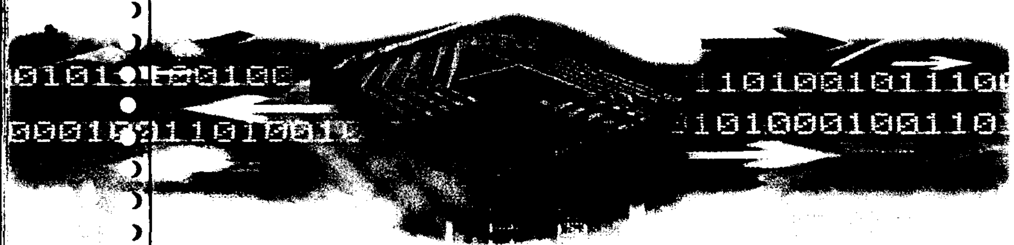
GPS and the Legal Traceability of Time

Judah Levine National Institute of Standards and Technology and the University of Colorado

As James Gleick notes in his recent book Faster, *"A man with a watch knows what time it is. A man with two watches is never sure." From the sundial, to the water clock, to the escapement, to the pendulum, to the quartz crystal, to the atomic clock, to the Global Positioning System, humanity has been obsessed with knowing what time it is. But just like the man with two watches, how do we know whose watch or clock is correct? In other words, as the rock band Chicago noted in one of their classic hits, "Does anyone really know what time it is? Does anyone really care?" The answer to both questions is a resounding "yes." Our modern society depends on knowing the correct time with higher and higher accuracies for everything from time-stamping electronic transactions to synchronizing telecommunications to navigating spacecraft. "Correct" means that the time must be technically, and in some cases legally, traceable to national or international standards. In this month's column, Dr. Judah Levine discusses these standards and the important role GPS plays in keeping the world's timepieces both technically and legally synchronized.*

Dr. Levine is a physicist in the Time and Frequency Division of the National Institute of Standards and Technology (NIST, formerly called the National Bureau of Standards) in Boulder, Colorado. He is also an adjoint professor in the Department of Physics of the University of Colorado. He received a B.A. in 1960 from Yeshiva College and M.S. and Ph.D. degrees from New York University in 1963 and 1966 respectively. Dr. Levine's research involves studies of the statistics of frequency standards and improving the accuracy of the distribution of time and frequency information using both satellite and terrestrial methods. He is also involved in the application of precision measurement techniques to problems of geophysical interest. In collaboration with colleagues at NIST, he is engaged in improving methods for realizing the definition of the second and for distributing accurate time and frequency information.



A "traceable" measurement is one that can be related to national or international standards using an unbroken chain of measurements, each of which has a stated uncertainty. In this article I will describe the traceability of time signals, with a special focus on the legal aspects of this question. As I will show below, legal traceability is not a purely technical question — the legal and technical definitions of time are not precisely the same (at least in the United States at present), and this difference could be significant in practice.

An unbroken chain of measurements is a necessary but not sufficient requirement for traceability. The fact that a previous time stamp from some source was found to be within an acceptable tolerance of a reference standard does not by itself imply (much less guarantee) that the current one will also satisfy the same requirement.

We can address this issue statistically by combining the interval since the last calibration with a statistical estimate of the stability of the reference to arrive at some confidence interval for the current measurement. The result is likely to be characterized in terms of a root mean square error, which is a function of the interval since the last calibration as well as of the uncertainties of the measurements themselves. The resulting uncertainty of the overall process (which is at best a statistical extrapolation and not an actual measurement) might or might not satisfy our initial requirements.

The uncertainty associated with basing traceability on previous calibrations exists for a mechanical artifact (a voltmeter, for example) as well, but our confidence in the stability of a properly maintained and locally available mechanical artifact usually is much higher than it is for a complex system based on a remote reference standard. The fact that the channel between our device and the reference is usually not under our direct control does not help matters.

Applications that require traceable measurements usually have documentation requirements as well as technical ones. Depending on the details of the application, these requirements might range from maintaining a simple log of the calibrations to real-time oversight or auditing by a disinterested third party using encrypted and digitally signed messages. Systems that can support these requirements can become quite complex, because they must be protected against both outsiders and insiders. The National Institute of Standards and Technology (NIST) (and some other national laboratories) provide only some of these services; other services (especially those intended for satisfying commercial or financial requirements) are (or will be) provided by private third parties using time signals that are traceable to national standards.

