THE POPULAR SCIENCE MONTHLY.

NOVEMBER, 1909

THE SHIFTING OF THE EARTH'S AXIS

By Dr. SIDNEY DEAN TOWNLEY
STANFORD UNIVERSITY

THE earth has two principal motions, one of revolution about the sun, the other of rotation upon an axis. The revolution about the sun is accomplished in 365¼ days at an average speed of nineteen miles per second, or thirty-three times the speed of the swiftest modern projectile. The rotation upon its axis is accomplished in twenty-four sidereal hours, and since the equatorial circumference of the earth is nearly 25,000 miles, a point on the earth's equator has a speed of rotation of over one thousand miles per hour.

In form the earth is an oblate spheroid, a flattened sphere, and the axis about which it rotates coincides very nearly with the shortest axis of the body. If a plane be passed through the center of the earth perpendicular to the *axis upon which it rotates,* not perpendicular to the shortest axis, this plane will cut the surface in a circle which is known as the equator. One of the two coordinates by which the location of a place on the earth's surface is designated is its distance north or south of the equator—measured in degrees, not in miles—and this coordinate is called latitude.

Let the small circle at the center of Fig. 1 represent a section of the earth through the plane of any meridian and the large circle the line in which this plane extended cuts the celestial sphere, supposedly at an infinite distance, $P'P''$ being the direction of the axis upon which the earth rotates and CE the line in which the plane of the equator cuts the given plane. Let O be the place of observation and NS the line in which a plane through the center of the earth parallel to the horizon plane at O cuts the plane of the meridian. According to the definition the arc EO is the latitude of the place O and it is easily seen from the figure that this arc is equal to the corresponding arc on the sky $E'Z$,

The Popular Science Monthly Vol. LXXV, No. 5 November, 1909

the declination of the zenith—declination being defined in a way exactly similar to latitude, *i. e.*, the angular distance of a point on the sky north or south of the celestial equator. Latitude is usually designated by the Greek letter ϕ and it may be seen from the figure that a third definition of latitude is the angular distance of the celestial pole above the horizon—the altitude of the celestial pole.

Many methods of determining latitude have been devised, some of them coming down to us from the ancient Chaldean and Egyptian astronomers. The simplest method is to measure the altitude of the sun at noon on the day it passes through the equinox. On that day, the sun will cross the meridian at the point E', and its altitude will then be $90° - \phi$, as may be readily seen from the figure. A rough value of this angle may be obtained by measuring the shortest shadow of a vertical stick on a level piece of ground on the day of the equinox. The height of the stick divided by the length of the shortest shadow is the tangent of the complement of the latitude.

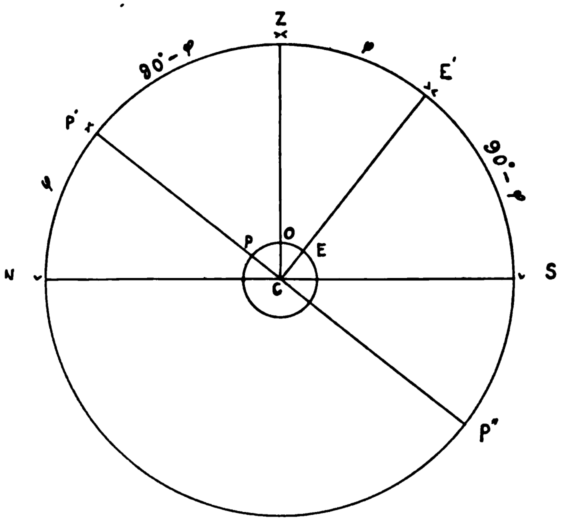


Fig. 1.

If the earth be considered a rigid body and the axis upon which it rotates *be fixed* within the body of the earth, the latitudes of all places upon its surface *will remain always the same*. If, however, the axis should shift its position within the earth, then the equatorial plane, which must be always perpendicular to the axis, must shift and consequently the latitudes of all places on the earth's surface must change accordingly.

It is well established that, at least during historic times, no changes of any considerable magnitude have occurred in the latitudes of places on the earth. It has long been suspected by astronomers, however, that minute changes of latitude were taking place, but it is only during the last quarter century that the methods of observation and calculation have reached that degree of refinement necessary to detect these small changes.

In 1884 and 1885 Dr. Küstner, astronomer at the Royal Observatory of Berlin, made a series of observations upon certain stars for the purpose of determining the constant of aberration—the maximum apparent displacement of a star due to the finite ratio between the speed of the earth in its orbit and the velocity of light. One of the quantities used in the reduction of these observations is the latitude of the place of observation. Dr. Küstner found his results to be discordant, much more so than he had good reason to believe that they should be from the known care and precision with which the observations were made. Upon investigation it was found that these discrepancies could be almost entirely explained away by assuming a change in the latitude. Dr. Küstner, therefore, in 1888, made the bold announcement that the latitude of the Berlin Observatory had changed during the period over which his observations extended.

This announcement aroused wide-spread interest and steps were immediately taken by the International Geodetic Association[1] to test the reality of the announced variation. Through the cooperation of the observatories at Berlin, Potsdam, Prague and Strassburg, observations for latitude were begun in 1889 and carried on continuously for over a year. These observations agreed in showing a minute but appreciable change in the latitude. In order to test the matter still further, an expedition was sent in 1891–2 to Honolulu, and observations for latitude were made there simultaneously with others made at the observatories just named. As Honolulu is on the opposite side of the earth from Europe, it is seen at once, from Fig. 1, that if the latitude were increasing at the European observatories a corresponding decrease should be shown at the Honolulu station. The results came out as expected and this was generally accepted as a complete demonstration of the reality of this phenomenon. Fig. 2 gives a graphical representation of the results, time being measured along the horizontal and latitude along the vertical line.

