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Time and Frequency Activities at the U.S. Naval Observatory for GNSS

Demetrios Matsakis
US Naval Observatory/Washington DC/USA
Phone: (202) 762-1587 Fax: (202) 762-1511 Email: Demetrios.Matsakis@usno.navy.mil

ABSTRACT

The U. S. Naval Observatory (USNO) has provided timing for the U.S. Department of Defence since 1830 and, in cooperation with other institutions, has also provided timing for the United States and the international community. The data used to generate UTC(USNO) are based upon about 70 HP5071cesiums and 24 hydrogen maser frequency standards located in three buildings at two sites, with a fourth building being made operational. 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. Several improvements are underway to meet our anticipated future demands, including requirements for GPS III and for interoperability between GPS and cooperating GNSS systems such as Galileo and QZSS. Our goal is to achieve subnanosecond timing precision in a thoroughly robust manner, and this requires improved frequency standards, physical facilities, electronic infrastructure, algorithms, and methodologies. Beyond this comes the need to improve all modes of time transfer, including carrier phase time transfer technology. Bringing each of these about is a matter of intense effort, which will be described.

KEYWORDS: Time, Frequency, GPS, Galileo

1. INTRODUCTION

The most important part of the USNO Time Service Department is its staff, which currently consists of 27 positions. Of these, the largest group, almost 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 working to develop new ones.

2. Timescale Operations and Methodology

The core stability of USNO time is based upon the clock ensemble. We currently have 69 HP5071 cesium clocks made by Hewlett-Packard/Agilent/Symmetricom, 4 cesium CsIII-EP clocks made by Datum/Symmetricom, and 24 cavity-tuned "Sigma-Tau/Datum/Symmetricom" hydrogen maser clocks, which are located in two Washington, D.C. buildings and 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%. The timescale is based only upon the Washington, D.C., clocks. On June 7, 2007, 53 standards were weighted in the primary timescale computations.

The clock outputs are sent to the measurement systems using cables that are phase-stable and of low temperature coefficient and where possible all the connectors are SMA (screw-on). The 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) RMS, which is less than the variation of a cesium clock over an hour. Because the 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 magnetic tape.

Before averaging data to form a timescale, real-time and postprocessed clock editing is accomplished by analysing deviations in terms of frequency and time; all the clocks are detrended against the average of the detrended cesiums (Breakiron, 1992). A maser average represents the most precise average in the short term, and the detrending ensures that it is equivalent to the cesium average over periods exceeding a few months. A.1 is the USNO's operational timescale; it is dynamic in the sense that it weights recent maser and cesium data by their inverse Allan variance at an averaging time (tau) equal to the age of the data. Plotable files of both A.1 and the maser mean are available below http://tycho.usno.navy.mil.

UTC(USNO) is created by frequency-steering the A.1 timescale to UTC using a steering strategy called "gentle steering" (Matsakis *et al.* 2000a Matsakis *et al*. 2000b, Koppang and Matsakis, 2000), which minimizes the control effort used to achieve the desired goal, although at times the steers are so small that they are simply inserted. To realize UTC(USNO) physically, 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). The AOG creates its output from the signal of a cavity-tuned maser steered to a timescale that is itself steered to UTC (Koppang *et al.*, 2004). The MC has a backup maser and an AOG in the same environmental chamber. On 29 October 2004, we changed the steering method so that state estimation and steering are achieved hourly with a Kalman filter with a gain function as described in Skinner *et al.* (2005). A second master clock (mc), duplicating the MC, is located in an adjacent chamber. 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 operations is the USNO Alternate Master Clock (AMC), located at Schriever AFB in Colorado, adjacent to the GPS Master Control Station. The AMC's mc is kept in close communication with the MC through use of Two-Way Satellite Time Transfer (TWSTT) and modern steering theory (Skinner and Koppang, 2002). The difference is often less than 1 nanosecond (ns). In 2005, we installed the hardware for replacement and upgrade of the switched and low-noise measurements systems, the dc backup power systems, and the computer infrastructure. We have not yet integrated the three masers and 12 cesiums at the AMC into the USNO's Washington, D.C., timescale, but it remains a possibility that carrier-phase GNSS techniques can be made reliable and accurate enough for this purpose.

