Time and Frequency Activities at the U.S. Naval Observatory

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), which has stayed within 4 ns RMS of UTC since January 1, 2001. The data used to generate UTC(USNO) are based upon 73 HP5071 cesium and 18 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 26 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 73 HP5071 cesium clocks and 18 cavity-tuned "Sigma-Tau/Datum/Symmetricom" 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 December 2003, 59 standards were weighted in our timescale computations. We also temporarily constructed a cesium fountain, which had a measured stability of 10^{-15} at 1 day; and are assembling parts for a rubidium fountain that we plan to have functional by 2005.

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 post processed 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"[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. A second master clock (mc), fully duplicating the MC, is located in an adjacent chamber and steered using the same algorithm as the MC. 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 using Two-Way Satellite Time Transfer (TWSTT) and modern steering theory [6] the difference is often less than 1 nanosecond (ns). We have not yet integrated the three masers and 12 cesiums at the AMC with the USNO's Washington, DC timescale, but it remains a possibility that carrier-phase TWSTTor 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 [7], 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 TAI itself. In 2003 we began field-testing an algorithm, which 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[8]. The steered cesium-only based timescale would either be based upon the Percival Algorithm [2], a Kalman-filter, or an ARIMA algorithm. Individual masers could be steered to the cesium-only timescale before being averaged to create the maser-only timescale.

III. 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.

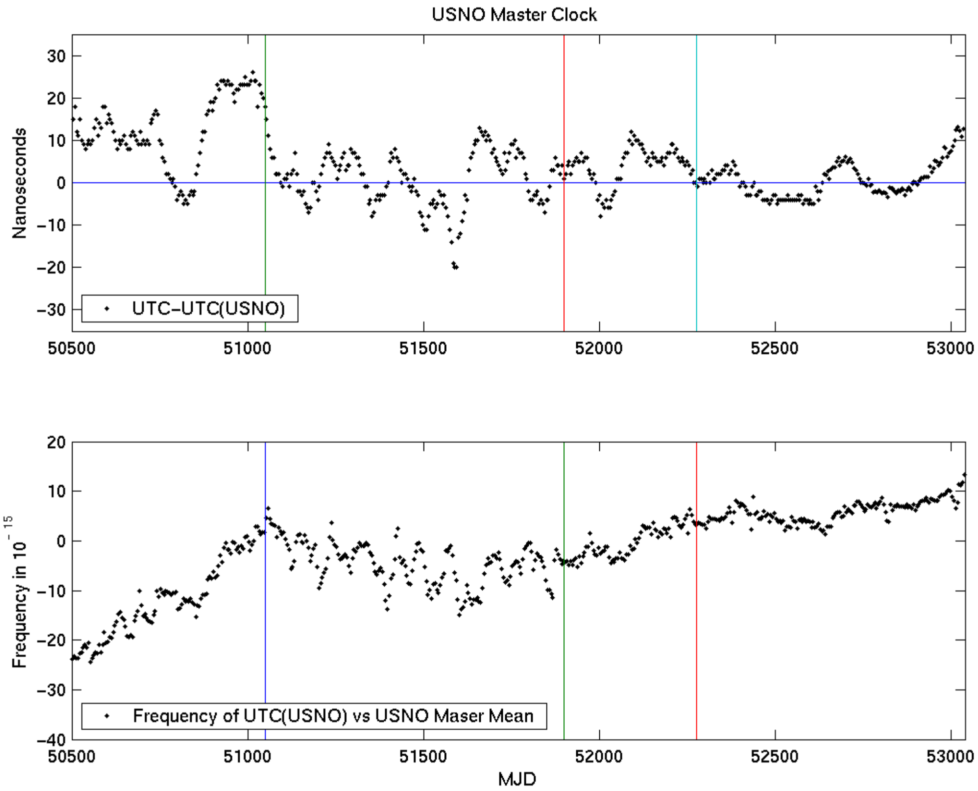


Figure 1. Interplay between time and frequency stability from February, 1997 to the present. Top plot is UTC-UTC(USNO) from the BIPM's Circular T. Lower plot shows the frequency of the Master Clock referenced to the maser mean. The rising curve previous to MJD 51000 is due to the graduated introduction 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 4 ns RMS of UTC for over 2 years.

