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DOES RELATIVISTIC TIME DILATION CONTRIBUTE TO THE DIVERGENCE OF UNIVERSAL TIME AND EPHEMERIS TIME?

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ABSTRACT

It is well known that two timescales, one based on the Earth's rotation and generically called Universal Time, and the other based on the Earth's orbital motion and generically called Ephemeris Time, diverge. The divergence is explained mostly by a secular slowing down of the Earth's rotation due to tidal braking. This paper investigates the question whether relativistic time dilation plays any role in this divergence, as it has sometimes been proposed. After a detailed analysis from the point of view of general relativity, we demonstrate that relativistic time dilation does not influence the divergence in question. We conclude that there is no reason to refute the present understanding of the secular variation of Earth's rotation.

Key words: celestial mechanics – Earth – reference systems – relativity – time

1. INTRODUCTION

In a recent paper, hereafter referred to as D&W2007, Deines & Williams (2007) claim to explain why two timescales, one based on the Earth's rotation and generically called Universal Time (UT), and the other one based on the Earth's orbital motion and generically called Ephemeris Time (ET), diverge, proposing that this divergence is due to a relativistic time dilation. We find that the paper conveys ideas that are wrong or misleading and that its conclusions are based on two errors which complement themselves in providing results which are apparently consistent with the authors' theory. In Section 2, we summarize D&W2007 and identify the most important problems in the authors' argumentation. In Section 3, we recall the basic explanation for the divergence between ET and UT. In Section 4, we present in more detail the most important problems identified in D&W2007, concluding in Section 5 that it does not provide a correct explanation for the divergence of ET and UT and that the classical explanation presented in Section 3 is not challenged.

2. SUMMARY OF D&W2007

In the introduction of the main topic, D&W2007 starts with two sections of a historical nature. It is not the purpose of this paper to examine these parts as they are essentially independent of the rest of D&W2007 and we concentrate on the parts of D&W2007 devoted to explaining the divergence between ET and UT. To summarize these parts, we retain three items that are the basis of the authors' argumentation and will be referred to in the following discussion. Item A is the exposition of the topic (divergence of ET and UT), while items B and C are the areas where we find that the argumentation of the authors is flawed. In the following paragraphs, we expose what we find in D&W2007, and therefore do not add any external references.

A. The authors state (Section 3 of D&W2007) the fact that UT1, based on the Earth's rotation and International Atomic Time (TAI)[3], diverge at a rate of about $0\overset{s}{.}78\,\mathrm{yr}^{-1}$ (2.5×10^{-8}) between 1958 and 1999. This divergence manifests itself by the insertion of leap seconds between Universal Time Coordinated (UTC)[4] and TAI, and is equivalent to the mean solar day being, on average over this period of time, longer by $0\overset{s}{.}0021$ than 86,400 s of TAI. Because the atomic second has been made consistent with the unit of ET when changing the definition of the second in 1967, the same divergence also exists between ET and UT1.

B. The authors claim that the ET second "is a measure of the scale of coordinate time" and that "the UT second is a measure of proper time of an observer moving with the Earth" (D&W2007, p. 64). From Section 4 of D&W2007, it is indeed clear that the authors identify UT with the proper time of an observer on the surface of the Earth. They claim to compute the relativistic transformation between this proper time and coordinate time, obtaining an average "time dilation" effect (Section 4 of D&W2007). They then infer that their "calculation of the time dilation effect matches the difference between the SI and UT seconds and also the leap second insertion rate to within 0.2%" (cited in the abstract of D&W2007), i.e., would explain the observed divergence between TAI (therefore ET) and UT over 1958–2000.

C. The authors claim to examine (Section 5 of D&W2007) the classical explanation in which tidal braking causes deceleration of the Earth's rotation. They estimate that "the deceleration of Earth's rotation (due to tidal braking) contributes less than 1% of this timescale divergence, according to the measurements from paleontological records of tidal friction" (cited in the abstract of D&W2007).

To further summarize D&W2007, the authors examine the divergence between ET and UT, reject the classical explanation of this phenomenon by the physical effect of tidal braking, and propose their own explanation in the form of a relativistic correction. However, they consistently misinterpret both the foundations of general relativity and the relativistic definitions of timescales. They wrongly identify UT with the proper time of

[3] Although TAI was officially introduced in 1971, it was preceded by an atomic timescale maintained by the BIH and will be called TAI for the whole period for simplicity.

