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The Ether-Drift Experiment and the Determination of the Absolute Motion of the Earth

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CONTENTS

THE ETHER-DRIFT EXPERIMENT, HISTORICAL 1878–1881

THE general acceptance of the theory that light consists of wave motion in a luminiferous ether made it necessary to determine the essential properties of the ether which will enable it to transmit the waves of light and to account for optical phenomena in general. Theories of the ether are intimately associated with theories of the structure of matter and these are among the most fundamental in the whole domain of physical science. The ether was presumed to fill all space, even that occupied by material bodies, and yet to allow all bodies to move through it with apparent perfect freedom. The question of whether the ether is carried along by moving bodies such as the earth has been considered since the early days of the wave theory. The discovery of the aberration of light, in 1728, was soon followed by an explanation according to the then accepted corpuscular theory of light. The effect was attributed to a simple composition of the velocity of light with the velocity of the earth in its orbit. Fresnel proposed an explanation based on the wave theory, which has been generally accepted, which presumes first that the ether is at rest in free space; and, second, that the "ether density" is different in different substances and that the velocity of propagation of light in any substance varies inversely as the square root of the ether density. These two hypotheses give a complete and satisfactory explanation of aberration; the second is considered to have been proved by the experiments of Fizeau and of Michelson and Morley on the velocity of light in moving media; the first hypothesis, that of an ether at rest in space, has always been in doubt.

The first suggestion of a method for measuring the relative motion between the earth and the ether by means of an optical experiment was made by James Clerk Maxwell in the article on "Ether," which he contributed to Vol. VIII of the 9th Edition of the *Encyclopaedia Britannica*, published in 1878. It is assumed that the ether as a whole is at rest, that light waves are propagated in the free ether in any direction and always with the same velocity with respect to the ether and that the earth in its motion in space passes freely through the ether without disturbing it. The experiment is based upon the argument that the apparent velocity of light would be different according to whether the observer is carried by the earth in the line in which the light is travelling or at right angles to this line. It would thus be possible to detect a relative motion between the moving earth and the stationary ether, that is to observe an "ether drift." The orbital motion of the earth has a velocity of thirty kilometers per second, while the velocity of light is ten thousand times as great, three hundred thousand kilometers per second. If it were possible to measure the direct effect of the earth's orbital motion on the apparent velocity of light, then the velocity measured in the line of motion should differ from the velocity at right angles to this line by thirty kilometers per second, that is by one part in ten thousand. This would be a "first-order effect." Maxwell explains that, since all practicable methods require that the light shall travel from one station to another *and back again* to the first station, a positive effect of the earth's motion on the ray going outward would be neutralized by a negative effect on the returning ray, except that on account of the motion of the observer during the time the light is travelling the neutralization would not be quite complete, and a "second-order effect," proportional to the square of the ratio of the velocity of the earth to the velocity of light, would be observable. Maxwell concludes with the statement, "The change in the time of transmission of the light on account of a relative velocity of the aether equal to that of the earth in its orbit would be only one hundred-millionth part of the whole time of transmission, and would therefore be quite insensible."

The late Professor Albert A. Michelson accepted the challenge of Maxwell's suggestion and while attending the University of Berlin in 1880–1881, he devised the remarkable instrument universally known as the Michelson interferometer which was especially adapted to the ether-drift experiment.[1, 2] In the interferometer a

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[1] A. A. Michelson, Phil. Mag. [5] **13**, 236 (1882); Am. J. Sci. **23**, 395 (1882); H. A. Lorentz, Astrophys. J. **68**, 345 (1928); Thos. Preston, *Theory of Light*, 5th ed., 229, 566 (1928); R. W. Wood, *Physical Optics*, 2nd ed. 265, 672 (1911).

[2] W. M. Hicks, Phil. Mag. [6] **3**, 9, 256, 555 (1902);

beam of light is literally split in two by a "half-silvered mirror," and the two beams of light may be made to travel paths at right angles to each other. At the end of the desired path, each beam is reflected back upon itself and the two come together where they first separated. If the two right-angled paths are optically equal, the reunited beams of light will blend with the waves in concordance. If, however, the paths of the light in the interferometer differ either in actual length or in the optical properties of the medium through which the light passes, differences of phase will result which may be observed as "interference fringes." Observation of these fringes enables one to detect exceedingly small changes in the relative velocities of the light in the two paths of the interferometer, the measurements being made in terms of the wave-length of the light.

Michelson at once applied his interferometer to detect the relative motion of the earth and the ether as proposed by Maxwell. Alexander Graham Bell provided for the construction of the new instrument, Fig. 1, which was made by Schmidt & Haensch of Berlin. The half-silvered mirror was placed over the central axis, and two arms at right angles, each 120 centimeters long, carried the end mirrors. The apparatus could be set with the telescope arm pointing in different azimuths and it should be possible to detect the effect of the orbital motion of the earth when the light travels in the direction of this motion and at right angles to it.

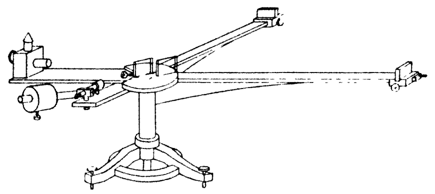

FIG. 1. Michelson's ether-drift interferometer of 1881.

The first trials of the ether-drift experiment were made at the *Physikalisches Institut* of the University in Berlin; but the disturbances produced by street traffic made it impossible to see the fringes except in the middle of the night. The experiment was transferred to the Observatory in Potsdam, the interferometer being mounted in a hollow place in the lower part of the brick pier which supported the big telescope. The report of the experiment, published in 1881[3] (with a correction explained in the paper of 1887),[4] states that, considering only the motion of the earth in its orbit, the displacement of the interference fringes to be expected would be 0.04 of the fringe width; the displacements actually observed varied from 0.004 to 0.015 of a fringe width and were considered to be merely errors of experiment. The conclusion was that the hypothesis of a stationary ether was not confirmed.

THE MICHELSON-MORLEY EXPERIMENTS, CLEVELAND, 1887

While he was still in Europe, in 1881, Michelson was appointed to the Professorship of Physics in the newly organized Case School of Applied Science in Cleveland and thus became acquainted with the late Professor Edward W. Morley, Professor of Chemistry in Western Reserve University, these two institutions being located side by side. Professor Morley proposed several important developments in the interferometer and in the method of using it, so that it became adequate to measure the *then expected* effect in the ether-drift experiment. Having secured an appropriation from the Bache Fund of the National Academy of Sciences, a new interferometer was constructed, embodying these improvements; the optical parts were made by the late John A. Brashear of Pittsburgh. In order to avoid disturbances of vibration and distortion, the optical parts were mounted on a solid block of sandstone, Fig. 2, which was floated on mercury contained in a circular tank of cast iron. This support by floatation made it possible to turn the interferometer to different azimuths while observations were in progress. The practicable limit for the size of the stone base was 150

Nature **65**, 343 (1902); E. W. Morley and D. C. Miller, Phil. Mag. [6] **9**, 669 (1905); A. Righi, Comptes Rendus **168**, 837 (1919); **170**, 497, 1550 (1920); **171**, 22 (1920). E. R. Hedrick, Astrophys. J. **68**, 374 (1928).

[3] A. A. Michelson, Am. J. Sci. [3] **22**, 120 (1881).

[4] A. A. Michelson and E. W. Morley, Am. J. Sci. [3] **34**, 333 (1887); Phil. Mag. [5] **24**, 449 (1887); J. de Physique [2] **7**, 444 (1888).

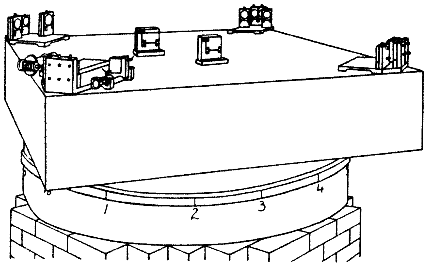

FIG. 2. The Michelson-Morley interferometer of 1887.

centimeters square and 30 centimeters thick. In order to obtain the necessary sensitivity, the effective light path was increased by reflecting the light back and forth so that it traversed the diagonal of the square stone block eight times, giving the effect of an interferometer with an arm about 1100 centimeters in length. The expected displacement of the fringes due to a velocity equal to that of the earth in its orbit was 0.4 of a fringe width.

Michelson and Morley performed the historic experiment in the northwest room of the basement of the Main Building of Adelbert College in Cleveland in 1887; their entire series of observations was of six hours' duration, one hour at noon on each day of July 8, 9 and 11, and one hour in the evening of July 8, 9 and 12 and consisted of thirty-six "turns" of the interferometer, readings being made at each of sixteen equidistant points in each turn. The method of observation was arranged to detect the preconceived effect of the motion of the earth toward a known point in space with a given velocity, and hence no general series of observations was made. The brief series of observations was sufficient to show clearly that the effect did not have the anticipated magnitude. However, and this fact must be emphasized, *the indicated effect was not zero;* the sensitivity of the apparatus was such that the conclusion, published[4] in 1887, stated that the observed relative motion of the earth and ether did not exceed one-fourth of the earth's orbital velocity. This is quite different from a null effect now so frequently imputed to this experiment by writers on Relativity. It also seems necessary to call attention to another historical fact: Michelson and Morley made only the one series of observations, in July, 1887, and never repeated the ether-drift experiment at any other time, notwithstanding many printed statements to the contrary.

