TIME AND FREQUENCY ACTIVITIES AT THE U.S. NAVAL OBSERVATORY

Demetrios Matsakis
Time Service Department
U.S. Naval Observatory
Washington, DC 20392, USA

Abstract

The U. S. Naval Observatory (USNO) has provided timing for the Navy and the Department of Defense since 1830 and, in cooperation with other institutions, has also provided timing for the United States and the international community. Its Master Clock is the source of UTC (USNO), which has stayed within 5 ns of UTC in the past year, with an RMS deviation of 3 ns. The data used to generate UTC (USNO) are based upon 73 HP5071 cesium and 18 hydrogen maser frequency standards in three buildings at two sites. The USNO disseminates time via voice, telephone modem, LORAN, Network Time Protocol, GPS, and Two-Way Satellite Time Transfer. The USNO would not be able to meet all the requirements of its users had it kept to the same technology it had 10 years ago; this paper will describe some of the changes being made to meet the anticipated needs of our users. While we aim to increase our accuracy and precision, we deem it equally important to bring about robustness, and we recommend this for our users as well. Further details and explanations of our services can be found online at http://tycho.usno.navy.mil, or by contacting the author directly.

I. RAW TIME

The most important part of the U.S. Naval Observatory (USNO) Time Service Department is its staff, which currently consists of 26 employees. Of these, the largest group, about half the staff, is directly involved in time transfer. The rest are fairly evenly divided between those who service the clocks, those who monitor them, and those who are trying to develop new ones.

The core stability of USNO time is based upon our clock ensemble. We currently have 73 HP5071 cesium clocks and 18 cavity-tuned "Sigma-Tau/Datum/Symmetricom" hydrogen maser clocks, which are located in two Washington, D.C. buildings and also at the USNO Alternate Master Clock (AMC), located at Schriever Air Force Base in Colorado. The clocks used for the USNO timescale are kept in 19 environmental chambers, whose temperatures are kept constant to within 0.1 degree C and whose relative humidities (for all masers and most cesiums) are kept constant to within 1%. Our timescale is based only upon the Washington, D.C. clocks. In December 2003, 59 standards were weighted in our timescale computations.

We have also constructed a cesium fountain, which had a measured stability of 10^{-15} at 1 day; and are assembling parts for a rubidium fountain that we plan to have functional by 2005. In July 2002, we accepted delivery of a "Linear Ion Trap Extended" (LITE) mercury frequency standard built by Jet Propulsion Laboratory (JPL). Preliminary results indicate stabilities better than 10^{-15} at 1 day and a frequency drift lower than 2×10^{-16} /day **[1]**. To maintain the stabilities of these standards will require improved environmental controls, and therefore part of our efforts have gone into requesting funding to construct a building that will be designed for optimal temperature and humidity stability.

We have found it is just as important to take care of our clock measurement systems as it is our clocks. That is why all our connecting cables are phase-stable and of low temperature coefficient, and all our connectors are SMA (screw-on). These measurement systems are designed to take into account the fact that our cavity-tuned hydrogen masers are about 50 times more precise than our cesium clocks in the short run, but over a period of months the precision of the masers falls to where they are not significantly better than the cesiums. Our operational system is based upon switches and counters that compare each clock against each of three master clocks once per hour and store the data on multiple computers, each of which generates a timescale and is capable of controlling the master clocks. The measurement noise is about 25 picoseconds (ps), which is less than the variation of a cesium clock over an hour. Because our masers only vary by about 5 ps over an hour, we also measure them using a system to generate comparisons every 20 seconds, with a measurement noise of 2 ps. For robustness, the low-noise system measures each maser two ways, with different master clocks as references. All clock data, and time transfer data, are gathered by redundant parallel computer systems that are protected by a firewall and backed up nightly on tape.

II. TRUE TIME

No clock is perfect, so we use the average to identify which ones are the most imperfect. We do it using both real-time and postprocessed means, to look for deviations in terms of frequency and time. Using the average of good (apparently stable) clocks, we also detrend our clocks by subtracting their long-term frequency rates and drifts compared to the others. Because cesiums are more stable in the long run, we detrend both cesiums and masers against the average of our best cesiums **[2]**. Then we create separate maser and cesium averages. The maser average represents our most precise average in the short term, and the detrending ensures that it is about as good as the cesium average in the long term. To make the very best average relevant to the current time, we create a hybrid timescale that weights recent maser data very heavily but old maser data hardly at all, relative to our cesiums. That time scale, called A.1, is available on our Web site. We also disseminate the maser-only average, called the "maser mean," whose utility as a frequency reference will be described later.

Although our timescale is extremely stable, we have found that we can increase stability through international cooperation. To do this, we provide our clock data to the BIPM (International Bureau of Weights and Measures), which averages together clock data from laboratories around the world to produce International Atomic Time (TAI). Adding leap seconds, this is Coordinated Universal Time (UTC). In that average, the USNO's Washington DC site contribution is now about 35% of the weight; with the USNO's AMC site, the combined weight has exceeded 50%. Once a month, the BIPM computes UTC and publishes the difference between UTC and the Master Clock (MC). We then steer our MC, by speeding it up or slowing it down, so that its time comes close to UTC **[3,4]**. Because the MC is a realization of UTC, its time is termed UTC (USNO). In order to combine the short-term precision of the USNO clocks optimally with the long-term frequency accuracy of UTC, we use a steering strategy called "gentle steering" **[5]**.

To steer the MC, we first create a steered version of our A.1 timescale so that it approximates UTC. We then steer our MC so that it is in line with our steered A.1. To physically realize UTC (USNO), we use the one pulse per second (1-PPS) output of a frequency divider fed by a 5 MHz signal from an Auxiliary Output Generator (AOG). This outputs the signal of a cavity-tuned maser steered to a timescale that is itself steered to UTC **[3-5]**. The MC has a backup maser and an AOG in the same environmental chamber. A second master clock (mc), fully duplicating the MC, is located in an adjacent chamber and steered using the same algorithm as the MC. In a different building we have the same arrangement for a third mc, which is steered to the MC. Its backup AOG is steered to a mean timescale, based only on clocks in that building, which is itself steered to the MC.

