The Definition of UTC

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Abstract. The current definition of Coordinated Universal Time (UTC) is related to the unpredictable, variable rotation rate of the Earth. This is accomplished by irregular insertions of leap seconds, creating unpredictable discontinuities in UTC. With the increasing importance of a continuous, uniform time scale for users, it is appropriate to re-examine the current definition of this time scale. There are several possibilities to address this problem, and it is appropriate that the International Astronomical Union establish a working group to investigate the continuing need for leap seconds and possible changes in the definition of UTC.

1. Introduction

Coordinated Universal Time (UTC), created by adjusting International Atomic Time (TAI) by leap seconds, is the uniform time scale that is the basis of most civil time keeping in the world. The concept of leap seconds was introduced to ensure that UTC would not differ by more than 0.9 seconds from UT1, the time determined by the rotation of the Earth. The principal reason for this was to meet the requirements of celestial navigation.

To determine longitude and latitude using a sextant to make observations of stars, the navigator needs to know the UT1 instant of the observations. An error of 1 second in time could translate into an error of about 500 meters in position. In order to minimize potential timing errors for celestial navigators, the current definition of UTC was adopted. However, with the growing use of satellite navigation and the crucial role of precise timing in high-speed electronic communications, it is now appropriate to reconsider this historical definition of UTC.

Modern commercial transportation systems are now almost entirely dependent on satellite navigation systems. The introduction of a leap second does not affect the operation of the Global Positioning System (GPS) because the time reference for GPS is GPS Time, which is not adjusted to account for leap seconds. GPS does provide the user UTC by transmitting the necessary data in its navigation message to allow the user's receiver to compute UTC from GPS Time. However, GLONASS uses UTC as its time reference. Consequently, it is affected by leap seconds and the satellite clocks must be reset to account for the leap second. During the process of resetting the GLONASS satellite clocks, the system is unavailable for navigation service because the clocks are not synchronized.

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Navigation is not the only service affected by leap seconds. Many spread spectrum systems rely on time synchronization for effective communications. When loss of synchronization occurs, coherent communications are also lost. Thus, during the time of the introduction of a leap second, communications can be lost between some systems until synchronization is re-established. While the leap second might appear to be necessary for some systems, such as celestial navigation, it may be detrimental to other systems that involve more critical safety considerations and create more life threatening situations.

In view of these emerging problems, user dissatisfaction with the definition of UTC is beginning to surface. There is growing concern that users will construct time scales independent of UTC that they perceive to be more suited to their individual requirements. This would lead to a growth in the number of non-standard time scales

We have accurate estimates of the deceleration of the Earth's rotation. Yet, there remain significant variations in the Earth's rate of rotation that prevent the prediction of leap seconds beyond a few months in advance. The inability to predict leap seconds coupled with the growing urgency for a uniform time scale without discontinuities make it appropriate to examine the future of the concept of leap seconds now.

2. Historical background

Historically, the recurrence of astronomical phenomena has been used to keep time. Until 1960, the average solar day was used as the basis for time keeping, and the second was defined as 1/86400 of the mean solar day. This meant that the length of the second depended on the Earth's rate of rotation. In the mid-1930s, it was concluded that the Earth did not rotate uniformly. We now know that a variety of physical phenomena affect the Earth's rotational speed (Lambeck, 1980; Eubanks, 1993). So, in 1960, the second was redefined in terms of the Earth's orbital motion around the Sun. The second defined in this manner was called the "Ephemeris" second, and the time scale derived from the use of this definition was called Ephemeris Time (ET). This name was chosen to call attention to the fact that the definition depended on the position and motion (*i.e.*, ephemeris) of the Sun (or Moon) used in the astronomical determination of time. It was thought that this would be a more uniform measure of the length of the second. However, Ephemeris Time is impossible to measure and observe in real time. In 1967, the second was redefined in terms of the resonance frequency of the cesium atom, which had already been calibrated with respect to Ephemeris Time. Cesium frequency standards, by the early 60s, had become known as reliable, uniform, accurate and precise clocks. The second defined in this way provides a uniform standard of time that could easily be measured in a laboratory with greater precision and accuracy than any astronomical phenomena.