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 (Breakiron and Matsakis, 2001), we have widened the definition of a "good clock" and are recharacterizing the clocks less frequently (Skinner and Koppang, 2007). We are also continuing to work on developing algorithms to optimally combine the short-term precision of the masers with the longer-term precision of the cesiums and the accuracy of International Atomic Time (TAI) itself, which is derived from the primary frequency standards operated by other institutions. It is planned to implement an algorithm that 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 *Circular T* (Koppang *et al.*, 2007). The steered cesium-only timescale would either be based upon the Percival Algorithm (Breakiron, 1992) or a Kalman-filter. Individual masers could be steered to the cesium-only timescale before being averaged to create the maser-only timescale.

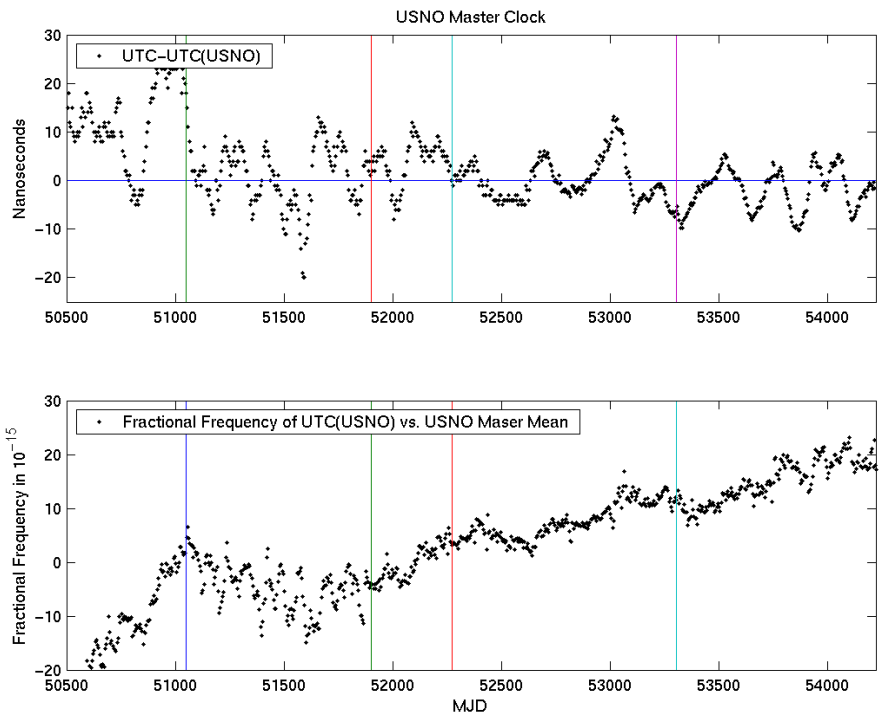
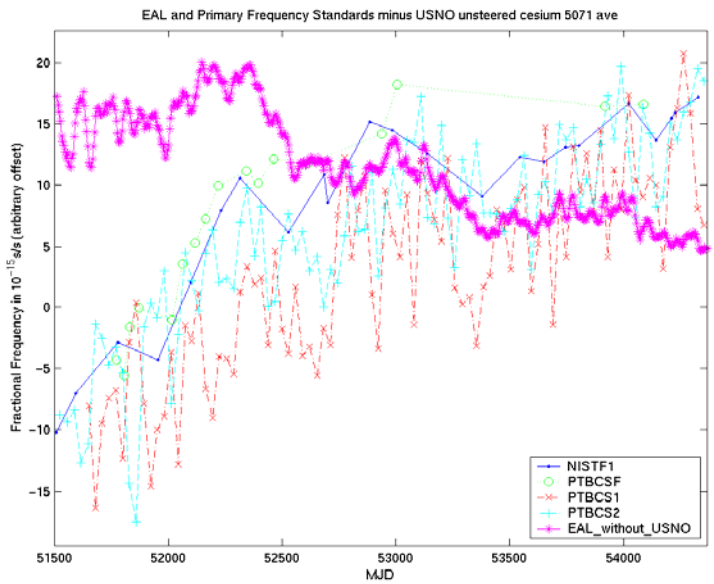


Figure 1. Interplay between the time and fractional frequency variations of the USNO Master Clock, from February, 1997 to the present.