An important part of our operations is our Alternate Master Clock (AMC), located at Schriever AFB in Colorado, adjacent to the GPS Master Control Station. We work very hard to keep close communications between the staff at our two sites. We also keep the AMC's mc in close communication with the MC; using Two-Way Satellite Time Transfer (TWSTT) and modern steering theory **[6]**, the difference is often less than 1 nanosecond (ns). We have not yet integrated the three masers and 12 cesiums at the AMC with the USNO's Washington, DC timescale, but it remains a possibility that carrier-phase TWSTT or GPS techniques can be made reliable and accurate enough to attempt this.

The operational unsteered timescale (A.1) is based upon averaging only the better clocks, which are first detrended using past performance. As a result of a study conducted in 2000 **[7]**, we have widened the definition of a "good clock" and are recharacterizing the clocks less frequently. We are also continuing to work on developing algorithms to combine optimally the short-term precision of the masers with the longer-term precision of the cesiums and the accuracy of TAI itself. We have this year begun field-testing an algorithm, which steers the MC hourly and tightly to a timescale based only upon masers, which is steered to a cesium-only timescale that itself is steered to UTC using the information in the Circular T **[8]**. The steered cesium-only based timescale would either be based upon the Percival Algorithm **[2]**, a Kalman-filter, or an ARIMA algorithm. Individual masers could be steered to the cesium-only timescale before being averaged to create the maser-only timescale.

III. THE QUALITY OF USNO TIME

The standard test for the quality of a master clock's time is how closely it conforms to UTC. However, this is only half the story. Also important is how stable a master clock is in frequency. Figure 1 shows how the USNO Master Clock has measured up to these two standards over the past several years. The figure does not show the stability over daily and subdaily periods of most interest to our users, particularly our navigational users. That is shown statistically in Figure 2.

Figure 1 makes the interplay between time and frequency stability very apparent. It is to be stressed that even before our switch to gentle steering, on MJD 51369, none of the changes described in the figure caption significantly affected the short-term stability of the MC, which is what is needed by navigational users and most other users of UTC (USNO). Figure 2 shows the stability of the MC when measured against our maser mean using our low-noise system for this year and last year.

Most of our users need and desire access to only the MC. This is accessible via GPS and other time transfer modes. Other users are interested in UTC, and for those we make predictions of UTC – UTC (USNO) available on our Web pages. The Web pages also provide the information needed for users who are interested in using the MC to measure absolute frequency. A very important class of users is made up of those who are interested mostly in frequency stability, and for them we have made available the difference between the MC and the maser mean using anonymous ftp. For almost everyone, however, the MC itself is sufficient as a measure of time or frequency.

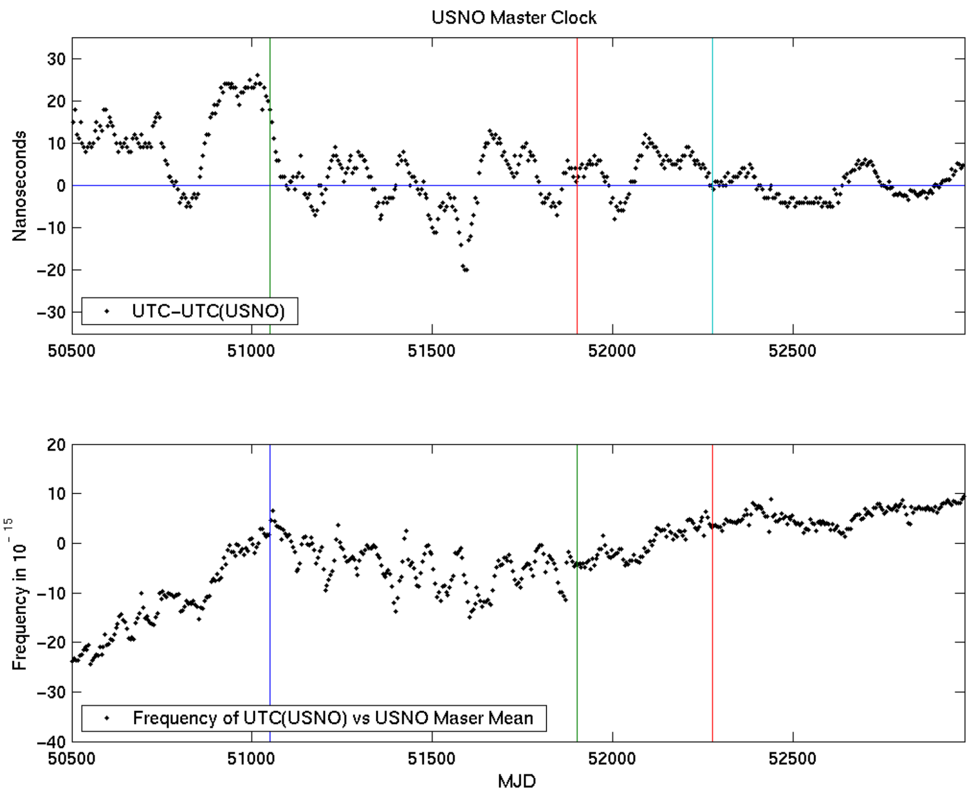

Figure 1. Interplay between time and frequency stability from February 1997 to the present. Top plot is UTC – UTC (USNO) from the BIPM's Circular T. Lower plot shows the frequency of the Master Clock referenced to the maser mean. The rising curve previous to MJD 51000 is due to the graduated introduction of the 1.7×10^{-14} blackbody correction to the primary frequency measurements. The steering time constant for the time deviations between the Master Clock and the mean was halved to 25 days on MJD 51050. Beginning about 51900, the mean has usually been steered so as to remove only half the predicted difference with UTC each month. Less aggressive clock characterization was implemented at around 52275. Vertical lines indicate the times of these changes. UTC (USNO) has stayed within 6 ns of UTC for over 2 years.