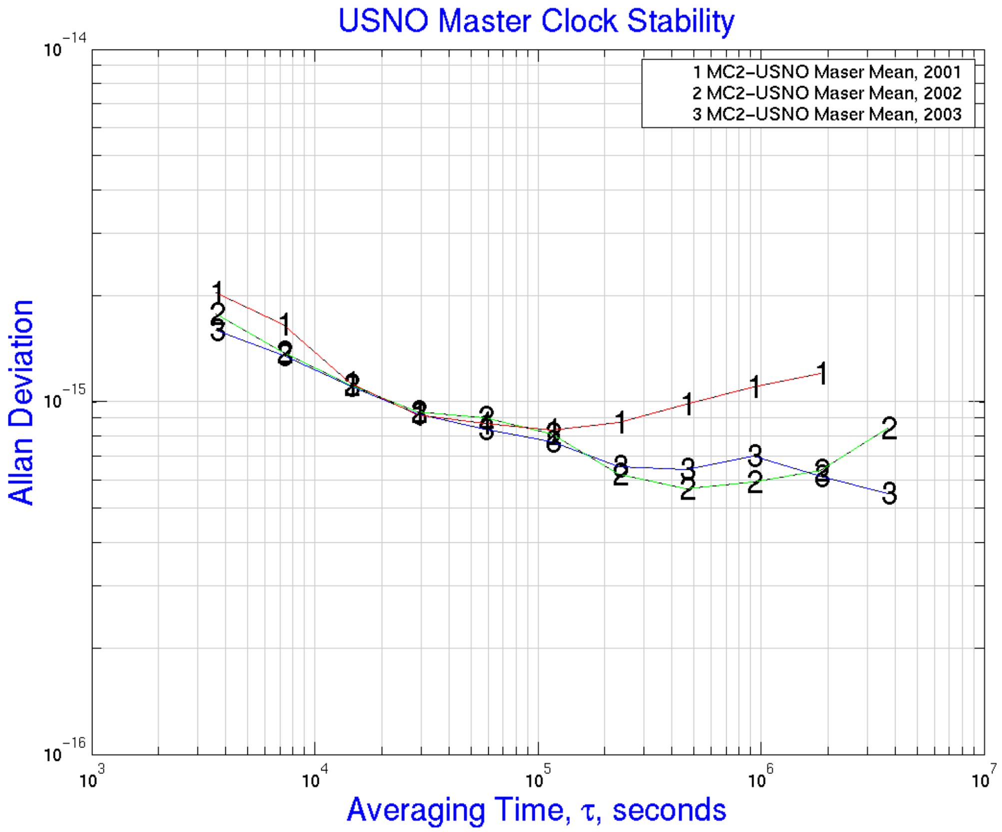


Figure 2. Short-term stability of the USNO Master Clock, referenced to the USNO maser mean. The Allan deviation measures how much the fractional frequency changes from one interval, τ, to the next. The improvements since 2001for τ longer than 1 day (~10^5 seconds) are probably due to our less aggressive clock characterization strategy. The difference for short τ is not significant since the Master Clock's maser is currently steered once per day.

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.

IV. 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. In addition, our server 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 have made plans to expand. In 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	60 million
Network Time Protocol (NTP)	100 billion

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, DC. 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. Figure 3 shows daily data from one of the chains we officially observe from our Washington, DC facility. Data from all our chains can be found in [9].

