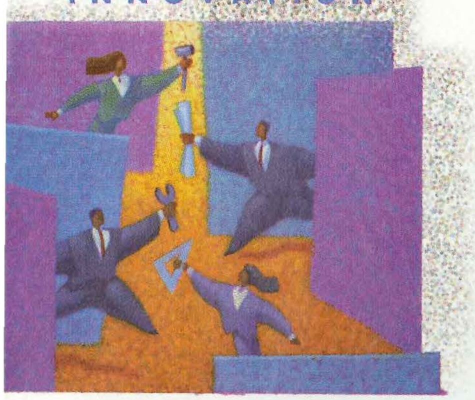


Time and Frequency Transfer
HIGH PRECISION USING GPS PHASE MEASUREMENTS

Thomas Schildknecht University of Bern
Gregor Dudle Swiss Federal Office of Metrology

"What time is it?" This question is asked an untold number of times each day. And the replies? They vary both in accuracy and precision, from "it's about one-thirty" to "10 hours, 32 minutes, and 3.682 nanoseconds." In both cases there is an implicit or explicit reference to some standard of time, accepted as a reference. We have long since abandoned the Earth's rotation as a time standard because its rotation rate varies from day to day and year to year. Instead, we rely on an ensemble of atomic clocks maintained by time-keeping laboratories around the world. The clocks are intercompared to establish a global standard.

Over the years, a variety of intercomparison techniques have been developed, but the time-keeping community has looked for ever higher accuracies. Intercomparisons are now routinely carried out using a simple GPS technique that has an accuracy limited to about one nanosecond, when the results are averaged over one day. But scientists would like to compare clocks with even higher accuracies over shorter intervals of time. In this month's column, two scientists from Switzerland — a country famous for its time pieces — describe a new GPS-based clock comparison technique, one that approaches the level of performance of the clocks themselves.

***Dr. Thomas Schildknecht** obtained a degree in astronomy from Switzerland's University of Bern in 1986. He subsequently worked on GPS code and phase data processing in the Astronomical Institute of the University of Bern (AIUB). Since 1989, this work has focused on high-precision GPS time and frequency transfer. In 1994, he received his Ph.D. from the University of Bern in the field of optical astrometry of fast moving objects. He currently leads the AIUB optical astrometry group.*

***Dr. Gregor Dudle** obtained a physics degree from the Swiss Federal Institute of Technology in Lausanne in 1991. He worked at the Observatoire de Neuchâtel on laser cooling and received a Ph.D. from the University of Neuchâtel in 1996. Through a fellowship from the Royal Society, he spent one year in the United Kingdom at the National Physical Laboratory with the primary frequency standard group. Since 1997, he has worked in the Time and Frequency Laboratory of the Swiss Federal Office of Metrology, where he is involved in the GPS carrier-phase project and the development of a new primary frequency standard.*

Successful time and frequency metrology relies not only on state-of-the-art standards but also on transfer methods that allow comparisons between devices often hundreds of kilometers apart. Time and frequency transfer measurements provide the basic input data for computing international time scales as well as allowing the time-keeping community to compare distant standards against each other.

Over the years, a variety of different techniques have been used to compare remote clocks, including longwave and shortwave time signal stations, the Loran-C radio navigation system, television signals, and travelling clocks flown around the world on commercial aircraft. Today, the most widely used technique for this task is the so-called GPS common-view (GPS CV) method where, according to a schedule issued by the Bureau International des Poids et Mesures (BIPM) in Sèvres just outside Paris, participating laboratories track a GPS satellite several times a day for 13-minute intervals using a dedicated GPS C/A-code timing receiver. For each tracking session, every laboratory computes the difference between the local reference clock and GPS Time as broadcast by the satellites.

The data are subsequently exchanged, thus enabling all participants to form the differences between any two local reference clocks. For averaging times of one day, GPS CV typically allows comparisons at a stability level of 10^{-14}. Until recently, this performance level was sufficient for most clock comparisons. But with the advent of laser cooling, important progress has been made in the field of frequency standards. Short-term stabilities with cesium fountains of 5×10^{-14} have already been reported, and comparable performances are likely to become available in several laboratories around the world within the next few years.

For comparisons between this new generation of standards, the usefulness of classical GPS CV as an adequate tool appears to have dwindled, because averaging times of several days are required to meet the performance levels of the standards. An alternative to GPS CV though, needs to fulfill criteria such as simplicity of use, global availability, a stability level sufficient to compare clocks at the 10^{-14} level in less than one day, and inexpensive operation.

