CHAPTER 16

Ephemeris Time

IN the ephemerides of the Sun, Moon, and planets computed from the gravitational theories of their motions, the tabular time is a measure of the uniform time defined by the laws of dynamics, instead of mean solar time defined by the variable rotation of the Earth; but before the actual occurrence of variations in the rate of rotation had been conclusively established and formally recognized in practice, the arguments of the ephemerides were designated as Universal Time. Consequently, the discrepancies which were found between the theoretical ephemeris positions and observed positions were not entirely due to errors of observation or imperfections of the theories. The mean solar time at any instant, corrected for variations of the meridian, differs from a uniform measure by the accumulated amount of the inequalities due to variations in the rotation of the Earth. The position of a body at an observed mean solar time deviates from the ephemeris position for the same numerical value of the tabular time, by the amount of the motion of the body during a time interval equal to this accumulated difference between the two measures of time. Analysis of the apparent departures of the Sun, Moon, and planets from their tabular positions eventually established the existence of a secular retardation of the rate of rotation, commonly ascribed to tidal friction, upon which are superimposed irregular changes from unknown geophysical causes. In addition, small periodic variations have been detected by comparing astronomical time determinations with crystal-controlled clocks.

Secular variations and irregular changes in the rate of rotation, even if far too minute to be detected directly, may produce observable phenomena after the lapse of a sufficiently long interval, because of their cumulative effects. Records of eclipses and occultations from ancient times have been the principal means of determining the secular retardation; the recorded times and circumstances differ by large amounts from calculations based on the gravitational theories of the Sun and the Moon. The irregular variations have been determined from the more accurate and complete observations of eclipses and occultations during modern times, and from comparisons of observations of the Moon and the inner planets with their gravitational theories.

The continued failure of successive theories of the motion of the Moon to represent the observed motion was the first actual evidence that the rate of rotation may not be constant. Deviations from theory are most evident in the case of the Moon because of the rapidity of the motion and the accuracy with which the inequalities can be observed because of the proximity to the Earth. The discrepancies are so large that at no time in the history of celestial mechanics has it been possible to represent the observed motion by a gravitational theory. The failures of the earlier lunar theories were partly due to deficiencies in the theories; but as the lunar theory was developed to continually greater perfection by successive investigators, and as similar discrepancies were detected in the motions of other bodies with the continued accumulation of observations, the evidence for the variability of the rotation of the Earth steadily increased.

The Moon departs from its ephemeris position by an irregularly varying amount, and meanwhile appears to be also steadily forging ahead of its calculated place, as if its motion were being timed by a clock that is gradually slowing down at an irregularly varying rate. Since the clocks used to time astronomical observations are kept in agreement with the rotation of the Earth, these deviations of the Moon from theory are evidence that the rate of rotation is gradually decreasing, while also fluctuating irregularly. The existence of parallel deviations from theory in the motions of the Sun and inner planets, by amounts proportional to their mean motions, was established by H. Spencer Jones.* In the case of the Moon, the discrepancy with the ephemeris position includes a departure due to an actual secular variation of the orbital motion which accompanies the tidal retardation of the rotation of the Earth in accordance with the law of conservation of momentum; otherwise, the departures of the Moon and the other bodies are the amounts by which their respective mean motions would displace them during the same interval of time. This is virtually conclusive evidence of the reality of the secular and irregular variations in the rotation.

Observations adequate for determining the irregular variations are not available before about 1650, and only very rough values can be obtained that far in the past. This limits the accuracy with which the secular retardation can be found. The rate of retardation determined from ancient observations is only the average value during the interval which has elapsed since the observations; it includes the accumulated effect of the unknown irregular variations which have meanwhile occurred, and moreover the rate of retardation probably does not remain constant over great intervals of time. A value commonly estimated for the order of magnitude of the rate at which the day lengthens by tidal friction is one second per 100,000 years, but this is subject to considerable uncertainty.

* H. Spencer Jones, *Mon. Not. Roy. Astr. Soc.* **99**, 541 (1939).

