# Timescale Research at the U.S. Naval Observatory (USNO)

*Demetrios Matsakis*[1]

[1]U.S. Naval Observatory
3450 Massachusetts Avenue, NW
Washington, DC 20392
USA
Matsakis.demetrios@usno.navy.mil

## Abstract

The USNO is undergoing an infrastructure and timing transformation so as to better meet anticipated future requirements for robustness and precision from GNSS and other users. Rubidium atomic fountains are reaching the installation stage, environmental controls are being redesigned, measurement systems upgraded, time transfer systems made more robust, and new timescale algorithms are being developed to allow for the significantly superior performance of masers on subweekly timescales, and the monthly periodicity of the BIPM's publication of UTC in the Circular T. These algorithms involve both the fundamental timescale and the control loops used to realize that timescale in the form of UTC(USNO). This paper will present the current state of those algorithms, and describe the success of initial implementations.

## 1. Time Generation

The core stability of USNO time is based upon the clock ensemble. We currently have 69 HP5071 cesium clocks, and 24 cavity-tuned "Sigma-Tau/Datum/Symmetricom" hydrogen maser clocks, which are located in two Washington, D.C. buildings and at the USNO Alternate Master Clock (AMC), located at Schriever Air Force Base in Colorado. The clocks used for the USNO timescale are kept in 19 environmental chambers, whose temperatures are kept constant to within 0.1 degree C and whose relative humidities (for all masers and most cesiums) are kept constant to within 1%. The timescale is based only upon the Washington, D.C., clocks.

Before averaging data to form a timescale, real-time and postprocessed clock editing is accomplished by analyzing deviations in terms of frequency and time; all the clocks are detrended against the average of the best detrended cesiums. A maser average represents the most precise average in the short term, and the detrending ensures that it is equivalent to the cesium average over periods exceeding a few months. A.1 is USNO's operational timescale; it is dynamic in the sense that it weights recent maser and cesium data by their inverse Allan variance at an averaging time (tau) equal to the age of the data.

UTC (USNO) is created by frequency-steering the A.1 timescale to UTC using a steering strategy called "gentle steering" **[1]**, which minimizes the control effort used to achieve the desired goal, although at times the steers are so small that they are simply inserted. To realize UTC (USNO) physically, we use the one pulse per second (1-PPS) output of a frequency divider fed by a 5 MHz signal from an Auxiliary Output Generator (AOG). The AOG creates its output from the signal of a cavity-tuned maser steered to a timescale that is itself steered to UTC. The MC has a backup maser and an AOG in the same environmental chamber. On 29 October 2004, we changed the steering method so that state estimation and steering are achieved hourly with a Kalman filter. 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.

The operational unsteered timescale (A.1) is based upon averaging only the better clocks, which are first detrended using past performance. New algorithms are under development 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, which is derived from the primary frequency standards operated by other institutions. It is planned to implement an algorithm that steers the MC hourly and tightly to a timescale

based only upon masers, which is steered to a cesium-only timescale that itself is steered to UTC using the information in the Circular T. Individual masers would be steered to the unsteered cesium-only timescale before being averaged to create the maser-only timescale.

In order to improve timescale operations, USNO has a staff of four developing rubidium-based atomic fountains. Figure 1 shows the performance of the prototype fountain over a 40-day period, while housed in a room subject to several-degree temperature variations.

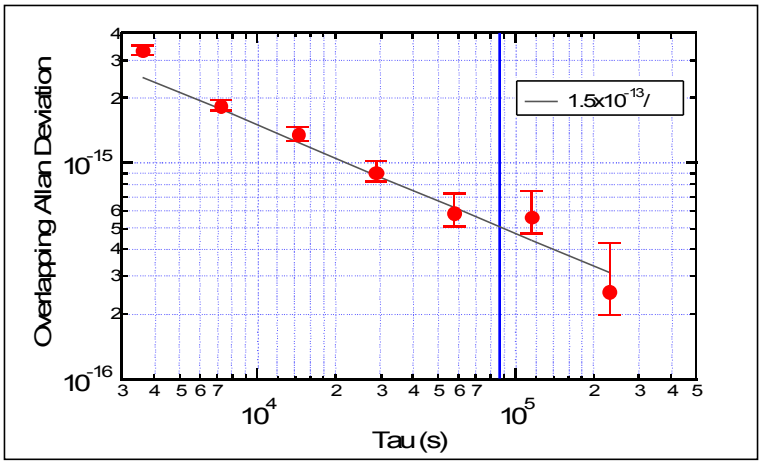


Figure 1. Performance of rubidium fountain against a USNO maser mean, as measured by the total deviation statistic. The straight line segment is a fit to the inverse square-root curve expected for white frequency noise.

