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

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Abstract

The U.S. Naval Observatory (USNO) has provided timing for the Navy since 1830 and via DoD Directives 4650.05 and 4650.07 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 4 ns rms in 2011. The data used to generate UTC(USNO) are based upon 87 cesium, 38 hydrogen maser, and now also 4 rubidium fountain frequency standards in four buildings at two sites. USNO disseminates time via voice, telephone modem, 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/time.

I. TIME GENERATION

The most important part of USNO's Time Service Department is its staff, which currently consists of 33 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. The clocks used for the USNO timescale are kept in environments whose temperatures are kept constant to within 0.1 deg C and whose relative humidities (for all fountains and masers, and most cesiums) are kept constant to within 1%. This year, a large number of our Washington clocks were moved into our new clock building, and several of the chambers that house the remaining clocks were upgraded to designs that should have a lower failure rate and require reduced maintenance. The timescale is based only upon the clocks located in Washington, D.C., and this number has been gradually decreasing for various reasons. On 29 October 2010, 51 of those standards were weighted in the operational timescale computations; this includes four atomic fountains, that are now initially weighted as if they were simple cesium beam clocks while also being used to predict UTC. Their performance since last winter has been excellent, although one unit displayed two frequency variations of $\sim10^{-15}$; these effects would appear only at averaging times longer than shown in the Allan Deviation plot in Figure 1.

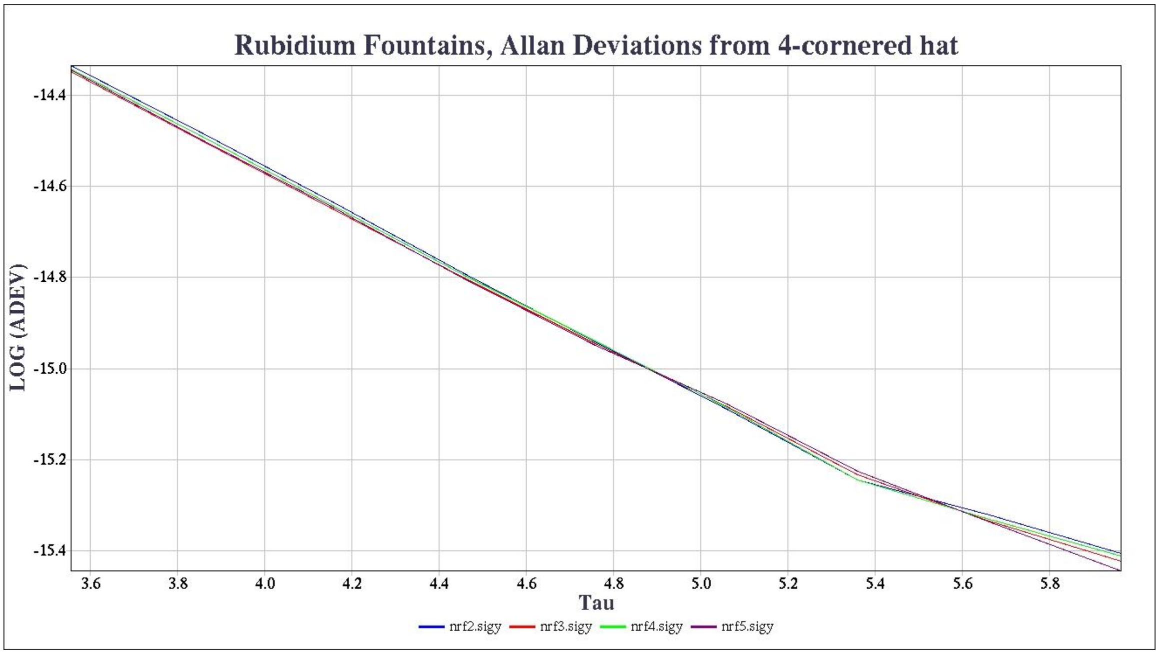

Figure 1. Allan Deviation of four USNO rubidium fountains, March-October 2011.

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. Where possible, all connectors are screw-on (SMA). The clock 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 through *http://tycho.usno.navy.mil.*

UTC(USNO) is created by frequency-steering the A.1 timescale to UTC. The atomic fountains are now being tested as predictors of TAI, as modifications of the past steering strategy called "gentle steering" **[2-4]**, that minimizes the control effort used to achieve the desired goal. 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) as measured. We have not yet integrated the four 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 currently better clocks, which are about 60% of the total and 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 steered either to the atomic fountain ensemble or a cesium-only timescale, that itself is steered to UTC using the information in the Circular T **[6, 10, 11]**.

II. STABILITY OF UTC(USNO)

Figure 2 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 2 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.

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.