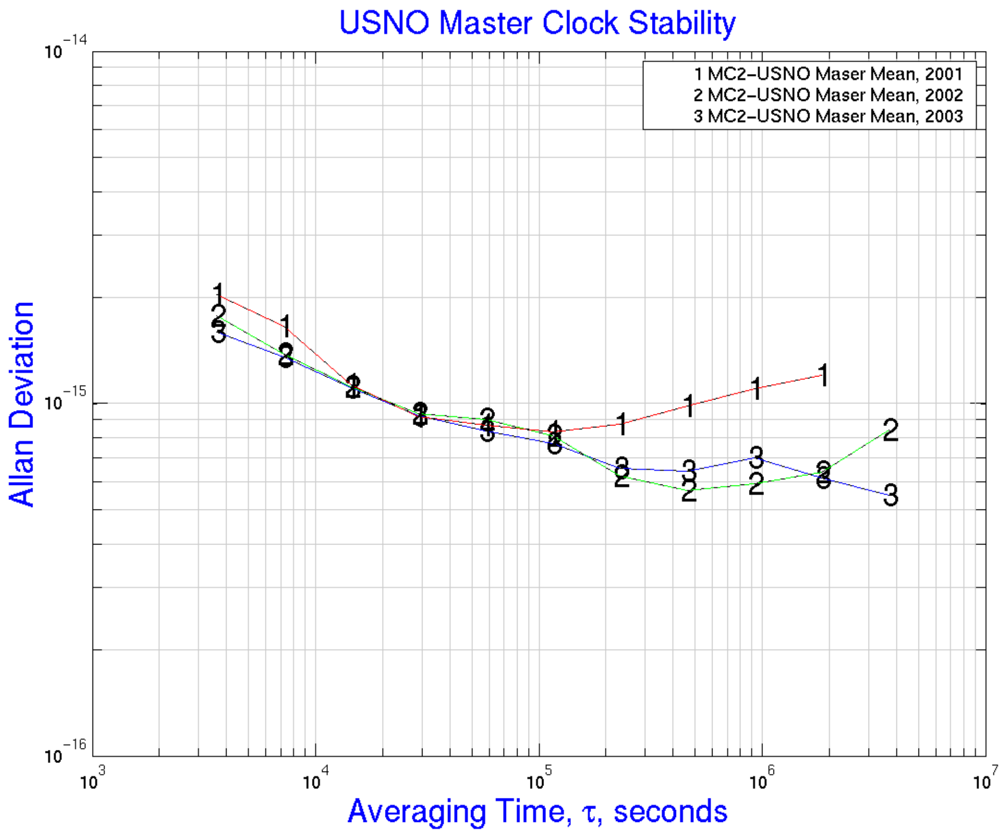

Figure 2. Short-term stability of the USNO Master Clock, referenced to the USNO maser mean. The Allan deviation measures how much the fractional frequency changes from one interval, τ, to the next. The improvements since 2001 for τ longer than 1 day (~10^5 seconds) are probably due to our less aggressive clock characterization strategy. The difference for short τ is not significant since the Master Clock's maser is currently steered once per day.

IV. TIME TRANSFER

Most of our users do not require our full precision, but we consider it just as important to meet their needs as it is to meet those of our highest-precision users. Table 1 shows how many times in 2003 we were queried by various systems. The fastest-growing service is our Internet service Network Time Protocol (NTP); the number of individual requests we received last year was more than double the preceding year. These billions of requests correspond to at least several million users. The number would be much larger if we counted the NTP-like service requests involving telnets through ports 13 and 37. Along with our public service, we also have an NTP service on the DoD's classified SIPRNET, which we have made plans to expand. This year we upgraded our entire NTP array so as to have identical units with up-to-date software capable of supporting authenticated NTP, which we have made operational at the AMC.

Table 1. Yearly access rate of low-precision time distribution services.

Telephone Voice-Announcer	820,000
Leitch Clock System	110,000
Telephone Modem	710,000
Web Server	60 million
Network Time Protocol (NTP)	100 billion

Greater precision is required for two services for which the USNO is the timing reference: GPS and LORAN. USNO monitors LORAN at three sites: Ft. Richardson, AK, Flagstaff, AZ, and Washington, DC. With some assistance from the USNO, the Coast Guard has developed its Time of Transmission Monitoring (TOTM) system so it can steer using data taken near the point of transmission using UTC (USNO) via GPS. Direct USNO monitoring at its three points of reception is used as a backup and sanity check. Figure 3 shows daily data from one of the chains we officially observe from our Washington, DC facility. Data from all our chains can be found in **[9]**.

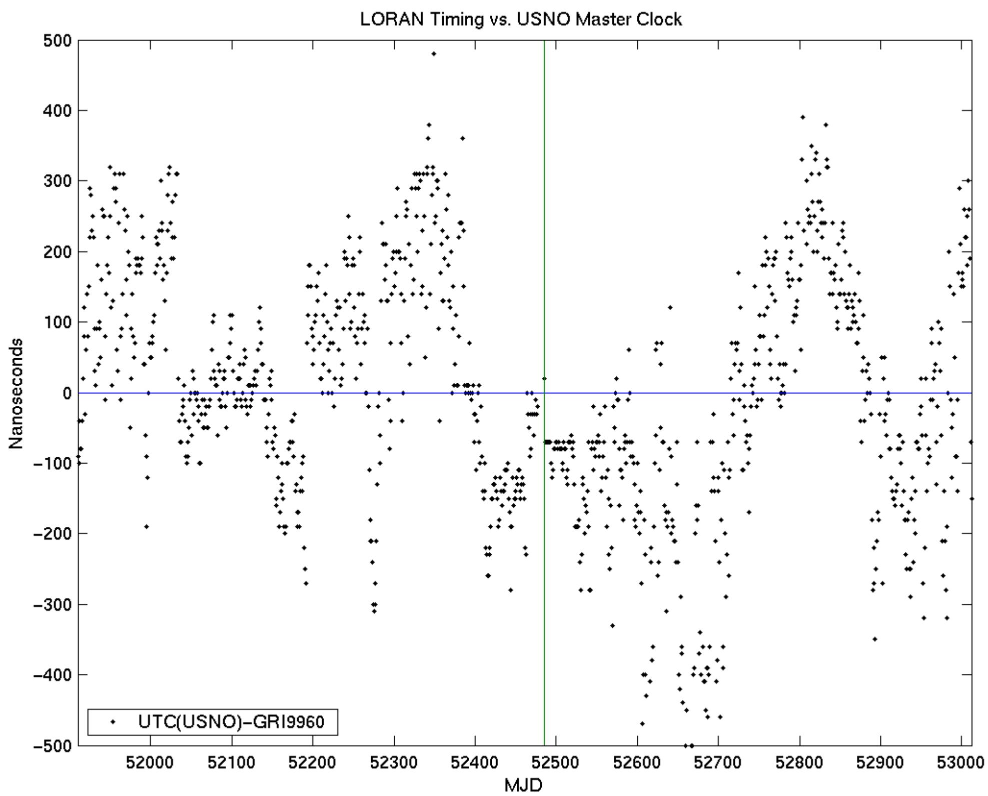

Figure 3. Timing performance of the LORAN chain GRI 9960 monitored from the USNO's Washington, DC facility, from January 2001 to December 2003. On MJD 52484, the computer system was upgraded. Note that the data are noisier and systematically offset during winter months.