In the original account of their experiment, Michelson and Morley give the actual readings for the position of the interference fringes in the six sets of observations. The upper one of the two long curves in Fig. 3, shows the average of the three sets of readings taken at noon, and the lower long curve is the average for the three sets taken in the evening. These curves show the fringe displacements for a full turn of the interferometer, while the ether-drift effect being sought is periodic in each half turn. To find the latter effect, the second half of the long curve is superimposed on the first half by addition, which

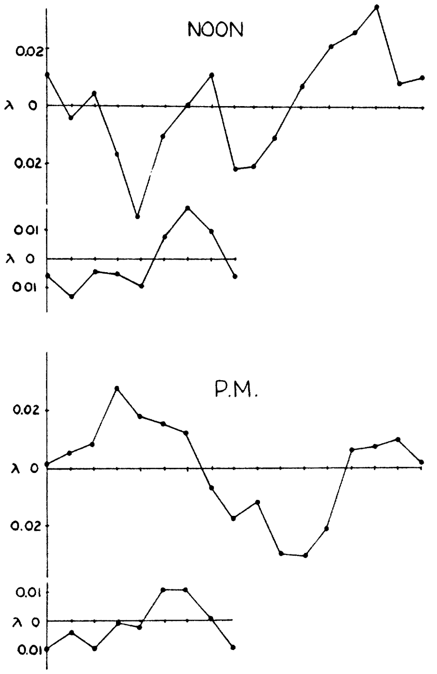

FIG. 3. Fringe displacements of the original Michelson-Morley experiments of 1887.

cancels the full-period effect and all odd harmonics, giving the shorter curve which is the desired half-period effect (together with any higher even harmonics which may be present). Inspection shows clearly that these curves are not of zero value, nor are the observed points scattered at random; there is a positive, systematic effect. These full-period curves have been analyzed by the mechanical harmonic analyzer, which determines the true value of the half-period effect; this, being converted into its corresponding value for the velocity of relative motion of the earth and ether, gives a velocity of 8.8 kilometers per second for the noon observations, and 8.0 kilometers per second for the evening observations. In Fig. 4, the smooth curve shows the value of the ether-drift throughout the day for the latitude of Cleveland, as determined by the specifications of the drift which are derived later in this report from the observations made at Mount Wilson. The two circles on this chart show the magnitude of drift actually obtained by Michelson and Morley for the noon and evening observations, indicating a result wholly consistent with the later work here reported.

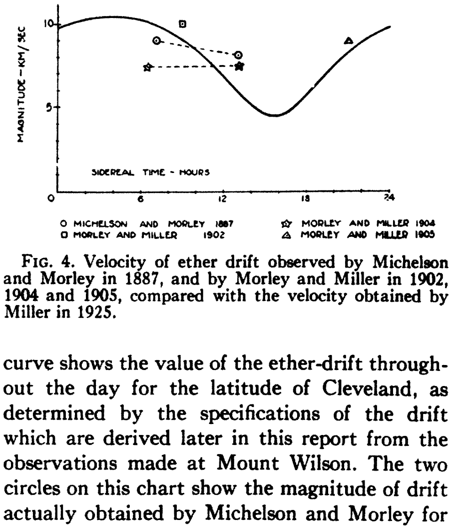

FIG. 4. Velocity of ether drift observed by Michelson and Morley in 1887, and by Morley and Miller in 1902, 1904 and 1905, compared with the velocity obtained by Miller in 1925.

The fact that the result obtained by Michelson and Morley was not negligibly small was very fully set forth by Professor Hicks of University College, Sheffield, in 1902, in his important theoretical examination of the original experiment.[2] Hicks also called attention to the presence of a full-period, first-order effect, which has never been sufficiently investigated; this first-order effect will be considered later.

THE LORENTZ-FITZGERALD HYPOTHESIS

The Michelson-Morley experiment, which indicated that the theory of the ether was either incomplete or incorrect, attracted world-wide attention because of its fundamental character and because the result was wholly unexpected. Professor FitzGerald of Dublin, in 1891, offered an explanation for the small effect on the hypothesis that the forces binding the molecules of a solid might be modified by the motion of the solid through the ether in such a way that the dimension of the stone base of the interferometer would be shortened in the direction of motion and that this contraction might be such as to neutralize the optical effect sought in the Michelson-Morley experiment. FitzGerald did not publish this theory in a scientific journal but he expounded it in his lectures. This hypothesis was given publicity by Sir Oliver Lodge in his address on *Aberration Problems and New Ether Experiments*, presented to the Royal Society on March 31, 1892, which address was published in the *Philosophical Transactions* for the year 1893.[5] Lodge has given further details of this historical fact in his recently issued autobiography.[6] In 1895 Professor Lorentz of Leyden developed the theory in a systematic manner, on the supposition that the particles of all solids are held together by electrical forces; and that a motion of the body as a whole would superpose upon the electrostatic forces between the atoms a magnetic effect due to the motion. There would result a contraction of the body in the direction of motion which is proportional to the square of the ratio of the velocities of translation and of light and which would have a magnitude such as to annul the effect of ether-drift in the Michelson-Morley interferometer.[7] If the contraction depends upon the physical properties of the solid, it was suggested by others that while the expected effect might be annulled in one apparatus, it might in an apparatus of different material give place to an effect other than zero, perhaps with a contrary sign.

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[5] G. F. FitzGerald, see O. J. Lodge, *Aberration Problems*, Phil. Trans. Roy. Soc. **184**, 749 (1894).

[6] Sir Oliver Lodge, *Past Years*, 204 (1932).

[7] H. A. Lorentz, *Versuch einer Theorie der electrischen und optischen Erscheinungen in bewegten Körpern* (Leyden, 1895); *Theory of the Electron*, 195 (1909).

THE MORLEY-MILLER EXPERIMENTS, CLEVELAND, 1902–1906

The interferometer of wood, 1902

At the International Congress of Physics held in Paris in connection with the International Exposition of 1900, Lord Kelvin gave an address in which he expounded certain theories of the ether, and he explained the significance of the results of the Michelson-Morley experiments as related to these theories.[8] Professor Morley and the writer were present and in a later conversation with Lord Kelvin he strongly urged the repetition of the ether-drift experiment with a more powerful apparatus. Morley and Miller then constructed an interferometer designed especially to test the Lorentz-FitzGerald hypothesis. The base of this instrument was in the form of a cross, made of planks of white pine wood about 430 centimeters long, providing a light-path more than three times as long as that used by Michelson and Morley in 1887. The general dimensions, optical parts and methods of observing with this apparatus were the same as for the steel interferometer described in detail in following sections of this paper. The instrument was mounted in the northwest corner room of the basement of the Main Building of Case School of Applied Science and three series of observations were made in August, 1902, and in June, 1903, consisting of 505 turns of the interferometer. A small positive effect was observed, indicated by the square in Fig. 4, which, while slightly larger than that of the previous experiment, was still so small as to indicate that if the reduction of the observed velocity is to be attributed to the hypothetical contraction, the pine is affected by about the same amount as is the sandstone. The changes in the wooden support due to variations in humidity and temperature made it difficult to obtain accurate observations and it was decided to abandon the pine apparatus and to construct one having a base of metal for supporting the heavy parts, while the length of the optical path could be determined by various substances, wood or metal, as desired.

While planning a new apparatus, experiments were made to show that differences of magnetic attraction on the iron parts of the instrument could not influence the observations. Massive bars of iron were suspended at the opposite ends of one of the long arms of the cross, so that one bar should be parallel to the earth's magnetic field while the other was transverse to this field, these relations being reversed on reversing the azimuth of the apparatus. Observations with this load gave the same results as before. In a further experiment, an analytical balance was placed on one arm with which to weigh a bar of iron having a mass of about 1200 grams. It was so oriented that at one azimuth of the apparatus the bar was parallel to the lines of the earth's magnetic field, while at another it was transverse to the field. A difference of half a milligram could have been detected but no such difference existed. By observing the effect produced by a known weight on one arm of the interferometer, it was shown that the earth's magnetism could not be a disturbing factor.

Description of the new steel interferometer

An appropriation from the Rumford Fund of the American Academy of Arts and Sciences made possible the construction, in 1904, of an entirely new apparatus of steel. The design for the base of the interferometer, made by Professor F. H. Neff of the Department of Civil Engineering of Case School of Applied Science, provided that all optical parts and accessories should be carried by two girders of structural steel, Figs. 5, 10 and 14, each about 430 centimeters long, which intersect in the form of a cross. The purpose of this design was to secure structural symmetry and the utmost rigidity.

The steel cross rests on a circular float of wood, Fig. 5, 150 centimeters in diameter; on the under

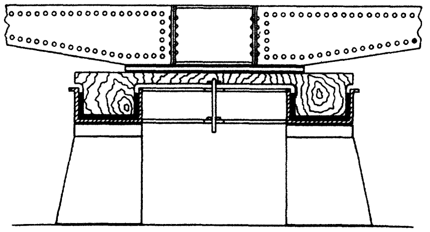
FIG. 5. Cross section of the mercury float for the interferometer.

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[8] Lord Kelvin, *Rapports présentés au Congres International de Physique* **2**, 1 (1900).

side of the circle is an annulus of wood having an outside diameter of 150 centimeters, an inside diameter of 80 centimeters, and a thickness of 20 centimeters. This float of wood rests on mercury contained in an annular trough of cast iron, of such dimensions as to leave a clearance of about one centimeter around the wood, which space is filled with mercury. It requires about 275 kilograms of mercury to float the entire apparatus which weighs about 1200 kilograms. The float is kept central by a loose-fitting centering pin which sustains no pressure. The annular iron tank is supported by piers of brick or concrete at such a height as to bring the eyepiece of the observing telescope level with the eye of the observer when he takes the posture for easy walking around with the interferometer as it rotates slowly on the mercury. The cast iron trough for the mercury together with the circular wooden float are the same parts as were used in the original Michelson-Morley interferometer of 1887 and these two pieces have been continued in use by the writer to the present time. The other parts of the apparatus of 1887 have been dispersed, excepting only three of the cast iron supports for the mirrors.

