Time and Frequency Dissemination
Advances in GPS Transfer Techniques

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The atomic clock is one of the greatest inventions of the 20th century. When the first commercial atomic clocks based on the resonance of the cesium atom were introduced in 1958, available clock accuracy jumped by orders of magnitude. The new clocks would not gain or lose one second in a thousand years. Scientists used laboratory versions of the cesium atomic clock to define the atomic second and to establish and maintain a time scale to which all clocks could be set. But how do you set a clock, particularly one which is accurate to a microsecond or better? Or once set, how do you keep track of its error? Clocks are monitored and synchronized using a time and frequency dissemination technique. In the past, radio signals and traveling clocks were used for this purpose. But GPS, itself dependent on atomic clocks for its operation, has become the best technique for intercomparing clocks and for helping to maintain the world's time systems. In this month's column, scientists from the United States' two national time-keeping laboratories, the National Institute of Standards and Technology and the U.S. Naval Observatory, discuss the past, present, and future use of GPS for accurately disseminating time and frequency. – R.B.L.

GPS is not only a high accuracy navigation system, it also delivers time with unprecedented accuracy. Free to the user, GPS is the world's most-accurate globally available one-way source of time and frequency. Declaration of full operational capability of GPS in 1995 revolutionized timing as well as navigation.

Dual use (by military and civilians) of GPS was announced as a formal goal in the wake of the 1983 downing of Korean Airlines Flight 007, and civilian users now far outnumber military users. In addition to navigation, GPS also has had a huge impact on the use of precise time.

Each GPS satellite contains several atomic clocks and continually broadcasts the time and its position. A GPS receiver tracking at least four GPS satellites can solve for the receiver's unknown position and time at virtually any location on the globe, with a precision of a few meters and a time error of a few tens of nanoseconds (ns), excluding receiver calibration errors. A timing user operating from a known fixed location can derive time from GPS using just one satellite, and with averaging, a timing accuracy of a few nanoseconds is possible.

Time from GPS is now used for many civilian purposes, including synchronization of communications systems, cell phone networks, and power grids. It also is used for many commercial applications where accurate time tagging is becoming increasingly important.

The international timing community utilizes GPS to help produce the world's coordinated atomic time scale, Coordinated Universal Time (UTC). In some instances, GPS serves as the primary transfer tool, while in others it serves as a backup to two-way satellite time and frequency transfer (TWSTFT).

The International Bureau of Weights and Measures, or Bureau International des Poids et Mesures (BIPM), in France is charged with providing the time standard UTC. The BIPM collects data via GPS or TWSTFT from more than 200 atomic clocks and a few primary "absolute" frequency standards from more than 50 institutions around the world. Once a month, BIPM uses these data to produce the standard international references for frequency and time, International Atomic Time (TAI) and UTC, which is equal in rate to TAI, but adjusted by an integer number of seconds to account for variations in the rotation of the Earth.

Most of the contributing laboratories produce real-time realizations of UTC. The U.S. Naval Observatory (USNO) and the National Institute of Standards and Technology (NIST) produce official real-time realizations of UTC for the United States. These time scales are identified as UTC(USNO) and UTC(NIST). UTC(USNO) is the external time reference for GPS, and consequently the UTC time derived from GPS is considered fully traceable to international standards for civil and legal time, subject to user equipment errors.

Recent years have seen a number of improvements in techniques and equipment that have resulted in improved time transfer. This article reviews several advances.

Time Directly from GPS

The simplest and most-direct way to obtain time from GPS is to use the signals broadcast directly by the GPS satellites as illustrated in **Figure 1**.