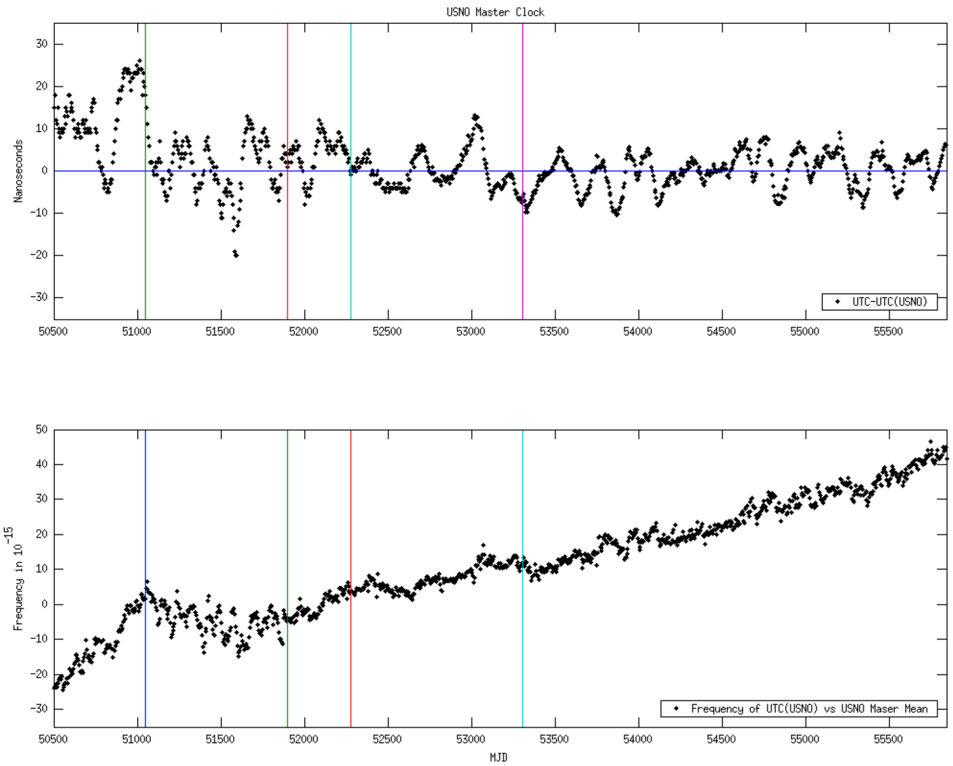

Figure 2. Interplay between the time and fractional frequency stability of the USNO Master Clock, from February, 1997 to the present.

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, Echelle Atomique Libre, which is the unsteered timescale generated by BIPM that is steered to primary frequency standards so as to create UTC. Since the time-averaged contribution of the USNO-DC cesiums to EAL 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). It appears that most of the drift in EAL is due to the intrinsic average drift of the cesium beam tubes, although the contribution of masers and other high-drift clocks to TAI's drift has been estimated to be 40% **[12]**.