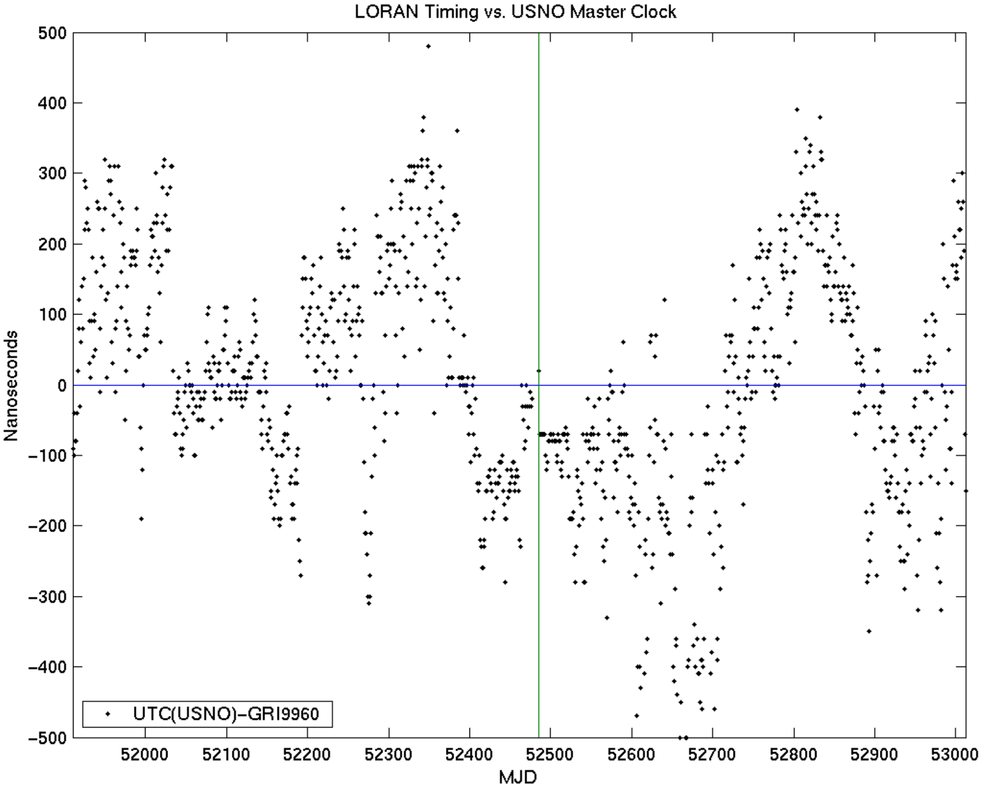


Figure 3. Timing performance of the LORAN chain GRI 9960 monitored from the USNO's Washington, DC facility, from January 2001 to December 2003. On MJD 52484 the computer system was upgraded. Note that the data are noisier and systematically offset during winter months.

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 2003 the RMS of the difference of its daily average values with UTC(USNO) was about 4 ns. As shown in Figure 4, users who need tighter access to UTC(USNO) can achieve 1.3 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.

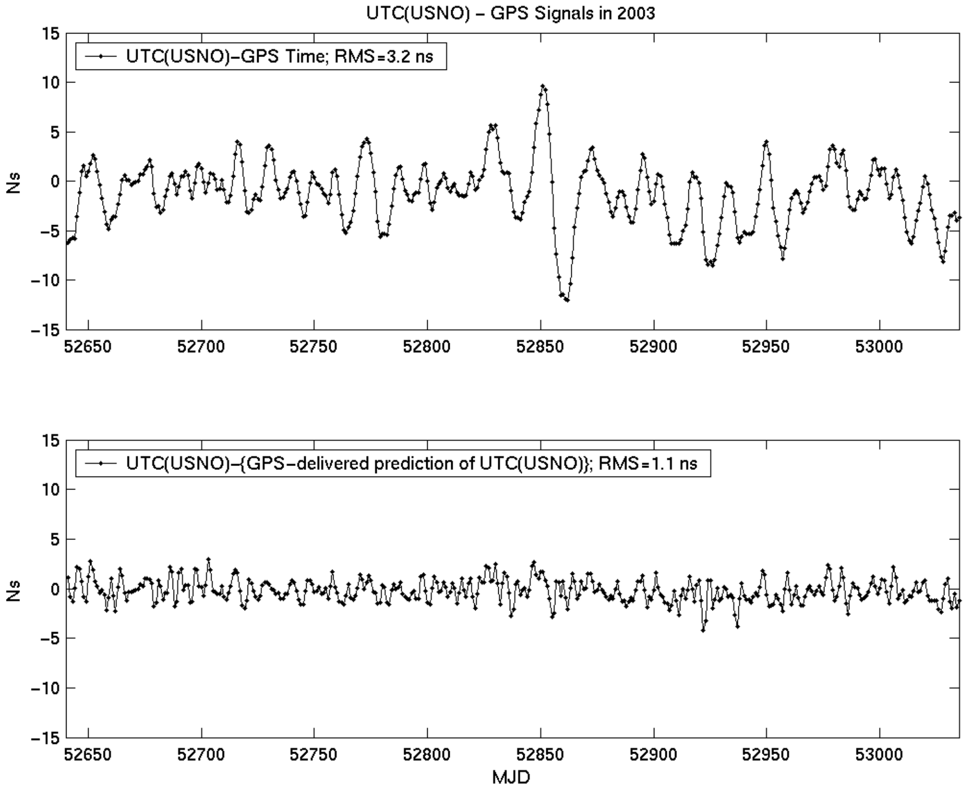


Figure 4. Daily averages of UTC(USNO) minus GPS Time and UTC minus GPS's delivered prediction of UTC(USNO) over 2003.

Figure 5 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.