The optical flat surfaces were all made in 1902 by that artist-optician, O. L. Petitdidier of Chicago, and proved to be exceptionally perfect; these consist of two plane-parallel plates, each 10.5×17.5 centimeters in size, and sixteen plane mirrors of circular shape, 10.25 centimeters in diameter. The general plan of the interferometer is shown in the diagram, Fig. 6, which, however, is not drawn to the exact scale. On a central plate, at the intersection of the arms of the cross, are mounted the half-silvered diagonal mirror, *D*, and its compensating plate, *C*, both having been cut from a single plane-parallel disk. At the outer end of each cross-arm, four of the circular mirrors are mounted in a metal plate which is supported in a vertical position. Each of the eighteen mirrors is held by springs against the points of three adjusting screws to permit the necessary adjustments for securing interference. In order to have everything about the two arms as symmetrical as possible, there is no micrometer screw for moving the end mirror parallel to itself, all the adjustment being obtained by means of the three simple screws, as for the other mirrors. Light from the source, *S*, is rendered parallel by the triple-lens condensing system, *L*, of 15 centimeters diameter, and reaches the half-silvered mirror, *D*. Part of this light is transmitted to the mirror, I-1; it is successively reflected to mirrors, 2, 3, 4, 5, 6, 7, and 8, having travelled a distance equal to about seven and a half times the length of the arm of the cross. From mirror 8 the light returns by the same path back to *D*, where it is partially reflected to the observing telescope, *T*. A second portion of the light incident on *D* is reflected along the other arm of the cross to II-1, is reflected to and fro and is returned to *D* and is in part transmitted to the observing telescope. In the actual apparatus, Fig. 10, the mirrors 5 and 7 are above mirrors 3 and 1 instead of at the side of them, and mirrors 6 and 8 are above mirrors 4 and 2. By this system of mirrors the effective length of the arm of the interferometer is greatly increased and in the actual apparatus it is 3203 centimeters, giving a total light-path, going and returning, of 6406 centimeters, equal to about 112,000,000 wave-lengths of the acetylene light used in the experiment. The telescope had an aperture of 3.3 centimeters, a focal length of 35 centimeters, and a magnifying power of thirty-five diameters. The telescope is focussed on the surface of mirror 8

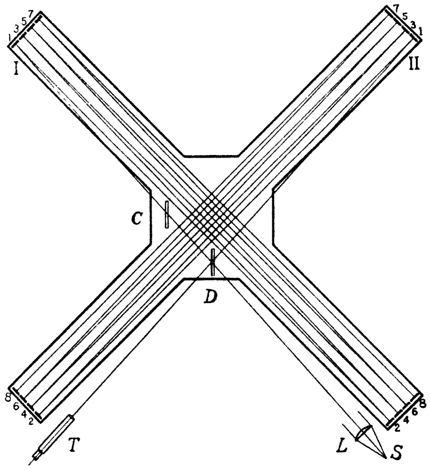


FIG. 6. Plan of the optical paths in the interferometer.

where, when the adjustments are completed, the interference fringes appear to be located.

The apparatus as described, consisting of the optical plane surfaces, the steel cross and the mercury tank and float, has been used by the writer in all experiments from 1904 to the present time, except that for the experiments of December, 1921, the steel cross was replaced with a base of concrete. In 1923, the small reading telescope was replaced by an astronomical telescope of 13 centimeters aperture, having a magnifying power of fifty diameters. The whole path of the light in the apparatus is enclosed; this cover was made of pine wood throughout for the experiments of 1904; in 1905 the cover had glass sides for all arms, thus making the apparatus wholly transparent in the horizontal plane; this arrangement, shown in Figs. 13 and 16, has been used to the present time.

Adjustment of the interferometer

When the mirrors are in position, the distances between them, about 425 centimeters, are compared by means of light wooden rods and the mirrors are adjusted so that the two light-paths, each consisting of eight different portions, are approximately equal. Sodium light from the common laboratory type of sodium lamp is used to establish interference; by observing the visibility maxima of the sodium interference system, the adjustment is made for the center of this system where the white-light fringes may be found. When the apparatus was first assembled on Mount Wilson, the time required for the approximate adjustment of the distances between mirrors with the wood rods was about one hour, for the centering of the mirrors fifteen minutes, for finding the fringes with sodium light thirty minutes, and for finding the fringes with white light forty-five minutes, or two hours and a half for the entire operation. Upon another occasion, the fringes for sodium light were found with ten minutes of searching and the white-light fringes in thirty-five minutes more. The mercury arc and other monochromatic sources have been tried for the preliminary adjustments but the sodium light is preferred because the middle portion of the interference system can be easily located, which corresponds to equal light-paths in the two arms of the interferometer. White-light fringes were chosen for the observations because they consist of a small group of fringes having a central, sharply defined black fringe which forms a permanent zero reference mark for all readings. Previous to 1924, a small acetylene lamp of the kind used on bicycles, was the source of light, the lamp being carried on a bracket attached to the end of one arm of the interferometer, as shown in Figs. 10 and 13. Such a lamp produces a concentrated, brilliant and very steady light with the minimum production of heat and the lamp itself is very simple and of small weight and it burns for several hours with little attention. For the observations of 1924 and for part of the observations of April, 1925, the source was placed outside of the interferometer room, as is explained later, and a larger lamp of the kind used for automobile headlights, shown in Fig. 14, was used. In April, 1925, the small acetylene lamp was again adopted, now being placed on the top of the cover of the interferometer, over the central axis, as shown in Fig. 16, the light being introduced into the light-path by two mirrors on the end of one arm. This arrangement has been continued to the present. Monochromatic fringes have never been used in the ether-drift observations, though experimental trials have been made, as is described later.

The interference fringes appear to be formed on the surface of the most distant mirror, optically speaking, No. 8, of the series as described. Attached to the supporting frame of this mirror is a small arrow-head of brass, which projects into the field of view, almost in contact with the mirror, forming a fixed fiducial mark for determining the position of the fringe system. Before beginning observations the end mirror, No. 8, on the telescope arm is very carefully adjusted to secure vertical fringes of suitable width. There are two adjustments of the angle of this mirror which will give fringes of the same width but which produce opposite displacements of the fringes for the same change in one of the light-paths. Very careful attention is required always to secure that adjustment of this critical angle which causes the arrow-head pointer to appear to the *right* of the central black fringe when the light-path of the telescope arm of the interferometer increases in effective length; a reading for such a position is recorded as plus. When the pointer appears to the left of the central fringe the reading is minus, corresponding to a shortening of the telescope arm. The adjustment commonly employed is such that from six to ten fringes appear in the field of view and so that the central black fringe is never more than two fringe-widths from the pointer. Fig. 7 shows the field of view with adjustments for narrow fringes and for wide fringes, the latter corresponding to the conditions of actual observation.

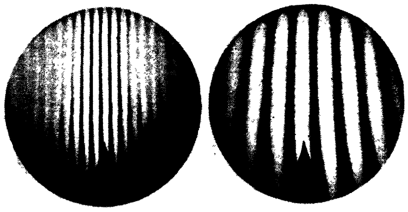


FIG. 7. The interference fringes as seen in the interferometer.

Method of using the interferometer

The method of using the interferometer for the detection of an ether-drift presumes that the telescope arm of the instrument will be placed in the line of motion of the earth with respect to the ether as projected on the plane of the interferometer, while the other arm is at right angles to this motion. The interference fringes will indicate a certain reading with respect to the pointer in the field of view. The apparatus is then turned through an angle of azimuth of 90° so that the effect of the earth's motion on the apparent velocity of light is transferred from the telescope arm to the other arm, with the result that the interference system will be displaced by an amount depending upon the square of the ratio of the velocity of the earth's absolute motion to the velocity of light. However, the direction of the earth's absolute motion is unknown and it is not possible to place the interferometer certainly in the desired positions. The interferometer is therefore caused to rotate slowly on the mercury float so that the telescope points successively to all azimuths. A relative motion of the earth and ether would then cause a periodic displacement of the interference fringes, the fringes moving first to one side and then to the other as referred to the pointer in the field of view, with two complete periods in each rotation of the instrument.

Uniform temperature conditions are important as regards the dimensions of the apparatus and the refraction of the air in the light path. Usually the apparatus is kept in motion for an hour or more before readings are begun; sometimes a fan is used to secure uniform temperature distribution and the opening of the windows on all sides is common. However, when observations are made in daylight, the windows must be covered with curtains or dark paper. The apparatus is set in rotation by a pull of a few ounces on a fine string attached to the wooden float; a moderate pull on this string, even up to its breaking point, does not produce any appreciable distortion in the steel interferometer which rests on the float. The interferometer turns so easily and has such inertia that when once started it will continue to turn for an hour and a half or more without any further pull or push. It rotates with such freedom that it is literally "floating" without acceleration or distortion.

