The effect of Delta T on astronomical calculations

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Universal Time (UT), or Greenwich Civil Time, which is needed for civil life, is based on the rotation of the Earth. But the Earth's rotation is slowing down and, moreover, this occurs with unpredictable irregularities. For this reason, UT is not a uniform time-scale. However, astronomers need a uniform time-scale for their accurate calculations (celestial mechanics, orbits, ephemerides). From 1960 to 1983, the great astronomical almanacs such as the *Astronomical Ephemeris* used a uniform time that was called **Ephemeris Time** (ET), and which was based on planetary motions.

In 1984 ET was replaced by **Dynamical Time**, which is defined by atomic clocks. In practice, Dynamical Time is a continuation of Ephemeris Time. One distinguishes a Barycentric Dynamical Time (TDB) and a Terrestrial Dynamical Time (TDT). These times differ by at most 0.0017 second, the difference being related to the motion of the Earth in its elliptical orbit around the Sun (relativistic effects). Because this very small difference can be neglected for most practical purposes, we shall make no distinction between TDB and TDT here, and we simply might name them both TD (Dynamical Time), not from the French 'Temps Dynamique', but rather as '$\text{Time}_{\text{Dynamical}}$', the letter D being considered as an index to 'T'.

Some years ago TDT was renamed 'Terrestrial Time' (TT), a rather odd designation: the mean solar time at Moscow, or the sidereal time at Liverpool, are 'terrestrial' times too! Personally I would prefer to use the abbreviation TD – and actually I do so in my books – but for the sake of official convention I will use TT in this paper.

Our clocks, locked on UT, are gradually slowing down with respect to the uniform TT. In fact, using UT, astronomical events seem to occur *earlier* than predicted in a uniform time-scale. If my watch is late by five minutes, a train arriving at 19.50 seems to arrive actually at 19.45, watch-time.

The difference between TT and UT is generally called ΔT (Delta T). Its exact value can be deduced only *a posteriori* from observations. Table 1 gives the value of ΔT for the beginning of the years 1974 to 1997. We notice that from 1974 to 1980 the increase was approximately 1 second per year. From 1984 to 1989 the yearly increase was half a second only.

Table 1. Value of ΔT, or TT minus UT, in seconds of time, on January 1 of the years 1974 to 1997

Year	ΔT	*Year*	ΔT
1974	44.49	1986	54.87
1975	45.48	1987	55.32
1976	46.46	1988	55.82
1977	47.52	1989	56.30
1978	48.53	1990	56.86
1979	49.59	1991	57.57
1980	50.54	1992	58.31
1981	51.38	1993	59.12
1982	52.17	1994	59.99
1983	52.96	1995	60.79
1984	53.79	1996	61.63
1985	54.34	1997	62.30

Table 2. Some astronomical events in 1999

No.	*Date, 1999*	*Event*	*UT if ΔT = 0 sec.*	*UT if ΔT = 64 sec.*	*Difference (seconds)*
1	June 21	Summer solstice	19:50:11	19:49:07	–64
2	July 28	Lunar eclipse, first contact with umbra	10:23:04	10:22:00	–64
3	Aug. 25	Perihelion of comet P/Giclas	03:10:08	03:09:04	–64
4	May 26	Transit of Spica at Greenwich	21:09:12	21:09:12	0
5	Sept. 18	Transit of Moon at Greenwich	18:35:05	18:35:07	+2
6	Aug. 11	Solar eclipse at Greenwich			
		First contact	09:05:05	09:03:44	–81
		Fourth contact	11:41:43	11:40:14	–89

One might think that, in order to obtain results expressed in UT, it suffices first to neglect the quantity ΔT, that is, taking $\Delta T = 0$, and then to subtract the quantity ΔT from the final times, at the end of the calculation. This is not always so, however, as we will see.

Extrapolation from Table 1 shows that we may expect that in 1999 the quantity ΔT will be equal to 64 seconds. In Table 2 six events occurring in 1999 are mentioned. In the fourth column their instants in UT are given as calculated by assuming that ΔT is equal to zero, that is, UT = TT. The UT times in the fifth column have been correctly calculated by using the value $\Delta T = 64$ seconds. In this paper we shall use the format hh:mm:ss to indicate times in hours, minutes and seconds.