The observations thus far made showed that the changes in latitude were periodic in character, that is, the latitude of any place would increase for a certain length of time and then decrease to a minimum value and so on, continuing to oscillate between certain limits. It is easily seen that such changes in the latitude of any place may be

---

[1] The International Geodetic Association has its headquarters at Potsdam, Germany, and is supported by the principal governments of Europe, the United States, the Argentine Republic and Japan. It carries out pieces of geodetic and astronomical work which are international in their scope.

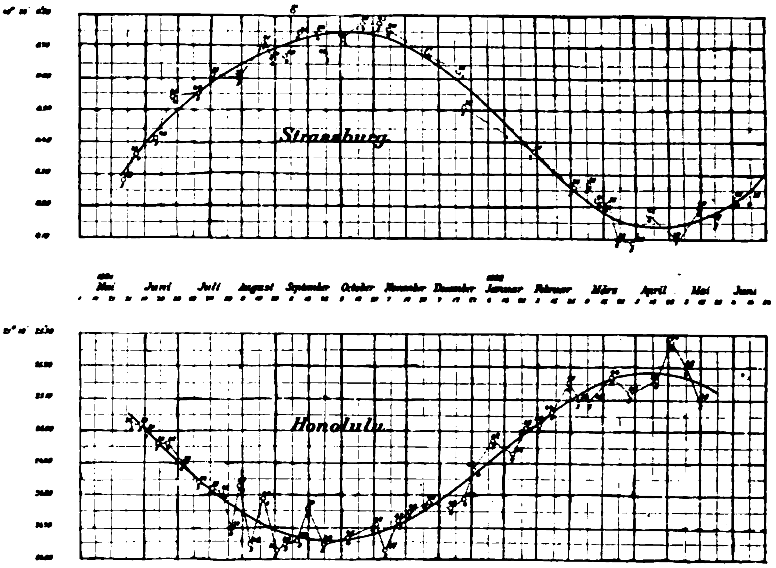


FIG. 2. The upper figures denote the number of stars observed, the lower figures, the number of days on which observations were made.

explained through the assumption of a revolution of the axis of rotation about the shortest axis of the earth, or the axis of figure as it is called.[2] In Fig. 3 let PP_1 be the axis of figure and $P'P_1'$ the position of the axis of rotation at a time when P and P' lie in the meridian of the place of observation O, and let $E'E_1'$ be the line in which the plane of the equator cuts the meridian plane of this place. If now the axis of rotation is given a motion of revolution about the axis of figure, then when one half a revolution has been completed the axis of rotation will be in the position $P''P_1''$, the equator line will have shifted to $E''E_1''$, and the latitude of the place O will have changed from $E'O$ to $E''O$, the whole change in the latitude, $E'E''$ being $2i$, or twice the angle between the axis of figure and the axis of rotation. After a complete revolution of the axis has been accomplished the latitude of the place O will again be $E'O$ and it will oscillate between the maximum value $E'O$ and the minimum value $E''O$. The reader should bear in mind that the figure is grossly exaggerated, the actual value of the angle i being less than one half of a second of arc. If the angle i remains constant and the axis of rotation revolves about the axis of figure with a uniform speed then the place of observation will apparently swing back and forth in its meridian through an arc equal to $2i$. If the

---

[2] The usual statement of the problem is the converse of that just given, that is, that the axis of figure revolves about the axis of rotation, but the effect is the same, provided the distance from O to the end of the shortest axis remains constant, and for purposes of illustration the above statement of the problem seems simpler. The direction of the axis in space remains nearly fixed, but its position within the earth is not fixed.

values of the latitude be plotted along a vertical line and time along the horizontal, we shall obtain the representation of a simple harmonic motion, the crest of the wave corresponding to a maximum value of the latitude and the trough of the wave to the minimum value.

About the time of the expedition to Honolulu, Dr. Seth C. Chandler, of Cambridge, Mass., one of America's foremost astronomers, took up the subject of the variation of latitude and through a brilliant series of researches, published in the *Astronomical Journal,* succeeded in setting forth a number of very interesting results. Dr. Chandler examined all the astronomical observations made with transit instruments, meridian circles, zenith tubes and allied forms of instruments, which were at all suitable for throwing light upon the subject. The first and most interesting result obtained by Dr. Chandler was that the period of the latitude variation was about 427 days. He showed that the observations of the eighties and nineties could be represented very well by assuming that the axis of figure of the earth revolves about the axis of rotation in a circle of thirty feet radius in a period of 427 days.

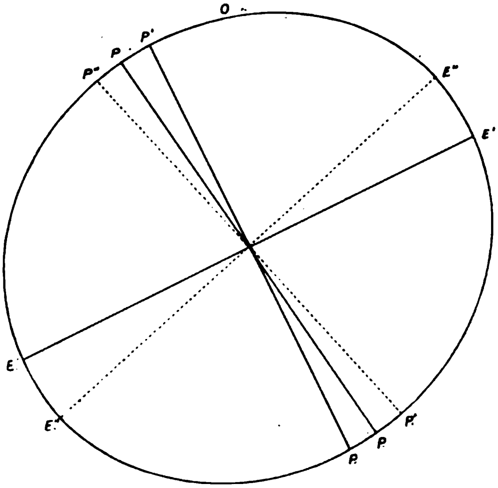


FIG. 3.

