for the length of the base line as measured by the United States Coast and Geodetic Survey. The data show a slight progressive increase in the means of each year's measures, which may be considered as a real change in the earth's surface. Interpolated values of the distance might have been used for the computations of the velocity of light, but, owing to large variations in the velocity results, it was thought that the simple mean value could be used without prejudice to the results. An earthquake which occurred on March 10, 1933, may explain the reduced value of the base line measured by Pease in July, 1933. Table II gives the various lengths involved in the light-path.

TABLE II

LENGTH OF LIGHT-PATH IN MILLIMETERS

Path	1931	1932	1932–1933
Rotating mirror to 5-in. diagonal corrected for air path..........	1661.3	1662.9	1661.9
5-in. diagonal to S concave........	13092.7	13098.6	13102.2
S concave to S 22-in. flat..........	13714.1	13713.5	13716.8
D_1 = sum of above three..........	28468.1	28475.0	28480.9
S 22-in. flat to pier B............	0.6	2.0	0.6
Pier B–E (mean)................	1594265.8	1594265.8	1594265.8
Pier E–N 22-in. flat..............	14.4	14.4	16.3
D_2 = sum of above three..........	1594280.8	1594282.2	1594282.7
$D_{10} = 2D_1 + 10D_2$..................	15999744.2	....	....
$D_8 = 2D_1 + 8D_2$..................	12811182.6	12811207.6	12811223.4

CALCULATION OF VELOCITY

The formula for calculating the velocity of light from the observed data is

$$V = \frac{D}{T} = \frac{32ND(1+b)}{(1-c)(1-a)} ,$$

or, with sufficient approximation, since b and c are small,

$$V = 32ND(1+a+b+c) .$$

The presence of a slight residuum of air in the tube at temperature T necessitates a small correction e, whence the formula becomes

$$V = 32ND(1+a+b+c+e) = 32NDf .$$

The value of e is computed from the formula for the refractive index of air given in the *Smithsonian Physical Tables:*

$$n-1=\frac{0.0002931\times P'\times 1333.2}{1+0.00367t\times 1.0136\times 10^6},$$

where P' is the pressure in millimeters of mercury and t the temperature in degrees centigrade. For the 10-mile distance a tuning fork giving 585 v.p.s. was used. For the 8-mile distance a fork was used, for which the whole number of vibrations was 365 or 366, N thus being either 2×365 or 2×366. The various values of $32ND$ used in the experiment are shown in Table III.

TABLE III

VALUES OF $32ND$

Velocity	Vibrations per Second	1931	1932	1932–1933
V_{10}	585	299515.2	....	....
V_8	365×2	299269.2	299269.8	299270.2
V_8	366×2	300089.1	300089.7	....

METHOD OF OBSERVATION

With the pump running continuously, the vacuum remained approximately constant, the pressure ranging from 0.5 to 5.5 mm according to the amount of leakage. During the day the influence of the sun on the air in the tube was such as to distort and blend the several images corresponding to the various distances and thus prevent work at such times. After sundown the images improved rapidly and in a half-hour were easily separable from each other. The tuning fork was started in advance in order to give it a chance to warm up. The procedure in lining up the mirrors was as follows: With the arc lamp on, the outgoing beam from the rotating mirror was centered on the upper half of the S concave mirror by means of the 5-inch diagonal flat. The arc lamp was then cut off; lamp 1 was turned on and the concave mirror in the S end adjusted until the light appeared in the center of the field. The N 22-inch flat was then adjusted until the image of the lamp as seen in the mirror G appeared superposed on the light itself. Next, lamp 2 was turned on, and a more careful adjustment of the *N* 22-inch plane was made in order to bring lamps 1 and 2 into superposition. Lamp 1 was then turned off, and the image of lamp 2 reflected from the *S* 22-inch flat was superposed on itself by adjusting the flat. Light 3 was next turned on and the *S* mirror again carefully adjusted to superpose lamps 2 and 3. When this had been done, lamps 3, 4, and 5 were all superposed. A number of images other than the one desired appeared in the field of view; but a study of their positions and foci soon showed which one was wanted.

This method of alignment was evolved when use of the *N* concave mirror was contemplated. It was found convenient to use the same method when adjusting for work without this concave, save that a small alteration in the inclination of the *S* 22-inch flat slightly raised the beam so that at the last reflection it fell with normal incidence on one or the other of the 22-inch flats. During all these operations the images were observed through the widened slit, which was then narrowed and placed in the observed focus of the light corresponding to the distance at which one wished to work. Since the field was divided, images also appeared in the eyepiece field. A slight adjustment of the 5-inch flat made the images in the eyepiece and behind the slit of equal intensity. The position of the image in the slit was carefully defined by occulting bars, and care was taken to line up the arc on the axis thus defined. When finally the arc was again turned on, the return light was visible in the eyepiece.

When the rotating mirror was set in motion, images corresponding to each of these reflections (because of diffusion and spreading of the beam) were seen in the field at distances from the crosswire proportional to the distance the light had traveled. Experience enabled one to make slight adjustments which concentrated the light in the image which was to be used. The apparatus was then ready for measurements. Observer A made a reading for the stroboscopic comparison of the fork and the pendulum (n), then read the temperature of the pendulum case (t). The mirror was then brought up to speed by manipulating the air control until the stroboscopic image was stationary. Observer B set the crosswire on the image and recorded the reading. In series 1–25 of 1931, 10 such readings were taken before the direction of rotation was reversed. To minimize the effect of a slight drift which had been noticed, subsequent readings (series 26–46, 1931) were made, 5 in the first direction, 10 in the opposite, and finally 5 more in the first direction. In series 47–54, 1931, 5 alternate sets of 5 readings were taken; the mean of 1 and 3 was used against 2, 2 and 4 against 3, and 3 and 5 against 4. The first readings of the successive group were alternately L and R. This method was used in all the remaining work except a few cases in which 7 sets were made. Observer A repeated the readings for n and t between each two sets, and the mean for the beginning and end of each set was used for the set.