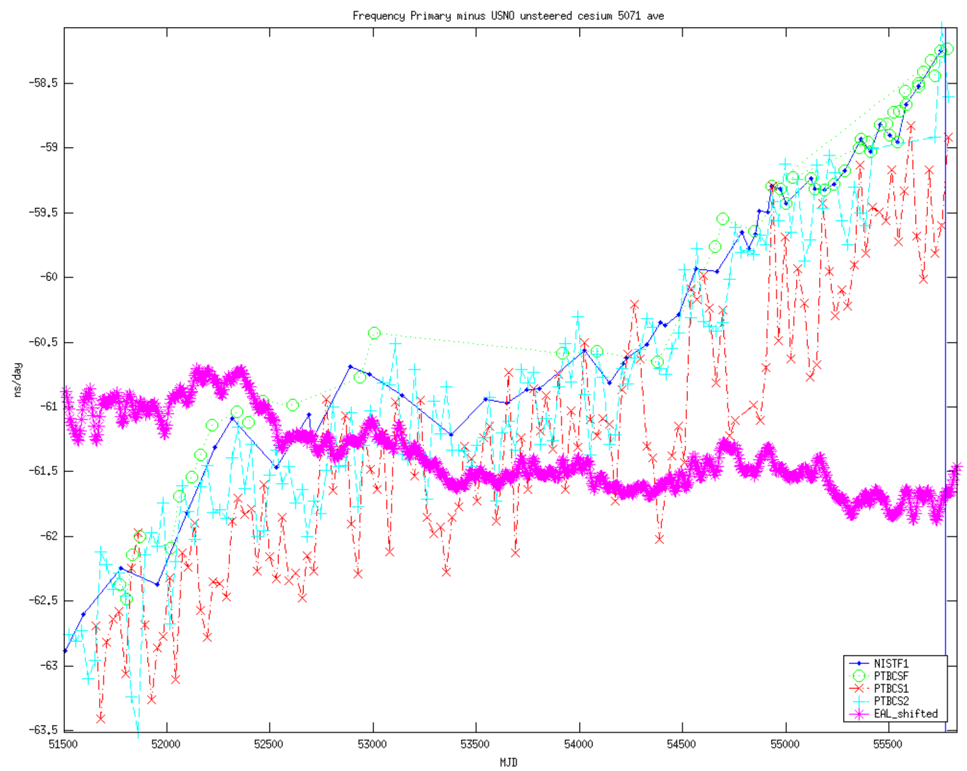

Figure 3. Fractional frequency of unsteered average of USNO-DC cesiums against that of EAL and also against several primary frequency standards. The frequencies have been shifted in the vertical direction for display, and the difference with the cesium average has been scaled in an effort to remove the contribution of USNO-DC cesiums to EAL. Beginning MJD 55574, the BIPM altered its algorithm for EAL so as to better follow the primary frequency standards.

III. TIME TRANSFER

III.1: TIME TRANSFER AT PRECISIONS EXCEEDING 100 NANOSECONDS

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 **[13]**. 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.

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

Telephone Voice-Announcer	4,000,000
Leitch Clock System	62,000
Telephone Modem	65,000
Web Server	700 million
Network Time Protocol (NTP)	200 billion

Our lowest precision service is our telephone voice announcer (202-7621401). Figure 4 shows very predictable patterns, as explained in the caption. The voice is 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.

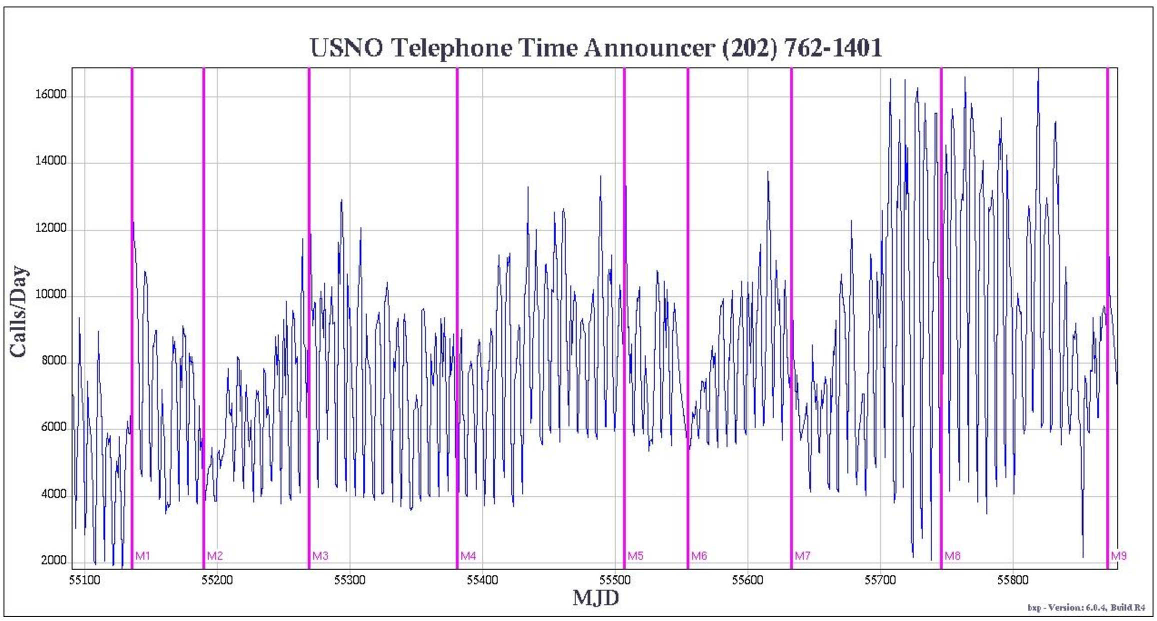

Figure 4. Daily number of telephone calls to USNO's DC Voice Announcer. The call volume decreases by almost 50% on the weekends and holidays, and is typically but not always high on the switches to and from Standard Time (which are indicated along with the Dec 25 and July 4 holidays). The long-term trends may be indicators of human behavior, or to variations in telephone connectivity. The large increase near MJD 55700 coincides with the local telephone company's termination of its time service; however, note that the call rate recently dropped to its previous value.