The time-keeping community is already considering several new techniques that all try to overcome the basic limitations of the classical common-view approach. These methods include using multichannel receivers to observe a number of satellites simultaneously; P-code receivers (including codeless and semi-codeless units) to reduce the intrinsic measurement noise; dual-frequency receivers to measure the ionospheric delays; two-way satellite time and frequency transfer (TWSTFT); and GPS carrier phase (GPS CP). In this article, we will examine the new GPS CP approach. After describing the principles of the technique, we will discuss some of the practical issues involved in implementing the technique and describe a system we have developed and used in several experiments to test the concept.

GEODETIC GPS PROCESSING

The GPS CP method is essentially the same technique that was pioneered by geodesists for high-precision surveying. In the early days of GPS, the geodetic community recognized that the system offers a much more precise observable than the code pseudorange, namely the carrier phase (sometimes termed reconstructed carrier phase to underscore the fact that the phases measured are actually those of the receiver's reference oscillator, which is locked to the phase of the received GPS signal). Carrier-phase measurements are approximately 100 times more precise than the corresponding pseudorange observations. Civil geodetic GPS receivers therefore record C/A-code pseudoranges and synthesized P-code pseudoranges (using codeless or semicodeless techniques) on both frequencies as well as the carrier phases on both frequencies. The raw data are stored at each station and then collected at a central processing center.

The position uncertainties obtained for global networks of stations are of the order of 1 centimeter. Because receiver clock errors are closely related to position errors, using geodetic GPS techniques for precise frequency and time transfer was suggested long ago. During the past few years, several groups began to publish results using this technique (see the "Further Reading" sidebar).

Both the pseudorange and carrier-phase observables are subject to various errors that must be eliminated or accurately modeled in order to be useful for time and frequency transfer. The C/A- and/or the P-code pseudorange, as registered by receiver i at time t_i from satellite j, is defined as

$$p_i^j = c\left(t_i - \tau^j\right)$$

where t_i is the arrival time, or observation time, of a signal as measured by the clock of receiver i and τ^j is the transmission time of the same signal, measured in the time frame of satellite j.

The pseudorange p_i^j may be related to the slant range ρ_i^j (the geometric distance between receiver at observation time t_i and the position of the satellite at time τ^j), receiver and satellite clock errors, and to the delays caused by the Earth's atmosphere:

$$p_i^j = \rho_i^j - c\,\Delta\tau^j + c\,\Delta t_i + \Delta\rho_{i,\,ion}^j + \Delta\rho_{i,\,trop}^j \quad (1)$$

where

- c is the vacuum speed of light,
- $\rho_i^j = \left|\vec{r}\left(\tau^j\right) - \vec{R}\left(t_i\right)\right|$

$\vec{r}\left(\tau^j\right)$ being the satellite position at transmission time,

$\vec{R}\left(t_i\right)$ being the position of receiver i at time t_i,

- $\Delta\tau^j$ is the error of the satellite clock with respect to GPS Time,
- Δt_i is the error of the receiver clock with respect to GPS Time,
- $\Delta\rho_{i,\,ion}^j$ is the delay of the signal caused by the ionosphere (ionospheric refraction), and
- $\Delta\rho_{i,\,trop}^j$ is the delay of the signal caused by the neutral atmosphere (tropospheric refraction).

We already mentioned that geodetic receivers also record the carrier phase ϕ_i^j of the received signal. The phase is, however, only measured modulo 2π, meaning that an integer number N_i^j of carrier-phase cycles must be estimated to derive a range measurement. As the receiver keeps track of the integer number of cycles as a function of time, only one so-called initial phase ambiguity N_i^j is needed per satellite pass. An additional difference between code and phase observables concerns the sign of the ionospheric refraction: a pseudorange delay corresponds to a phase advance. This leads us to the following phase observation equation:

$$\lambda\phi_i^j = \rho_i^j - c\,\Delta\tau^j + c\,\Delta t_i + \lambda\,N_i^j - \Delta\rho_{i,\,ion}^j + \Delta\rho_{i,\,trop}^j \quad (2)$$

where N_i^j is the initial phase ambiguity parameter for satellite j and receiver i and λ is the wavelength of the carrier.