Since the total angle measured was exceedingly small, the lever arm r was measured with an ordinary rule. Allowance was made for the prism thickness except for series 47–54 (1931), for which a mirror was used. Even with the vacuum as low as 0.5 mm, sufficient air remained in the tube to be affected by temperature conditions. The best images were obtained when a quiet fog settled around the tube, evidently providing a constant temperature throughout the tube. On days when the sun shone, the images drifted completely out of the field, usually returning again at night. A tube wet with dew gave comatic images when the wind blew. In 1931 it was noted that the interval during which work could be done became less and less as summer advanced, owing to the fading of the image and the necessity for constant readjustment. A satisfactory explanation for fading may be found in temperature deformations of the 22-inch flat glass mirrors which dispersed the light. In 1932 and 1933 it became the practice to work principally during the early hours of the night, since otherwise much valuable time during the interval of good observing conditions would be lost in resetting on the following night. A few observations were, however, made around midnight and 3:00 A.M.

Typical observation.—Table IV shows a typical set of observations, together with the values of the various factors calculated from the data. Columns 1, 3, and 5 give the micrometer readings made for a left-hand, columns 2 and 4 for a right-hand, rotation of the mirror, the unit being 1/1000 of an inch. Immediately below are their sums and mean values. The mean of the differences,

$$\frac{L_1+L_3}{2}-R_2\,,\qquad \frac{R_2+R_4}{2}-L_3\,,\qquad \frac{L_3+L_5}{2}-R_4\,,$$

shown farther below, gives the value of d in column 6 which is used to calculate $\alpha=d/r$. Column 6 also lists the time of starting and various other data as follows: p is the pressure in the tube; n_b and n_e

TABLE IV

SAMPLE SET: OBSERVATIONS AND REDUCTIONS, JUNE 30, 1932

(1) L	(2) R	(3) L	(4) R	(5) L	(6)
13.6	19.2	14.0	18.8	13.2	$N=365\times 2$
13.8	19.6	14.2	18.9	14.2	B 7:24 P.M.
13.7	20.0	14.0	19.2	13.5	E 7:30
13.4	19.9	13.1	19.5	13.6	p 3.4 mm
13.9	20.0	13.5	19.4	14.2	n_b 2/26 0.07692
					n_e 3/35 0.08571
					0.16263
68.4	98.7	68.8	95.8	68.7	n +0.08132
					t_b 29°.7, t_e 29°.7, t 29°.7 C
13.68*	19.74	13.76	19.16	13.74	s_b 4.1, s_e 4.1, s 4.1 mm
13.76	19.16	13.74			r 11.80 in.
					d − 0.00571 in.
13.72	19.45	13.75			a − .0006161
19.74	13.76	19.16			b + .0002228
					c + .0008314
− 6.02	− 5.69	− 5.41			e + 0.0000012
− 5.69					f 1.0016715
− 5.41					V 299769.81 km/sec.
−17.12					
− 5.71					

* Mean of five readings above.

the observed and n the mean value of the fractional number of vibrations of the fork; t_b and t_e the observed and t the mean temperature of the pendulum case; s_b and s_e the observed and s the mean swing of the pendulum; r is the measured distance from the rotating mirror to the crosswires, with corrections added for glass thickness when the prism is used. Values of $a=4\alpha/\pi$, $b=n/N=n/365\times 2$ are calculated from the data. The value of $c=\nu$ is taken from the chart showing the true time of the pendulum beat for the mean temperature t and the swing s. The residual air correction e is taken from the chart showing the relation between n, p, and the tube temperature t_t; f is the algebraic sum, $1+a+b+c+e$, by which $32ND$ is multiplied to give the velocity V.

OBSERVATIONS

Table V shows two typical series of observations on successive nights. Column 1 indicates the number of the series, column 2 the date and hour of observation, column 3 the itemized values of the deflections found by subtracting the midvalue of the micrometer reading from the mean of those each side of it, and column 4 the mean value of the deflection. Columns 5, 6, 7, 8, and 9 give the values of a, b, c, e, and f. Column 10 gives the resulting velocity of the set of three velocity determinations, column 11 the residuals in km/sec. for the velocity relative to the mean for the group, and column 12 the number of single determinations of the velocity.

Table VI shows the results from each of the 233 series of observations. Details are as follows:

Hours of observation (col. 3).—Many of the records of the 1931 observations are incomplete as to the time of beginning and ending of the observations. Where inspection permitted or other notes supplied information, approximate times have been inserted. Hours between 12^h0^m and 4^h9^m are A.M.; all others are P.M.

Mean velocity (col. 4).—Each set of observations usually furnished three values of the velocity. Several sets were arbitrarily grouped into a series covering about an hour's time. Some special groupings will be noted, made either to cover a scattered series or to divide a night's readings into several small series. The velocity V given is the simple mean for the series.

Residuals (col. 5).—The residuals are the values which, applied to the mean velocity for a series, give the individual values for each set.

Average deviations (col. 6).—The mean without regard to sign of the residuals in column 5.

Weights (col. 7).—The weight is the number of single determina-

TABLE V

TWO TYPICAL SERIES OF OBSERVATIONS

SERIES	DATE, P.S.T.	d Individual	d Mean	a	b	c	e	f	V	v	WT.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
98..........	1932 Apr. 28										
	$8^h 25^m$	421,417,392	−0.00410	+0.0003934	+0.0004475	+0.0008327	+0.0000014	1.00016750	299,771	−14	3
	8 46	340,377,391	369	3541	4852	8340	14	16747	771	−14	3
	9 5	450,445,446	447	4289	5125	8347	14	17775	802	+17	3
	9 16	357,382,400	380	3646	5518	8350	14	17528	794	+ 9	3
	9 24	318,313,301	−0.00311	+0.0002984	+0.0005819	+0.0008354	+0.0000014	1.00017171	299,785	0	3
	Mean	....	....	....	....	....	....	....	299,785	±11	15
99..........	1932 Apr. 29										
	$8^h 31^m$	704,688,697	−0.00696	+0.0006103	+0.0003086	+0.0008340	+0.0000017	1.0017546	299,795	+16	3
	8 40	669,648,628	648	5682	3255	8347	17	17301	788	+ 9	3
	8 50	591,541,510	550	4823	3479	8354	17	16673	769	−10	3
	9 5	539,542,523	535	4584	3923	8357	17	16881	775	− 4	3
	9 18	505,518	511	4378	4012	8357	17	16764	772	− 7	2
	9 31	558,521,513	−0.00531	+0.0004549	+0.0004065	+0.0008363	+0.0000017	1.0016994	299,778	− 1	3
	Mean	....	....	....	....	....	....	....	299,779	± 8	17