Dr. Chandler's investigations of earlier observations, which run back as far as Bradley's classic observations for the determination of the constants of precession and nutation made with a zenith tube in the early part of the eighteenth century, seem to show that the period of variation was formerly considerably shorter than at present, the observations of the eighteenth century seeming to demand a period of about 370 days. Later observations showed also that the *amplitude* of the change is not constant, so that the change in latitude can not be accurately represented by assuming that one axis revolves about the other in a circle of thirty feet radius. Chandler's later conclusion is that the motion of the earth's pole may be conveniently separated into two motions, one an annual revolution in a narrow ellipse about thirty feet long and eight feet wide, but varying in form and position, the other a revolution in a circle about twenty-six feet in diameter with a period of 427 days; both motions being counter clockwise. The resultant of these two motions is quite irregular, as may be seen by referring to Fig. 6, which will be explained later.

From Dr. Chandler's investigations and from the observations for latitude made during the early nineties, it became evident that the movement of the earth's pole was a very complicated one and that an accurate determination of its motion could be obtained only through continuous observations of the latitude at various places on the earth's surface. In 1896 a plan was promulgated by the International Geodetic Association whereby it was proposed to establish stations for the express purpose of observing the latitude. For reasons to be stated later these observatories were all to be located on the same parallel of latitude and in selecting them, social, hygienic, seismological and meteorological, as well as mathematical, conditions were considered, the prime requisite being, of course, that all of the stations have a fair proportion of clear nights at all seasons of the year. Seventeen different combinations of stations lying between latitudes + 36° 48′ and + 44° 50′, and including two combinations in the southern hemisphere on parallels — 33° 54′ and — 33° 27′, were considered. The parallel of + 39° 8′ was finally chosen with the stations located in Japan, in Italy and the eastern and western parts of the United States. Two other stations were subsequently added, one in Central Asia and the other in the central part of North America, at Cincinnati.

The preliminary work of establishing the stations occupied about three years and observations were begun at all of them in the fall of 1899. The Japanese station is situated very close to the city of Mizusawa (10,000 inhabitants), which lies in a fertile valley 290 miles north of Tokio. The valley is nearly enclosed by two ranges of mountains, having a general northerly and southerly direction, the highest peak of which is 6,700 feet above sea-level. The meteorological conditions at this station are not especially favorable. There is a large range between summer and winter temperatures and the percentage of cloudiness is greater than at any other station. Nevertheless, the two observers, Dr. H. Kimura, director, and Dr. T. Nakano, observer, who have served continuously since the observatory was established, have obtained a most excellent series of results. The number of earthquakes at Mizusawa is large, but the locality is not affected by these disturbances as much as some other portions of Japan. Since the observatory was established there has been none of sufficient intensity to seriously affect the observations.

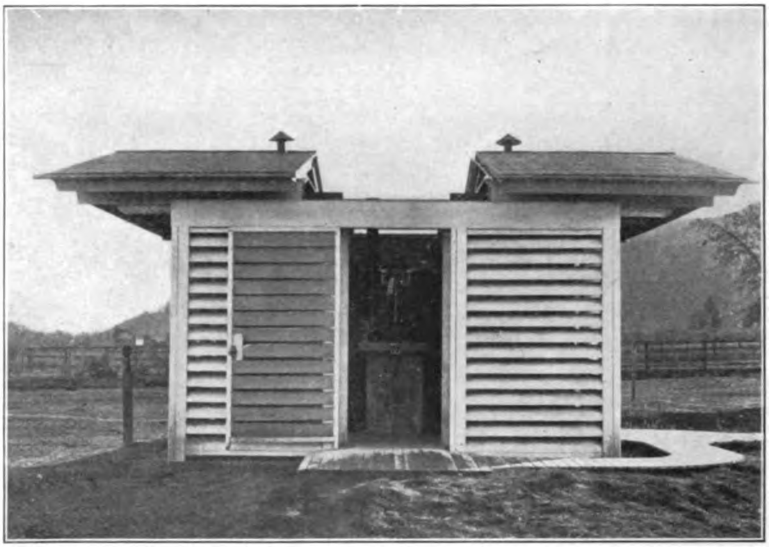
The Central Asian station is located in the Russian possessions east of the southern end of the Caspian Sea, six miles northwest of the city of Tschardjui and two miles from the left bank of the Amu Daria, or River Oxus. The observatory is located on an oasis in a sand-waste traversed by many canals. There is a greater range in the annual temperature at this station than at any of the others. Tschardjui is affected by very few earthquakes. The observations at this station are made by a single observer, several having taken part thus far, all of them officers of the Russian army.

The Italian station is very picturesquely located on an old tower, San Vittorio, close to the city of Carloforte, on the island of San Pietro, which lies west of the southern end of the island of Sardinia. The tower is located on a peninsula on the east side of the island, so that the meridian of the observatory lies almost entirely over the Mediterranean Sea, and anomalies in refraction would seem to be absolutely excluded. The island is free from mountains, the highest point being some 650 feet above sea-level. Carloforte has 8,000 inhabitants and can be reached from Cagliari, the chief city of Sardinia, in eight hours. The meteorological conditions at Carloforte are very favorable. The annual variation of temperature is less than at any other station and over 70 per cent. of the nights are clear, a condition which prevails, I believe, in no other section of the world than that surrounding the Mediterranean Sea. The island is free from earthquakes, there having been only four in nearly four hundred years of any considerable intensity, and none of these destructive. The observations at this station are made by two observers, who alternate with the nights. Several changes in the staff have taken place thus far, but all its members have been Italian astronomers.

The station in the eastern part of the United States is located half a mile south of the village of Gaithersburg, Maryland, twenty-one miles northwest of the city of Washington. The surrounding country is hilly, the observatory has an altitude of 540 feet above sea level and the meteorological conditions are fairly favorable. Mr. Edwin Smith, of the Coast and Geodetic Survey, made the observations at this station during the first year; Dr. Herman S. Davis during the succeeding five years. The work is now in charge of Dr. Frank E. Ross.