GPS is an extremely important vehicle for distributing UTC (USNO). This is achieved by a daily upload of GPS data to the Second Space Operations Squadron (2SOPS), where the Master Control Station uses the information to steer GPS Time to UTC (USNO) and to predict the difference between GPS Time and

UTC (USNO) in subframe 4, page 18 of the broadcast navigation message. GPS Time itself was designed for use in navigational solutions, and last year the RMS of the difference of its daily average values with UTC (USNO) was about 4 ns. As shown in Figure 4, users who need tighter access to UTC (USNO) can achieve 1.3 ns RMS by applying the broadcast corrections. For subdaily measurements, it is a good idea, if possible, to examine the age of each satellite's data so that the most recent correction can be applied.

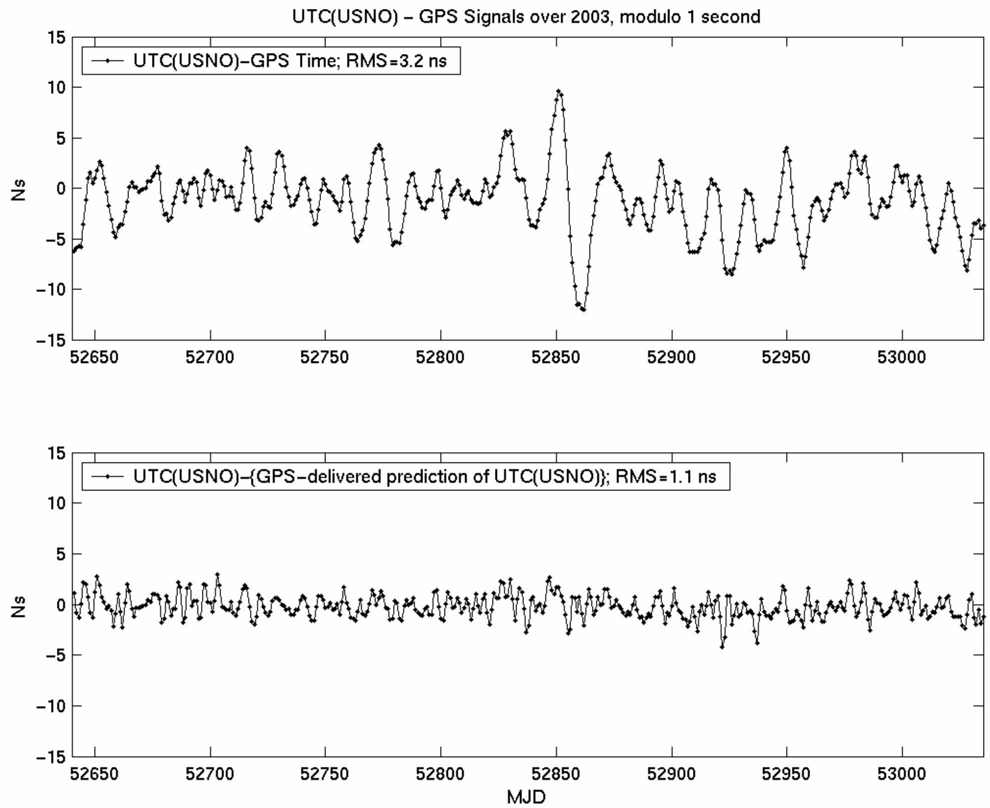

Figure 4. Daily averages of UTC (USNO) minus GPS Time and UTC minus GPS's delivered prediction of UTC (USNO) over 2003.

Figure 5 shows the RMS stability of GPS Time and that of GPS's delivered prediction of UTC (USNO) as a function of averaging time. Note that RMS corresponds to the component of the "Type A" (random) component of a user's achievable uncertainty.

Figure 6 shows the RMS of frequency accuracy and the frequency stability as measured by the Allan deviation (ADEV) over the same time period as Figure 5. The ADEV is shown for comparison; however, there is little justification for its use, since the measured quantity is stationary. In this case, the sample standard deviation is not only unbiased, it is the most widely accepted estimator of the true deviation. Improved performance with respect to the predictions of the USNO Master Clock's frequency can be realized if the most recently updated navigation messages are used in the data reduction.