[4] UTC is derived from TAI so as to keep approximate synchronization with the Earth's rotation. Since 1972, UTC has differed from TAI by an exact number of seconds.

an observer on the surface of the Earth. They then make another mistake in estimating the time dilation between the proper time of an observer on the surface of the Earth and a barycentric coordinate time (item B above). Furthermore, they make an additional mistake in interpreting the effect of the deceleration of Earth's rotation (item C above). Because the divergence in the timescales of TAI and UT (item A) is an undisputed fact, all these errors are needed so that item B can provide an apparent explanation for the divergence, while tidal braking no longer can (item C).

3. WHY ET AND UT DIVERGE

UT is a generic name for a timescale based on the rotation of the Earth, i.e., a time that conforms to the mean diurnal motion of the Sun. Astronomical observations can measure the angle (named Greenwich sidereal time; GST) between a reference meridian on Earth and a reference direction in inertial frame, and UT1 is related to GST by a conventional relation. UT1 is now obtained with an uncertainty of a few μs (corresponding to an uncertainty below 0.1 mas for the angle of rotation) from very long baseline interferometry (VLBI) observations of extragalactic radio sources and is disseminated by its difference to atomic time UTC (Ray et al. 1995). Thus, astronomical techniques allow us to obtain the mean solar day, of which the duration in UT1 is named the length of day (LOD) and is often just expressed as its difference to 86,400 SI seconds (so-called excess length of day).

The motions of the Earth and Moon in the solar system are obtained by the integration of the equation of motion in terms of an independent time variable, ET. All observations support a more or less regular increase in the length of mean solar day (LOD) over time, when it is compared to a unit of time based on the orbital motion of the Earth. Evidence is provided by astronomical observations since the beginning of the 17th century, historical records of ancient eclipses from 700 B.C.E., and paleontological records allowing an estimation of the number of days in a year several hundred millions years ago (Stephenson & Morrison 1995; Lambeck 1980).

The main cause for the steady increase in LOD is the tidal braking of the Earth's rotation by the dissipation of energy in the oceans and the associated exchange of angular momentum with the Moon. This is estimated to cause an average increase in the LOD of the order 20 μs yr^{-1}. In addition, any global redistribution of mass in the Earth will cause a change in the Earth's rotation. For the last few thousand years, the second most important cause of LOD variation is the change in the Earth's shape associated with deglaciation, yielding an average decrease of the LOD of order 6 μs yr^{-1}, consistent with the change in Earth's oblateness observed with space geodesy (Wu & Peltier 1984). On average, the observed increase in LOD over the past 2700 years is 17 μs yr^{-1} (Stephenson & Morrison 1995). Note that neither tidal braking nor change of Earth's shape due to deglaciation are expected to have a constant rate over very long durations and similarly the observed increase in LOD seems to slightly vary over the past millennia. Therefore, we cannot expect an exact match between the predicted and observed increase in LOD, given that they are determined over different intervals and with some uncertainty. However, the difference between predicted and observed LOD increase is of the order of 10% of the value, thus provides very good evidence for the proposed explanation.

ET has been defined by the IAU (1952) as the adoption of a conventional expression for the mean longitude of the Sun, determined by Newcomb (1898), and cited as Equation (1) in D&W2007. Because this expression had been determined from observations obtained mostly during the 19th century, and dated in UT, the unit of ET has been implicitly matched to the average LOD over the 19th century (Guinot 1989; Seidelmann 1992). Because LOD increases on average by 17 μs yr^{-1}, the LOD in the second half of the 20th century and now (i.e., about 150 years later than the middle of the 19th century) is longer than the LOD value that was used when defining ET, by about 2 ms. Therefore, it is longer than 86,400 ET seconds by the same amount.

During the 1950s, when Cs atomic clocks appeared to be the most promising candidate for an atomic definition of time, the frequency of the Cs atomic transition was determined in terms of ET with a relative uncertainty of 2×10^{-9} (Markowitz et al. 1958). In 1967, the second of the international system of units, SI, became defined by the Cs transition (CGPM 1969) and in 1971 TAI was defined as "time reference coordinate ... in accordance with the SI second (CIPM 1970)." Therefore, TAI and ET have the same rate, and do not diverge, at the level of 2×10^{-9} in relative value. Thus, the LOD over the end of the 20th century is longer than 86,400 s of TAI by about 2 ms. For this reason, leap seconds had to be inserted in UTC about every 500 days.

The simple explanation to the divergence between the timescales is thus the following. Tidal braking and other long-term mass transfer processes have caused the mean solar day to increase by about 17 μs yr^{-1} over the past millennia. ET has been defined so that 86,400 ET seconds match the average LOD over the 19th century, and atomic time TAI has been defined with the same rate as ET. Therefore, the mean solar day now lasts about $86{,}400^{\mathrm{s}}.002$, which causes a divergence between TAI and UT1.