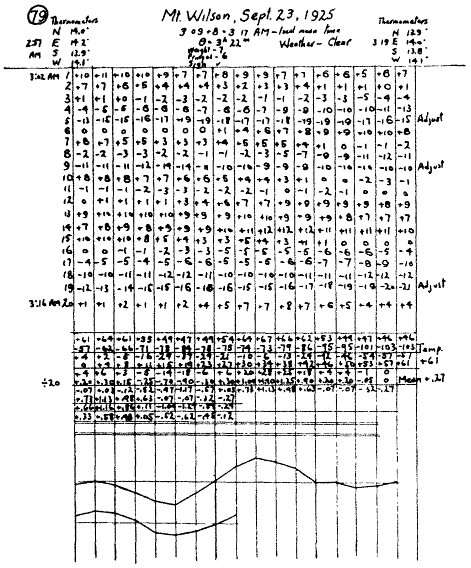
The purpose of the observation is to determine the amount of the displacement of the fringes and the direction in which the telescope points when this displacement is a maximum. The observer has to walk around a circle about twenty feet in diameter, keeping his eye at the moving eyepiece of the telescope attached to the interferometer which is turning on its axis steadily, at the rate of about one turn in fifty seconds; the observer must not touch the interferometer in any way and yet he must never lose sight of the interference fringes, which are seen only through the small aperture of the eyepiece of the telescope, about a quarter of an inch in diameter. The string attached to the float, mentioned above, may be used as a sensitive guide to assist the observer in maintaining the proper circular path. A delicate metal brush attached to the wood float touches in succession sixteen equidistant contact pieces on the mercury tank, closing an electric circuit which operates a small sounder and indicates the instants at which readings are to be made.

It is entirely practicable to make the readings of the positions of the interference fringes corresponding to the sixteen equidistant azimuths of one complete turn of the interferometer when the instrument is turning at the rate of one turn in about fifty seconds. A "set" of readings which corresponds to a "single observation," represented by one point on the charts of the original observations, usually consists of twenty turns, involving three hundred and twenty readings, made in about eighteen minutes. The time midway between the beginning and ending of the set of readings is taken as the time of the observation. The twenty turns are ordinarily observed in continuous succession; however, if a single reading at any one azimuth is lost, due to vibration of the support or other cause, the entire turn is cancelled. The adjustments are maintained so that the central fringe of the field of view, Fig. 7, is never more than two fringe-widths from the fiducial point. Often the temperature drift is such that the fringes shift more than this before a set of twenty turns is completed. When this occurs, the fringe system is restored to its central position simply by placing a small weight of two or three hundred grams on the end of the arm or by removing a weight from the arm. This is done without stopping the uniform turning of the apparatus and usually without interrupting the readings; if a reading is lost, the entire turn is cancelled and the observations are continued until twenty complete turns of readings have been secured. Only rarely is it necessary to readjust the fringes by means of the screws against which the end mirror rests. On some occasions the temperature conditions are so steady that no adjustment of fringes is required through several sets, which may cover an interval of an hour or more. Such sets of observations are repeated continuously during the several hours of the working period.

It is considered very important that the interferometer should not be enclosed in a metallic casing, nor even in an opaque covering; also that it should not be placed inside a room with heavy walls such as are required for a constant-temperature room. The apparatus should be, as nearly as possible, in the open so that there is no possibility of entrainment of the ether in massive materials surrounding it. The instrument is very sensitive to changes of temperature and to vibration of the support and the quantity to be measured is extremely small. When the apparatus is used with the least possible covering, it is subjected to greater temperature disturbances than when fully protected, which results in greater dispersion among the separate readings; it is therefore necessary to accumulate a larger number of readings as rapidly as possible under these conditions and to arrange and combine them in such a manner that the systematic ether-drift effect will be fully preserved while the temperature changes which proceed more slowly will be eliminated in the final average. As the readings are taken at intervals of about three seconds, the position of the maximum displacement is dependent upon readings covering an interval of less than ten seconds. A complete period of the displacement takes place in about twenty-five seconds. Any temperature effect or other disturbing cause which is not strictly *periodic* in every twenty-five seconds over an interval of fifteen minutes would largely be cancelled out in the process of averaging, while a real periodic effect persists. Thus the observations for the direction of the absolute motion are largely independent of ordinary temperature variations. The observation is a differential one and can be made with considerable certainty under all conditions. Disturbances, due to temperature or other causes lasting for a few seconds or for a few minutes, might affect the actual amount of the observed displacement and give less certain values for the velocity of the ether-drift while, at the same time, the position of maximum displacement is not altered.

Previous to 1925, the time of actual readings had been confined to one or two hours at a predetermined time of day; the time required for preparation and preliminary adjustments would perhaps be two hours more. The procedure adopted in 1925 makes it necessary to have observations equally distributed over the twenty-four hours of the day to determine the curve of diurnal variation. Allowing a few minutes for reading thermometers and for making readjustments of fringes and also a few minutes for relaxation, two sets of readings may be made in each hour through a working day, or night, of eight hours. The accumulation of a hundred sets of readings, distributed over the twenty-four hours of the day will, under favorable weather conditions, occupy a period of six or eight days. Such a series of observations is finally reduced to one group, corresponding to the mean date of the epoch; several series of this extent are represented in Fig. 22.

The observer has only one single thing to do, that is to note and announce the position of the central black fringe with respect to the fiducial point, plus or minus, in units of a tenth of a fringe width, at the instant of the click of the electric sounder. An assistant records these readings in order, on a prepared form, starting with the reading corresponding to the north or other noted azimuth, as shown in Fig. 8, which is the record of actual observations made at Mount Wilson on September 23, 1925. The observer gives no attention to the azimuth. The reading is determined by instantaneous visual estimation; it is quite impracticable to use any kind of a scale in the field of view because the width of the fringes is subject to slight variation. That this method is sufficient is shown by the uniformly consistent and systematic periodic curves representing the observations. The numerical quantity used as the result of a "single observation" is the average of forty such readings (the function being periodic in each half-turn) and it approaches an accuracy of a hundredth of a fringe.



(79) Thermometers N 14.0° 2:57 AM E 14.2° S 12.9° W 14.1°

Mt. Wilson, Sept. 23, 1925

3 09 + 8 = 3 17 AM—local mean time

θ = 3h 22m Weather—Clear

Thermometers N 12.9° 3 19 E 14.0° S 13.8° W 14.1°

3:02 AM 1	+10	+11	+10	+10	+9	+7	+7	+8	+9	+9	+7	+7	+6	+6	+5	+8	+7	
2	+7	+7	+6	+5	+4	+4	+4	+3	+2	+3	+3	+4	+1	+1	+1	+0	+1	
3	+1	+1	+0	-1	-2	-3	-2	-2	-2	-1	-1	-2	-3	-3	-5	-4	-4	
4	-4	-5	-5	-6	-8	-8	-7	-8	-8	-7	-9	-9	-10	-10	-10	-11	-13	
5	-13	-15	-15	-16	-17	-19	-19	-18	-17	-17	-18	-19	-19	-19	-17	-16	-15	Adjust
6	0	0	0	0	0	0	0	+1	+4	+6	+7	+8	+9	+9	+10	+10	+8	
7	+8	+7	+5	+5	+3	+3	+3	+4	+5	+5	+5	+4	+1	0	-1	-1	-2	
8	-2	-2	-3	-3	-2	-2	-1	-1	-2	-3	-5	-7	-9	-9	-11	-12	-11	
9	-11	-11	-11	-12	-14	-14	-11	-10	-10	-9	-9	-9	-10	-10	-14	-10	-10	Adjust
10	+8	+8	+8	+7	+7	+6	+6	+5	+4	+4	+3	+1	0	0	-2	-3	-1	
11	-1	-1	-1	-2	-3	-3	-2	-2	-2	-1	0	-1	-2	-1	0	0	0	
12	0	+1	+1	+1	+1	+3	+4	+6	+7	+7	+9	+9	+9	+9	+9	+8	+9	
13	+9	+10	+10	+10	+10	+9	+9	+9	+10	+10	+9	+9	+9	+8	+7	+7	+7	
14	+7	+8	+9	+8	+9	+9	+9	+10	+11	+12	+12	+12	+11	+11	+11	+11	+10	
15	+10	+10	+10	+8	+5	+4	+3	+3	+5	+4	+3	+1	+1	0	0	0	0	
16	0	0	-1	-1	-2	-3	-3	-5	-5	-5	-5	-5	-6	-6	-6	-5	-4	
17	-4	-5	-5	-4	-5	-6	-6	-5	-5	-5	-6	-6	-7	-7	-8	-9	-10	
18	-10	-10	-11	-11	-12	-12	-11	-10	-10	-10	-10	-11	-11	-11	-12	-12	-12	
19	-12	-13	-14	-15	-15	-16	-18	-16	-15	-15	-16	-17	-18	-19	-19	-20	-21	Adjust
3:16 AM 20	+1	+1	+2	+1	+1	+2	+4	+5	+7	+7	+8	+7	+6	+5	+4	+4	+4	

Temp. +61

÷20 Mean +.27

FIG. 8. Form of record of ether-drift observations.

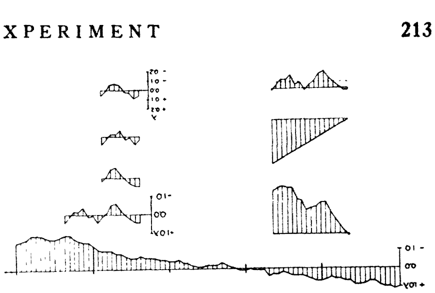


FIG. 9. Interferometer readings and the process of reducing them for the ether-drift effect.

While readings are being taken, neither the observer nor the recorder can form the slightest opinion as to whether any periodicity is present, much less as to the amount or direction of any periodic effect; the taking of observations is quite unprejudiced and is simply mechanical. That this must be true will be evident from an inspection of the numbers representing the readings as recorded in the chart, Fig. 8, and shown graphically in Fig. 9.

