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), which has stayed within 5 ns of UTC in the past year, with an rms deviation of 3 ns. The data used to generate UTC (USNO) are based upon 72 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. While we aim to increase our accuracy and precision, we deem it equally important to bring about robustness, and we recommend this for our users as well. Further details and explanations of our services can be found online at **http://tycho.usno.navy.mil,** ***or by contacting the author directly.***

I. RAW TIME

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 72 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 September 2002, 58 standards were weighted in our timescale computations.

We have also constructed a cesium fountain, which has a measured stability of 10^{-15} at 1 day; and we are ordering parts for a rubidium fountain that we plan to have operational by 2005. In July 2002, we accepted delivery of a "Linear Ion Trap Extended" (LITE) mercury frequency standard built by Jet Propulsion Laboratory (JPL) **[1]**. Preliminary results indicate stabilities better than

10^{-15} at 1 day and a frequency drift lower than 10^{-16}/day. Maintaining the stabilities of these standards will require improved environmental controls, and therefore part of our efforts have gone into requesting funding to construct a building that will be designed for optimal temperature and humidity stability.

We have found it is just as important to take care of our clock measurement systems as it is our clocks. That is why all our connecting cables are phase-stable and of low temperature coefficient, and all our connectors are SMA (screw-on). These measurement systems are designed to take into account the fact that our cavity-tuned hydrogen masers are about 50 times more precise than our cesium clocks in the short run, but over a period of months the precision of the masers falls to where they are not significantly better than the cesiums. 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.

II. TRUE TIME

No clock is perfect, so we use the average to identify which ones are the most imperfect. We do it using both real-time and postprocessed mean timescales (“Means”), to look for deviations in terms of frequency and time. Using the average of good (apparently stable) clocks, we also detrend our clocks by subtracting their long-term frequency rates and drifts compared to the others. Because cesiums are more stable in the long run, we detrend both cesiums and masers against the average of our best cesiums **[2]**. Then we create separate maser and cesium averages. The maser average represents our most precise average in the short term, and the detrending ensures that it is about as good as the cesium average in the long term. To make the very best average relevant to the current time, we create a hybrid timescale that weights recent maser data very heavily but old maser data hardly at all, relative to our cesiums. That time scale, called A.1, is available on our Web site. We also disseminate the maser-only average, called the “maser Mean,” whose utility as a frequency reference will be described later.

Although our timescale is extremely stable, we have found that we can increase stability through international cooperation. To do this, we provide our clock data to the BIPM (International Bureau of Weights and Measures), which averages together clock data from laboratories around the world to produce International Atomic Time (TAI). Adding leap seconds, this is Coordinated Universal Time (UTC). In that average, the USNO’s Washington DC site contribution is now about 40% of the weight; with the USNO’s AMC site the combined weight sometimes exceeds 50%. Once a month, the BIPM computes UTC and publishes the difference between UTC and the Master Clock (MC). We then steer our MC, by speeding it up or slowing it down, so that its time comes close to UTC **[3,4]**. Because the MC is a realization of UTC, its time is termed UTC (USNO). In order to combine the short-term precision of the USNO clocks optimally with the long-term accuracy of UTC, we use a steering strategy called “gentle steering” **[5]**.

To steer the MC, we first create a steered version of our A.1 timescale so that it approximates UTC, and we then steer our MC so that it is in line with our steered A.1. 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), which outputs 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, located at Schriever AFB in Colorado, adjacent to the GPS Master Control Station. We work very hard to keep close communications between the staff at our two sites. We also keep the AMC's mc in close communication with the MC; using Two-Way Satellite Time Transfer (TWSTT), the difference is often less than 1 nanosecond (ns). Although the fundamental steering has always been based upon Linear Quadratic Gaussian control theory, we are always finding ways to improve our algorithms, and this year have implemented a more optimal steering limit **[6]**. 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 the GPS carrier-phase technique 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 reported a couple years ago **[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. We have this year begun 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. The steered cesium-only 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. THE QUALITY OF USNO TIME

The standard test for the quality of a master clock's time is how closely it conforms to UTC. However, this is only half the story. Also important is how stable a master clock is in frequency. Figure 1 shows how the USNO Master Clock has measured up to these two standards over the past several years. 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 makes the interplay between time and frequency stability very apparent. It is to be stressed that even before our switch to gentle steering, on MJD 51369, none of the changes described in the figure caption significantly affected the short-term stability of the MC, which is what is needed by navigational users, and most other users of UTC (USNO). Figure 2 shows the stability of the MC when measured against our maser Mean using our low-noise system for this year and last year.