The Treaty of the Meter

The Treaty of the Meter (Convention du Metre) is the basis for all international cooperation on questions of standards and precision metrology. The treaty was signed in 1875 in Paris and was ratified by the U.S. Senate in 1878. The treaty was modified in 1921, and the modified version was ratified by the U.S. Senate in 1923. The modifications did not make any substantial changes to the original document. There are currently 49 member states of the treaty.

The treaty established the International Bureau of Weights and Measures (Bureau International des Poids et Mesures or BIPM), which is currently located in Sèvres, a suburb of Paris. The BIPM is managed by the International Committee of Weights and Measures (Comité International des Poids et Mesures or CIPM). The President of the CIPM is currently Professor J. Kovalevsky, who is at the Observatoire de la Côte d'Azur, and the U.S. representative is Dr. Karen Brown, the Deputy Director of NIST.

The organizational structure defined in the Treaty of the Meter was initially intended to deal with maintaining and calibrating artifact standards, such as the standard meter and kilogram. The responsibilities of the BIPM were expanded over time to include other standards activities. In what follows, we will discuss only the current arrangement, which dates from 1987 when the responsibility for dealing with standards of time and frequency was transferred to the BIPM from the Bureau International de l'Heure.

The CIPM appoints a number of consultative committees to provide technical advice on questions that are referred to them. The committee that is important for this discussion is the Consultative Committee on Time and Frequency (CCTF), which was formerly called the Consultative Committee for the Definition of the Second (CCDS). The CCTF in turn appoints a number of working groups and subcommittees to deal with specific questions. Two that are important for this discussion are the Working Group on International Atomic Time (TAI) and the subgroup on GPS and GLONASS Time Transfer Standards. The Web page of the BIPM has additional organizational details (see "Further Reading"). In particular, that page describes other relevant working groups such as the one that is concerned with the realization of primary frequency standards and another which deals with time and frequency transfer using non-GPS methods such as two-way satellite time transfer.

Time, Frequency, and the BIPM

Although time and frequency were originally thought of as distinct quantities with independent definitions, this distinction has not been significant for about 30 years. When frequency standards based on atomic transitions were first developed in the 1950s, the initial plan was to use these standards to realize the standard of frequency but to maintain the standard of time astronomically. That method proved to be very cumbersome, and the realization of the standards for time and frequency were unified into their current configuration on 1 January 1972.

Since 1972, the length of the second has been defined using the frequency of a hyperfine energy-state transition in the ground state of the cesium atom. International atomic time (TAI, using the French word order) is a time scale based on that definition of the second. The length of the day defined in that way is somewhat shorter than the current length of the day defined by astronomical methods; the difference is removed by introducing leap-seconds as needed to keep the absolute magnitude of the difference less than 0.9 seconds.

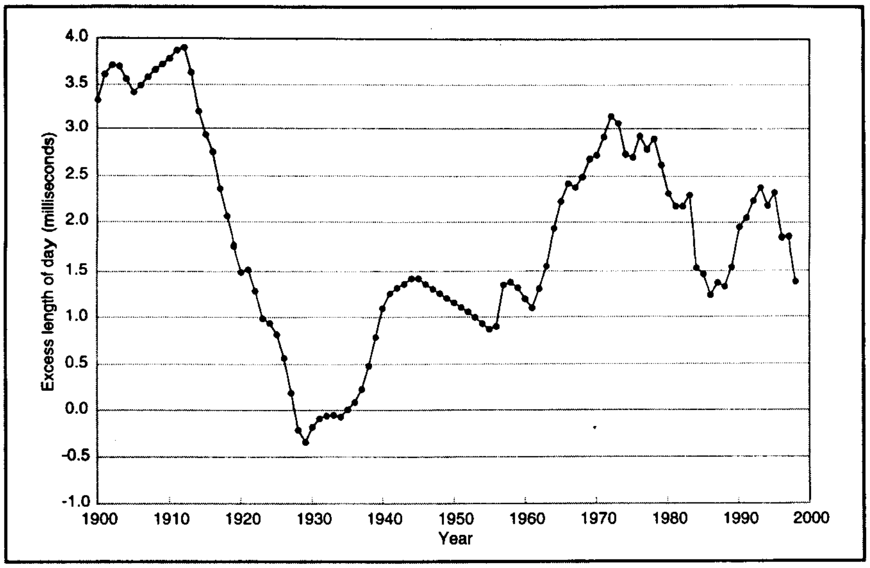


FIGURE 1 The length of the astronomical day varies because of several different phenomena including tidal friction and the exchange of angular momentum between the Earth's core, mantle, and atmosphere. This plot of the annual mean differences between the actual length of day and a day containing exactly 86,400 seconds (the UTC day) illustrates that during the past 100 years, the day based on the Earth's rotation has almost always been longer than the UTC day with a maximum departure of about 4 milliseconds.

