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 since 1830 and, via DoD Directive 4650.05, is the sole source of timing for the Department of Defense. In cooperation with other institutions, the USNO also provides timing for the United States and the international community. Its Master Clock (MC) is the source of UTC (USNO), USNO's realization of Coordinated Universal Time (UTC), which has stayed within 5 ns rms of UTC since 1999 and within 3.9 ns rms in 2009. The data used to generate UTC (USNO) are based upon 60 cesium and 24 hydrogen maser frequency standards in four buildings at two sites. USNO disseminates time via voice, telephone modem, LORAN, Network Time Protocol (NTP), GPS, and Two-Way Satellite Time Transfer (TWSTT). This paper describes some of the changes being made to meet the future needs for precision, accuracy, and robustness. Further details and explanations of our services can be found online at http://www.usno.navy.mil/USNO.

I. TIME GENERATION

The most important part of USNO's Time Service Department is its staff, which currently consists of 32 positions. Of these, the largest group, about 40% of 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.

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, and 24 cavity-tuned "Sigma-Tau/Datum/Symmetricom" hydrogen maser clocks, which are located in three 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 deg C and whose relative humidities (for all masers and most cesiums) are kept constant to within 1%. The timescale is based only upon the clocks located in Washington, D.C., and this number has been gradually decreasing for various reasons. On 10 November 2009, 38 of those standards were weighted in the 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 maser clocks 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, duplicate low-noise systems measure each maser, 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 analyzing deviations in terms of frequency and time; all the clocks are detrended against the average of the best detrended cesiums **[1]**. 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 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. Plottable 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" **[2-4]**, 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 **[2-5]**. 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 **[6]**. 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 **[7]**. The difference is often less than 1 nanosecond (ns). We have not yet integrated the three masers and 12 cesiums at the AMC into USNO's Washington, D.C., 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 **[8]**, we have widened the definition of a "good clock" and are recharacterizing the clocks less frequently, and new methods of clock characterization are under development **[9]**. 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 International Atomic Time (TAI) itself, which is frequency-calibrated using the primary (fully calibrated) 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 are individually or collectively steered to a cesium-only timescale that itself is steered to UTC using the information in the Circular T **[6, 10]**. The steered cesium-only timescale is based upon a Kalman-filter **[12]**. Individual masers would be steered to the cesium-only timescale before being averaged to create the maser-only timescale.

II. STABILITY OF UTC (USNO)

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.

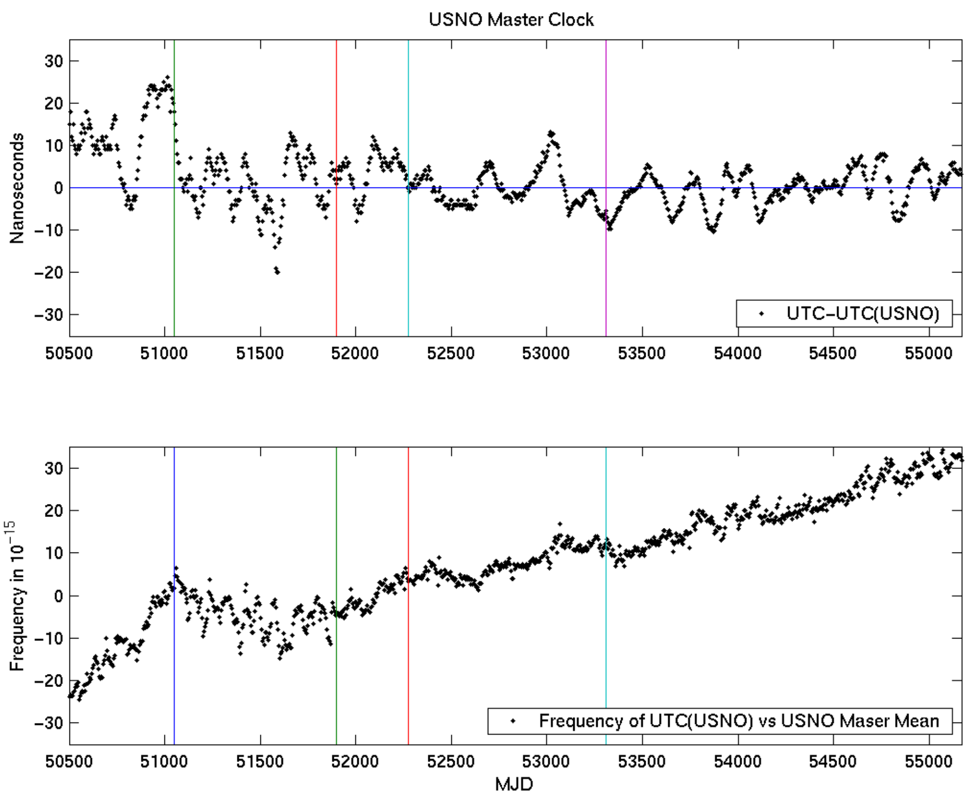

Figure 1. Interplay between the time and fractional frequency stability of the USNO Master Clock, from February, 1997 to the present.

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 difference of the Master Clock against the maser mean, derived by subtracting an arbitrary constant (for plot display) from the difference between the Master Clock and mean frequencies, measured in Hz and divided by the 5 MHz frequency of the signal-realization. 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. Hourly steers were implemented on 53307. Vertical lines indicate the times of these changes.

Figure 2 shows that the monthly stability of UTC (USNO) has decreased as the number of USNO clocks has decreased.