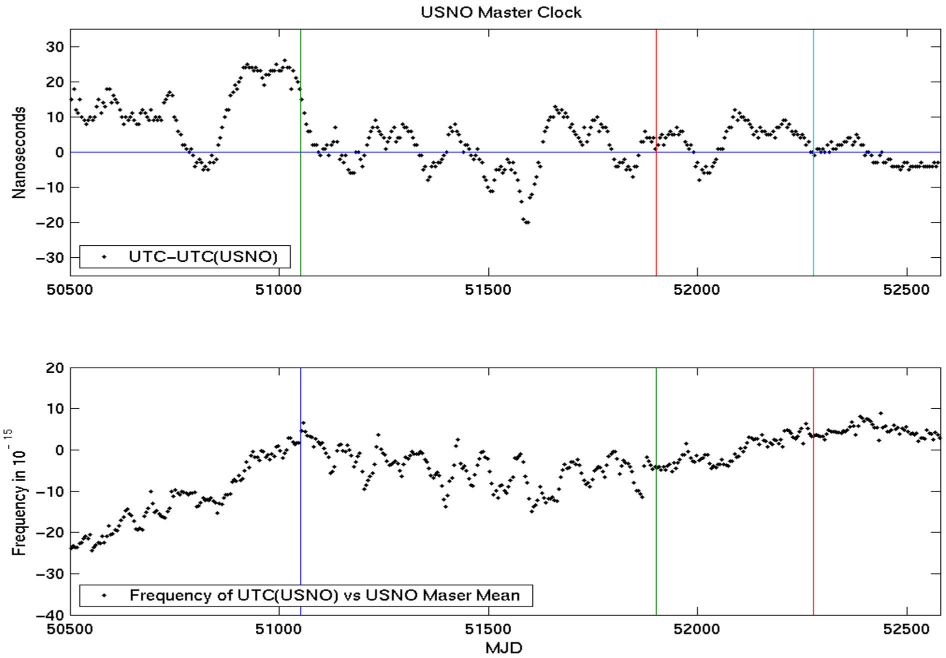


Figure 1. Interplay between time and frequency stability. Top plot is UTC-UTC(USNO) from the BIPM's Circular T. Lower plot shows the frequency of the Master Clock referenced to the maser Mean. The rising curve previous to MJD 51000 is due to the graduated introduction of the 1.7 10^{-14} blackbody correction 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.

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. A very important class of users is made up of those who are interested mostly in frequency stability, and for them we have made available the difference between the MC and the maser mean using anonymous ftp. For almost everyone, however, the MC itself is good enough as a measure of time or frequency.

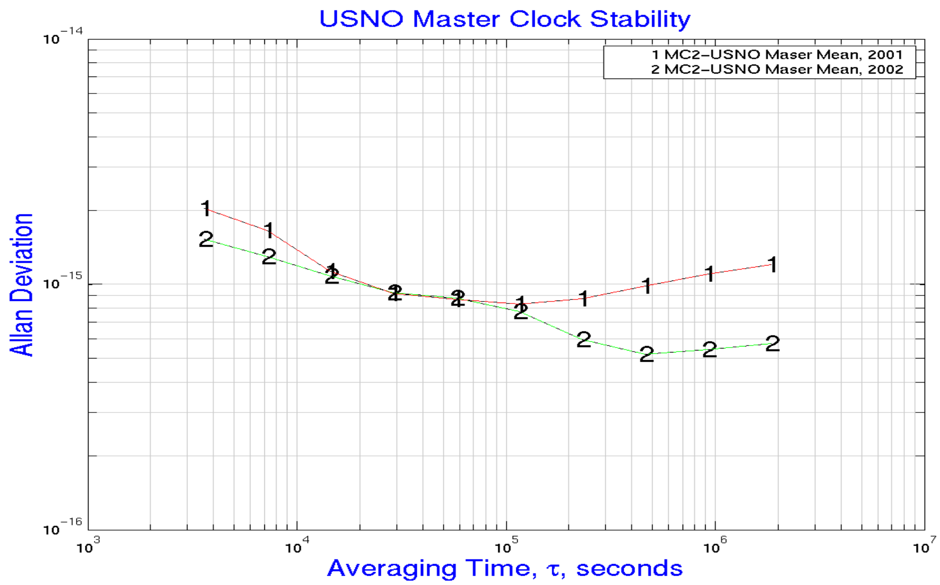


Figure 2. Short-term stability of the USNO Master Clock, referenced to the USNO maser mean. The Allan deviation measures how much the fractional frequency changes from one interval, τ, to the next. The improvement for τ longer than 1 day (~10^5 seconds) is probably due to our less aggressive clock characterization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

IV. TIME TRANSFER

Most of our users do not require our full precision, but we consider it just as important to meet their needs as it is to meet those of our highest-precision users. Table 1 shows how many times in 2001 we were queried by various systems. The fastest-growing service is our Internet service Network Time Protocol (NTP); the number of individual requests we received last year was more than double the preceding year. These billions of requests correspond to at least several million users. The number would be much larger if we counted the 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, and we are now considering development of an authentication service for DoD users.

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

Telephone Voice-Announcer	718,000
Leitch Clock System	721,000
Telephone Modem	520,000
Web Server	60 million
Network Time Protocol (NTP)	34 billion

Greater precision is required for two services for which the USNO is the timing reference: GPS and LORAN. Data are provided daily to those systems so that they can steer to UTC (USNO). USNO monitors LORAN at three sites: Elmendorf AFB, AK, Flagstaff, AZ, and Washington, DC. With some assistance from the USNO, the Coast Guard has developed its "TTM" system so it can steer using data taken near the point of transmission using UTC (USNO) via GPS. Once that system is made operational, direct USNO monitoring at its three points of reception will be used as a backup. Figure 3 shows data from one of the chains we officially observe from our Washington, DC facility. Data from all our chains can be found in **[8].**