After the parallel of 39° 8′ had been selected for the location of the latitude observatories it was found that this parallel passed through the grounds of the Observatory of the University of Cincinnati, and Professor J. G. Porter, director of the observatory, volunteered to carry on observations if he were provided with an instrument. The observatory is located on a hill, five miles northeast of the city, and one mile east of the Ohio River. The altitude of the observatory is 800 feet above sea-level and the meteorological conditions are fairly favorable. Thus far all of the observations, except a few during the summer months, have been made by Professor Porter.

The sixth station is situated in California, 112 miles north of San Francisco, one mile south of the city of Ukiah, the county seat of Mendocino County. The observatory is located toward the western edge of one of the numerous small valleys in the Coast Range of mountains. The valley, which is traversed by the Russian River, is about ten miles long and from two to three miles wide, and surrounded by mountains of an average height of about 1,300 feet above the floor of the valley. The altitude of the observatory is 700 feet above sea-level. The meteorological conditions at this station are very favorable, standing next to those of Carloforte in this respect. Snow seldom falls and, although the summer temperatures are sometimes extreme, the nights are always cool, which adds much to the comfort of the observer if not to the accuracy of the observations. Up to May, 1903, the observations at this station were made by Dr. Frank Schlesinger, now director of the Allegheny Observatory; from that time until September, 1907, the observations were made by the writer of this article. The work is now in charge of Dr. James D. Maddrill.



INTERNATIONAL LATITUDE OBSERVATORY, UKIAH, CALIFORNIA. (Looking South.)

From a seismological point of view, all the American stations are favorably located. Although the Pacific Coast of the Americas is well recognized as a region of seismic activity, yet the mountainous nature of the country surrounding Ukiah seems to afford a measure of protection from these disturbances. No earthquake since the observatory was established, not even the great shock of April 18, 1906, has been of sufficient intensity to interfere in any way with the progress of observations.

The four stations first established, Mizusawa, Carloforte, Gaithersburg and Ukiah, are provided with zenith telescopes of exactly the same pattern, and constructed especially for this work of observing latitudes by the Talcott method.[3]

These instruments, illustrated in Fig. 4, were made by Wanschaff, of Berlin, and have objectives of 4¼ inches aperture and focal lengths of fifty-one inches. The instruments at Tschardjui and Cincinnati are of similar design by the same maker, but smaller. From the figure it may be seen that the telescope is fixed perpendicular to the end of a horizontal axis. By placing this axis in an east and west direction the telescope will move only in the plane of the meridian as the horizontal axis is rotated in its supports. The whole instrument may be revolved about the vertical axis, *m*, and by properly adjusted stops on the base-piece the amount of rotation may be limited to 180°, thus giving two east and west positions for the horizontal axis, one, telescope east, the other, telescope west. It is readily seen that if the telescope is set to point say 10° north of the zenith when east of the vertical axis, then, without disturbing the setting of the telescope, if the whole instrument be revolved about the vertical axis, the telescope will, when it comes into the position west of the axis, be pointed 10° *south* of the zenith. It is thus possible to measure the *difference* of zenith distance of two stars,

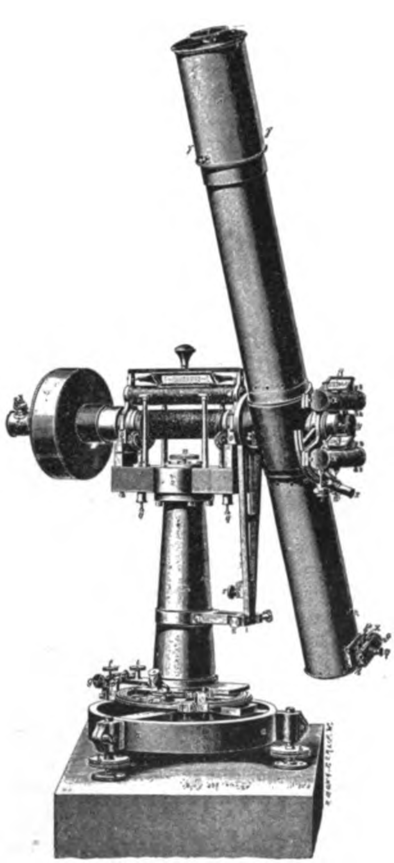


FIG. 4.

---

[3] Descriptions of this method may be found in any work on practical astronomy. The following statements concerning the method may be of help to those who are not familiar with its details. In order to make a determination of the latitude by this method it is necessary to measure, by means of an eye-piece micrometer attached to the zenith-telescope, the *difference* of zenith distance of two stars of known declination which culminate at nearly equal zenith-distances, one north of and the other south of the zenith. The telescope is set at the mean of the zenith-distances of the two stars and the first to culminate will pass a little above or below the middle of the field of view. The distance from the

one of which culminates on one side of the zenith and the other at nearly the same distance on the opposite side of the zenith, by means of an eye-piece micrometer rather than a graduated circle, and herein lies the chief advantage of the Talcott method over all others, the micrometer being a much more delicate and accurate instrument than the graduated circle.