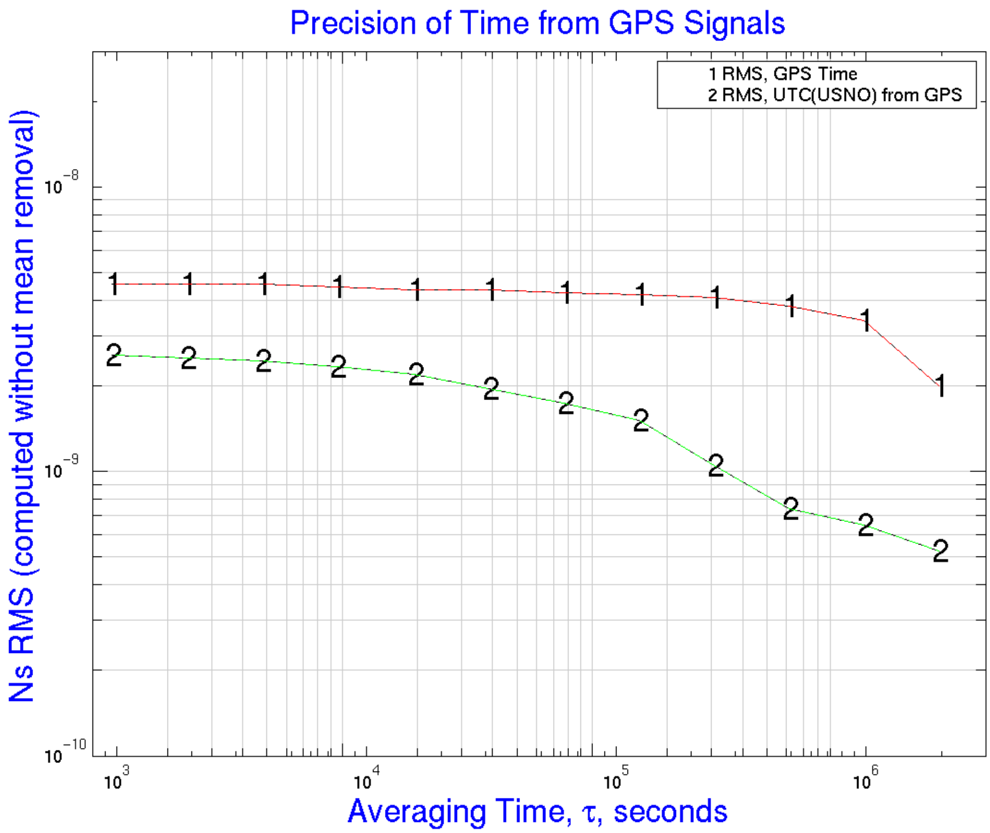

Figure 5. The precision of GPS Time and of GPS's delivered prediction of UTC (USNO), using TTR-12 data from 11JUL02 to 9JAN04, measured by the attainable external precision (RMS, mean not removed) as a function of averaging time, and referenced to UTC (USNO). Improved performance in the predictions of UTC (USNO) could be realized if only the most recently updated navigation messages are used. The attainable accuracy is the precision degraded by the error of the user's calibration relative to the USNO GPS receivers.

Since 9 July 2002, the official GPS Precise Positioning Service (PPS) monitor data have been taken with the TTR-12 GPS receivers, which are all-in-view and dual-frequency **[10]**. Our standard setup includes temperature-stable cables and flat-passband, low-temperature-sensitivity antennas. In addition, we have upgraded our single-frequency Standard Positioning Service (SPS) receivers from single-channel TTR-6 to multi-channel BIPM-standard Motorola units, and we are calibrating and evaluating temperature-stabilizing circuits. Operational antennas are installed on a 4-meter-tall structure built to reduce multipath by locating GPS antennas higher than the dome on our roof (Figure 7).

We have also funded the development of a beam-steered antenna, which we hope will eliminate multipath effects directly (Figure 8 and **[11]**). This is scheduled for delivery in early 2004.

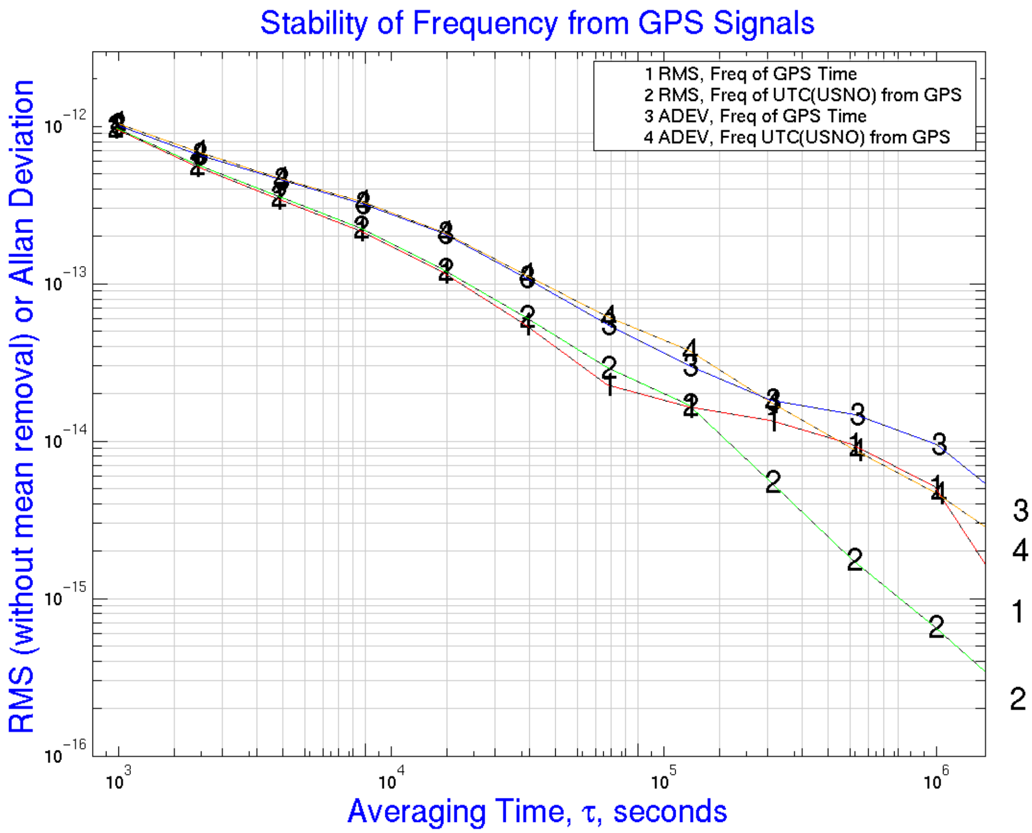

Figure 6. RMS (mean not removed) frequency external precision and the frequency stability, as measured by the Allan deviation, of GPS Time and for GPS's delivered prediction of UTC (USNO), using TTR-12 data from 11JUL02 to 9JAN04. Reference frequency is that of UTC (USNO).

The low-noise and all-in-view capabilities of the TTR-12's make it possible to contemplate increasing the frequency of our daily GPS monitor informational uploads to 2SOPS at Schriever AFB from daily to perhaps every 15 minutes. This should improve the stability of GPS's delivered prediction of UTC (USNO) considerably, and the stability of GPS Time as well. One issue we have not resolved is how to ensure the robustness of an automated system, but it is clear that a large part of the answer will be in multiple hardware arrangements.

Although not directly required by frequency transfer users, all users ultimately benefit from calibrating a time transfer system, because repeated calibrations are the best way to verify long-term precision. For this reason, we are working with the U.S. Naval Research Laboratory (NRL), the BIPM, and others to establish absolute calibration of GPS receivers **[12]**. Although we are always trying to do better, bandpass dependencies, subtle impedance-matching issues, power-level effects, and even multipath within anechoic test chambers could preclude significant reduction of 2.5 ns 1-sigma errors at the L1 and L2 frequencies, as reported in **[13]**. Since this error is largely uncorrelated between the two GPS frequencies, the error in ionosphere-corrected data becomes 6.4 ns. Experimental verification by side-by-side comparison contributes an additional square root of two. For this reason, it seems that relative calibration, by means of traveling GPS receivers, is a better operational technique. As always, care must be taken that there are no systematic multipath differences between antennas. We strongly support the

BIPM's relative calibration efforts for geodetic GPS receivers, and in particular are looking forward to comparisons with the multipath-free TWSTT calibrations.

