

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 20 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 will describe some of the changes being made to meet the anticipated needs of our users 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 22 onboard employees. Of these, the largest group, about 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 trying to develop new ones.

The core stability of USNO time is based upon our clock ensemble. We currently have 74 HP5071 cesium clocks made by Hewlett-Packard/Agilent, 4 cesium CsIII-EP clocks made by Datum/Symmetricon, and 21 cavity-tuned "Sigma-Tau/Datum/Symmetricon" hydrogen maser clocks, which are located in two Washington, D.C., buildings and also 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%. Our timescale is based only upon the Washington, D.C., clocks. In November 2004, 74 standards were weighted in our timescale computations. We also are assembling parts for a rubidium fountain that we plan to have functional in late 2005, and are experimenting with a stored-ion mercury-based frequency standard [1].

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 2005		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Time and Frequency Activities at the U.S. Naval Observatory				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Naval Observatory 3450 Massachusetts Avenue, N.W. Washington, DC 20392-5420				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES 2005 Proceedings of the 36th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, held 7-9 December 2004 in Washington, D.C. (http://tycho.usno.navy.mil/ptti) , The original document contains color images.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 14	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

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

Before averaging data to form a timescale, real-time and postprocessed clock editing is accomplished through deviations in terms of frequency and time; all our clocks are detrended against the average of our best detrended cesiums [2]. A maser average represents our most precise average in the short term, and the detrending ensures that it is equivalent to the cesium average in the long term. A.1 is our operational timescale; it is dynamic in the sense that it weights recent maser and cesium data by their inverse Allan variance at a tau equal to the age of the data. Both A.1 and our maser mean are available on our Web pages.

UTC (USNO) is created by steering the A.1 timescale to UTC using a steering strategy called “gentle steering” [3-5], which minimizes the control effort used to achieve our desired goal. To physically realize UTC (USNO), 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 [3-5]. The MC has a backup maser and an AOG in the same environmental chamber. On 29 October 2004, we changed our steering method so that state estimation is achieved with a Kalman filter with a gain function as described in [6]. Because the Kalman filter takes as inputs only the most recent hourly observation of the Master Clock’s difference with the maser mean, it can steer very closely to the A.1 because that timescale is maser-dominated in the short run. 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 our operations is our 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). This year we have purchased 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 with 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, and it is our plan 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]. The steered cesium-only timescale would either be based upon the Percival Algorithm [2], 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 the USNO Master Clock's time has compared to UTC and also how its frequency has compared to our unsteered maser mean. The figure does not show the stability over daily and subdaily periods of most interest to our users, particularly our navigational users. That is shown statistically in Figure 2.