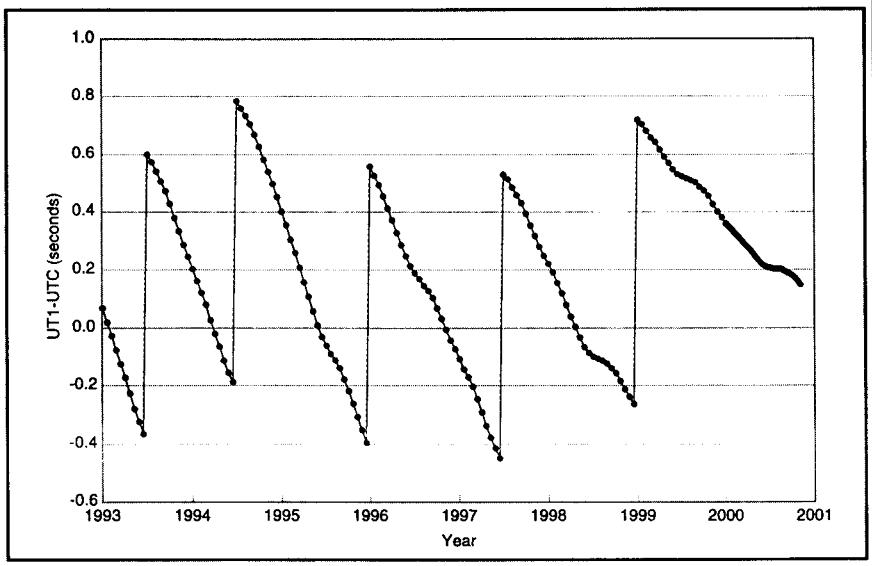


FIGURE 2 The longer astronomical day requires the insertion of leap seconds into the UTC time scale in order to keep the difference between UT1 and UTC less than 0.9 second. The five leap seconds which have occurred since 1993 are clearly evident in this plot of UT1-UTC as determined by the International Earth Rotation Service. Values at 0.05 year intervals are plotted up to the beginning of the year 2000 and at five-day intervals after that.

The resulting time scale (TAI + leap seconds) is called Coordinated Universal Time (UTC), and it is the basis for all civil timekeeping. (This process of adding leap seconds is what makes UTC a "coordinated" time scale.) The rates of TAI and UTC are identical between leap seconds. During the past 10 years or so, the length of the UTC day has been shorter than the astronomical day by about 2 milliseconds (a fractional offset of about 2.3×10^{-8} – see Figure 1), so that leap seconds were required about every 12 or 18 months. The most recent

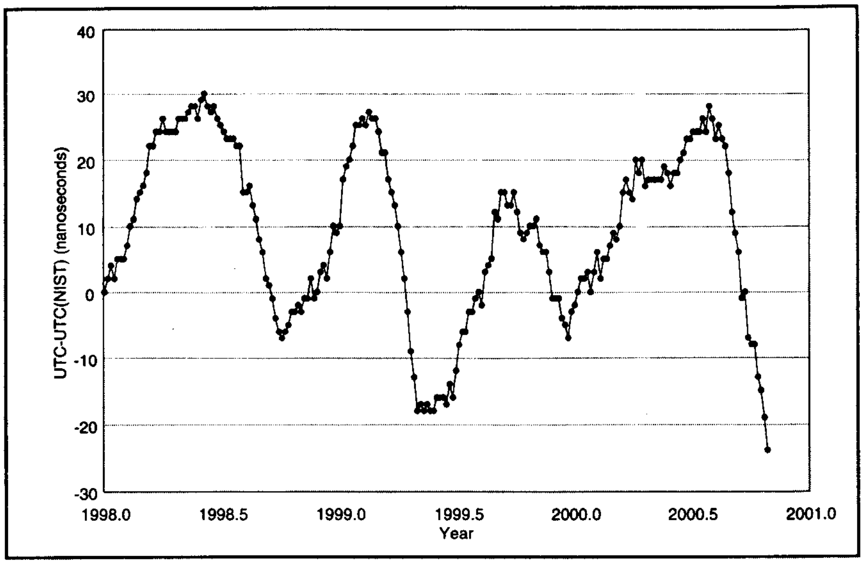


FIGURE 3 The difference between UTC(NIST) and UTC as determined by the Bureau International des Poids et Mesures from a global ensemble of atomic clocks is at most a few tens of nanoseconds. The time variation shown in this figure is consistent with a random walk in frequency with an amplitude of about 6×10^{-15} at periods of a few months.