The total increase in the length of the day during any given period must be carefully distinguished from the accumulated loss in the measure of time obtained from the rotation of the Earth. At the rate of one second in 100,000 years, the day is now longer than it was 2000 years ago by only 2000/100,000 = $0^s.02$; but the continuous change in the rate of rotation causes the accumulated clock error to increase as the square of the elapsed time. The *average* length of the 730,000 days in this interval was $0^s.01$ greater than the length at the beginning, and therefore the total accumulated loss in the measure of solar time due to the retardation of the rotation has been $0.01 \times 730{,}000 = 7300^s$. The Earth, regarded as a clock, has lost about two hours during the past 2000 years. At the rate of one second per 100,000 years, the increase in the length of the day is 2.74×10^{-8} seconds/day; in n days, the sum of the amounts by which the successive days are longer than at the beginning is, with sufficient accuracy,

$$2^s.74 \times 10^{-8}(1 + 2 + 3 + \cdots + n) = 1^s.37\, n^2 \times 10^{-8},$$

where on the right n has been neglected in comparison with n^2, in the formula for the sum of an arithmetic progression.

Periodic variations in the rotation of the Earth do not cause cumulative effects, and are significant only if large enough to be observed directly by some means. With the great increase in the precision of astronomical time determinations, and the development of increasingly uniform clocks, short period variations have been detected directly in the determinations of time. The periodic inequalities which have been observed are partly due to the variations of the moments of inertia caused by the tidal deformations of the Earth and the oceans; but the principal periodic inequality in the rate of rotation is an annual variation which is of meteorological origin.

Evidence for these short period variations was first obtained by Stoyko in 1937 from intercomparisons of the rates of crystal clocks at different national time services. The clocks at Paris, Washington, and Berlin appeared to run faster than usual in spring, slower in autumn, gaining and losing in unison with one another by about the same amounts. This could reasonably be explained only by a seasonal variation in the rate of rotation of the Earth. During subsequent years, Stoyko's results were confirmed by others. During the early part of the year, the rotation is slower than on the average, and a uniformly running clock gains on mean solar time; the Earth rotates faster in autumn, and the clock appears to lose.

The variation is not greatly different from year to year. The annual variation in the length of the day is less than $0^s.001$. Harmonic analysis of the inequality in mean solar time gives an annual term with an amplitude of 30 msec, due principally to meteorological causes; a term of period 6 months, with an amplitude of 10 msec, due to the solar tide *Ssa*; a term of period 13.6 days and amplitude 1 msec, due to the lunar tide *Mf*; and a term of period 27.6 days and amplitude 1 msec, due to the lunar tide *Mm*.

Beginning with 1 January 1956, determinations of Universal Time by the national time services have been corrected for the variation of the meridian due to the observed motion of the geographic pole, and for an extrapolated value of the annual variation in the rate of rotation of the Earth. The Universal Time obtained directly from observation is denoted U.T.0. The time obtained by correcting U.T.0 for polar motion is denoted U.T.1; it is virtually proportional to the angular rate of rotation of the Earth, since the inequalities from tidal variations of the vertical are practically negligible. The measure obtained by further correcting U.T.1 for the seasonal inequality is designated U.T.2; apart from errors of observation and effects of errors in the star places, it contains only the small inequalities due to irregular variations of the rotation and to tidal deformations of the Earth, since the secular variation is inappreciable.

Corrections for the polar motion were first applied at the Greenwich Observatory beginning 1 January 1947. Only an approximate correction was possible as the polar motion was not immediately known from observavation; but an estimate could be made, based on the daily determinations of the variation of latitude at Washington, since the difference of longitude is sufficiently near 90°. Corrections for the seasonal inequality were applied at Greenwich beginning 1 July 1953. Various corrections were also introduced from time to time at several other observatories. In 1956 a coordinated program was established in which observations of the variation of latitude at several cooperating observatories are made rapidly available to the International Latitude Service; on the basis of these observations, and a correction for seasonal variation based on observations from preceding years, the Bureau International de l'Heure issues the corrections for reducing U.T.0 to U.T.2.

The transmission of time signals based on U.T.2 provides, without delay, a *relatively* uniform standard of time and frequency for practical use over intervals of the order of a year; but in order to obtain a strictly uniform measure, it is necessary to determine the correction ΔT that reduces Universal Time to Ephemeris Time.

