Q. Jl R. astr. Soc. (1968) **9**, 281–293.

The Presidential Address

ASTRONOMICAL MEASURES OF TIME

Mr D.H.Sadler

(Delivered at the Anniversary Meeting on 1968 February 9)

The duty and responsibility of preparing a Presidential Address is a heavy one, but it has its compensations. It provides a unique opportunity to speak to the assembled Fellows of the Society, without fear of interruption or opposition, and without examination by discussion. There is a good chance that one can get away with opinions that one might not otherwise care to express in public. Several Presidents have taken full advantage of this 'presidential licence' in the past, but I propose only to do so in a mild and gentle way.

Those of us who are old-fashioned enough to work in the field of positional astronomy have recently been assailed by the physicists who, having developed atomic clocks of incredible accuracy, now consider that the natural time-scales of astronomy can be replaced by the natural frequencies of atomic or molecular transitions. I hope to convince you that this is not so.

We have also been assailed by the politicians, to whom centuries of scientific tradition and usage are apparently of little account compared to the fleeting and meaningless results of a newspaper competition; I refer, of course, to the name now being proposed for permanent Summer Time. But I shall not abuse this platform by deigning to say any more on this subject than how fortunate we are that we were able to commence business at this Anniversary Meeting of 1968 at 'half-past four o'clock in the afternoon' Greenwich Mean Time, which is currently also British Standard Time.

As far as I can discover this is the first occasion on which a President of the Society has chosen the subject of 'time' for his Address. I do so now for two reasons: firstly, to try to explain some of the mystique that has arisen in connection with Ephemeris Time, and, secondly, to clarify the respective roles in astronomy of Ephemeris Time and Atomic Clock Time.

Before doing so I would like to review, briefly, the historical relationship between astronomical determinations of time and 'mechanical' time-keepers or clocks; in doing this I shall try to establish some concepts, definitions and terminologies that may be useful in understanding the main objectives.

The first concept is that of an *observed time-scale*, depending on some naturally-occurring observable phenomenon, which for our purposes will be an astronomical phenomenon; examples are: the alternation of lightness and darkness; the phases of the Moon; the rising and setting of the Sun, Moon or stars; the succession of the seasons; eclipses and occultations; the phenomena of Jupiter's satellites; the meridian transits of the Sun, Moon and stars; the orbital positions, relative to the stars, of the Sun, Moon and planets. The list is endless, proceeding from observations that force themselves on the consciousness to those that require the most sophisticated techniques. But all such time-scales have one thing in common: they define a set of *instants* corresponding to the times at which the phenomena are observed. There is no difference in principle in using the statement 'it is *now* the instant of' in relation to (for example): spring, sunset, full moon, noon, 0^h U.T. or 0^h E.T. The differences, which are purely practical, relate to the precision with which the observations can be made, to the necessity for interpolation between observations, and to the uniformity, or not, of the intervals between successive phenomena.

Such an observed time-scale does not need to be either continuous or uniform; primitive man was content with the observations of sunrise and sunset. But the practical demands of everyday life increasingly require a measure of time that is both reasonably continuous and uniform; and this leads to two developments. Firstly, to the development of mechanical methods of measuring equal time-intervals—such as, in the most elementary forms, the time-intervals required: to perform a given task; to empty a water-clock, or sand-glass; to swing a pendulum; for oscillations of a quartz crystal; and for atomic transitions. Secondly, to the development of theoretical adjustments to the times corresponding to the observations to improve the uniformity of the time-scale.

It so happens that the most readily available observed time-scale, based on the apparent solar day, was amply good enough for almost all requirements; the sundial, which supplied the elementary theory to interpolate between successive meridian transits of the Sun, was all that was necessary before the days of rapid transport and communication. In designing *The Nautical Almanac and Astronomical Ephemeris* for 1767, Maskelyne had no hesitation in using the non-uniform apparent time as the time-argument of the ephemerides. Why should he, when observations gave apparent time direct?

It was not until the Almanac for 1834, on the recommendation of the Society, that the time-argument was changed to mean solar time—the reason being the increasing availability of man-made time-keepers that could not be adjusted to maintain non-uniform apparent time. The then President of the Society, Sir James South, condemned the change on the grounds that mean solar time was alien to astronomical thinking and suitable only for 'culinary philosophy'!