Authorized GPS users, who have access to the encrypted P-code on both GPS frequencies (L1 at 1575.42 MHz and L2 at 1227.60 MHz) can directly estimate the ionospheric delay of the signals, which allows for a more-accurate position, velocity, and timing (PVT) solution. Most civilians can utilize only the C/A-code on L1, but in early 2005 GPS will introduce its first IIR-M satellite, which will broadcast a new unencrypted civil L2 signal, and in 2006 GPS will add a third civil signal, L5. There also are several commercial code-

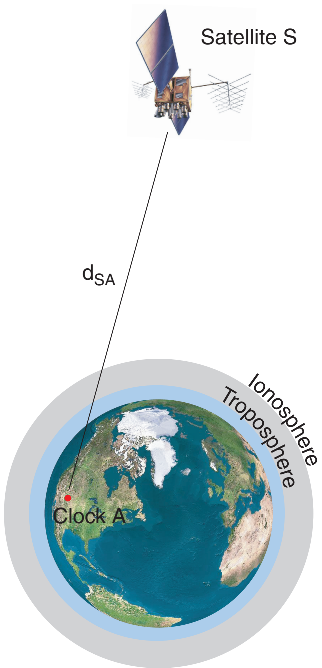


FIGURE 1 GPS direct broadcast (one-way) time transfer. The electrical path length between the satellite and the clock's GPS receiver, d_{SA}, includes contributions from the ionosphere and troposphere (not to scale).

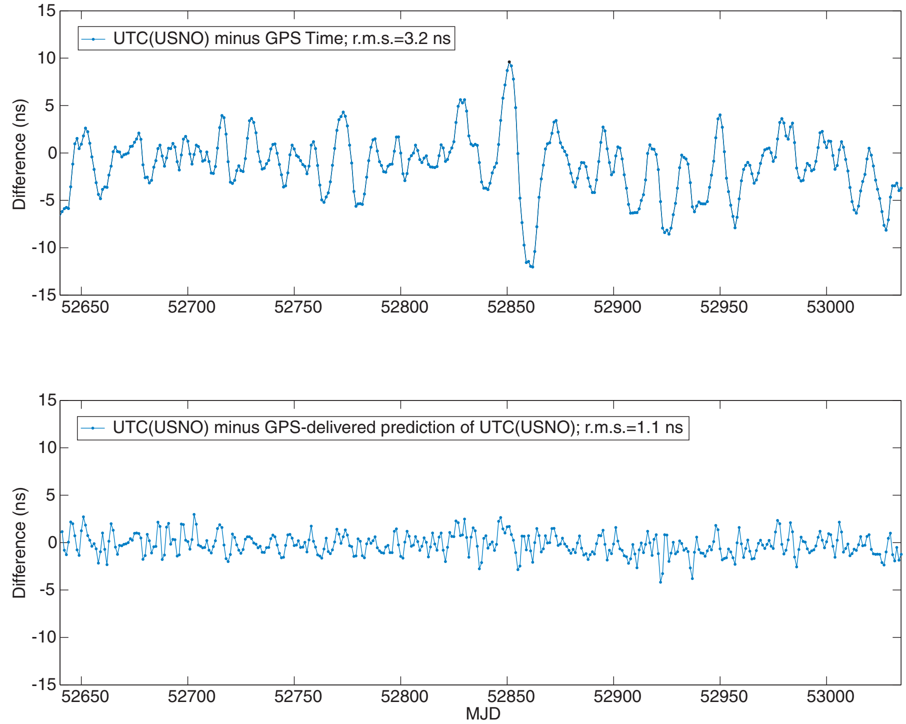


FIGURE 2 Daily averages of the navigation time scale, GPS Time, and the prediction of UTC(USNO) during 2003. The horizontal axis, Modified Julian Date (MJD), is the number of days elapsed since November 17, 1858.

less and semicodeless GPS timing receivers available to all users that can derive timing information from L1 *and* L2.

Each GPS satellite includes in its navigation message a prediction of its orbit, an estimate of the difference between its internal clock and GPS (System) Time, and an estimate of the difference between GPS Time and UTC(USNO). These predictions are updated on the ground every 15 minutes by the GPS Master Control Station Kalman filter, but each satellite's broadcast information is updated approximately once per day by the Control Segment.