Reduction of the interferometer observations

The numerical reduction of a set of readings is a simple arithmetical process. In the record, Fig. 8, the horizontal lines give the sixteen readings for one turn of the interferometer, the first reading being that when the telescope points to the north; the readings for twenty turns are shown. The seventeenth number at the end of each line is the first reading of the next succeeding line or turn; if an adjustment of fringes is made, this number is for the beginning of the next turn, before the adjustment is made. The twenty numbers in each column are added with respect to the plus and minus values. Under ideal conditions, all the numbers in column one (and in column seventeen) should be the same integer but actually there is always some shift of the fringe system with respect to the fiducial point. This shift is assumed to be steady, or linear, throughout the time of one turn, about twenty-five seconds, which is equivalent to assuming that the periodic displacements of the fringes take place with respect to an inclined axis. A compensation for the shift is made by adding to the sum of the seventeenth column such a number as will make it equal to the sum of the first column and by adding one-sixteenth, two-sixteenths, etc. of this compensating number to the second, third, etc. columns; this renders the axis of reference horizontal. These compensated sums of the sixteen columns of readings are divided by twenty, the number of turns of recordings, giving the average positions of the central black interference fringe for each of the sixteen azimuths of one complete turn around the horizon. The mean ordinate is now subtracted from the ordinate of each point and these points, plotted, will give the curve of fringe displacement referred to its own time axis.

In the definitive study of the ether-drift effect, this set of sixteen average readings for the position of the interference fringes is plotted to a large scale and is subjected to mechanical harmonic analysis to evaluate precisely the second harmonic component, which represents the second-order, half-period ether-drift effect; this process is illustrated in Fig. 21 in a later section. For the purpose of a preliminary study of the observations, it is convenient to obtain an approximate graphic representation of the effect by the following procedure. The second half of the line of sixteen average readings is placed under the first half and the mean of the two numbers in each column is obtained; by this addition any periodic full-period effect is eliminated and also any effect of all higher odd harmonic components. The final line of eight numbers represents the mean values of the ordinates of the half-period effect, together with higher even harmonics which may be present, obtained from *forty* sets of readings of this second-order effect. At the bottom of the chart, Fig. 8, are plotted the readings for the full turn of the interferometer, which contain all the effects observed and below this the readings for the half-period effects.

The set of readings here illustrated is not exceptional; it is a fair sample as to magnitude and periodicity of the ether-drift effect. This particular displacement corresponds to an ether-drift velocity of 9.3 kilometers per second. Every set of readings shows a very definite periodicity which varies both as to magnitude and phase in a systematic manner.

The method of reducing the observations is further illustrated by the graphic representation of Fig. 9 which shows the complete process as applied to the first five turns of the record given in Fig. 8. The readings for the five turns are plotted to scale at the top of the figure. Below this at the left is shown the summation of the five turns for the sixteen azimuths of one complete turn in which the periodic displacements clearly oscillate about the downwardly inclined axis; below this are the linear compensations for the shift and next below this the sums of the readings with the shift eliminated. The mean of the sixteen ordinates is subtracted from each ordinate, giving the curve referred to its own true axis, as shown at the right. Below this are shown the two halves of the full-turn curve, one below the other; still lower is the half sum of the two curves, from which the full-period effect is now eliminated. This is the average effect for the half period obtained from the sum of the five turns; for final evaluation the ordinates are to be divided by five; this is indicated by a change of scale in the figure. It is interesting to note that the full-turn and the half-turn curves obtained from the readings for five turns are almost identical with the corresponding curves obtained from the full set of readings for twenty turns shown in Fig. 8.

Stability of the interferometer

The steel cross which forms the base of the interferometer has proved to be remarkably stable and dependable. The length of the light path, going and returning, is about 112,000,000 wave-lengths and, for the production of the interference fringes in white light, the two light paths, which are at right angles to each other and each of which consists of sixteen separate parts, must be exactly equal to the fraction of a wave-length. A difference in length of from five to ten wave-lengths displaces the white-light interference system so much that it is no longer visible in the telescope when the adjustment is made for wide fringes. The screws used for the adjustment of the end mirror, No. 8, have threads 0.635 millimeter apart, and a turn of the screw through 16° causes a change of 100 wave-lengths in the light path. These screws are turned by means of capstan pins in order to secure sensitive adjustment. Usually the final adjustment of the central fringe to the fiducial point is secured by means of small weights placed on the end of the arm of the cross, causing a change of length by flexure.

Tests have been made at various times to determine the rigidity of the steel cross; these show that the four arms are about equally rigid and that a weight of 282 grams placed on the end of one arm produces an elongation in the multiple light-path sufficient to displace the fringe system one fringe-width, which is less than one hundred-millionth part of the light path. Similar tests made on the concrete base used for the interferometer in December, 1924, showed that 30 grams on the end of the arm produce a displacement of one fringe-width; the concrete base was therefore nearly ten times as sensitive to distortion as is the steel.

A change in temperature of the apparatus as a whole causes a slight change in the relative lengths of the arms. The white-light fringes having been adjusted to the center of the field of view, a change in temperature causes the fringes to be displaced out of view; however, the change is quite reversible and a return to the first temperature brings the fringes again into view. It has occurred repeatedly that at the close of a day's work the fringes would be in the field of view and upon returning the next day, after the drop and rise in temperature of the night, the fringes would be in the field without any readjustment. The temperature influence on the apparatus is so consistent that a scale of temperature is provided for the capstan pin of the adjusting screws. A change of 10° in temperature requires a change of about 18° in the turning of the screw, corresponding to a displacement of 112 wave-lengths in the double light-path.

The sodium light is used in making the adjustments when the apparatus is first assembled at the beginning of a series of observations. After the white-light fringes have been found these are rarely lost and it is not necessary to resort to the monochromatic light again during the entire period of observations, unless the apparatus is disassembled for some cause. The white-light fringes have been kept in adjustment during a period of two weeks or more. Upon the completion of observations at Mount Wilson in September, 1925, the mirrors and other optical parts were removed and packed for safekeeping. When observations were resumed in February, 1926, the mirrors were repolished and all parts were reassembled; the fringes in white-light were found in less than one minute without the use of the sodium light.

Since 1927, the interferometer has been mounted on the campus of Case School of Applied Science, about 330 feet from Euclid Avenue; the passage of street cars and the motor traffic of the city thoroughfare do not interfere with the making of observations. However, it is interesting to note that the sound of the imperfectly muffled exhaust of a motor-truck or a motorcycle, which may be a thousand feet or more distant, will cause the fringes to disappear completely without the slightest tremor. When observations were being made on the Fourth of July, 1904, the discharge of large fire crackers twelve hundred feet distant, produced the same effect. This is due not to mechanical vibration, but to the passage of the sound waves through the air in the light path of the interferometer. On several occasions in the observations made at Mount Wilson, there were minute but very distinct seismic disturbances which for a few seconds completely obliterated the fringes. After one such "earthquake," or micro-seismism, it was necessary to readjust the end mirror through a distance of twenty wave-lengths. A man chopping a stump of wood, several hundred feet away, disturbed the fringes, as also did workmen on a highway three miles distant; the passing of an airplane overhead caused the disappearance of the fringes.

Observations by Morley and Miller in 1904

The interferometer with the steel-girder base was first used by Morley and Miller in a continuance of the test of the Lorentz-FitzGerald contraction hypothesis. For this purpose the mirrors were so mounted that the distances between them could be made to depend upon the lengths of rods of pine wood. On two ends of the cross, *S* and *T*, Fig. 6, are two upright frames of

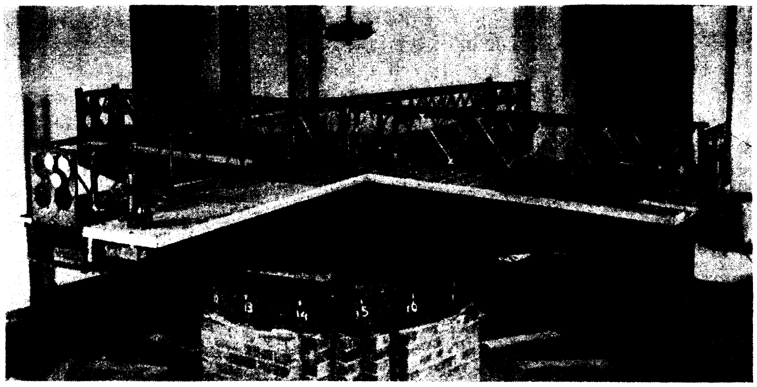


FIG. 10. The Morley-Miller ether-drift interferometer arranged for tests of the Lorentz-FitzGerald hypothesis, 1904.

cast iron, fastened by bolts; each frame carries four mirrors. Against the corners of each of these frames rest four pine rods, about 2 centimeters in diameter and 425 centimeters long. Each rod is supported throughout its length by a brass tube, 2.5 centimeters in diameter, and each pair of tubes is joined together in a vertical truss, as shown in Fig. 10. Against the farther ends of the wood rods, rest the frames which hold the other sets of mirrors. Each of the latter frames is freely suspended by two thin steel ribbons and is held firmly against the pine rods and through these against one of the two fixed mirror-holders; contact is maintained by means of adjustable spiral springs. Thus the distances between the opposite systems of mirrors depend upon the pine rods only, while the whole optical system is adequately supported by the steel cross.

