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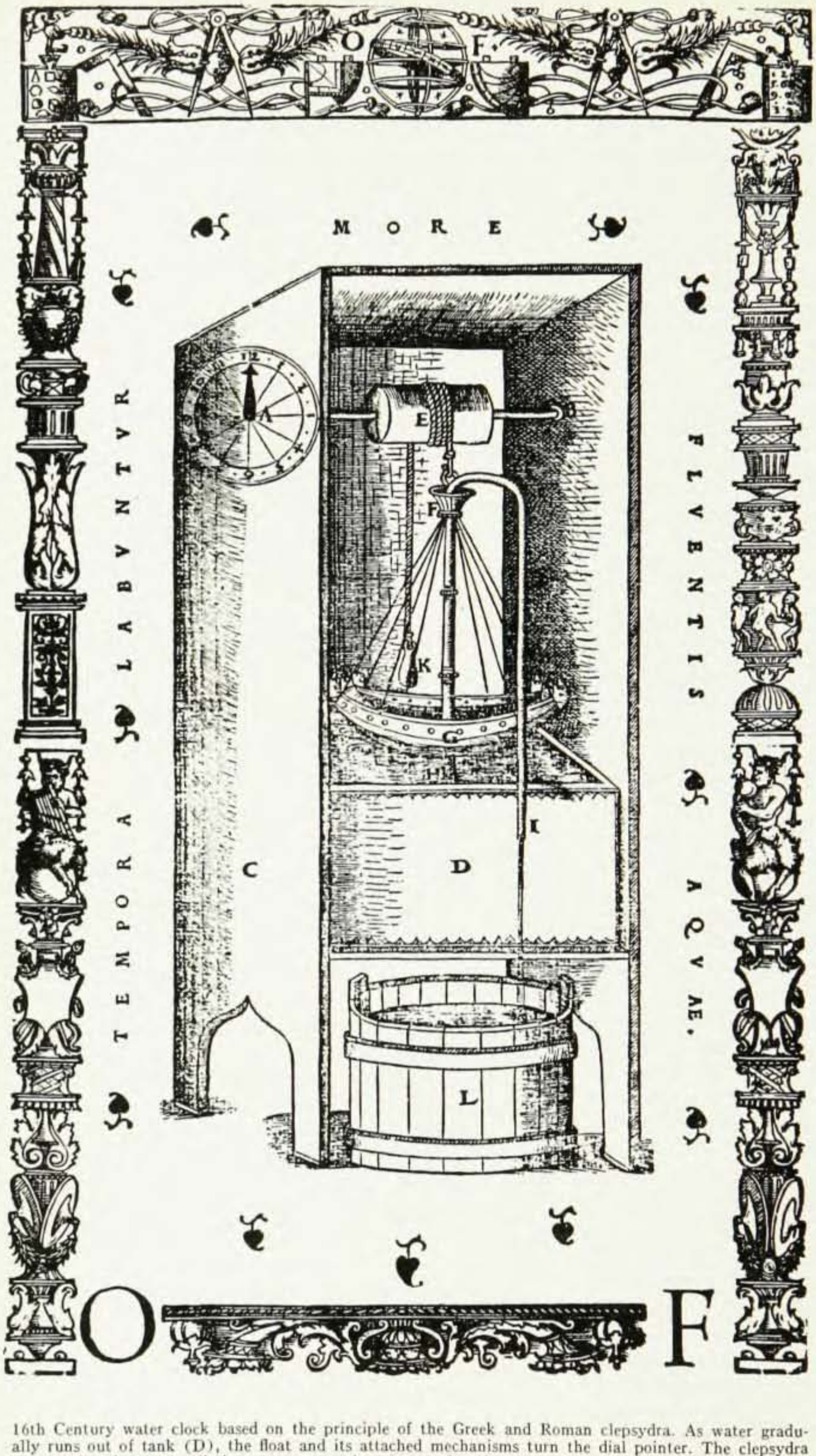
The science of measuring time as it has been practiced for thousands of years is linked closely with astronomical observations. While the accuracy of time measurement has been vastly improved, the search for even greater precision is continuing.



16th Century water clock based on the principle of the Greek and Roman clepsydra. As water gradually runs out of tank (D), the float and its attached mechanisms turn the dial pointer. The clepsydra was employed to set a limit to court speeches, hence the phrases *aquam dare* (to give the advocate speaking time) and *aquam perdere* (to waste time). One Roman version of the instrument is said to have made use of a large water tank in which a swimming man served as the float. One serious disadvantage of the clepsydra was that variations in temperature and air pressure altered the rate of flow and thus the accuracy of the clock. Courtesy Bettmann Archive.

ccurate Measurement of Time

By Dirk Brouwer

IF a Babylonian who lived four thousand years ago could reappear in the modern world, one of the very few scientific appliances which he could recognize would be the sundial. In use at least as early as 2000 B.C. in Mesopotamia, it has survived in innumerable variations in design to the present day. The limitation of the sundial is, of course, that it serves only on clear days. Watchers of the sky at night must have learned at an equally early age to read the time from the appearance of the night sky.

Eventually the need was felt for a means of keeping time during intervals when celestial timekeepers could not be consulted. The first invention of this sort appears to have been the water clock or clepsydra of the Greeks and the Romans. Their use in the second century B.C. is well-established, but they may have originated at a much earlier date. W. I. Milham, in *Time and Timekeepers* (616 pp., The Macmillan Company, New York, 1941), devotes a chapter to the clepsydra and other early timekeepers. Descriptions of sandglasses and of graduated candles and lamps find their place in this chapter. The emphasis is, however, on the mechanical complications that were gradually introduced in the construction of the clepsydra.