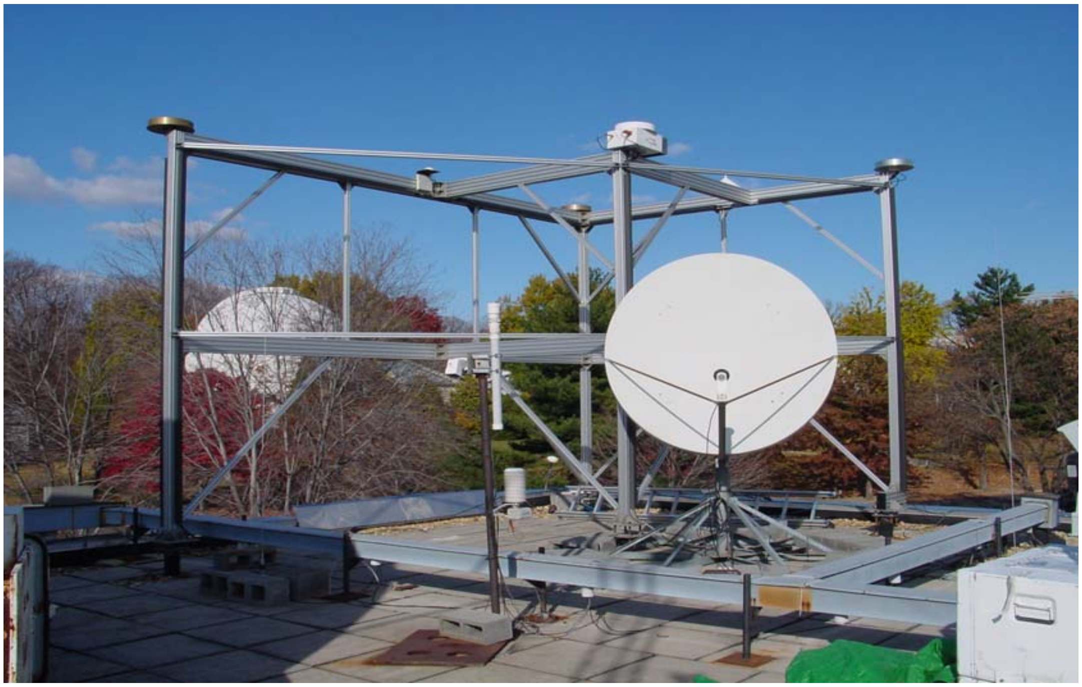

Figure 7. GPS antenna mount, now operational for GPS monitoring, has reduced multipath by roughly a factor of 3. Right of center is a directional antenna used to monitor WAAS signals.

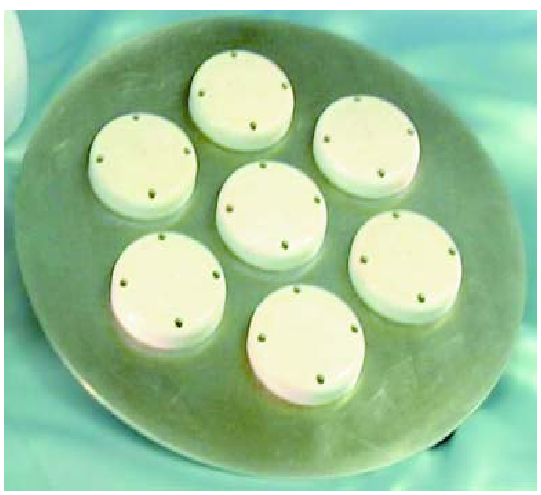

Figure 8. A seven-element HAGR antenna array **[11]**. As of this writing, the system has not been delivered to or tested by the USNO.

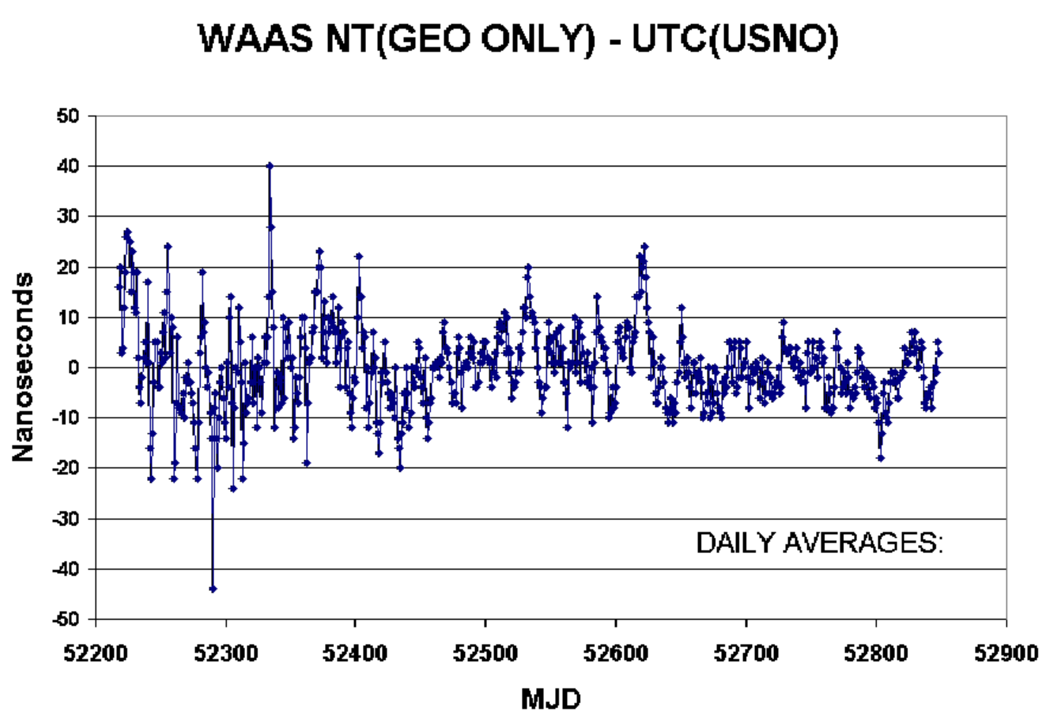

Figure 9. Improvement in WAAS Network Time, as measured using only transmissions from geostationsary satellite observations. Data are daily averages shifted to be zero-mean.