TABLE VI

Observations

(1) Series	(2) Date	(3) P.S.T.	(4) Mean Velocity	(5) Residuals	(6) A.D.	(7) Wt.
	1931		km/sec.		±	
1......	Feb. 19	$9^{h}25^{m} - 10^{h}\,5^{m}$	299,792	+8, −7	7	2
2......	20–21	− 2 0	774	+26, −27, −45, +4, +27, +15	24	6
3......	23	9 0 −10 20	767	+27, +7, −34	23	3
4......	24	9 50 −11 10	760	−1, +18, −17	12	3
5......	26	12 30 − 2 40	773	−15, +37, −24, −8, +10	19	5
6......	26	8 20 −10 0	768	+40, +10, −15, −17, −18	20	5
7......	26	10 1 −11 10	758	−8, +17, +1, 0, −10	7	5
8......	26–27	11 10 − 2 2	766	−1, −11, −30, +29, +9, +10, −6	14	7
9......	27	8 16 − 9 26	796	+66, +33, +33, −23, −38, −12, −35, −25	33	8
10......	27	9 27 −11 5	772	+26, −9, +2, −12, −13, +5, +9, −8	10	8
11......	Mar. 1	9 0 −11 10	795	−2, +18, −8, −2, −6	7	5
12......	2	8 22 − 9 4	756	−28, −29, +49, −23, +31	32	5
13......	2	9 5 − 9 46	772	+23, +9, −22, −3, −7	13	5
14......	25	....	750	+14, +19, −17, −21, −18, +22	18	6
15......	26	....	750	−21, −3, +25, −4, +2	11	5
16......	26	....	745	−28, −9, +20, +7, −10, +10	10	7
17......	27	8 33 − 9 31	748	−10, +6, −16, +9, +6, +6	9	6
18......	27	9 35 −11 9	743	+10, −3, −11, −3, −11, +18	8	6
19......	30	9 0 − 9 59	744	−14, +18, +43, −31, −13, 0, −3	17	7
20......	30	10 0 −11 12	745	−17, +5, −3, +13, +24, −12, −11	12	7
21......	31	1 20 − 1 43	728	−2, +4, −24. +22	13	4
22......	31	8 30 − 9 24	755	+10, +36, −33, +6, −24, +6	19	6
23......	31	9 25 −10 0	757	0, +11, 0, −17, +7	7	5
24......	Apr. 3	9 55 −10 34	741	+14, +1, −1, −11, −3	6	5
25......	3	10 36 −11 18	741	+1, +8, −14, +16, −11	10	5
26......	8	8 25 − 9 0	755	−52, +38, +14	35	6
27......	15	8 0 − 9 28	754	+5, −63, +31, +11, +15	25	10
28......	15	10 14 −10 49	770	+7, +15, −22	15	6
29......	16	7 50 − 9 12	775	+8, −13, −27, +10, +11, +13, +1, +2	11	16
30......	16	9 17 −10 31	776	−2, −12, −7, −4, +16, −1, −6, +16	8	16
31......	17	8 23 − 9 18	771	+4, +12, −7, −7, −2	6	10
32......	17	9 10 − 9 51	776	−7, −11, +18, 0	9	8
33......	21	7 45 − 8 38	793	+37, +11, −12, −6, −13, +1, −18	14	14
34......	21	8 39 − 9 39	779	−20, +10, −6, +8, +4, +4	9	12
35......	21	9 41 −10 33	772	+5, −14, +1, −3, +8, +3	6	12
36......	22	7 54 − 8 22	778	+6, +5, +1, −12	6	8
37......	May 7	9 35 −10 24	789	−13, +14, +12, −13	13	8
38......	14	7 40 − 8 30	774	−7, +1, +3, +2, +6, −6	4	12
39......	14	8 31 − 9 41	770	+8, −11, −2, −7, −3, −8	6	12
40......	14	9 42 −10 30	777	−7, −17, +6, +15, +3	10	10
41......	14–15	11 48 −12 36	773	0, −3, −1, 0, +5, −2	2	12
42......	15	12 37 − 1 15	775	+1, −8, −7, +3, +11	6	10
43......	15	7 29 − 8 23	779	+15, +4, −9, +9, −19, −11, +11	11	14
44......	15	8 52 − 9 39	767	+10, −4, −9, +9, +7, −7, −6	7	14
45......	15	9 56 −10 38	775	−6, −4, −3, +15, +12, −16	9	12
46......	16	12 5 −12 58	778	−1, −9, −12, +1, +6, +2, +10, +2	5	16
47......	July 1	8 8 − 9 52	776	−10, +12, −18, −5, −9, +30	13	16
48......	3	7 15 − 8 18	775	+6, 0, −7, +14, −13	7	13
49......	6	7 33 − 8 22	774	+8, +1, −8	6	9
50......	7	7 15 − 8 3	773	−23, −25, −2, +25, +25	20	15
51......	7	8 14 − 9 18	764	−12, +26, +2, −7, −10	11	15
52......	8	7 15 − 8 45	777	+12, +13, +6, −16, −6, −9	7	18
53......	13	7 6 − 8 25	779	−30, +21, +5, +15, +30, −41	24	18
54......	14	7 25 − 8 24	778	+20, −6, −10, +9, −14	12	15
	1932					
55......	Mar. 3	9 20 − 9 49	299,815	−2, +1	1	6

