GPS and Leap Seconds

Time to Change?

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Since ancient times, we have used the Earth's rotation to regulate our daily activities. By noticing the approximate position of the sun in the sky, we knew how much time was left for the day's hunting or farming, or when we should stop work to eat or pray. First sundials, water clocks, and then mechanical clocks were invented to tell time more precisely by essentially interpolating from noon to noon.

As mechanical clocks became increasingly accurate, we discovered that the Earth does not rotate "like clockwork," but actually has a slightly nonconstant rotation rate. In addition to periodic and irregular variations caused by atmospheric winds and the interaction between the Earth's core and the mantle, the tidal interaction of the Earth and the Moon causes a secular slowing down of the Earth's rotation. So rather than use the variable time scale based on the Earth's rotation, we now use time scales based on extraordinarily precise atomic time, the basis for all the world's civil time systems — Coordinated Universal Time (UTC).

However, because of the desire to keep UTC more or less in synchronization with the Earth's rotation as an aid in determining navigation fixes using astronomical observations, leap seconds are added to UTC — currently about every 18 months.

In contrast, the time scale used to regulate the Global Positioning System — GPS Time — is a "pure" atomic time scale without leap seconds. In this month's column, Drs. Dennis McCarthy and William Klepczynski suggest that the practice of adding leap seconds to UTC be done away with or at least modified, as more and more navigators adopt Global Navigation Satellite Systems as their primary means of positioning.

Just as leap years keep our calendar approximately synchronized with the Earth's orbit about the Sun, leap seconds keep precise clocks in synchronization with the rotating Earth, the traditional "clock" that humans have used to determine time. Coordinated Universal Time (UTC), created by adjusting International Atomic Time (TAI) by the appropriate number of leap seconds, is the uniform time scale that is the basis of most civil timekeeping in the world. The concept of a leap second was introduced to ensure that UTC would not differ by more than 0.9 second from UT1, the time determined by the rotation of the Earth — a choice made primarily to meet the requirements for celestial navigation.

To determine longitude and latitude using a sextant and observations of stars, one needs to know UT1 at the instant of the observations. An error of one second in time could translate into an error of about 500 meters in position. Celestial navigation was one of the major navigation techniques used throughout the world in 1972, when the first leap second was introduced. With the recent proliferation of satellite navigation, however, it is appropriate to reconsider this historical position, as the leap second may in fact be detrimental to some systems, possibly creating life-threatening situations.

Modern commercial transportation systems now almost entirely depend on satellite navigation systems. In the future, commercial aviation is expected to rely on various augmentation systems to improve satellite navigation accuracy, reliability, integrity, and availability beyond current capabilities. The introduction of a leap second does not affect GPS operations because its time system is GPS Time, which is not adjusted to account for leap seconds. But GPS does provide UTC by transmitting the necessary data in its navigation message, permitting a receiver to compute UTC from GPS Time.

By contrast, GLONASS uses UTC as its time reference (actually UTC + 3 hours which is Moscow Time), and so its satellite clocks must be reset to account for any leap seconds. While resetting the GLONASS clocks, the system is unavailable for navigation service because the clocks are not synchronized. If worldwide reliance on satellite navigation for air transportation increases in the future, depending on a system that may not be operational during some critical areas of flight could be a difficulty. Recognizing this problem, GLONASS developers plan to significantly reduce the outage time with the next generation of satellites.

Navigation is not the only service affected by leap seconds. Spread-spectrum systems also rely on time synchronization for effective communications. When sychronization is lost, so too is coherent communication. Thus, while a leap second is being introduced, and until sychronization is established, communications can be disrupted between some systems.

In view of these emerging problems, user dissatisfaction with leap seconds is beginning to surface, and concern is growing that users will construct time scales independent of UTC that they perceive are more suited to their individual requirements. This would lead to an increased number of nonstandard time scales.