This year the Wide-Area Augmentation System (WAAS) became operational. We have been collecting data on WAAS network time (WNT), and Figure 9 shows how that time has improved over the past few years. The data shown here extract WNT using only the geostationary satellite, and are not directly calibrated. Daily averages generated by averaging WNT with WAAS-corrected time from GPS satellites are very similar. WNT obtained by narrow-beam antenna, such as shown in Figure 7, may be the optimal solution for a non-navigational user for whom interference is a problem or jamming may be a threat.

The most accurate means of operational long-distance time transfer is TWSTT **[14]**, and the USNO has strongly supported the BIPM's switch to TWSTT for TAI generation. We plan to calibrate and recalibrate our TWSTT with 20 sites in the coming year, and in particular to maintain the calibration the transatlantic link with the PTB, which is being reported on at this conference as a separate paper **[15]**. Our calibration van (Figure 10) happened to be close enough to San Diego at this time that we have brought it here for a demonstration. Although intended mostly for operation within the continental United States (CONUS), it is small enough to fit on two different types of military transport planes. It also has an improved satellite-finding system and can be upgraded to simultaneously do TWSTT between two sites operating at two different frequencies. For improved robustness, we have begun constructing loop-back setups at the USNO and developed temperature-stabilizing equipment to test on some of our outdoor electronics packages.

Figure 9. Mobile Earth Station for TWSTT calibration has been driven 18,000 miles this year. Small enough to be carried on a C141 military transport plane, it could be equipped to serve as a hop-link by communicating through two different satellites and/or frequencies simultaneously. Its automated pointing system makes it easy to find a satellite in the field. In the background, one can see a functional copy of the Time Ball originally built to transfer time to ships sailing up the Potomac River.

The Time Service Department of the USNO has also actively pursued development of GPS carrier-phase time transfer, in cooperation with the International GPS Service (IGS). With assistance from the Jet Propulsion Laboratory (JPL), the USNO developed continuous filtering of timing data and showed that it can be used to greatly reduce the day-boundary discontinuities in independent daily solutions without introducing long-term systematic variations **[16]**. Working with the manufacturer, the USNO has helped to develop a modification for the TurboRogue/Benchmark receivers, which preserve timing information through receiver resets. Using IGS data, the USNO has developed a timescale that is now being tested as a possible IGS product **[17]**. The USNO is currently contributing to real-time carrier-phase systems run by JPL/NASA **[18]** and the Canadian real-time NRCan networks **[19]**.

The continuous real-time sampling by highly precise systems will reach a climax when the USNO-DC becomes a full-fledged GPS monitor site, in cooperation with the National Geospatial-Intelligence Agency (NGA). This is currently scheduled to happen late in 2004 as part of the Accuracy Improvement Initiative (AII). We anticipate that NGA will install improved GPS receivers so that we could provide time directly to GPS, in addition to the frequency we currently provide to the Schriever Monitor Station, through our AMC.

V. ROBUSTNESS, AND MORE ROBUSTNESS

The most common source of nonrobustness in our systems is the occasional failure of our environmental chambers. In order to minimize such variations, and to house our fountain clocks, we are seeking funding for a new building. Our design calls for it to be partially underground, with no large internal heat sources, and thermal control generated by air piped in from either of two immediately adjacent buildings, whose systems are themselves redundantly generated. We expect a funding decision this year, and a building start date that could be as early as 2005.

Every aspect of the Master Clock requires dependable power, and we rely upon an uninterruptible power system (UPS) fed by two external power feeds, each one capable of supplying sufficient power. Should they both fail, we have two independent sets of battery backups, either one of which can supply power to essential systems for at least 40 minutes. However, we only need them to work for the few minutes required for our two diesel generators to power up, either of which can cover the load for several days using available fuel. Should all this fail, we have local batteries at the clocks, which will last another 8 hours. To further save power, we do not use the UPS for computer terminals, room lights, and nonessential equipment. Although we have never experienced a complete failure of this system, most of the components have failed at least once. In 2003, we installed a third external power feed to give added redundancy. Although the installation was completed in time, it fortunately proved unnecessary to protect against Hurricane Isabel, which passed over our Washington facility without damaging the Master Clock or our time transfer systems.

Even instrumental calibration requires robustness. For our calibrated TWSTT service, we recommend the instrumental calibration be repeated every 6 months, although the changes in calibration are almost always subnanosecond. Similar recalibrations of GPS equipment are common in the international timing community.

The common theme in all our operations and improvements is reliance upon multiple parallel redundant systems continuously operated and monitored. Such a scheme can be no more reliable than the monitoring process. For this reason, we have also ordered the parts to upgrade our computers. The scheme, due for completion in 2004, envisions two interchangeable computers in two different buildings. Each would be capable of carrying the full load of our operations and sensing when the other has failed so it can instantly take control. Each computer could access data continuously being stored in either of two mirrored disk arrays in the two buildings, and each of those disk arrays has redundant storage systems so that three components would have to fail before data are lost. In addition, we will continue our daily tape backup of all data, and of course maintain a restrictive firewall policy. To supplement the automated system, we have installed a password-protected Web-based monitoring system so that any employee who has access to the Internet can check the health, documentation, and status of our key systems at any time.

VI. ROBUSTNESS FOR THE USER

Just as the USNO has emphasized robustness and calibration throughout its operations, it is equally important for the users to ensure the robustness of their systems.

A common problem occurs with inadequate system calibration. Failure of an uncalibrated component and its replacement by another equally uncalibrated component can result in a catastrophic failure. A single calibration itself can be suspect, as equipment can fail gradually or the calibration itself could have a subtle error. We have seen these things happen more than once.

Equally important is robustness for connectivity to one's timing reference. While GPS is often more than adequate as a time-delivery or navigational system, it is not immune to failure. Interference or jamming could occur just at the time it is needed most. Reliance upon the Wide Area Augmentation Service (WAAS), through a directional antenna, LORAN, or TWSTT for time transfer could provide an important backup for many users.

VII. DISCLAIMER

Although some manufacturers are identified for the purpose of scientific clarity, the USNO does not endorse any commercial product nor does the USNO permit any use of this document for marketing or advertising. We further caution the reader that the equipment quality described here may not be characteristic of similar equipment maintained at other laboratories, nor of equipment currently marketed by any commercial vendor.