TABLE VI—*Continued*

(1) Series	(2) Date	(3) P.S.T.	(4) Mean Velocity	(5) Residuals	(6) A.D.	(7) Wt.
	1932		km/sec.		±	
56......	Mar. 4	7h23m – 8h11m	299,772	−2, −2, −1, +7	3	12
57......	4	8 20 –10 1	814	+16, *−37*, +16, +8, −15, *−6*	17	14.5
58......	4	10 23 –11 14	815	−4, +1, +12, −7	6	12
59......	8	7 55 – 8 45	796	−3, −6, +5, +4	4	12
60......	8	8 49 – 9 54	782	+1, +6, −18, +12	9	12
61......	8	9 56 –10 59	789	−5, +16, *+24*, −19	14	10
62......	9	7 39 – 8 40	800	−4, +11, +11, −1, −14	8	15
63......	9	9 6 – 9 52	821	+25, −12, −1, −10	12	12
64......	9	10 15 –11 11	809	−12, −1, +11, −6, +9	8	15
65......	10	7 35 – 9 39	751	*+14*, +14, +7, −8, −16, *+5*	11	13
66......	11	7 58 – 8 40	789	+23, −11, +4, −15	12	12
67......	11	8 49 –10 11	766	+1, +10, −11, −2	6	12
68......	11	10 12 –10 57	772	−17, +10, +5, +1	8	12
69......	15	7 59 – 9 34	773	+11, −7, +10, −16	11	12
70......	15	10 13 –10 41	774	−5, −15, +20	13	9
71......	16	7 51 – 8 27	775	−2, −7, 0, +11	5	12
72......	16	8 30 – 9 25	779	+5, −5, −6, +6	5	12
73......	16	9 50 –10 42	784	+2, +10, *−9*, −18, +9	10	13
74......	16	11 3 –11 46	764	−20, +4, +15, +4	11	12
75......	17	7 7 – 8 3	794	+58, +1, −17, −31, −11	24	15
76......	17	8 6 – 9 37	776	+16, +23, −30, −1, −10	16	15
77......	18	7 35 – 8 53	743	−19, −37, −7, 0, +21, +43	21	18
78......	18	9 10 – 9 50	792	+9, −11, +3	8	9
79......	Apr. 7	9 28 – 9 36	736	....	...	3
80......	8	9 50 –10 40	787	−42, +31, +11	28	9
81......	12	7 26 – 8 44	770	+11, +9, +12, −10, −13, −11	11	18
82......	12	9 31 –10 13	779	+9, 0, −12, +4	6	12
83......	13	7 35 – 8 22	780	−18, +30, −1, −2, −9	12	15
84......	13	8 25 – 9 02	783	−6, −2, +9	6	9
85......	14	7 25 – 8 27	788	0, −7, +6, +29, −32	15	14
86......	14	8 36 – 9 22	768	+4, +7, −10, −1	5	12
87......	15	7 23 – 8 11	768	−57, *−51*, +17, +36, +39	38	14
88......	15	8 27 – 9 8	807	+16, −1, +17, −16, −15	13	15
89......	18	8 32 –10 9	786	−22, +20, −12, +13, −1	8	25
90......	20	8 2 – 8 30	789	0, 0	0	10
91......	21	7 14 – 8 18	773	+7, +45, −28, −23	15	20
92......	21	8 23 – 9 26	761	−24, +21, +1	8	15
93......	26	7 34 – 8 15	776	−29, +19, +7, +6	15	12
94......	26	8 43 – 9 26	783	−16, +9, +5, 0	7	12
95......	27	7 50 – 8 55	759	−23, −27, +23, +14, +16, −2	17	18
96......	27	8 59 –10 16	790	−35, +5, +5, +5, +13, +5	11	18
97......	28	7 34 – 8 23	784	+21, +6, +3, −25, −3	12	15
98......	28	8 25 – 9 33	785	−14, −14, +17, +9, 0	11	15
99......	29	8 31 – 9 40	779	+16, +9, −10, −4, −7, −1	8	17
100.....	May 3	7 44 – 8 25	766	+3, +7, +10, −21	10	12
101.....	3	8 41 – 9 58	776	+6, −11, +5, +16, −16	11	15
102.....	4	7 39 – 8 33	787	+1, −3, +14, −2, −10	6	15
103.....	4	8 34 – 9 49	780	+6, −12, +3, −3, +6, −2	5	18
104.....	5	7 31 – 8 03	770	+10, −5, −6	7	9
105.....	6	7 34 – 8 16	779	0, +8, −9, 0	4	12
106.....	10	7 37 – 8 57	770	+7, −10, +4	7	9
107.....	11	7 40 – 9 1	786	+1, +25, +1, −14, −8, −8	9	18
108.....	12	7 36 – 8 25	767	−6, +2, −6, +2, +8	5	15
109.....	8	8 47 – 9 34	775	−7, +1, +2, −3, +7	4	15
110.....	13	7 38 – 8 38	765	−4, −11, +19, +13, −8, +1, −13	10	21
111.....	13	9 0 – 9 18	770	−4, +4	4	6
112.....	17	7 40 – 9 9	773	+9, −10, +4, −3	6	12
113.....	18	7 36 – 9 5	775	−42, +21, *+14*, +7, +23, *+26*, +7, +11	19	20
114.....	19	7 45 – 9 7	781	+6, −9, +16, −8, 0, +2, −8	7	21
115.....	20	7 32 – 8 42	299,759	−7, *+50*, *−12*, *−4*, −9, +5	10	11