leap second, which made TAI-UTC = 32 seconds, was added at the end of December 1998 (see Figure 2). Over the past few years, the Earth's average rate of rotation has increased slightly and consequently the need for an additional leap second has not yet been announced (as of December 2000).

UTC is sometimes called Greenwich Mean Time (GMT). However, there are actually two currently used GMTs, and the potential for confusion exists. Originally, the GMT time scale was based solely on astronomical observations and this astronomically determined GMT differs from UTC by some fraction of a second. However, the standard time of the United Kingdom and some other countries near the Greenwich meridian is also called GMT. In this usage, GMT is synonymous with UTC.

The BIPM computes UTC and TAI using data from a world wide ensemble of about 250 commercial cesium standards and hydrogen masers. These clocks are located mostly at national laboratories. The clocks at the different locations are compared using a number of different techniques, including common-view GPS (described below) and two-way satellite time transfer.

The computation at the BIPM assigns a weight to each commercial clock based on its previous stability; the scale also includes data from a number of primary frequency standards. These data are used to make small adjustments to the rate of the scale; a typical adjustment would change the rate of TAI by about $\Delta f/f = 1 \times 10^{-15}$. These steering corrections are too small to be seen by most users, but they are comparable to the stability of the time scales maintained by many national laboratories and must be included in local time scales.

The algorithm that is used by the BIPM to compute UTC is called ALGOS; it was introduced in the 1970s. The basic algorithm has remained unchanged, although its detailed operation has been modified a number of times since then. It is designed to optimize the long-term stability of the scale at the expense of real-time output.

The desire to maximize the long-term frequency stability of UTC and the mechanics of collecting the data from the contributing laboratories mean that both UTC and TAI are computed after the fact and are not available in real time. Generally, the computing for any month is not completed until the 16th day of the following month; although some of this delay could be reduced by more rapid data collection by the BIPM, some part of it is an inevitable consequence of the retrospective nature of the computation.

UTC(NMI) and Circular T

Since UTC and TAI are not available in real time, most national metrology institutes (NMIs) define a local realization of UTC using data from an ensemble of the atomic clocks at the laboratory. The data from these clocks are combined to compute a time scale that is used to realize an estimate of UTC in real-time. These real-time versions are identified as UTC(NMI) to distinguish them from UTC as computed by the BIPM. At NIST, for example, the average time of the local clock ensemble is computed using an algorithm called AT1 (which is similar in concept to ALGOS), and the UTC derived from this computation is identified as UTC(NIST). The U.S. Naval Observatory uses an analogous procedure to define UTC(USNO). A prediction of UTC(USNO) is broadcast by the GPS satellites.

The differences between UTC and each UTC(NMI) are published monthly by the BIPM in its *Circular T*. The magnitudes of these differences vary from month to month but are on the order of a few tens of nanoseconds for laboratories like NIST or the U.S. Naval Observatory (see Figure 3). (These fluctuations are caused by the flicker and random-walk frequency changes that characterize both the clock ensembles at the laboratories and TAI itself. There may also be a smaller annual term resulting from a sensitivity to long-period temperature fluctuations.)

Most laboratories make small adjustments to UTC(NMI) to steer it to UTC. The steering algorithm used by each laboratory must be a compromise between the conflicting goals of timing accuracy and frequency smoothness. At NIST, for example, these steering corrections are made only at the start of a month and are announced in advance. The magnitude of the monthly frequency correction is generally in the order of ±1 nanoseconds/day ($\Delta f/f = \pm 1.2 \times 10^{-14}$) or less. Time adjustments (so-called clock jumps) are never used.

Mutual Recognition Arrangements

In 1999, the directors of many of the metrology laboratories that subscribe to the Treaty of the Meter agreed to establish agreements under which measurements and calibrations performed at one laboratory would be deemed equivalent (at some specified accuracy level to a given measurement at another laboratory. These agreements were a response to the increasingly international character of calibration and measurement activities. These agreements are still being developed, but there are already some prototypes in the area of time and frequency metrology. Examples are the North and Central America Metrology Cooperative (NORAMET), which links NIST with laboratories in Canada and Mexico, and a memorandum of understanding between NIST and USNO regarding equivalence of time and frequency signals generated at the two laboratories.