The two observed time-scales with which we shall be concerned are: Universal Time (U.T.), which is identical with Greenwich Mean Time and is a direct measure of the rotation of the Earth; and Ephemeris Time (E.T.), which can be described as the time-argument of the ephemerides of the Sun, Moon and planets.

Man-made time-keepers, or *clocks*, provide an *integrated time-scale*, depending on the continued mechanical addition of the basic time-interval. Time-scales derived from such clocks thus differ fundamentally

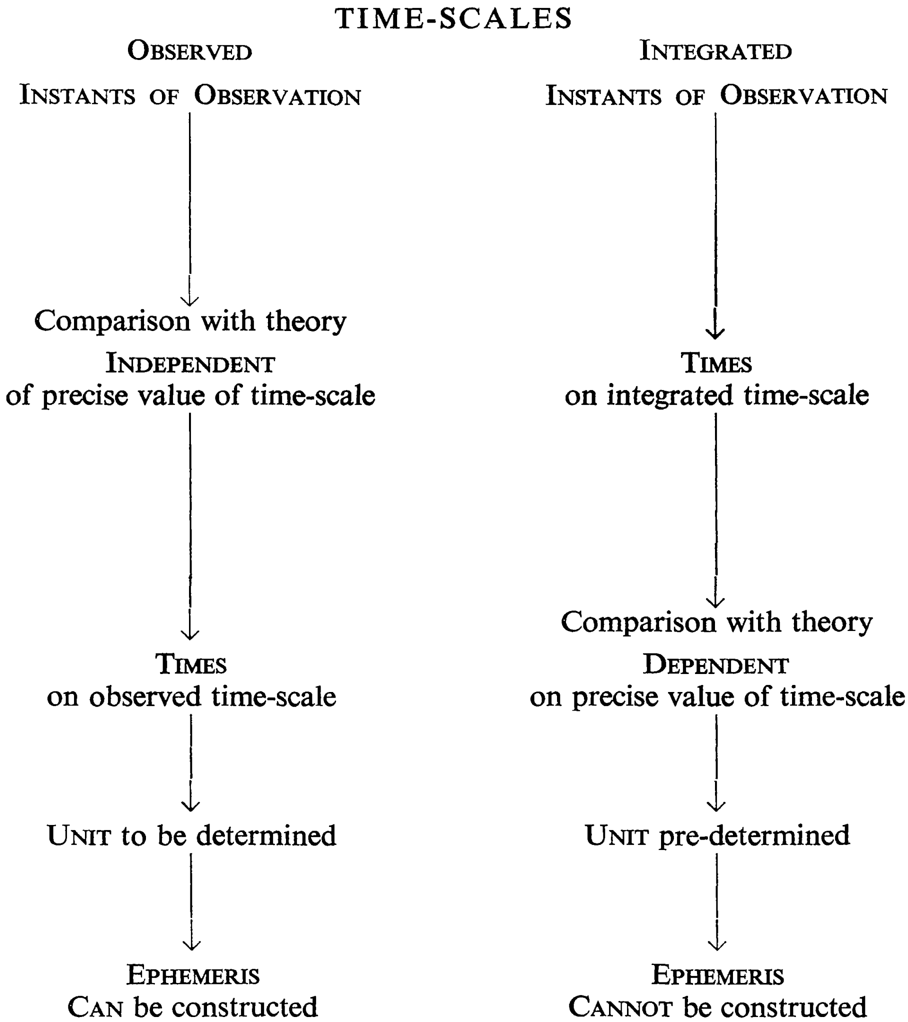

FIG. 1. A comparison between observed and integrated time-scales indicating the fundamental differences in respect of the comparison of observation with theory and the construction of an ephemeris.

in principle from the *observed time-scales* of astronomy (see Fig. 1). Until recent years the long-term precision derived from man-made clocks was inferior to that obtainable direct from astronomical observations; clocks were recognized and used as a means of interpolating within, and extrapolating slightly beyond, observed time-scales. Apart from brief historical references we shall this evening be concerned only with the integrated time-scale derived from the recently-adopted definition of the second, to which I shall refer as Atomic Clock Time.