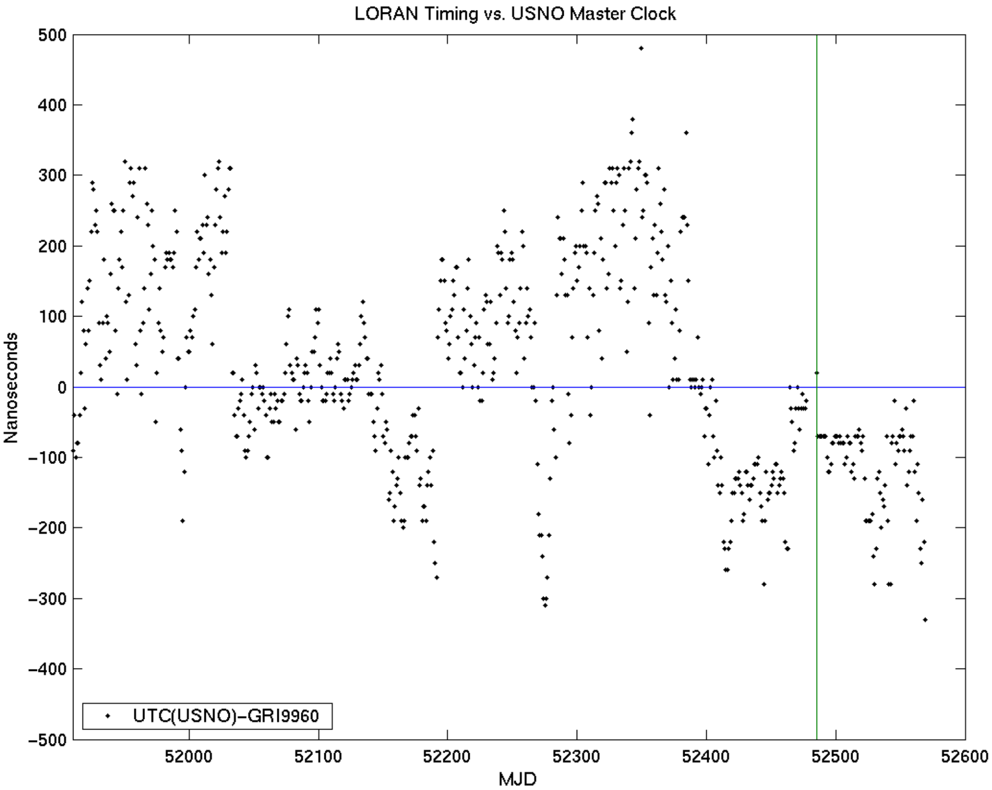


Figure 3. Timing performance of the LORAN chain GRI9960 monitored from the USNO's Washington, DC facility, from January 2001 to October 2002. On MJD 52484, the computer system was upgraded. Note that the data are noisier and systematically offset during winter months.

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 last year 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 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.

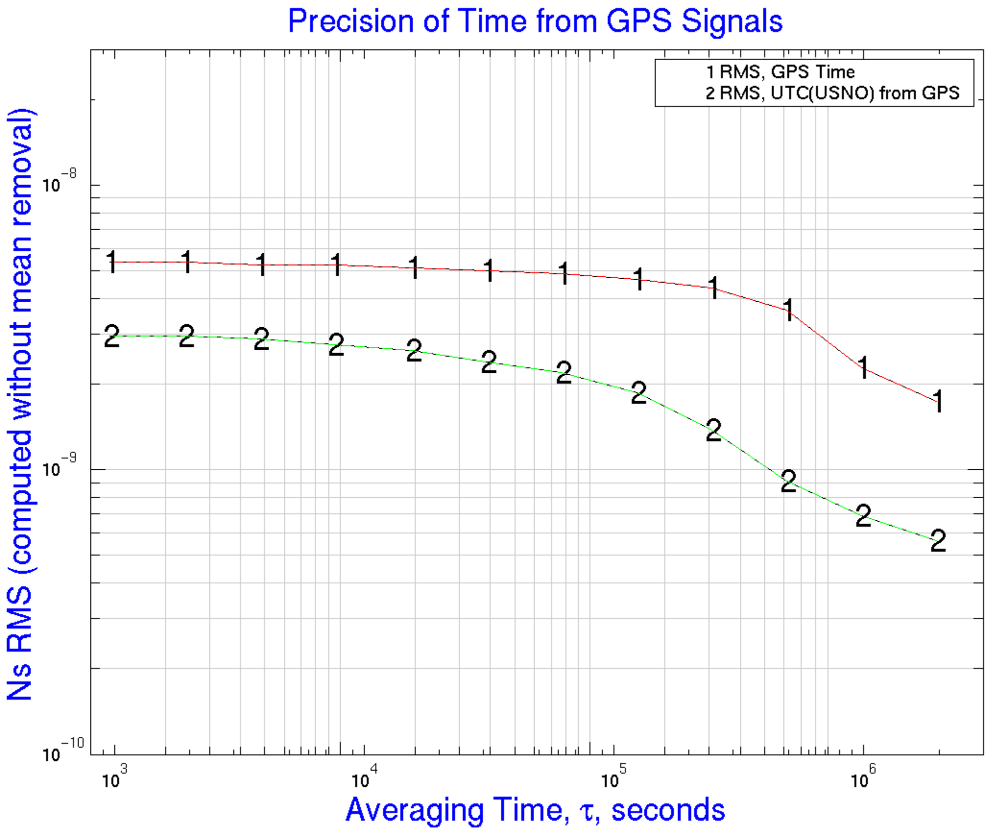


Figure 4. Daily averages of UTC (USNO) minus GPS's delivered prediction of UTC (USNO) for 12 November 2001 to 14 November 2002.

Figure 6 shows the rms of frequency accuracy and the frequency stability as measured by the Allan deviation (ADEV) over the same time period. 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 receivers, which are all-in-view and dual-frequency **[9]**. Our new setup is based upon temperature-stable cables and includes flat-passband, low-temperature-sensitivity antennas. In addition, the USNO has also upgraded its single-frequency Standard Positioning Service (SPS) receivers from single-channel TTR-6 to multi-channel BIPM-standard Motorola units, and we are installing temperature-stabilizing circuits for them. In order to reduce multipath, a 4-meter tall structure was built to locate GPS antennas higher than the dome on our roof (Figure 7).

