ASTRONOMICAL UNITS, CONSTANTS AND TIME-SCALES

G. A. WILKINS

H. M. Nautical Almanac Office, Herstmonceux, England

As I have already reported (*Trans. IAU* **XVA**, 9, 1973), the Working Group on Units and Time-scales was not able to reach any firm conclusions on whether the concepts of the astronomical unit and ephemeris time should be retained or replaced by the SI unit of length (metre) and atomic time. This disagreement was not unexpected as the membership was deliberately chosen to cover a wide spectrum of opinion. The following comments and suggestions represent a middle-of-the-road approach that is intended to meet the requirements of most astronomers and others who use the astronomical data. It has been suggested to me that this approach is not appropriate for use in those precise applications where relativistic concepts are necessary, and that therefore we should abandon completely the use of astronomical units of mass, length and time. There are, however, many applications where Newtonian concepts are perfectly adequate, and astronomical units are widely in use because of their general suitability and convenience. We should therefore continue to define a system of astronomical units, but should state quite clearly their relationships to SI units. An individual may use either system according to the circumstances, and standard conversion factors will be available for use by those who prefer the other system.

The system of astronomical units may be defined and related to SI units in the following way: the currently adopted values of the relevant constants have been used to illustrate the form of the system, but more accurate values should be substituted if the new system is adopted.

Definition of the Astronomical Units

- The astronomical unit of mass = mass of Sun, S.
- The astronomical unit of time = 1 day, D, of 86400 SI seconds. In what follows the terms day and second will be used without qualification.
- The astronomical unit of length is that length (A) for which the Gaussian constant of gravitation, k, takes the value of 0.017202098950 when the units of measurement are the astronomical units of mass, length and time. The dimensions of k^2 are those of the (Newtonian) constant of gravitation, G, i.e. $L^3 M^{-1} T^{-2}$

Primary Constants in SI Units

- Speed of light $c = 299792500 \text{ m s}^{-1}$
- Constant of gravitation $G = 6.670 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$
- Light-time for unit distance $\tau = 499.012 \text{ s}$

Derived Constants in SI Units

- Astronomical unit of length $A = c\tau = 149600 \text{ Mm}$

Contopoulos (ed.), Highlights of Astronomy, 229–232.

– Helio-gravitational constant $GS = k^2 A^3/D^2 = 132.718 \text{ Mm}^3 \text{ s}^{-2}$

– Astronomical unit of mass $S = 1.990 \times 10^{30}$ kg

For some purposes it is convenient to use the light-second as a unit of length, and this unit is related to the SI and astronomical units as follows:

1 light-second = 299792500 m

1 astronomical unit of length = 499.012 light-seconds.

The numerical values are identical to those of constants c and τ above. It may also be useful to state the values of c (173.142) and τ (0.0057756) in astronomical units in order to show clearly that the astronomical units form a self-contained system.

It is now generally recognized that the difference between the international atomic time-scale (TAI) and the ephemeris time-scale may be regarded as essentially constant over the period for which both scales are known (i.e. from 1956 to the present time). The adoption of the astronomical unit of time as defined above, namely the day of 86400 SI seconds, for the unit of ephemeris time would not introduce any practical change in the use of ephemeris time. It would, on the contrary, remove the uncertainty that arises from the present necessity of attempting to relate current intervals of time to the tropical year of 1900.0. Similarly, it would be convenient for future work if the difference between the scale values for a particular instant were to be zero, so that for most practical astronomical applications the two scales could be regarded as equivalent. The arbitrary constants of new theories of motion would be adjusted so as to give the best fit between observations recorded against the scale of TAI, and the ephemerides based on the theories. In due time further comparisons would be expected to reveal systematic departures between new observations and the ephemerides. Such departures could arise merely from the deficiencies of the initial adjustments, but they could also be due to deficiencies in the theories, such as inadequate allowance for the effects of tidal friction. It is also conceivable that the constant of gravitation could be varying with respect to atomic time. If this were found to be the case the equations of motion would be modified and any additional parameters determined from the comparison with observation. The differences between the scale of TAI and the implied scales of the ephemerides could easily be taken into account by developing tables of the differences between TAI and the ET-scale of each ephemeris, as is now the practice for UT and the various lunar ephemerides.

It is clear that we cannot hope to determine any scale of ephemeris time that will not be subject to later adjustment as new observational data are obtained and compared with ephemerides based on the theory for the dynamical system concerned. We can, however, visualize an ideal scale that is defined by adopting a particular definition of the unit of time-interval and a particular scale-value for some identifiable instant. The most precise way in which this can now be done is by reference to the scale of international atomic time. This idealized scale could be called the reference scale of ephemeris time and denoted by, say, the acronym TER. It could be carefully defined so that it would be appropriate for use in conjunction with relativistic theories. It could be regarded as being of unlimited extent, whereas it is meaningless to refer to TAI before about 1956 since it is a scale that is defined operationally in terms of the weighted mean of the system of national atomic time-scales.