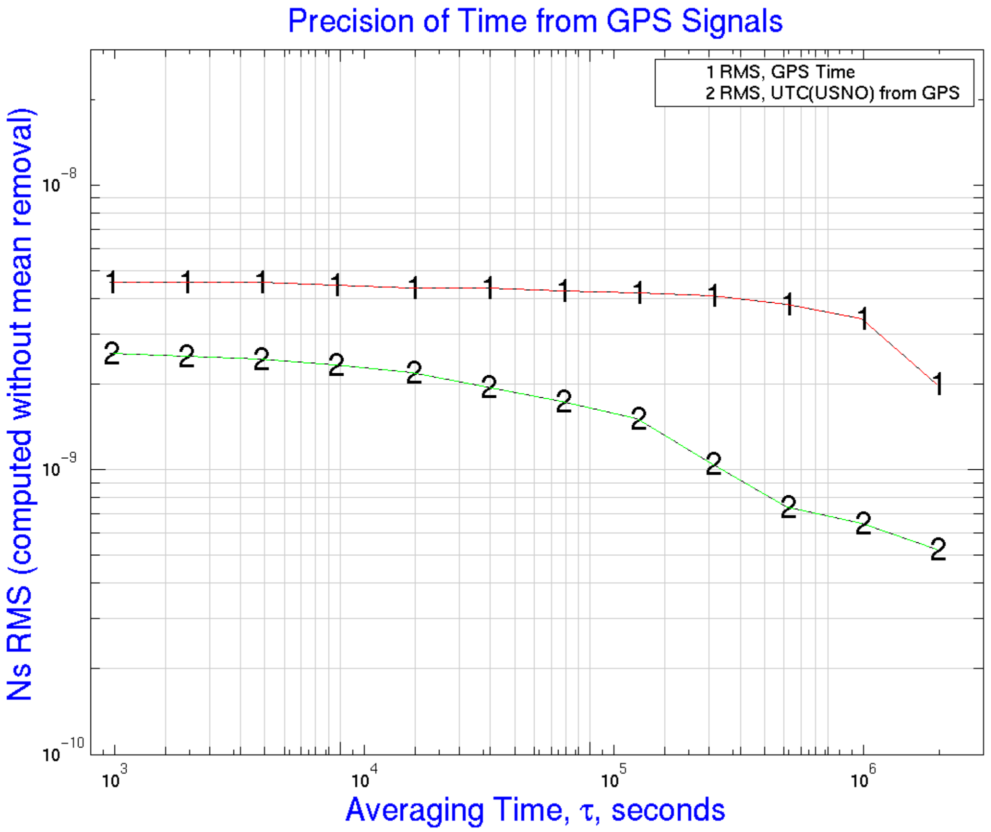


Figure 5. The precision of GPS Time and of GPS's delivered prediction of UTC(USNO), using TTR-12 data from 11JUL02 to 9JAN04, measured by the attainable external precision (RMS, mean not removed) as a function of averaging time, and referenced to UTC(USNO). Improved performance in the predictions of 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.

Figure 6 shows the RMS of frequency accuracy and the frequency stability as measured by the Allan deviation (ADEV) over the same time period as Figure 5. 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.