Note that UT and LOD are subject to other variations over a range of characteristic times due to tidal effects and other mass redistribution processes in the Earth, e.g., atmospheric circulation or mass transfer in the Earth's interior. While tidal effects are predictable and can be well modeled, other processes are less known. It is likely that such processes are the cause of decadal variations (Dickey 1995) that are consistently observed in LOD, including the change in LOD apparent since 1999. Detailed results for UT1 and LOD have been available since 1962 after the introduction of UTC. Decadal variations are clearly visible in the LOD results, see, e.g., http://www.iers.org/plots/EOPC04_05_62-NOW_IAU1980-LOD.png, and it can be verified that the recent period since 1999 does not have any abnormal behavior in this respect. Therefore, to explain the 1999 change, there is no need to invoke the new definition of UT1 decided by the IAU in 2000, as done in Section 3 of D&W2007. Moreover, the change of definition has been designed to keep continuity of UT1 in phase and rate, and in fact took effect in 2003.

4. MAIN PROBLEMS IDENTIFIED IN D&W2007

4.1. Statement that the ET–UT Divergence Corresponds to a Relativistic Time Dilation (Item B)

The authors' arguments related to relativity are completely misleading. From D&W2007, it is obvious that the authors misinterpret the basic principles of general relativity. Thus, they claim that (any) coordinate time t is "the uniform independent variable of the equations of celestial mechanics" (the beginning of Section 4 in D&W2007). This statement is wrong. First,

it is unclear how one can define the claimed "uniformity" of a coordinate time ("uniform" with respect to what?). Second, a coordinate time is simply one of the four coordinates of a four-dimensional relativistic reference system. According to the basic principles of general relativity, one can use any reference system (and any coordinate time) to describe some given physical phenomena. Also the motion of the solar system can be described in a variety of reference systems using a variety of coordinate times. However, in practice for this purpose, one uses a particular reference system called the Barycentric Celestial Reference System (BCRS; Soffel et al. 2003). The coordinate time of the BCRS can be, to some extent, associated with ET. However, it should be clear that at the time when ET was used, the whole modeling of the data was basically Newtonian.

The metric given by Equation (14) of D&W2007 is not suitable to describe the spacetime of the solar system as a whole. This metric is a simplified form of the metric given by Nelson (1990; see Equations 53–55). That metric is one of the possible forms of the formal post-Newtonian solution of Einstein's field equations for the metric of spacetime of the N-body system expressed in the reference system with the origin having a 4-acceleration $\mathbf{W}$ (as measured by an accelerometer co-moving with the origin) and with the spatial axes rotating with an angular velocity ω relative to a momentarily co-moving locally inertial reference system (as measured by an ideal gyroscope co-moving with the origin). Such a solution can be used for certain investigations of physical phenomena in the vicinity of an observer moving with a 4-acceleration (e.g., due to some nongravitational forces). The equations of motion of the N-body system derived from the metric (14) in the Newtonian approximation does not coincide with the normal Newtonian equations of motion for the N-body problem as used in classical celestial mechanics (see Equation 62 of Nelson 1990). This clearly shows that the coordinate time of that reference system cannot be associated with ET. It is unclear why the authors think that the metric of Nelson (1990) is useful for their purposes. Independent of this, the authors make another important mistake; they misinterpret the word "acceleration". Nelson (1990) clearly explains just after his Equation (55) that $\mathbf{W}$ is the "translational acceleration of the observer's frame of reference relative to the instantaneous rest frame, as measured by an accelerometer." It is the so-called 4-acceleration which is meant here. For the Earth this acceleration is as small as 4×10^{-11} m s^{-2} (Soffel et al. 2003) and comes from the interaction of the Moon's gravitational field and the figure of the Earth. This acceleration has nothing to do with the Newtonian acceleration of the Earth relative to the barycentre of the solar system which is as large as 6×10^{-3} m s^{-2} and indeed can be approximately computed by the formula $\mathbf{W} = \ddot{\mathbf{r}} = -\mu\,\mathbf{r}/r^3$ as it is done by the authors (just after Equation 16 in Section 4). That latter acceleration cannot appear in the general-relativistic metric tensor according to the basic principle of general relativity—the Einstein equivalence principle. Since $\mathbf{W}$ is utterly small, one can neglect it in Equation (16) of D&W2007. This changes the rate between t and τ given by Equation (20) and makes it incompatible with the divergence rate between TAI and UT1.