A simple clepsydra may have been merely an earthen vessel with a small hole in the bottom. In another type, water would be permitted to trickle from a reservoir into a cylindrical vessel, graduated on the inside to indicate the hour. This type was further developed by introducing a float which rose with the level of the water. A pointer attached to the float read the hour on a graduated scale. Beginning with such simple original forms, inventive designers added one accessory after another to the water clocks. Using the float to move a hand over a dial was perhaps the simplest of these. The addition of more and more complicated mechanical devices requiring trains of cogged wheels eventually led to the construction of purely mechanical clocks in which water was replaced by a weight as the driving power. The significance of the latter step was that it led to the introduction of controlling devices to cause the clocks to run more slowly and regularly.

The earliest examples of mechanical clocks are the tower and cathedral clocks of perhaps about the eleventh century A.D. Sundials remained popular; the timekeeping quality of these mechanical clocks was so poor that they had to be reset frequently with the aid of a sundial. In fact, the clockmakers of the Middle Ages appear to have taken much more pride in making their clocks strike, beat drums, and perform all sorts of mechanical tricks than in making them keep time.

The great advance in clockmaking was the introduction of the pendulum as a part of the control mechanism. This is usually ascribed to Christian Huygens of Holland in the year 1658. Mechanical clocks before this date were so inferior in performance to even the simplest pendulum clock that it would seem superfluous to devote any space at all to the early clocks as timekeepers. From this point of view the fact of interest is that there is a direct line of development from the simple water clock to the modern pendulum clock. It is also important to note that the clockmakers of the seventeenth century had a tradition of hundreds of years in the making of mechanical clocks. They were technically equipped to make use of the advantages offered by the invention of the pendulum control. There are many instances in the history of science of new inventions or theoretical developments requiring a long period of time before their possibilities are used to a considerable extent. The invention of the telescope is a case in point. With a telescopic sight it is possible to point more accurately at a star than with a nontelescopic sight. Yet, it took a hundred years from the invention of the telescope before astronomical instruments had improved sufficiently to take full advantage of the telescopic sight in measuring positions of celestial bodies. No such delay was experienced with the construction of tolerably good pendulum clocks.

Christian Huygens, it should be remembered, lived when the laws of mechanics were emerging. He under-

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stood the mechanics of the pendulum even if Newton's laws of motion had not yet appeared in print. The construction of the first clocks sufficiently accurate for use by astronomers and physicists therefore coincided very nearly with the first logical definition of time.

Whatever concepts of the universe were current, astronomers from the Babylonian times onward based their notions of time on the rotation of the celestial sphere. Hence, in effect, they were using the rotation of the earth as the basic timekeeper. Even after Copernicus this remained intuitive until Newton's laws of motion made it possible to say that a rigid oblate ellipsoid of revolution, rotating on its shortest axis and not affected by any exterior forces, will retain its moment of momentum and hence rotate uniformly. This is, in effect, a step toward the practical definition of time based on the rotation of the earth.

Nothing prevents us from basing the measurement of time on periodic motions in other simple mechanical systems. The motion of a pendulum oscillating without friction and with constant amplitude, and the motion of two point masses about their common center of mass under their mutual gravitational attraction, are important examples of suitable mechanical systems. Whatever method is used, it may be said that time is defined as the independent variable of Newtonian mechanics.

This definition of time was proposed by de Sitter. He was the first to examine the astronomical consequences of the general theory of relativity, and to demonstrate that the approximation yielded by Newtonian mechanics is so perfect for the treatment of the classical problems concerning us here (including that of planetary motion) that the necessity of applying corrections arises in very few problems in this category.

The trouble with the practical use of any of these methods of measuring time is that nature does not present us with any mechanical system free from complications of one sort or another. For example: the earth is not a rigid ellipsoid of revolution, it does not rotate about its axis of rotational symmetry, and because there are external forces acting on the earth, the axis of rotation is not fixed in space. All these deviations from the ideal mechanical model must be properly allowed for before the rotation of the earth can be used as a suitable timekeeper. After all this has been done to the best of the astronomer's ability, the time derived from the earth's rotation is called *astronomical time*. The question remains whether or not astronomical time corresponds to the independent variable of Newtonian mechanics. Whenever the distinction from astronomical time had to be made, the terms *Newtonian time* or *uniform time* were used. There are objections to both these adjectives. An international conference on the fundamental constants of astronomy, held in Paris in the spring of 1950, decided to recommend the term *ephemeris time*. The motions of celestial bodies are obtained as solutions of differential equations with the time as independent variable, and the calculated ephemeris positions are tabulated as functions of this variable. Ephemeris time, used as argument of the astronomical ephemerides, therefore is the independent variable of Newtonian mechanics, modified by relativity corrections such as in the motions of the perihelia of the inner planets.

The Rotation of the Earth on its Axis

Simon Newcomb wrote in 1906, "The time of this rotation we are obliged, in all ordinary cases, to treat as invariable, for the reason that its change, if any, is so minute that no means are available for determining it with precision and certainty. There are theoretical reasons for believing that the speed of rotation is slowly diminishing from age to age, and observations of the moon make it probable that there are minute changes from one century to another. If such is the case the retardation is so minute that the change in the length of any one day cannot amount to a thousandth of a second. Yet, by the accumulation of a change even smaller than this through an entire century, the total deviation may rise to a few seconds and, in the course of many centuries, to minutes."

For thirty-five years Newcomb had given a good deal of attention to this subject, and yet he could not state his conclusions except in these carefully chosen words. Now, forty years later, it is possible to point to very considerable gain in knowledge. This has been principally due to the accumulation of rich additional observational material, and its discussion.