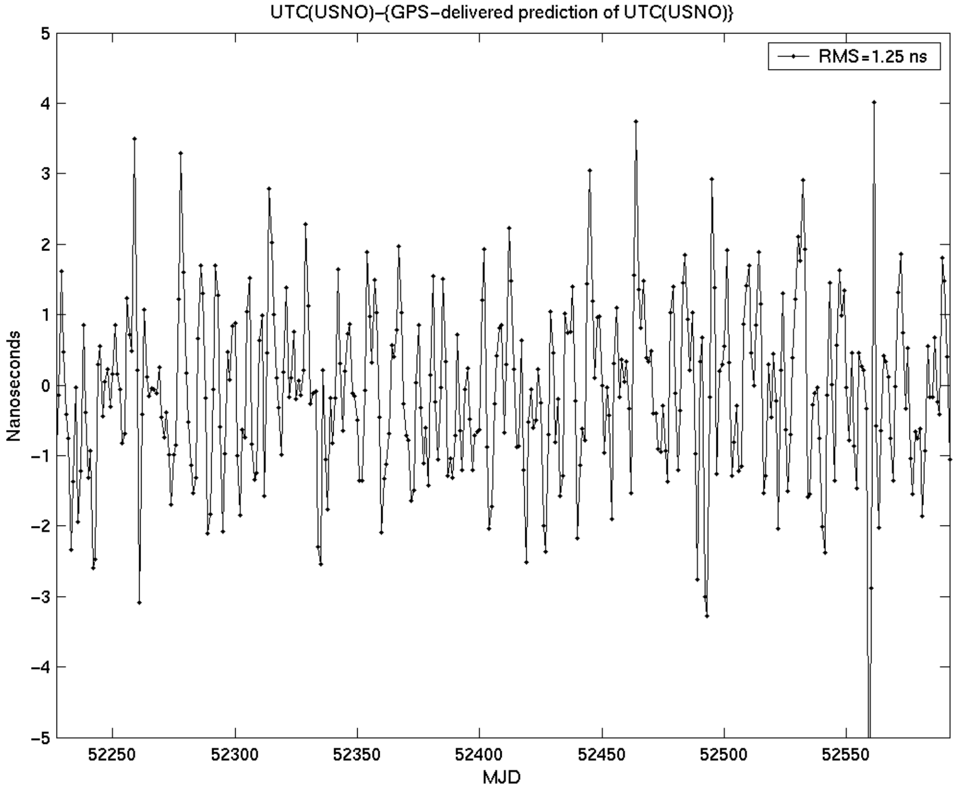


Figure 5. The precision of GPS Time and of GPS's delivered prediction of UTC(USNO), using TTR-12 data from 9 July 2002 to 10 December 2002, measured by the attainable external precision (rms, mean not removed) as a function of averaging time, and referenced to UTC(USNO). Improved performance in the predictions 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 8 shows 13-minute USNO common-clock common view GPS PPS data. The upper plot shows data from our older single-channel dual-frequency systems that ceased to be our primary receivers on MJD 52464 (9 July 2002), but which continued to collect data as previously. These use antennas located about 4 feet above our roof and their data show an rms of 4.4 ns. The bottom plot shows data from the all-in-view dual-frequency TTR-12's that are our current primary receivers. The least noisy periods are when the receivers were on a common antenna, and the 0.1 ns rms is a measure of the receiver noise. The times when the antennas had different antennas show noticeably more noise, and have an rms of 1.3 ns, roughly 1/3 that of the original system. Repeating daily patterns of individual satellite tracks show that the rms's of new and old systems are dominated by multipath, except when they share an antenna.

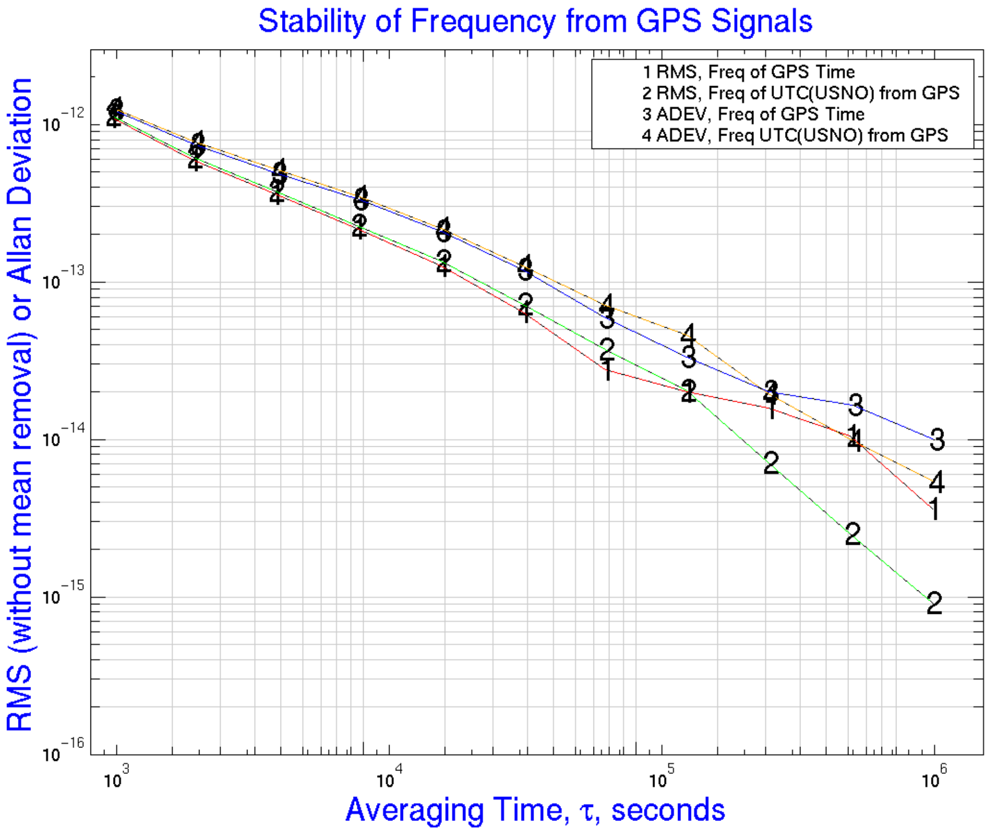


Figure 6. Rms (mean not removed) frequency external precision and the frequency stability, as measured by the Allan deviation, of GPS Time and for GPS's delivered prediction of UTC (USNO), using TTR-12 data from 9 July 2002 to 10 December 2002. The reference frequency is that of UTC (USNO).