If we define TER so that the difference between it and TAI was zero at a particular instant (e.g. 1958 Jan. $1^{d}.0$ TAI), the difference between it and the current scales of ET will be about 32 seconds. For the Moon this corresponds to an adjustment of about $1^{s}.3$ in right ascension of the current ephemeris, but for the Sun and planets the effects are much smaller and can easily be treated differentially.

My conclusion is that it would be worthwhile to retain the general concept of ephemeris time, but to determine the constants of new theories in such a way that the time-scales of the ephemerides would correspond closely to TER and hence to TAI. We would need to prepare tabulations of the best estimates of the difference between UT and TER and, where appropriate, of the differences between TER and the time-scales implied in the published ephemerides. The publication of such tabulations should be the responsibility of some internationally-recognized organisation, such as BIH, although individual astronomers or groups could submit or publish their estimates as has already been done by Morrison (1973).

It also appears to be desirable that the following changes should also be made in the interests of simplicity. Firstly, that Greenwich mean sidereal time should be defined so that it is unique; this implies that the corrections for polar motion should be applied in the reduction of observed sidereal time to GMST, rather than as a correction in universal time. Secondly, that universal time (UT or TU) should be defined so that it is unique; it should be identified with the scale now denoted by UT1 (TU1) and the scales now denoted by UT0 and UT2 should no longer be used.

Reference

Morrison, L. V.: 1973, *Nature* **241**, 519.

DISCUSSION

Mulholland: I am in complete agreement with the proposals relating to the astronomical system of units. I have some cautionary remarks, however, about possible hazards associated with the proposals relative to time scales. First, it is proposed to introduce a new time scale, based on the SI second, as the fundamental argument of the ephemerides. This seems a particularly good idea, since it will only be a recognition of what is already now done in critical applications. It seems likely, however, that the present construct now called 'ephemeris time' will continue to be useful for studying common features of ephemeris inadequacies. Thus, if the new scale is to be called 'ephemeris time', a new name will have to be found for the old concept.

This seems an unnecessary invitation to confusion. I suggest that a new name be applied instead to the new scale, perhaps dynamical time. Second, if the name 'ephemeris time' is applied to the new scale, it seems very desirable that the epoch of the new scale not differ significantly from the presently-used epoch of ET. The potential hazards of introducing a discontinuity in epoch between ET and TER are strikingly illustrated by the experience following the 1925 epoch change of 12 h in astronomical time. As late as 40 years after, a major paper appeared in which the pre-1925 residuals were very bad, because the observation times had been mishandled. While it is true that a 32^{s} discontinuity will not be as serious a hazard as 12 h, there seems no good reason to introduce this risk.

Markowitz: I think that ephemeris time should be dropped from the Almanacs. Only UT and atomic time should be used for all purposes.

https://doi.org/10.1017/S1539299600001945 Published online by Cambridge University Press

Williams: I would like to point out that defining the difference between the new ephemeris time (TER) and TAI to be an integral number of seconds at a particular date will cause their mean difference to be non-integral. This is because there are periodic terms in the transformation from one to the other. It seems much better to me to make their mean values differ by an integral number of seconds.

Winkler: If we change the definition of ephemeris time, it will be related to SI units, and it is better to have a single ideal time parameter.

We should be concerned about what should be the time-keeping mechanism.

If we base our scale on atomic time, this will be evidently solved. One should take advantage of the fact that the atomic time scale is new, to absorb the 32-s difference in the epochs. The 180 ms can be easily absorbed in the incertainties in the ET.

Herrick: May I remind that 'ephemeris time' has been invented to suppress the errors in the tables of the Sun.

Fliegel: I have two remarks with respect to what Dr Winkler has just said:

(1) There is already some confusion over the 32^s... offset between TAI and the existing ET. When AI was the standard of atomic time in the USA, the ET-AI offset was universally adopted as $32\overset{s}{.}15$.

When the change was made to TAI, the U.S. Naval Observatory approximated ET-TAI $= 32\overset{s}{.}180$ exactly.

However, at JPL, we changed to ET-TAI = 32.18438..., not because we thought that ET was so well known, but because it was necessary to prevent any discontinuity in ET in computer operations.

Rather than adopt an offset of 32 s exactly when new definitions are adopted, thus producing a discontinuity of about 184 ms, we would rather see an offset of zero, simply because a small discontinuity is more likely to cause mistakes that will be overlooked by future workers than a large one.

(2) If the gravitational time scale proves to be different from the atomic scale, is it proposed to use a new parameter t in the dynamical equations for planetary motions?

Winkler: Yes.

Becker: In the paper circulated among us, Dr Winkler described ephemeris time to be coordinate time and TAI to be 'proper time'. This cannot be accepted: many different coordinate time scales are feasable. TAI is designed as a coordinate time with respect to the Earth's surface. I should like to mention that at the IAU General Assembly 1967 in Prague I proposed to define a new ephemeris time on the basis of astronomic time by making to it relativistic corrections in such a way that a coordinate time results, having a reference point outside the solar system, where the gravitational potential of the solar system is zero, and with no movement relative to the solar system. Apparently Dr Winkler's ideas are on the line of my proposal of 1967.

At the conclusion of the meeting, a motion was proposed and accepted that, at this point, the Working Groups set up by Commission 4 should continue their work.