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, 4 cesium CsIII-EP clocks made by Datum/Symmetricom, and 24 cavity-tuned "Sigma-Tau/Datum/Symmetricom" hydrogen maser clocks, which are located in two Washington, D.C. buildings and at the USNO Alternate Master Clock (AMC), located at Schriever Air Force Base in Colorado. The clocks used for the USNO timescale are kept in 19 environmental chambers, whose temperatures are kept constant to within 0.1 degree C and whose relative humidities (for all masers and most cesiums) are kept constant to within 1%. The timescale is based only upon the Washington, D.C., clocks. On July 7, 2006, 60 standards were weighted in the timescale computations.

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

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(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.

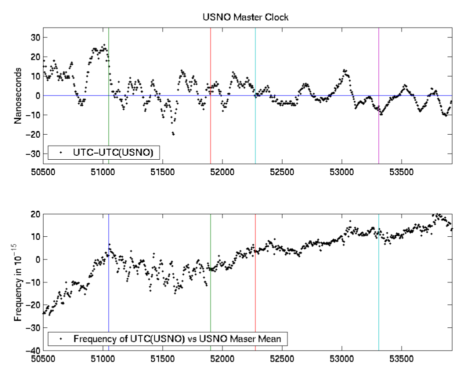

Figure 1. Interplay between the time and frequency stability of the USNO Master Clock, from February, 1997 to the present.

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 $\times 10^{-14}$ 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 are 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.

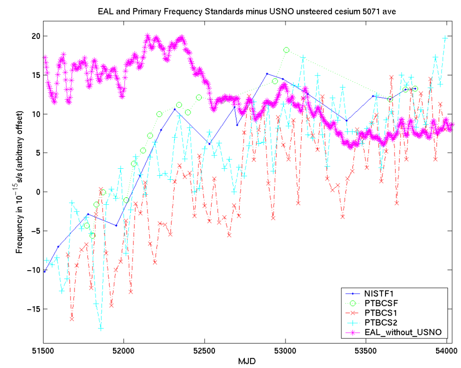

Figure 2. Frequency of unsteered average of USNO-DC cesiums against that of EAL and of primary frequency standards. The frequencies have been shifted in the vertical direction for display, and the difference with the cesium average has been scaled to remove the contribution of USNO-DC cesiums to EAL.

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.

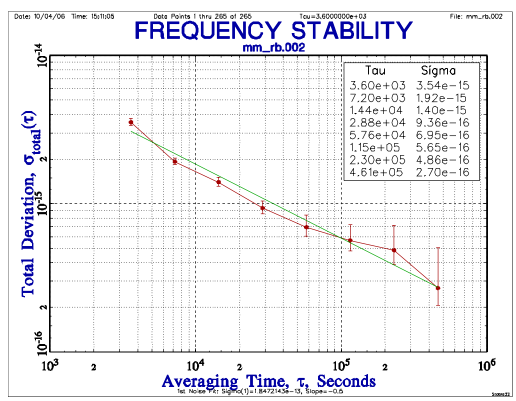

Figure 3. Performance of rubidium fountain against a USNO maser mean, as measured by the total deviation statistic. The straight line segment is a fit to the inverse square-root curve expected for white frequency noise.

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)

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, 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. 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 USNO has been participating in discussions involving the interoperability of GPS, Galileo, QZSS, and GLONASS. In December of 2006, a Galileo monitor station was installed, and detailed plans have been made to monitor the GPS/Galileo timing offset (GGTO) **[13]** in parallel and in concert with the Galileo Precise Timing Facilities (GPTF). The GGTO will be measured by direct comparison of the received satellite timing, and by the use of TWSTT to measure the 1-pps offset between the time signals at the USNO and GPTF. The GGTO will eventually be broadcast by both GPS and Galileo, for use in generating combined position and timing solutions. To exchange similar information with the QZSS system, plans are underway to establish a TWSTT station in Hawaii.

With the use of multiple GNSS systems, problems involving receiver and satellite biases will become more significant. These have been shown to be related to the complex pattern of delay variations across the filtered passband, and correlator spacing. In principle, every satellite would have a different bias for every receiver/satellite combination **[14]**. USNO has analyzed how 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 4) **[15]**

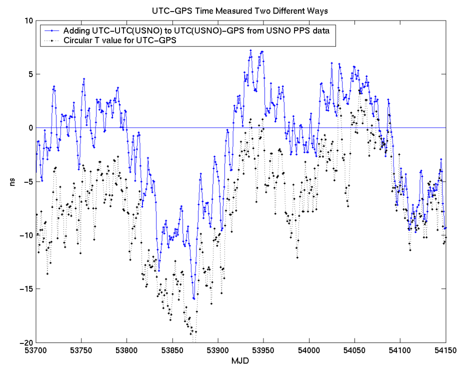

Figure 4. UTC-GPS as reported in the Circular T, and UTC-GPS inferred by subtracting UTC(USNO)-GPS from UTC-UTC(USNO). UTC(USNO)-GPS can be obtained form satellite broadcasts, and is also measured directly at the USNO.

The most accurate means of operational long-distance time transfer is TWSTT **[16-18]**, 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 **[19]** 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 **[20]**. 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.

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 5). 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 vibrationaly isolated piers. The instrument racks will be standardized at all USNO locations.

Figure 5. New clock building, November 2006

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.

VI. ACKNOWLEDGEMENT

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