Figure 1 shows how UTC(USNO) has compared to UTC and also how its fractional frequency has compared to the unsteered maser mean, relative to an overall constant offset. The top plot of Figure 1 is UTC - UTC(USNO) from the International Bureau of Weights and Measure's (BIPM's) Circular T. The lower plot shows the fractional frequency of the Master Clock referenced to the maser mean, after a constant has been removed. The rising curve previous to MJD 51000 is due to the gradual introduction of the 1.7×10^{-14} blackbody correction to the primary frequency measurements (*Circular T* 100-123). 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. Hourly steers were implemented on 53307. Vertical lines indicate the times of these changes. UTC(USNO) has stayed within 5 ns RMS of UTC for 5 years.

Most of our users need and desire access to only UTC(USNO), which 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 the Web pages. The Web pages also provide the information needed for users who are interested in using the MC to measure absolute frequency. For those users interested mostly in frequency stability, we have made available the difference between the MC and the maser mean using anonymous ftp.



The long-term stability of the Master Clock is set by steering to UTC. The exceptional stability of the USNO's unsteered mean can also be used to attempt to diagnose issues involving the long-term stability of UTC itself. The dense purple line in Figure 2 shows the fractional frequency difference between our unsteered cesium average and other timescales. EAL is the unsteered timescale generated by the BIPM that is steered to primary frequency standards to create UTC. Since the contribution of USNO-DC cesiums to EAL (and therefore UTC) is about 25%, the resulting diminution of the difference was allowed for by a 25% scaling. Also plotted are the unsteered cesium average fractional frequency against the SI second as measured by primary frequency standards at National Institute of Standards and Technology (NIST) and PTB. Initially, it appeared that the HP5071 beam tubes had a frequency drift compared to the primary frequency standards, however since MJD 52500 the pattern has become less clear. The differences are likely due to the contribution of masers and other high-drift clocks to TAI (Petit, 2007)

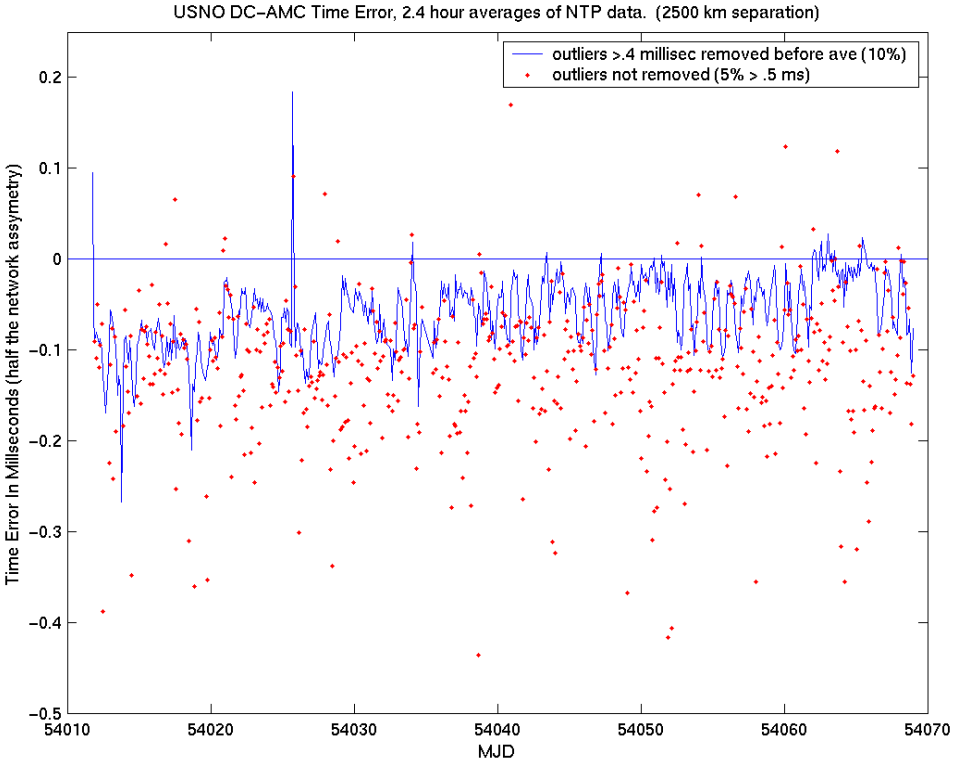


Figure 2. Fractional frequency of unsteered average of USNO-DC cesiums against EAL and against primary frequency standards. The frequencies have been shifted in the vertical direction for display, and the difference with the cesium average has been scaled to remove the contribution of USNO-DC cesiums to EAL.