We have also funded the development of a beam-steered antenna, which we hope will eliminate multipath effects directly (Figure 9 and **[10]**). This is currently being tested at an antenna test range, and scheduled for delivery in 2003.

The low-noise and all-in-view capabilities of the TTR-12's make it possible to contemplate increasing the frequency of our daily GPS monitor informational uploads to 2SOPS at Schriever AFB from daily to perhaps every 15 minutes. This should improve the stability of UTC (USNO) via GPS considerably, and the stability of GPS Time as well. One issue we have not resolved is how to ensure the robustness of an automated system, but it is clear that a large part of the answer will be in multiple hardware arrangements.

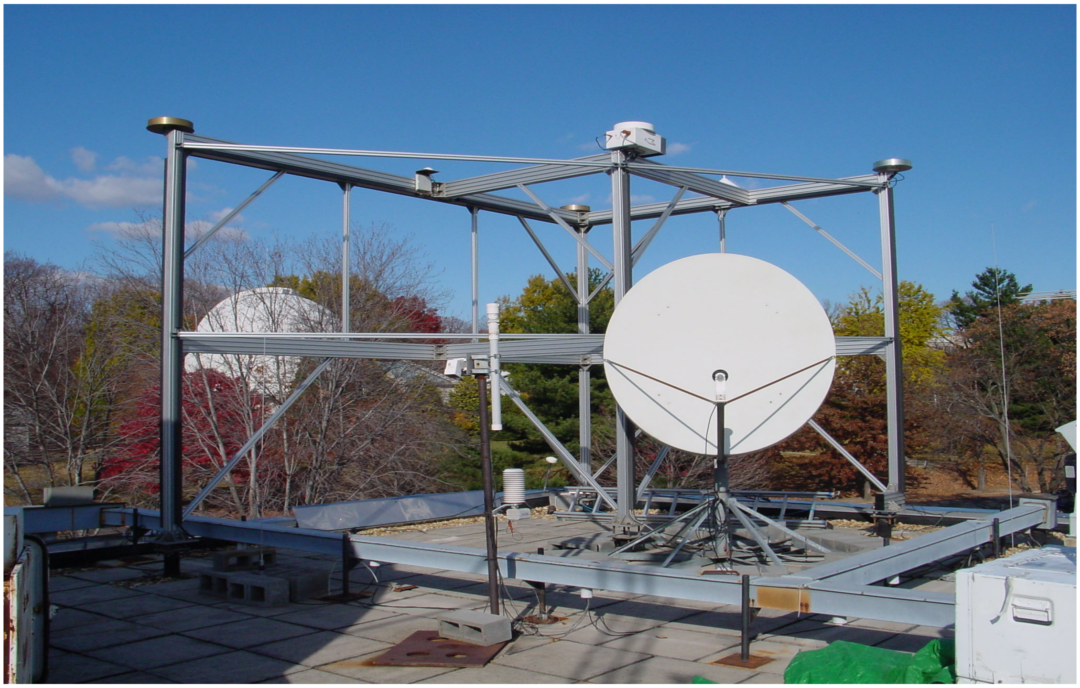


Figure 7. GPS antenna mount, now operational for GPS monitoring, has reduced multipath by roughly a factor of 3. Right of center is a directional antenna used to monitor WAAS signals.

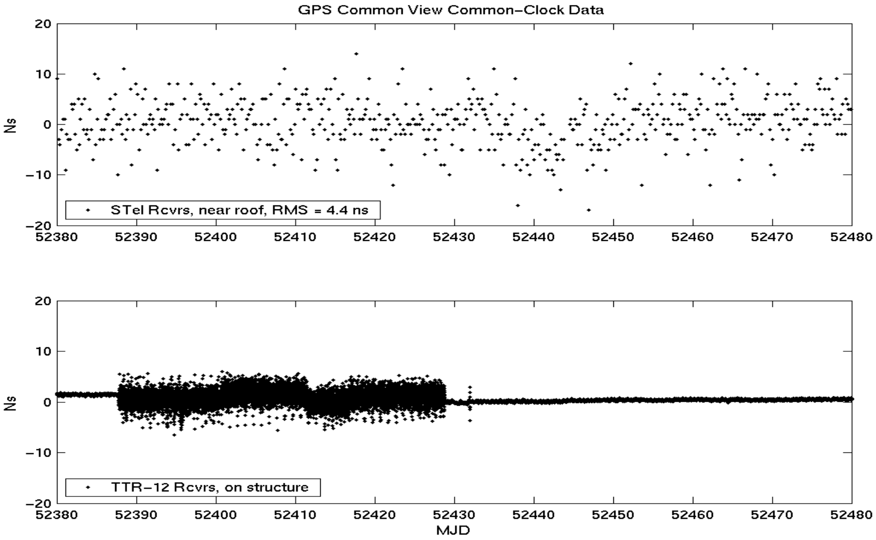


Figure 8. Common-clock common-view data from old and new GPS monitoring systems. As explained in the text, daily repetition of the variations show that the noise is dominated by multipath. except for the low-noise portion of the lower plot, wherein the receivers share a common antenna.