The program of work calls for sixteen determinations of the latitude each night, which means the observation of sixteen pairs of stars. Particular stars have been chosen in such a way as to give convenient intervals between the culmination times of each and the work consumes four hours of time each night. As the stations are all located on the same parallel of latitude the zenith of each observatory will traverse the same path in the sky and the same stars may therefore be observed at each station. Exactly the same program of work, weather and other conditions permitting, is carried out at each station every night of the year. About 12,000 determinations of the latitude are obtained each year, the total to the beginning of 1908 being 99,313. The greatest number of observations are obtained at the Italian station, the next greatest at Ukiah, as may be seen from the following table:

TOTAL OF LATITUDE OBSERVATIONS UP TO 1908

Mizusawa	13,561	Cincinnati	12,190
Tschardjui	14,901	Ukiah	18,676
Carloforte	25,302	Total	99,313
Gaithersburg	14,683		

middle is measured by means of the micrometer. The instrument is then reversed about its vertical axis, without disturbing the setting, and the telescope will then point as far south as it did north of the zenith before reversal, or *vice versa*. The second star will then pass through the field of view as far below or above as the first star was above or below the center, and this distance from the center is again measured by means of the micrometer. The proper combination of the micrometer settings on the two stars gives the actual difference of their zenith-distances, which may be turned into arc measure, provided the value of one revolution of the micrometer-screw be known. The latitude, ϕ, of the place of observation is computed by means of the formula,

$$\phi = \tfrac{1}{2}(\delta_n + \delta_s) + \tfrac{1}{2}(m_n - m_s)R + \tfrac{1}{2}(l_n + l_s) + \tfrac{1}{2}(r_n - r_s),$$

in which the first term of the right-hand member of the equation represents one half the sum of the declinations of the two stars of the pair observed; the second term one half the difference of the zenith-distances of the two stars as measured by means of the micrometer; the third term a small correction for any change in the pointing of the telescope after reversal, detected by means of two very delicate levels attached to the telescope; and the last term a small correction for the *difference* in the atmospheric refraction affecting the rays of light coming from the two stars. It might be noticed that if the two stars are at *exactly* the same zenith-distance, and the instrument is reversed without disturbing the pointing, then the second, third and fourth terms each become zero in the equation above, and the latitude is simply the mean of the declinations of the two stars, or the declination of the zenith, as may be seen by referring to Fig. 1.

The percentage of nights upon which observations were obtained, during the first five years at the various stations, is given in the following table:

PERCENTAGE OF OBSERVING NIGHTS

	Per Cent.		Per Cent.
Mizusawa	50	Gaithersburg	42
Tschardjui	35	Cincinnati	32
Carloforte	72	Ukiah	48

The conditions at Carloforte, in the Mediterranean Sea, must be almost ideal from an astronomical standpoint, still the above tabulation can not be taken as a true index of the weather at the stations. At Carloforte and at Mizusawa two observers are constantly employed, and probably nearly every favorable night is utilized. At the other stations, where all the observations are made by a single observer, some favorable nights must of necessity be allowed to pass. At Ukiah, for instance, the percentage could be increased by at least ten, perhaps fifteen, if two observers were employed. In considering the above table, the further fact should be taken into consideration that Professor Porter, who makes the observations at Cincinnati, has many other duties in connection with his position as director of the Cincinnati Observatory and professor of astronomy in the University of Cincinnati. We should also consider the still further fact that at some stations—for instance, Mizusawa—many nights are rendered incomplete by fog or clouds, and a night upon which only one pair is obtained enters into the above tabulation with the same weight as a complete night of sixteen pairs.

On account of the uncertainties of the weather it seldom happens that observations are obtained at all the stations on the same night—and a complete set of sixteen determinations at all stations on the same night is indeed a rare event. During the first five years that observations were made, there were but nineteen nights upon which *some* observations were obtained at all the stations, and not a single night on which a complete set of sixteen determinations was obtained at every station.

This seems a little strange at first thought, but a simple computation according to the principles of probability shows that such a result should be expected. Let us ask, first, What is the probability of obtaining at least some observations at each station on the same night? If we assume that observations are made on the average on fifty per cent. of the nights, then the probability of obtaining observations at any one station on any particular night will be one half, and manifestly the probability of obtaining observations at two stations on the same night will be $\frac{1}{2} \times \frac{1}{2}$, or $\frac{1}{4}$, and the probability of obtaining observations at three stations on the same night $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2}$, and the probability of obtaining observations at six stations $(\frac{1}{2})^6 = \frac{1}{64}$.

Observations would therefore be made at all six stations on the same night on an average of once in every sixty-four nights. The assumption, however, that observations are made upon fifty per cent. of the nights is somewhat in error, the true percentage being almost exactly 46.5. The probability of this event occurring would be therefore $(465/1000)^6$ which equals $1/99$. The event would occur on an average therefore of once in every ninety-nine days, or nineteen times during the five years under consideration. This result is in exact agreement with the observed number.[4]

Let us now ask, What is the probability of obtaining a complete night's work at all six stations on any particular night? The ratio between the number of complete nights and the total of nights is not given in the published results, but is probably not far from one half. At Ukiah about sixty per cent. of the nights upon which observations are made are complete, but the percentage is known to be less at some of the other stations. If now we assume that observations are made upon fifty per cent. of the nights, and fifty per cent. of these are complete, then a process of reasoning similar to that just used will bring us to the result that the probability of the occurrence of the event under consideration is $(1/64)^2 = 1/4096$. That is to say, a complete night's work will be obtained at all six stations on an average, in round numbers, of once in every 4,000 nights, or once in about eleven years, so that it is not at all surprising that this rare event did not occur at all during the first five years of observations.[5]

The observations made during the first five years after the international latitude stations were established, and the results deduced from them, have been published in two quarto volumes.[6] These observations show periodic changes in the latitude similar to those found from earlier observations. The results obtained at the various stations, from the beginning of 1902 to the end of 1905, are represented graphically in Fig. 5, taken from the second volume just mentioned. All the observations obtained at each station during a certain period, about a month, are combined into an average value, these mean results are plotted, and represented in the figure by the small circles. The small figures standing adjacent to the circles indicate the number of

---

[4] The exact method of computing this probability is, of course, to take the product of the six separate probabilities rather than the sixth power of the average probability. The result comes out sixteen rather than nineteen.