The mechanical problem of the earth's rotation is essentially that of the spinning top. The difficulty of the problem is the requirement that the solution be carried out to the high degree of precision that is required of all problems in dynamical astronomy. The solution should be as accurate as the best observations and preferably a little better. Under the influence of the attractions by the sun and the moon this axis of rotation of the earth does not remain fixed in space. Its principal motion is the precessional cone which would cause the axis to complete a cycle in about 26,000 years. But superposed on this motion are periodic oscillations called the nutation. The principal one of these oscillations has a period of a little under 19 years. This period coincides with the period of revolution of the line of intersection of the moon's orbit with the plane of the earth's orbit. Let it be assumed that the theory of the motion of the earth's axis is completely known. It is possible, then, to state at any time the position of the plane of the earth's equator or its equivalent: the great circle of the celestial equator.

The only way in practice is to refer this great circle to "fixed" stars. Owing to the rotation of the earth from west to east the whole celestial sphere appears to rotate in the opposite direction, and the period of the earth's rotation is that of an equatorial star without proper motion.

A star without proper motion is an abstraction. Catalogues of fundamental stars have been constructed as compilations of almost two centuries of observations with meridian circles. Proper motions, determined for each star individually from long series of observations, are furnished in these catalogues so that the positions may be obtained for any date. Clock stars are a selection of stars from such a fundamental catalogue within a belt extending 30° on either side of the celestial equator. The meridian transit of any such clock star will then suffice to furnish the equivalent of a star without proper motion.

The essential difficulties are that stars have systematic motions, and that no fixed reference system is really available. It has been suggested that the extragalactic nebulae be used as such a fixed reference system. Their distances are so enormous that their transverse velocity components in seconds of arc per century should be negligibly small. Suitable galaxies, though numerous, unfortunately are very faint; at present this solution exists only as a promising scheme for future generations of astronomers. Actually, at the Lick Observatory, a series of photographic plates is being secured for this purpose with the new 20-inch Ross camera. A repetition of this undertaking, say 25 years hence, will furnish a first solution of the problem of referring proper motions of stars to a background of distant galaxies.

This may well be the standard method of the future. In the past, astronomers have used the bodies of the solar system for the purpose of defining a suitable reference system. Observations of the sun, moon, and planets are continuously made at the principal observatories where fundamental star position work is being carried out. These observations permit the determination of both the celestial equator among the stars and of the location of the intersections of the sun's path with the celestial equator, the equinoxes. The vernal equinox, i.e. the intersection of the sun's path with the celestial equator where the sun crosses from south to north, has been used as a zero point for reckoning angles in the celestial equator. Similarly, the sidereal day was defined as the interval between successive transits of the vernal equinox. Since the vernal equinox has a retrograde (i.e. westward) motion among the stars of about 50 seconds of arc per annum, the sidereal day is shorter than the true period of rotation of the earth by 0.009 second of time.

The sidereal day thus defined may well be used as unit of time based on the rotation of the earth. For practical use, sidereal time is unsuitable because it gets out of step with the sun, gaining on the average 3 minutes and 56.555 seconds on the sun with each rotation, which builds up to a full day in the course of a year. In order to define astronomical time from the nonuniformity of apparent time and free from the disadvantages of sidereal time, astronomers introduced mean solar time as the time indicated by a fictitious body that moves uniformly eastward along the celestial equator at the same rate as the average motion of the true sun. The interval between two successive transits of the mean sun is then the mean solar day. In units of mean solar time,

$$\text{one sidereal day} = 23^h\,56^m\,4^s\!.091.$$

Radio time signals sent out by the Naval Observatory in this country indicate mean solar time. They are based, ultimately, on observations of stars. The sidereal time furnished by the stars is converted into solar time by calculations that allow for the motion of the fictitious mean sun relative to the vernal equinox.

The technique of determining time from star observations has been improved tremendously since 1904 when the U. S. Naval Observatory began to send out radio time signals. Pendulum clocks and crystal clocks are now such good timekeepers that their rates may confidently be extrapolated for days or even weeks while the time signals regulated by such clocks are still correct to within 0.01 second. By a comparison with star observations the definitive clock corrections are obtained to 0.001 second and subsequently published.

As a consequence of the greater accuracy attained in recent years, several expedients that were acceptable in the past had to give way to more rigorous methods. The principal one of these is the circumstance that the sidereal day used to be determined by the meridian transit of the true equinox. The motion of the true equinox is not uniform, but affected by periodic oscillations, the nutation in right ascension. The principal nutation term has a period of 18.6 years and a coefficient of 1.2 seconds of time. Another significant term has a period of 6 months and a coefficient of 0.1 second of time. In addition there are numerous smaller terms. These nutation terms are now applied in the determination of both sidereal and mean solar time.

A more difficult adjustment is required in order to eliminate the effect due to the movements of the body of the earth relative to the axis of rotation. The north and south poles of the earth wander over areas usually not more than 30 feet from their mean positions. The effects upon the latitudes of observatories are being obtained continuously with high precision from series of observations at stations in different longitudes. The effect of the wandering of the terrestrial poles upon the longitudes has been taken into account in accurate time determinations only during the past two decades. Since Greenwich and Washington are nearly 90° different in longitude, the error in time determined at Greenwich is affected by the displacement of the instantaneous poles in the meridian of Washington. Conversely, the displacement of the poles in the meridian at Greenwich affects the time determinations at Washington. By using latitude variations currently observed at Washington, the Greenwich time determinations are now being corrected to the mean meridian of Greenwich. The corresponding corrections to the Washington time determinations may be obtained from the Greenwich latitude results when a new photographic zenith tube being constructed for the Royal Observatory, Greenwich, can be put into operation.