Ephemeris Time has been superseded by a set of dynamical time scales that were defined to meet special relativistic requirements (Seidelmann and Fukushima, 1992). At the level of accuracy with which ET could be determined (approximately 0.001 second), these time scales are equivalent. This family of time scales includes Barycentric Dynamical Time (TDB), Terrestrial Dynamical

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Time (TDT), Terrestrial Time (TT), Geocentric Coordinate Time (TCG), and Barycentric Coordinate Time (TCB).

When the definition of the second based on the cesium atom was introduced, it was known that there would be a time varying discrepancy between a clock running at a uniform rate and a theoretical one using a second defined by the Earth's rotation rate. Starting from 1961, many of the observed variations were accounted for by making small adjustments on the order of a few milliseconds (thousandths of a second) and by making small adjustments to the adopted frequency of cesium clocks from time to time. In 1972, Coordinated Universal Time (UTC) was adopted. The second of UTC is the SI second, the atomic second defined by the resonance frequency of cesium, but the epoch of the time scale is set to be within 0.9 seconds of astronomical time. When the difference between UT1 and UTC is predicted to be about to exceed 0.9 seconds, a leap second is introduced to bring UTC back into closer agreement with UT1. Because the rate of rotation of the Earth can vary, the leap second can be positive or negative.

Astronomical observations show that the major component of the change in the Earth's rotation rate is the near-constant deceleration (McCarthy & Babcock, 1986; Stephenson, 1997). This deceleration accounts for the fact that the length of the astronomical day is approximately two milliseconds longer today than at the beginning of the twentieth century. This fact, in turn, explains the need currently to insert about one leap second per year in UTC, since the difference between UTC and UT1 will grow at the rate of those two milliseconds per day (0.7 seconds/year). The astronomical observations provide a clear estimate of the magnitude of the deceleration of the Earth's rotation rate. Using the data from McCarthy & Babcock (1986) along with more recent observations the difference between the astronomical time and a uniform time can be represented in seconds by

$$\Delta T = TDT(Y) - UT1(Y) = 58.0934 + 0.5970(Y - 2000) + 0.00134(Y - 2000)^2 \tag{1}$$

where Y is the epoch in years and TDT is equivalent to Ephemeris Time defined above. Figure 1 shows the observational data and a quadratic fit.

3. International Atomic Time

International Atomic Time (TAI) is the uniform time scale from which UTC is derived. It is produced by the Bureau International des Poids et Mesures (BIPM) where clock data are gathered from timing laboratories around the world. Approximately 200 clocks in fifty laboratories are used in the formation of TAI. This information is combined to provide a time scale without a relationship to the Earth's rotational speed. No leap second adjustments are made to TAI. UTC is currently derived from TAI, however, using the expression

$$UTC = TAI - (10 + \text{Number of Leap Seconds}). \tag{2}$$

One advantage to the use of TAI is the absence of leap seconds. It is based on the internationally accepted definition of the second, but no adjustments

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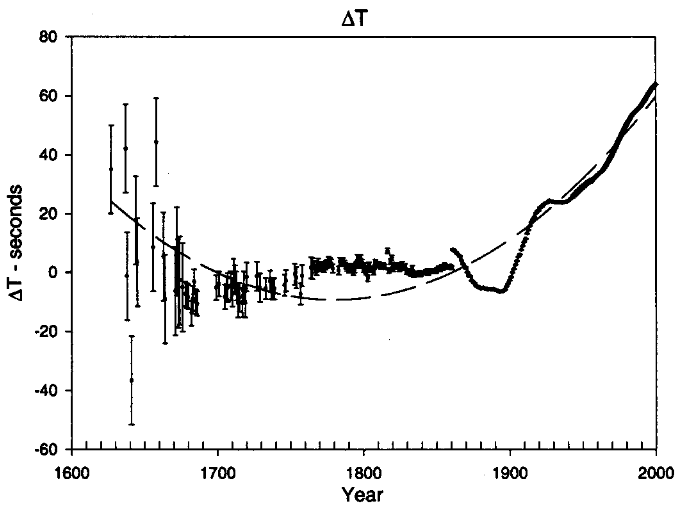

Figure 1. Observations and quadratic fit of the difference between a uniform time scale and one based on the rotation of the Earth.

are made to relate it to the Earth's rotation. Consequently it would appear to be the ideal time scale for those concerned with the use of leap seconds. A problem with TAI, however, is that it is not easily accessible from the national time keeping laboratories. While some timing laboratories may maintain an approximation close to TAI, it is generally not accessible to the average precise time user except through the local realization of UTC. The reason for this is, of course, the fact that UTC is the basis for civil time in the world. Should the use of TAI become more popular in order to avoid problems with leap seconds in the future, time keeping laboratories would need to consider making this time scale more accessible to the user.

