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 and the Department of Defense since 1830 and, in cooperation with other institutions, has also provided timing for the United States and the international community. Its Master Clock (MC) is the source of UTC (USNO), the USNO's realization of Coordinated Universal Time (UTC), which has stayed within 5 ns RMS of UTC since 1999. The data used to generate UTC (USNO) are based upon 73 cesium and 21 hydrogen maser frequency standards in three buildings at two sites. The USNO disseminates time via voice, telephone modem, LORAN, Network Time Protocol (NTP), GPS, and Two-Way Satellite Time Transfer (TWSTT). The USNO would not be able to meet all the requirements of its users had it kept to the same technology it had 10 years ago; this paper 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 on-line at *http://tycho.usno.navy.mil*, ***or by contacting the author directly.***

I. TIME GENERATION

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.

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, four cesium Cs III-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 7 July 2006, 60 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 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 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 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. Both A.1 and the maser mean are available on the Web pages.

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). 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 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. 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. 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 the Circular T **[6,9]**. The steered cesium-only timescale would either be based upon the Percival Algorithm **[1,10]**, a Kalman-filter, or an ARIMA algorithm. As an alternative variation, individual masers could 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 then UTC (USNO) has compared to UTC and also how its frequency has compared to the unsteered maser mean, relative to an overall constant offset.

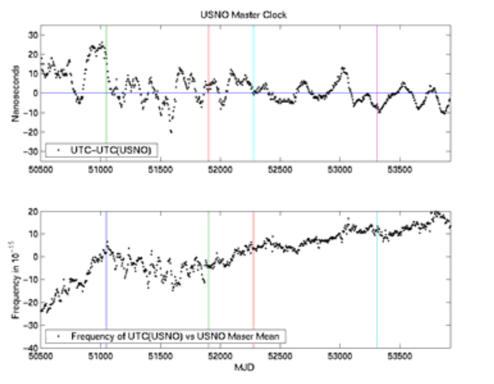

Figure 1. Interplay between the time and frequency stability of the USNO Master Clock, from February, 1997 to the present.

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 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 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. 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 frequency difference between our unsteered cesium average and EAL, which is the unsteered timescale generated by the BIPM that is steered to primary frequency standards so to create UTC. In this figure, the contribution of USNO-DC cesiums to UTC has been removed by a 25% scaling. Also plotted is the unsteered cesium average frequency against the SI second as measured by primary frequency standards at NIST and 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.

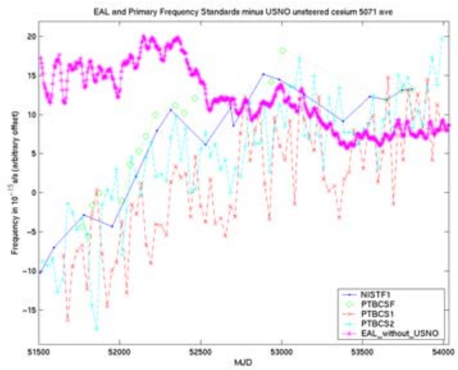

Figure 2. Frequency of unsteered average of USNO-DC cesiums against that of EAL and of primary frequency standards. The frequencies have been shifted in the vertical direction for display, and the difference with the cesium average has been scaled to remove the contribution of USNO-DC cesiums to EAL.

In order to improve timescale operations, the USNO has a staff of four developing rubidium-based atomic fountains **[11]**. Figure 3 shows the performance of the prototype fountain over a 40-day period, while housed in a room subject to several-degree temperature variations.

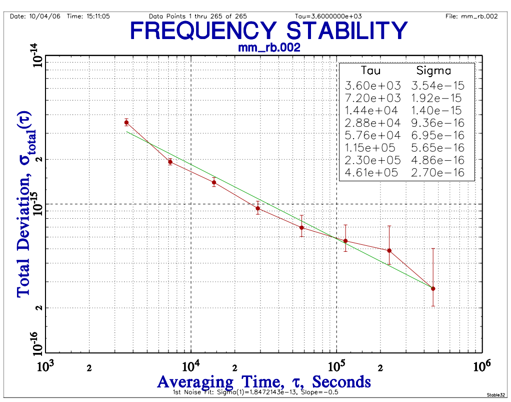

Figure 3. Performance of rubidium fountain against a USNO maser mean, as measured by the total deviation statistic. The straight line segment is a fit to the inverse square-root curve expected for white frequency noise.

III. 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 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 **[12]**. 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 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.