TABLE VI—*Continued*

(1) Series	(2) Date	(3) P.S.T.	(4) Mean Velocity	(5) Residuals	(6) A.D.	(7) Wt.
	1932		km/sec.		±	
116.....	May 24	7h39m – 8h41m	299,774	+9, +4, 0, –11, –2	5	15
117.....	26	7 27 – 8 23	765	+8, –*15*, –11, –7, +15	11	13
118.....	27	7 34 – 7 42	760	....	....	3
119.....	June 1	8 5 – 9 13	778	–28, +4, +20, +13, –10	15	15
120.....	2	7 34 – 8 47	787	–11, –3, +6, +2, –1, +12, –5	6	21
121.....	3	7 24 – 8 14	780	+7, +12, +6, –6, –18	10	15
122.....	3	8 16 – 8 58	775	–2, –17, +1, +18	10	12
123.....	6	7 38 – 8 55	759	–6, +8, –*8*, +*2*	7	8
124.....	7	7 32 – 8 56	758	–11, –7, –5, +1, +10, +12	8	18
125.....	8	12 12 –12 21	781	....	....	3
126.....	9	7 32 – 8 52	762	–13, –5, –2, –8, +4, +17, +6	8	21
127.....	10	7 36 – 8 45	757	–11, –11, +12, +7, –9, +8, +5	9	21
128.....	13	7 31 – 8 52	782	–13, +4, +14, +4, +3, –6, –5	7	21
129.....	14	7 24 – 8 41	781	0, –4, +19, +23, –14, –7, –18	12	21
130.....	15	7 24 – 9 11	774	–1, +15, –2, +2, –7, –3, –4	5	21
131.....	16	7 27 – 8 38	772	–23, +11, +13, +13, –17, +4, 0	12	21
132.....	17	7 46 – 8 32	763	–7, +10, +1, –3, –1	4	15
133.....	20	7 46 – 8 24	735	+4, –11, +*45*	12	6.5
134.....	21	7 44 – 8 43	762	–2, –6, –12, 0, +9, +11	8	18
135.....	22	7 35 – 8 54	762	–2, +12, –4, –*20*	7	10
136.....	23	7 23 – 8 33	772	+11, –3, +9, –21, +1, +1, +2	7	21
137.....	24	7 21 – 8 30	770	+16, –8, –4, –5, +4, +1, –5	6	21
138.....	27	7 28 – 8 35	785	+3, –25, +11, –8, –8, +18, +3	11	20
139.....	28	7 25 – 8 27	773	+7, –2, –10, +5, –15, +12, +3	8	21
140.....	29	7 45 – 8 47	770	–20, –14, +6, +2, +12, +21, –8	12	21
141.....	30	7 15 – 8 19	786	–4, –16, +21, +14, 0, –11, –5	10	21
142.....	July 1	7 50 – 8 35	776	+8, –11, +11, +1, –10	8	15
143.....	5	7 28 – 8 34	768	–11, –1, –1, +19, +3, +12, –19	9	20
144.....	6	7 22 – 8 24	757	–10, +4, –2, +8, +13, +1, –14	7	21
145.....	7	7 37 – 8 15	775	+1, +3, +1, –5	2	12
146.....	July 8	7 24 – 8 21	773	–9, +6, +11, +4, –6, –5	7	18
147.....	11	7 23 – 8 11	775	–5, +5, –7, –1, +9	5	15
148.....	12	7 56 – 8 42	768	–16, –2, +25, –2, –5	10	15
149.....	13	7 28 – 8 23	778	–8, –12, +1, +25, –4, *0*	9	16
150.....	14	7 27 – 8 41	781	–23, +12, 0, +21, –10	13	15
151.....	15	7 22 – 8 37	770	–*28*, –*57*, +*22*, +13, +16, –3, –4	14	15.5
152.....	18	8 2 – 8 43	776	+5, –*9*, –*16*, +6	7	9
153.....	20	8 1 – 8 43	760	–5, +4, +11, –5, –6	6	15
154.....	21	7 28 – 8 13	783	+1, +1, +10, –9, –3	5	15
155.....	22	7 27 – 8 15	765	–6, –9, +12, +10, –7	8	15
156.....	25	8 7 – 8 43	777	–8, +1, +*20*	7	7
157.....	Aug. 3	7 38 – 8 33	752	–9, –20, +24, +21, –17	18	15
158.....	4	8 7 – 8 48	779	–4, –*13*, +*18*, –2	8	10
159.....	Dec. 3	8 5 – 9 10	805	–2, +1, +1	1	9
160.....	5	8 36 – 9 30	756	+2, –2, 0	1	9
161.....	5–6	11 55 –12 51	776	–26, –12, +22, +12, +3	15	15
162.....	6	3 22 – 4 9	784	+8, +3, +15, –26	13	12
163.....	6	7 15 – 8 22	795	+19, +6, +2, –13, –15	11	15
164.....	7	7 19 – 8 7	792	+6, –1, +4, –19, +9	8	15
165.....	7–8	11 54 –12 40	784	+9, +4, +1, –8, –6	6	15
166.....	8	3 6 – 3 52	772	+12, –8, –13, +6, +2	8	15
167.....	9	12 3 –12 50	786	+11, +16, +1, –5, –23	11	15
168.....	9	3 9 – 4 5	765	–13, +6, +16, –8, –1	9	15
169.....	9	7 31 – 8 21	791	+1, +8, +8, –1, –17	7	15
170.....	10	12 25 – 1 14	797	+43, +5, –27, –25, +3	21	15
171.....	19	8 4 – 8 45	775	–17, –18, +14, +22	18	12
172.....	20	7 38 – 8 31	770	+2, +21, –2, –10, –12	9	15
173.....	20–21	11 57 –12 44	764	–11, –3, +6, +9	7	12
174.....	22	7 14 – 8 4	779	–9, –21, –9, +16, +24	16	15
175.....	23	12 6 – 1 0	299,777	–3, +3, –9, +5, +5	5	15