Equations 1 and 2 immediately reveal that the receiver clock errors (with respect to GPS Time) can be determined under the provision that all remaining terms can either be accurately determined from the data or may be inferred from an independent source. To compare two receiver clocks, the difference of two quasi-simultaneous observations of the same satellite by two receivers i and k may be formed. This difference, also known as a single difference, will no longer contain the satellite clock error $\Delta\tau^j$ because it is common to both observations.

It is essential that each receiver makes measurements to several satellites quasi-simultaneously — ideally to all in view. *Quasi* means simultaneity is achieved except for the small receiver and satellite clock errors. The multiple measurements not only improve the statistics of estimated quantities but also lead to improved accuracy because of a more homogeneous geometrical distribution of the observed satellites in the receiver's field of view. A further benefit of this method is the reduction of the correlations between the different parameters to be determined from the data, for example, between the tropospheric refraction and the receiver clock term.

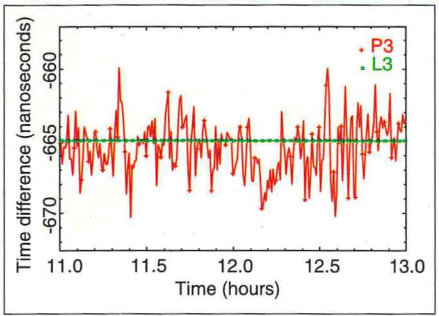


Figure 1. The much higher precision of the GPS carrier-phase clock comparison technique is clearly evident in this plot of the time difference between two hydrogen masers at the U.S. Naval Observatory as estimated from P-code (P3) and carrier-phase (L3) measurements.

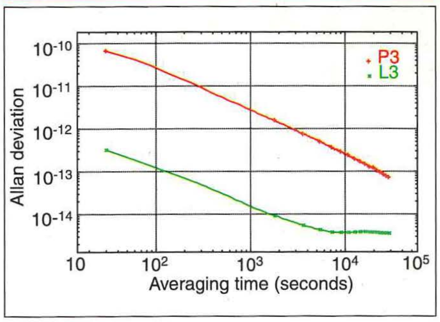


Figure 2. The Allan deviation characterizes the stability of frequency standards, clocks, and time and frequency comparison techniques. This figure shows the Allan deviation of the GPS code and carrier-phase techniques using the 24-hour data set from which the differences shown in Figure 1 were extracted.

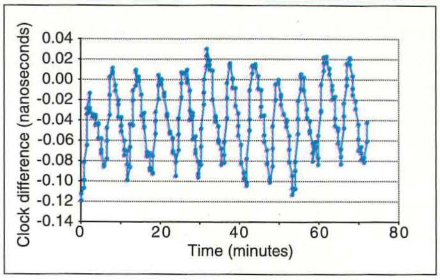


Figure 3. The carrier-phase technique was tested on the 750-kilometer baseline between the National Physical Laboratory (NPL) in Teddington (near London), England, and the Physikalisch-Technische Bundesanstalt in Braunschweig, Germany. This plot of the results shows an anomalous modulation with a period of 724 seconds and an amplitude of about 50 picoseconds resulting from an instrumentation problem at NPL.

Given the much higher precision of the phase observable, we would like to directly use Equation 2 to derive the receiver clock error Δt_i. Solving for the initial phase ambiguities N_i^j at this point, however, is impossible. The phase measurements thus provide information about the receiver clock behavior (with respect to GPS Time — or in the case of single differences — with respect to a second receiver clock). But an unknown "calibration" constant remains. The phase measurements, however, already provide all information needed to perform frequency transfer because frequency is nothing more than the phase rate of change.

For time transfer, on the other hand, we cannot avoid using the low-precision code observations to help determine the phase ambiguities. We note, however, that the code measurements are used to determine a few parameters only. In other words, we could also say that all code observations of an uninterrupted measurement series (which may last weeks) are used to estimate a single clock offset parameter for the beginning of the series.

Figure 1 shows a short interval of a clock comparison between two hydrogen masers at the United States Naval Observatory (USNO) as estimated from ionospherically corrected (codeless) P-code measurements (P3) and from corresponding carrier-phase measurements (L3). The figure illustrates the dramatic difference in the intrinsic precision of the two observables. This is also reflected in the Allan deviation for the same data given in Figure 2. (The Allan deviation, introduced by physicist David Allan in the mid 1960s, is a generally accepted statistic for characterizing clock performance that does not depend critically on the data length or the sampling cutoff frequencies. The classical standard deviation, on the other hand, diverges for commonly observed clock noise processes.) In the case of the phase observations, the P-code observations were used only to determine the initial offset of about –665 nanoseconds.