Although we have accurate estimates of the deceleration of the Earth's rotation, significant variations prevent the prediction of leap seconds beyond a few months in advance. This inability to predict leap seconds, coupled with the growing urgency for a uniform time scale without discontinuities, makes it appropriate to re-examine the leap second's role. Later in this article, we will outline several possible scenarios for dealing with leap seconds in the future, but first, let's review how the present system came to be.

A BRIEF HISTORY

Historically, humans used astronomical phenomena to keep time. The passage of the Sun across a north–south (meridian) line determined noon. Until 1960, the average solar day was used as the basis for timekeeping, with the second defined as 1/86,400 of the mean solar day. Under this system, the length of the second depended on the Earth's rate of rotation, because its rotation causes the Sun to appear to move across the sky.

During the mid-1930s, astronomers concluded the Earth did not rotate uniformly, basing their findings on measurements of the most precise clocks then available. We now know that a variety of physical phenomena affect the Earth's rotational speed. This caused the second to be redefined in 1960 in terms of the Earth's orbital motion around the Sun. The new second was called the "Ephemeris" second and the time scale derived from this definition was called Ephemeris Time (ET).

The name called attention to the fact that the definition depended on the position and motion (ephemeris) of the Sun (or Moon) used in the astronomical determination of time. It was originally thought that the new definition would provide a more uniform measure of the second's length. ET is very difficult to measure and observe, however, requiring a series of accurate astronomical observations stretching over years.

In 1967, the second was again redefined, this time in terms of the resonance frequency of the cesium atom, which had already been calibrated with respect to ET. By the early 1960s, cesium frequency standards became known as reliable, uniform, and accurate clocks. Defining the second this way provided a uniform standard that easily could be measured in a laboratory with greater precision and accuracy than any astronomical phenomena.

Increasing Accuracy. Subsequently, ET was superseded by a set of dynamical time scales defined to meet special relativistic requirements. At the level of accuracy with which ET could be determined (approximately 0.001 second), these new time scales are equivalent to ET and include Terrestrial Dynamical Time (TDT), Barycentric Dynamical Time (TDB), Terrestrial Time (TT), Geocentric Coordinate Time (TCG), and Barycentric Coordinate Time (TCB). The advantage of these scales over ET is the incorporation of relativistic effects and a defined relationship to atomic time.

With the advent of more accurate observational techniques, astronomers and geodesists could measure variations in the Earth's rotation rate by comparing the passage of astronomical objects across the sky with laboratory clocks. They established that the Earth's rotation rate is slowing down with respect to a uniform atomic time scale. Thus, if we were to observe a recurring astronomical event, we would see it occurring earlier each day. To bring our clock back into agreement with the astronomical event, we would have to add some time to the face of our atomic clock, which is exactly what we do when we add a leap second to our clocks. We are bringing the faces of our laboratory clocks back into agreement with the time kept by the rotating Earth, so that sunrise will occur at the "correct" time from year to year.