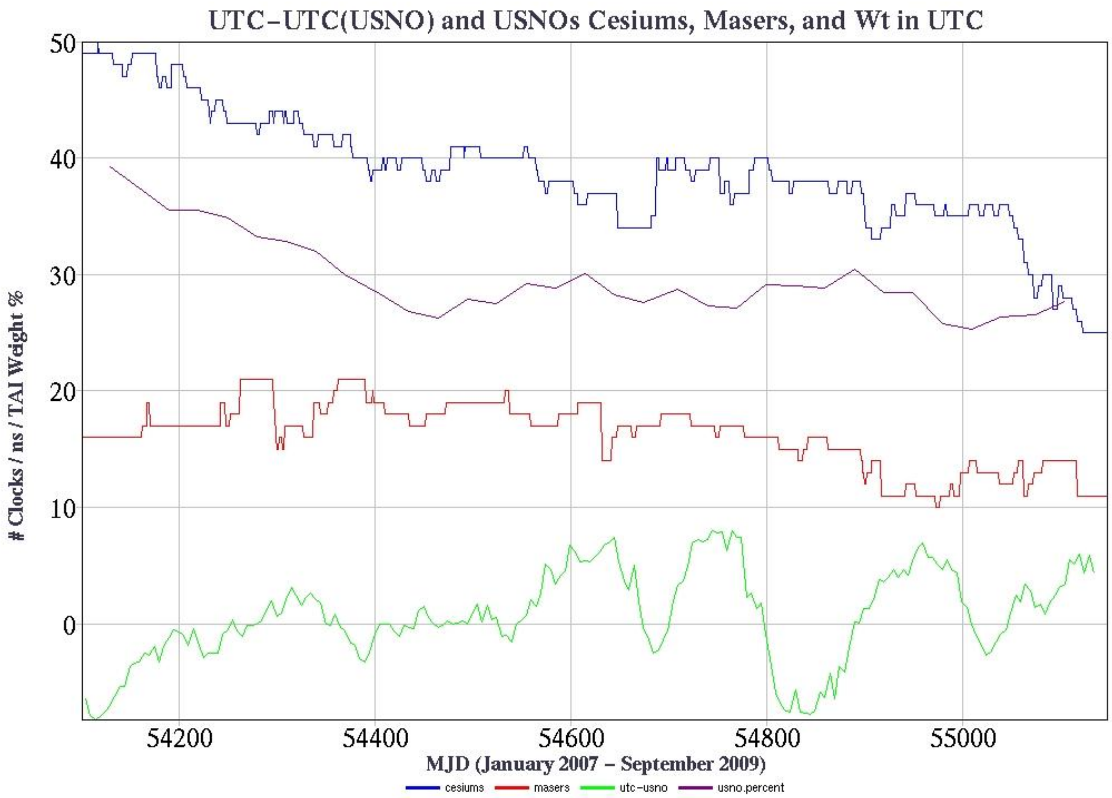

Figure 2. Recent trends, which may not be directly correlated. The highest plot is the number of USNO cesium 5071s used to compute the steering timescale. The next highest plot, solid line, is the total weight of USNO clocks in UTC generation (including AMC). The third plot is the number of cavity-tuned masers used in the USNO steering timescale, and the lowest plot is UTC – UTC (USNO).

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.

While the long-term stability of the Master Clock is set by steering to UTC, the exceptional stability of 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 3 shows the fractional frequency difference between our unsteered cesium average and EAL, which is the unsteered timescale generated by BIPM that is steered to primary frequency standards so as to create UTC. Since the contribution of the USNO-DC cesiums to EAL (and, therefore, UTC) is about 25%, the resulting reduction of the difference was allowed for by a 25% scaling. Also plotted are the unsteered cesium average fractional frequencies against the SI second as measured by primary frequency standards at National Institute of Standards and Technology (NIST) and the Physikalisch-Technische Bundesanstalt (PTB). Initially, it appeared that the HP5071 beam tubes had a very small frequency drift; 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 **[12]**.

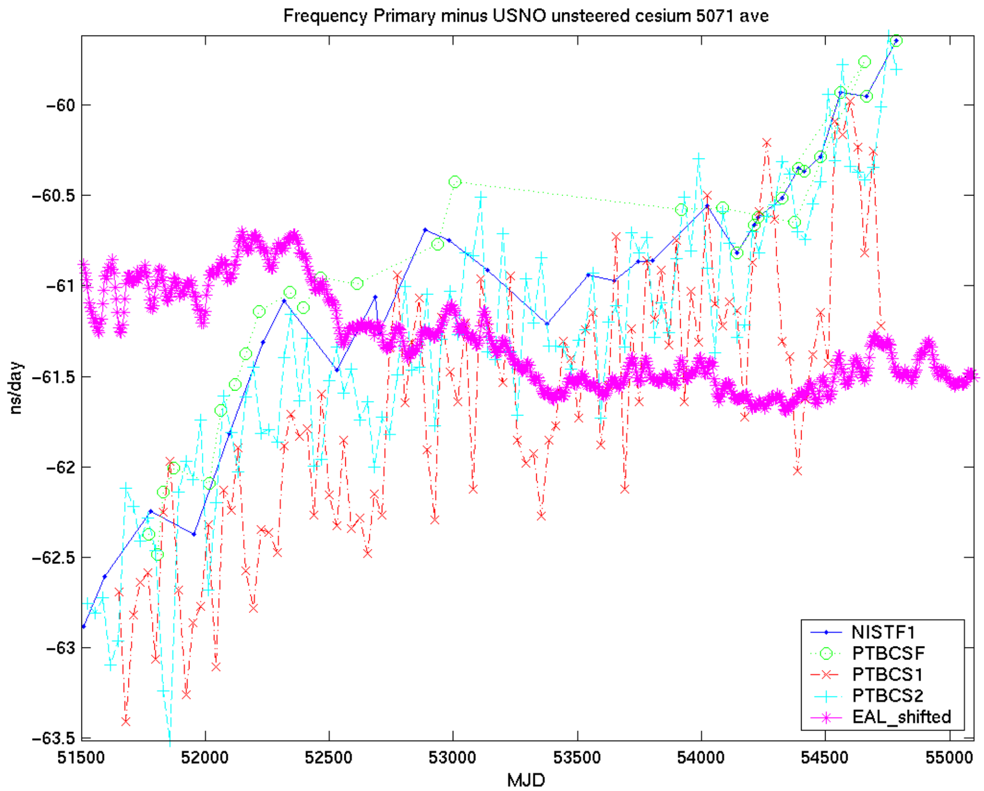

Figure 3. Fractional frequency of unsteered average of USNO-DC cesiums against that of EAL and also against several primary frequency standards. The frequencies have been shifted in the vertical direction for display, and the difference with the cesium average has been scaled in an effort to remove the contribution of USNO-DC cesiums to EAL.