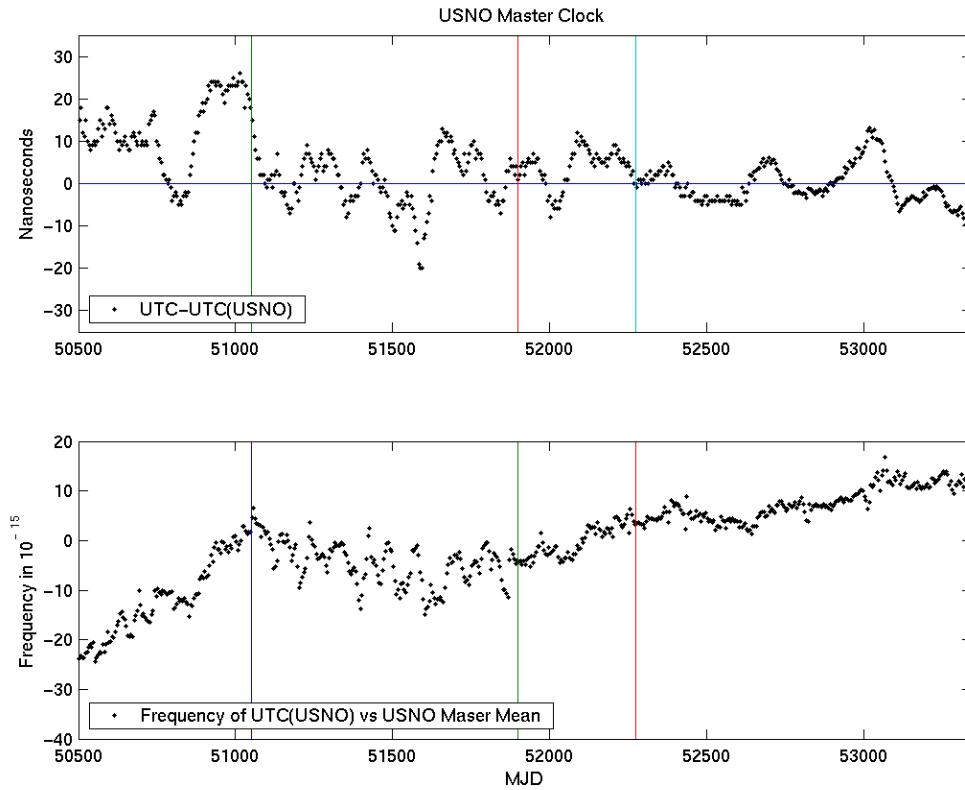


Figure 1. Interplay between time and frequency stability from February, 1997 to the present. Top plot is UTC - UTC (USNO) from the International Bureau of Weights and Measure's (BIPM's) Circular T. Lower plot shows the frequency of the Master Clock referenced to the maser mean. The rising curve previous 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. Vertical lines indicate the times of these changes. UTC (USNO) has stayed within 5 ns rms of UTC for 6 years.

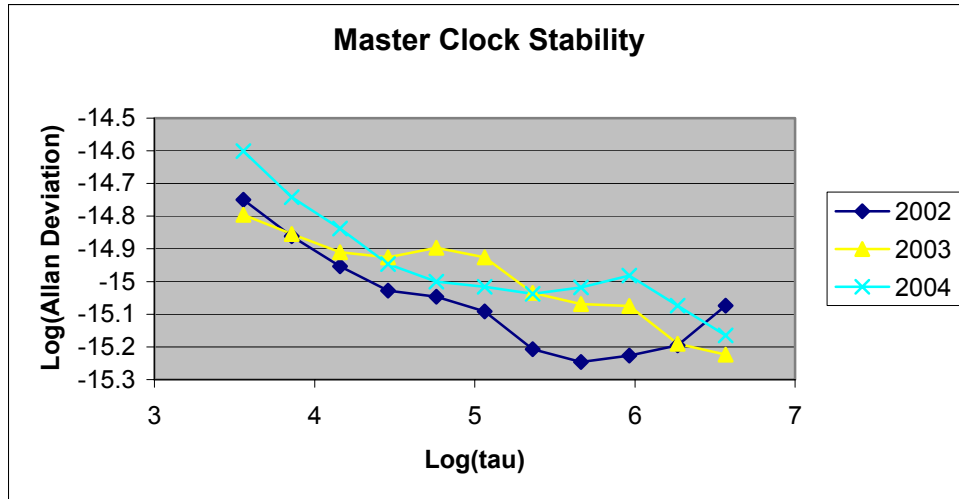


Figure 2. Short-term stability of the USNO Master Clock, referenced to the USNO maser mean. The Allan deviation measures how much the fractional frequency changes from one interval, τ , to the next.

Most of our users need and desire access to only the MC. This 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 our 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.

III. TIME TRANSFER

Table 1 shows how many times in 2003 we were queried by various systems. The fastest-growing service is our Internet service Network Time Protocol (NTP); the number of individual requests has 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 our Washington, DC site, which saturated the Internet connections [9]. Due to this saturation, perhaps a third of the NTP requests sent to our Washington site are not responded to. We expect to upgrade our capacity in a few months, but frequent upgrading of our Internet capacity may prove insufficient to cope with the projected growth. Our server also responds to a large but unknown number of NTP-like service requests involving telnets through ports 13 and 37. Along with our public service, we also have an NTP service on the DoD's classified SIPRNET, which we are now increasing to include two overseas sites. In late 2003, we upgraded our entire NTP array so as to have identical units with up-to-date software capable of supporting authenticated NTP, which we have made operational at the AMC.