In order to improve timescale operations through increased component frequency stability, the USNO is developing rubidium-based atomic fountains (Peil *et al*., 2005). Figure 3 shows the performance of the prototype fountain over a 40-day period of 2007, while housed in a room subject to several-degree temperature variations.

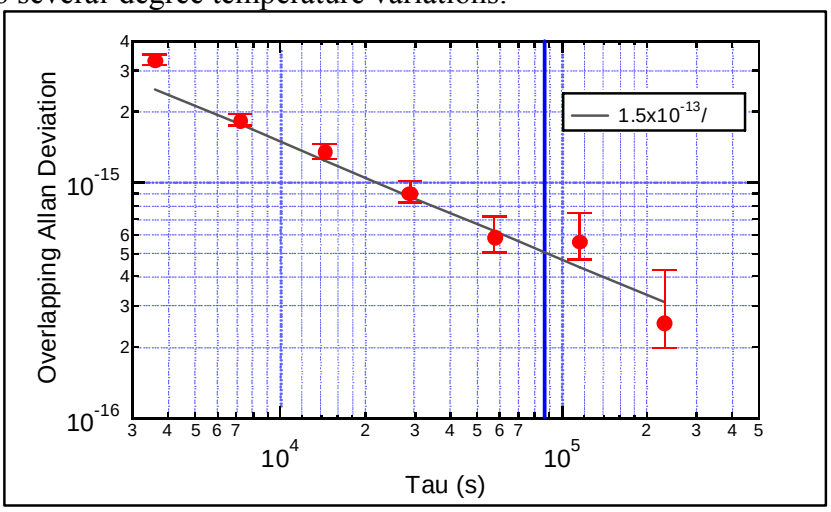


Figure 3. Performance of rubidium fountain against a USNO maser mean. The straight line segment is a fit to the inverse square-root curve expected for white frequency noise.

3. Time Transfer

Table 1 shows how many times the USNO was queried by various time-transfer systems in the past year. The fastest-growing service is the Internet service Network Time Protocol (NTP). Until recently, the number of individual requests doubled every year since the program was initiated. The billions of requests originate from several million IP addresses, some of which are known to serve thousands of secondary users. Unfortunately, in late 2004 the NTP load reached 5000 queries per second at the Washington, DC site, which saturated the Internet connections (Schmidt, 2005). Due to this saturation, perhaps a third of the NTP requests sent to the Washington site went unanswered. In August 2005, the Defense Information Services Agency (DISA) provided higher-bandwidth Internet access and the query rate increased to 6000 packet requests/second. Although the query rate has remained near this level since then, such upgrades of Internet capacity may prove insufficient to cope with the projected growth.

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

Telephone Voice-Announcer	800,000
Leitch Clock System	90,000
Telephone Modem	200,000
Web Server	850 million
Network Time Protocol (NTP)	200 billion (see text)

As an example of NTP Time Transfer, accuracy, Figure 4 shows the error between our AMC and Washington facilities, which are separated by about 2500 km.

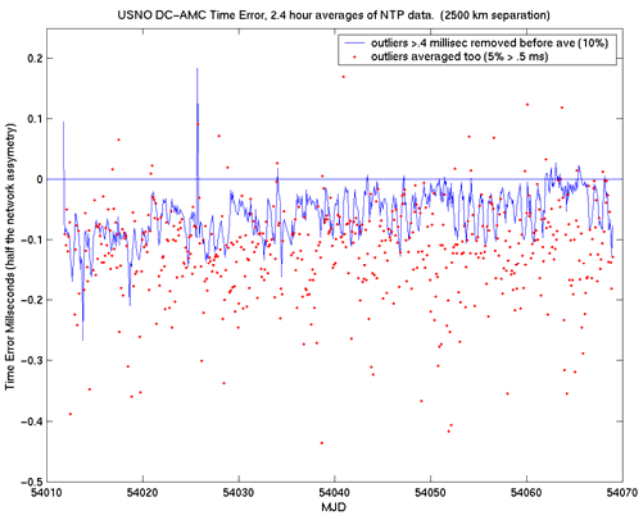


Figure 4. Observed error in NTP Time transfer between USNO-DC and USNO-AMC. Blue plot shows 0.1-day averages when the 10% of the data exceeding 0.4 msec error are removed. Red dots are simple 0.1-day averages of all the data, of which 5% exceed 0.5 ms deviation.