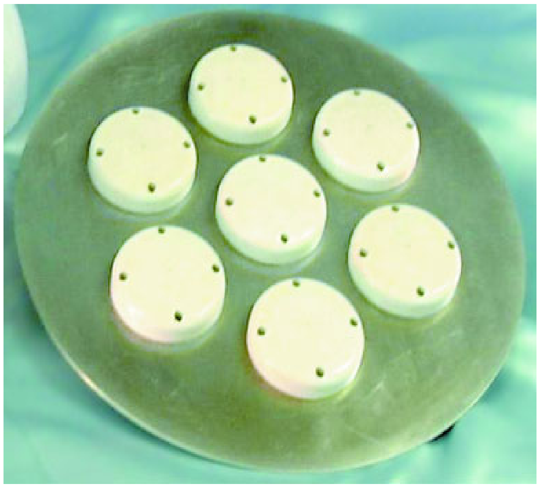


Figure 9. A seven-element HAGAR antenna array **[10]**. As of this writing, the system has not been delivered to, or tested by, USNO.

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), BIPM, and others to establish absolute calibration of GPS receivers **[11]**. 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/frequency 1-sigma errors reported in **[12]**. 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, it seems that relative calibration, by means of traveling GPS receivers, is a better operational technique. As always, care must be taken that there are no systematic multipath differences between antennas. We strongly support BIPM's relative calibration efforts for geodetic GPS receivers, and in particular are looking forward to comparisons with the multipath-free TWSTT calibrations.

The most accurate means of operational long-distance time transfer is TWSTT **[13]**, and the USNO has strongly supported BIPM's switch to TWSTT for TAI generation. In May 2001, we replaced our 16-year-old Mitrex modem used for the links with the European laboratories with a carrier-phase-capable SATRE modem. In May 2000, we calibrated the USNO link to the Physikalisch-Technische Bundesanstalt (PTB), in Germany; however, the change in satellite configuration in March 2001 rendered that calibration obsolete. Since then, we have calibrated the USNO-NPL Ku-band link to the National Physical Laboratory (NPL) in England using a temporary calibrated transatlantic X-band link, and in June of 2002 we set up an independent parallel system of calibrated hourly X-band TWSTT observations with PTB **[14]**. Details of our PTB calibration are given in Appendix I. The calibration was repeated in January 2003, and no variation was found to well within the 1 ns uncertainty. Figure 10 shows a double-difference comparison between the two independent TWSTT modes, Ku-band and X-band.

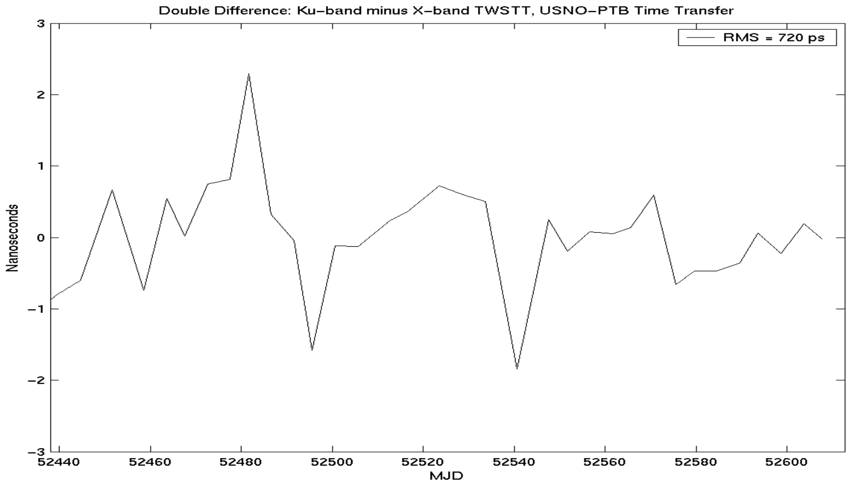


Figure 10. Double-difference between Ku and X-band TWSTT time transfer links on the USNO/PTB baseline from 5 June through 4 December 2002. Hourly X-band data are interpolated before subtracting from the Ku-band data taken at 14:45 UTC on the MWF of each week. The 720 ps rms is consistent with 500 ps rms stability for each frequency.

We plan to calibrate our TWSTT with 20 sites in the coming year, including NIST and a recalibration of the PTB. We have so far logged 18,000 miles on the improved calibration van (Figure 11) that was delivered at the end of last year. 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. Another important development is mobile TWSTT, which we have accomplished from an automobile and hope to achieve with an airplane **[15]**. For improved robustness, we have ordered parts for loop-back setups at the USNO and temperature-stabilizing equipment to test on some of our outdoor electronics packages.

The Time Service Department of USNO has also actively pursued development of GPS carrier-phase time transfer, in cooperation with the International GPS Service (IGS). With assistance from the Jet Propulsion Laboratory (JPL), the USNO has developed continuous filtering of timing data and shown 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, USNO has helped to develop a modification for the TurboRogue/Benchmark receivers, which preserve timing information through receiver resets. Using IGS data, USNO has developed a timescale that is now being tested as a possible IGS product **[17]**. USNO is currently contributing to real-time carrier-phase systems run by JPL/NASA **[18]** and the Canadian network **[19]**.

The continuous real-time sampling by highly precise systems will reach a climax when the USNO-DC becomes a full-fledged GPS monitor site, in cooperation with the National Imagery and Mapping Association (NIMA). This is currently scheduled to happen as part of the Accuracy Improvement Initiative (AII). We anticipate that NIMA 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.