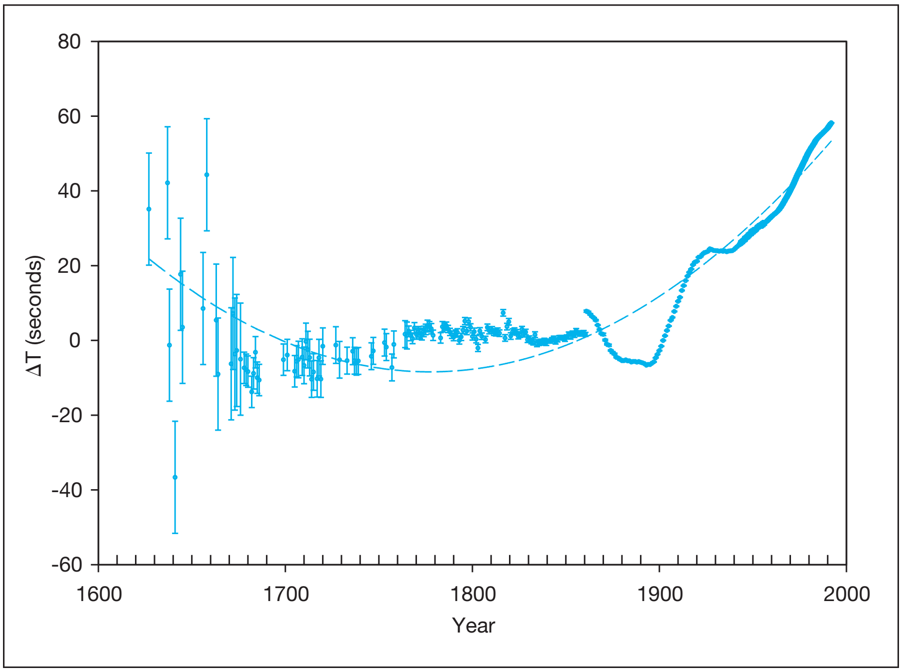

Figure 1. Observations and quadratic fit of the difference between a uniform time scale and one based on the Earth's rotation

The Move to Cesium. With the introduction of the cesium atom–based definition of the second, 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 solely by the Earth's rotation rate. Beginning in 1961, the Bureau International de l'Heure (the forerunner of the International Earth Rotation Service) accounted for these observed variations by making small adjustments, on the order of a few milliseconds, to our civil time clocks and by making occasional small adjustments to the frequency of the cesium clocks.

In 1972, the present system of UTC was adopted. The second of UTC is the Système International (SI) second, the atomic second defined by the resonance frequency of cesium. But the "face of the clock" is set to be within 0.9 second of astronomical time, UT1. When the difference between UT1 and UTC approaches a point when it will exceed 0.9 second, a leap second is introduced to bring UTC back into closer agreement with UT1. The leap second can be positive or negative, because the rate of rotation of the Earth can vary either way. So far, all leap seconds have been positive.

Astronomical observations show a near-constant deceleration of the Earth's rotation rate caused by the braking action of the tides. This deceleration explains why the length of the astronomical day is approximately two milliseconds longer today than at the beginning of the twentieth century. With the difference between UTC and UT1 growing at the rate of two milliseconds per day, or 0.7 second per year, currently about one leap second per year must be inserted in UTC.

The astronomical observations provide a clear estimate of the magnitude of the deceleration of the Earth's rotation rate. Figure 1 combines data from as far back as the 1600s with data recently acquired using modern space geodetic techniques to show the difference between astronomical time and uniform time, along with a parabola fit to the data.

INTERNATIONAL ATOMIC TIME

International Atomic Time (TAI) is the uniform time scale from which UTC is derived. It is produced at the Bureau International des Poids et Mesures (BIPM), where clock data are gathered from timing laboratories around the world. Approximately 200 clocks in 50 laboratories are used to form TAI. This information is combined to provide a time scale without a relationship to the Earth's rotational speed. No leap second adjustments are

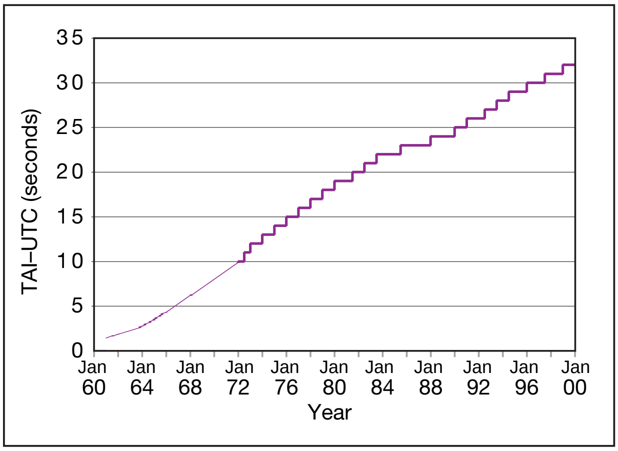

Figure 2. Since 1972, the difference between International Atomic Time (TAI) and UTC is an integer number of seconds — currently 32. Prior to 1972, UTC was adjusted in smaller steps and its rate was also varied.