Greater precision is required for two services for which the USNO is the timing reference: GPS and LORAN. USNO monitors LORAN at its Washington, DC site. With some assistance from the USNO, the U.S. 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 crude check (Matsakis and Chadsey, 2003), and the USNO is pursing a collaborative effort with the Loran Support Unit (LSU) to test an Enhanced Loran (ELORAN) receiver system.

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 is not adjusted for leap seconds. As shown in Figure 5, users can achieve tighter access to UTC(USNO) 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. The continuous real-time sampling by highly precise systems was increased in 2006 when the USNO-DC became a full-fledged GPS monitor site, in cooperation with the National Geospatial-Intelligence Agency (NGA). The NGA is improving its GPS receivers, and this would make possible a supplemental means to the direct monitoring for providing time directly to GPS, both at the Washington site and at the AMC. Although the architecture of GPS III has not yet been finalized, it is likely that closer and more frequent ties between GPS Time and UTC(USNO) will be established.

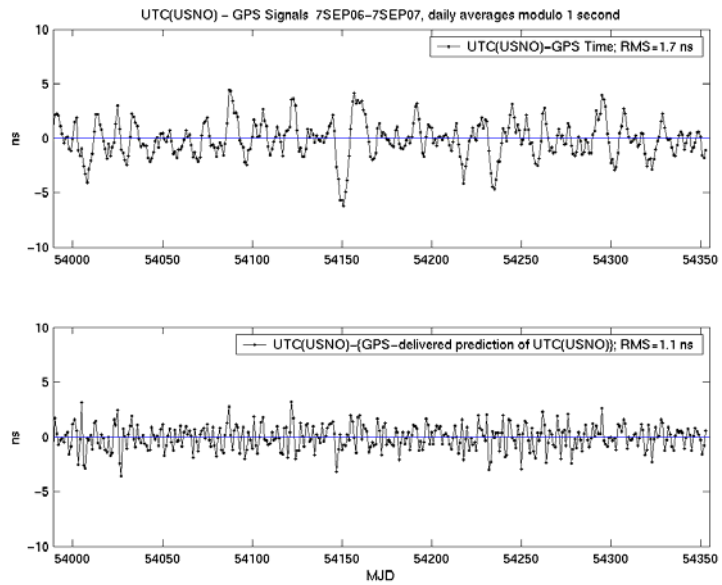


Figure 5. Recent daily averages of TTR-12 monitor data showing UTC(USNO) minus GPS Time and UTC(USNO) minus GPS's delivered prediction of UTC(USNO).

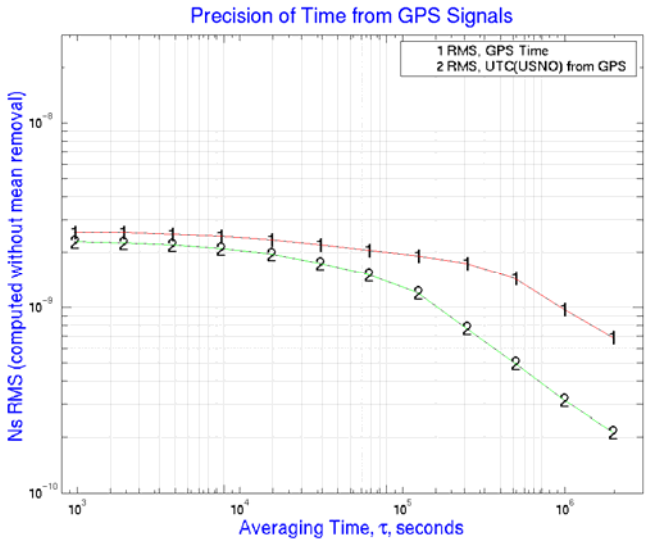


Figure 6. The precision of GPS Time and of GPS's delivered prediction of UTC(USNO), using TTR-12monitor data since 7FEB2005, measured by the attainable external precision (RMS, mean not removed) as a function of averaging time, and referenced to UTC(USNO). Improved performance in accessing UTC(USNO) could be realized if only the most recently updated navigation messages are used. The accuracy attainable over a given averaging time also depends upon the calibration of the user's receivers.

Figure 6 shows the RMS stability of GPS Time and that of GPS's delivered prediction of UTC(USNO) as a function of averaging period. Note that the RMS corresponds to the component of the "Type A" (random) component of a user's achievable uncertainty.