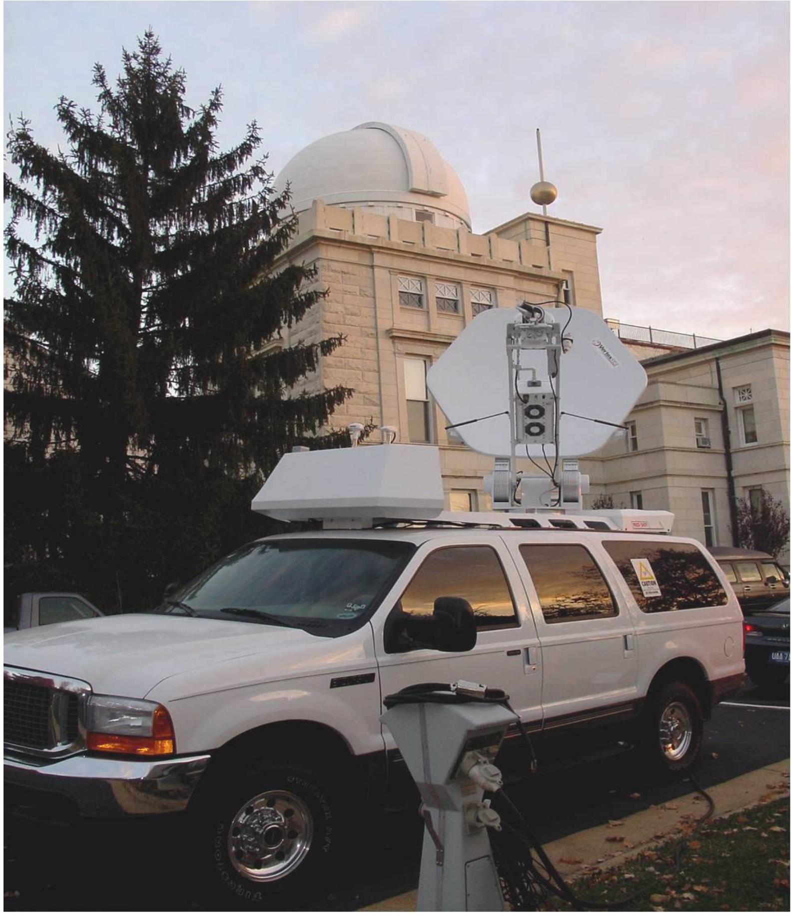


Figure 11. Mobile Earth Station for TWSTT calibration has been driven 18,000 miles this year. Small enough to be carried on a C141 military transport plane, it could be equipped to serve as a hop-link by communicating through two different satellites and/or frequencies simultaneously. Its automated pointing 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.

V. ROBUSTNESS, AND MORE ROBUSTNESS

The most common source of non-robustness is the occasional failure of our environmental chambers. In order to minimize such variations, and to house our fountain clocks, we are seeking funding for a new building. Our anticipated design calls for it to be partially underground, with no large internal heat sources, and thermal control generated by air piped in from either of two immediately adjacent buildings, whose systems are themselves redundantly generated. We expect a funding decision this year, and a building start date that could be as early as 2004.

Every aspect of the Master Clock requires dependable power, and we rely upon 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. We are now awarding the contract so that we can in 2003 install a third external power feed to give added redundancy.

Even instrumental calibration requires robustness. For our calibrated TWSTT service, we recommend the instrumental calibration be repeated every 6 months, although the changes in calibration are almost always sub-nanosecond. Similar recalibrations of GPS equipment are common in the international timing community, although the repeat rate is slower due to the large number of laboratories to be recalibrated.

The common theme 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 begun to upgrade our computers. The completed scheme envisions two interchangeable computers 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 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 will continue our daily tape backup of all data, and are strengthening our firewall as well.

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 and status of our key systems at any time.

VI. ROBUSTNESS FOR THE USER

Just as USNO has emphasized robustness and calibration throughout its operations, it is equally important for the users to ensure the robustness of their systems.

A common problem occurs with inadequate system calibration. Failure of an uncalibrated component and its replacement by another equally uncalibrated component can result in a catastrophic failure. A single calibration itself can be suspect, as equipment can fail gradually or the calibration itself could have a subtle error. We have seen these things happen more than once.

Equally important is robustness for connectivity to one’s timing reference. While GPS is often more than adequate as a time-delivery or navigational system, it is not immune to failure. Interference or jamming could occur just at the time it is needed most. Reliance upon the Wide Area Augmentation Service (WAAS), through a directional antenna, LORAN, or TWSTT for time transfer could provide an important backup for many users.

VII. DISCLAIMER

Although some manufacturers are identified for the purpose of scientific clarity, USNO does not endorse any commercial product nor does USNO permit any use of this document for marketing or advertising. We further caution the reader that the equipment quality described here may not be characteristic of similar equipment maintained at other laboratories, nor of equipment currently marketed by any commercial vendor.