The first observations with this apparatus were made in July, 1904, and consisted of 260 turns of the interferometer arranged in two series. The procedure was based upon the effect to be expected from the combination of the diurnal and annual motions of the earth, together with the presumed motion of the solar system towards the constellation Hercules. On the dates chosen for the observations there were two times of the day when the resultant of these motions, about 33.5 kilometers per second, would lie in the plane of the interferometer, 11:30 o'clock, A.M., and 9:00 o'clock, P.M. The calculated azimuths of the motion would be different for these two times but the velocities would be the same and the observations at these two times were, therefore, combined in such a way that the presumed azimuth for the morning observations coincided with that for the evening. The observations for the two times of day gave effects having positive magnitudes but having nearly opposite phases; when these were combined, the half sum was nearly zero. This small result was opposed to the theory then under consideration and it seemed impossible to reconcile the observations with the known orbital motion of the earth. The report of these experiments, published in the *Philosophical Magazine*,[9] in May, 1905, concludes with this statement: "If pine is affected at all as has been suggested, it is affected to the same amount as is sandstone. Some have thought that this experiment only proves that the ether in a certain basement room is carried along with it. We desire, therefore, to place the apparatus on a hill to see if an effect can be there detected." The two curves for the ether-drift obtained from the morning and the evening observations of July, 1904, are shown in Fig. 11, being superimposed, as explained above; the lower curve represents the mean displacement thus obtained, which is the result given in the published account of these experiments.

In accordance with the results set forth later in this report, this procedure of 1904 was incorrect,

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[9] E. W. Morley and D. C. Miller, Phil. Mag. [6] **9**, 680 (1905); Proc. Am. Acad. Sci. **41**, 321 (1905).

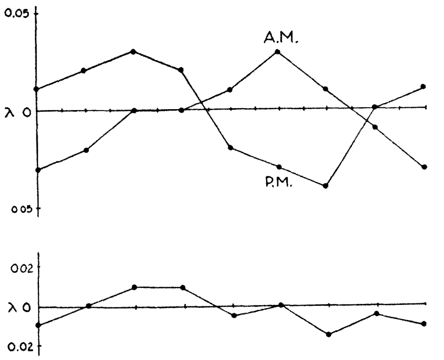

FIG. 11. Method of combining the ether-drift observations of July, 1904, now considered erroneous.

being based upon an erroneous hypothesis as to the resultant absolute motion of the earth. The morning and evening observations each indicate a velocity of ether drift of about 7.5 kilometers per second; these values are charted in Fig. 4 in relation to the magnitudes predicted by the new hypothesis of a much larger predominating cosmic motion of the solar system and show reasonable consistency.

Observations by Morley and Miller in 1905

In 1905, the interferometer was mounted in a temporary hut on a site in Cleveland Heights, free from obstruction by buildings and at an altitude of about 285 meters. The house was provided with glass windows at the level of the interferometer so that there should be no opaque screens in the plane of drift. The test of the contraction hypothesis was continued; the wooden rods which determined the length of the optical path in the experiments of 1904 were omitted and all the mirror frames were fastened to the steel base, so that, for contrast, the optical distances were now determined by the steel. The program also included an investigation of an ether drift with the apparatus at the higher elevation and free from obstruction by buildings. The observations made here in July, October and November, 1905, consisting of 230 turns in three sets, showed a very definite positive effect slightly larger than that previously obtained, but still too small to be reconciled with the expectation. The velocity of relative motion of the earth and ether obtained from the observations made in October is 8.7 kilometers per second; this is shown on the chart, Fig. 4; as compared with the result to be expected from the new theory here presented, the agreement is almost perfect. Plans were made for testing various modifications of theory but before these were carried out circumstances beyond control required that the interferometer be dismounted. Professor Morley retired from active service and it devolved upon the writer to continue the experiments. It seemed desirable that further observations should be carried out at a much higher altitude but several causes prevented the immediate resumption of the work. Other interests developed and though the expectation of continuing the experiments persisted, a long delay ensued.

THE INCEPTION OF THE THEORY OF RELATIVITY, 1905

The Theory of Relativity had its inception at this time when Einstein published his paper entitled *Zur electrodynamik bewegter Körper*, in November, 1905,[10] and was elaborately developed in succeeding years. The tests of the theory of relativity, made at the solar eclipse of 1919, were widely accepted as confirming the theory. Since the Theory of Relativity postulates an exact null effect from the ether-drift experiment which had never been obtained in fact, the writer felt impelled to repeat the experiment in order to secure a definitive result. An elaborate program was prepared and ample funds to cover the very considerable expense involved were very generously provided by Mr. Eckstein Case of Cleveland.

THE MOUNT WILSON EXPERIMENTS, 1921

Observations of April, 1921. Steel interferometer

Through the courtesy of the Carnegie Institution of Washington, the ether-drift interferometer was set up on Mount Wilson in March, 1921, on the grounds of the Mount Wilson Observatory, on Rock Crusher Knoll or "Ether Rock" as it came to be called, near the site of the 100-inch telescope, at an altitude of about 1750 meters. A concrete foundation was laid on the bare rock of

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[10] A. Einstein, Ann. d. Physik 17, 891 (1905).

the knoll and four concrete piers were formed to support the iron mercury tank at a suitable height. This was enclosed in a light housing, Fig. 12, twenty feet square and about twelve feet high at the ridge of the roof. The sides of the house were enclosed with sheets of corrugated iron, except that at a height of from four to seven feet above the floor, on *all* sides there were continuous "windows" of white canvas cloth. The canvas was attached to a series of frames so that the windows could be opened on all sides at the level of the interferometer, for a width of three feet. In the south end was a small door with iron and canvas panels to match the sides of the house. A rough flooring was placed a little above the rock; on this floor a smooth circular track was constructed on which the observer could walk comfortably while following the interferometer as it turns slowly on its axis. This house was purposely constructed with wide cracks at the various joints in the sides and floor and under the eaves, so that there should be a very free circulation of air to secure equalization of temperature with the outside air. The opening of the windows on all sides greatly facilitated this condition. In order to secure sufficient darkness for the observation of the fringes in the daytime, sheets of thin black paper were placed over the canvas windows and over such holes and cracks as admitted too much light. Electric current was supplied to the house and several fixed and portable lamps were available. Common and precision thermometers were hung on each side of the house and were read at the beginning and end of each set of observations. A barograph and a thermograph were carried at all times on the interferometer itself. An anemometer was attached to the roof of the house. A copy of the Mount Wilson Observatory meteorological records was also secured for the duration of the observations. These general arrangements apply to all subsequent experiments.

FIG. 12. Interferometer house on "Ether Rocks," Mount Wilson.

Observations were begun on April 8 and continued till April 21, 1921, by means of the apparatus and methods employed by Morley and Miller in 1904 and 1905, with certain modifications and developments in details. The first observations of sixty-seven sets consisting of 350 turns gave a positive effect such as would be produced by a real ether-drift, corresponding to a relative motion of the earth and ether of about ten kilometers per second. Before announcing such a result, it seemed necessary to study every possible cause which might produce a displacement of fringes similar to that caused by ether-drift; among the causes suggested were radiant heat, centrifugal and gyrostatic action, irregular gravitation effects, yielding of the foundation, magnetic polarization and magnetostriction. In order to test the first, the metal parts of the interferometer were completely covered with cork about one inch thick, and fifty sets of observations consisting of 273 turns were made; there was a periodic displacement of the fringes, as in the first observations, showing that radiant heat is not the cause of the observed effect.

Observations of December, 1921. Concrete interferometer

In the summer of 1921, the steel frame of the interferometer was dismounted and a base of one piece of concrete, Fig. 13, reinforced with brass, was cast in place on the mercury float. All the metal parts which were supported on the concrete base were made of aluminum or brass. The entire apparatus was free from magnetic effects and the possible effects due to heat were much reduced. In December, 1921, forty-two sets of observations, consisting of 422 turns, were made with the nonmagnetic interferometer. These show a positive effect as of an ether drift, which is

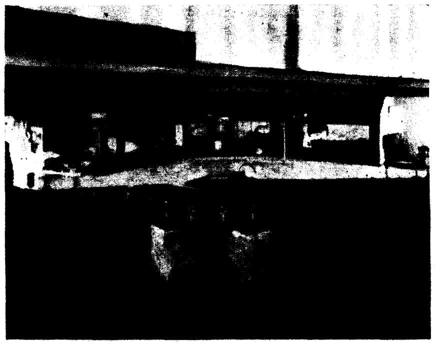

FIG. 13. Interferometer with base of concrete, 1921.

entirely consistent with the observations of April, 1921.

Many variations of incidental conditions were tried at this epoch. Observations were made with the centering pin tight in its socket and then loose; with rotation of the interferometer clockwise and counterclockwise; with a rapid rotation of one turn in 40 seconds and a slow rotation of one turn in 85 seconds; with a heavy weight added first to the telescope arm of the main frame and then to the lamp arm; with the float extremely out of level because loaded first in one quadrant and then in the next quadrant; with the recording assistant walking round in different quadrants and standing in different portions of the house, near to and far from the apparatus. The results of the observations were not affected by any of these changes.

It was demonstrated that the use of the concrete base did not change the effect observed with the steel base either in magnitude or azimuth. The concrete base was less affected than the steel by change of dimensions due to changes of temperature; but this slight advantage was counterbalanced by the fact that it accommodated itself more slowly to a change of temperature. In spite of the fact that the concrete was considerably heavier than the steel parts which it displaced, it was much less rigid. Tests showed that a weight of 30 grams placed on the end of the arm of the interferometer would produce a displacement of the fringes of one fringe width, while nearly ten times as much weight is required to produce the same effect with the steel base. The concrete base was abandoned and the original steel base has been used in all subsequent observations.