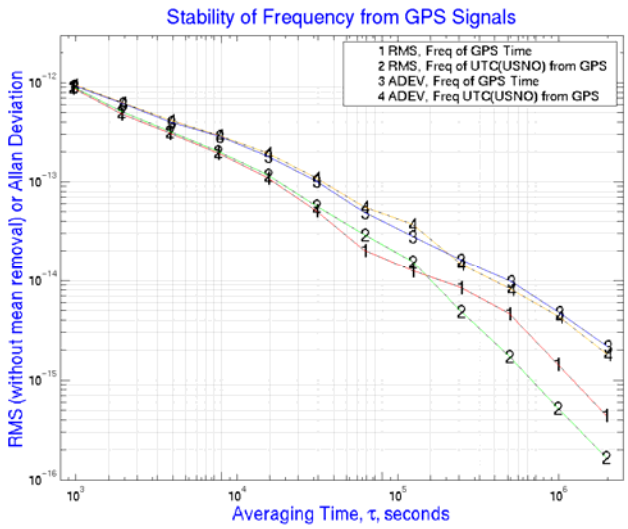


Figure 7. RMS fractional frequency external precision and the fractional frequency stability, as measured by the Allan deviation, of GPS Time and for GPS's delivered prediction of UTC(USNO), using TTR-12 data since 7FEB05. Reference frequency is that of UTC(USNO).

Figure 7 shows the RMS frequency accuracy along with the frequency stability as measured by the Allan deviation (ADEV) over the same time period as Figure 6. The ADEV is shown for comparison; however, there is little justification for its use, since the measured quantity is stationary and since in this case the RMS is unbiased. 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.

Since 9 July 2002, the official GPS Precise Positioning Service (PPS) monitor data have been taken with the TTR-12 GPS receivers, which can track up to 12 satellites on both the L1 (1575 MHz) and L2 (1227 MHz) frequencies (Miranian *et al.*, 2001). The standard setup includes temperature-stable cables and flat-passband, low-temperature-sensitivity antennas. Our single-frequency Standard Positioning Service (SPS) receivers are now the BIPM-standard "TTS" units, whose calibration (instrumental group delay) is measured in-house. Operational antennas are installed on a 4-meter-tall structure built to reduce multipath by locating GPS antennas higher than the existing structures on the roof.

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 (White *et al*. 2001). 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 Landis and White (2003). Since this error is largely uncorrelated between the two GPS frequencies, the error in an ionosphere-corrected measurement becomes 6.4 ns. Experimental verification by side-by-side comparison contributes an additional $\sqrt{2}$. For this reason, relative calibration, by means of travelling GPS receivers, is a better operational technique, provided care is 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.

The USNO has been collecting data on Wide-Area Augmentation System (WAAS) network time (WNT) vs. UTC(USNO). Daily averages generated by averaging WNT with WAAS-corrected time from GPS satellites are observed to be very similar to WNT-only averages. WNT obtained by narrow-beam antenna may be the optimal solution for a non-navigational user for whom interference is a problem or jamming may be a threat.

The USNO has been participating in discussions involving the interoperability of GPS, Galileo, QZSS, and GLONASS. In December of 2006, a Galileo monitor station was installed, and detailed plans have been made to monitor the GPS/Galileo timing offset (GGTO) (Hahn and Powers, 2006) in parallel and in concert with the Galileo Precise Timing Facilities (GPTF). The GGTO will be measured by direct comparison of the received satellite timing, and by the use of TWSTT to measure the 1-pps offset between the time signals at the USNO and GPTF. The GGTO will eventually be broadcast by both GPS and Galileo, for use in generating combined position and timing solutions. To exchange similar information with the QZSS system, plans are underway to establish a TWSTT station in Hawaii.

With the use of multiple GNSS systems, problems involving receiver and satellite biases will

become more significant. These have been shown to be related to the complex pattern of delay variations across the filtered passband, and correlator spacing. In principle, every satellite would have a different bias for every receiver/satellite combination (Hegarty *et al.*, 2005). USNO has analysed how calibration errors associated with the Timing Group Delay (TGD) bias measurements of GPS result in a noticeable offset in GPS Time vs. UTC, as measured in the *Circular T* and shown in Figure 8 (Matsakis, 2007).