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

Telephone Voice-Announcer	820,000
Leitch Clock System	110,000
Telephone Modem	710,000
Web Server	400 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 three sites: Ft. Richardson, AK, Flagstaff, AZ, and Washington, D.C. 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 sanity check [10], and we have this year initiated 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 in 2004 the rms of the difference of its daily average values with UTC (USNO) was below 3 ns. As shown in Figure 3, users who need tighter access to UTC (USNO) can achieve 1.1 ns rms 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 4 shows the rms stability of GPS Time and that of GPS's delivered prediction of UTC (USNO) as a function of averaging time. Note that rms corresponds to the component of the "Type A" (random) component of a user's achievable uncertainty.

Figure 5 shows the rms of frequency accuracy and the frequency stability as measured by the Allan deviation (ADEV) over the same time period as Figure 4. The ADEV is shown for comparison; however, there is little justification for its use, since the measured quantity is stationary. In this case, the sample standard deviation 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 [11]. Our standard setup includes temperature-stable cables and flat-passband, low-temperature-sensitivity antennas. In addition, we have upgraded our single-frequency Standard Positioning Service (SPS) receivers from single-channel TTR-6 to multi-channel 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 dome on our roof.

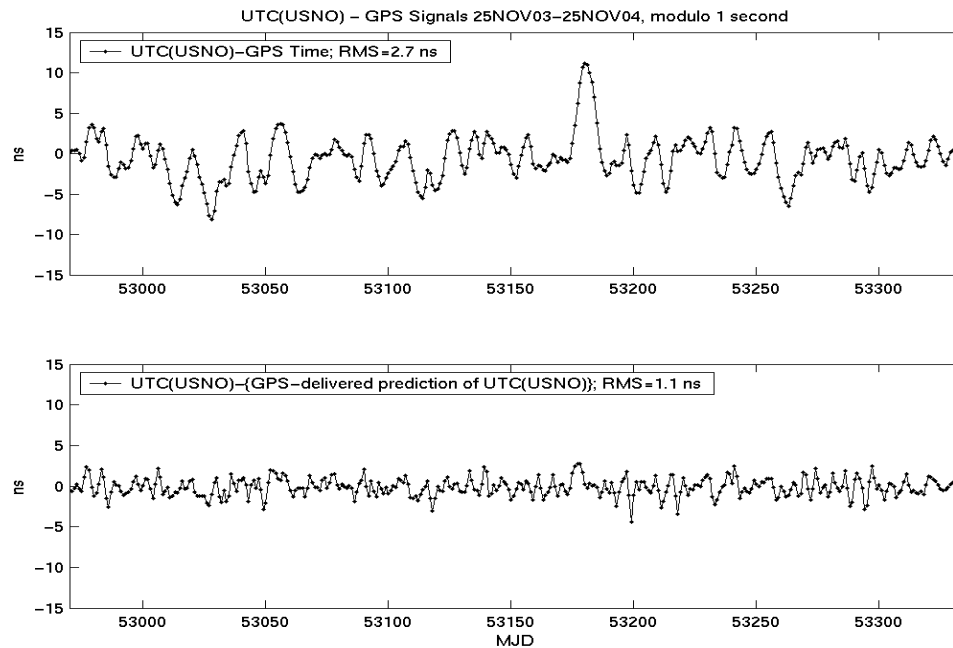


Figure 3. Daily averages of UTC (USNO) minus GPS Time and UTC minus GPS's delivered prediction of UTC (USNO) from December 2003 through November 2004.

This year we accepted a prototype SAASM GPS monitor receiver, designated PTTR-12CS. In previous years, we funded the development of a beam-steered antenna, which we hope will eliminate multipath effects directly [12]. This is currently scheduled for delivery in 2005.

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 [13]. 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 [14]. 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.