The Reduction of Mean Solar Time to a Uniform Measure of Time

In principle, the discrepancy between the theoretical and the observed motions of the celestial bodies that is due to the use of uniform time in the theories and mean solar time in observations could be avoided by transforming the gravitational theories to the mean solar measure of time as the independent variable. Implicitly, the equivalent of this procedure was used in practice before the occurrence of variations in the rate of rotation of the Earth had been conclusively established, and until a practical necessity had developed for distinguishing between mean solar time and a uniform measure. In the ephemerides computed from gravitational theories, the argument was designated as Universal Time; and when necessary, as in precise calculations of eclipses and occultations, and occasionally in navigational almanacs, corrections determined from observations during the immediately preceding years were applied to the tabular positions in order to bring them as nearly as possible into agreement with the positions that presumably would be observed during the period covered by the ephemeris.

However, the increasingly large corrections necessary to the ephemerides, particularly for the Moon, are complex and difficult to determine when great precision is required, and are inevitably more or less uncertain when calculated in advance. The alternative of applying corrections to the observed measure of mean solar time to reduce it to a uniform measure has the advantage of leaving gravitational theories and ephemerides unchanged, and avoiding the difficult transformation of the theories from uniform dynamical time to mean solar time; and the adoption of this alternative became practically necessary as the need increased for explicitly recognizing the departures of Universal Time from uniformity with high accuracy. To the precision that is now often required, the construction of exact ephemerides by transforming the theoretical expressions to Universal Time is entirely impracticable, especially for the Moon. The variations from uniformity cannot be determined in advance with certainty; they can be accurately obtained only by continued observation. Furthermore, an explicit uniform standard of time has come to be needed for many practical purposes.

For the purpose of obtaining a uniform measure of time, the epoch and the initial value of the correction ΔT to Universal Time are arbitrary. A number of different tables of corrections have been given in the past by different writers obtained either from different data or on different systems of reckoning. The particular correction that has been adopted by international agreement is the correction derived by Clemence* for reducing Universal Time to the measure of time defined by Newcomb's *Tables of the Sun*. The uniform time obtained with this correction was adopted as the standard by the International Astronomical Union in 1952, and was designated Ephemeris Time, in accordance with recommendations that had been made by the Paris Conference of 1950 on astronomical constants. As thus defined, Ephemeris Time agreed with Universal Time at some instant between 1900 and 1905, and the ephemeris

* G. M. Clemence, *Astr. Jour.* **53**, 169 (1948).

day is approximately the average of the mean solar days during the nineteenth century.

This correction was derived from the discrepancy between the observed and the tabular values of the mean longitude of the Sun that had been found by H. Spencer Jones. The departure of the observed value from the tabular value is the sum of a secular variation and an irregularly varying deviation. The irregular departures are proportional to the irregular variations that likewise occur in the observed mean longitude of the Moon; the amount of the irregular deviation of the Sun in mean longitude from the tabular value is 0.0748 B, where B is the concomitant departure of the Moon and the coefficient is the ratio of the mean motions.

According to the determination by Jones, the correction that is required to the tabular mean longitude of the Sun in Newcomb's tables, in order to obtain the observed value when the times of observation are in Universal Time, is

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

where T denotes Universal Time reckoned in Julian centuries from 1900 January 0, Greenwich Mean Noon, and at this epoch $B = -15''.94$. However, this correction includes both the actual motion of the Sun $(\Delta L)_T$ during the interval ΔT, and also the error $(\Delta L)_e$ in Newcomb's formula that is due partly to the errors in the observations from which it was derived, and partly to the fact that these observations were referred to mean solar time; only $(\Delta L)_T$ is significant for the determination of the variation of mean solar time from uniformity. Newcomb's formula for the mean longitude of the Sun was derived by discussing observations of the Sun without reducing the times of observation to a uniform measure, and is consequently of the form

$$L_N = L_0 + L_1 T_M + L_2 T_M^2;$$

the corrected formula, in terms of the uniform measure of time $T_M + \Delta T$, with the coefficients corrected for this transformation to the proper independent variable of the dynamical formula and for errors of observation, neglecting effects on the term in the square of the time, is

$$\begin{aligned} L &= L_N + \Delta L_N \\ &= (L_0 + \Delta L_0) + (L_1 + \Delta L_1)(T_M + \Delta T) + L_2 T_M^2 \\ &= L_N + \{\Delta L_0 + (\Delta L_1) T_M + (L_1 + \Delta L_1)\,\Delta T\}, \end{aligned}$$

in which ΔT denotes the value of the reduction that is obtained from $(\Delta T)_T$.