TABLE VI—*Continued*

(1) Series	(2) Date	(3) P.S.T.	(4) Mean Velocity	(5) Residuals	(6) A.D.	(7) Wt.
	1932		km/sec.		±	
176.....	Dec. 23	$7^h43^m - 8^h34^m$	299,776	+11, +14, −15, −14, +3	11	14
177.....	24	12 7 −12 54	755	+29, −15, −2, −13	15	12
178.....	24	3 19 − 3 56	760	+16, −19, +21, −18	18	12
179.....	27	8 30 − 9 15	774	−7, −14, +24, −3	12	12
180.....	27–28	11 51 −12 38	777	−13, +13, +4, −3	8	12
181.....	28	2 53 − 3 42	764	+9, +2, −15, +4	8	12
182.....	28	7 36 − 8 21	776	+33, −47, +18, −4	26	12
183.....	28–29	11 46 −12 39	777	−10, −12, +5, +17	11	12
184.....	29–30	11 52 −12 26	782	+15, +9, 0, −23	12	12
185.....	30	8 29 − 9 05	774	−29, +11, 0, +17	15	11
186.....	31	12 11 −12 30	780	−35, +35	35	6
	1933					
187.....	Jan. 3	7 30 − 8 4	775	−5, +9, −3, −2	5	12
188.....	5	7 27 − 8 10	765	+4, −13, +13, −4	8	12
189.....	6	12 0 −12 32	796	+3, +2, −26, +21	13	12
190.....	9	8 3 − 8 28	763	+9, −9, 0	6	9
191.....	10	12 5 −12 32	770	+1, +6, −7	5	9
192.....	10	7 29 − 8 2	764	+29, −6, −15, −8	14	12
193.....	11	7 17 − 7 48	758	+39, −10, +3, −32	21	12
194.....	12	12 2 −12 48	764	+6, +9, +5, −20	11	10
195.....	12	7 6 − 7 40	753	−3, −23, +8, +18	13	12
196.....	12–13	11 54 −12 31	766	+20, −4, −21, +5	12	12
197.....	13	2 56 − 3 30	765	+21, −9, −5, −7	10	12
198.....	13	7 10 − 7 30	786	−5, +5	5	4
199.....	16	7 57 − 8 30	761	+10, +8, −5, −13	9	12
200.....	16–17	11 53 −12 24	749	+7, +8, −6, −9	8	12
201.....	17	3 3 − 3 37	767	0, −7, +2, +5	4	12
202.....	17	7 57 − 8 25	764	−19, +7, +12	13	9
203.....	18	12 0 −12 31	764	−12, −11, +23	15	9
204.....	18	7 25 − 7 56	777	−1, −18, +9, +9	9	12
205.....	19	12 13 −12 45	774	+6, +10, +5, −21	10	12
206.....	19	2 59 − 3 34	771	−2, −1, +10, −7	5	12
207.....	19	8 18 − 8 42	759	+17, −15, −2	11	9
208.....	25	7 48 − 8 28	771	−10, −4, +2, +12	7	12
209.....	26	12 16 −12 41	769	−19, +20, 0	13	9
210.....	26	3 12 − 3 42	770	+2, −22, +19	14	9
211.....	26	7 19 − 7 59	765	+4, −14, −4, +14	9	12
212.....	27	7 28 − 7 59	779	+4, −2, +4, −6	4	12
213.....	31	7 9 − 7 42	771	+3, −4, +7, −7	5	12
214.....	Feb. 1	12 4 −12 28	774	+11, −8, −3	7	9
215.....	2	7 9 − 7 48	753	+1, −3, +6, −4	4	12
216.....	2–3	11 52 −12 21	766	+3, +5, −2, −7	4	12
217.....	3	3 13 − 3 45	801	+13, −11, −1, −1	6	12
218.....	3	7 6 − 7 35	776	+16, −23, +9, −2	12	12
219.....	6	7 44 − 8 6	756	+6, −6, 0	4	9
220.....	7	7 8 − 7 40	775	−20, −20, +23, +17	20	12
221.....	8	7 10 − 7 43	785	+18, +1, −9, −11	9	12
222.....	9	7 15 − 7 44	790	+23, −8, −5, −10	12	12
223.....	10	7 15 − 7 56	763	+20, −33, −1, −4, +18	14	13
224.....	13	7 16 − 7 43	771	−11, −10, +16, +5	10	12
225.....	14	7 7 − 7 36	789	+28, −8, −16, −4	14	12
226.....	15	7 22 − 7 50	767	+8, +13, −2, −19	10	11
227.....	16	7 10 − 8 16	767	+18, +9, 0, −7, −5, −15	9	18
228.....	17	7 8 − 7 52	779	+1, +32, +5, −35, −4	6	12
229.....	20	7 11 − 7 47	782	+12, +7, −14, +5, −10	10	15
230.....	21	6 59 − 7 28	784	+14, −21, +23, −16	18	12
231.....	22	7 22 − 7 50	774	+36, −16, −14, −6	18	12
232.....	24	7 4 − 7 46	807	−18, −15, +16, +17	16	12
233.....	27	7 5 − 7 34	299,788	−4, +11, +9, −16	10	12

tions of the velocity for the series. An italicized number in the residuals column indicates that the reading has a weight less than that of the normal value for the group. For series 1–25, 1931, when 10 *R* and 10 *L* readings were made, each set of 20 readings was given a weight of 1. In series 26–46, 1931, when 5 *R* and 5 *L* and then 5 *L* and 5 *R* readings were made, each set of 20 readings was given a weight of 2. From series 47, 1931, on, practically all the readings were made 5 *R*, 5 *L*, 5 *R*, 5 *L*, 5 *R*, and each set of 25 readings was given a weight of 3. In a few cases, the set of 25 readings being incomplete, weights of $\frac{1}{2}$, 1, and 2 were allotted, and in a few others, involving seven sets of 5 each, weight 5 was given.

TABLE VII

SUMMARY OF TABLE VI

Series	Date	No. Separate Determinations	Mean Velocity	A.D.
1– 54..........	1931 Feb. 19–July 14	493	299,770	±12
55–110..........	1932 Mar. 3–May 13	753.5	299,780	11
111–158..........	1932 May 13–Aug. 4	742	299,771	9
159–233..........	1932 Dec. 3—1933 Feb. 27	897	299,775	±11
	....	2885.5	299,774	±11

The low rating given to the 1931 readings is due, first, to the way in which they were taken, which did not eliminate drift, and, second, to the fact that errors may have crept into the readings because the pendulum case was not controlled for temperature. The 1931 observations might have been considered as preliminary results and omitted altogether; but, owing to the large fluctuations in the individual values, it was decided to include every observation in the final mean velocity.