IGS PRODUCT POTENTIAL

So far, we have assumed that apart from the receiver clock term in Equations 1 and 2, all remaining terms may either be accurately determined from the data or may be inferred from an independent source. An obvious optimum strategy would thus use external high-precision information whenever possible. This is a considerable advantage, which is possible because the raw GPS data are postprocessed rather than used in real time.

The International GPS Service (IGS) provides a series of products that are of interest when GPS data are postprocessed. In particular, we may take advantage of the high-precision geometrical information such as satellite orbits and station coordinates, which IGS provides.

The classical common-view technique determines the receiver clock error with respect to GPS Time for each individual receiver in real time. Consequently, the method relies on information broadcast by the satellites themselves, the most critical being the broadcast satellite ephemerides. Moreover, it is difficult to change any models, such as for atmospheric refraction, because they are implemented in the receiver firmware.

We note that the quality of broadcast orbits is around 2–5 meters whereas the IGS orbits are consistent at the 5-centimeter level.

ACCESSING THE RECEIVER CLOCK

One fundamental question is common to all GPS techniques that attempt to compare clocks: How can we relate the receiver internal time tags to the external signals of the clock to be compared? The epochs used in the GPS data processing are receiver-internal epochs that are related by way of software to a receiver-internal hardware clock. This hardware clock is not directly accessible in most geodetic GPS receivers. Clock estimates from geodetic GPS receivers are therefore estimates of virtual internal clocks only. In principle, there are two possibilities to tie this internal clock to the laboratory clock to be compared: either by forcing the receiver clock to operate synchronously with the laboratory clock or by measuring clock signals from the internal clock with respect to the external clock.

Many geodetic GPS receivers possess an option to synchronize their internal time base with an external time base by means of a frequency input. This synchronization must be performed very carefully to avoid compromising the phase stability of the external time base, for example, by the phase noise of phase-locked loops. The use of this external frequency input thus allows a comparison between laboratory clock frequencies.

To compare time we must, in addition to the frequency synchronization, either synchronize the receiver internal clock and the laboratory clock or measure the phase of the receiver clock with respect to the external clock. Currently, geodetic receivers are generally not fitted with either a 1-pulse-per-sec-

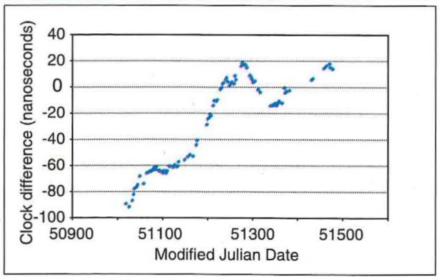


Figure 4. The carrier-phase technique was used to compare clocks at the United States Naval Observatory (USNO) and the Physikalisch-Technische Bundesanstalt (PTB) — a baseline of 6,275 kilometers. The clocks differed by some 80 nanoseconds (USNO minus PTB) when the measurements began but differed by only a few nanoseconds some seven months later.

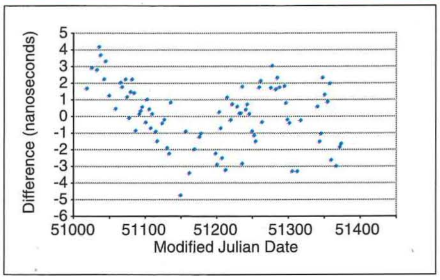


Figure 5. A comparison of the results shown in Figure 4 with those provided by the two-way satellite time and frequency transfer technique reveals clear systematic differences which are, as yet, unexplained.

ond (pps) synchronization input or a 1-pps output. (The steered 1-pps GPS Time output of some receivers should not be confused with a 1-pps output of the internal clock. This is because the 1-pps output is typically steered using the receiver's GPS data.)

In all high-precision time-transfer experiments using GPS phase observations, the commercial geodetic receivers have to be modified to provide access to the internal clock at the subnanosecond level. Moreover, a good knowledge of the receiver's internal design and functioning is necessary to understand the relationship between any external clock input or output and the "virtual" epochs used in the data processing.