made to TAI. UTC is currently derived from TAI (see Figure 2), however, using the expression

$$\text{UTC} = \text{TAI} - (10 + \text{number of leap seconds}).$$

At first glance, TAI would appear to be the ideal time scale for those who consider the UTC leap seconds a nuisance. One problem with TAI, however, is the fact that it is not easily accessible from the national timekeeping laboratories. Although 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. This is because UTC is the basis for civil time around the world. Should the demand for TAI increase, timekeeping laboratories may need to consider making this time scale more accessible to the user.

OPTIONS FOR UTC

Even with the possible increased use of TAI, the leap second problem cannot be dismissed. GPS users, for example, will still need to relate GPS Time to civil time. And with UTC as the basis for civil time, the practice of inserting leap seconds will continue as a regular duty of maintaining the civil time scale. The requirement for the current practice to maintain UTC and the tolerance adopted for the difference between UT1 and UTC must be reviewed to understand if the current procedure is still required for general usage. Only when the needs of modern precise time users are well understood will it be possible to carefully evaluate any options for the continued maintenance of UTC. Outlined below are some options for handling leap seconds in the future.

Continue Current Procedure. If current procedures continue into the twenty-first century, we can expect to insert more than one leap second per year, on average. By 2050, we will have to add approximately 1.5 leap seconds each year. The current emerging problems and the resulting dissatisfaction with leap seconds will only continue to grow. One advantage of the status quo, however, is there would be no need to re-educate users of time. The possibility also exists that those users will adapt to an increased number of one-second discontinuities in time. Figure 3 shows graphically the projected number of leap seconds that might be added in the coming years. This projection is based on the deceleration rate shown earlier.

Of course, if we continue the current practice, there will be no change for GPS. The GPS navigation message (see "The GPS Navigation Message" sidebar) includes the number of leap seconds a GPS receiver should subtract from its determination of GPS Time to obtain UTC. Eight bits in the navigation message are used to convey this information, accommodating 1,023 leap seconds. With the Earth's current deceleration rate, a leap-second "rollover" wouldn't occur for about a thousand years. Figure 4 graphically portrays the current relationship between GPS Time and the other time systems.

Discontinue Leap Seconds. Discontinuing the use of leap seconds would eliminate the problems discussed at the beginning of this article. The concerns associated with a growing difference between UT1 and UTC would remain, however, and grow to be more of a potential problem. The difference between UT1 and UTC would 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 foreseeable future. Figure 5 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 earlier. By the end of the twenty-first century, we see that UTC would be expected to differ from UT1 by more than two minutes.

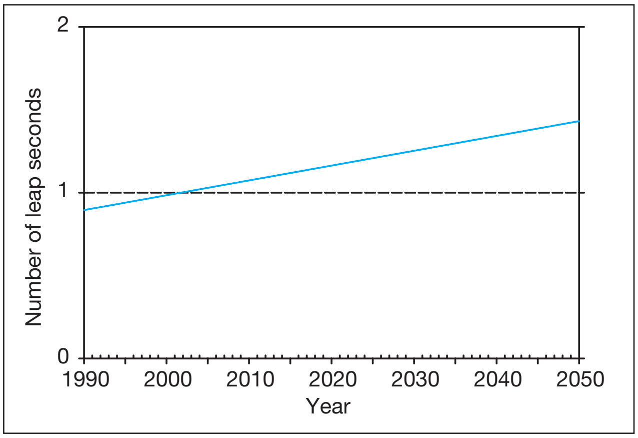

Figure 3. The number of leap seconds expected to be inserted in UTC per year as a function of time