At first sight, it may seem surprising that the values in the last column are not equal. For the first three events, the UT time is 64 seconds earlier than the TT time, as expected. But for event No. 4 a change in the value of ΔT has no effect at all on the instant in the UT scale. For the fifth event, the difference is small and *positive*. For the last event the differences are negative again, but sensibly *larger* than ΔT itself in absolute value. So what is the reason for this disparity?

The first three events of Table 2 are not related to the orientation of the Earth's globe, and so they have nothing to do with the rotation of the Earth. By definition, summer solstice occurs when the apparent longitude of the Sun, *i.e.* calculated by including the effects of aberration and nutation, is exactly 90°. In 1999 this will take place on June 21 at 19:50:11 TT. So just subtract the quantity ΔT in order to obtain the instant in UT, namely 19:49:07. No problem here.

The same holds for the second and the third events in our list. Using the classical rule of 1/50 for the enlargement of

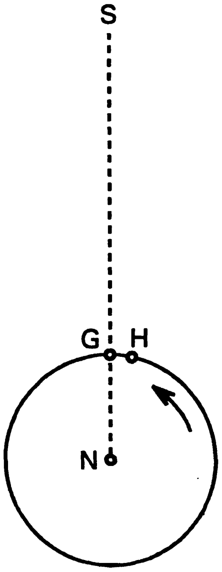

Figure 1. Transit of a star at Greenwich

the Earth's shadow, and assuming the latter to be exactly circular, a rigorous calculation shows that the first contact of the Moon with the umbra will take place at 10:23:04 TT. Again, subtract ΔT, or 64 seconds, to obtain the UT time.

The same again for the predicted instant of passage of periodic comet Giclas at perihelion. According to *Minor Planet Circular* No. 27082, this instant is 1999 August 25.13204 TT, or 1999 August 25 at 03:10:08 TT. For all astronomical phenomena not related to the rotation of the Earth we have the same rule: UT = TT – ΔT. So are, for instance, the phenomena of the satellites of Jupiter, the *geocentric* phases of a transit of Mercury over the solar disk, the times of the lunar phases, the instant of an opposition of Mars, and so on.

Let us now look at event No. 4 of Table 2. Figure 1 shows the Earth's globe as seen 'from above'. *N* is the North Pole, *S* the direction of a star, say Spica. The observer's place, say Greenwich, is 'dragged' along with the rotation of the Earth. When the observer arrives at *G*, star *S* transits the meridian. Suppose first that ΔT is zero. In this case, on 1999 May 26, Greenwich arrives at *G* at 21:09:12 TT = 21:09:12 UT, and Spica transits the meridian at that instant.

But the actual value of ΔT is 64 seconds. Because the Earth's rotation is late by 64 seconds with respect to an Earth with uniform rotation, at 21:09:12 TT Greenwich is still at *H*. Not before 64 seconds later will Greenwich be at *G*. So in reality, in the uniform time-scale ΔT, Spica's transit occurs 64 seconds *later* than would be the case if ΔT were zero. Now, to convert the TT time to UT, the quantity ΔT has to be subtracted, so the time of transit in the UT scale is 21:09:12 + 64 seconds – 64 seconds, which gives 21:09:12 UT again. Hence, *in the UT scale*, times of transits of stars are not affected by the quantity ΔT. Star transits really occur later in the uniform TT scale, but our UT clocks retard by the same quantity. (To be precise, the UT times of star transits *are* affected by ΔT, but by an extremely small quantity only, because the effects of aberration and nutation vary during the short time interval ΔT).

For transits of the Moon we have almost the same situation, except that the Moon is moving a little around the Earth during the time interval ΔT. Figure 2 again shows the Earth as seen from above. Suppose ΔT = zero. In this case, on 1999 September 18, Greenwich arrives at *G* at 18:35:05 TT = 18:35:05 UT, and the Moon *M* transits the meridian at that instant.