LABORATORY TESTS OF THE INTERFEROMETER, CLEVELAND, 1922–1924

The entire apparatus was returned to the laboratory at Cleveland; during the years 1922 and 1923 many trials were made under various conditions which could be controlled and with many modifications in the details of the apparatus. An arrangement of mirrors and prisms was made so that the source of light could be placed outside of the observing room, Fig. 14, the

FIG. 14. The interferometer in the laboratory, 1923.

light entering the rotating interferometer along the axis of rotation. A further arrangement of mirrors, rather complicated in practice, was tried, for observing the fringes from a stationary telescope; the necessity for frequent adjustment of the fringes in the field of view made this method impracticable. Experiments were made with devices for the photographic registration of the positions of the fringes, both from the fixed observing station and by means of a motion picture camera carried on the interferometer. Even with an arc light as the source, there was not sufficient illumination to produce a satisfactory photographic record without slowing the rotation of the apparatus more than is consistent with our method of procedure, and the necessity for frequent adjustment of the fringes also made this method unsuitable. After abandoning the photographic method, an astronomical telescope having an objective of 13 centimeters aperture and a focal length of 190 centimeters was mounted on the interferometer. The object-glass is attached to the steel base near the half-silvered diagonal glass and the eyepiece is supported on the end of the arm, there being no tube for the telescope. With a magnification of fifty diameters, the fringes are observable on a large scale and with ample illumination, so that direct reading with the eye was very satisfactory; this arrangement has been used in all subsequent observations.

Trials were made with various sources of light; with electric arc and incandescent lamps, the mercury arc, acetylene lamp and also with sunlight. The interchange between sunlight and laboratory sources in no way altered the results. The final choice for the stationary source placed outside of the interferometer room (or house, on the mountain) was a large acetylene lamp of the kind commonly used for automobile headlights. This arrangement was used in Cleveland in 1924 and at Mount Wilson in September, 1924, and in April, 1925. The use of a stationary light source with the light brought to the interferometer in the axis of rotation required very careful adjustment of the several mirrors involved in order to avoid a periodic displacement of fringes due to non-axial alignment. Careful trials were made which showed that it was better to place the source on the interferometer outside of the cover and near the axis; thus the relation of source to the instrument remained constant. When this method was adopted, the small acetylene lamp, such as was used in the earlier experiments, was employed. This method of illumination has been used exclusively since April 9, 1925.

An extended series of experiments was made to determine the influence of inequality of temperature in the interferometer room and of radiant heat falling on the interferometer. Several electric heaters were used, of the type having a heated coil near the focus of a concave reflector. Inequalities in the temperature of the room caused a slow but steady drifting of the fringe system to one side but caused no periodic displacement. Even when two of the heaters, placed at a distance of three feet from the interferometer as it rotated, were adjusted to throw the heat directly on the uncovered steel frame, there was no periodic effect that was measurable. When the heaters were directed to the air in the light-path which had a covering of glass, a periodic effect could be obtained only when the glass was partly covered with opaque material in a very nonsymmetrical manner, as when one arm of the interferometer was completely protected by a covering of corrugated paper-board while the other arms were unprotected. These experiments proved that under the conditions of actual observation, the periodic displacements could not possibly be produced by temperature effects.

The Mount Wilson Experiments, 1924

Upon the conclusion of the experiments just described, in July, 1924, the interferometer was taken again to Mount Wilson. In 1921 the apparatus had been located on the very edge of a deep canyon; it was feared that the air currents up and down the face of the canyon might produce a disturbance and also that the unsymmetrical distribution of the rock of the mountain itself might be undesirable. In August, 1924, a new site was chosen on a very slightly rounded knoll, removed from the canyons. The interferometer house, Fig. 15, was erected with its orientation, as regards the ridge of the roof and the location of the door, changed by 90° from

FIG. 15. Ether-drift house at Mount Wilson in 1924–1926.

that of 1921. The house was about twenty-two feet square, and there were canvas windows all around as before; but instead of the corrugated iron for the sides, beaver-board was used, as this material is less absorbent of heat from the sun. Large pieces of canvas were placed over the entire house and at the end, to protect the house from the direct rays of the sun, greatly facilitating the making of observations throughout the period of daylight. The interferometer, Fig. 16, had the improved mirror mountings, protection from heat, improved light-source, large viewing telescope and other refinements which had been developed in the laboratory tests at Cleveland in 1923 and 1924.

This series of observations, of September, 1924, at Mount Wilson, was undertaken in a wholly unprejudiced but very confident state of mind. The extended laboratory tests had involved every suggested source of instrumental and external disturbance and had proved that none of these was operative in the experiment. The method of observing was so developed that there was perfect confidence in the readings. It was felt that if any of the suspected disturbing causes had been responsible for the previously observed effects, now these were removed, the result would be a true null effect. Such a conclusion would have been accepted with entire satisfaction; and indeed it was almost expected. On the other hand, if the observations continued to give the positive effect, it would certainly have to be considered as real.

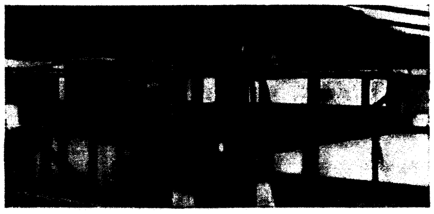

FIG. 16. The ether-drift interferometer as used at Mount Wilson in 1924–1926.

Ten sets of readings, consisting of 136 turns of the interferometer, were made on September 4, 5 and 6, 1924. These observations all show a positive periodic displacement of the interference fringes, as of an ether-drift, of the same magnitude, about ten kilometers per second, as had been obtained in previous trials. Part of these observations were made with the glass case over the light-path covered with corrugated paper board, which had been found in the Cleveland experiments to exclude all effects of radiant heat; the results were not altered in any way by this covering. The effects were shown to be real and systematic, beyond any further question.

In spite of the long continued efforts, it had so far been impossible to account for the effects observed in the interferometer as being due to terrestrial causes or to experimental errors. Very extended calculations were made in the effort to reconcile the observed effects with the accepted theories of the ether and of the presumed motions of the earth in space. The observations had been repeated at various epochs to test one after another of the hypotheses which had been suggested. At the end of the year 1924 when a solution seemed impossible, a complete calculation was made, for all hours of the day and for twenty-four epochs during the year, of the then expected effects due to the orbital motion and the apparent motion towards Hercules. This indicated that the effect to be expected had its greatest magnitude in April and that the minimum in April should be two and a half times as great as the effect at the time of the observations which had been made in September and that the maximum effect in April should be four and a half times as great. Furthermore, the effect in September would be directed to the northward at all times of the day while in April the azimuth of the effect would move progressively all around the horizon, the maximum value being attained at midnight with a direction exactly east and again at noon with a direction exactly west. Observations for verifying these contrasting predictions were made at Mount Wilson between March 27 and April 10, 1925. The effect was equal in magnitude to, but not larger than, the effects previously observed; it was not directed successively to all points of the compass, that is, it did not point in directions 90° apart at intervals of six hours. Instead of this, the direction merely oscillated back and forth through an angle of about 60°, having, in general, a northerly direction, as before. This proved that the presumptions as to the absolute motion of the earth, upon which these calculations were based, were invalid.

General Analysis of the Ether-Drift Problem

The various component motions involved

Previous to 1925, the Michelson-Morley experiment had always been applied to test a specific hypothesis. The only theory of the ether which had been put to the test is that of the absolutely stationary ether through which the earth moves without in any way disturbing it. To this hypothesis the experiment gave a negative answer. The experiment was applied to test the question only in connection with specific assumed motions of the earth, namely, the axial and orbital motions combined with a constant motion of the solar system towards the constellation Hercules with the velocity of about nineteen kilometers per second. The results of the experiments did not agree with these presumed motions. The attention was given almost wholly to this velocity of the ether drift, and no attempt was ever made to determine the apex of any indicated motion. The experiment was applied to test the Lorentz-FitzGerald hypothesis that the dimensions of bodies are changed by their motions through the ether; it was applied to test the effects of magnetostriction, of radiant heat and of gravitational deformation of the frame of the interferometer. Throughout all these observations extending over a period of years, while the answers to the various questions have been "no," there has persisted a constant and consistent small effect which has not been explained.

The ether-drift interferometer is an instrument which is generally admitted to be suitable for determining the relative motion of the earth and the ether, that is, it is capable of indicating the direction and the magnitude of the *absolute motion* of the earth and the solar system in space. If observations were made for the determination of such an absolute motion, what would be the result, independent of any "expected" result? For the purpose of answering this general question, it was decided to make more extended observations at several epochs when the earth is in contrasting positions in its orbit and this was done in the months of April, August and September, 1925, and in February, 1926.

It may be asked: why was not such a procedure adopted before? The answer is, in part, the fact already stated that the purpose had been the verification of certain predictions of the so-called classical theories; and, in part, that it is not easy to develop a new hypothesis, however simple, in the absence of direct indication. Probably a considerable reason for the failure is the great difficulty involved in making the observations at all times of day at any one epoch. Very few, if any, scientific experiments require the taking of so many and continuous observations of such extreme difficulty; it requires greater concentration than any other known experiment. Half the time, perhaps, the observations are interrupted before they become numerous enough to be useful, because of excessive displacement of the fringes by temperature changes or by earth or aerial vibrations. The mere adjustment of an interferometer for white-light fringes and the keeping of it in adjustment, when the light path is 210 feet long, made up of sixteen different parts, and when it is in effect in the open air, requires patience as well as a steady "nerve" and a steady hand. Professor Morley once said, "Patience is a possession without which no one is likely to begin observation of this kind."