Before proceeding further I cannot resist referring back to the time, over 400 years ago, when there first arose the demand for a method of finding longitude at sea. This is, of course, equivalent to finding the phase of the Earth's rotation relative to some adopted zero longitude (such as the Greenwich meridian), or to the time-difference between the two meridians. A mechanical clock was early suggested, but no time-keeper of adequate precision became available until the 1760s, and it was not until the advent of radio time-signals in the 1920s that checks on the going of chronometers by means of direct astronomical observations could be entirely dispensed with. The other method was that of lunar distances, first suggested for the purpose in 1514, but neither the requisite theory of the motion of the Moon nor the instruments of observation became adequate until the 1760s—at almost the same time as Harrison's marine time-keeper. The interesting point is that lunar distances were used to determine Greenwich Apparent (or later Mean) Time, based on the rotation of the Earth, while the same observations are now in principle used to determine Ephemeris Time; the unrecognized variability of the Earth's rotation added considerably to the limitations of the method.

It may interest you to see the dire consequence of neither method of finding time being available. In 1741 Anson, then a Commodore, attempted to sail round Cape Horn with his squadron against the prevailing westerly winds; after a long struggle he calculated that he was clear of the Horn to the west, but when he turned north he unexpectedly sighted land—his reckoning was many degrees in error to the east. After correcting his position, and after much further delay, he rounded the Horn and sailed north into the Pacific Ocean in search of fresh water; since the mainland ports were closed to him on account of the war with Spain, he sailed to the latitude of the isolated island of Juan Fernandes and then turned to sail along the parallel. Anson, convinced that he was well to the west of the island, turned eastwards and it was not until he sighted the Andes that he realized his mistake and had to turn back; but when he finally reached the island, many of his men had died.

Observed time-scales give the *time* corresponding to any *instant*, either direct or by interpolation using a clock as an auxiliary; the measure of *time-interval* is obtained as the difference between the *times* of its end-points. On the other hand, *integrated time-scales* give both *time-interval* and *time* direct by the use of a clock to integrate the reciprocal of the fundamental frequency (see Fig. 1). The two time-scales thus serve two quite distinct requirements, but clocks have always been an essential auxiliary to the astronomer.

With the spectacular increase in the accuracy of atomic clocks, Atomic Clock Time can in practice be now made available continuously to a precision far in excess of that to which any astronomical time-scale can be observed. Comparison of accuracies is not straightforward since, in principle, absolute errors in the determination of time, or of time-interval, are constant in an observed time-scale, while they are proportional to interval from initial epoch for an integrated time-scale; but many factors tend to increase the errors of the former, and possibly reduce those of the latter. Fig. 2 illustrates the order of

ERROR OF DETERMINATION OF
THE LENGTH OF A DAY

(Order of magnitude only)

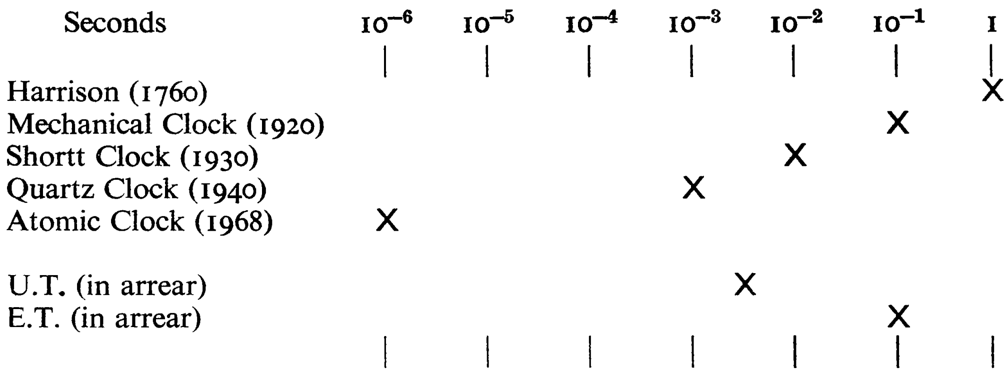

FIG. 2. Illustrating the order of magnitude with which a time-interval of one day can be measured by various clocks. (The value for the atomic clock is now almost certainly too large!) For comparison there are included indications of the precisions with which U.T. and E.T. can be observed.

magnitude of the error with which a time-interval of one day can be measured in terms of U.T., E.T. and Atomic Clock Time; values for earlier clocks are included for comparison. No point is given for the hydrogen masers currently used as the basis for the U.S. time-service, for which stabilities of 1 part in 10^{13} are claimed. The relative precisions are so widely different that closer discussion would serve no useful purpose: astronomical time-scales have already been left far behind.