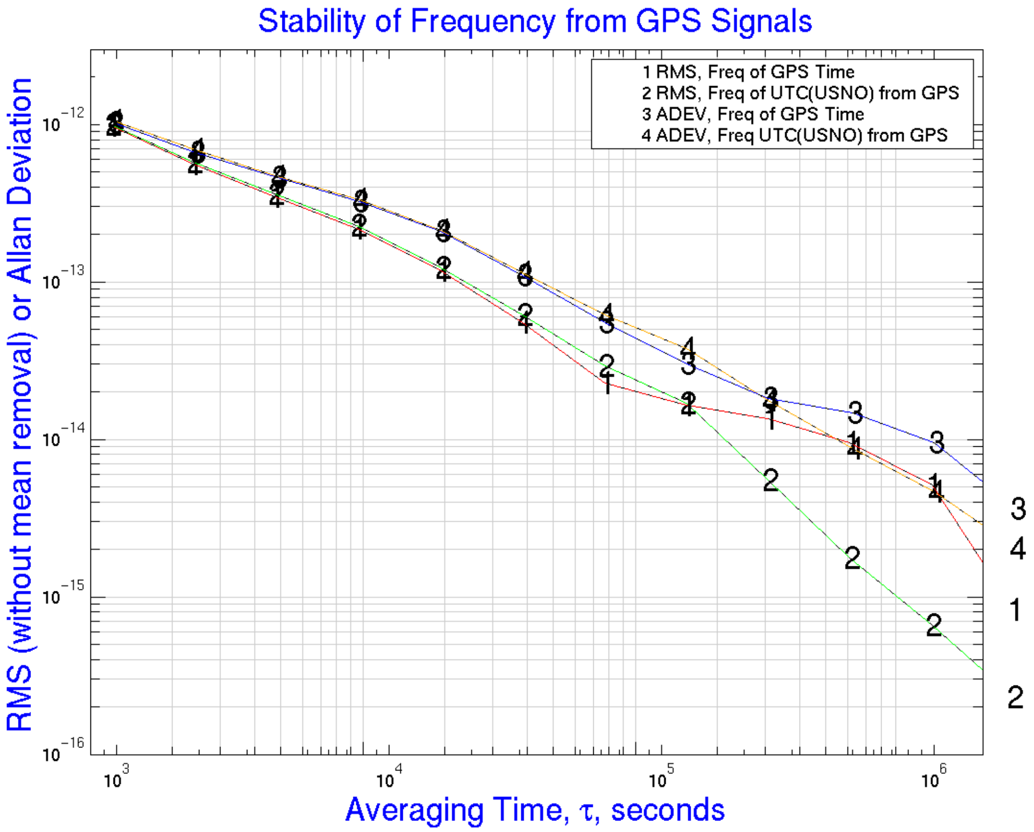


Figure 6. RMS (mean not removed) frequency external precision and the frequency stability, as measured by the Allan deviation, of GPS Time and for GPS's delivered prediction of UTC(USNO), using TTR-12 data from 11JUL02 to 9JAN04. Reference frequency is that of UTC(USNO).

Since July 9, 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 [10]. 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 7).

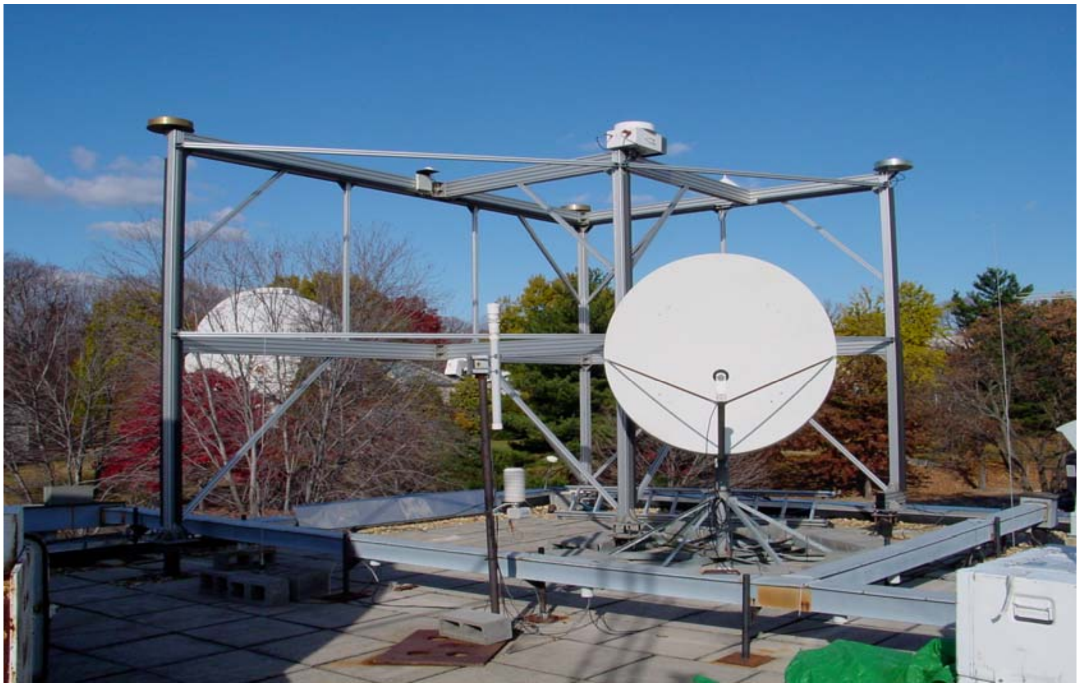


Figure 7. GPS antenna mount, now operational for GPS monitoring, has reduced multipath by roughly a factor of 3. Right of center is a directional antenna used to monitor WAAS signals.

We have also funded the development of a beam-steered antenna, which we hope will eliminate multipath effects directly (Figure 8 and [11]. This is scheduled for delivery in early 2004.