Gentle Steering. GPS Time is the internal GPS navigation time scale, which is not adjusted for leap seconds, and is very gently steered to UTC(USNO) modulo 1 second. GPS Time is specified to be maintained to within one microsecond (μs) of UTC(USNO) (modulo integral seconds); for the past seven years it has been maintained to within 22 ns of this goal. One reason advanced for such gentle steering is that it lessens the discontinuity when satellites are asynchronously uploaded with improved clock information. Since the next-generation system, GPS III, currently is envisioned to have crosslinks enabling the entire constellation to be uploaded at once, it has been argued that stronger steering is justified. In any event, the intention has always been that time would be derived by first computing the user position and time offset relative to GPS Time, and then applying the UTC correction terms, including the integer seconds offset. **Figure 2** shows performance of both time scales.

The daily average of GPS broadcast estimates of UTC(USNO) generally are accurate to a few nanoseconds root-mean-square (r.m.s.) and UTC(USNO) has been within 3 ns r.m.s. of UTC for the past two years. Thus the UTC time obtained from GPS has been accurate to better than 5 ns r.m.s. In the future, there will be improved time delivery as new frequencies become generally available, more monitor stations are established (among them the USNO), and when GPS initiates crosslinks so that all satellites can quickly refresh their broadcast parameters in near synchrony.

Disciplined Oscillator. In March 1996, a Presidential Decision Directive was issued that outlined a path that would lead to discontinuing use of GPS Selective Availability (SA) within a decade. SA was a deliberate degradation of the GPS signal intended to reduce the navigational accuracy available to so-called unauthorized users. When SA was set to zero in May 2000, the timing accuracy from GPS improved significantly for civilian users. A commercial product that has benefited greatly from this new capability is the GPS disciplined oscillator (GPSDO). The GPSDO is a combination of a good internal clock (quartz or atomic) and a multichannel GPS receiver. The phase (or time) of the internal clock is locked to the time of the broadcast GPS signal. The GPSDO may operate from a known position or use GPS to derive its position dynamically.

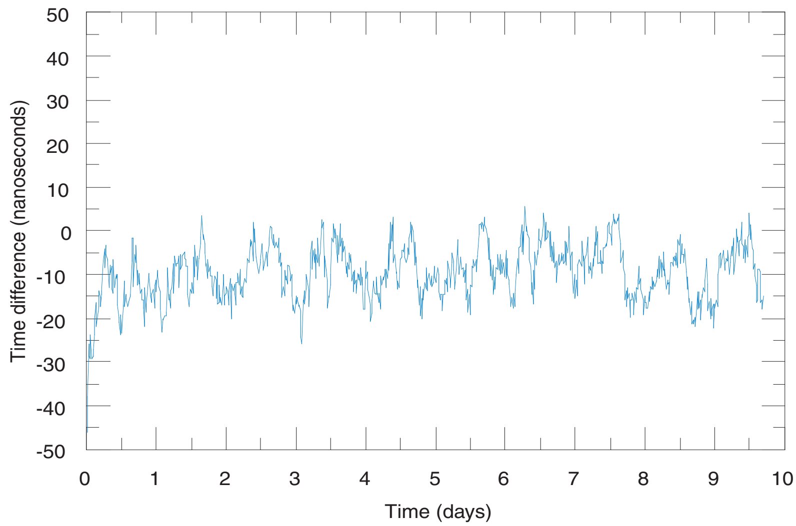
Since the GPS signal is much noisier in the short term than the internal clock, the signal usually is averaged for a relatively long time. This can range from a few minutes to many hours, depending on the quality of the internal clock. The better the clock, the longer the averaging time, and this generally leads to better overall performance. GPSDOs with internal rubidium or quartz clocks are widely available, new or used, for less than U.S.$10,000.

With some care in setup and measurement of cable lengths, these devices will give time accurate to within 50–100 ns.