In order to improve timescale operations, USNO has a staff of five developing rubidium-based atomic fountains **[13]**. Figures 4 and 5 show the performance of the prototype fountain over an 82-day period, while located in the new clock building.

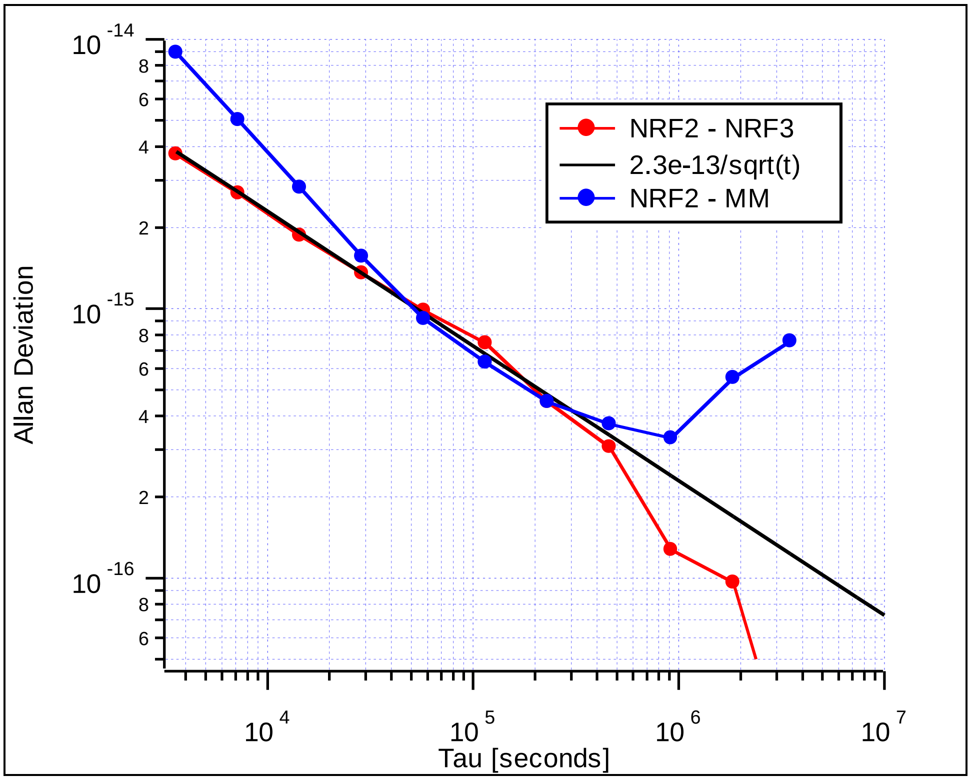

Figure 4. Performance of rubidium fountains NRF2 and NRF3 against each other, and against a USNO maser mean. The straight line segment is a fit to the inverse square-root curve expected for white frequency noise. The subdaily statistics are contaminated by switch measurement noise, while the large-tau statistics have a high uncertainty.

III. TIME TRANSFER

Table 1 shows how many times 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 2005, the number of individual requests doubled every year since the program was initiated. The billions of requests correspond to at least several million users. Unfortunately, in late 2004 the NTP load reached 5000 queries per second at the Washington, DC site, which saturated the Internet connections **[14]**. Due to this saturation, perhaps a third of the NTP requests sent to the Washington site were not responded to. In August 2005, the Defense Information Services Agency (DISA) provided higher-bandwidth Internet access and the measured query rate increased to over 5000 packet requests/second. An increase to almost 6000 requests/second was recently observed when a fourth server was added behind the load balancer. The access rate is much higher at the start of each hour. Although the query rate seems to have leveled off, future upgrades of Internet capacity may be required to cope with growth. An indication of the potential for increased demand is that late in 2008, we experienced a quadrupling of the request rate for several hours.

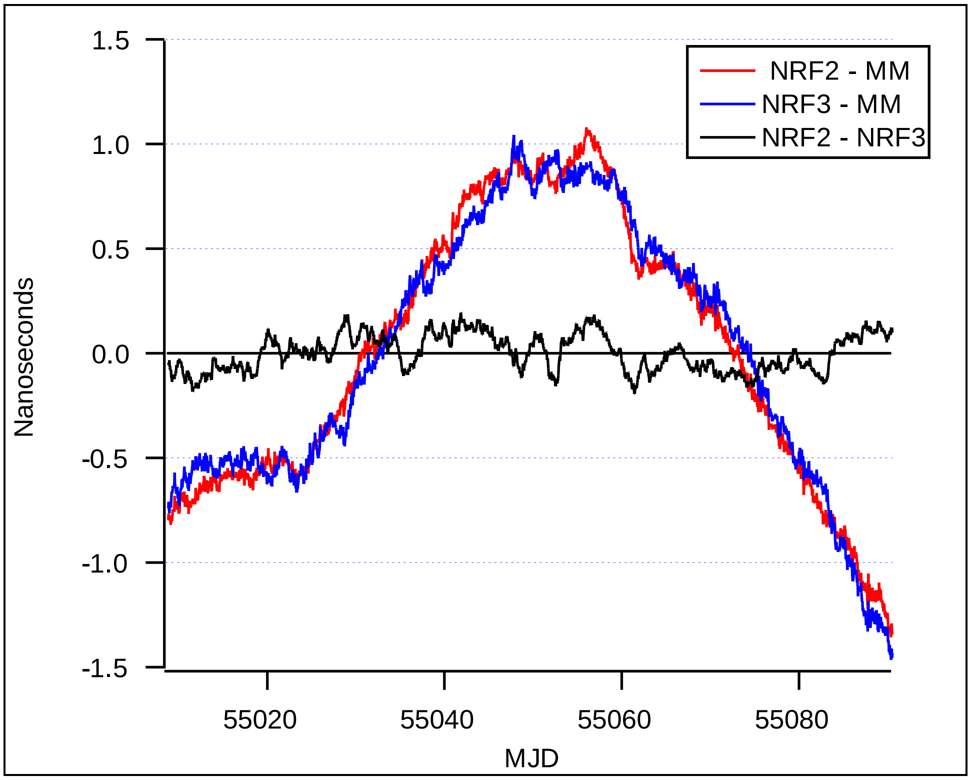

Figure 5. Slope-removed data which form the basis for the previous figure. The two rubidium fountains (NRF2 and NRF3) stay with 200 ps of each other while the USNO Maser Mean deviates by 1.5 ns from both.