Table VII is a summary of the data given in Table VI. The average deviations in the last column are relative to the mean in the preceding column.

DISCUSSION

Distribution of velocities.—The mean velocities shown in column 4, Table VI, have been grouped into divisions covering a range of 5 km/sec. and are shown in Table VIII. A plot of these data in

Figure 8 resembles a probability-curve and indicates that the probable value of a constant velocity would be 299,774 km/sec.

TABLE VIII

FREQUENCY DISTRIBUTION OF MEASURED VELOCITIES

Velocity Range	Number	Velocity Range	Number
299000+		299000+	
726–731	4	776–780	515
731–735	6.5	781–785	270
736–740	3.0	786–790	236
741–745	55	791–795	90
746–750	29	796–800	62
751–755	86	801–805	33
756–760	184	806–810	30
761–765	304	811–815	32.5
766–770	353.5	816–820	0
771–775	580	821–825	12

Time-velocity curves.—A plot of velocity readings with respect to time is shown in Figure 9, the abscissae representing days of the year and the ordinates velocity. Four periods of the night are distinguished by the characters shown in the legend. The heavy line

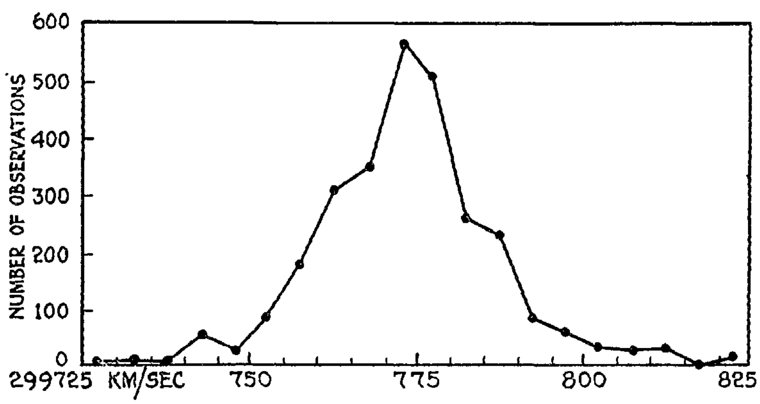


FIG. 8.—Velocity distribution-curve

joins the weighted mean values of small groups of readings covering a few days' time, while the light line shows the axis drawn at a mean value of 299,774 km/sec.

All the 1931 observations lie close to the axis with the exception of series 14–25, whose mean is 299,746 km/sec. The 1932 curve begins at 299,800 km/sec., suddenly drops to 299,776 km/sec., con-

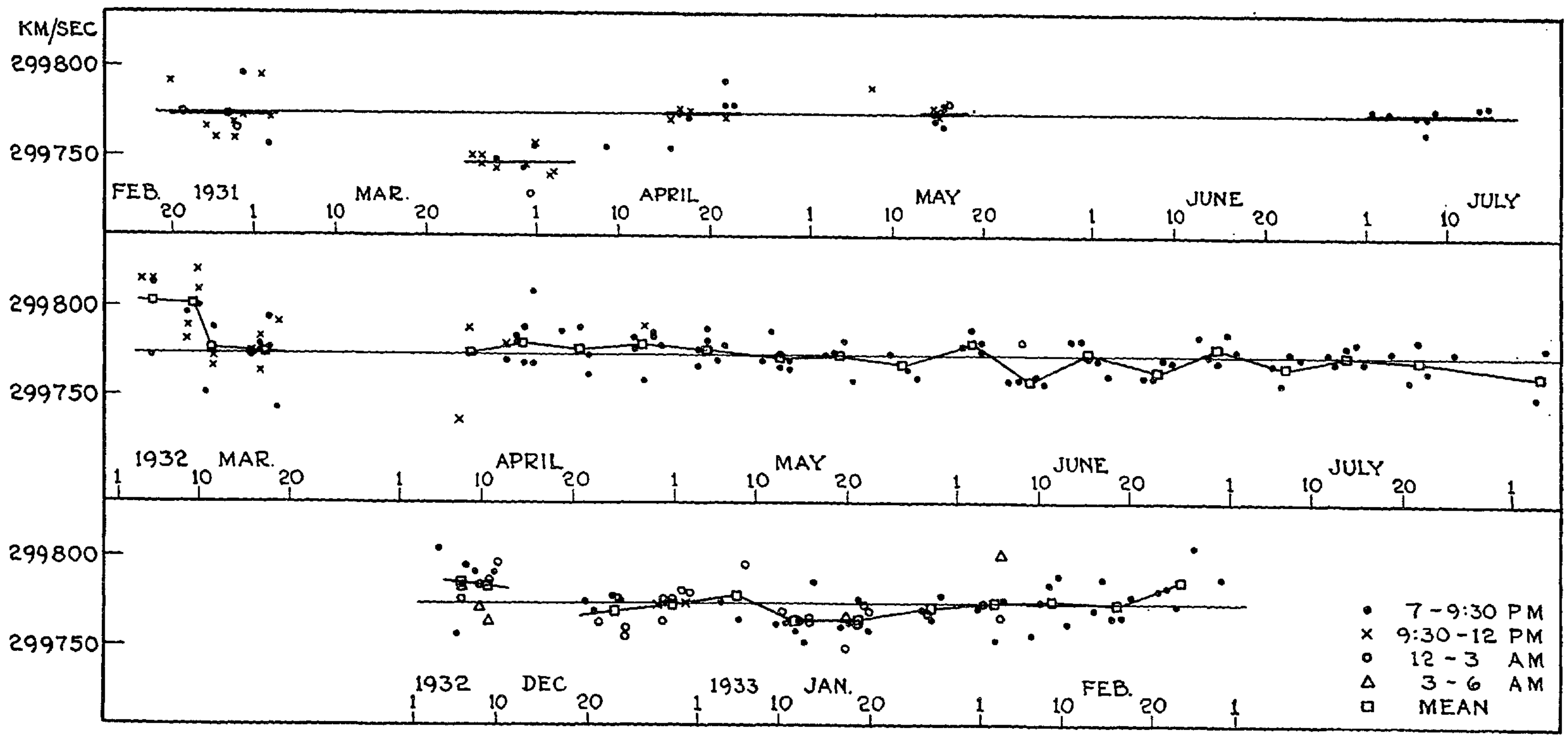


FIG. 9.—Velocity-time curve

tinues just above the axis until early in May, then drops to 299,760 km/sec. early in June. Several fluctuations occur in the curve at this time. The curve remains below the axis until the end of the observations on August 4. The 1932–1933 curve begins at about 299,785 km/sec. early in December, crosses the axis twice, and reaches a value of 299,765 km/sec. on January 15. It then gradually rises to a value of 299,787 km/sec. by the end of February.