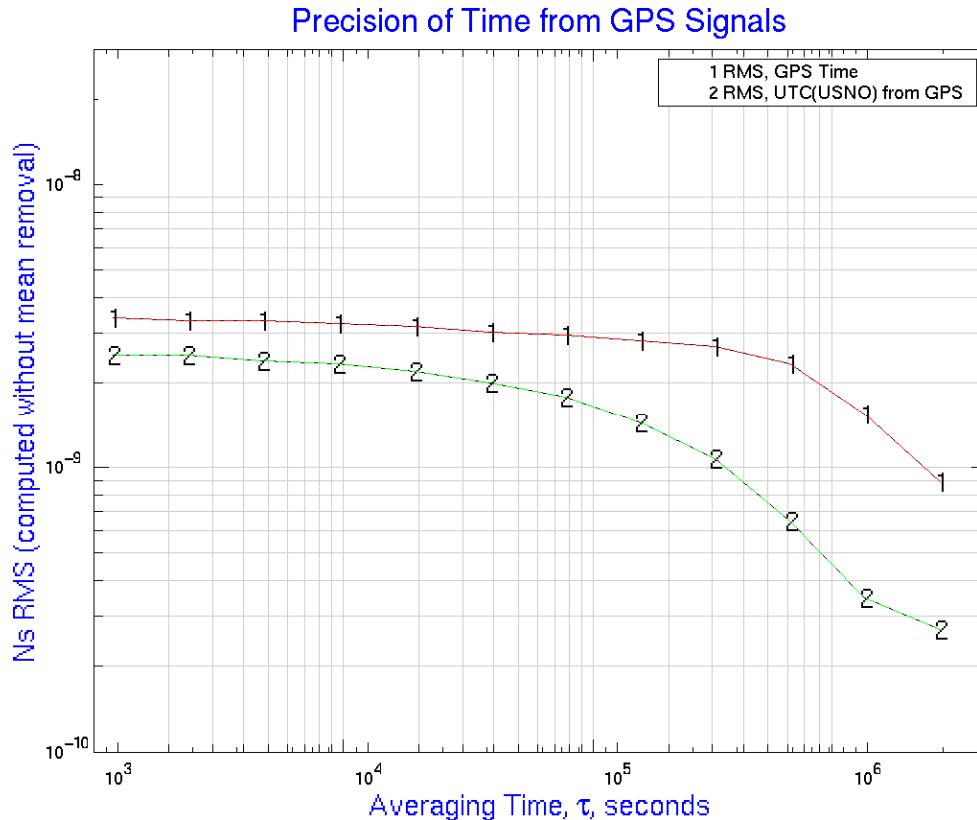


Figure 4. The precision of GPS Time and of GPS's delivered prediction of UTC (USNO), using TTR-12 data from 11JUL02 to 16DEC04, measured by the attainable external precision (rms, mean not removed) as a function of averaging time, and referenced to UTC (USNO). Improved performance in the predictions of UTC (USNO) could be realized if only the most recently updated navigation messages are used. The attainable accuracy is the precision degraded by the error of the user's calibration relative to the USNO GPS receivers.

In 2003, the Wide-Area Augmentation System (WAAS) became operational. We have been collecting data on WAAS network time (WNT), and Figure 6 shows how that time has improved over the past few years. The data shown here extract WNT using only the geostationary satellite, and are not directly calibrated. Daily averages generated by averaging WNT with WAAS-corrected time from GPS satellites are very similar. 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 most accurate means of operational long-distance time transfer is TWSTT [15-17], and the USNO has strongly supported the BIPM's switch to TWSTT for TAI generation. We routinely calibrate and recalibrate our TWSTT with 20 sites each year, and in particular we maintain the calibration the transatlantic link with the PTB through comparisons with observations at a second TWSTT frequency [18] and with the carrier-phase GPS receivers whose IGS designations are USNO, USN1, and PTBB. Our calibration van is shown in Figure 7; although intended mostly for operation within the continental United States (CONUS), it is small enough to fit on two types of military transport planes. It also has an improved satellite-finding system and can be upgraded

to simultaneously do TWSTT between two sites operating at two different frequencies. For improved precision, we have made some efforts to develop carrier-phase TWSTT [19]. 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 our outdoor electronics packages (Figure 8).