## 2. Time Transfer

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.

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

With the use of multiple GNSS systems, problems involving receiver and satellite biases will become more significant. These have been shown to be related to the complex pattern of delay variations across the filtered passband, and correlator spacing. In principle, every satellite would have a different bias for every receiver/satellite combination **[2]**. USNO has analyzed how calibration errors associated with the Timing Group Delay (TGD) bias measurements of GPS result in a noticeable offset in GPS Time vs. UTC, as measured in BIPM's Circular T (Figure 2) **[3]**

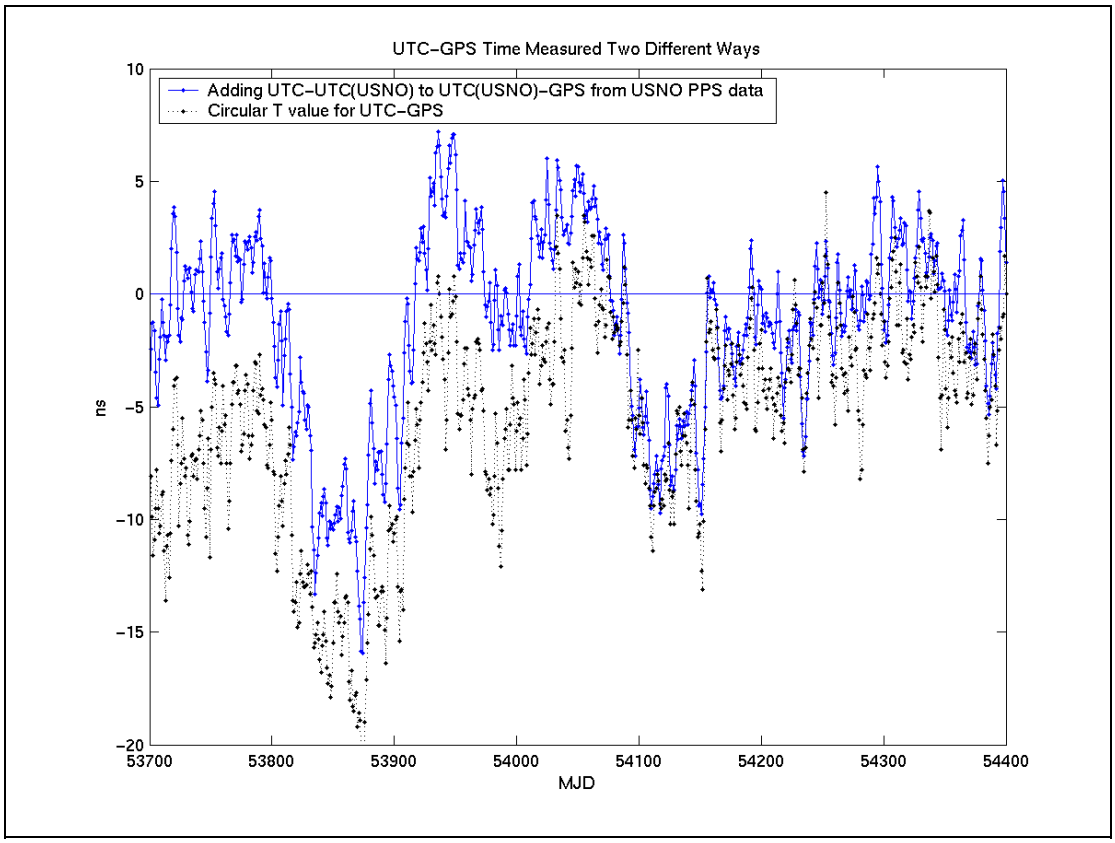


Figure 2. UTC – GPS as reported in the Circular T, and UTC – GPS inferred by subtracting UTC (USNO) – GPS from UTC – UTC (USNO). UTC (USNO) –GPS can be obtained from the satellite broadcasts, and is also measured directly at USNO.