Figure 3 shows the time — UTC(USNO) from GPS — delivered by a quartz-oscillator-based GPSDO relative to UTC(NIST) over a 10-day period. During this interval, UTC minus UTC(NIST) was about +8 ns and UTC minus UTC(USNO) was about -3 ns. The timing output of the GPSDO varies over a peak range of 20–30 ns due to noise in the GPS signal and from other factors such as temperature, ionosphere, troposphere, multipath, and position errors. Researchers carefully measured all cable delays for this test, and the short-term time error over the test period was within ± 50 ns at all times. By averaging over 24 hours, one can improve the accuracy to under 20 ns with a precision (stability) of about 2 ns. A 24-hour average accuracy on the order of a few nanoseconds could be obtained with careful calibration of the receiver delay. The device delivers r.m.s. frequency accuracy better than 1×10^{-11} for averaging times greater than 1 second, and is better than 2×10^{-13} at an interval of 1 day.

Cable Delays. Virtually any GPSDO will deliver time to better than 1 μs if the manufacturer's instructions are followed. However, if care is taken in measuring cable delays and choosing the antenna site to be as free from multipath as possible, most GPSDOs will deliver time accurate to within 100 ns over short time intervals, and considerably better if a 24-hour average is used. Note that the user must have a reliable local clock such as a high-quality commercial cesium standard if a 24-hour average is to be used effectively. The short-term stability (averaging time less than 1,000 seconds) varies considerably among products, with the best performance generally being obtained with the more-costly, rubidium-based oscillators.

Authorized users who have access to the P(Y)-code on both L1 and L2 can achieve performance considerably better than L1 C/A-code-only receivers because their receivers can measure the ionospheric delay correction directly. Codeless receivers also offer some benefits. However, all users are limited by errors in the broadcast orbit and clock corrections that have accumulated since the satellites were last uploaded (age of data).

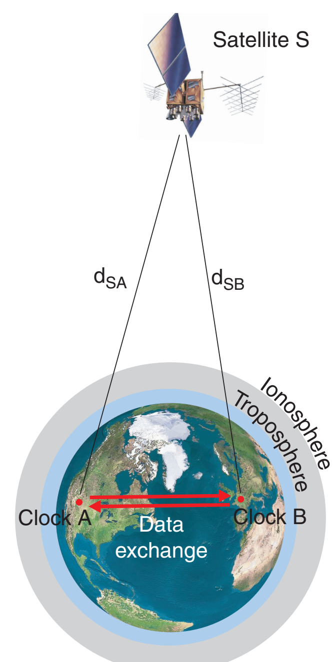


▲ **FIGURE 3** UTC(USNO) as delivered by GPS from a quartz-oscillator-based GPSDO relative to UTC(NIST). Note the short-term variations due to transfer noise.

An example of a direct broadcast calibration service is the NIST Frequency Measurement and Analysis Service. It is based on direct-broadcast GPS Time and provides frequency traceability to NIST with an uncertainly of 2×10^{-13} over a day.

GPS Common-View

GPS common-view is a variation on the direct broadcast of time from a GPS satellite, used primarily to compare or synchronize two widely-spaced clocks on the ground. GPS common-view is carried out by having two ground stations observe the same satellite at the same time, as illustrated in **Figure 4**. This technique has the advantage of removing the GPS satellite clock error, including SA if present, and depending on the baseline length, reducing errors due to atmosphere, broadcast orbit, and broadcast ionospheric corrections. GPS common-view has helped compare clocks around the world for years, and was particularly attractive before SA was set to zero. Even in the absence of SA, it can provide modestly better performance than time broadcast directly from the satellites for baselines shorter than a few thousand kilometers. It has been used by the international timing community as a primary means to coordinate time around the world for nearly 20 years.



▲ **FIGURE 4** GPS common-view technique. Measurements made of a commonly viewed satellite at Clock A and Clock B are exchanged to determine the relative behavior of the clocks.

In the days of single-channel receivers, a tracking schedule was required so that both stations observed the same satellites at exactly the same time. With multi-channel receivers, the tracking schedule generally is not needed. However, in either case, data must be exchanged between the two stations to calculate the time difference between the local clocks. With multi-channel receivers, the all-in-view data files simply are compared to find common observations. Common-view is not a real-time system for time dissemination since data must be transferred, but through the use of the Internet it can be near real time.