Even after the introduction of these refinements, there remains a minute effect caused by the nonuniform motion of the vernal equinox. The rate of motion of the vernal equinox varies in cycles of many thousands of years. At the present time this rate is increasing, and will continue to do so for many centuries. Related to this feature is the presence of a quadratic term in the mean longitude of the sun. The two combined produce a discordance increasing with the square of the time by which mean solar time falls behind the true sun. In ten centuries it increases to only two seconds. For any year the amount can be evaluated and allowed for. Actually, it is small compared with other nonuniformities present in astronomical time.

The Earth's Nonuniform Rotation Rate

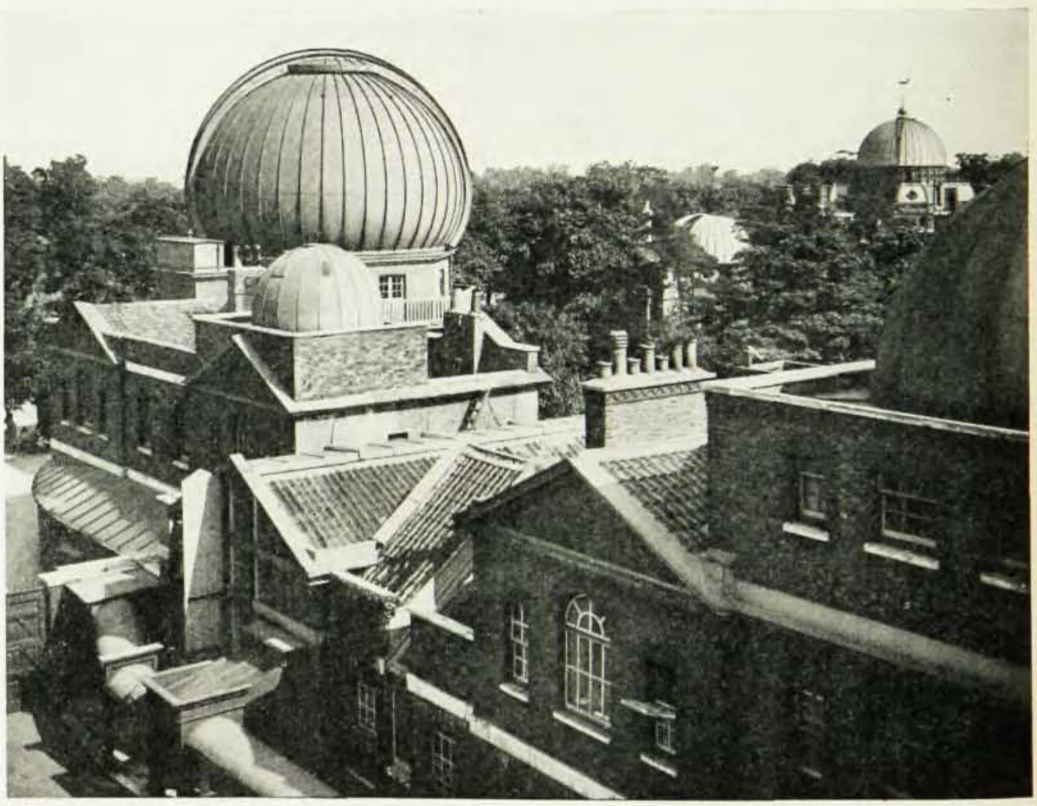
In the *Principia*, Newton made a first attack on the explanation of the motion of the moon on the basis of gravitational theory. The development of analytical methods during the eighteenth century produced rapid advances in this subject, stimulated also by the need for accurate lunar tables for the use of navigators in obtaining longitudes at sea. The theory of the moon's motion is one of the most exacting problems in celestial mechanics, in part because the attraction of the sun on the earth-moon system produces large perturbations that require lengthy calculations for their evaluation with the accuracy required by the observations. The most difficult part of the theory is, however, the treatment of the effects on the moon's motion caused by the attractions of the planets. Many hundreds of terms must be examined. While many produce only insensible effects, other terms turn out to be quite significant. The utmost care is required in order to be certain that no significant terms are overlooked. It was particularly in this part of the lunar theory that uncertainty remained until a relatively late date.

The importance of this subject in connection with the subject of the earth's rotation is due to the rapid motion of the moon among the stars, averaging 1 second of arc in 1.82 seconds of time. Modern observations determine the average deviation of the moon's position from the ephemeris prediction for any year with an uncertainty not greater than 0.05 second of arc. If the moon's motion may be regarded as a reliable clock, this is equivalent to obtaining an annual clock reading independent of the earth's rotation to an accuracy of about 0.1 second. Obviously, the reliability of this clock depends upon the completeness with which the lunar tables represent the actual motion.

The first indication of slowing down of the earth's rate of rotation was obtained in 1693 by Edmund Halley who discussed eclipses recorded in Ptolemy's *Almagest*, eclipses observed by Arabian astronomers in the 9th century A.D., and observations of the moon in his own time. If T is the number of centuries elapsed since any convenient epoch, the result may be expressed as the difference, observed minus calculated mean longitude of the moon in its orbit in the form

$$\Delta L = a + bT + cT^2.$$

The quantities a and b are of no particular interest; they simply represent small corrections to the mean longitude at the epoch and the mean angular motion. The reality of the term cT^2 was clearly established by Halley's discussion of the observations.



The Greenwich Observatory near London, founded in 1675, houses the clock which establishes the standard of time throughout the United Kingdom. Photo by Burton Holmes, from Ewing Galloway.

Following Halley, several authors busied themselves with the problem and obtained for c values varying from 6".7 to 10".0, but the question as to the cause of this secular acceleration remained open. After unsuccessful attempts by Euler, Lagrange, and others, Laplace in 1787 announced that a term $10''.2T^2$ in the moon's mean longitude could be accounted for by the gradual decrease of the eccentricity of the earth's orbit that has been in progress during many thousands of years. Laplace's result was confirmed by other investigators until J. C. Adams in 1853 found that on account of an error in the derivation committed by Laplace, the theoretical coefficient should be halved. In that same year the Astronomer Royal, G. B. Airy, redetermined the coefficient from observations, and found the observed term $10''.72T^2$. The subject remained controversial for a period. Owing to work by Delaunay, Newcomb, and E. W. Brown on the theory and by J. K. Fotheringham on the observations, the matter was finally completely cleared from former obscurities.