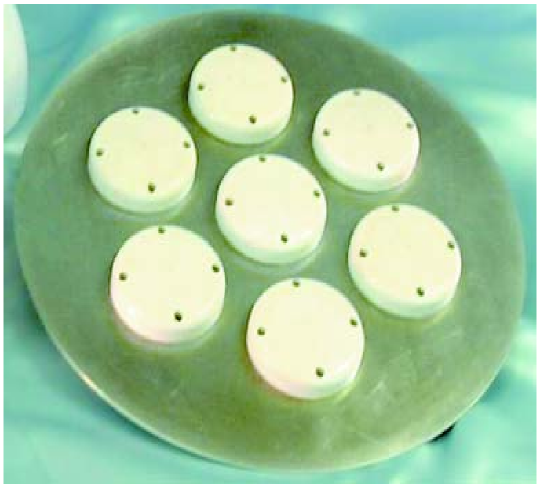
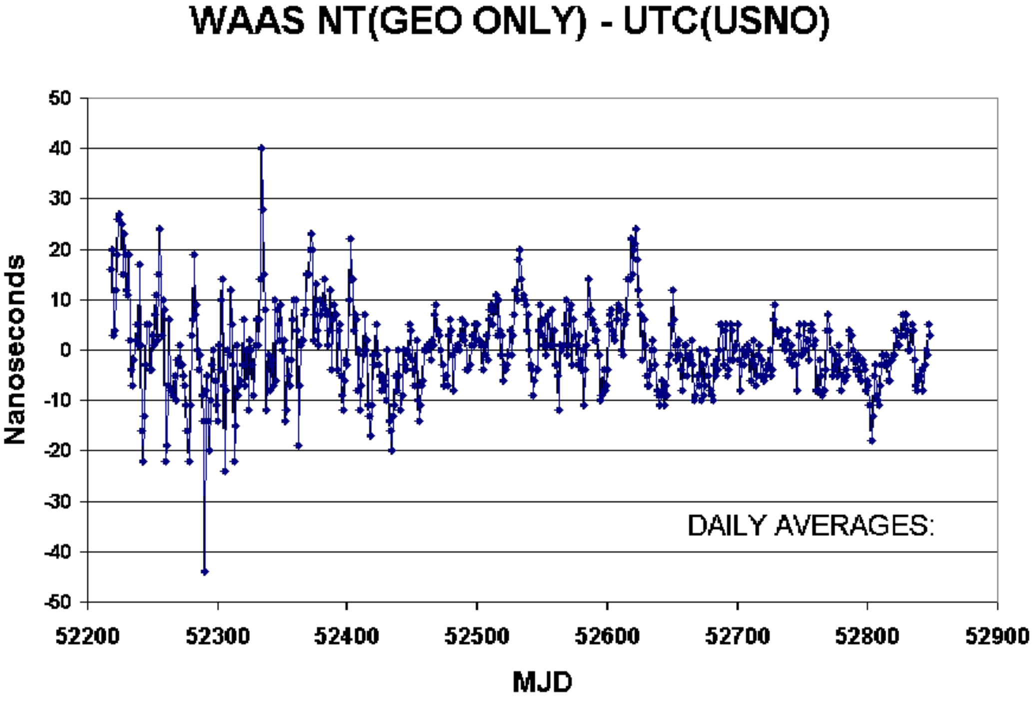


Figure 8. A seven-element HAGR antenna array [11]. As of this writing, the system has not been delivered to or tested by the USNO.

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 [12]. 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 [13]. 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.

In 2003 the Wide-Area Augmentation System (WAAS) became operational. We have been collecting data on WAAS network time (WNT), and Figure 9 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, such as shown in Figure 9, may be the optimal solution for a non-navigational user for whom interference is a problem or jamming may be a threat.

Figure 9 Improvement in WAAS Network Time, as measured using only transmissions from geostationsary satellite observations. Data are daily averages shifted to be zero-mean.

The most accurate means of operational long-distance time transfer is TWSTT [14], and the USNO has strongly supported the BIPM's switch to TWSTT for TAI generation. We routinely calibrate and re-calibrate our TWSTT with 20 sites each year, and in particular we maintain the calibration the transatlantic link with the PTB. Our calibration van is shown in Figure 10; 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 robustness, we have begun constructing loop-back setups at the USNO and developed temperature-stabilizing equipment to test on some of our outdoor electronics packages.

Figure 10. Mobile Earth Station for TWSTT calibration has been driven 18,000 miles this year. 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.

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 [16]. 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 [17]. The USNO is currently contributing to real-time carrier-phase systems run by JPL/NASA [18] and the Canadian real-time NRCan networks[19].

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 to happen late in 2004 as part of the Accuracy Improvement Initiative (AII). We anticipate that NGA will install improved GPS receivers so that we could provide time directly to GPS, in addition to the frequency we currently provide to the Schriever Monitor Station, through our AMC.