In some respects common-view time transfer is easier to calibrate than direct access, since one does not need to know absolute delays, only differential delays, which can be measured with a traveling GPS receiver. Also, common-view has the advantage for short baselines that some sources of error, such as unmodeled ionospheric delays and satellite position errors, will be at least partially common to both legs and will partially cancel. Common-view carried out with the L1 C/A-code is about a factor of two better in both accuracy and stability than direct-access time transfer with the L1 C/A-code for baselines shorter than 3,000 kilometers.

Baselines. Accuracies of a few nanoseconds can be achieved with a 24-hour average, whereas for shorter time intervals the accuracy will be limited by peak instabilities of 10–40 ns. The stability (or precision) with 1 day of averaging is about 1 ns for stations within the United States, and more like 2 ns over intercontinental baselines. For baselines on the order of 10,000 kilometers, the stability of common-view and direct access are about the same. For longer baselines and daily averaging times, a time-transfer mode termed "melting pot," based upon differencing two averages of GPS Time minus the site clocks, is superior to satellite-by-satellite common-view, particularly if the orbital and satellite clock corrections are applied to GPS broadcast parameters.

If processing delays of up to a week can be tolerated in the time comparison, improved performance can be achieved by using postprocessed ionospheric maps and precise orbits. Their use has the most impact on long baselines and will reduce the instabilities of transatlantic common-view to about 1 ns at 1 day.

A number of national laboratories provide a time and frequency calibration service using common view (such as the Global Time Service at NIST). Subscribers typically use the Internet or a phone service to send their receivers' observations to the national laboratory, which reduces the data to compute the difference between the laboratory and subscriber clocks. Accurate time-transfer comparisons can be made for users if their relative system delays are fully calibrated.

GPS Carrier Phase

It has long been recognized that observations of the GPS carrier frequency, in conjunction with the GPS spread-spectrum code, have the potential to provide extremely precise estimates of many parameters. However, it took many years of development by groups such as the Jet Propulsion Laboratory (JPL) and the Universität Bern in Switzerland to develop software that optimally estimates quantities, including the inherent code-to-carrier ambiguity, that allow use of the carrier-phase GPS measurement to more accurately estimate the GPS orbit and clock offsets.

In 1992, a consortium of international geodetic institutions, universities, and government agencies formed a technical confederation, the International GPS Service (IGS). The IGS produces high-accuracy estimates of GPS orbits and clock offsets, with postprocessed 1-sigma accuracies better than 5 centimeters. IGS data also yield an accurate time scale. Fundamentally, the comparative advantage of carrier-phase observations is due to the fact that the 600–800 picosecond period of the GPS carrier frequencies is 1,000 times smaller than the 0.9766 μs chip length of a C/A-code bit, and 100 times smaller than the GPS P-code, which greatly reduces multipath sensitivity and measurement noise. However, the carrier phase has an inherent wavelength ambiguity that must be resolved in the data processing.

The problems and principles involved in the reduction of raw GPS carrier phase data are largely understood at the nanosecond-level. A significant problem in the past was that many receiver designs did not phase-lock their internal signals unambiguously to the input timing reference, and as a result measurements would jump by an unspecified time offset with every receiver reset. However, receivers whose output is insensitive to power cycling are now available, and some others can be modified by their manufacturers for a fee.

Timing carrier-phase receivers typically output data in the form of RINEX files, which can be input directly into the software used for precise timekeeping. Through the codeless and semi-codeless dual-frequency GPS receivers, the user has the ability to measure the line-of-sight ionospheric delay of each observation. The user potentially can combine data worldwide to solve for all relevant parameters in one grand solution.

Precise Point Solutions. However, it often is faster to generate time or frequency transfer solutions by applying previously determined measurements or predictions of satellite orbit, clock, and other parameters — solving only for site-specific parameters, among them the site-clock time offsets from the reference clock. Such solutions are termed precise point solutions. JPL, for example, offers a free Internet-based service entitled Auto GIPSY (GPS-Inferred Positioning System) that will provide precise point solutions using IGS final orbits.