Brown's theory gives a theoretical secular term due to gravitational causes: $+6''.0T^2$. Fotheringham's discussion of the ancient solar eclipses, lunar eclipses, occultations, and Hipparchus' equinox gives an observed secular term $+10''.8T^2$ in the moon's motion, and $+1''.5T^2$ in the sun's motion. The latter was detected by P. H. Cowell in 1906, and confirmed by Fotheringham. The amounts are freed from any effect due to the accelerated motion of the equinox. There remains, therefore, the discordance of $4''.8T^2$ between theory and observation in the moon's motion and $1''.5T^2$ in the sun's motion. As a result of a revision of Fotheringham's data by de Sitter and Spencer Jones, the values currently adopted are $5''.22T^2$ for the moon and $1''.23T^2$ for the sun.

G. H. Darwin established tidal friction as an important factor in the history of the earth-moon system. While Darwin's work was essentially qualitative, the quantitative aspect was first successfully handled by G. I. Taylor in 1919. It had been found that the friction in deep oceans was entirely insufficient to account for the change in the rate of rotation of the earth required by the observed secular acceleration in the moon's motion. Taylor recognized that the dissipation of energy takes place principally in shallow seas, where tidal currents have velocities much greater than the currents in open oceans. The first evaluation made by Taylor was for the Irish Sea. Harold Jeffreys extended the investigation and found that the friction in the Bering Sea accounts for a large portion of the total amount required. The subject has also been treated theoretically, especially by Jeffreys. Although the simplified model of tidal friction that would apply to the case of a deep ocean covering all of the earth's surface is not applicable in the case of the actual earth, it should still be possible to introduce a tidal couple produced by the moon's attraction to account for the retardation of the earth's rotation. There must then be a force acting on the moon with a moment equal but opposite to that of the couple produced by the moon's attraction on the earth. A component of this force is directed perpendicular to the line joining the earth and the moon and in the direction of the moon's motion. The effect of this force is to increase the distance of the moon from the earth and hence to increase its period of revolution, a secular retardation in the moon's mean longitude. In the case of the sun similar couples exist, but it is easily seen that the retardation in the sun's mean longitude is negligibly small. A difficulty of the quantitative analysis is the evaluation of the ratio between the tidal couples produced by the moon and the sun. The principal conclusion derived by Jeffreys is that a term $+0''.9T^2$ in the sun's mean longitude is the maximum that can be accounted for. This term is smaller than the lowest value permitted by Fotheringham's solution.

Leaving aside the imperfect agreement between theory and observation, the inescapable conclusion is that a retardation of the earth's rate of rotation will produce apparent secular acceleration terms in the motion of the sun and in all other bodies both in the solar system and outside. In the case of the moon's motion this apparent secular acceleration is in part cancelled by the true secular retardation in the moon's orbital motion. Hence, while in the sun, planets, and satellites the effects are accelerations directly proportional to the angular mean motions, i.e. inversely proportional to the periods of revolution, in the case of the moon the net effect is less than would correspond to the moon's mean motion.

Newcomb first suspected that the observations of the moon gave evidence of the occurrence of changes in the rotation of the earth of an irregular character. He expressed this opinion with extreme caution as early as 1870, warning that it was necessary to have more positive knowledge of the possible inequalities that may be produced in the moon's motion by gravitational action, and that confirmation by the corresponding effects in the motions of other bodies in the solar system would be necessary.

As far as the theory of the moon's motion was concerned, the work of E. W. Brown advanced the subject to such a high level of perfection that his new tables of the moon, introduced in 1923, could be considered to supply that positive knowledge that was lacking fifty years earlier. It was particularly the publication of Brown's new tables that made the subject of the irregular "fluctuations" in the moon's motion one of the chief topics in the astronomical literature from 1925 until about 1932.

A distinction between the gradual changes in the earth's rate of rotation connected with the secular acceleration and the irregular changes connected with the fluctuations is that the former always diminish the angular velocity of the earth's rotation while the latter may either increase or diminish this angular velocity. It has been clearly established that the effects of the fluctuations are directly proportional to the mean motions of the bodies concerned. The importance of the recognition of the fluctuations in the motions of the sun and the inner planets is that this rules out the possibility of ascribing them to unexplained deviations in the moon's motion; they must be ascribed to the rotation of the earth.

The most valuable and most complete analysis of the observational data is contained in a revision of Newcomb's discussion of observations of occultations of stars by the moon since 1672, published by Sir Harold Spencer Jones, now Astronomer Royal, in 1932. At that time the available reductions of observations of the sun and the inner planets were sufficient to show for these bodies that the observed deviations from prediction by gravitational theory correspond to the deviations observed in the moon's motion. The observations of the sun in the nineteenth century did not, however, agree as well as might be desired and caused uncertainties in the interpretation. Considerable improvement in this respect was achieved in 1939 by a new discussion by Spencer Jones. It is easily recognized how high a precision is required of the sun observations; while in the moon's motion a deviation of 1 second of arc corresponds to 1.82 seconds of time, a deviation of 1 second of arc in the sun's motion corresponds to 24.35 seconds of time.