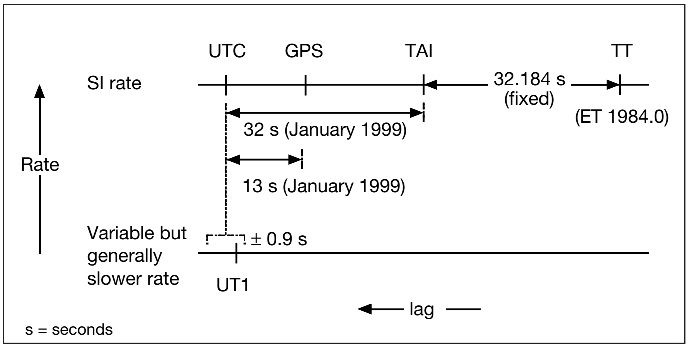

Figure 4. The differences between GPS Time and International Atomic Time (TAI) and Terrestrial Time (TT) are constant at the level of some tens of nanoseconds while the difference between GPS Time and UTC changes in increments of seconds, each time a leap second is added to the UTC time scale.

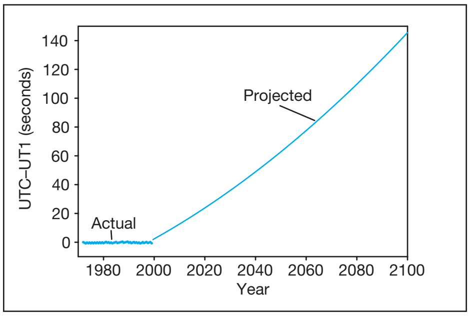

Figure 5. The difference between UT1 and UTC that would be expected if leap seconds were to be discontinued

Abandoning leap seconds would give us an almost constant relationship between GPS Time and UTC. No further updates to the leap-second parameters in the navigation message would be required. As long as no confusion would ensue, either GPS Time or UTC could be redefined to remove the integer number of seconds between them, leaving us, effectively, with just one time scale.

Change the Tolerance for UT1–UTC. One compromise between the extremes of discontinuing leap seconds and maintaining the status quo is to increase the tolerance for the difference between UT1 and UTC. The current limit of 0.9 second could be increased to some acceptable limit, with the advantage that it could be accomplished relatively easily and quickly. However, the disadvantages to this approach are threefold: the larger discontinuities might cause more problems to the users, the original problem of unpredictability remains unresolved, and 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 (such as those used by time signal radio stations WWV and WWVB) could not accommodate the greater number of digits required. This would also be the case if leap seconds were discontinued completely and we still wished to broadcast the difference between UTC and UT1 by radio.

Changing the tolerance for UT1–UTC would have no effect on GPS. It would simply mean that the leap second parameters would stay constant for longer periods of time and that changes in the number of leap seconds would be greater than one.

Redefine the Second. The most fundamental solution to the problem would be to redefine the accepted length of the second, making it more consistent with the appropriate fraction of the length of the day as 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, as it would affect all time scales, including GPS Time. Also, this solution would only be temporary, because the current problems would likely resurface in another hundred years or so.

Periodic Insertion of Leap Seconds. Yet another solution would introduce a discontinuity to UTC after a specified time interval, to reduce the accumulated difference in time between UTC and UT1 to an acceptable limit. 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 presumably larger discontinuities are likely to still cause concern.

This solution would not cause problems for GPS. The GPS Master Control Station would simply have to check about a week or so before “Leap Second Day” whether a change to the navigation message leap-second parameters was required and, if yes, upload the new number of leap seconds to the satellites.