LOCAL RECEIVER DELAYS

When using zero- or single-difference GPS observations for time transfer, the signal delay from the receiver antenna phase center to the point where the observables are measured has to be taken into account. This is in contrast to the standard geodetic techniques where the so-called double-differencing eliminates virtually all receiver internal delays in the processing.

Local delays are not critical as long as they are stable over time. In the case of frequency comparison, constant delays are of no influence at all. For time comparison between laboratory clocks, the receiver internal as well as the external delays, such as those in the cables interconnecting the equipment, need to be calibrated. The simplest approach is to calibrate an ensemble of time-transfer terminals by mutually comparing them with their 1-pps input connectors as reference points. This is performed by driving two or more terminals by the same clock on a short baseline of a few meters.

The crucial point, especially for time transfer, is the long-term stability of the local delays. For most delays it is very difficult to measure them in a direct way during the observations. We may therefore try to either stabilize them by some means or correct for the variations in the processing by means of a calibrated model of their dependency on environmental parameters. We use a mixture of both approaches, depending on the type of delay.

Three major delays may be distinguished: the delay through the antenna and the associated preamplifier, the delay through the cable from the antenna to the receiver, and the receiver internal delays. The variation of these delays depends only, to the first order, on the ambient temperature's variation. Antenna delay variations are very dependent on the antenna/preamplifier type and may be as large as 50 picoseconds per Celsius degree for code and 5 picoseconds per Celsius degree for phase. Measurements for the standard RG-213 antenna cables have shown variations as much as 1.44 picoseconds per Celsius degree per meter. For one manufacturer's dual-frequency semicodeless receiver internal delays, we measured variations as large as 165 picoseconds per Celsius degree.

Antenna delay variations may be minimized by thermally stabilizing the preamplifier. Commercial versions of stabilized antennas are available. We decided to measure the antenna temperature continuously and to apply corresponding corrections in the processing on the basis of a calibrated model.

In many cases, the antenna cable is the most critical element. This may be surprising, but unprotected cables on rooftops can easily exhibit seasonal delay variations of as much as 0.1 nanosecond per meter of cable. Simple remedies are available, including the use of so-called "phase-stabilized" cables, minimizing the length of cable exposed to the outside environment, and protecting the cables from direct sunlight.

The receiver internal delays and delay variations may be very different for different types of receivers. For subnanosecond time transfer, the receivers must be placed in a temperature-stabilized environment.

AN INTERNATIONAL EFFORT

Recent progress in the field of GPS-based time and frequency transfer led to the establishment of the IGS and BIPM "Pilot Project to Study Accurate Time and Frequency Comparisons" in December 1997. This joint project plans to exploit the potential of the IGS network and analysis centers by using the precise orbit and position information from the IGS and by including geodetic GPS receivers at timing laboratories into the IGS processing schemes.

Frequency Transfer. Central to the IGS/BIPM project is the further development and testing of the GPS CP technique. This technique has an important advantage over competing frequency-transfer techniques, namely that measurements are performed continuously at a relatively high rate of one measurement each 30 seconds, with the data rate easily increased if necessary. GPS CV, on the other hand, is not continuous by the design of the method, and TWSTFT is limited by the availability and rental costs of satellite transponder channels. On most TWSTFT baselines, measurements are currently performed only three times per week.

This high temporal resolution makes GPS CP perfectly suitable for frequency transfer. This capability was demonstrated during a GPS CP experiment between the German Physikalisch-Technische Bundesanstalt (PTB) and the United Kingdom's National Physical Laboratory (NPL). During this experiment, a Geodetic Time-Transfer Terminal (GeTT) was set up at both sites.

The heart of the GeTT terminals consists of a custom modified geodetic receiver and associated signal distribution electronics, all enclosed in a thermally stabilized box to isolate them from ambient temperature changes. The terminals were built in the framework of a joint project between the Astronomical Institute of the University of Bern and the Swiss Federal Office of Metrology. The comparison of the two hydrogen masers driving the terminals by way of GPS CP yielded an unexpected result. A distinct modulation with an amplitude of 50 picoseconds and a period of 724

FURTHER READING

For an introduction to atomic clocks and time and frequency transfer techniques, see

- *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 at the following URL:<http://www.tmo.hp.com/tmo/Notes/English/5965-7984E.html>.