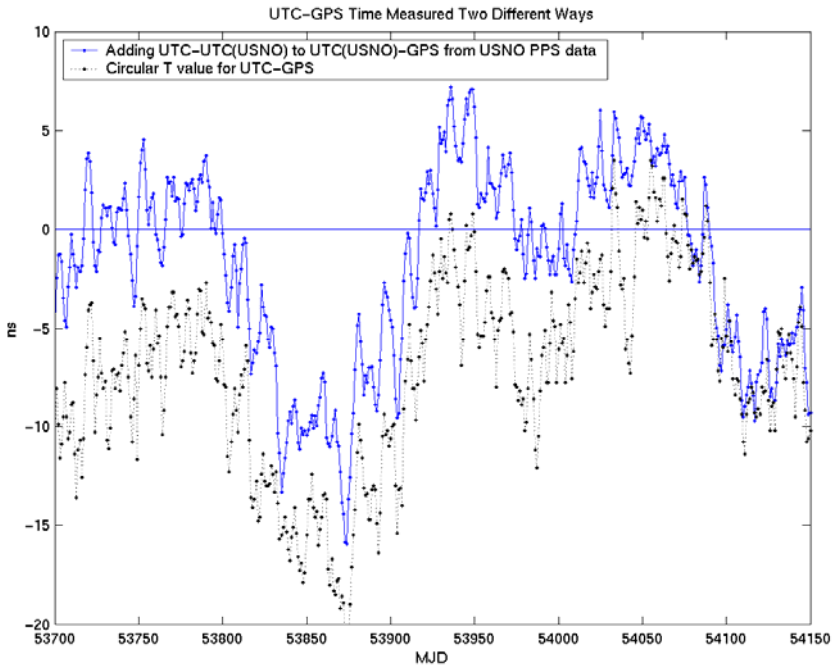


Figure 8. UTC-GPS as reported in the Circular T, and UTC-GPS inferred by subtracting UTC(USNO)-GPS from UTC-UTC(USNO). UTC(USNO)-GPS can be obtained from the satellite broadcasts, as in Figure 5 and is also measured directly at the USNO. Further details can found in Matsakis (2007).

The most accurate means of operational long-distance time transfer is TWSTT (Kirchner, 1999, Breakiron *et al.*, 2005, Matsakis *et al*., 2002) and the USNO has strongly supported the BIPM's switch to TWSTT for TAI generation. We routinely calibrate and recalibrate the TWSTT at 20 sites each year, and in particular we maintain the calibration of the transatlantic link with the Physikalisch-Technische Bundesanstalt (PTB, Braunschweig, Germany) through comparisons with observations at a second TWSTT frequency (Piester *et al.*, 2004) and with the carrier-phase GPS receivers whose IGS designations are USNO, USN3, and PTBB. For improved robustness and reduction of diurnal signals, we have set up short-baseline common-clock observations at the USNO, moved electronics indoors where possible, and developed temperature-stabilizing equipment to test on some of the outdoor electronics packages. For improved precision, we have made some efforts to develop carrier-phase TWSTT (Fonville *et al*., 2005), although it appears the most promising technology would include a frequency standard in the satellite (Takahash*i et al.*, 2004).

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, which continuously propagate past day boundaries and can be used to greatly reduce the day-boundary discontinuities in independent daily solutions without

introducing long-term systematic variations (Matsakis *et al.*, 2002). Working with the manufacturer, the USNO has helped to develop a modification for the TurboRogue/Benchmark receivers, so that they no longer lose their calibration through receiver resets or power-downs. Using IGS data, the USNO has developed a timescale that is now an IGS product (Senior *et al.*, 2001). The USNO is currently contributing data to real-time carrier-phase systems run by JPL/NASA (Powers *et al.*, 2002) and the Canadian real-time NRCan networks (Lahaye *et al.*, 2002).

While the promise of Carrier Phase GNSS for time transfer is on its way to fulfilment, one of the greatest impediments to sub nanosecond operations is receiver instabilities. For example, the receivers used at the USNO and elsewhere have exhibited both sudden and gradual delay variations at the 1 ns level (Matsakis *et al.*, 2006). All of these were designed in the 20th century, and therefore the USNO is experimenting with more modern components. Figure 9 shows the measured temperature-dependence of three recently-purchased systems, whose long-term behavior will also be scrutinized (Fonville *et al.,* in prep.). By working with manufacturers, it is possible that still more stable equipment can be developed. While several algorithms are insensitive to short-term variations of the receiver's pseudorange calibration (Matsakis *et al.*, 2002; Dach *et al.*, 2006), only human intervention in the form of calibration monitoring and recalibration can correctly account for non-transient receiver variations.

