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Practical Ephemeris Calculations

With 41 Figures

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2.2 The Different Definitions of Time

2.2.1 International Atomic Time (TAI)

International Atomic Time is today the best representation of the idea of a uniformly flowing time. Its unit is the SI second of the International System of Units:

> *An SI second is equal to the duration of* 9 192 631 770 *oscillations of the radiation emitted in the transition of the two hyperfine levels of the ground state of caesium 133.*

TAI was introduced in 1972 and replaced the ephemeris time used until then as the basis of time measurement.

2.2.2 Ephemeris Time (ET) and Dynamic Time (TDT, TDB)

According to Newcomb the mean longitude of the sun (mean anomaly + longitude of perihelion) is given in relation to the mean vernal equinox of the date by the following:

$$L = 279°41'48''.04 + 129\,602\,768''.13 \cdot T + 1''.089 \cdot T^2 \quad .$$

Here T denotes the number of centuries since midday on the 0 January 1900.

Since the above formula represents a direct consequence of the law of gravity, T is an independent variable of the underlying theory. One can therefore use the expression for L to define with its help the so-called ephemeris time (the time which forms the basis of the calculation of ephemerides). The starting point of the enumeration is the instant denoted by 0 January 1900 12.00 ephemeris time, at which the mean longitude of the sun amounts to $279°41'48''.04$ ($T = 0$). The variation dL/dT at this instant amounts to $129\,602\,768''.13$. If one further defines

the unit of T as 100 ephemeris years, each of 365.25 ephemeris days, each of 86 400 ephemeris seconds – a total of 3 155 760 000 ephemeris seconds – then

$$\frac{360 \cdot 3600''}{129\,602\,768.''13} \cdot 3\,155\,760\,000\,\mathrm{s} = 31\,556\,925.9747\,\mathrm{s}$$

of ephemeris time would elapse as the solar longitude varied by 360°, if the above velocity were constant. Since this involves one circuit from vernal equinox to vernal equinox, this interval corresponds to a tropical year. Starting from these ideas one finally arrives at the following definition of the ephemeris second which was passed by the International Astronomical Union (IAU):

An ephemeris second is the 31 556 925.9747*-th part of the length of a tropical year at 0 January 1900 12.00 ephemeris time.*

An ephemeris second has practically the same length as an SI second, so that ET and TAI differ essentially only by a constant:

$$\mathrm{ET} = \mathrm{TAI} + 32.184\,\mathrm{s} \quad .$$

Since 1984, instead of Ephemeris Time we have used Barycentric and Terrestrial Dynamic Time (TDB and TDT). The unit of TDT is the SI second and for the sake of continuity one sets

$$\mathrm{TDT} = \mathrm{TAI} + 32.184\,\mathrm{s} \quad .$$

For describing motions relative to the centre of mass of the solar system TDB is used, whilst because of relativistic effects an observer on the earth needs a different time measure (TDT). TDB and TDT differ by at most 0.002 s, which can be neglected in the framework of most calculations.

2.2.3 Universal Time (UT)

In contrast to Atomic and Ephemeris Time there is no uniform measure of time in the Universal Time now to be described. Its purpose is rather to maintain good long-term agreement with the diurnal and annual motion of the sun. The motion of the sun as the cause of day and night is, after all, still the ruling influence of our life.

If the sun did not move in relation to its stellar background, then sidereal time would provide a measure with the desired characteristics. In order to adapt the time to the motion of the sun we proceed in the following way:

The motion of the sun is first replaced by a so-called mean sun with a definite uniformly increasing right ascension A. The mean solar time is then defined as the hour angle of this mean sun, increased by 12 hours, so that the moment of the meridian passage (hour angle = 0) coincides with midday (12 o'clock). By the introduction of the mean sun one obtains a measure of time which is free of short-term variations (= equation of time) caused by the projection of the solar orbit on the equator and the elliptic orbit. The mean solar time is therefore approximately uniform and adjusted to the motion of the sun. Since at 12 o'clock solar time the

hour angle of the mean sun is 0^h, the hour angle of the vernal equinox (= sidereal time) is equal at this moment to the right ascension A of the mean sun.

From these considerations one eventually arrived at today's Universal Time:

By definition (IAU 1981) Greenwich Mean Sidereal Time (GMST; see Sect. 2.2.5) at 0 hours Universal Time is given by:

$$\text{GMST}(\text{UT} = 0^h) = 24110^s.54841 + 8\,640\,184^s.812866 \cdot T + 0^s.093104 \cdot T^2 - 0^s.0000062 \cdot T^3 \quad .$$

Here T is the time elapsed since 1 January 2000, 12^h UT (JD 2451545) measured in centuries, each consisting of 36525 days Universal Time.

Since Greenwich sidereal time can be determined from observations of the meridian passage, the Universal Time at any instant can be calculated from this relation.

The definition of the ephemeris time was collated with that of Universal Time so that the difference ΔT = ET − UT was approximately zero at the beginning of this century. The exact value of ΔT can only be determined subsequently. The general trend, however, is that ΔT increases by about 0.5 to 1 second per annum. This value corresponds to the slowing of the earth's rotation by tidal friction. The remaining amount is not foreseeable and is probably caused by mass movements in the earth's interior as well as by the influence of the atmosphere.

A table of the known values of ΔT = ET − UT is presented in the Appendix. For times between 1900 and 1985 one can use the following polynomial approximation:

$$\Delta T = (((-339^s.84.T - 516^s.52)T - 160^s.22)T + 92^s.23)T + 71^s.28$$

$$\Delta T = \text{ET} - \text{UT}$$

T = centuries since the year 2000 $(-1.0 \leq T \leq -0.15)$

$(T = (\text{JD} - 2\,451\,545.0)/36525)$.

The accuracy amounts in general to about 1–2 s. If one goes outside this specified period, then before 1900 one very soon obtains false (negative) values. After 1985 the trend of the latter years is somewhat repeated, but an accurate prediction is naturally impossible.

2.2.4 Coordinated Universal Time (UTC)

As a compromise of UT and TAI, UTC was introduced and is used for time signals. It deviates from TAI by whole seconds and from UT by not more than 0.9 s. This is achieved by extra seconds, which are inserted as needed at the end of June or the end of December.

The UTC is therefore the time displayed by an "adjusted" clock, if one takes account of the corresponding time zone.