The interval ΔT is the accumulated effect of the variations of rotation from uniformity. In terms of uniform time T, the rate of rotation is

$$\omega = \omega_0 + cT + \delta\omega,$$

where the second term represents the secular variation, and the last term the irregular and periodic variations. The mean solar time is proportional to

$$\int \omega \, dT = T_0 + \omega_0 T + \tfrac{1}{2}cT^2 + \int (\delta\omega) \, dT.$$

The correction that reduces a measure of mean solar time to a uniform measure is therefore proportional to

$$-\tfrac{1}{2}cT^2 - \int (\delta\omega) \, dT + \Delta T_0,$$

in which the constant of integration ΔT_0 represents the correction at the epoch; the coefficient c is negative, since ω is being retarded.

The terms of ΔL_N which represent the motion of the Sun in mean longitude during the interval ΔT are therefore

$$\begin{aligned}(\Delta L)_T &= -(L_1 + \Delta L_1)\left[\tfrac{1}{2}\,cT^2 + \int (\delta\omega) \, dT\right] \\ &= +1''.23\;T^2 + 0.0748\,B;\end{aligned}$$

this correction to the tabular mean longitude is the apparent discrepancy with the observed value when the tabular time is reckoned in a uniform measure and the observed time is in mean solar measure. The remaining terms of ΔL_N represent an actual correction required to the tabular values of the mean longitude in Newcomb's tables, in order for the tabular argument to represent the dynamical measure of time. These terms represent corrections to the tabular mean longitude at the epoch and to the tabular mean motion which make the coefficients consistent with the dynamical reckoning of time, and since at the epoch the value of $0.0748\,B$ is $-1''.19$, we have for these terms

$$\begin{aligned}(\Delta L)_e &= \Delta L_0 + \{(L_1 + \Delta L_1)\,\Delta T_0 + (\Delta L_1)T\} \\ &= -0''.19 + \{1''.19 + 2''.97\;T\} \\ &= +1''.00 + 2''.97\;T.\end{aligned}$$

In principle, a correction which will reduce mean solar time to a uniform measure may be derived from ΔL_N in either of two ways. From the standpoint of the traditional concept of the fictitious mean sun, the correction $(\Delta L)_e$ to the mean longitude of the Sun represents a correction to Newcomb's formula for the right ascension of the fictitious mean sun, and consequently is equivalent to a change in the measure of mean solar time directly by the amount $(\delta T)^s = -(\Delta L)_e^s$. The further correction which reduces this revised measure to uniform time is the interval ΔT required for the Sun to move in mean longitude by the amount $(\Delta L)_T$; since the period of L is 365.2422 days,

$$(\Delta T)^s = \frac{365.2422 \times 86400}{1296000} (\Delta L)''_T$$
$$= 24^s.349 (\Delta L)''_T$$

The total correction to the measure of mean solar time defined by Newcomb's *Tables of the Sun* is then

$$\Delta T^s = -\tfrac{1}{15}(\Delta L)''_e + 24^s.349(\Delta L)''_T$$
$$= -0^s.066\,667 - 0^s.198\,000\,T + 29^s.949\,T^2 + 1.821\,B;$$

the first two terms represent the correction due to the correction $+1''.00 + 2''.97\,T$ to the mean sun, and the other two terms represent the motion of the mean sun in longitude at the rate of $1''$ in $24^s.349$ during the interval ΔT by which the observed time is corrected in order to obtain a uniform measure.