NTP is far more precise than telephone time transfer, and USNO can achieve submillisecond precision over very short distances. USNO monitors the time-transfer performance of its NIPRnet NTP sites from Washington and the AMC. Because there is a block on NTP packets leaving the NIPRnet, USNO monitors its internet sites from an external location that is not on the NIPRnet. Figure 5 is a "worst-case" (i.e. very long-baseline) situation, which shows the timing difference between the USNO and the Maui High-Performance Computing Center's server in Hawaii. To generate the figure, NTP timing data whose round-trip time deviated by 10% from the average were excluded; however on a daily scale this editing would only be noticeable if all data were excluded. USNO has begun experimenting with and implementing a more precise form of network time transfer is known as Precise Time Protocol, PTP, which uses the IEEE-1588 format **[14].**

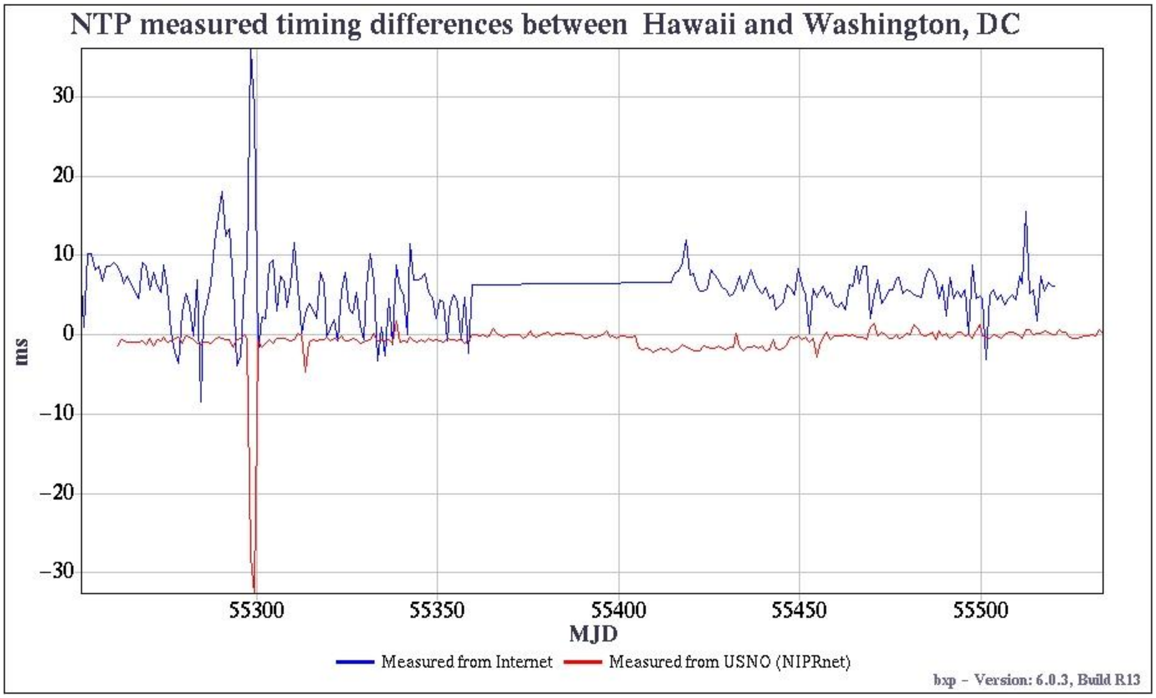

Figure 5. Daily average time differences measured via NTP between USNO's Washington, DC and Hawaii NIPRNet servers from the USNO and from an Internet site that is also in Washington, DC. Since the Hawaii site is timed to UTC(USNO) via GPS, ideal systems would produce zero offsets. The unaveraged internet data are about twice as noisy as NIPRnet data; however, different internet providers or configurations could show different results. That gap in the internet plot (upper plot) is due to a configuration change. Performance over shorter baselines is much better than in the figure.

Although USNO is not directly involved, we have learned that the National Electric Reliability Corporation (NERC), is considering eliminating the process of timing the 60 Hz line signals to UTC (*http://www.nerc.com/page.php?cid=6|386*). The frequency would instead always be kept as closely to 60 Hz as possible. This would introduce a random walk accumulating to about 20 minutes a year on the East Coast. USNO has set up a monitor of 60 Hz time and frequency, and we show our observations in Figure 6. The daily cycles are evident, and the ability of the power companies to compensate for frequency variations is measured in seconds.