Distributing Time and Frequency Signals

At all timing laboratories, UTC(NMI) is defined at a point called the reference plane, and the time delay between this point and the user's equipment must be measured. Because this delay is at least 3 nanoseconds per meter (the speed of light inverse), it is often much larger than the difference between UTC and UTC(NMI) or between UTC(NMI_1) and UTC(NMI_2). There are a number of methods of measuring this delay, including direct calibration of the time-transfer equipment and estimating it as one-half of the measured round-trip delay. The uncertainties in this delay often limit (and may even dominate) the overall error budget for the entire time transfer process. Although a quantitative estimate of this problem depends on the details of the time transfer equipment, loosely speaking it is relatively easy to keep the overall uncertainty in the estimate of the channel delay to less than 1 microsecond, and it is almost impossible to achieve an overall uncertainty of less than 1 nanosecond. It is possible, but quite difficult, to achieve an overall uncertainty of less than 10 nanoseconds. Many of the effects that contribute to the delay change slowly with time, often with a nearly diurnal signature. Nearly diurnal effects can be attenuated by averaging, provided that the clock at the user's location is sufficiently stable to support this.

The uncertainties and the fluctuations in the delays through the different channels between a user and the various national timing laboratories may limit the practical usefulness of the equivalence defined by a Mutual Recognition Arrangement. For example, it does not help much if NIST and USNO have an agreement that stipulates that their two time scales are equivalent at some level of uncertainty if the channels between the institutes and a user are not calibrated to the same level of accuracy.

Legal Time in the United States

To complicate matters further, legal time in the United States is not UTC but mean solar time as referenced to the Greenwich meridian (United States Code, Title 15, Chapter 6, subchapter IX, sections 260–267). As we have described above, the difference between mean solar time and UTC (often called DUT1) has a sawtooth-like character, decreasing slowly between leap seconds and increasing precipitously when a leap second is inserted. The peak-to-peak amplitude of this variation can be as large as 1.8 seconds in the long term, but is typically less than this value.

The value of DUT1 is transmitted by a number of time services, including the NIST digital telephone service (Automated Computer Time Service) and the NIST radio stations WWV, WWVB, and WWVH. Because the correction changes by approximately 50 milliseconds per month and is transmitted with a resolution of 0.1 seconds, it is possible to monitor these services occasionally and cache the value received. Depending on the details of this process, different clients might have values that differ by 0.1 second (or even more in the immediate vicinity of a leap second).

Although it would not be difficult to use mean solar time for legal time stamps in principle, this is rarely done in practice. Even if the correction were more widely available than at present, the relatively poor resolution at which it is transmitted would totally dominate the accuracy of the message. A simpler approach would be to change the legal definition of time to be UTC; perhaps this has not been done yet because of the lack of clients in need of legally traceable time with a resolution substantially better than 1 second.

Practical Difficulties at Leap Seconds

Although it is not strictly an issue of legal traceability, many digital systems have difficulties assigning an unambiguous time stamp in the vicinity of a UTC leap second. The leap second is always added as the last second of the day, and UTC time stamps in the vicinity of the leap second are identified as follows in the left-hand column:

	UTC time stamps	Equivalent computer time
Day N	23:59:58	23:59:58
	23:59:59	23:59:59
	23:59:60*	23:59:59
Day N+1	00:00:00	00:00:00

**the leap second*

Most computer systems keep time internally as the number of seconds since some epoch (0000 UTC on 1 January 1970 or 1 January 1900 are common choices), and there is no way of representing the leap second in this format. In the case of computer clocks, the most common practice is to stop the clock for 1 second during the leap second, effectively transmitting 23:59:59 twice. This is shown in the right-hand column above. An event that happens during the leap second therefore receives a time stamp that is indistinguishable from an event that happened in the previous second.

GPS (System) Time does not include leap seconds at all, but the current and future leap second counts are transmitted by each satellite and can be subtracted from GPS Time to construct UTC. Not all receivers parse this field correctly, and it cannot always be used to compute UTC in the past or very far into the future.