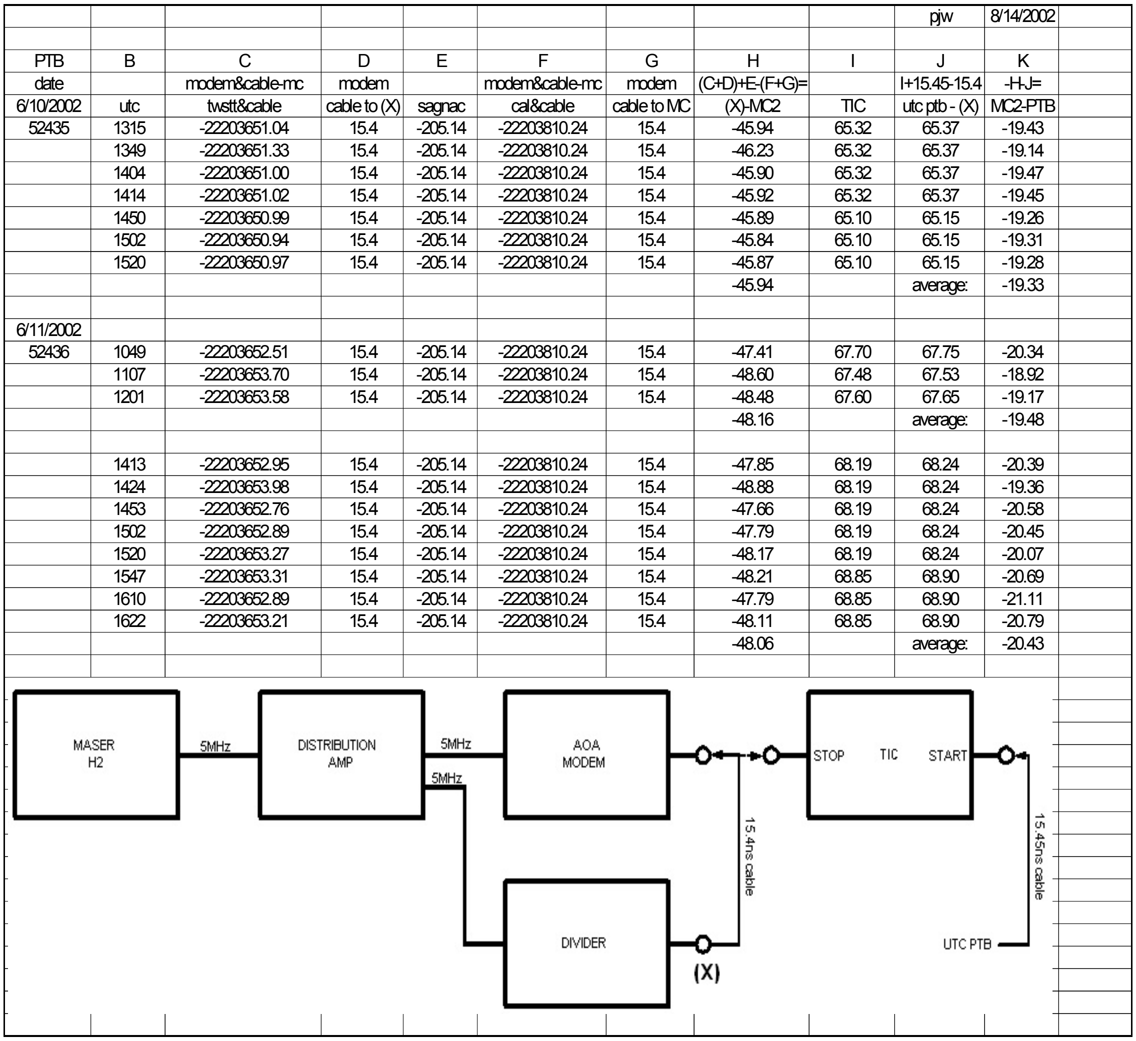
VIII. ACKNOWLEDGMENTS

We would like to thank the staff of the USNO Time Service Department for their dedication and efforts on behalf of the Master Clock. We also wish to thank A. Bauch, J. Becker, P. Hetzel, D. Piester, and T. Polewka at PTB for their full assistance with and participation in the TWSTT calibration.

APPENDIX I. DETAILS OF USNO-PTB CALIBRATION

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 PTB in Germany, where it was reassembled and used to make more measurements against the fixed antenna at USNO. The mobile system was then returned to 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's 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 8 months later, in January 2003, and found unchanged to well within the estimated uncertainty.

Figure 12 shows the USNO calibration spreadsheet for the June 2002 calibration. This calibration involved only the permanent X-band system at USNO and the mobile X-band system shipped to PTB for calibration; it did not involve the fixed X-band system at PTB or either Ku-band TWSTT system. The block diagram shows the TWSTT calibration setup at 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 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 12. 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 PTB. Column D is the delay between UTC (PTB) and PTB's TIC. Column E is the Sagnac correction **[13]**. 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 USNO fixed system's when the mobile system was at USNO; and column G is the cable delay between the mobile system's time reference at 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 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 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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QUESTIONS AND ANSWERS

TOM CLARK (Syntonics): Just a real quick question. You said UTC minus UTC (USNO) was under 5 nanoseconds, which was very good news. What fraction of UTC is UTC (USNO) now?

DEMETRIOS MATSAKIS: That is a very good point. We vary between 30 and 40 percent. We went up a little bit when they started weighting the good clocks more, as did many of the other labs that were involved with it. It does mean that 30 to 40 percent of any variation that takes place inside of our clocks will be forgiven, because it goes into the average. But that is true with any group of numbers.

WLODZIMIERZ LEWANDOWSKI (Bureau International des Poids et Mesures): I would like to add a comment that this outstanding performance of UTC (USNO) time is not only due to the number of clocks that are participating in TAI, but also to the quality of the link between USNO and other clocks, which is two-way. So what we observed for several months is that the difference is UTC minus UTC (USNO) is almost 4 nanoseconds, sometimes 3 nanoseconds. It is very, very stable. And with classical GPS, you could not achieve this. This is the quality of two-way that we can observe in the difference with UTC minus UTC (USNO).

MATSAKIS: Yes, you are right. Also, the quality of the people, but that is another issue. There is one point to make, too, that UTC is selective. All of our clocks are not weighted highly. Some of our clocks are down-weighted. And it is all public; you can check it out.

JIM ROMBERG (Boeing): Demetrios, you mentioned the prediction of time for the future. Is that available to other folks, do you disseminate that, in other words? Is that like getting maybe an ephemeris update to a GPS satellite before they update the satellite?

MATSAKIS: On our Web pages, we predict what UTC minus UTC (USNO) would be. And coming in as part of the GPS message, sub-frame 4. Also, there is a correction that should be applied. And so that is a real time. That was the 1.3 nanoseconds number I quoted as rms.

LEWANDOWSKI: A very short comment – this is linked to my presentation before on UTC (USNO). Because of this quality of UTC (USNO), the resolution we are getting in Circular T is not enough; we are giving the difference to within 1 nanosecond. We should switch very soon to 0.1 nanoseconds because of the quality of UTC (USNO).

MATSAKIS: So we see the BIPM, too, has to change to meet the needs of its users.