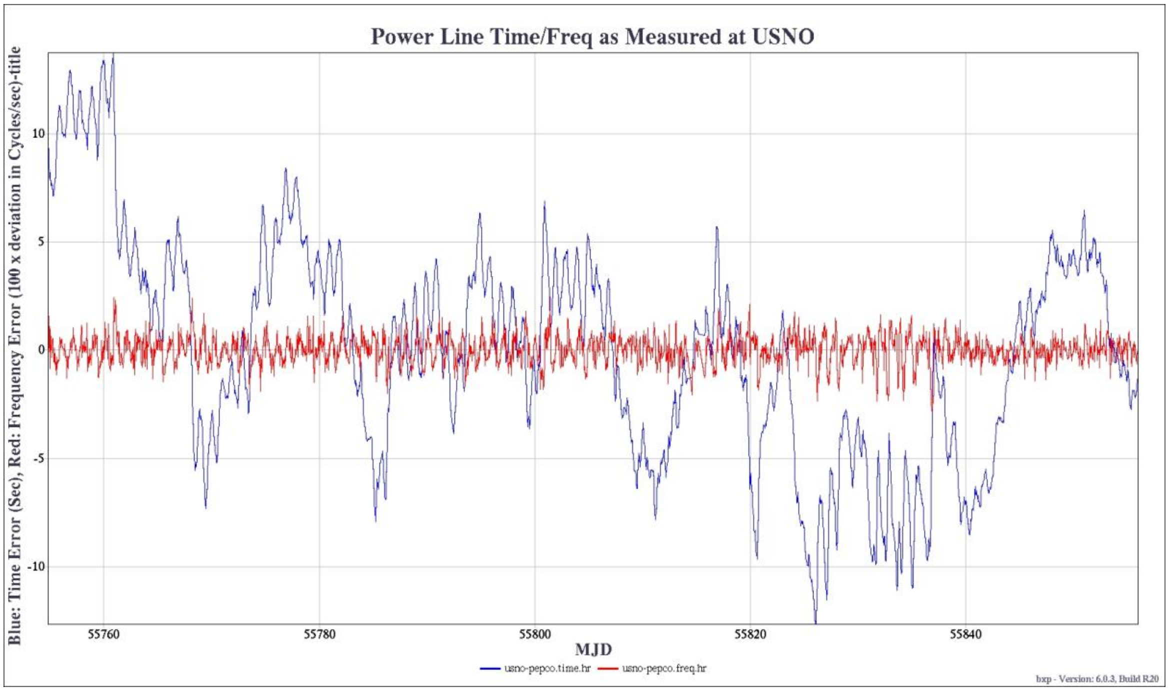

Figure 6 Frequency offset of AC power at USNO (shore power) from nominal 60 Hz, and the time offsets of the 60 Hz zero crossings (arbitrary constant removed).

III.2: TWO-WAY SATELLITE TIME TRANSFER (TWSTT), ALSO REFERRED TO AS TWO-WAY SATELLITE TIME AND FREQUENCY TRANSFER (TWSTFT)

The most accurate means of operational long-distance time transfer is generally believed to be TWSTT **[15-18]**, although the most precise, on subdaily scales, is via GPS carrier phase, which for TAI-generation is computed using Precise Point Positioning (PPP). We routinely calibrate and recalibrate the TWSTT at 20 sites each year, and in particular we have maintained the calibration of the transatlantic link with the Physikalisch-Technische Bundesanstalt (PTB) [**19]** via Ku-band TWSTT observations and the carrier-phase GPS receivers whose IGS designations are USNO, USN3, and PTBB. In July 2010, USNO had to terminate X-band TWSTT observations with PTB due to the loss of the satellite. 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. This year our modifications have reduced the diurnal signature in their data by a factor of 2 at some sites. For improved precision, we have made some efforts to develop carrier-phase TWSTT **[20]**, although it appears the most promising technology would include a frequency standard in the satellite **[21]**.

III.3: TIME TRANFER VIA GPS

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 7, users can achieve tighter access to

UTC(USNO) by applying these 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.