The most accurate means of operational long-distance time transfer is TWSTT [4], and USNO has strongly supported BIPM's switch to TWSTT for TAI generation. We routinely calibrate and recalibrate the TWSTT at 20 sites each year, and in particular we maintain the calibration of the transatlantic link with the Physikalisch-Technische Bundesanstalt (PTB) through comparisons with observations at a second TWSTT frequency and with the carrier-phase GPS receivers whose IGS designations are USNO, USN3, and PTBB. For improved robustness, we have begun constructing loop-back setups at USNO, moved electronics indoors where possible, and developed temperature-stabilizing equipment to test on some of the outdoor electronics packages.

The Time Service Department of 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), 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 [5]. While the promise of Carrier Phase GNSS for time transfer is on its way to fulfillment, one of the greatest impediments to subnanosecond operations is receiver instabilities. For example, the receivers used at USNO and elsewhere have exhibited both sudden and gradual variations at the 1 ns level. All of these were designed in the 20$^{th}$ century and, therefore, USNO is experimenting with more modern components. By working with manufacturers, it is possible that still more stable equipment can be developed.

## 3. Measures to Secure Robustness of the Master Clock

The most common source of non-robustness is the occasional failure of the environmental chambers. In order to minimize such variations, and to house the fountain clocks, we have are equipping a new clock building. The building has redundant environmental controls designed to keep the entire building constant to within 0.1 deg C and 3% relative humidity even when an HVAC unit is taken offline for maintenance. The clocks themselves will be kept on vibrationaly isolated piers. Standardized instrument racks will facilitate rapid and accurate repairs.

The clocks in all DC buildings are protected by an electrical power system whose design includes multiple parallel and independent pathways, each of which is capable of supplying the full electrical power needs of the Master Clock. The components of each pathway are automatically interchangeable, and the entire system is supplemented by local batteries at the clocks that can sustain performance long enough for staff to arrive and affect most possible repairs. Although we have never experienced a complete failure of this system, most of the components have failed at least once. These failures and periodic testing give some confidence in the robustness of the system.

## 4. 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.

## 5. Acknowledgements

I thank the staff of USNO's Time Service Department for their skill and dedication in maintaining, operating, and improving the USNO Master Clock.

## 6. References

**[1]** P. A. Koppang and D. N. Matsakis, 2000, *"New Steering Strategies for the USNO Master Clocks,"* in Proceedings of the 31st Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 7-9 December 1999, Dana Point, California, USA (U.S. Naval Observatory, Washington, D.C.), pp. 277-284.

[2] C. Hegarty, E. Powers, and B. Fonville, 2005, *"Accounting for the Timing Bias Between GPS, Modernized GPS, and Galileo Signals,"* in Proceedings of the 36th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 7-9 December 2004, Washington, D.C. (U.S. Naval Observatory, Washington, D.C.) , pp. 307-317.

**[3]** D. Matsakis, 2007, *"The Timing Group Delay Correction (TGD) and GPS Timing Biases,"* Proceedings of the 63rd Annual ION National Technical Meeting, 23-25 April, 2007, Cambridge, Massachusetts, USA (Institute of Navigation, Alexandria, Virginia).

**[4]** D. Kirchner, 1999, *"Two Way Satellite Time and Frequency Transfer (TWSTFT),'* **Review of Radio Science** (Oxford Science Publications), pp. 27-44.

**[5]** D. Matsakis, K. Senior, and P. Cook, 2002, "Comparison of Continuously Filtered GPS Carrier Phase Time Transfer with Independent GPS Carrier-Phase Solutions and with Two-Way Satellite Time Transfer," in Proceedings of the 33rd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 27-29 November 2001, Long Beach, California, USA (U.S. Naval Observatory, Washington, D.C.), pp. 63-87.