However, since it is not essential for the purpose of measurement that the fictitious mean sun conform exactly to the actual mean sun, we may equally well, and more conveniently, retain Newcomb's tabular mean sun and derive a reduction directly from the entire discrepancy ΔL_N. Instead of representing the correction required by the first two terms of ΔL_N as a correction to the fictitious mean sun, it may be represented by a correction to the measure of mean solar time defined by the same fictitious mean sun, of the amount $24^s.349\ (\Delta L)''_e$ necessary for the motion of the fictitious mean sun in right ascension to produce the same effect. The entire correction is then expressed as a correction to the observed time on the system defined by retaining Newcomb's mean sun unchanged; in this form

$$\Delta T = +24^s.349 + 72^s.3165\,T + 29^s.949\,T^2 + 1.821\,B \qquad (170)$$

where T is reckoned in Julian centuries from 1900 January 0, Greenwich Mean Noon. This is the form in which ΔT was derived by Clemence; and Ephemeris Time was originally defined as the measure obtained by applying this correction to Universal Time.*

The last two terms, in which B represents the effect of irregular variations in the rotation of the Earth and must be evaluated from observation, constitute the reduction of Universal Time to a uniform measure of time. The other two terms, depending on the method adopted for deriving ΔT, are essentially arbitrary; the first determines the epoch at which ΔT vanishes, and the second determines the length of the uniform solar day.

* *Trans. Int. Astr. Union* **8**, 66 (1952).

Ephemeris Time

The definition of Ephemeris Time as

$$\text{E.T.} = \text{U.T.} + \Delta T,$$

in which ΔT is given by (170), is equivalent to defining it as the specific numerical measure of uniform time defined by Newcomb's *Tables of the Sun*. The definition of ΔT is expressed in terms of the departure of the Moon in mean longitude from Brown's lunar tables, and in principle may be calculated from the observed value of B; but in practice ΔT may be evaluated directly by comparing observed positions of celestial bodies, recorded in Universal Time, with gravitational ephemerides in which the argument is the same measure of uniform time as defined by Newcomb's tables. The tabular time for which the ephemeris position is the same as the observed position is the Ephemeris Time of the observation.

Since Ephemeris Time is defined as the measure in which Newcomb's solar tables agree with observation, its determination must depend ultimately on observations of the Sun. However, because of the relatively slow motion of the Sun and the difficulty of making accurate observations of its position, the principal practical means of determining current values is by observations of the Moon. Over very long intervals, observations of the Sun and planets are used in addition to the Moon.

Ephemeris Time is not as immediately accessible as mean solar time. Its determination depends upon observations recorded in Universal Time, and their comparison with ephemerides in order to determine ΔT. An accurate determination requires complex special instrumental and computing facilities, and a more or less extended interval of time. Ephemeris Time is not a feasible standard for practical use in astronomical observation or in navigation and surveying. Mean solar time is essential for civil timekeeping and immediate practical purposes. Moreover its determination is necessary for measuring the variations in the rate of rotation of the Earth since they are unpredictable.

Measurement of Ephemeris Time

The epoch and the unit of Ephemeris Time are determined by the mean longitude of the Sun at epoch, and the mean motion, equivalent to two of the orbital constants of the Earth.

The fundamental epoch from which Ephemeris Time is reckoned is the epoch that Newcomb designated as 1900 January 0, Greenwich Mean Noon, but which actually is 1900 January 0^{d} 12^{h} E.T. The instant to which this designation is assigned is the instant near the beginning of the calendar year

A.D. 1900 when the geometric mean longitude of the Sun referred to the mean equinox of date was 279°41′48″.04.*

The primary unit of Ephemeris Time is the tropical year, defined by the mean motion of the Sun in longitude at the epoch 1900 January 0^d 12^h E.T. Its length in ephemeris days is determined by the coefficient of T in Newcomb's expression for the geometric mean longitude of the Sun referred to the mean equinox of date. The ephemeris day is 86400 ephemeris seconds; the ephemeris second is defined as 1/3155 6925.9747 of the tropical year for 1900 January 0^d 12^h E.T., and has been formally adopted as the fundamental invariable unit of time by the Comité International des Poids et Mesures.† The former fundamental unit of time was the mean solar second, defined as 1/86400 of the mean solar day.