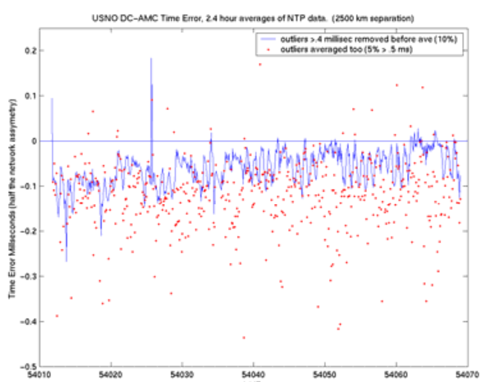

Figure 4. Observed error in NTP Time transfer between USNO-DC and USNO-AMC. Blue plot shows .1-day averages when the 10% of the data exceeding .4 ms error are removed. Red dots are simple .1-day averages of all the data, of which 5% exceed .5 ms deviation.

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 **[13]**, 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.

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 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. 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 **[14]**. 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.

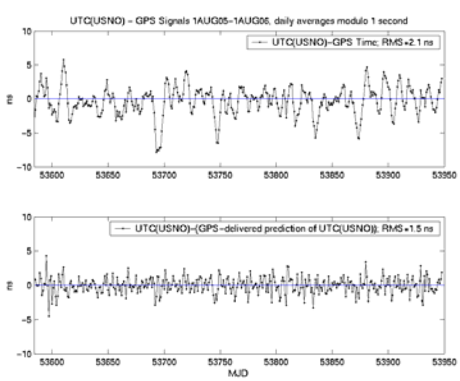

Figure 5. Recent daily averages of UTC (USNO) minus GPS Time and UTC minus GPS's delivered prediction of UTC (USNO).

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 **[15]**. 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 **[16]**. Since this error is largely uncorrelated between the two GPS frequencies, the error in ionosphere-corrected data becomes 6.4 ns. Experimental verification by side-by-side comparison contributes an additional square root of two. For this reason, 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 the BIPM's relative calibration efforts for geodetic GPS receivers, and in particular are looking forward to comparisons with the multipath-free TWSTT calibrations.

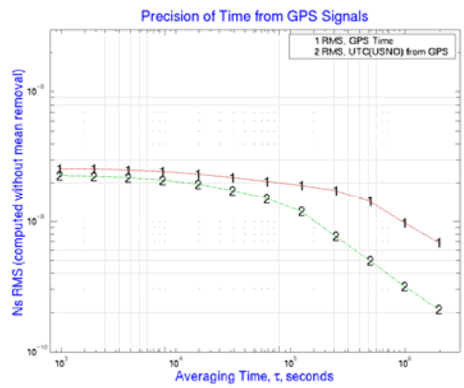

Figure 6. The precision of GPS Time and of GPS's delivered prediction of UTC (USNO), using TTR-12 data since 7FEB05, measured by the attainable external precision (rms, mean not removed) as a function of averaging time, and referenced to UTC (USNO). Improved performance in accessing UTC (USNO) could 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.

In 2003, the Wide-Area Augmentation System (WAAS) became operational. The 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.

The USNO has been participating in discussions involving the interoperability of GPS, Galileo, QZSS, and GLONASS. In December 2006, a Galileo monitor station was installed, and detailed plans have been made to monitor the GPS/Galileo timing offset (GGTO) **[17]** 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.

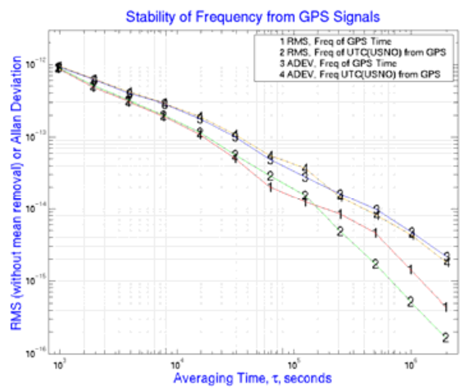

Figure 7. RMS frequency external precision and the frequency stability, as measured by the Allan deviation, of GPS Time and for GPS's delivered prediction of UTC (USNO), using TTR-12 data since 7 February 2005. Reference frequency is that of UTC (USNO).

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 **[18]**. Calibration errors associated with the TGD bias measurements of GPS result in a noticeable offset in GPS Time vs. UTC, as measured in the BIPM's Circular T (Figure 8; **[19]**).