Until about 1950 the only time-scale in general use was that of Universal Time, although the short- and long-term variability of the rotation of the Earth had by then been fully recognized. Its determination and dissemination have since both been greatly improved, so that it is now adequate for almost all purposes of astronomy and geodesy; it is no longer required to serve as the basis for the definition and determination of the second. And, more than ever before, it is essential to recognize that U.T. is not a rigorous measure of the hour angle of the mean sun; it is a measure of the rotation of the Earth, determined from observations of the stars, and must be independent of the actual motion of the Sun.

I need not go into detail: a correction is now applied to the observed time (U.T.0) for the effect of polar motion to give U.T.1, which is then independent of the position of the observer; a further correction for the annual variation in the speed of rotation of the Earth is then applied to give U.T.2, which is then approximately uniform over short periods. We shall doubtless hear about the geophysical reasons for these, and other, variations in the Earth's rotation from our Gold Medallist, W.H.Munk, when he gives the Harold Jeffreys Lecture.

Most time-signals are now disseminated in terms of Co-ordinated Universal Time (U.T.C.), which is an internationally agreed time-scale based on Atomic Clock Time; at present it is adjusted both in rate and actual time-reading so as not to diverge by more than about $0^{s}\cdot100$ from U.T.2. Corrections to the disseminated U.T.C., from which U.T.1 and U.T.0 can be formed for any station, are published in arrear by the Bureau International de l'Heure (B.I.H.), which co-ordinates time determinations and transmissions.

U.T.C. is essentially Atomic Clock Time and is connected with it by precise linear relations; but because of the unpredictable long-term variations in the speed of the Earth's rotation, the relation has frequently to be changed. This is a source of much current argument and discussions: the physicists, who are not in general interested in time, require that the *rate* of the transmitted time scale shall be precisely that of the recently-adopted unit of time-interval (in terms of the Caesium transition); whereas astronomers, navigators and surveyors, interested in their position on the rotating Earth, need to have a close approximation to U.T.1. There are other objections to the frequent discontinuities in the times of transmission that would be necessary if the rate was fixed.

Fig. 3 shows the deviation in recent years between Atomic Clock Time and U.T.2, together with the changes of rate and discontinuities of time that were introduced to keep U.T.C. within the limit of $\pm0^{s}\cdot1$ of U.T.2. The accumulated difference of a few seconds would have little effect on civil operations, and all precise astronomical and geodetic observations must, in any case, be corrected in arrear. On the other hand, the navigators and surveyors, who require to know their positions immediately, have no means of obtaining the corrections, which cannot be predicted to the precision required more than a few months ahead. I find it difficult to reconcile this requirement with the recent statement, by a Commission of the International Union for

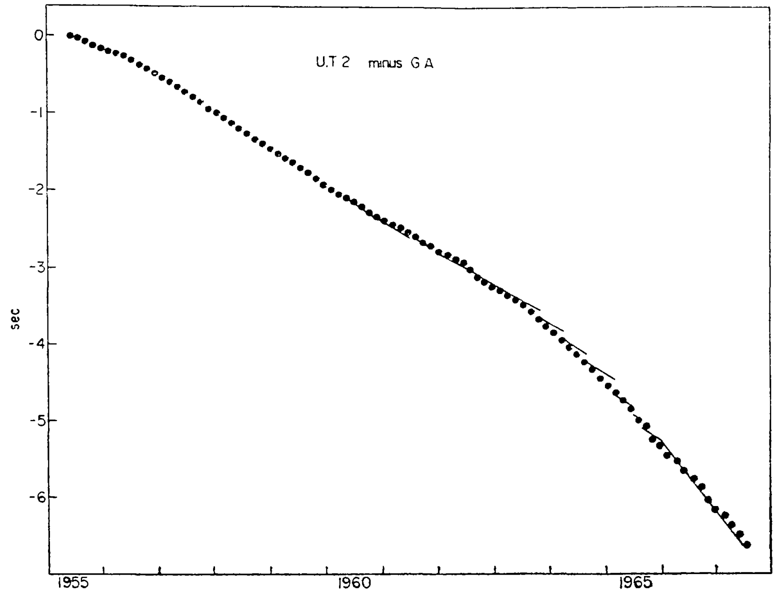

FIG. 3. Showing the increasing deviation between the observed time-scale of U.T.2 and the integrated time-scale of G.A. (atomic clock time as determined at the Royal Greenwich Observatory). The continuous lines show how U.T.C. was adjusted, both by changes of rate and actual discontinuities, to keep within the agreed tolerance of U.T.2.