Let us note that the task to relate the proper time of an observer situated on the surface of the Earth and the coordinate time of a reference system is fairly standard in general relativity. Its solution is given in great detail in many textbooks (see, e.g., Brumberg 1991). To an accuracy of about 2×10^{-17}, the proper time of such an observer (at sea level) is equal to the well-known coordinate timescale called TT (Soffel et al. 2003). On the other hand, practical relativistic modeling of the planetary motion uses a scaled version of the BCRS and its coordinate time called TDB. The latter is defined in such a way that to a high level of accuracy (again about 10^{-17}) there is no linear drift between TDB and TT. Therefore, in terms of rate, TDB, TT, and TAI are equivalent and present no systematic difference with ET, at least to the level to which ET and TAI were aligned, i.e., of order 2×10^{-9}.

It is also totally unclear why the authors think that one can identify UT with the proper time of an observer on the surface of the Earth. This idea is misleading and against the basic principles of relativity: the Earth's rotation as a physical process is determined from observations performed by a large number of observers on the surface of the Earth and cannot be modeled in a proper reference frame of any single observer. The process of the Earth's rotation should be modeled in a reference system covering the whole Earth and its vicinity. From the point of view of modern theory of relativistic modeling, Earth's rotation should be modeled in the Geocentric Celestial Reference System (GCRS; Soffel et al. 2003) and parameterized by its coordinate time (e.g., by TT). As mentioned in the preceding section, UT1 is, in fact, directly derived from an angle measuring the rotation of the Earth and, as such, is subject to variations following the laws of mechanics.

4.2. Statement that Earth's Tidal Braking Does Not Explain the ET–UT Divergence (Item C)

In D&W2007, Section 5, the authors correctly state that all historical and paleontological observations are consistent with an increase in LOD of order 17 μs yr^{-1}, i.e., the same order of magnitude as that from tidal breaking. They then state that the presently observed divergence between ET and UT represents an increase in LOD of 2137 μs yr^{-1}, concluding that tidal braking cannot explain it. In fact, the authors wrongly interpret the observed divergence between TAI and UT as necessitating an *LOD increase* of 2 ms yr^{-1}, while it just needs the *LOD* to be "*too long*" by 2 ms on average. Indeed data in Figure 1 can be used to determine that the mean solar day (LOD) is longer than 86,400 s by 2137 μs, on average, over 1958–1999. Therefore, the value of LOD increase obtained from paleontological records is in good agreement with those obtained from historical eclipses and from modern astronomical measurements, and tidal braking does explain the ET–UT divergence.

5. CONCLUSIONS

To conclude, we summarize our views on the three items identified in the introduction.

A. UT1 and TAI appear to diverge at a rate of about 0.78 s yr^{-1} (2.5×10^{-8}) between 1958 and 1999. This is equivalent to the mean solar day being, on average, longer (by $0^{\mathrm{s}}.0021$) than 86,400 s over this period of time. Because the atomic second has been made consistent with the unit of ET when changing the definition of the second in 1967, this divergence also appears between ET and UT1.
B. Both the motion of the solar system and the Earth's rotation should be modeled in suitable relativistic reference systems. In modern astronomical practice, the BCRS is used to model the motion of solar system bodies while the Earth's rotation is modeled in the GCRS (Soffel et al. 2003). The coordinate times used here are TDB and TT, correspondingly. TAI

is a practical realization of TT. In terms of average rate, TDB, TT, and TAI are equivalent, and have no significant rate difference with ET which was defined in a Newtonian framework. UT1 is an angle measuring the Earth's rotation (currently determined by VLBI), but is usually regarded, for historical reasons, as a time determined by the rotation of the Earth. UT1 cannot be identified with the proper time of an observer on Earth.

C. Tidal friction accounts for most of the deceleration of Earth's rotation. This deceleration is equivalent to an increase in the LOD of about 17 μs yr^{-1}. Because the unit of ET has been matched to the average LOD over the 19th century, the LOD over the end of the 20th century is longer than 86,400 ET seconds (or 86,400 TAI seconds) by about 2 ms. For this reason, UT1 and TAI diverge by about $0\overset{s}{.}7$ yr^{-1}, a fact which is accounted for by the insertion of leap seconds in UTC.

We have shown that the general behavior of the Earth's rotation and the related divergence between UT and the more accurate timescales ET and TAI are reasonably well understood, and we see no reason to refute the present understanding. In any case, an explanation based on a relativistic time dilation, as proposed by D&W2007, is clearly flawed.

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