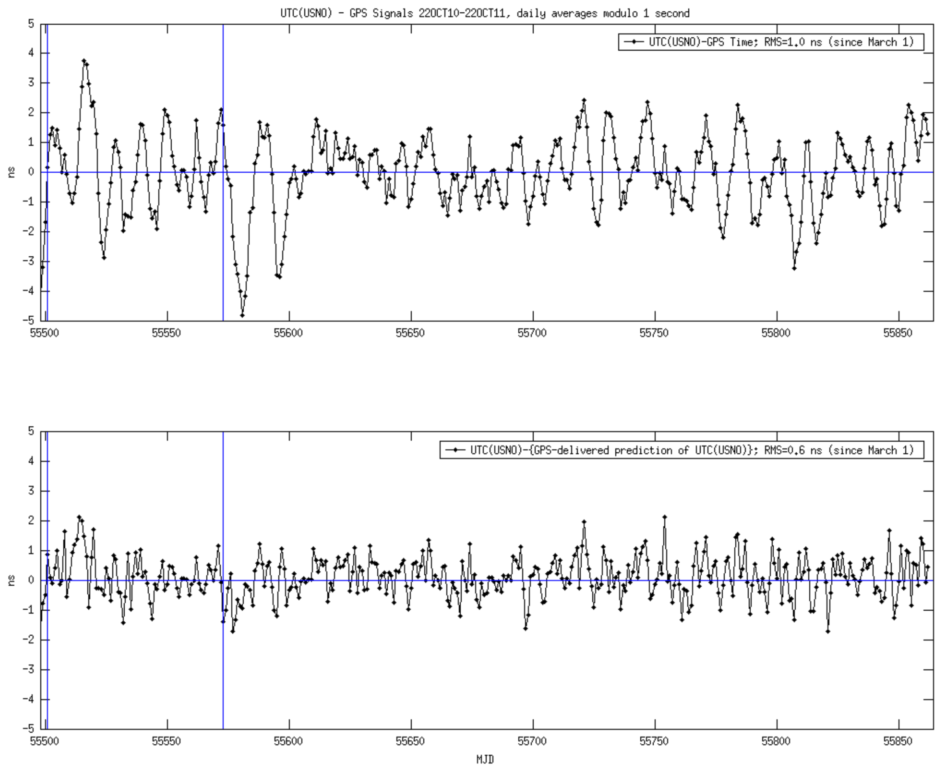

Figure 7. Recent daily averages of UTC(USNO) minus GPS Time and UTC minus GPS's delivered prediction of UTC(USNO). The markers indicate the times when USNO introduced ERD-corrections to its monitoring (November 1, 2010) and when the GPS bang-bang algorithm was numerically modified by lowering its acceleration to 5×10^{-20} (January 12, 2011).

Figures 8 and 9 show the rms time and frequency 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. On November 1, USNO began reducing its GPS observations using the "ERD" satellite and clock corrections directly from the GPS Master Control Station Kalman filter, rather than from broadcast parameters, which improved our precision.

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 **[22]**, including SAASM-enabled variants. The standard setup includes temperature-stable cables and flat-passband, low-temperature-sensitivity antennas. Our single-frequency Standard Positioning Service (SPS) receiver remains the BIPM-standard "TTS" units; however, this is slated to be replaced by a carrier phase GPS receiver. 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, and a second structure has been built.