[5] If more exact figures were used in this computation it is certain that the probability of this event would be much reduced, perhaps by nearly one half, so that the event would not occur more than once in twenty years.

[6] *Resultate des Internationalen Breitendienstes.* Band I. (1903), von Th. Albrecht. Band II. (1906), von Th. Albrecht und B. Wanach. *Centralbureau der Internationalen Erdmessung;* neue Folge der Veröffentlichungen, Nos. 8 und 13. A review of these volumes was published by the writer in *Publications of the Astronomical Society of the Pacific,* Vol. 19, pp. 139–58.

observations entering into each average. The small circles are connected by straight lines. The smooth curves in each case are obtained by combining, by means of a mathematical analysis, the results at all of the stations into a general result, and then from this general result computing the variation of the latitude for each individual station. The vertical distance between any small circle and the smooth curve will be, very nearly, the actual error of the average result represented

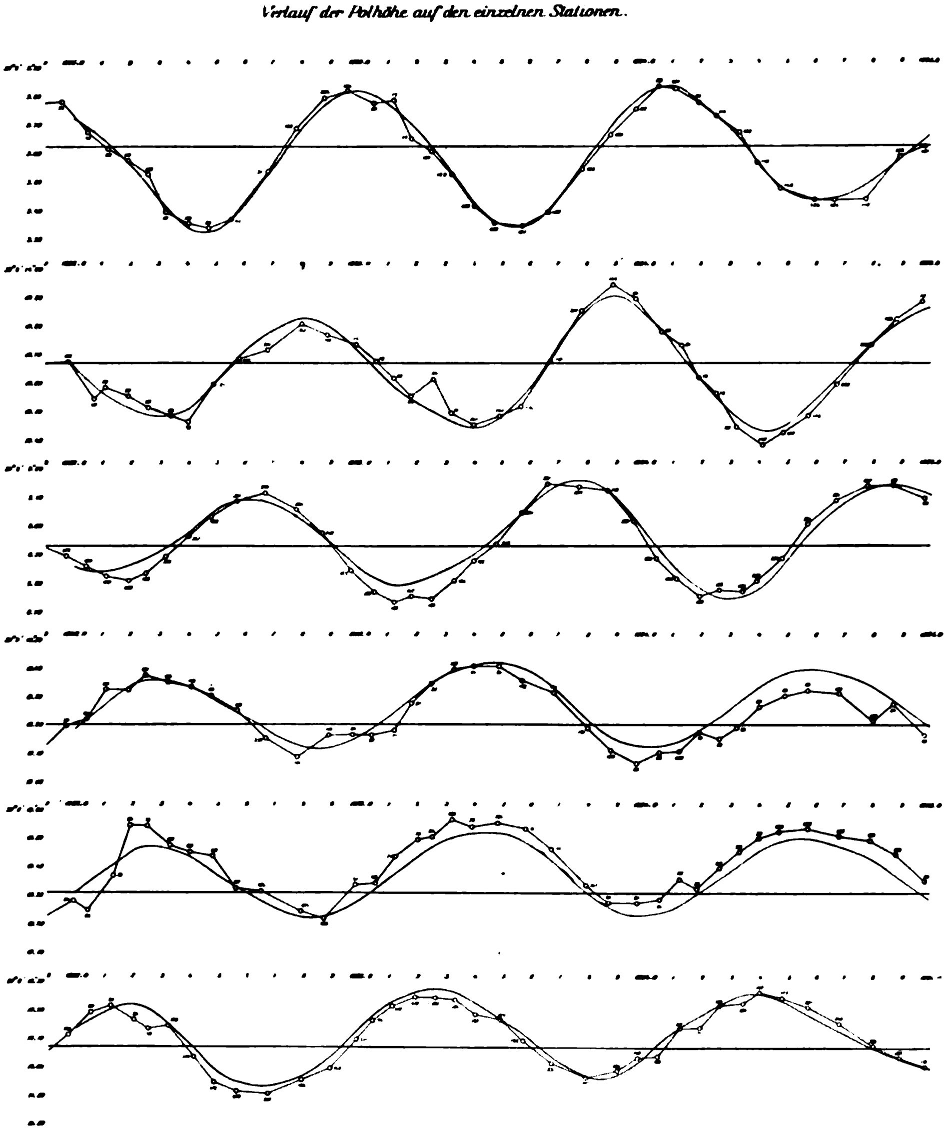


FIG. 5. Observations taken at Mizusawa, Tschardjui, Carloforte, Gaithersburg, Cincinnati, Ukiah. (Reading from the top, down.)

by the circle. The station where these vertical distances are the smallest will, in general, have obtained the most accurate results. An inspection of the figure shows that the best agreement was obtained at Mizusawa. It is rather significant that at Carleforte, where more than twice as many observations are obtained than at some of the other stations, and the meteorological conditions are exceptionally fine, yet the agreement between the observed and the computed curves is not so close as at some other stations. This is a good illustration of the precept that, in general, little or nothing is to be gained by increasing beyond a certain moderate amount the number of observations made with the same instrument under similar circumstances. In fact it is quite possible that just as good results could be obtained by limiting the number of observations taken at each station to a monthly average of a hundred or thereabouts.

As Tschardjui and Ukiah are separated by nearly 180° of longitude, the curve of the one is almost the counterpart of the other. It may be seen from Fig. 5 that the maximum change in the latitude, during the time represented, is less than $0''.5$, which corresponds to about fifty feet on the surface of the earth. The observatory then apparently swings back and forth in the meridian to a distance of twenty-five feet on either side of the mean position.