Practical Determination of Ephemeris Time

For the determination of ΔT from the apparent discrepancies between observed and theoretical positions, an ephemeris is required that is calculated from a strictly gravitational theory in which the measure of time is the same as in Newcomb's solar tables. A highly accurate theory is necessary, since the discrepancies include the defects of the theory as well as the effects of the irregularities in mean solar time. Observations of the Moon are the most effective means for the practical determination of the variations in mean solar time, particularly the irregular variations, but a direct comparison with an ephemeris calculated from Brown's lunar tables does not give ΔT immediately. Brown's lunar theory is not entirely gravitational, because the tabular mean longitude contains an empirical term which was incorporated in the attempt to construct tables that would agree with observation; and the measure of time which the theory implicitly defines is not precisely the same as in Newcomb's solar tables. In order to obtain a gravitational theory expressed in the same measure of time as Newcomb's tables, Brown's theory has therefore been amended by removing the empirical term and applying a correction to the mean longitude that reduces the theory to the measure of time defined by (170). Ephemeris Time may then be determined by a direct comparison of observations in Universal Time with an ephemeris calculated from the amended theory.

The required correction to Brown's tables was derived by Clemence‡ from the correction to the tabular mean longitude of the Moon that had been found by H. Spencer Jones. Brown constructed the tables with the theoretical gravitational secular acceleration, neglecting tidal friction; the mean

* *Trans. Int. Astr. Union* **X,** 72 and 500 (1960).

† *Procès-Verbaux des Séances, Ser.* **2, XXV,** 77 (1957).

‡ G. M. Clemence, *Astr. Jour.* **53,** 172 (1948).

longitude at epoch, the mean motion, and the empirical term were determined to satisfy modern observations as well as possible. The neglected effect of tidal friction comprises an apparent secular acceleration due to the retardation of the rotation of the Earth, and also an actual diminution in the angular mean motion of the Moon. The empirical term failed to represent subsequent observations. The observed mean longitude of the Moon in terms of the Universal Time of observation is

$L_☽$ = tabular mean longitude
  − empirical term
  $+\ 5''.22\ T^2$ Reduction of secular acceleration to observed value
  $+\ 12''.96\ T + 4''.65$ Correction to mean motion and epoch
  $+\ B$ Correction for irregular variation in rotation.

The departure $O—C$ of the observed longitude from the tabular longitude is the sum of (a) an apparent departure due to the difference ΔT between Universal Time and Ephemeris Time, and (b) an actual departure due to the deficiency of the empirical term and to other defects of the tables. Removing the apparent departure (a) from the total observed correction leaves the correction (b) required to the tables to obtain the observed longitude at the instant of the observed Universal Time. When this correction is applied to the tabular ephemeris, the residual $O—C$ is entirely due to the departure of Universal Time from Ephemeris Time, and determines ΔT directly.

The apparent departure (a) is the amount of the motion of the Moon in mean longitude during the interval ΔT. The mean motion of the Moon is 13.37 times as rapid as the mean motion of the Sun, amounting to 1″ in $24^s.349/13.37 = 1^s.821$, or $1''/1^s.821 = 0''.5490$/sec. Therefore, from either the expression for ΔL_N or the expression (170) for ΔT, the apparent departure from theory is

$$+13''.37 + 39''.71\ T + 16''.44\ T^2 + B = 13.37\ (\Delta L_N)'' = (1''/1^s.821)\ \Delta T^s.$$

Subtracting this amount from the total correction obtained by Jones leaves

$$\Delta L_☾ = -8''.72 - 26''.75\ T - 11''.22\ T^2 - \text{empirical term.} \qquad (171)$$

Applying the correction (171) to the tabular mean longitude, and the consequent corrections required to the periodic terms in the ecliptic longitude, latitude, and parallax of the Moon, gives a gravitational ephemeris with Ephemeris Time as the argument.

Beginning with 1960, the lunar ephemeris in the national ephemerides is calculated from this amended theory, directly from the theoretical expressions for the longitude, latitude, and parallax, instead of from Brown's tables. This improved ephemeris was also made available for 1952–1959 in a supplementary volume. Direct comparison of the Universal Time of an observed position of the Moon with the tabular time at which the ephemeris position agrees with the observed position determines ΔT. The value of B may be calculated from ΔT by means of (170).