The absolute motion of the earth may be presumed to be the resultant of two independent component motions. One of these is the orbital motion around the sun, which is known both as to magnitude and direction. For the purposes of this study, the velocity of the orbital motion is taken as 30 kilometers per second and the direction changes continuously through the year, at all times being tangential to the orbit. The second component is the cosmical motion of the sun and the solar system. Presumably this is constant in both direction and magnitude but neither the direction nor magnitude is known; the determination of these quantities is the particular object of this experiment. The well-known motion of the solar system towards the constellation Hercules, with a velocity of 19 kilometers per second, is only a *relative* motion of the sun with regard to the group of nearby stars and it may give no information as to the motion of the group as a whole. In fact, the previous ether-drift experiments have clearly shown that the motion towards Hercules is not a component of the absolute motion of the earth. The rotation of the earth on its axis produces a velocity of less than four-tenths of a kilometer per second in the latitude of observation and is negligible as far as the velocity of absolute motion is concerned; but this rotation has an important effect upon the apparent direction of the motion and is an essential factor in the solution of the problem. However, since the orbital component is continually changing in direction, the general solution is difficult; but by observing the resultant motion when the earth is in different parts of its orbit, a solution by trial is practicable. For this purpose it is necessary to determine the *variations* in the magnitude and in the direction of the ether-drift effect throughout a period of twenty-four hours and at three or more epochs of the year.

The interferometer continually rotates in a horizontal plane about a vertical axis at the latitude of the observatory. As the earth rotates on its axis, the axis of the interferometer extended may be considered as the generating element of a cone, the apex of which is at the center of the earth. The earth in its orbital motion carries this cone around the orbit, the axis of the cone, the earth's axis, always pointing in the same direction in cosmic space. At the same time this system with rotations about three different axes is being translated through space in an unknown manner. It is presumed, further, that the ether-drift interferometer will detect *only* that single component of the complicated combination of translations and rotations which at the instant lies in the optical plane of the interferometer; it gives the magnitude and direction of this one component. Fig. 17 shows a globe with a model representing an interferometer attached at a point corresponding to Mount Wilson. The wire extending from the pole of the globe indicates the direction of an assumed resultant absolute motion. With the earth in the position shown in the left view, the projection of the motion indicated by the wire, on the plane of the interferometer, passes through the north and south points and has a magnitude less than the full value of the motion. When the earth has turned on its axis to the position shown in the middle view, the projection of the absolute motion in the plane of the interferometer lies to the west of north; as the interferometer rotates on its axis the telescope will detect the maximum component when it points west of north. When the earth has turned to the position shown at the right, the projected component of motion will again be north and south and will have a maximum value, slightly less than the full value. Thus there is a diurnal variation in the observed azimuth of ether-drift. It is evident, further, that the angle which the absolute motion makes with the plane of the interferometer varies throughout the day as the interferometer is carried around on the cone described by its axis. In the illustration, the absolute motion most nearly coincides with the plane of the interferometer in the right view which corresponds to a maximum observed effect; in the left view, the motion is more nearly perpendicular to the plane of the interferometer and the effect is a minimum. It follows that there is a diurnal variation in the magnitude of the effect and this is quite independent of the

FIG. 17. Models illustrating the diurnal variation in the magnitude and direction of the ether-drift effect.

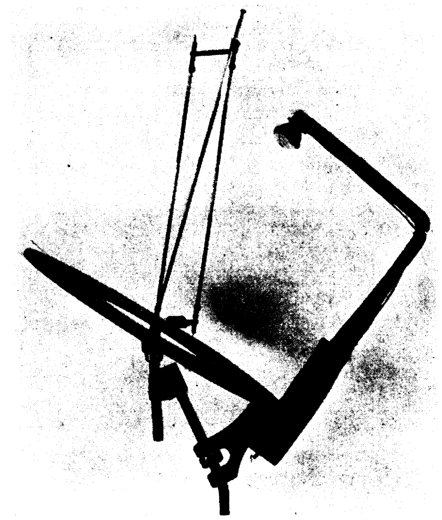

FIG. 18. Model for studying the components of ether-drift.

azimuth variation, except insofar as they may be produced by one cause.

The model shown in Fig. 18, was prepared to assist in a study of the ether-drift effect in its astronomical relations. The large circular disk represents the plane of the interferometer which can be rotated around the inclined polar axis, bringing its plane into all the possible diurnal positions, corresponding to the Mount Wilson location. At the center of the disk is mounted a parallelogram whose sides can be made to represent any assumed values for the two components of the absolute motion, while the directions can be set as desired and the corresponding resultant will be reproduced. A small electric lamp is so supported that, as the interferometer is rotated around the polar axis and while the parallelogram remains stationary, the lamp casts the shadow of the resultant on the plane of the interferometer, showing how the azimuth of the drift varies with the time of day. The angle which the resultant makes with the plane can be observed and thus the variation in magnitude of the drift for the assumed motion is determined. A probable value for the cosmical component of motion having been selected, a single wire representing the resultant for any epoch is substituted for the parallelogram and the diurnal variations in azimuth and magnitude are studied. Three views of the model, Fig. 19, show how the azimuth swings to the west of north and then to the east, for the motion assumed.

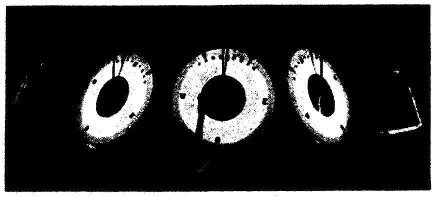

FIG. 19. Model illustrating the diurnal variation in the azimuth of the ether-drift.

It is evident from these models that the observed ether-drift effect would be very different for different resultant motions, as for different epochs, and that it would vary greatly in different latitudes. The conditions shown correspond approximately to the results here to be considered.

Solution for the absolute motion of the solar system

The point on the celestial sphere towards which the earth is moving because of its absolute motion is called the apex of its motion. This point is defined by its right ascension and declination, as is a star, and the formulae of practical astronomy are directly applicable to its determination from the interferometer observations. The theoretical consideration of the determination of the apex of the motion of the earth has been given in a paper by Professor J. J. Nassau and Professor P. M. Morse, which appeared in the *Astrophysical Journal* for March, 1927.[11]

Knowing the latitude of the observatory, ϕ, and the sidereal time, θ, of the observation, two independent determinations may be obtained for the right ascension, α, and for the declination, δ, of the apex of the earth's absolute motion, one determination from the observed velocity, V, and one from the azimuth, A, of the ether-drift effect. The ether-drift effect being a second order effect, periodic in each half turn of the apparatus,

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[11] J. J. Nassau and P. M. Morse, Astrophys. J. **65**, 73 (1927).

it follows that if a certain magnitude of effect is observed when the telescope points in a given direction, exactly the same effect will be obtained when the interferometer has been rotated 180° and the telescope points in the opposite direction. The interferometer observations determine the line in which the motion takes place but do not distinguish between the plus and minus directions of the motion in this line; the choice between the plus sign, northward, and the minus sign, southward, must be determined from the consistency of the result when this motion is combined with the known orbital motion of the earth. For simplicity in the presentation of the formulae, they will be given for an apex having a north declination and for an observatory located in the northern hemisphere. If the final solution requires a motion to the southward, the new apex will be diametrically opposite the one first determined; its right ascension will be the right ascension of the first apex minus 12 hours and its declination will have the same numerical value as that for the first apex but with the minus sign. For an observatory located in the southern hemisphere there would be certain systematic differences in the formulae which need not be given here.

The apex of the absolute motion determined from the magnitude of the ether-drift effect

It is shown in the paper by Nassau and Morse, what is also evident from a study of the model, Fig. 17, that the sidereal time, when the component of motion in the plane of the interferometer is a minimum, $\theta_{v=\min}$, measures the right ascension of the apex; that is

$$\alpha=\theta_{v=\min}.$$

It is evident that the component of motion in the plane of the interferometer is

$$v=V\sin z,$$

V being the velocity of the absolute motion and z the zenith distance of its apex.

If $\delta \geqq 90°-\phi$, it may be seen from the model that the minimum value of v occurs when z is equal to $\delta-\phi$, that its maximum value occurs when z is equal to $180°-(\delta+\phi)$ and that the maximum and minimum values occur at times separated by twelve sidereal hours. If the observations cover the entire sidereal day, the maximum and minimum effects may be obtained. Let R be the ratio of minimum to maximum observed velocities; then

$$R=v_{\min}/v_{\max}=\sin(\delta-\phi)/\sin(\delta+\phi),$$

from which the declination of the apex of the absolute motion is derived:

$$\tan\delta=[(1+R)/(1-R)]\tan\phi.$$

If $\delta<90°-\phi$, the line of motion will coincide with the plane of the interferometer twice in each day and the maximum observed velocity, $v_{\max}$, will be equal to the actual velocity V. As the minimum velocity occurs when the apex crosses the meridian of the observer, its zenith distance will be $\phi-\delta$ and hence the observed velocity will be the velocity V multiplied by the sine of $\phi-\delta$. Therefore:

$$v_{\min}/v_{\max}=V\sin(\phi-\delta)/V=\sin(\phi-\delta)$$

and

$$\delta=\phi\pm\sin^{-1}(v_{\min}/v_{\max}).$$

Since the apex dips below the horizon, the observed velocity will have two maximum values during the sidereal day and two minimum values. The maxima occur when the apex crosses the horizon of the observer and the minima when it crosses the meridian. The two maxima coalesce when $\delta=90°-\phi$.

The apex of the absolute motion determined from the azimuth of the ether-drift effect

For $\delta\geqq\phi$. From the manner in which the motion of the earth is projected on the plane of the interferometer, Fig. 17, it is evident that the rotation of the earth on its axis from west to east will cause the azimuth of the apex to oscillate back and forth, crossing the meridian twice in each sidereal day at times twelve hours apart. The sidereal time, θ_{E-W}, when the apex crosses the meridian from east to west, is the right ascension of the apex. Then

$$\alpha=\theta_{E-W}.$$

If the time, θ_{W-E}, when the apex crosses the meridian from west to east is also determined, then

$$\alpha=\tfrac{1}{2}(\theta_{E-W}+\theta_{W-E})+6^h.$$