Having now the actual observed variations in the latitude at six different stations, separated widely in longitude, it is a comparatively simple problem in mathematical analysis to compute what the actual motion of the pole, with respect to its mean position, must be in order to produce the observed changes in the latitudes. If the difference between an instantaneous value of the latitude and the mean value be represented by $\Delta\phi$; the rectangular coordinates of the instantaneous pole, with respect to the mean position of the pole, by x and y; and the longitude of the observing station by λ; then the following equation, the derivation of which is given in the review mentioned above, may be written,

$$\Delta\phi = x \cos \lambda + y \sin \lambda.$$

Early investigations showed that the observations were not represented to the highest degree of accuracy by this equation and Dr. Kimura, the Japanese astronomer, suggested the addition to the equation of a third term, z, independent of the longitude. The observations are satisfied much better by an equation of this form, and z turns out to be a small variable quantity of an annual period. No satisfactory physical explanation of this term has as yet been given. Several have been suggested, one of which is that perhaps there is a small annual shift in the position of the center of gravity of the earth.

In order to solve the problem connected with this term, two additional latitude stations were established in the southern hemisphere in

1906. They are both located in south latitude 31° 55′—one at Bayswater, near Perth, West Australia, and the other at Oncativo, in the Argentine Republic, about forty-five miles from the National Observatory at Cordoba.[7] Definite results from these observations have not yet been obtained, but Dr. Albrecht has recently published a short note stating that a provisional reduction of the observations obtained at the two southern stations shows that z has the *same sign* at the south parallel as at the north, and probably the same magnitude. If this is true the hypothesis of a shift in the center of gravity of the earth must be abandoned. This term is zero about ten days before the equinoxes and reaches its maximum values, $-0''.048$ and $+0''.044$, about ten days before the summer and winter solstices, respectively. These facts would seem to favor the meteorological explanation of origin of this term.

The motion of the earth's north pole, from the time the International Latitude Stations were established in the fall of 1899 to the be-

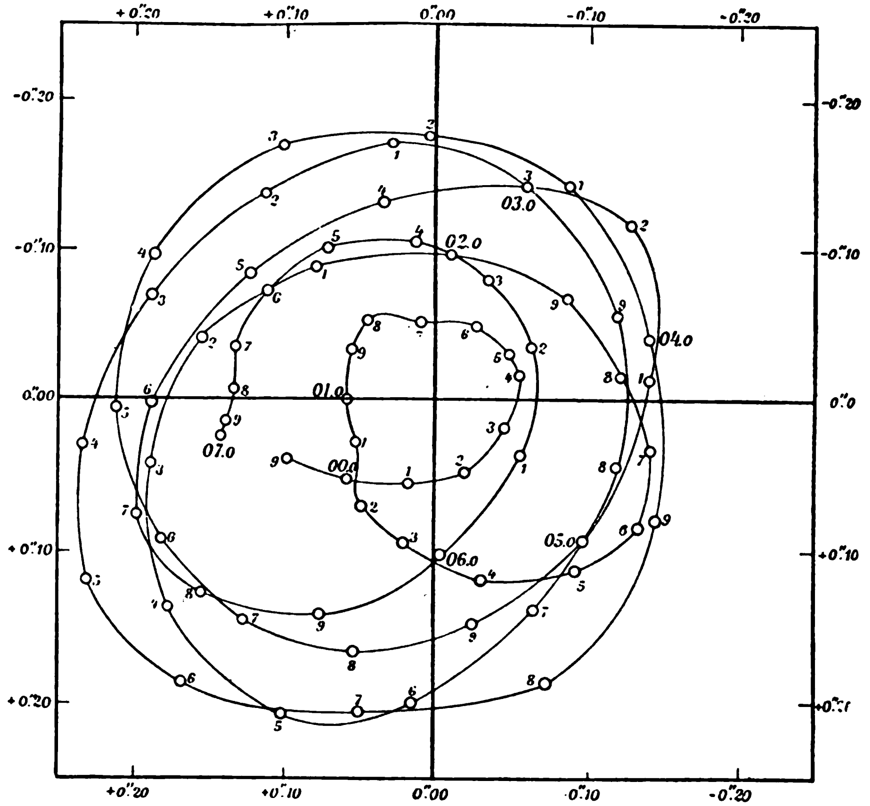


FIG. 6.

---

[7] In addition to these eight stations under the International Geodetic Association regular observations for latitude are made at Poulkova, Russia, in latitude + 59° 46′; at Leiden, + 52° 9′; and at Tokio, + 35° 39′.

The Popular Science Monthly Vol. LXXV, No. 5 November, 1909

ginning of 1907 is represented in Fig. 6 taken from the *Astronomische Nachrichten,* No. 4187. The large square represents a piece of ground fifty feet on a side. The small circles represent the position of the pole for each tenth of a year beginning with 1899.9 and ending with 1907.0. By starting at the beginning and following out the motion of the pole a roughly spiral path is found with a clearly marked period of about seven years, the position of the pole at the beginning of 1907 almost coinciding with the initial position, 1899.9.

The observations made at the International Latitude Observatories have determined the motion of the pole with a degree of refinement and continuity never before attained, and it is now found that the laws deduced by Chandler fifteen years ago are no longer sufficient to accurately represent the observed motion. Dr. Kimura has recently made a harmonic analysis of the variation of latitude and finds, in addition to the two principal motions of periods of fourteen months and one year found by Chandler, two smaller motions with periods of 0.75 and 0.6 of a year. Kimura also finds that the principal motion of fourteen months is in an ellipse and not in a circle as found by Chandler, the interpretation of which would be, that the equator is an ellipse and not a circle, if we assume the earth to be made up of homogeneous layers, or, in technical language, that the equatorial moments of inertia are unequal.

The change of latitude being so very small is, of course, of no consequence whatever to the navigator who has to determine his position at sea. It is, however, of great interest and importance from a scientific standpoint, and it is hoped that the work at the various stations may be carried on long enough to make a definitive determination of the laws of the polar motion possible, so that a mathematical formula may be constructed from which the position of the pole, or the latitude of any place, may be computed for any time past or future.