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

Telephone Voice-Announcer	800,000
Leitch Clock System	90,000
Telephone Modem	2,500,000
Web Server	1500 million
Network Time Protocol (NTP)	150 billion

Our lowest precision service is our telephone voice announcer (202-7621401), which was upgraded this year to an all-digital system, which enables digital counting. Figure 6 shows very predictable patterns, as explained in the caption. The voice remains that of Fred Covington, a well-known actor whose history is given in *http://www.imdb.com*. The bias of the system was measured to be < 100 ms at the source, but this was degraded to 500 ms when sampled with a cell phone.

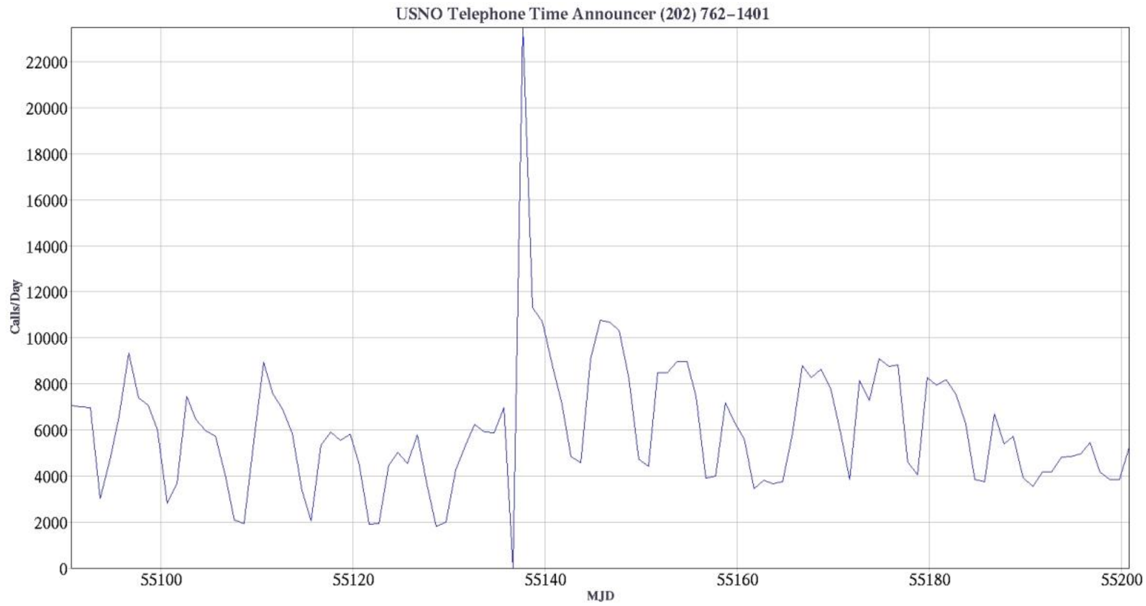

Figure 6. Daily number of telephone calls to USNO's DC Voice Announcer. The call volume decreases by almost 50% on the weekends, and also was low over the "End of Year Holiday Season," since 25 December 2009 was MJD 55190. The spike on MJD 55136 is the time of the switch to Standard Time. The slight increase after 55140 is not understood, but may be related to the activation of one of the 18 input channels.

NTP is far more precise than telephone time transfer, and Figure 7 shows the difference between our Washington facilities and our other NIPRnet servers, as measured by NTP packets sent from Washington. The Hawaii link shows large outliers, which could be removed by editing away data with long round-trip times, which are indicative of network asymmetry. However, in that instance, all Hawaii data from 55112-55133 would be removed. Such effects are the reason why short-baseline NTP is preferred. The millisecond-level bias between two AMC servers is also evident.

Greater precision is required for two services for which USNO is the timing reference: GPS and LORAN. USNO monitors LORAN at its Washington, DC site. With some assistance from 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 **[15]**, and USNO is pursuing a collaborative effort with the Loran Support Unit (LSU) to test an Enhanced Loran (eLORAN) receiver system.