4. Options for Coordinated Universal Time

Even with possible increased use of TAI, the problem of leap seconds cannot be dismissed. Since UTC has become the basis for civil time, the practice of inserting leap seconds will continue to be an increasing part of civil time scale maintenance. Outlined below are some possible options for the future of leap seconds. Also included are thoughts regarding each possibility.

4.1. Continue current procedure

If current procedures are continued into the 21st Century we can expect to insert more than one leap second per year, on average. Based on equation (1), by 2050 we should be planning to insert approximately 1.5 leap seconds each year. The current emerging problems and the consequent dissatisfaction with the concept of leap seconds will only continue to grow. On the other hand, should the current procedure be continued, there would be no need to re-educate users of time, and the possibility exists that those users will adapt to an increased number of one-second discontinuities in time. Figure 2 shows the projected number of leap seconds that might be added in the coming years.

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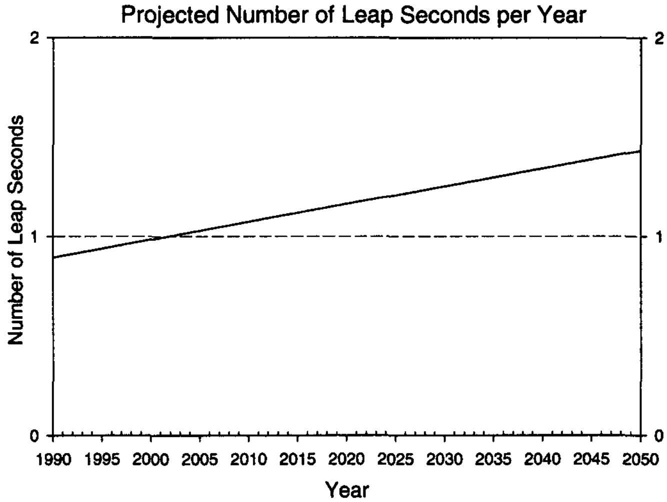

Figure 2. The number of leap seconds expected to be inserted in UTC per year as a function of time.

4.2. Discontinue leap seconds

The discontinuance of the use of leap seconds would eliminate the problem. The concerns associated with a growing difference between UT1 and UTC would remain, however, and grow to be more of a potential problem. Again based on equation (1), the difference between UT1 and UTC would be near one minute in 2050 if no further leap seconds were inserted in UTC. On the other hand it is likely that the difference, although large and growing, would be well-known to users by means of electronic dissemination through navigation and timing systems. It is unlikely that the growing difference between clock time and levels of daylight would be noticeable to a significant percentage of the population for the future. Figure 3 shows the historical (labeled actual) and the projected difference between UT1 and UTC if the leap second were to be abandoned, again assuming the constant deceleration of the Earth's rotation rate given in Section 2. By the end of the 21st Century we see that UTC would be expected to differ from UT1 by more than 2 minutes.

A problem could arise from the fact that most civil time scales adopted as standards by national governments are based on historical laws that refer to "mean solar time." Since UTC remains closely related to UT1, a realization of mean solar time, there is no requirement for changes in laws regarding civil time. This situation might have to be reexamined if leap seconds were discontinued.

4.3. Change the tolerance for UT1−UTC

One compromise between the extremes of discontinuing leap seconds and the *status quo* is to increase the tolerance for the difference between UT1 and UTC. The current limit of 0.9 seconds could be increased to some limit determined to be acceptable. The advantage to this approach is that it could be accom-