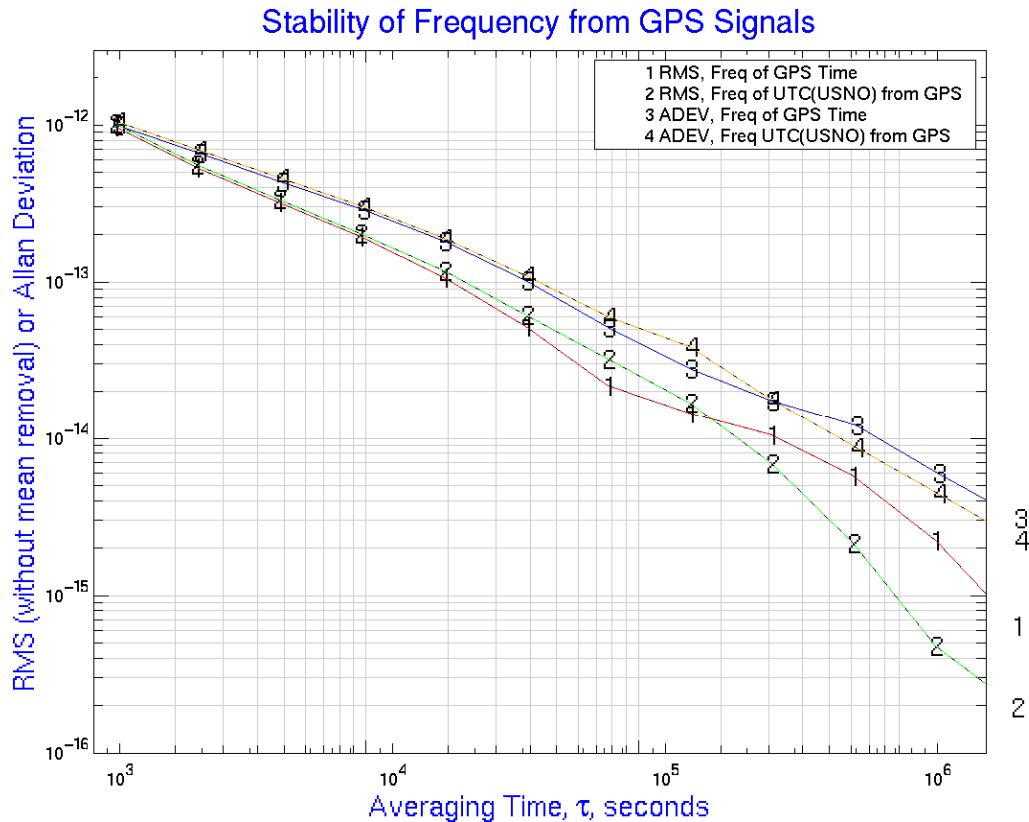


Figure 5. Rms (mean not removed) frequency external precision and the frequency stability, as measured by the Allan deviation, of GPS Time and for GPS's delivered prediction of UTC (USNO), using TTR-12 data from 11JUL02 to 16DEC04. Reference frequency is that of UTC (USNO).

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 [17]. 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 being tested as a possible IGS product [20]. The USNO is currently contributing to real-time carrier-phase systems run by JPL/NASA [21] and the Canadian real-time NRCan networks [22].