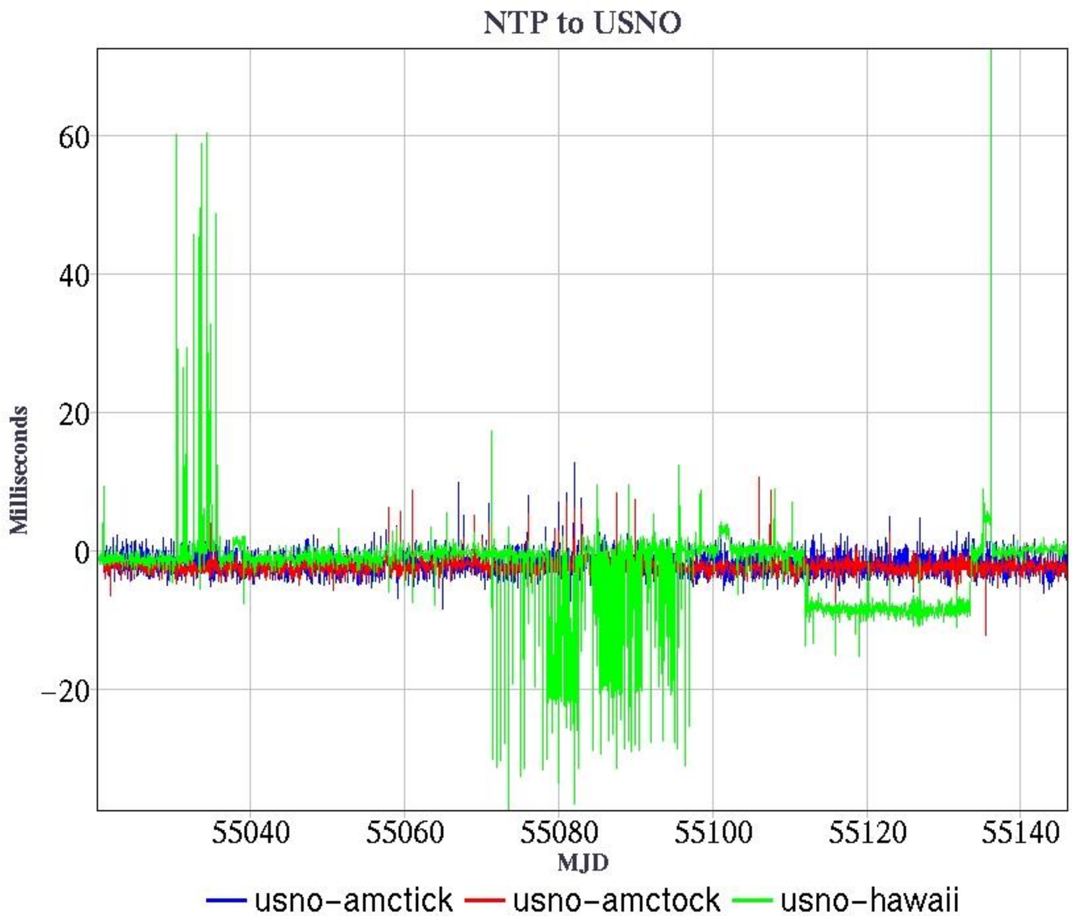

Figure 7. Time difference measured via NTP between USNO-DC and servers in Hawaii and AMC, which are 2500 miles apart. Plot is intentionally scaled so as to emphasize outliers associated with long-distance NTP. Clients on Hawaii would be expected to observe large outliers when accessing the Washington DC server, not their local one. Similarly, CONUS clients west of the Mississippi would attain greater precision by querying the AMC server instead of the Washington, DC one.

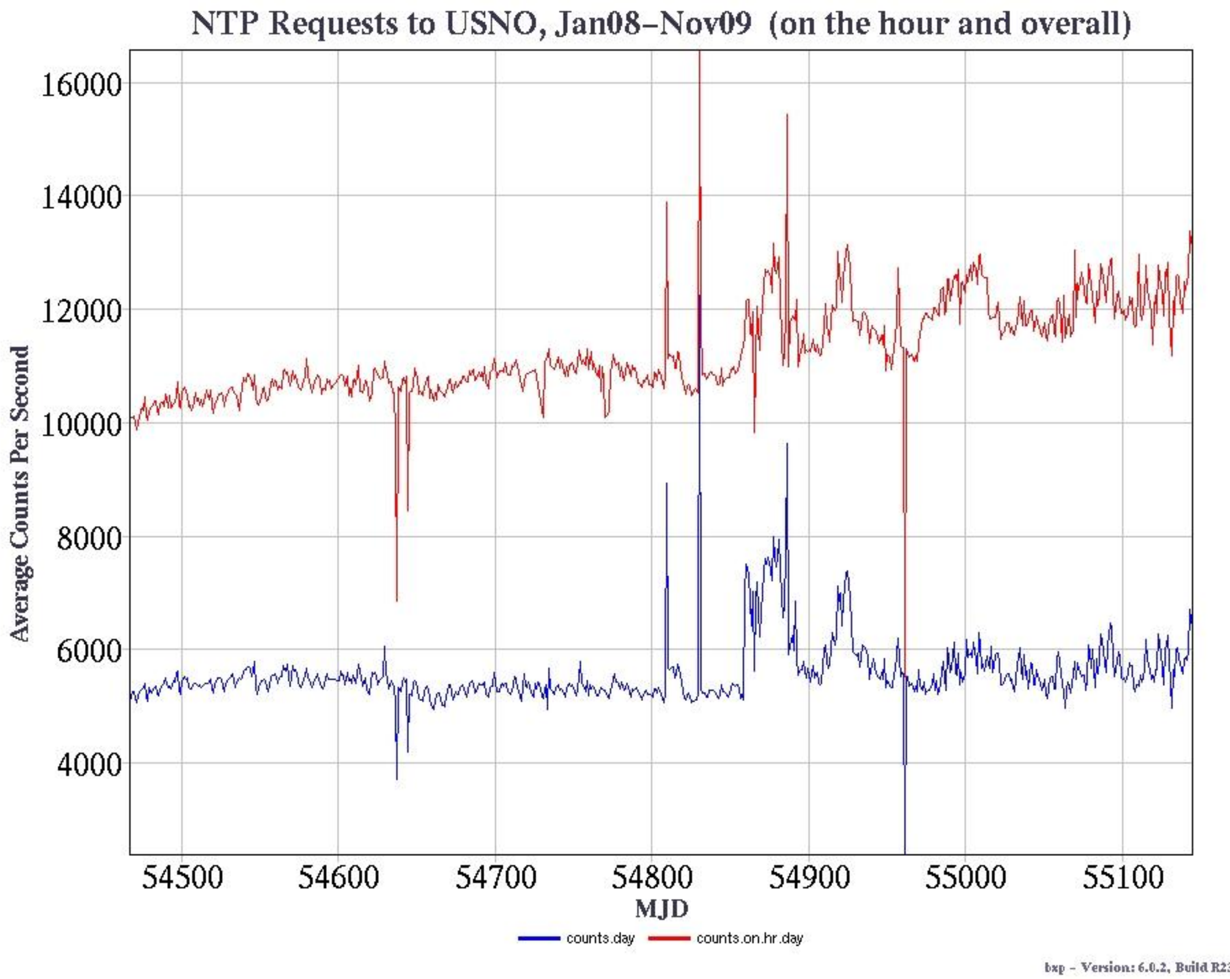

Figure 8. Measured NTP request rates to Washington DC servers since 2008. The upper plot is the request rate on the first second of every hour, which is the time when most clients are configured to query. The lower pot is the request rate averaged over the hour. The increase in February 2009 was due to a software modification.

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 9, 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 USNO-DC became a full-fledged GPS monitor site, in cooperation with the National Geospatial-Intelligence Agency (NGA). The NGA is installing improved GPS receivers, which would make possible an alternate means of 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.