Of particular usefulness is the rapidly moving planet Mercury; a deviation of 1 second of arc in the orbital longitude of this planet corresponds to 5.86 seconds of time. Transits of Mercury (i.e. observations of crossings of this planet over the sun's disk), recorded since the seventeenth century, were used effectively by Spencer Jones. A complete re-reduction of all the meridian observations of Mercury was published in 1943 by G. M. Clemence, director of the Nautical Almanac, U. S. Naval Observatory. A discussion of all the meridian observations of Venus is now in progress in the Nautical Almanac Office. There is no doubt that the inclusion of these results will add additional weight to a discussion similar to Spencer Jones' analysis of 1939, but they will not affect his principal conclusions. If the fluctuation in seconds of arc in the moon's longitude is designated by B, the terms in the moon's mean longitude caused by tidal friction and changes in the earth's rate of rotation are represented by the terms

$$5''.22T^2+B.$$

From the observations of the sun since 1790 Spencer Jones found for the deviation from Newcomb's tables

$$\Delta L_\odot = 1''.00+2''.97T+1''.23T^2+0.0748B,$$

the factor 0.0748 representing the ratio between the mean motions of the sun and the moon. The expressions for the planets are entirely similar, with the coefficients of T^2 and B changed in proportion to the mean motions. For example, the corresponding terms are

for Mercury,	$+5''.10T^2+.311B$
for Venus,	$+2''.00T^2+.112B.$

The last two terms in the expression for $\Delta L_\odot$ must be ascribed to changes in the earth's rate of rotation, and the errors in astronomical time are directly proportional to them. The first two terms represent adjustments of the orbital constants and have no other significance. Yet it is convenient to include them in the correction to astronomical time, which then becomes:

$$\Delta t = 24^s.35+72^s.32T+29^s.95T^2+B_t,$$

with

$$B_t = 1.821B.$$

Hence B_t expresses the part of the reduction from astronomical time to Newtonian time that is due to the irregular changes in the rate of rotation of the earth, while Δt is the total reduction which includes also the effect of the gradual changes due to tidal friction. The term $29^s.95T^2$ corresponds to an increase in the length of the day at the rate of 0.00164 second per century.

Since the ratio between the coefficients of T^2 in the deviations in the longitudes of the sun and moon is different from the ratio between the coefficients of B, it is possible in principle to obtain a separation of the T^2 and B terms from modern observations alone, without adopting the value of the secular acceleration in the moon's motion derived from ancient eclipses. The observations during the past two centuries alone give for the coefficients of T^2

in the motion of the moon	$+3''.11,$
in the motion of the sun	$+1''.07.$

The obvious interpretation that in recent centuries the secular acceleration has amounted to about sixty percent of the average value during the past 2500 years must be accepted with caution until further evidence can be accumulated. Even if it may be questioned whether sufficient changes in depth and current conditions in shallow seas occurred during the last 2500 years to produce so large a change in the secular accelerations, it would be unwise to reject the provisional observational evidence on the grounds that no complete theory is readily available to account for it.

Professor Harold C. Urey in his Silliman Lectures at Yale University dealt with the chemical and physical processes in progress in the interior of the earth. If allowance is made for these effects in the theory of secular accelerations, some of the unsolved problems in this field may find their solutions. Discussions with Professor Urey led me to examine in detail some questions concerning the fluctuation curve. In the upper diagram of Figure 1a the black dots represent the best values for B_t that I could obtain from available data on the moon's motion. Previous to 1850 the points plotted agree with the data published by Sir Harold Spencer Jones. After 1850 I have combined his occultation results with those from other series of observations of the moon. Special precautions were taken not to introduce systematic effects present in the older meridian circle observations. The points plotted are three-year means since 1820; before that date only occasional normals are available. The dotted line in this diagram consists of straight lines that change their directions in 1755, 1786, 1864, 1876, 1896, and 1918. This interpretation was proposed by de Sitter in 1928. It was based upon the Greenwich meridian circle observations which, especially before 1850, are inferior to the results from the occultations. While on the whole the dotted line follows the three-year means reasonably well, the observational results show distinct deviations from the de Sitter interpretation. The large open circle represents the residuals obtained by Clemence from Mercury. They are in excellent agreement with the moon.

The second curve (Figure 1b) gives as the dotted line the annual changes of de Sitter's B_t. Since B_t consists of straight-line sections, the derivative has constant values with discontinuous changes in the years indicated. The black dots in this diagram are the values of the derivative obtained by the simple rough process of taking the difference between two consecutive three-year means and dividing by three. Even if proper allowance is made for the unavoidable inaccuracies in the derivatives so obtained, it is evident that de Sitter's interpretation must be ruled out. The changes in the derivative of B_t are not instantaneous. This was remarked by Spencer Jones in 1932; he did not, however, make an attempt to study the character of the derivative.

A considerable loss of accuracy is incurred in obtaining the derivative from consecutive three-year means. In order to refine the determination I was led to obtain the derivative by fitting by the method of least squares parabolas through each nine consecutive annual means of B_t. The resulting expression yields the derivative for