The rate of rotation of the Earth has varied little in this period; very much larger changes have occurred in the past hundred years.

Scientific Radio, that 'the advantages of dispensing with frequency offsets and step adjustments are overwhelming and there seems to be no scientific reason why this should not be done immediately'. But I am sure that a solution can, and will, be found.

Long-term and irregular variations in the speed of rotation of the Earth had been suspected from the eighteenth century onwards, but it was not until Spencer Jones' comprehensive analysis of the observed motions of the Sun, Moon and planets, published in 1939, that the necessity for a new astronomical time-scale, independent of the rotation of the Earth, became evident. The introduction of Ephemeris Time for this purpose was recommended by the 1950 Paris Conference on the Fundamental Constants of Astronomy, and formally confirmed at the 1952 (Rome) General Assembly of the International Astronomical Union. Four years later, in 1956, the Comité International des Poids et Mesures adopted the second of ephemeris time, as defined by the IAU, as the unit of time-interval in the Système International des Unités as (in translation):

'The second is the fraction 1/31 556 925·9747 of the tropical year for 1900 January 0 at 12^h E.T.'

This replaced the obviously unsatisfactory definition of the second as 1/86 400 of a mean solar day. In October 1967, the Conférence

Générale des Poids et Mesures replaced this definition by (again in translation):

'The unit of time in the Système International des Unités is the second defined in the following terms:

The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the atom of Caesium 133'.

The number 9 192 631 770 was chosen so that as far as possible the duration of the unit, the second, should be unchanged. It was originally derived by some pioneering work, based only on a short interval of three years, by W.Markowitz and R.Glen Hall of the U.S. Naval Observatory and by L.Essen and J.V.L.Parry of the National Physical Laboratory. Analysis of subsequent observations, including refinements to limb corrections and the ephemeris of the Moon, confirms that it is within the probable error of the observations. The uncertainty lies entirely with the observational determination of Ephemeris Time, but strenuous efforts are being made still further to improve the determination.

There can be no question that the new unit is greatly superior to the second of ephemeris time for all purposes other than fundamental astronomy; using hindsight it is a great pity that the second of ephemeris time was ever adopted as the S.I. unit of time. The new unit is now reproducible from off-the-shelf commercial apparatus with a precision of about 1 part in 10^{11}; and, as has been mentioned, even greater precision is already available. It is appropriate here to pay tribute to the magnificent work of Dr Essen, and his colleagues at the National Physical Laboratory, who first developed the caesium oscillator in a practical form and who has been responsible for much of its subsequent refinements.

In spite of a formal request by the General Assembly of the International Astronomical Union, the Conférence Générale des Poids et Mesures abrogated the former resolution defining the second as the ephemeris second, without recognizing that the ephemeris second continues to be the fundamental unit of time-interval in the IAU System of Astronomical Constants. This has already given rise to the suggestion that Atomic Clock Time, an integrated time-scale based on the second as now (exclusively) defined, could be used for all purposes of dynamical astronomy as well as for time-signals. I have already referred to the practical consequences of the latter; and the astronomical view is that there are such fundamental differences between the observed time-scale of Ephemeris Time, and the integrated time-scale of Atomic Clock time, as to make the suggestion untenable.

It is now twenty years since ephemeris time was first specifically suggested by Clemence in his paper on the system of astronomical constants; and a review of subsequent developments is by no means overdue.

The objective was always quite clear—namely to introduce an astronomical time-scale, independent of the rotation of the Earth and, as far as possible, of other unpredictable influences, that could be used in the gravitational theories of the motions of the bodies in the solar system. On the assumption that the non-gravitational secular acceleration of the Sun could be determined from observation, and that no other non-gravitational effects were present, Ephemeris Time was defined in principle as the time-argument of the ephemeris of the Sun as derived from Newcomb's expression for the geometric mean longitude. However, the motion of the Sun (1 second of arc in 24 seconds of time) is too insensitive for practical determination and an operational definition was adopted by which ephemeris time could be obtained by comparing observations with the existing ephemeris of the Moon (which moves 1 second of arc in 1·8 seconds of time). On the basis of this operational definition, an *Improved Lunar Ephemeris* was constructed with ephemeris time as the time-argument.