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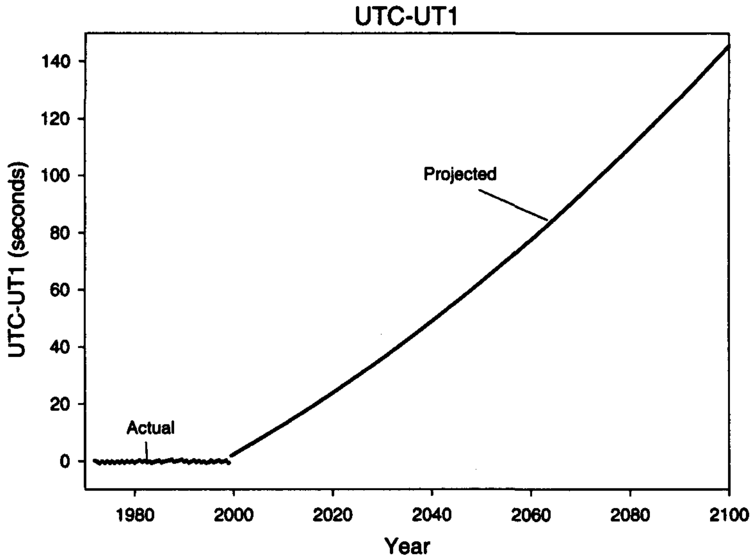

Figure 3. The difference between UT1 and UTC that would be expected if leap seconds were to be discontinued.

plished relatively easily and quickly. The disadvantages to this approach are (1) that the larger discontinuities might cause more problems to the users, (2) the original problem of unpredictability remains, and (3) an acceptable limit might be difficult to establish. Another consideration is that most current radio codes used to broadcast the difference between UTC and UT1 would not be able to accommodate the greater number of digits required. This would, of course, also be the case if leap seconds were to be discontinued completely and it was still desirable to broadcast the difference between UTC and UT1.

4.4. Re-define the second

The most fundamental solution to the problem would be to redefine the length of the second to make it more consistent with the appropriate fraction of the length of the day defined by the current (or expected) rotation of the Earth. While this approach would solve the problem in a fundamental way, it would require a redefinition of all physical units and systems that depend on time. Also, this solution remains a temporary solution in that the current problems will re-surface in the future.

If we characterize time in terms of the units of the period of time corresponding to one cycle of the frequency defined by the transition between the two hyperfine levels of the cesium atom, then at some epoch T, using the current definition of the second, TAI(T) can be expressed as

$$TAI(T) = \frac{1}{s}(T - T_0) + c_1, \qquad (3)$$

$$s = 9,192,631,770 \text{ cycles per second},$$

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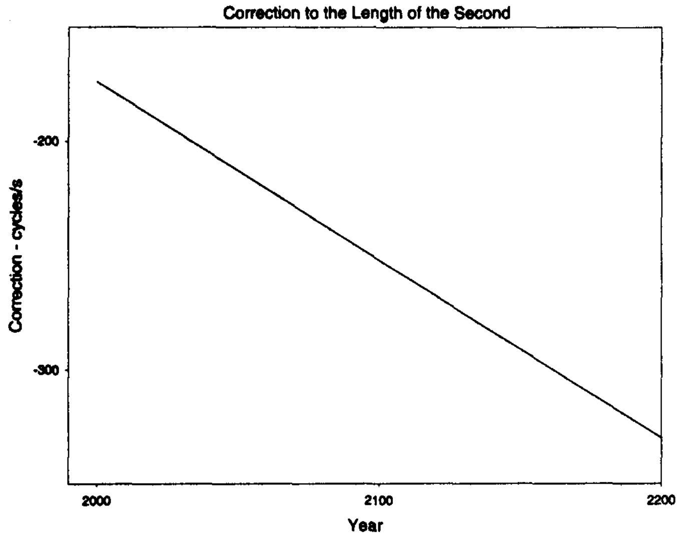

Figure 4. The correction to the frequency of cesium in cycles per second expected from observations of the deceleration of the Earth.

where UTC is given in seconds and $T - T0$ is expressed in the units defined above (*i.e.*, "cycles of Cesium"). The rate of the difference between the two time scales is then

$$\frac{d}{dt}(TAI - UT1) = \frac{1}{s} = \varrho(T), \quad \text{and} \tag{4}$$

$$\Delta\varrho(T) = -\frac{1}{s^2}, \text{ or } \Delta s = -s^2 \Delta\varrho(T). \tag{5}$$

Equation (1) shows that the current definition of the second leads to a difference between the rotational time scale and a uniform time scale that can be represented by

$$TAI(T) - UT1(T) = a_0 + b_0 \frac{1}{s}(T - T_0) + c_0 \frac{1}{s^2}(T - T_0)^2. \tag{6}$$

The rate at which the two scales are observed to differ is then

$$\frac{d}{dt}(TAI - UT1) = \frac{b_0}{s} + \frac{2c_0}{s^2}(T - T_0) = \Delta\varrho(T). \tag{7}$$

So

$$\Delta s = -s^2 \left[\frac{b_0}{s} + \frac{2c_0}{s^2}(T - T_0)\right] = -b_0 s - 2c_0(T - T_0). \tag{8}$$

Values of b_0 and c_0 from Equation 1 can be used to estimate the change that would be required for the definition of the second. Figure 4 shows the expected correction to s in cycles per second.