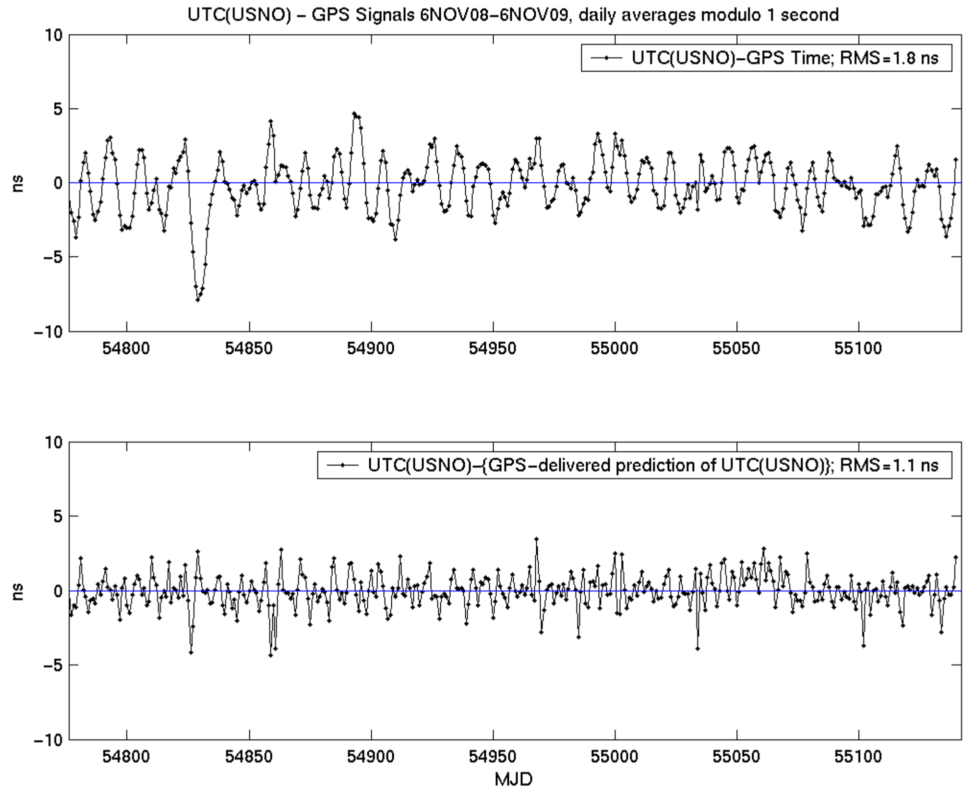

Figure 9. Recent daily averages of UTC (USNO) minus GPS Time and UTC minus GPS's delivered prediction of UTC (USNO).

Figure 10 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 11 shows the rms frequency accuracy along with the frequency stability, as measured by the Allan deviation (ADEV) over the same time period as Figure 10. The ADEV is shown for comparison; however, there is little justification for its use, since the measured quantity is stationary. In this case, the rms 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.

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 **[16]**. 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, 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 existing structures on the roof.

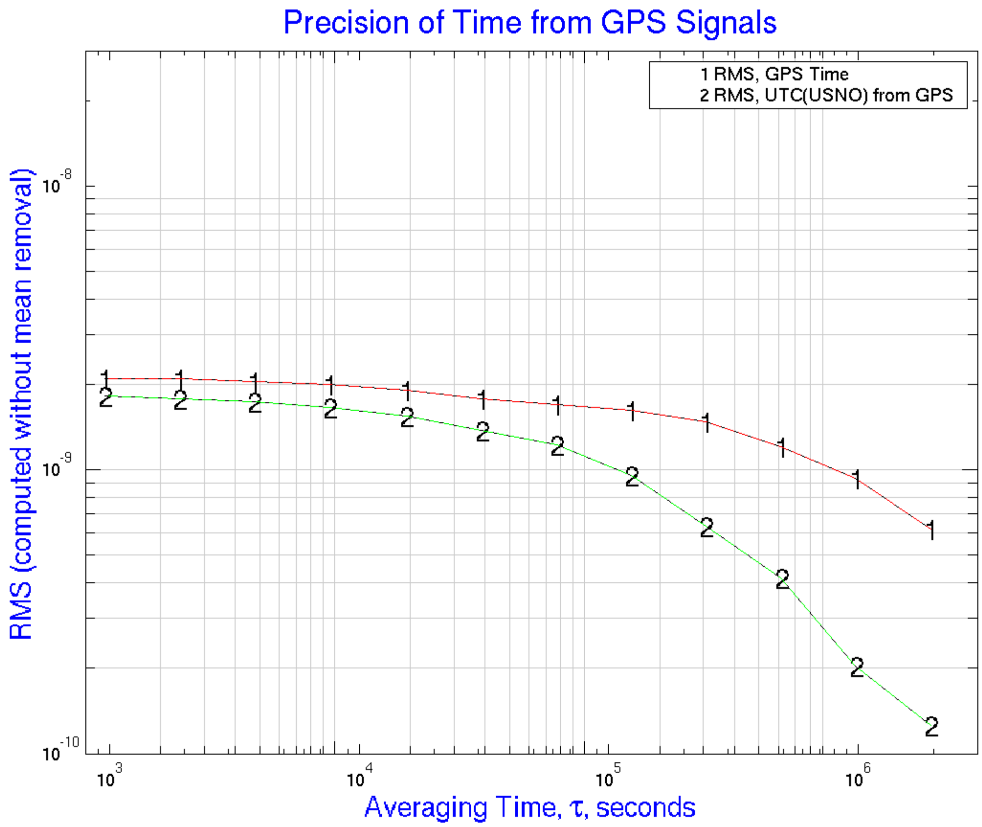

Figure 10. The precision of GPS Time and of GPS's delivered prediction of UTC (USNO), using TTR-12 data since 12 July 2002, measured by the attainable external precision (rms, mean not removed) as a function of averaging time, and referenced to UTC (USNO). Improved performance in accessing UTC (USNO) 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.

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), BIPM, and others to establish absolute calibration of GPS receivers **[17]**. 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 **[18]**. 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 $\sqrt{2}$. For this reason, relative calibration, by means of traveling GPS receivers, is a better operational technique, provided care is taken that there are no systematic multipath differences between antennas. We strongly support BIPM's relative calibration efforts for geodetic GPS receivers, and in particular are looking forward to comparisons with the multipath-free TWSTT calibrations.