For further information on the International GPS Service/Bureau International des Poids et Mesures pilot project on GPS time and frequency transfer, see

- "IGS/BIPM Pilot Project to Study Time and Frequency Comparisons Using GPS Phase and Code Measurements," by J.R. Ray in *GPS Solutions,* Vol. 2, No. 3, pp. 37–40, 1999.
- "IGS/BIPM Pilot Project to Study Accurate Time and Frequency Comparisons Using GPS Phase and Code Measurements," <http://maia.usno.navy.mil/gpst.html>.

For discussions of recent experiments using GPS carrier-phase observations, see

- "GPS Time Transfer Using Geodetic Receivers: Middle Term Stability and Temperature Dependence of the Signal Delays," by F. Overney, L. Prost, U. Feller, T. Schildknecht, and G. Beutler, in *Proceedings of the 11th European Frequency and Time Forum,* Neuchâtel, Switzerland, March 4–7, 1997, pp. 504–508.
- "First Results on a Transatlantic Time and Frequency Transfer by GPS Carrier Phase," by G. Dudle, F. Overney, L. Prost, T. Schildknecht, and T. Springer, in *Proceedings of the 30th Precise Time and Time Interval Meeting,* Reston, Virginia, December 1–3, 1998, pp. 271–280.
- "Use of GPS Ashtech Z12T Receivers for Accurate Time and Frequency Comparison," by G. Petit, C. Thomas, Z. Jiang, P. Uhrich, and F. Taris in *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control,* Vol. 46, No. 4, pp. 941–949, 1999.
- "Carrier-phase Time Transfer," by K.M. Larson and J. Levine in *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* Vol. 46, No. 4, pp. 1001–1012, 1999.

seconds could be found (see Figure 3). It is obvious that no other technique would have revealed this behavior over the 750-kilometer baseline. The effect could be traced back to a problem in the local signal chain between the maser and the GeTT terminal at NPL.

Time Transfer Experiment. The second important application of GPS CP is time transfer over long baselines. In this domain, the technique is competing first of all with TWSTFT. To verify the time-transfer capabilities of GPS CP on an intercontinental baseline, GeTT terminals have been deployed at PTB and at USNO, a baseline of 6,275 kilometers. Thanks to the routine TWSTFT measurements on this baseline, the two techniques may be directly compared. Figure 4 shows the comparison between the USNO and the PTB clock over a period from July 1998 to July 1999 as measured by GPS CP. Figure 5 shows the difference between the GPS CP and the TWSTFT time transfer over approximately the same period.

The rather low number of data points is due to the lack of available TWSTFT measurements on this baseline. Nevertheless, we can see a clear signature in this data, and the root-mean-square of the difference between GPS CP and TWSTFT is about 1.9 nanoseconds. It is the first time that TWSTFT could be checked over an intercontinental baseline and over a substantial time period with a completely independent technique of comparable precision. In both cases, the long-term variation of instrumental delays are carefully monitored or controlled. The observed discrepancy thus cannot be attributed to simply one of the techniques. Obviously the story is far from over, and results such as these will drive improvements in both techniques.

CONCLUSIONS

The GPS carrier-phase time and frequency transfer technique is exploiting the potential of GPS in an optimum way by using all available observables and taking full advantage of IGS products. Frequency-transfer experiments over long baselines have shown unique results because of the high intrinsic precision of the phase observable in combination with the high temporal resolution of the continuous measurements.

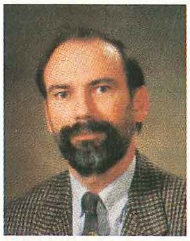
In the time-transfer domain, the technique has matured to become a serious competitor of the TWSTFT, the most precise, routinely used time-transfer technique over long baselines. However, researchers have not yet conducted many continuous GPS CP experiments over long time intervals. Being young, the technique still has substantial potential for improvement, especially concerning the control of long term stability.

ACKNOWLEDGMENTS

We thank USNO, PTB, and NPL for hosting and operating the GeTT terminals as well as the Swiss Federal Office of Metrology for funding the GeTT terminal development. We thank the IGS Center for Orbit Determination in Europe for the routine processing of the GPS CP measurements from time and frequency transfer experiments. We also acknowledge the IGS for providing GPS measurements from their global network, GPS orbits, and Earth rotation parameters. ■

MANUFACTURERS

The heart of the Geodetic Time Transfer Terminal is a custom-modified Ashtech Z-12 dual-frequency GPS receiver from **Magellan Systems Corp., Ashtech Precision Products** (Santa Clara, California).



"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.