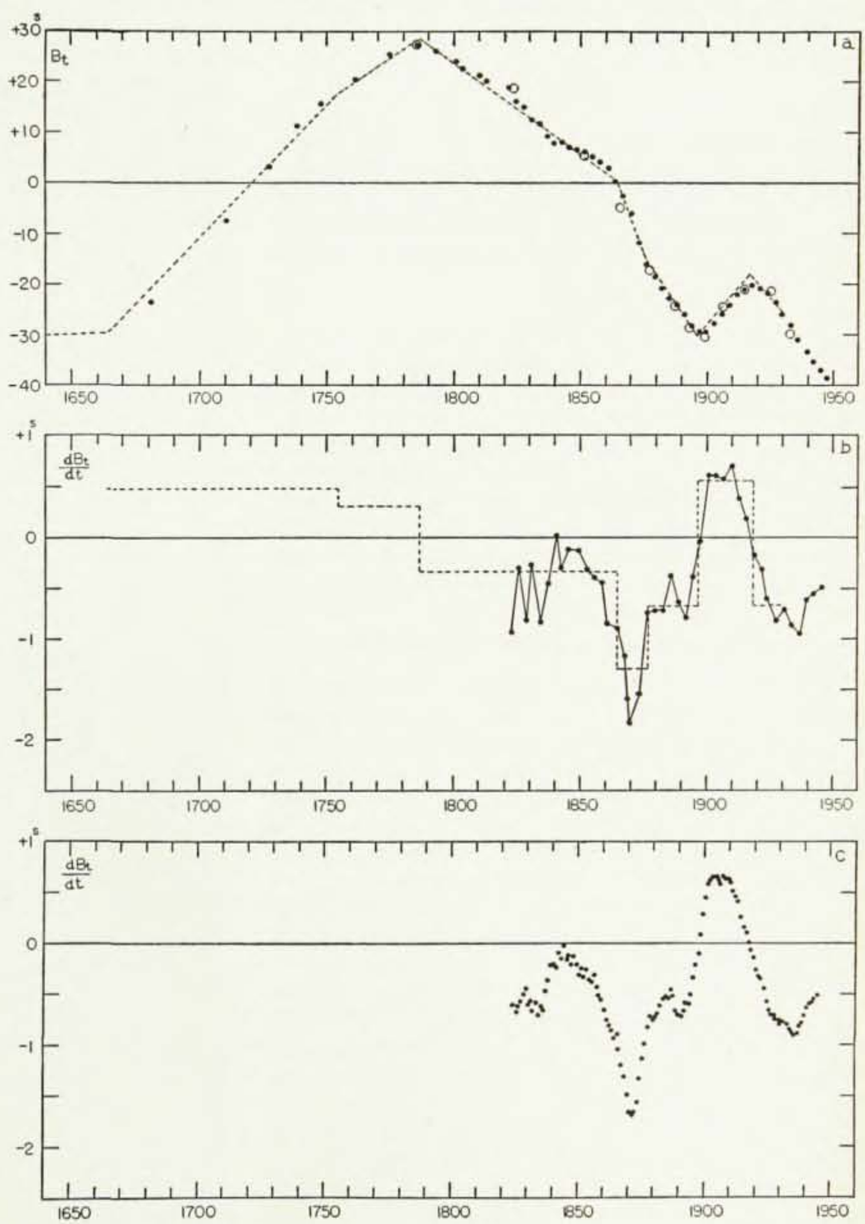


Figure 1a. Deviations from uniformity in the earth's rotation. The black dots are derived from observations of the moon, the open circles from Mercury. A positive value of B_t indicates that the rotation of the earth lags behind, a negative value that the earth's rotation is ahead. The dotted line represents an interpretation of the fluctuation curve proposed by de Sitter in 1928. The fluctuations B_t are superimposed on the effect of the gradual slowing down of the earth's rotation.

Figure 1b. Black dots represent values obtained by differencing the three-year means of Figure 1a. The dotted line represents the derivative corresponding to de Sitter's fluctuation curve. The value of dB_t/dt equals the number of seconds by which the length of any year differs from the mean value for that date.

Figure 1c. Annual variation of the fluctuation obtained by a more accurate calculation.

the middle of each nine-year stretch on the assumption that the curve may be approximated by a parabolic curve. The resulting annual values are plotted in Figure 1c. These values suggest strongly that the curve giving the annual changes in the fluctuations consists of straight-line sections, so that the second derivative of B_t, rather than the first derivative, changes abruptly.

The only other publication of a curve giving the annual variations of B_t is that by N. Stoyko of the Paris Observatory (*Bulletin Astronomique*, Vol. XV, pp. 239–242, 1950). He appears to have adopted a smoothed curve for the fluctuations and obtains a more rounded curve than indicated by Figure 1c.

The fluctuations in the earth's rate of rotation may be explained by assuming changes in the moment of inertia about the axis of rotation. If Ω is the angular velocity of rotation, and I the moment of inertia, then evidently

$$I\Omega = \text{constant}.$$

Abrupt changes in Ω, suggested by de Sitter, require abrupt changes in I at the dates of discontinuity; during the last century in 1864, 1876, 1896, and 1918. The derivatives in Figure 1c suggest abrupt changes in the derivative of Ω and in the derivative of I related by

$$\frac{1}{\Omega}\frac{d\Omega}{dt}+\frac{1}{I}\frac{dI}{dt}=0,$$

with the principal discontinuities in these derivatives about 1856, 1871, 1877, 1887(?), 1890, 1902, 1911, 1925, and 1936.

The geophysical causes of the changes in the moment of inertia are not understood. If they are movements of masses in the interior of the earth, a search among geophysical records for discontinuities that coincide with or are closely related to the dates listed may offer a clue to the solution of this problem.

Pendulum Clocks and Crystal Oscillators

Until 1890 pendulum clocks were merely convenient means of interpolating time during periods between star observations. The Riefler clock introduced at that time was an outstanding advance. Changes in daily rates of Riefler clocks have been found to average about 0.015 second. The next great improvement in this field was the introduction of the Shortt free pendulum clock in 1921, the performance of which for intervals up to a few weeks is superior to the best time determinations from star observations. The best determination of the clock errors is to draw a smooth curve between plotted points that represent the star observations. Extensive comparisons, especially at the Royal Observatory, Greenwich, and at the U. S. Naval Observatory at Washington have demonstrated that a Shortt clock has a tendency to wander back and forth on either side of its mean indication to the extent of several milliseconds. Observed secular changes of rate are ascribed to secular growth of the invar pendulums, which can be predicted reasonably well on the basis of past performance. For a period longer than a few days a Shortt clock is capable of keeping time with an accuracy of about one part in 30 million. Consequently, the error can be foretold a year in advance with an uncertainty of about a second. Much has been learned by comparing several Shortt clocks among themselves and with crystal oscillators.