In 2003, the Wide-Area Augmentation System (WAAS) became operational. USNO has been collecting data on WAAS network time (WNT). Daily averages generated by averaging WNT with WAAS-corrected time from GPS satellites are 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.

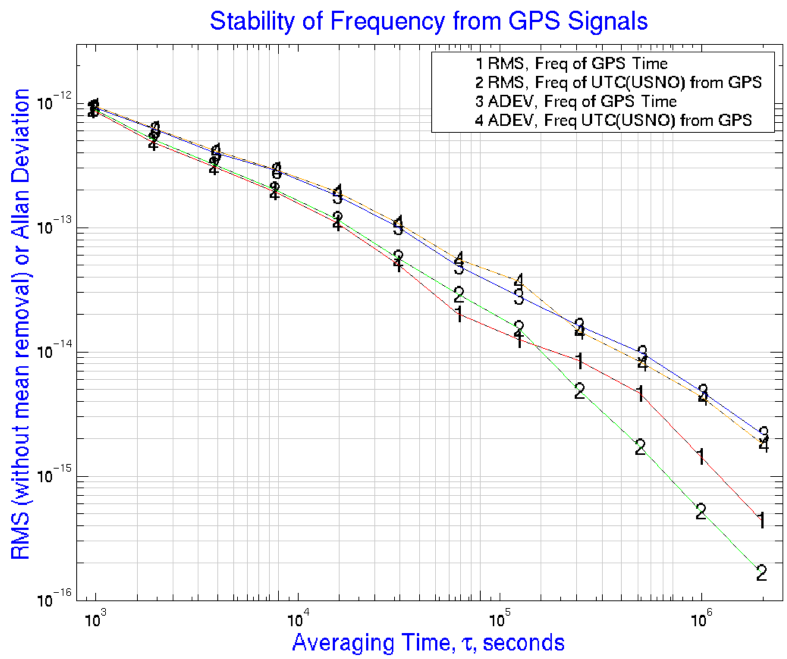

Figure 11. RMS fractional frequency external precision and the fractional frequency stability, as measured by the Allan deviation, of GPS Time and for GPS's delivered prediction of UTC (USNO), using TTR-12 data since 7 February 2005. The reference frequency is that of UTC (USNO).

USNO has been participating in discussions involving the interoperability of GPS, Galileo, QZSS (Quasi-Zenith Satellite System), and GLONASS. In December 2006, a Galileo monitor station was installed, and detailed plans have been made to monitor the GPS/GNSS timing offset (GGTO) [**19**] 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 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 **[20]**. USNO has analyzed 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 BIPM's Circular T (Figure 12) **[21].** This bias has increased recently, for reasons not yet understood but possibly related to delay variations in the several time transfer systems involved in the process.

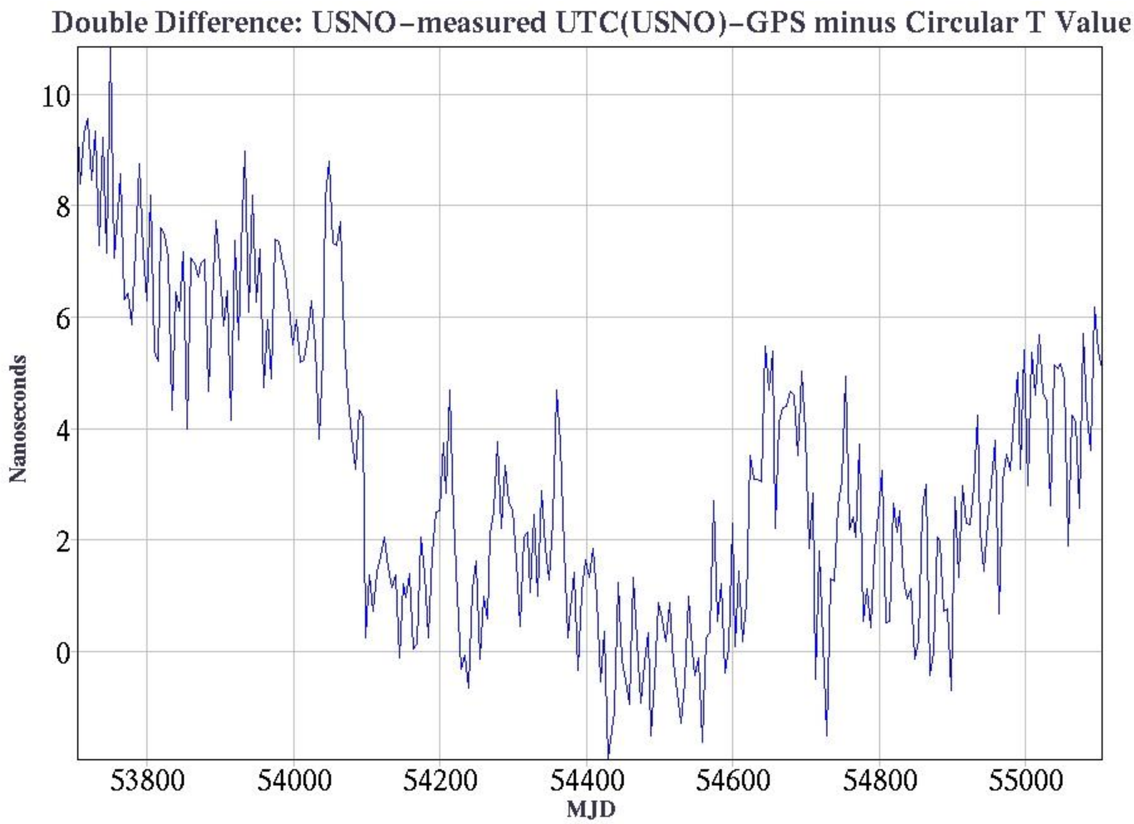

Figure 12. The difference between UTC – GPS as reported in the Circular T, and UTC – GPS inferred by subtracting UTC (USNO) – GPS from UTC – UTC (USNO). UTC (USNO) – GPS can be obtained from the satellite broadcasts, as in Figure 9, and is also measured directly at USNO. The reduction at MJD 5400 is related to specific improvements as described in the references.