The most accurate means of operational long-distance time transfer is TWSTT **[20-22]**, 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 PTB through comparisons with observations at a second TWSTT frequency **[23]** and with the carrier-phase GPS receivers whose IGS designations are USNO, USN3, and PTBB. For improved precision, we have made some efforts to develop carrier-phase TWSTT **[24]**. For improved robustness, we have begun constructing loop-back setups at the USNO, moved electronics indoors where possible, and developed temperature-stabilizing equipment to test on some of the outdoor electronics packages.

The Time Service Department of the USNO has also actively pursued development of GPS carrier-phase time transfer, in cooperation with the International GPS Service (IGS). With assistance from the Jet Propulsion Laboratory (JPL), the USNO developed continuous filtering of timing data and showed that it can be used to greatly reduce the day-boundary discontinuities in independent daily solutions without introducing long-term systematic variations **[22]**. Working with the manufacturer, the USNO has helped to develop a modification for the TurboRogue/Benchmark receivers, which preserve timing information through receiver resets. Using IGS data, the USNO has developed a timescale that is now an IGS product **[25]**. The USNO is currently contributing to real-time carrier-phase systems run by JPL/NASA **[26]** and the Canadian real-time NRCan networks **[27]**. The current operational USNO receiver models are subject to apparently spontaneous calibration variations at the 1-ns level **[28]**. In 2007, we will be experimenting with three different receiver models based upon newer technology.

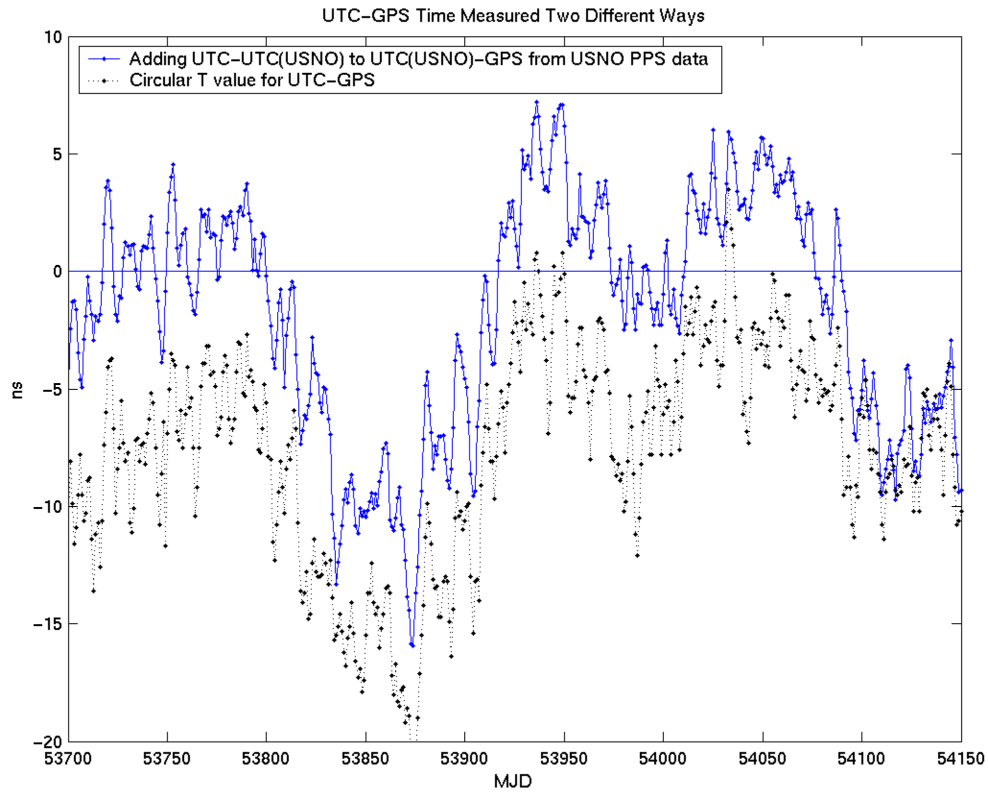

Figure 8. UTC-GPS as reported in the Circular T, and UTC-GPS inferred by subtracting UTC (USNO) – GPS from UTC – UTC (USNO). UTC (USNO) – GPS can be obtained from the satellite broadcasts, as in Figure 5 and is also measured directly at the USNO.

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 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.

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 begun plans for a new clock building, whose completion is scheduled in early 2007 (Figure 9). 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 off-line for maintenance. The clocks themselves will be kept on vibrationally isolated piers. The instrument racks will be standardized at all USNO locations.

Figure 9. New clock building, November 2006.

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 affect 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 too have been taken.

V. 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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