4.5. Conventional adjustment of UTC

Still another solution might be the establishment of a conventional model for the insertion of leap seconds. This solution would require that the difference between

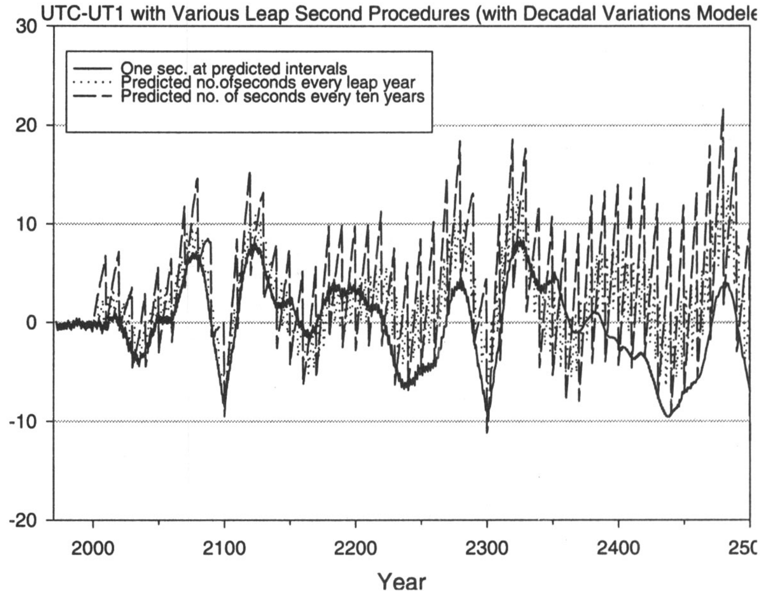

Figure 5. Simulated UTC−UT1 with various possible conventional procedures for the adjustment of UTC.

UTC and UT1 would have to be allowed grow to more than one second. One possibility would be the adoption of a specified period of time after which the accumulated difference in time between the two time scales would be reduced to less than an acceptable limit by the introduction of a discontinuity in UTC. Some possibilities might include inserting leap seconds each leap year or every ten years. While the date of the insertion of leap seconds would be predictable, the number of leap seconds would not. This would remove the problem with predictability but the larger discontinuities might cause concern.

Another possibility might be the adjustment of UTC by leap seconds using the historical deceleration data as a model for the designated insertion of leap seconds. In this case both the insertion dates and the number of leap seconds would be predictable. Again, however, the difference between UTC and UT1 would grow to more than one second.

Figure 5 shows the results of simulations based on the observations displayed in Figure 1 of the likely results of various conventional procedures to adjust UTC. This shows that the difference between UTC and UT1 could reach 10 to 20 seconds.

5. Conclusion

Serious consideration should be given to possible new procedures to relate a uniform time scale to the Earth's rotation. The continued requirement for leap seconds should be evaluated and plans to provide a worldwide standard for time that meets the needs of future timing users need to be formulated now. Failure

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to provide such plans could lead to a chaotic increase in the number of non-standard time scales resulting in confusion and a disservice to users.

All of the suggestions listed above are possible to implement. However, the redefinition of the second appears to be the most awkward to attempt. Continuing the current procedure and ignoring the coordination of uniform time with the Earth's rotation altogether are equally problematic possibilities. This leaves some conventional insertion of leap seconds and the relaxation of the tolerance between UT1 and UTC as the most likely candidates for consideration.

The time is now appropriate for the International Astronomical Union to address this problem by establishing a working group in cooperation with the International Telecommunications Union (ITU-R), BIPM, International Association of Geodesy (IAG), International Earth Rotation Service (IERS), International Union of Radio Science (URSI), and concerned navigation organizations. This group is required to evaluate the need to continue leap seconds and to formulate a plan for possible changes in the definition of UTC.

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