The amendment to Brown's tables is equivalent to the formula (170) that defines ΔT. The correction ΔT is defined in terms of B, and was derived from Jones' expression for $L_☾$; therefore B was originally defined by the expression

$$B = L_{\text{obs}} - L_{\text{tab}} + \text{empirical term} - (4''.65 + 12''.96\,T + 5''.22\,T^2),$$

where the observed mean longitude is referred to the Universal Time of the observation and the tabular mean longitude is from Brown's tables. Consequently, ΔT must be determined strictly in accordance with this original definition of B; in particular, the position of the Moon from which ΔT is derived must be referred to the equinox defined by Newcomb's fundamental catalog.* The lunar ephemeris calculated from the amended theory is on this basis; but observations are referred to the equinox of the fundamental system in current use, and must be reduced to Newcomb's equinox before comparison with the ephemeris.

Because of the uncertainty in the value of the secular acceleration, the actual partition of the departure from Brown's tables between B and the secular variation may be somewhat different from that given by Jones, but this does not affect the measurement of time. Other imperfections of the lunar theory affect the accuracy with which Ephemeris Time is obtained from observation, but not the definition.

The development of means for photographic determinations of the position of the Moon among the stars, and the introduction of the improved lunar ephemeris with which the observed position may be directly compared, enable Ephemeris Time to be obtained more expeditiously than by the methods previously available. Formerly ΔT was calculated from the value of B determined principally by means of meridian observations of the Moon and observations of occultations of stars, compared with the tabular positions in the lunar ephemeris calculated from Brown's tables; the determination of a definitive value by these methods required several years. From photographic positions of the Moon obtained with the dual-rate camera devised by Markowitz in 1952, compared with the improved lunar ephemeris, accurate values of ΔT may be determined much more easily and quickly.†

With the dual-rate camera, the Moon is photographed simultaneously with

* *Astr. Pap. Amer. Eph.* **VIII**, Pt. II.

† W. Markowitz, *Astr. Jour.* **59**, 69–73 (1954).

the surrounding stars, but the image of the Moon is held fixed relative to the stars during the exposure. The light from the Moon passes through a dark plane-parallel glass filter which is tilted during the exposure by being rotated around an axis in its own plane, to shift the image of the Moon at the rate and in the direction required to hold the image fixed on the plate while the plate carriage is being driven to follow the stars. The stars are photographed through a fixed light yellow filter. An electrical contact records on a chronograph the instant when the two filters are parallel. At this instant the filters produce no optical displacement of the Moon relative to the stars; the Universal Time at this instant is the time at which the actual position of the Moon among the stars was the same as shown on the plate.

Conversion of Ephemerides to Universal Time

The adoption of the term *Ephemeris Time* to designate the argument in the fundamental ephemerides, in place of the former designation Universal Time, has no effect on the methods of calculating these ephemerides. It is only a correction of terminology; the tabular entries are the same as before when they are obtained from the same basic tables. However, in calculating any quantities that depend upon the rotation of the Earth such as hour angles and meridian transits, corrections to former procedures are necessary for the effects of the variations in the rate of rotation that formerly were neglected, and for this purpose the value of ΔT is required. Likewise, in preparing almanacs for navigation and surveying, corrections must be applied to the fundamental ephemerides to convert them from Ephemeris Time to Universal Time.

In general, these calculations must be made some years in advance, and are therefore necessarily based on extrapolated values of ΔT; but the uncertainty of the extrapolation, over the relatively short intervals necessary, is within the order of accuracy to which the calculations need be made.

The methods required for constructing ephemerides and calculating astronomical phenomena with Universal Time as the argument depend principally upon whether hour angles are involved. When the tabular quantities are independent of the rotation of the Earth, an ephemeris for 0^h E.T. on successive dates may be converted to an ephemeris for 0^h U.T. by interpolating the tabular entries to an interval ΔT *after* 0^h E.T., because at 0^h U.T. the general relation E.T. = U.T. + ΔT gives E.T. = ΔT. If second differences are negligible, the interpolated values are obtained by adding algebraically to each of the tabular values for 0^h E.T. the correction $(\Delta T/h)\delta_{1/2}$, where h is the tabular interval and $\delta_{1/2}$ denotes the first difference.