One way in which the variation of latitude might have political or commercial significance is in cases where a certain parallel is designated as the boundary line between two countries, states or counties. For instance, the forty-ninth parallel is, for a portion of the distance, the boundary line between the United States and the Dominion of Canada. If any question should be raised, however, a court of arbitration would probably decide that, inasmuch as the actual line shifts its position, the one already established, if not egregiously in error, should continue to be considered the boundary line. A case similar to this has recently been decided by the courts of California. The boundary line between Mendocino and Trinity counties is defined as being the fortieth parallel of latitude. When the counties were first established a surveyor was employed to locate this line, but some score or so of years afterward other surveyors found that the established line lay about two miles too far south. Thereupon Mendocino County brought suit against Trinity

The Popular Science Monthly Vol. LXXV, No. 5 November, 1909

County to have this two-mile strip taken from the latter and added to the former. After dragging through the courts for a number of years the matter was finally decided in favor of Trinity County, the argument being that, inasmuch as it is impossible, by ordinary processes of surveying, to locate the parallel with absolute accuracy, the original survey, made by due process of law and accepted by both counties, although admittedly largely in error, should remain the official boundary line. The amount of territory, mountainous and sparsely settled, is a comparatively small part of either county, Mendocino County being nearly as large as the state of Connecticut. The question was, however, of considerable importance to the property owners of the two-mile strip. After the land was claimed by Mendocino County, it was assessed and taxed by both counties, and the taxpayers who cast their lot with Mendocino County now have several years of back taxes to pay in Trinity County.

Doubtless most of the readers of this article have already wondered what may be the cause of the shifting of the earth's axis. In 1765, Euler, a famous Swiss mathematician, demonstrated, as a proposition in dynamics, that if a free rigid oblate spheroid rotates about an axis which differs slightly from the axis of figure, or shortest axis, then the axis of figure will revolve about the axis of rotation in a period the length of which will depend upon several factors. He computed that, if the assumed conditions obtained for the earth, then the period of revolution of the axis of figure about the axis of rotation would be 306 days. Obviously, however, the earth is not rigid; the oceans are quite plastic and the ground itself is possessed of some elasticity. Professor Newcomb computed some years ago that, if we assume the earth as a whole to possess the rigidity of steel, then the period of revolution of the one axis about the other would be 441 days, as against 306 days found by Euler on the assumption that the earth is perfectly rigid. The actual observed period is fourteen months, or 427 days, and the legitimate conclusion to be drawn is that the earth as a whole is somewhat more rigid than steel—a conclusion that agrees with that derived by Lord Kelvin and others from entirely different considerations.

Now the question arises, Why does the earth not rotate upon its shortest axis? The explanation is simple. If the earth ever did rotate upon its shortest axis it could not continue to do so because of the shifting of matter upon and within the surface. Winds, rains, rivers and ocean currents are ceaselessly transporting matter from point to point, and during the winter great masses of snow and ice accumulate in the temperate and frigid zones only to disappear again in the summer. Although these effects will, to a large extent, neutralize each other, the sum total can not be other than to produce at least a theoretical lop-sidedness to the earth; and as soon as this takes place there must be a shifting of the axis of rotation. The time of revolution of

The Popular Science Monthly Vol. LXXV, No. 5 November, 1909

the one axis about the other could be accurately computed if the exact form of the earth, the structure of the earth's interior and its coefficient of elasticity were known.

In addition there are other phenomena, namely, volcanoes and earthquakes, through which considerable quantities of matter may be displaced. That the amplitude of the polar motion might be affected by earthquakes was pointed out by Professor Milne ten or fifteen years ago and a French scientist has more recently compiled a table showing the number of severe earthquakes each year and the amplitude of the polar displacement. A rough proportionality between the two seems to exist, that is, the greater the number of earthquakes each year the greater the amplitude of the polar displacement. Such results, however, are to be taken with several grains of allowance. The term "severe earthquakes" is rather indefinite and by modifying its definition quite a variety of results may be obtained from the given data. It might be pointed out that in 1906, the year of the great earthquakes in California and Chile, the amplitude of the polar displacement was small.

We have then a rational explanation of the phenomenon of the variation of latitude. The axis upon which the earth rotates is not in exact coincidence with the shortest axis; such being the case, according to the principles of dynamics, the axis of figure must revolve around the axis of rotation giving rise to the changes of latitude. But on account of the changes incessantly taking place in the distribution of matter upon the earth's surface, and perhaps also within the surface, the amplitude of the polar displacement, and perhaps the principal period of revolution of the one axis about the other, are changeable, the changes taking place in a rather complicated way according to laws as yet not fully determined.

In connection with this explanation we should not lose sight of the fact that all the material moved through meteorological, volcanic and seismic agencies is probably almost infinitesimal as compared with the total mass of the earth, and no one, so far as I know, has as yet shown that the shifting masses are sufficient in magnitude to properly account for the observed annual and other unexplained components of the polar motion.

Indeed, if one desires to follow the path of least resistance, he might abandon the above explanation altogether and adopt the one given by a colored preacher living in the oil region of Texas, who met some brethren at the corner grocery one day and delivered himself of the following explanation of this puzzling scientific phenomenon:

> Ah see by de papers dat de urf's axis am a wobbling an' dey dunno wat fo'. But ah know wat makes de urf's axis wobble. Do you see all dis oil dese men am a takin' out of de urf? Well wat do you spose de good Lord put dat oil in dere fo'? Wy to grease de axis wif, of couse, an' when dey take it all out, wat else can de axis do but to wobble an' to squeak?