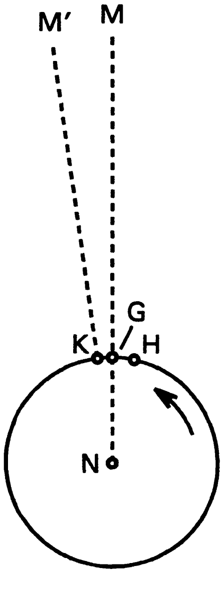

Figure 2. Transit of the Moon at Greenwich

As before, because the actual value of ΔT is not zero, but 64 seconds, Greenwich is still at *H* at 18:35:05 TT. Only 64 seconds later will Greenwich reach point *G*. But during these 64 seconds the Moon has moved from *M* to *M′*, so the Earth must still rotate a little further, from *G* to *K*, before the Moon is exactly in the meridian. This takes an additional 2 seconds. And, finally, we have to subtract the quantity ΔT to convert from TT to UT. The time of transit in the UT scale thus is

18:35:05 + 64 seconds + 2 seconds – 64 seconds,

or 18:35:07, explaining why the Moon's transit takes place two seconds *later* (in the UT scale) as compared with the case if ΔT were zero. In the uniform TT scale, the transit occurs 66 seconds later.

Finally, let us say something about the last item of Table 2. Figure 3 shows a part of the Earth's surface, *p* being the parallel of latitude of Greenwich. Again, we first suppose that ΔT is zero. The dashed line is the edge of the lunar penumbra on the Earth's surface. Its position *u* is shown at the moment it reaches Greenwich, *G*. It is the instant of the first contact of the eclipse. Let *t* be this instant in the scale of TT.

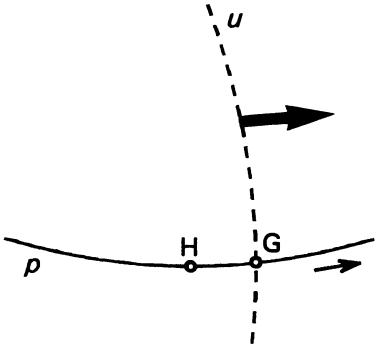

Figure 3. Solar eclipse at Greenwich

Due to the diurnal rotation of the Earth, *G* moves along *p* in the direction of the thin arrow. The edge of the penumbra moves to the east too, in the direction of the thick arrow, but at a greater speed than *G*, so the penumbra is overtaking *G*.

But in 1999 the quantity ΔT will be 64 seconds, not zero. Therefore, with ΔT equal to 64 seconds, Greenwich will not yet have reached position *G* at time *t*, but will be at *H*, and the lunar penumbra has already overtaken it. In other words, first contact actually occurs several seconds before *t*. For the eclipse of 1999 August 11, at Greenwich, this difference amounts to 17 seconds, and the distance *HG* is 19 kilometres. To obtain the instant in the time-scale of UT, we still have to subtract 64 seconds, the difference between TT and UT. Therefore, the total difference is –(17+64) seconds, or –81 seconds, as indicated in the table.

As the velocity of the Moon's penumbra with respect to the observer varies from one place to another, the above-mentioned difference is not equal to 81 seconds for all places. There is even a difference between first and last contact, as seen in the last line of Table 2.

I cannot go into more details as to why for that particular eclipse, at Greenwich, the 'adjustments' differ from 64 seconds by the amounts they do. The differences of 81 and 89 seconds, respectively, are the result of an accurate calculation using the so-called Besselian elements of the eclipse in question, involving the use of classical formulae – see, for instance, pages 555 and 556 of *The Astronomical Ephemeris* for the year 1980 (London, 1979).

Some practical tips

For events *not* related to the Earth's rotation, perform the calculation in the uniform time-scale TT, then subtract the quantity ΔT from the obtained times.

For the times of rise, meridian transit and setting of a celestial body, use is made of local sidereal time. The latter is obtained directly in terms of UT, so the calculation should be performed in this time-scale. For a given time in UT, then, the position of the celestial body should be calculated for the instant UT + ΔT, Dynamical Time. The resulting times of rise, etc., will be directly given in UT, so no further correction $-\Delta T$ is needed.

For the local circumstances of a solar eclipse or an occultation by the Moon, the so-called Besselian elements are generally used. These elements are given in the TT scale. It suffices to mention here that in the calculation of the local hour angle of the Sun (or star) a correction of $-1.002738\ \Delta T$ is applied, the sidereal equivalent of ΔT. The final TT times of the contacts, etc., are converted to UT by subtracting the quantity ΔT.

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