Phenomena depending upon hour angle and geographic location, when calculated from the fundamental ephemerides in the same way as prior to

1960, are referred not to the Greenwich meridian and to Universal Time but to Ephemeris Time and to a meridian which *in space* is located where the Greenwich meridian would be if the rotation of the Earth had been uniform. This slightly different meridian is called the *ephemeris meridian.* Because of the accumulated effect of the variations in rotation, the Greenwich meridian is at an angular distance west of this position, by the amount of the sidereal equivalent of ΔT, or 1.002738 ΔT; therefore on the surface of the Earth the ephemeris meridian is 1.002738 ΔT *east* of the geographic meridian of Greenwich. To facilitate the practical calculation of phenomena that depend upon the rotation of the Earth, it is used as an auxiliary reference meridian. Hour angles and longitudes reckoned from the ephemeris meridian are distinguished by the terms *ephemeris hour angle* and *ephemeris longitude.* The ephemeris hour angle of the equinox is called *ephemeris sidereal time.*

When referred to the ephemeris meridian, phenomena depending on the rotation of the Earth may be calculated in terms of Ephemeris Time by methods which formally are exactly the same as the methods for calculations referred to the Greenwich meridian in terms of Universal Time. The practical calculations are based on the principle that the tabular Greenwich sidereal time of 0^h U.T. is numerically equal to the ephemeris sidereal time of 0^h E.T.; the hour angle of the equinox which determines the sidereal time of 0^h U.T. is referred to the actual geographic meridian of Greenwich, but the equinox at 0^h E.T. is at the same hour angle from the ephemeris meridian as it is from the Greenwich meridian at 0^h U.T.

Until ΔT is known, local hour angles referred to a specific meridian of geographic longitude cannot be calculated. Hour angles and phenomena depending upon them may be determined only in terms of ephemeris longitude and Ephemeris Time. When ΔT becomes known, the ephemeris longitude where the local hour angle has any particular value is converted to geographic longitude by applying the correction $-1.002738\ \Delta T$; the Ephemeris Time when the hour angle has this value on this meridian is converted to Universal Time by subtracting ΔT.

If ΔT is known, the hour angle of a celestial body reckoned from the geographic meridian of Greenwich at a given instant of Universal Time is obtained by interpolating the right ascension α from Ephemeris Time to Universal Time, and calculating

$$\text{GHA} = \tau - \alpha,$$

(where GHA indicates Greenwich hour angle), in which τ is the Greenwich sidereal time taken directly from the ephemeris of the sidereal time of 0^h U.T. without regard to ΔT, because the tabular values are already referred to Universal Time and to the geographic meridian of Greenwich by virtue of defining the instants of 0^h U.T.

The term *ephemeris transit* is used to denote the time formerly given for meridian transit at Greenwich. The ephemeris transit is the Ephemeris Time at the instant of transit across the *ephemeris* meridian; the Ephemeris Time is by definition the time on the *Greenwich* meridian at this instant. Interpolation to any local meridian by using the ephemeris longitude as the interpolating factor gives the Ephemeris Time of local transit across this meridian; in forming first differences of the tabular ephemeris transits for this purpose, it must not be overlooked that the *day* is part of each tabular time. At ephemeris transit, the ephemeris sidereal time is equal to the right ascension.

The Universal Time of transit of the Sun, Moon, or a planet across the meridian of Greenwich may be found by subtracting ΔT from the Ephemeris Time of Greenwich transit that is obtained by interpolating the ephemeris transit from the geographic longitude of the ephemeris meridian, 1.002738 ΔT east, to longitude 0°. The Greenwich transit follows ephemeris transit at an interval which to a first approximation exceeds ΔT by the time equivalent of the motion in right ascension during the interval ΔT. The Universal Time of Greenwich transit is therefore algebraically greater than the tabular ephemeris transit by approximately the amount $(\Delta T/h)\ \delta_{1/2}\alpha$, where h is the tabular interval.