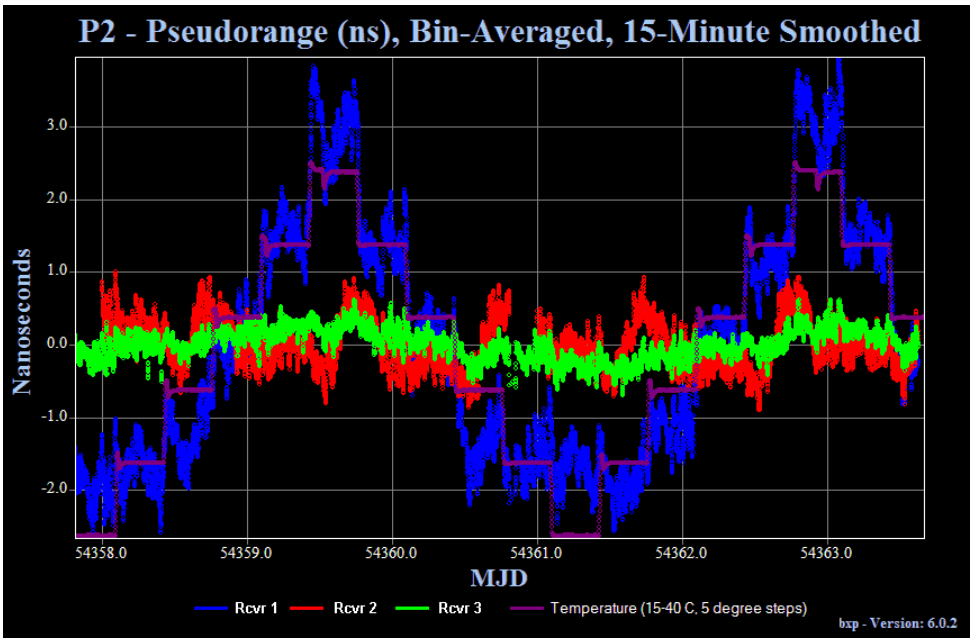


Figure 9. Sensitivity of code (pseudorange) calibration of three different receivers to temperature variations (purple) from 15 to 40 degrees C.

Despite receiver variations, it has been shown that carrier phase GPS analysis can be improved by appropriate algorithmic innovations. Frequency transfer has been shown to be achievable at a few parts in 10^{-16} if one removes the discontinuities at day boundaries, which are largely due to instabilities in the pseudorange reception (Hackman *et al.*, 2006) Simulations by Hackman and Levine (2006) have shown that, in the absence of receiver calibration variations, frequency errors due to misestimation of satellite orbits, receiver position, and other effects can be reduced still further if sufficient signal to noise exists to enable double-difference ambiguity resolution. Given these theoretical advances, we suspect that UTC's stability would be improved on all but the longest scales if the BIPM had available data from timing laboratories that was extracted from several improved receivers,

observing all available frequencies, in thermally, humidity, and multipath-optimized environments.

4. Robustness of the Master Clock and Associated Systems

The most common source of non-robustness is the occasional failure of the environmental chambers. In order to minimize such variations, and to house the fountain clocks, we are equipping a new clock building (Figure 10). The building has redundant environmental controls designed to keep the temperature and relative humidity of the clock and computer rooms constant to within 0.1 deg C and 3% relative humidity even when an HVAC unit is taken off-line for maintenance. The clocks themselves will be kept on vibrationally isolated piers. Standardized instrument racks, USNO-wide, will facilitate rapid and accurate repairs.

Figure 10. New clock building

The clocks in all DC buildings are protected by an electrical power system whose design includes multiple parallel and independent pathways, each of which is capable of supplying the full electrical power needs of the Master Clock. The components of each pathway are automatically interchangeable, and the entire system is supplemented by local batteries at the clocks that can sustain performance long enough for staff to arrive and complete most possible repairs. Although we have never experienced a complete failure of this system, most of the components have failed at least once. These failures and periodic testing give some confidence in the robustness of the system.

The common design in all the 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 create a system wherein we will have two fully real-time interchangeable and redundant computer systems in two different buildings. Each would be capable of carrying the full load of 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 do a daily tape backup of all data, and maintain a restrictive firewall policy. Other measures have also been taken.

5. 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.

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