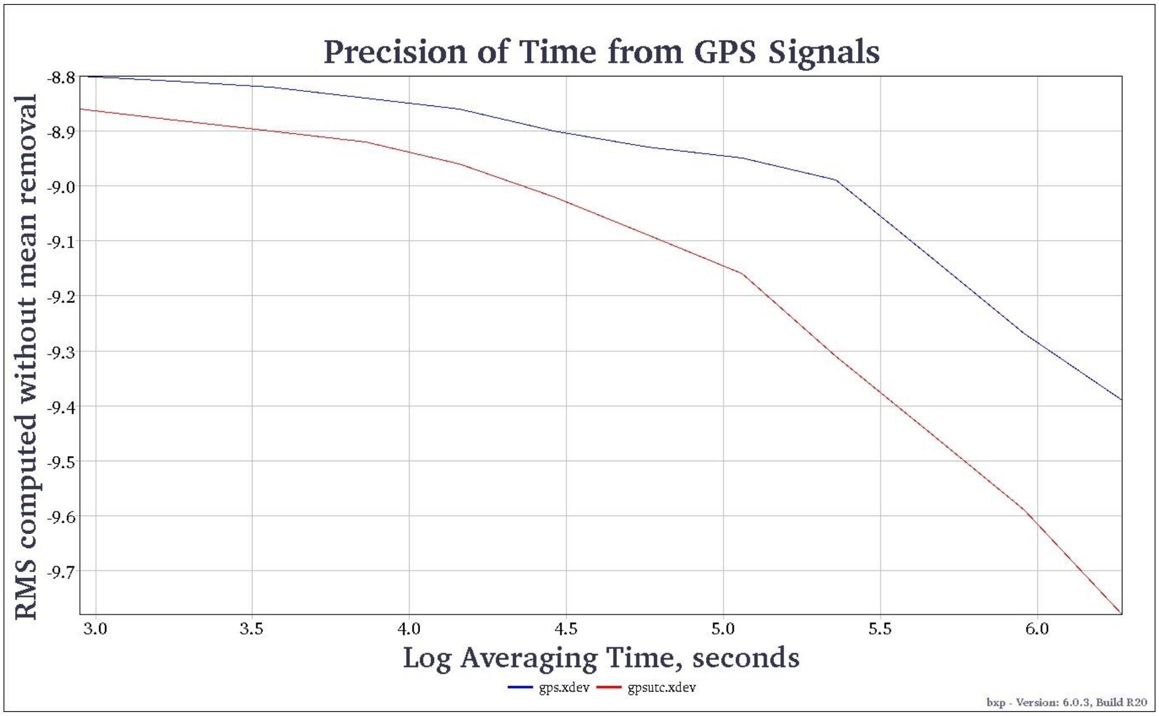

Figure 8. The precision of GPS Time and of GPS's delivered prediction of UTC(USNO), using TTR-12 data since March 30, 2011, measured by the attainable external precision (rms, mean not removed) as a function of averaging time, and referenced to UTC(USNO). Improved performance in accessing UTC(USNO) could 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 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 **[23-24]**. Recent work suggests that 1-sigma errors at the L1 and L2 frequencies can be as low as 0.64 ns at the receiver, and 1 ns overall**[25]**. Since this error is largely uncorrelated between the two GPS frequencies, the error in ionosphere-corrected data becomes a factor of almost 3 larger. Experimental verification by side-by-side comparison contributes an additional $\sqrt{2}$, pushing the formal error of a link calibration above 5 ns if undertaken by absolute calibration. For comparison, relative calibration by means of traveling GPS receivers can provide an estimated overall time transfer accuracy of 0.64 ns **[26]**.

We strongly support BIPM's relative calibration efforts for geodetic GPS receivers, and in particular are looking forward to comparisons with the 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.

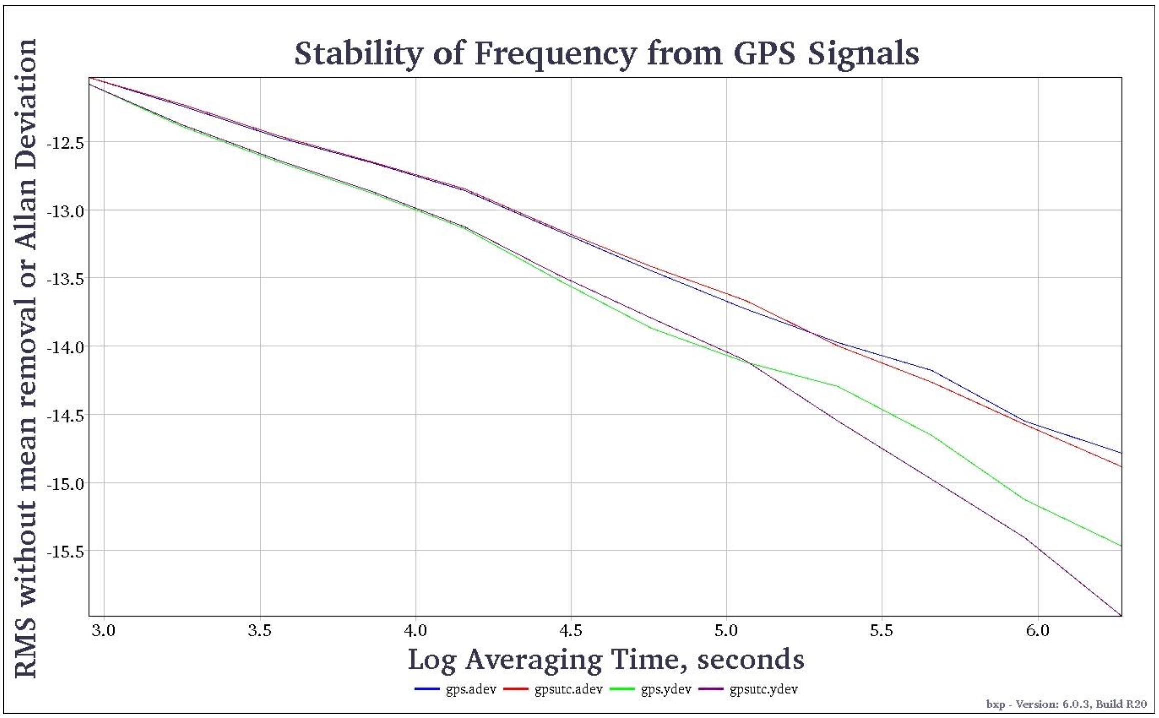

Figure 9. RMS fractional frequency external precision and the fractional frequency stability, as measured by the Allan deviation, of GPS Time and for GPS's delivered prediction of UTC(USNO), using TTR-12 data as with the previous figure.

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 USNO has developed the ability to monitor the GPS/GNSS timing offset (GGTO) [**27**] in parallel and in concert with the Galileo Precise Timing Facilities (PTF). 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 PTF. 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, a TWSTT station became functional in Hawaii in July 2010, as a relay point for daily TWSTT with NICT in Japan. Since NICT and USNO do TWSTT with the PTB, from opposite sides of the Earth, this has enabled us to link data around the northern hemisphere.

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 **[28]**. 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 10) **[29]**. The discrepancy in the plot is probably due to a calibration difference between the Observatory of Paris (OP) and the USNO; a dedicated direct calibration of USNO-OP is scheduled for the near future.