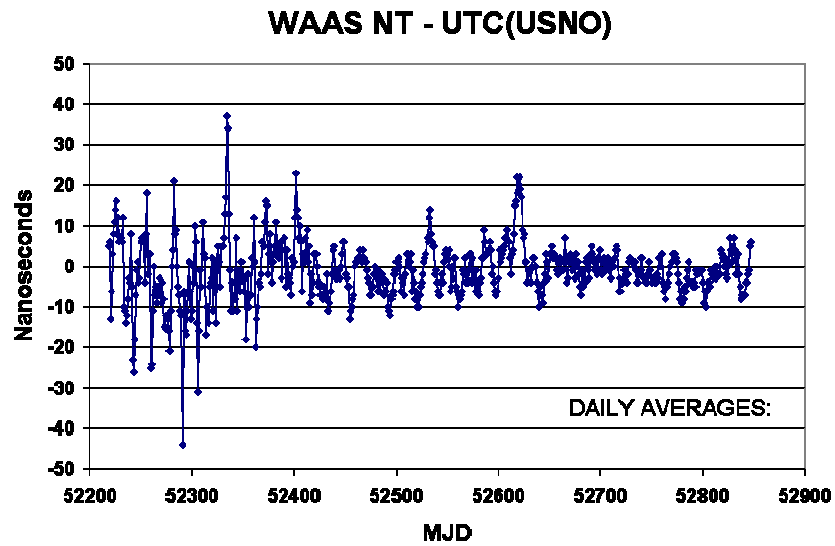


Figure 6. Improvement in WAAS Network Time, as measured using only transmissions from geostationary satellite observations. Data are daily averages shifted to be zero-mean.

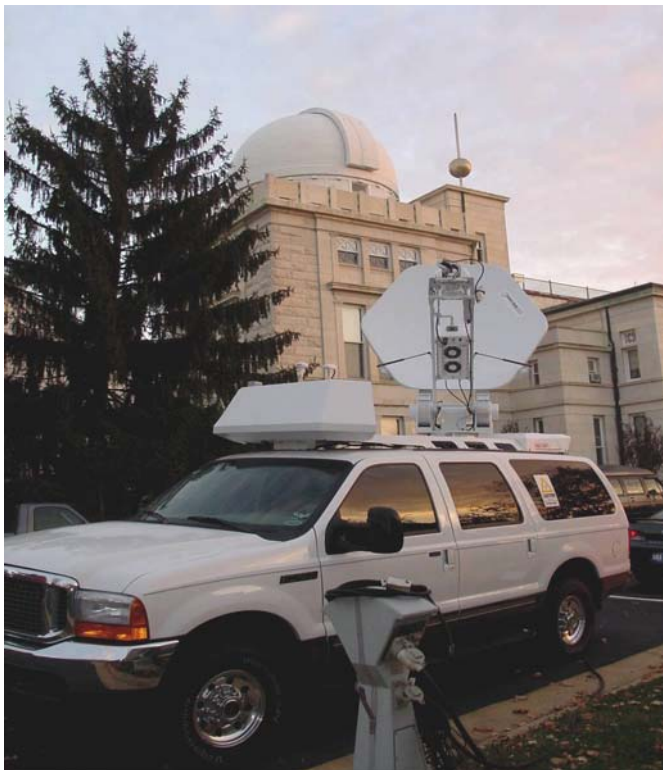


Figure 7. The Mobile Earth Station for TWSTT calibration made two cross-country multiple-stop round trips this year, and several shorter ones. Small enough to be carried on a C141 military transport plane, it could be equipped to serve as a hop-link by communicating through two different satellites and/or frequencies simultaneously. Its automated pointing system makes it easy to find a satellite in the field. In the background one can see a functional copy of the Time Ball originally built to transfer time to ships sailing up the Potomac River.



Figure 8. Thermoelectric all-weather chamber for TWSTT electronics.

The continuous real-time sampling by highly precise systems will be increased when the USNO-DC becomes a full-fledged GPS monitor site, in cooperation with the National Geospatial-Intelligence Agency (NGA). This is currently scheduled for 2005 as part of the Accuracy Improvement Initiative (AII). We anticipate that NGA will install improved GPS receivers, which would make possible an alternate means of providing time directly to GPS, both at our Washington site and at the AMC.

IV. MEASURES TO SECURE THE ROBUSTNESS OF THE MASTER CLOCK

The most common source of non-robustness in our systems is the occasional failure of our environmental chambers. In order to minimize such variations, and to house our fountain clocks, we have been approved for a new clock building, whose design phase will begin in early 2005.

Our clocks are protected by an electrical power system whose design includes multiple parallel and independent pathways, each of one 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 effect 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 to the robustness of the system.

The common design in all our 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 our 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. To supplement the automated system, we have installed a password-protected Web-based monitoring system so that any employee who has access to the Internet can check the health, documentation, and status of our key systems at any time.

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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