V. 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 uninterruptible power system (UPS) fed by two external power feeds, each one capable of supplying sufficient power. Should they both fail, we have two independent sets of battery backups, either one of which can supply power to essential systems for at least 40 minutes. However, we only need them to work for the few minutes required for our two diesel generators to power up, either of which can cover the load for several days using available fuel. Should all this fail, we have local batteries at the clocks, which will last another 8 hours. To further save power, we do not use the UPS for computer terminals, room lights, and non-essential equipment. Although we have never experienced a complete failure of this system, most of the components have failed at least once. In 2003 we installed a third external power feed to give added redundancy. Although the installation was completed in time, it fortunately proved unnecessary to protect against Hurricane Isabel, which passed over our Washington facility without damaging the Master Clock or our time-transfer systems.

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.

VII. 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.

Appendix I. Details of USNO-PTB calibration, from reference [21]

The USNO calibration of the link with PTB is based upon using TWSTT technology to measure the time difference between two on-time 1-pps time-ticks, which are directly traceable to UTC(USNO) and UTC(PTB). Once the time difference is known absolutely, it can be used for relative calibration of all TWSTT and GPS links by correcting for the difference between the actual measured time difference and the nominal value of each system being calibrated. In order to be independent of satellite transponder delays, absolute calibration was achieved with an X-band satellite to which the two sites share a common footprint. The first step in the calibration is to measure the common-clock difference between a fixed X-band antenna and a portable X-band system that was set adjacent to it. The portable system was then dismantled and shipped to the PTB in Germany, where it was reassembled and used to make more measurements against the fixed antenna at the USNO. The mobile system was then returned to the USNO, and the calibration consistency was verified by a repetition of the common-clock observations against the USNO's fixed TWSTT system. Verification was only possible to a sigma of 40 ps due to the failure of a critical component shortly after the returned system was set up. It is USNO experience that the consistency between pre-shipment and post-shipment measurements is always as expected from statistical considerations, unless there is already evident equipment malfunction. After applying the Sagnac and other standard corrections, the absolute time difference between the USNO and PTB reference times was found. This calibration was subsequently applied to both the X-band and the Ku-band TWSTT links. The calibration was repeated eight months later, in January of 2003, and found unchanged to well within the estimated uncertainty.

Figure 11 shows the USNO calibration spreadsheet for the June 2002 calibration. This calibration involved only the permanent X-band system at the USNO and the mobile X-band system shipped to the PTB for calibration; it did not involve the fixed X-band system at the PTB or either Ku-band TWSTT system. The block diagram shows the TWSTT calibration setup at the PTB. The modem's time reference was the 1-pps output of a divider whose input was the amplified 5 MHz output of a PTB maser (designated H2). The 1-pps time-reference was calibrated against UTC(PTB) using a Time Interval Counter (TIC). The arrangement at the USNO was somewhat simpler, as the modem's time reference for the mobile setup was UTC(USNO) delayed by a cable of 15.4 ns electrical length, while the time reference for the modem used with a fixed X-band antenna is UTC(USNO) delayed by an amount that is automatically compensated for as part of the common-clock calibration step.

									pjw	8/14/2002
PTB	B	C	D	E	F	G	H	I	J	K
date		modem&cable-mc	modem		modem&cable-mc	modem	(C+D)+E-(F+G)=		I+15.45-15.4	-H-J=
6/10/2002	utc	twstt&cable	cable to (X)	sagnac	cal&cable	cable to MC	(X)-MC2	TIC	utc ptb - (X)	MC2-PTB
52435	1315	-22203651.04	15.4	-205.14	-22203810.24	15.4	-45.94	65.32	65.37	-19.43
	1349	-22203651.33	15.4	-205.14	-22203810.24	15.4	-46.23	65.32	65.37	-19.14
	1404	-22203651.00	15.4	-205.14	-22203810.24	15.4	-45.90	65.32	65.37	-19.47
	1414	-22203651.02	15.4	-205.14	-22203810.24	15.4	-45.92	65.32	65.37	-19.45
	1450	-22203650.99	15.4	-205.14	-22203810.24	15.4	-45.89	65.10	65.15	-19.26
	1502	-22203650.94	15.4	-205.14	-22203810.24	15.4	-45.84	65.10	65.15	-19.31
	1520	-22203650.97	15.4	-205.14	-22203810.24	15.4	-45.87	65.10	65.15	-19.28
							-45.94		average:	-19.33
6/11/2002										
52436	1049	-22203652.51	15.4	-205.14	-22203810.24	15.4	-47.41	67.70	67.75	-20.34
	1107	-22203653.70	15.4	-205.14	-22203810.24	15.4	-48.60	67.48	67.53	-18.92
	1201	-22203653.58	15.4	-205.14	-22203810.24	15.4	-48.48	67.60	67.65	-19.17
							-48.16		average:	-19.48
	1413	-22203652.95	15.4	-205.14	-22203810.24	15.4	-47.85	68.19	68.24	-20.39
	1424	-22203653.98	15.4	-205.14	-22203810.24	15.4	-48.88	68.19	68.24	-19.36
	1453	-22203652.76	15.4	-205.14	-22203810.24	15.4	-47.66	68.19	68.24	-20.58
	1502	-22203652.89	15.4	-205.14	-22203810.24	15.4	-47.79	68.19	68.24	-20.45
	1520	-22203653.27	15.4	-205.14	-22203810.24	15.4	-48.17	68.19	68.24	-20.07
	1547	-22203653.31	15.4	-205.14	-22203810.24	15.4	-48.21	68.85	68.90	-20.69
	1610	-22203652.89	15.4	-205.14	-22203810.24	15.4	-47.79	68.85	68.90	-21.11
	1622	-22203653.21	15.4	-205.14	-22203810.24	15.4	-48.11	68.85	68.90	-20.79
							-48.06		average:	-20.43