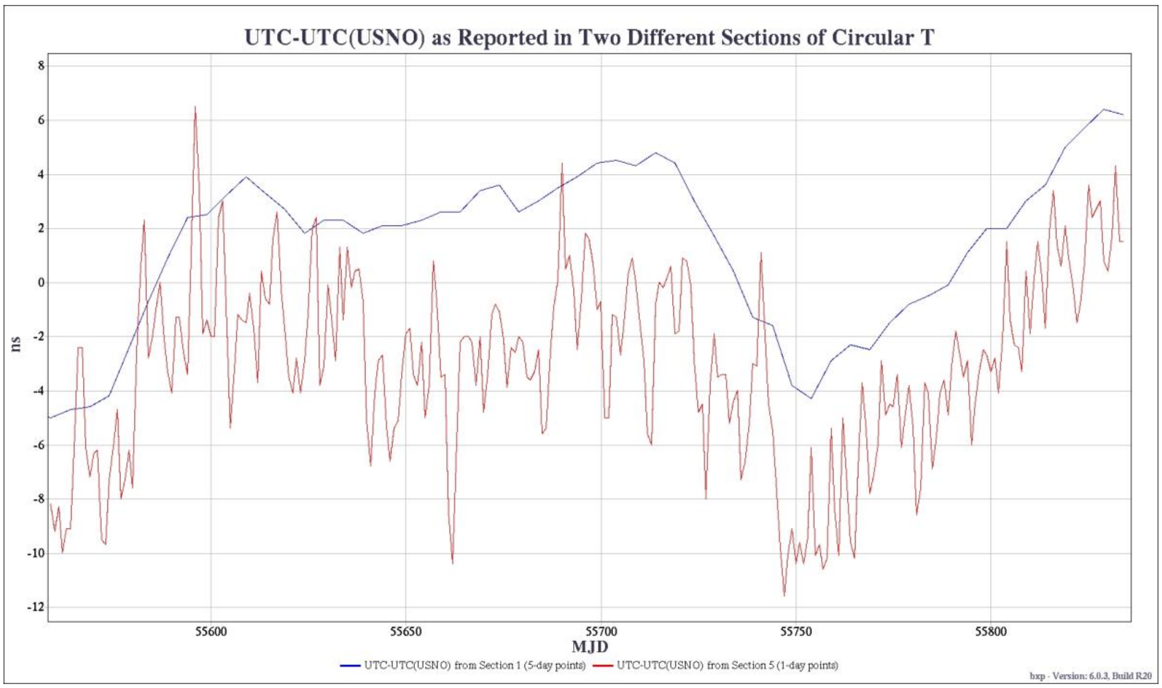

Figure 10. UTC – UTC(USNO) 5-day points as reported in the Circular T section 1, and UTC – UTC(USNO) via GPS, reported in Section 5 of the Circular T as smooth 1-day points. UTC(USNO) – GPS can be obtained from the satellite broadcasts, and was reported by the Observatory of Paris (OP).

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 **[15]**. 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 **[30]**. USNO is currently contributing to real-time carrier-phase systems run by JPL/NASA **[31]** and the Canadian real-time NRCan networks **[32]**.

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 **[33]**. All of these receivers were designed in the 20th century and, therefore, USNO is experimenting with more modern components **[34, 35]**. 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 **[15, 36-38]**, only human intervention in the form of calibration monitoring and recalibration can correctly account for non-transient receiver variations. In order to provide a reliable service, USNO in April 2009 moved USN3 and a backup receiver into a more temperature-stable environment, and this year we have improved the control of their environment still further.

The examples shown here do not contradict the fact that TWSTT calibrations, in the best of times, have subnanosecond repeatability, but they are contrary to the popular belief that between calibrations TWSTT accuracy is always better than GPS carrier phase. As noted in our PTTI-10 paper **[39]**, some TWSTT systems have displayed many-nanosecond variations over 100-day periods, which could or could not be due to components supplying the reference signal to the hardware. Although many key TWSTT components are outdoors, GPS systems allow us to maintain receiver ensembles under benign environmental conditions, with only the antennas exposed to the elements. Therefore, USNO now has three modern carrier-phase GNSS receivers recording data with our operational unit. This is consistent with the opinion of this author that multiple independent redundant time transfer systems that are frequently calibrated remain the best way to ensure performance, although TWSTT remains unrivalled for many real-time applications that require simple instantaneous results independent of GPS.

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 **[17]**. 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 **[37]**. 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.

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 have constructed a special clock building (Figure 11) **[40]**. 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. The temperature and humidity specifications appear to have been met through relatively minor design modifications completed in the summer of 2011. Although no system is ever perfect, the building has been put into operational use.

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. To protect against aging effects, we have this year let a contract to replace most of our components, many of which have been in use for decades. Our ability to maintain continuous operations, while bringing about quick replacement of the failed components and periodic testing, gives some confidence in the robustness of the system.

Figure 11. 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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