Realization of UTC using GPS

There are a number of ways of using GPS to receive UTC time signals. (This section is concerned with subsecond resolution and assumes that the integer leap second correction has already been applied.) If the location of the receiver is known, receiving the signal from a single GPS satellite is enough to allow the receiver to solve for the difference between the local clock time and GPS Time. At a minimum, this solution requires the ephemeris broadcast by the satellite, and it may also use other parameters in the navigation message such as the ionospheric model coefficients. If the receiver can process both the L1 and L2 signals, then the delay through the ionosphere can be estimated from the L1–L2 dispersion. (If the location of the receiver is not known, it must be found using similar data from additional satellites.) The conversion from GPS Time to UTC can be accomplished in several different ways:

1. Using the offset between GPS Time and UTC(USNO) broadcast by the satellites. This has the advantage that it requires no additional hardware or other data. However, the transmitted value is an extrapolation. The offset values transmitted by different satellites may differ because the parameter values transmitted by the various satellites were uploaded at different times.

2. Estimating the difference between GPS Time and UTC using measurements from a timing laboratory rather than from the broadcast message itself. For example, NIST publishes the differences between GPS Time and UTC(NIST) for each satellite that can be viewed from Boulder, Colorado, with a delay of about 1 day; USNO and many other timing laboratories do something similar. Using these measurements could cancel or attenuate problems with the satellite clock, errors in the broadcast ephemeris, and ionospheric effects. This method does not depend on the extrapolations that form the basis of the previous method, but it requires ancillary data from another site, and it cannot be completed in real time.

3. Using real-time common-view data with a timing laboratory substantially improves the cancellation of the effects mentioned in the previous paragraph, because the two sites observe the satellite at the same time and use the same method to average the data. The common-view method is potentially the most accurate for this reason. However, it requires an active collaboration between the two sites. NIST provides this service to some customers using the common-view schedules published by the BIPM.

No matter how the offset between the GPS Time and UTC is calculated, the final data must be corrected for the delay through the receiving equipment, including any offset between the GPS Time computed internally by the receiver and the emission of the physical pulse that is used to calibrate an external device. The apparent delay may vary with time as the satellites move across the sky due to changes in signal multipath effects at the antenna.

Receivers can be calibrated by operating them in common view with a second receiver located nearby whose delay is known. A common reference clock is used for the two receivers, and the two antennas are placed near each other. Another method measures the response of the receiver to a signal generated by a satellite simulator. Both of these methods have advantages, but neither is simple.

FURTHER READING

For further information about the various time scales and their relationship 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.
- "GPS and Leap Seconds: Time to Change?" by D.D. McCarthy and W.J. Klepczynski in *GPS World*, Vol. 10, No. 11, November 1999, pp. 50–57.

For a review of the use of GPS for time transfer, see

- "GPS: Primary Tool for Time Transfer," by W. Lewandowski, J. Azoubib, and W.J. Klepczynski in *Proceedings of the IEEE*, Vol. 87, No. 1, January 1999, pp. 163–172.

For a detailed description of the role of the Bureau International des Poids et Mesures in setting time standards, see

- "The BIPM and the Accurate Measurement of Time," by T.J. Quinn in *Proceedings of the IEEE*, Vol. 79, pp. 894–905, July 1991.

For further details on BIPM, IERS, NIST, and USNO and their time-related activities, consult their respective Web sites:

- "BIPM Internet Home Page" <http://www.bipm.fr/>
- "International Earth Rotation Service" <http://hpiers.obspm.fr/>
- "Time and Frequency Division Home Page" <http://www.boulder.nist.gov/timefreq/>
- "Time Service Department" <http://tycho.usno.navy.mil/>

Summary

National laboratories maintain real-time estimates of UTC and disseminate this time scale using a number of different methods. GPS is currently the method of choice when the highest possible accuracy is required. Depending on how the signals are used and how carefully the receiving equipment is calibrated, GPS signals can provide traceability to national and international standards with an accuracy between about 10 nanoseconds and 1 microsecond. At the highest levels, the accuracy is usually limited by uncertainties in the delay through the channel between the satellite and the equipment at the receiving station. Estimating these delays is complicated by the presence of time-varying effects, including multipath reflections received by the antenna and the sensitivity of the receiving equipment to changes in the ambient temperature. Uncertainties in this delay may limit the technical traceability of the time stamps at the receiver.

In addition to issues of technical traceability, legal traceability may impose additional auditing and documentation requirements on the client system. These requirements will vary with the application; in their most comprehensive form they may require external monitoring of the client system. This sort of arrangement cannot be realized using only a one-way broadcast system. ⊕

"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 4 of this issue.