Almost independently of this operational definition, fundamental definitions were adopted of both the ephemeris second (as later adopted by the Comité International des Poids et Mesures) and the initial epoch from which ephemeris time is measured. Although these are formally equivalent to the original definition, difficulties have arisen in both realization and interpretation. They arise in the following way. The initial epoch of ephemeris time is defined to be the instant which Newcomb, from analysis of all available observations, associated with a specific value of the geometric mean longitude of the Sun; but the value of the constant of aberration that Newcomb used, in reducing the observations, differs from its most recent determination. If this affected only the observations of the Sun (it does not affect those of the Moon), the interpretation would be clear; however, it affects, in greater or lesser degree, the reference system of the stars to which observations of the Sun are ultimately referred. The effect is very small in the solar ephemeris itself, but could result in a sizeable change (about $0^s\!\cdot\!6$) in the epoch of ephemeris time and in the ephemeris of the Moon. There seems little possibility of resolving this difficulty in the near future (IAU Commission 4 deferred doing so in Prague in August 1967); but fortunately the operational definition as the time-argument of the lunar ephemeris can be, and is being, continued for all practical purposes, and without any change in the definition of the ephemeris second. To regularize matters the IAU has specifically recognized three precisely-defined lunar ephemerides, representing successively improved versions; to each of these it has assigned a reference number j=0, 1 or 2 and a corresponding scale of Ephemeris Time, E.T.0, E.T.1 or E.T.2. These are not different time-scales, such as are U.T.0, U.T.1 and U.T.2, but merely represent significant stages in the gradual improvement of the lunar ephemeris. As further improvements, either in the theory or in the values of the constants, are introduced further reference numbers will also be introduced. All that has been done is to put the definition of the epoch of Ephemeris Time into cold storage, probably until the observations can be rediscussed; it can then be confirmed or, if necessary modified, to confirm with the operational definition.

To recapitulate: Ephemeris Time is the independent time argument of dynamical astronomy; it is, in principle but not necessarily in practice, the time-argument of Newcomb's ephemeris of the Sun; it is, in practice, the time-argument of the lunar ephemeris.

Now let us take a closer look at some of its limitations.

The ephemeris of the Moon, with Ephemeris Time as argument, depends on the observational determination of the coefficients of a quadratic correction $a+bT+cT^2$ to the Moon's mean longitude to bring it into accord with the solar ephemeris; this requires precise theories of the motions of the Sun and Moon, valid for all recorded observations.

The corrections to the linear terms are of little theoretical importance, but the correction to the coefficient of T^2 (centuries squared) certainly is; assuming that the gravitational secular terms have been correctly calculated by theory, it arises through the unknown increase in the angular momentum of the Moon in its orbit arising from the decrease in the angular momentum of the rotating Earth, due to tidal friction. An error of one second of arc in the coefficient would imply a spurious change of 1 part in 10^{11} a year in the second of ephemeris time. It is becoming urgent that Spencer Jones' work should be redone using modern theories and 30 years' more modern observations.

It is now clear that Newcomb's theory of the motion of the Sun (and particularly the tables based on that theory) is not really adequate; Clemence is working on a new theory, but even with modern computers a general theory to full precision is a formidable task.

The theory on which the ephemeris of the Moon is based is even now not quite good enough for the determination of ephemeris time from observations of the Moon, and will certainly be quite inadequate for the analysis of laser distances to an accuracy of some 10 cm as may soon become possible; although the determination of time from observed distance is inefficient, observations to such accuracy would be more powerful than the present directional observations.

Eckert, in addition to recomputing Brown's theory with a substantial increase in precision, has a new theory of the solar terms in the press.

But the planetary terms remain in the form in which they were calculated by Brown. Although relatively simple in principle, the practical determination of the planetary perturbations of the Moon poses such problems that it is rightly regarded as one of the most difficult in the field of celestial mechanics. The method, for which Brown was awarded the Smith's Prize for 1907, is relatively straightforward; but Brown was content to include only those 600 terms in longitude and latitude with amplitudes greater than 0″·003. The number of terms increases rapidly with decreasing limit, and each is increasingly difficult to calculate; estimates of the number of terms with amplitudes greater than 0″·0001 start around 10 000! It is a serious problem even with the help of a fast computer—Brown did almost all the calculation himself because of the impracticability of instructing even a human computer!