The most accurate means of operational long-distance time transfer is TWSTT **[22-25]**, and USNO has strongly supported 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) through comparisons with observations at a second TWSTT frequency **[26]** and with the carrier-phase GPS receivers whose IGS designations are USNO, USN3, and PTBB. For improved robustness, we have begun constructing loop-back setups at 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 **[27]**, although it appears the most promising technology would include a frequency standard in the satellite **[28]**.

The Time Service Department of 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), 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 **[23]**. Working with the manufacturer, USNO has helped to develop a modification for the TurboRogue/Benchmark receivers, which preserve timing information through receiver resets. Using IGS data, USNO has developed a timescale that is now an IGS product **[29]**. USNO is currently contributing to real-time carrier-phase systems run by JPL/NASA **[30]** and the Canadian real-time NRCan networks **[31]**.

While the promise of Carrier Phase GNSS for time transfer is on its way to fulfillment, one of the greatest impediments to subnanosecond operations is receiver instabilities. For example, the receivers used at USNO and elsewhere have exhibited both sudden and gradual variations at the 1 ns level **[32]**. All of these receivers were designed in the 20th century and, therefore, USNO is experimenting with more modern components **[33]**. 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 pseudo-range calibration **[22,34,35]**, only human intervention in the form of calibration monitoring and recalibration can correctly account for non-transient receiver variations.

Instrumental variations are evident in the USNO's time transfer links to the PTB. The blue link is carrier-phase GPS differenced with Ku-band TWSTT. Although, in general, the double-differences involving Ku-band TWSTT show larger variations, the "odd-man out" approach does not validate any pair of time transfer modes. We do note that no spontaneous jumps have been observed in the short time period since April 2009, when the USNO's carrier-phase GPS receivers were moved to a room whose temperature stays constant to better than 1 deg C peak to peak overall, and usually 0.2 deg C over weeks.

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 **[36]**. Simulations have shown that, in the absence of receiver calibration variations, frequency errors due to misestimating of satellite orbits, Earth orientation, receiver position, and other effects can be reduced still further if sufficient signal to noise exists to enable double-difference ambiguity resolution **[35]**. Given these theoretical advances, we suspect that UTC's stability would be improved on all but the longest scales if BIPM had available data from timing laboratories that were extracted from several improved receivers, which are observing all available frequencies, in thermally, humidity, and multipath-optimized environments.

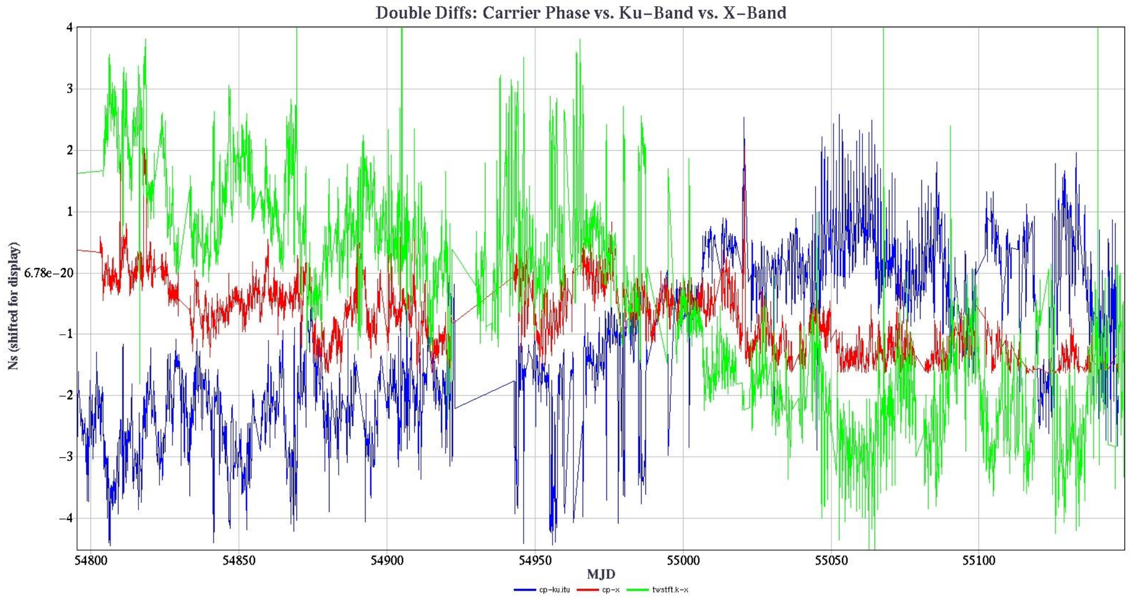

Figure 13. Double-differences of three time transfer links between USNO and PTB over the past year. The blue link is carrier-phase GPS difference with Ku-band TWSTT, the red is carrier-phase GPS differenced with X-band TWSTT, and the green is the difference between X-band and Ku-band TWSTT. The data gap is due to the GPS receiver's being moved to a more temperature-stable room. Curves were shifted for display.

IV. MEASURES TO SECURE THE ROBUSTNESS OF THE MASTER CLOCK

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 14), whose ribbon-cutting ceremony was held on 7 November 2008 **[37]**. The building has redundant environmental controls designed to keep the entire building constant to within 0.1 deg C and 3% relative humidity even when an HVAC unit is taken offline for maintenance. The clocks themselves will be kept on vibration-isolated piers. Standardized instrument racks will facilitate rapid and accurate repairs. Although the building is not yet operational, most of the infrastructure is now in place, with the temperature and humidity specifications being met through relatively minor design modifications.

The clocks in all Washington, 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. Our ability to maintain continuous operations while bringing about quick replacement of the failed components, and periodic testing, give some confidence in the robustness of the system.

Figure 14. New clock building.

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. Additional measures for robustness, beyond the scope of this paper, have also been taken.

V. DISCLAIMER

Although some manufacturers are identified for the purpose of scientific clarity, USNO does not endorse any commercial product, nor does 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.

VI. ACKNOWLEDGMENTS

I thank the staff of USNO's Time Service Department for their skill and dedication in maintaining, operating, and improving the USNO Master Clock.

VII. REFERENCES

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