VIII. ACKNOWLEDGMENTS

We would like to thank the staff of the USNO Time Service Department for their dedication and efforts on behalf of the Master Clock.

REFERENCES

[1] R. Tjoelker, J. Prestage, P. A. Koppang, and T. B. Swanson, 2003, *"Stability Measurements of a JPL Multi-pole Frequency Standard at the USNO,"* in Proceedings of the 2003 IEEE International Frequency Control Symposium & PDA Exhibition Jointly with the 17th European Frequency & Time Forum (EFTF), 5-8 May 2003, Tampa, Florida, USA (IEEE Publication 03CH37409C), pp. 1066-1072.

[2] L. A. Breakiron, 1992, *"Timescale Algorithms Combining Cesium Clocks and Hydrogen Masers,"* in Proceedings of the 23rd Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 3-5 December 1991, Pasadena, California, USA (NASA Conference Publication 3159), pp. 297-305.

[3] D. N. Matsakis, M. Miranian, and P. A. Koppang, 2000, *"Alternative Strategies for Steering the U.S. Naval Observatory (USNO) Master Clock,"* in Proceedings of the ION 56th Annual Meeting, 26-28 June 2000, San Diego, California, USA (Institute of Navigation, Alexandria, Virginia), pp. 791-795.

[4] D. N. Matsakis, M. Miranian, and P. A. Koppang, 2000, *"Steering the U.S. Naval Observatory (USNO) Master Clock,"* in Proceedings of 1999 ION National Technical Meeting, 25-27 January 2000, San Diego, California, USA (Institute of Navigation, Alexandria, Virginia), pp. 871-879.

[5] P. A. Koppang and D. N. Matsakis, 2000, *"New Steering Strategies for the USNO Master Clocks,"* in Proceedings of the 31st Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 7-9 December 1999, Dana Point, California, USA (U.S. Naval Observatory, Washington, D.C.), pp. 277-284.

[6] J. G. Skinner and P. A. Koppang, 2002, *"Effects of Parameter Estimation and Control Limits on Steered Frequency Standards,"* in Proceedings of the 33rd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 27-29 November 2001, Long Beach, California, USA (U.S. Naval Observatory, Washington, D.C.), pp. 399-405.

[7] L. A. Breakiron and D. N. Matsakis, 2001 *"Performance and Characterization of USNO Clocks,"* in Proceedings of the 32nd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 28-30 November 2000, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 269-288.

[8] P. A. Koppang, J. Skinner, and D. Johns, 2004, *"Application of Control Theory in the Formation of a Timescale,"* in these Proceedings, pp. 319-325.

[9] D. Matsakis and H. Chadsey, 2003, *"Time for Loran,"* in Proceedings of the 31st Annual Convention and Technical Symposium of the International Loran Association, 27-30 October 2002, Washington, D.C., USA (International Loran Association, Santa Barbara, California), *http://www.loran.org/Meetings/Meeting2002/ILA2002CDFiles/A-Index/ HTMLBrowserIndex.htm*

[10] M. Miranian, E. Powers, L. Schmidt, K. Senior, F. Vannicola, J. Brad, and J. White, 2001, *"Evaluation and Preliminary Results of the New USNO PPS Timing Receiver,"* in Proceedings of the 32nd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 28-30 November 2000, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 79-90.

[11] A. Brown, N. Gerein, and E. Powers, 2002, *"Test Results from a Digital P (Y) Code Beamsteering GPS Receiver Designed for Carrier-Phase Time Transfer,"* in Proceedings of ION-GPS 2001, 11-14 September 2001, Salt Lake City, Utah, USA (Institute of Navigation, Alexandria, Virginia), pp. 2238-2245.

[12] J. White, R. Beard, G. Landis, G. Petit, G., and E. Powers, 2001, *"Dual Frequency Absolute Calibration of a Geodetic GPS Receiver for Time Transfer,"* in Proceedings of the 15th European Frequency and Time Forum (EFTF), 6-8 March 2001, Neuchâtel, Switzerland (Swiss Foundation for Research in Microtechnology, Neuchâtel), pp. 167-172.

[13] P. Landis and J. White, 2003, "Limitations of GPS Receiver Calibration," in Proceedings of the Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 3-5 December 2002, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 325-332.

[14] D. Kirchner, 1999, *"Two Way Satellite Time and Frequency Transfer (TWSTFT),"* **Review of Radio Science** (Oxford Science Publications), 27-44.

[15] D. Piester, A. Bauch, J. Becker, T. Polewka, A. McKinley, and D. Matsakis, 2004, *"Time Transfer Between USNO and PTB: Operation and Results,"* in these Proceedings, pp. 59-69.

[16] D. Matsakis, K. Senior, and P. Cook, 2002, "Comparison of Continuously Filtered GPS Carrier Phase Time Transfer with Independent GPS Carrier-Phase Solutions and with Two-Way Satellite Time Transfer," in Proceedings of the 33rdAnnual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 27-29 November 2001, Long Beach, California, USA (U.S. Naval Observatory, Washington, D.C.), pp. 63-87.

[17] K. Senior, P. A. Koppang, D. Matsakis, and J. Ray, 2001, *"Developing an IGS Time Scale,"* in Proceedings of the IEEE & PDA Exhibition International Frequency Control Symposium, 6-8 June 2001, Seattle, Washington, USA (IEEE Publication 01CH37218), pp. 211-218.

[18] E. Powers, K. Senior, Y. Bar-Server, W. Bertiger, R. Muellerschoen, and D. Stowers, 2002, *"Real Time Ultra-Precise Time Transfer to UTC Using the NASA Differential GPS System,"* in Proceedings of the 2002 European Frequency and Time Forum (EFTF).

[19] F. Lahaye, P. Collins, P. Héroux, M. Daniels, and J. Popelar, 2002, *"Using the Canadian Active Control System (CACS) for Real-Time Monitoring of GPS Receiver External Frequency Standards,"* in Proceedings of ION-GPS 2001, 11-14 September 2001, Salt Lake City, Utah, USA (Institute of Navigation, Alexandria, Virginia), pp. 2220-2228.

[20] W. Lewandowski and P. Moussay, 2002, *"Determination of the Differential Time Corrections for GPS Time Equipment Located at the OP, IEN, ROA, PTB, NIST, and USNO,"* Rapport BIPM-2002/02.