Web Sites of Interest

NIST Frequency Measurement and Analysis Service: *http://tf.nist.gov/service/fms.htm*

USNO Time Service Department: *http://tycho.usno.navy.mil/*

BIPM Time Section: *http://www1.bipm.org/en/scientific/tai/*

IGS Central Bureau: *http://igscb.jpl.nasa.gov/*

IGS Timing Activities: *https://goby.nrl.navy.mil/IGStime/*

Auto GIPSY: *http://milhouse.jpl.nasa.gov/ag/agfaq.html*

PTTI Meetings: *http://tycho.usno.navy.mil/ptti.html*

Many institutions provide professional-level software capable of reducing carrier-phase data, and some research groups have written their own. In the timekeeping community, perhaps the best known are JPL's GIPSY and Bernese (available from Astronomisches Institut Universität Bern). Reductions of the same data by different institutions may vary and the differences are loosely labeled "analysis noise."

Biases. As with any technique, when corrections are not uniformly applied, systematic differences of a few nanoseconds can be observed — just as they could occur with satellite-based biases, which are used by the GPS receiver's algorithm for measuring the L1-L2 difference. Even in global solutions without such biases, time-transfer solutions may differ if the other receivers used in the solution are not identical. For a small array, adding sites can shift time-transfer results at the single nanosecond level. Errors due to GPS satellite orbits can affect time-transfer determinations.

For example, use of IGS rapid orbits instead of IGS final orbits shifted time-transfer results by 200–300 ps r.m.s. for arrays of about 20 receivers. Although the entire tropospheric delay correction, for a near-sea-level site, is very roughly 7 ns divided by the sine of the satellite elevation angle, most of this can be removed by simple modeling and fitting techniques. Tests of differences between fitted troposphere models typically show post-fit time-transfer changes of less than 10 ps.

Discontinuities. Other forms of noise are the discontinuities at the boundaries between independent parameter solutions. In the IGS time and frequency solutions, day-boundary discontinuities can be several hundred picoseconds r.m.s., and are mostly, if not entirely, due to the noise and bias in the GPS code data used to provide the constant offset generating time transfer from frequency transfer. Although carrier-phase time transfer is subject to the same bias variations as common-view time transfer, in many cases the carrier-phase technique provides some means to study this.

Important examples are the temperature-dependence and multipath of the GPS receiver systems. An advantage of using independent solutions from data parsed into one-day batches is that no correlations between fitted parameters can grow with time. For example, if site positions (or any parameters that depended upon satellite azimuth and elevation angle) were not solved for, then errors in the assumed site positions would lead to consistently incorrect ambiguity determinations in some parts of the sky and this would affect the time measurements in continuously filtered solutions. However, no such variations have been reported in long-term comparisons between continuously filtered solutions and independent day-boundary solutions. If such differences were observed, the optimal approach would be to steer continuously filtered solutions to long-term averages of independent daily solutions.

Another advantage of continuously filtered solutions is due to the temperature-dependence of a system's delay being greater for code data than carrier-phase data. Code data corrected for carrier-phase-determined orbit, position, and clock frequency values can show up to several nanoseconds of temperature-dependent daily variations for systems that have exterior cables not temperature-compensated. For data reduced in independent daily solutions, the large systematic diurnal variations in the code data result in noticeable day-boundary discontinuities.

In the past several years, Natural Resources Canada and NASA/JPL have developed real-time GPS networks that use carrier phase to estimate all relevant GPS

Further Reading

For a comprehensive introduction to the physics of time and time measurement, see:

The Measurement of Time: Time, Frequency and the Atomic Clock by C. Audoin and B. Guinot, published by Cambridge University Press, Cambridge, U.K., 2001.

For an introduction to time keeping and GPS, see

"Time, Clocks, and GPS" by R.B. Langley in *GPS World*, Vol. 2, No. 10, November/December, 1991, pp. 38-42.

For additional information on GPS time transfer techniques, see

"GPS Time Transfer" by W. Lewandowski and C. Thomas in *Proceedings of the IEEE, Special Issue on Time and Frequency*, Vol. 79, No. 7, 1991, pp 991-1000.