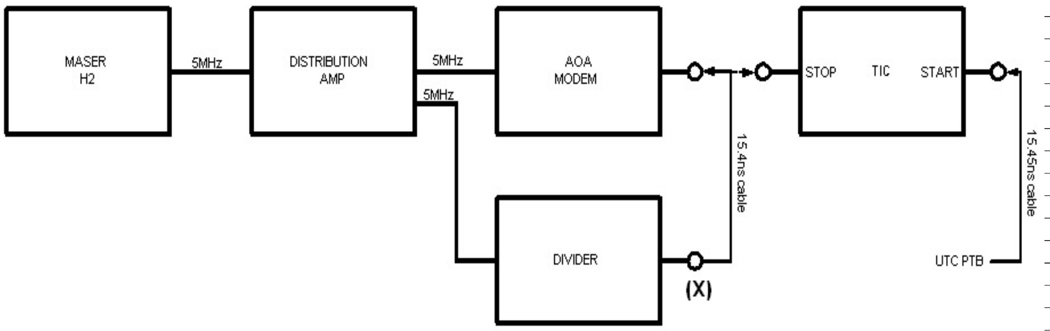


Figure 11. USNO internal spreadsheet providing numerical summary of USNO-PTB calibration. Column C is half the unprocessed time difference measured by the mobile system's modem minus the USNO fixed system's modem when it was at the PTB. Column D is the delay between UTC(PTB) and the PTB's TIC. Column E is the Sagnac correction [14]. Relative calibration of the modems and electronics is achieved using the unchanging values in columns F and G; column F is half the

unprocessed time difference measured by the mobile systems' modem minus the USNO fixed system's when the mobile system was at the USNO, column G is the cable delay between the mobile system's time reference at the USNO and UTC(USNO). The TIC-measured offset of the PTB time reference is indicated in column I. Note that the time-delay of the cable used to carry the signal from the PTB's divider (position X in the plot) to either the modem at the PTB or the TIC is not relevant to the computation. Columns H and J provide intermediate arithmetic steps for the computation of UTC(USNO)-UTC(PTB), shown in column K. The block diagram describes the setup of the portable TWSTT system at the PTB, and is described in the text. The 1.1 ns variation between the two days may be due to clock variations.

The type A (random) errors of the 1-pps calibration are estimated from the standard deviation of the mean of the 1-second differences to be approximately 150 ps; additional errors would apply to the application of those values to any given time transfer system. Unfortunately, equipment failure soon after the mobile system was returned to the USNO precluded a precise check for closure errors. As noted above, the author generally estimates the total uncertainty of operationally calibrated TWSTT measurements as 1 ns RMS, except in cases of equipment failure. The 1.1 ns difference between the two days is consistent with the observed difference in two days of parallel Ku-band TWSTT data, and may reflect site clock variations. As a result of this work, the assumed calibration of the USNO/PTB link was adjusted by 3.5 ns from the Circular T value, which was assigned on the basis of a historical GPS-based calibration.

As a general check on the calibration, common-view data from the USNO and PTB operational GPS receivers were adjusted using IGS ionosphere and orbit information and by applying the most recent BIPM-derived GPS receiver calibration [20] and used to derive a value of UTC(USNO)-UTC(PTB) of –16 ns. The 3 ns difference with the TWSTT results could be due to a combination of Type A GPS errors, estimated at 1.3 ns from the RMS of the daily averages, and Type B errors such as systematic multipath.

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