Quartz crystal oscillators were first developed by W. A. Marrison at the Bell Telephone Laboratories. They can keep time for short periods with much greater accuracy than Shortt clocks; an accuracy of one part in 100 million is easily obtained, and one part in 1000 million seems possible. Experience over only relatively few years with crystal oscillators in time services is now available. Reports on the performance of crystals over longer periods will be awaited with much interest.

The most serious difficulty with crystals has been the occurrence of marked secular changes of rate, due to aging. This has suggested prediction with quadratic formulae. With the use of a quadratic formula a crystal oscillator in the British time service at Abinger was reported to have had a maximum variation of 0.02 second from uniform rate during a period of 18 months. Fur-

Making use of an entirely new principle for measuring time, the atomic clock of the National Bureau of Standards is controlled by a constant frequency derived from a microwave absorption line of ammonia gas. The clock was developed by Harold Lyons and his associates at the Bureau. Shown in the photo is NBS director E. U. Condon.

ther improvements in the timekeeping quality of the quartz clocks may be expected. The performance of these clocks has increased almost continuously since their introduction by Dr. Marrison twenty-five years ago. Reports from the Bell Telephone Laboratories show that important recent progress has been made.

The performance of Shortt clocks and crystal oscillators has been good enough to detect a small annual variation in the earth's rate of rotation. The earth is ahead of its average rotation by 0.065 second in the autumn and behind by about the same amount in the spring. The seasonal variation was first discovered in 1937 by N. Stoyko in Paris by comparison of clock performances in Paris, Washington, and Berlin with astronomical observations at various observatories. A more recent comparison of quartz clocks with transit observations at Greenwich yielded results in excellent agreement with those obtained elsewhere.

Three Belgian astronomers, F. H. van den Dungen, J. E. Cox, and J. van Mieghem, have examined the possibility of accounting for the seasonal change in the rate of rotation by seasonal variations of the distribution of air masses over different parts of the earth. W. H. Munk and R. L. Miller, at the Institute of Geophysics and Scripps Institution of Oceanography, University of California, conclude that this cause can account for only two per cent of the observed effect. They find, however, that fluctuations in atmospheric circulation, computed from weather maps, are adequate to produce the observed seasonal changes in the earth's rate of rotation, both as to magnitude and phase. Variations in oceanic circulation contribute about one-eighth the effect produced by the atmosphere.

An interesting difference between a pendulum clock and a crystal oscillator is that, while the rate of the former depends on the acceleration of gravity, the latter does not. Since there exist tidal oscillations in the acceleration of gravity caused by the direct and indirect attractions of the moon and the sun, there should exist tidal differences between the readings of crystal and pendulum clocks. A tidal oscillation with a period of one-half a lunar day and a coefficient of 0.15 millisecond was actually found in an analysis of Shortt clock readings in the laboratory of A. L. Loomis, compared with crystal oscillators in the Bell Telephone Laboratories in New York.

The Atomic Clock

The newest timekeeping device is the so-called atomic clock developed at the National Bureau of Standards by Dr. Harold Lyons and his associates. The clock is controlled by a constant frequency derived from a microwave absorption line of ammonia gas.

This is an exciting new principle: processes in atoms and molecules are not affected by whatever changes may impair the performance of astronomical timekeepers. The atomic clock therefore offers the possibility of establishing a standard of time measurement entirely independent of the astronomical standard. The first atomic clock ever built provided a time constancy of one part in ten million, but a much higher potential accuracy may eventually be realized.

Two essentially different problems concerning the measurement of time present themselves, that of long-range time and that of short-range time.

In the long-range problem we are interested in having a clock running continuously and we want to know what the clock reading means. A statement that "the battered old earth has fallen into disrepute as a timekeeper" applies only if astronomical time based upon the rotation of the earth is thought to be the only astronomical clock available. Modern astronomical practice permits obtaining annual corrections to the time based upon the rotation of the earth to 0.1 second. The length of a century (3×10^9 seconds) can then be obtained to within 0.15 second or one part in twenty billion. This indicates why astronomers must use ten significant figures in the mean motions of the moon and Mercury.

Corrections from astronomical time to ephemeris time cannot be furnished instantaneously; they may be made available with a delay of about a year, but can usually be extrapolated for a year or two with an uncertainty of only a few tenths of a second.

The short-range problem is especially that of maintaining frequency standards. Time based on the rotation of the earth is affected by the gradual lengthening of the day and the erratic changes in the earth's rate of rotation. For example, Figure 1c shows that in 1870 the earth's rate of rotation was fast by about 1.6 seconds per year compared with the average rotation at that epoch, or one part in twenty million. In 1900 it was slow by 0.6 second per year or one part in fifty million. The deviations from the average rate during the past two hundred years are known to astronomers and can be allowed for in obtaining frequency standards from astronomical time. The record of the earth's rotation during the last century shows that the rate can be predicted for one year ahead with an uncertainty rarely exceeding 0.3 second, or one part in a hundred million. An atomic clock providing a time constancy of 0.1 second per year, or one part in three hundred million, could serve as a more instantaneous check on the constancy of the earth's rotation than is now available with the aid of the moon's motion.

During the last twenty-five years astronomers were putting their house in order as far as the astronomical measurement of time is concerned. This progress sprung from the purely scientific needs of astronomy. Until recently no scientific or technical application outside astronomy required the precision with which astronomers measured time for their own purposes. Almost overnight physicists and engineers have acquired an interest in precise time, as the need of standard frequencies became important for keeping all kinds of radio, radar, and electronic devices properly tuned. This overlapping of interests in various branches of science is bound to bring unforeseen progress, of benefit to all.