For information on Two-Way Satellite Time and Frequency Transfer, see

"Two-Way Time Transfer Via Communication Satellites" by D. Kirchner, *Proceedings of the IEEE*, Vol 79, No. 7, 1991, pp. 983-990.

For information on carrier-phase GPS time transfer, see

"Time and Frequency Transfer: High Precision Using GPS Phase Measurements" by T. Schildknecht and G. Dudle in *GPS World,* Vol. 11, No. 2, February 2000, pp. 48-52.

"Comparison of Continuously Filtered GPS Carrier-Phase Time and Frequency Transfer with Independent Daily GPS Carrier-Phase Solutions and with Two-Way Satellite Time Transfer" by D. Matsakis, K. Senior, and P. Cook in *Proceedings of the 33rd Annual Precise Time and Time Interval (PTTI) Systems and Application Meeting*, Long Beach, California, November 27-29, 2002, pp 63-87. This paper can be downloaded from *http://tycho.usno.navy.mil/ptti/ptti2001/paper6.pdf*.

For an overview of USNO's current time transfer practices, see

"USNO and GPS: It's About Time" by D. Matsakis in *GPS World*, Vol. 11, No. 2, February 2000, pp. 32-40.

For information on IGS clock products, see

"A Global Time Transfer Assessment: New IGS Clock Products" by J. Ray and K. Senior in *GPS World*, Vol. 13, No. 11, November 2002, pp. 45-51.

parameters including clocks. They and the IGS are coordinating these networks at a higher level.A real-time continuously filtered solution for the timing difference between the USNO Master Clock located in Washington, D.C., and the USNO Alternate Master Clock located at the Schriever Air Force Base in Colorado Springs, Colorado, can be seen at *http://galia.gdgps.net/igdg/demo_usn3_clock/*. Every second, the network's clock differences are estimated with a precision of 20 ps.

The IGS provides a time-transfer service, in which data from participating laboratories are made publicly available from their Web sites using either their final orbit or rapid orbit values. The IGS clock products are averages of reductions from different analysis centers, which can vary among themselves by about 1 ns peak to peak. The clock products are referenced to the IGS time scale loosely steered to GPS Time.

Precise Calibration

A common concern for all modes of extracting time from GPS is the calibration. The precise calibration bias of a GPS system (including receiver, antenna, and cabling) typically is one of the largest errors in providing an accurate and traceable UTC timing signal. Most commercial GPS timing receivers produce a time output that is accurate to better than 1 μs, and products are available that are accurate to better than 100 ns, or even a few tens of nanoseconds. Absolute calibration can be achieved by using a GPS signal simulator to calibrate the group delay through the GPS antenna, receiver, and cables. Calibration is more commonly achieved by using a GPS receiver whose calibration has been previously determined. Both USNO and NIST offer calibration services that allow a receiver to be calibrated to within the random error of the receiver bias stability. Using great care, the calibration bias error can be reduced to less than 5 ns.

Even in the best-designed system, GPS receivers can vary by several nanoseconds in their calibration over time (months to years). It is important to frequently check the calibration of GPS systems. The BIPM has begun systematic calibration monitoring of receivers maintained at approximately 20 timekeeping institutions, and one important byproduct of this effort will be a quantification of long-term receiver calibration variations. Calibration is achieved by means of a traveling receiver system used for parallel measurements at each site visited. Based upon the long-term repeatability of these calibrations, the BIPM has ascribed a very conservative value of 5 ns r.m.s. for the calibration accuracy.

Multipath is a well known error source for all forms of GPS observations. However, timekeeping has an added multipath concern due to reflections in the cabling. Care should be taken in impedance matching between the elements of the user's GPS system. Failure to do so can cause large temperature and time-dependent variations in the measurements (up to 10 ns).

Other Transfer Techniques

In addition to GPS, there are other techniques for disseminating time and frequency.

Radio broadcasts, dial-up phone services, and Internet time transfer using, for example, Network Time Protocol are much less precise but are used by millions of people. However, it's important to note that even these systems are often calibrated using GPS.