CONCLUSION

It is important that potential new procedures to relate a uniform time scale to the Earth’s rotation with respect to the Sun be given serious consideration. The continued requirement for leap seconds within the user community should be evaluated. Plans to provide a worldwide standard for time that meets the needs of future timing users should be formulated now. Failure to provide well thought-out plans is likely to lead to a chaotic increase in the number of nonstandard 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 periodic insertion of leap seconds and the relaxation of the tolerance between UT1 and UTC as the most likely candidates for consideration. These options appear equal in feasibility with the most serious difficulty being the establishment of an acceptable magnitude for a time step in view of current customs and coding protocols. ■

The GPS Navigation Message

Words six through 10 of page 18 of subframe four of the GPS broadcast navigation message contain the values of Coordinated Universal Time (UTC) parameters that permit a GPS receiver to determine UTC corresponding to a particular instant of GPS Time. This page is transmitted once during the 12.5-minute-long navigation message. The parameters include the current number of UTC leap seconds since January 1980, when GPS Time was set equal to UTC, as well as information on the most recent or announced future leap second. The navigation message also transmits the coefficients of a first-order polynomial describing the subsecond relationship between GPS Time and UTC. Table 1 shows the values of the navigation message UTC parameters received on October 2, 1999. They indicate that currently the number of leap seconds to be subtracted from a receiver’s determination of GPS Time is 13, and that the most recent leap second was introduced at the end of day 5 (Thursday) of GPS week 990, which began on December 27, 1998 — in other words, at midnight (UTC) ending December 31, 1998. At the subsecond level, GPS Time is essentially equal to UTC as it is steered to follow UTC as maintained by the U.S. Naval Observatory. At the (future) UTC data reference time of 147,456 seconds of GPS week 6, this subsecond difference was estimated to be approximately 8.4 nanoseconds (GPS Time leading UTC) and increasing over the short term at the rate of about 0.02 picosecond per second (about 1.7 nanoseconds per day). – R.B.L.

Table 1. GPS UTC parameters

Parameter	Value
A_0 (seconds)	$8.381903172 \times 10^{-9}$
A_1 (sec/sec)	$2.042810365 \times 10^{-14}$
Δt_{LS} (seconds)	13
t_{ot} (seconds)	$1.474560000 \times 10^{5}$
WN_t (weeks)	6
WN_{LSF} (weeks)	990
DN (days)	5
Δt_{LSF} (seconds)	13

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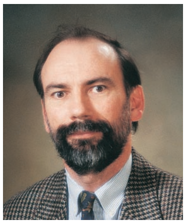

"Innovation" is a regular column featuring discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by Richard Langley of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who appreciates receiving your comments as well as topic suggestions for future columns. To contact him, see the "Columnists" section on page four of this issue.

FURTHER READING

For further information about the various time scales and their relationships to GPS, see

- "Time, Clocks, and GPS," by R.B. Langley in *GPS World*, Vol. 2, No. 10, November/December 1991, pp. 38–42.
- "A Brief History of Precise Time and GPS," by D.W. Allan, N. Ashby, and C. Hodge in *Precise Timing*, supplement to *GPS World*, December 1998, pp. 6–40.
- *The Science of Timekeeping*, by D.W. Allan, N. Ashby, and C. Hodge, Hewlett-Packard Application Note AN 1289, Hewlett-Packard Company, Test and Measurement Organization, Santa Clara, California, 1997. This publication is available electronically as a PDF file by way of the Internet at the following URL: <http://www.tmo.hp.com/tmo/Notes/English/5965-7984E.html>.
- "A Matter of Time," by R.B. Langley <http://www.rnw.nl/realradio/practical/html/time.html>
- The Web site of the United States Naval Observatory's Time Service Department <http://tycho.usno.navy.mil/>

For further information about the Earth's variable rotation, see

- *Historical Eclipses and Earth's Rotation,* by F.R. Stephenson, Cambridge University Press, 1997.
- "Predicting Earth Orientation," by D.D. McCarthy and A.K. Babcock, published in the *Proceedings of the Fourth International Geodetic Symposium on Satellite Positioning*, Austin, Texas, April 28–May 2, 1986, Vol. 1, pp. 137–150.