Another serious practical difficulty, first raised by Clemence, arises. If the number of terms greater than a certain limit increases very rapidly as the limit decreases, the error arising in the calculation by summation of the rounded-off terms may also increase—even though the series may be convergent. It is also known, from Eckert's work, that the sum of many small terms of this nature, not completely independent, may give rise to occasional runs of values much larger than the random statistical expectation.

Numerical integrations can be used to calculate the planetary perturbations (or even the total motion of the Moon) over a few years, but the difficulties of much greater extension are severe; the periods of the terms vary from a few days to several thousands of years.

Occultations of stars by the Moon still seem to provide the best universal method of observing the position of the Moon relative to the stars, and two factors are combining to increase their power and the number of observations. The systematic application of limb corrections has markedly decreased the probable error of an observation; and the availability of computers has enabled almost immediate comparison with the ephemeris, leading to increasing enthusiasm for making the observations. Many such individual observations, preferably spread more uniformly round the Moon, are required to enable the observations to be corrected empirically for the difference in position between the centre of figure and the centre of mass of the Moon. But Moon-camera and meridian observations, although smaller in number, also contribute to the determination of Ephemeris Time.

Now that we have Atomic Clock Time (A.T.) currently available with a precision far in excess of that to which we can determine Ephemeris Time, why do we still need E.T.? When E.T. was first introduced it was associated with U.T. and the difference $\Delta T = \text{E.T.} - \text{U.T.}$ was used as a measure of the irregularities in the rotation of the Earth, and was thus of geophysical interest. But since 1956 A.T. has made the use of E.T. for this purpose quite obsolete; ΔA=A.T. – U.T. provides the same information to a much higher precision and very much more quickly. Moreover, since A.T. and E.T. are nearly linearly connected, ΔT and E.T. can be obtained by extrapolation (for, say, the reduction of observations) more accurately than they can be obtained by single observations! This has certainly reduced the urgency for, but by no means the importance of, the determination of E.T. and ΔT. It is a great pity that a suitable atomic time-scale was not available in 1950; Ephemeris Time could then have been defined quite independently of U.T., and could, for example, have been measured in years and decimals, thus eliminating many conceptual misunderstandings.

Although intercomparisons between observations of the Sun, Moon and planets, can be referred to any time-scale, only absolute observations of position can be used for improvement of the theories and of the constants on which they are based. We may not know the scale of E.T., or even the length of the ephemeris second, but we can nevertheless construct consistent ephemerides (within the limitations mentioned) in terms of Ephemeris Time. For example, we can predict correctly the times of eclipses, and other phenomena, centuries in advance (or in arrear); the times will, of course, be in E.T. and not directly related either to U.T. or to A.T. On the other hand, if ephemerides were constructed with Atomic Clock Time as argument, they would have to be changed whenever a significant new determination were made of the relation between A.T. and E.T. (see also Fig. 1). However, observations will in future be made in terms of Atomic Clock Time (possibly as U.T.C.); we shall therefore eventually have a well-determined relationship between E.T. and A.T.

The nature of that relationship is a matter of deep interest. A.T., as defined, can be identified with the proper time of relativity theory whereas E.T. must be identified with co-ordinate time. There is thus a small relativistic-gravitational variation between the two time-scales, of which the main term is about $0^s{\cdot}0017$ with a period of a year (due to the eccentricity of the Earth's orbit round the Sun); but this is at present too small to be detected in the determinations of E.T.

The theories of the motions of the Sun, Moon and planets are strictly gravitational; any non-gravitational effects, such as is observationally allowed for in the case of the secular acceleration of the Moon, or any cosmological variation from Newtonian gravitational theory, will show itself as an acceleration of E.T. on A.T. Atomic Clock Time, for which astronomers must always be indebted to the physicists, is already known to adequate precision of at least 1 part in 10^{11}, and E.T. can be defined sufficiently accurately over a long enough interval—provided the sources of error mentioned above can be eliminated. In fact some have already claimed to have detected a change of rate between A.T. and E.T. since 1956, but the observational material and the theory both seem inadequate. However, there seems a good probability that the two quite independent time-scales can be rigorously compared to high precision in the not too distant future.

It intrigues me to think that very much the same observations as were made by navigators 200 years ago in order to find longitude are now being made (mainly by amateur astronomers) as an essential link towards that comparison.