The Wide Area Augmentation System (WAAS) satellites are designed to closely emulate a GPS satellite. Although the prime motivation for the system is to provide safety-of-life enhancement to GPS, WAAS also provides a precise ranging (timing) signal that can be used as an additional satellite signal to form a navigation and time solution. Since the WAAS satellites are geostationary, they can be used by a stationary timing user to obtain time without tracking GPS satellites. A highly directional

TABLE 1 Nominal r.m.s. values for various time-transfer error sources

Error Source	Direct Single-Frequency GPS UTC(USNO)_Lab_Y	Common-View GPS Lab_X_Lab_Y	Carrier Phase GPS Parameter Solution Lab_X_Lab_Y	TWSTFT Lab_X_Lab_Y
Multipath Bias (24-hour average)	1–3 ns	1–4 ns	1–4 ns	< 1 ns
Multipath Precision (13-minute observation)	1–10 ns	1–14 ns	< 20 ps	< 100 ps
Model Ionosphere	3–6 ns	3–6 ns*	0 ns	30–300 ps**
Troposphere at Zenith	300 ps (no fit)	500 ps (no fit)*	10 ps after fit	0
Broadcast Orbits	< 3 ns/observation	< 3 ns/observation*	—	<100 ps*
Broadcast Clocks	< 3 ns/observation	0	—	—
Hardware Variations	2 ns per year	3 ns per year	3 ns per year	< 1 ns per year
Receiver Noise (averaged over 5 minutes)	< 1 ns	< 1 ns	< 20 ps	< 20 ps
Earth Tide (at any instant)	300 ps**	300 ps**	< 10 ps*	0 ps

* Baseline dependent, better for short baselines
** Assuming effect is not modeled. Baseline dependent for common-view and TWSTFT.

TABLE 2 Typical r.m.s. performance of time-transfer modes for calibrated systems

Type	Time Stability (1,000 Seconds)	Time Stability (24 Hours)	Time Accuracy (24 Hours)	Frequency Accuracy (24 Hours)
GPS Direct Broadcast (GPSDO single frequency)	5–10 ns*	2 ns	3–10 ns	4×10^{-14}
GPS Common-View (2,500 kilometer baseline)	5 ns	1 ns	1–5 ns	2×10^{-14}
GPS Carrier-Phase	20 ps	0.1 ns	1–3 ns	2×10^{-15}
TWSTFT	< 0.1 ns	0.1–0.2 ns	1 ns	$2\text{–}4 \times 10^{-15}$

* Equipment dependent

antenna could be used for this purpose, which would be much less susceptible to interference and mutipath.

TWSTFT is another technique used by some timing laboratories. It often is used as a standard for comparison against GPS time-transfer modes because it generally is more precise than direct-broadcast GPS or common-view GPS, and comparable if not superior in accuracy to carrier-phase GPS. This technique requires microwave transmitting and receiving equipment at both stations, and use of a geostationary communication satellite (usually a commercial satellite) as a relay station. If both stations transmit and receive simultaneously, most of the path delays and related instabilities cancel. USNO uses TWSTFT to support GPS by transferring time to the USNO Alternate Master Clock in Colorado.

Summary

GPS provides a cost-effective method for users to get high-quality time and frequency, and this service will improve as GPS advances with time.

The quality experienced by the user depends in many ways upon the user's system. **Table 1** summarizes many of the individual error sources in GPS and TWSTFT, with the understanding that quantitative values depend strongly on system configuration and data-reduction techniques.

Table 2 summarizes the overall performance for these time-transfer techniques. The common-view numbers are for time transfer without using IGS ionospheric maps or precise orbits. For a 10,000 kilometer baseline, common-view performance would be similar to that of direct broadcast. Note that performance may vary over time due to changes in the environmental conditions.

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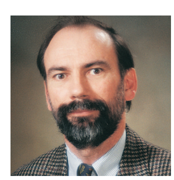

"Innovation" is a regular column featuring discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by **RICHARD LANGLEY** of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who appreciates receiving your comments and topic suggestions. To contact him, see the "Columnists" section on page 2 of this issue.