Tidal-force-velocity curves.—When the time-velocity curves were first plotted, a curve freely drawn through the individual points appeared to resemble the tidal curve of the water depth at the nearby

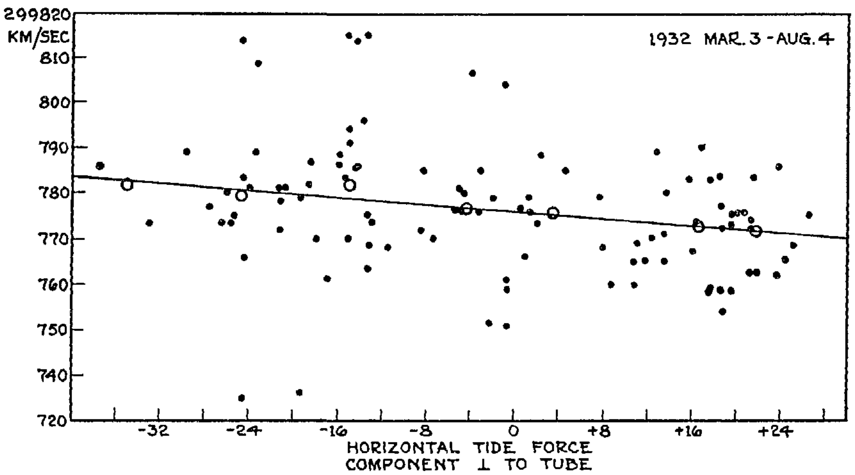


FIG. 10.—Velocity-tide-force curve

coast, if the tidal curve were displaced 10 hours forward. Since the lunitidal interval in this locality is 10 hours, the agreement seemed to suggest a relationship with sun-moon tidal forces acting at the time of observation and not with earth displacements due to the changing weight of water on the coast. The direct action of the tidal forces in producing earth expansion or in changing the period of the pendulum is too small to produce displacements of the order noted. Nevertheless, component curves of the sun-moon tide forces were kindly drawn by the United States Coast and Geodetic Survey on their tide-predicting machine, from which values of component tidal forces were obtained for the times of observation. A slight correlation with the velocity is suggested in the case of the horizontal component perpendicular to the tube. The plot for early 1932 readings (Fig.

10) shows large velocities for a strong tidal force pulling in a southeasterly direction, and small velocities for a force directed northwesterly. A change of 10 km/sec. corresponds to a change of 1.35×10^{-7} g. The scattering of the points is so large, however, that it is questionable whether the plot has any real significance.

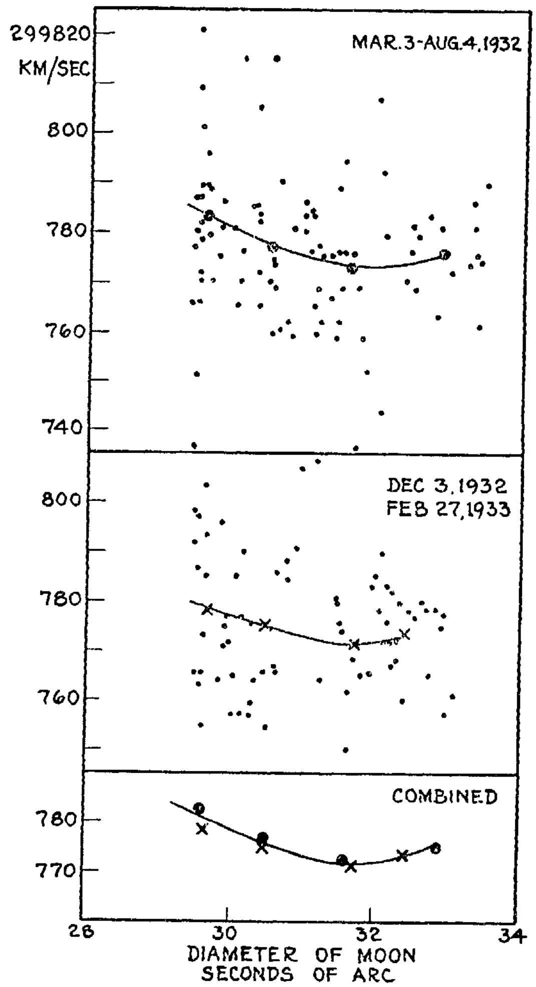


FIG. 11.—Velocity-moon-diameter curve

Moon-diameter-velocity curves.—The diameter of the moon, which can be taken as a measure of its distance at the times of observation, was plotted against velocity for both the early 1932 and the 1932–1933 data (Fig. 11). Both curves show the same feature, namely, a curve convex downward, almost coincident in the plots, indicating high velocities for both large and small diameters of the moon and suggesting tidal effects. The scattering, however, is large and the results of low weight.

Repeated measures of the base line and checks on the clock rate revealed nothing capable of accounting for the residual differences between the mean curve and the axis. A vibration of the mirror system with a period equal to a fraction of that of the rotating mirror conceivably may have produced the rapid fluctuations observed in the individual readings. Further experiments on a more stable terrain, with improved self-recording apparatus, carried on continuously over an extended period of time will be necesssary to clear up the problem.

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