TIME AND FREQUENCY ACTIVITIES AT THE U.S. NAVAL OBSERVATORY

Demetrios Matsakis
Time Service Department
U.S. Naval Observatory
Washington, DC 20392, USA

Abstract-- The U.S. Naval Observatory (USNO) has provided timing for the Navy 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), USNO's realization of Coordinated Universal Time (UTC), which has stayed within 5 ns rms of UTC since 1999 and within 3.1 ns rms in 2008. The data used to generate UTC (USNO) are based upon 70 cesium and 24 hydrogen maser frequency standards in four buildings at two sites. USNO disseminates time via voice, telephone modem, LORAN, Network Time Protocol (NTP), GPS, and Two-Way Satellite Time Transfer (TWSTT). This paper describes some of the changes being made to meet the future needs for precision, accuracy, and robustness. Further details and explanations of our services can be found online at http://tycho.usno.navy.mil, which will shortly be transformed to http://www.usno.navy.mil.

I. TIME GENERATION

The most important part of USNO's Time Service Department is its staff, which currently consists of 33 positions. We also currently have 69 HP5071 cesium clocks, and 24 cavity-tuned hydrogen maser clocks, which are located in three Washington, D.C. buildings and at the USNO Alternate Master Clock (AMC), located at Schriever Air Force Base in Colorado.

The clock outputs are sent to the measurement systems using cables that are phase-stable and of low temperature coefficient and, where possible, all the connectors are SMA (screw-on). The 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) rms, which is less than the variation of a cesium clock over an hour. Because the maser clocks 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, duplicate low-noise systems measure each maser, 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 magnetic tape.

Before averaging data to form a timescale, real-time and postprocessed clock editing is accomplished by analyzing deviations in terms of frequency and time; all the clocks are detrended against the average of the best detrended cesiums **[1]**. A maser average represents the most precise average in the short term, and the detrending ensures that it is equivalent to the cesium average over periods exceeding a few months. A.1 is 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" **[2-4]**, which minimizes the control effort used to achieve the desired goal. 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 **[2-5]**. The MC has a backup maser and an AOG in the same environmental chamber. State estimation and steering are achieved hourly with a Kalman filter **[6]**.

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 **[7,8]**, we have widened the definition of a "good clock" and are recharacterizing the clocks less frequently, and new methods of clock characterization are under development **[9]**. It is planned to implement an algorithm that steers the MC hourly and tightly to a timescale based only upon masers, which is steered to a cesium-only timescale that itself is steered to UTC using the information in the Circular T **[6, 10-12]**.

II. STABILITY OF UTC (USNO)

Figure 1 shows how UTC (USNO) has compared to UTC and also how its fractional frequency has compared to the unsteered maser mean, relative to an overall constant offset.

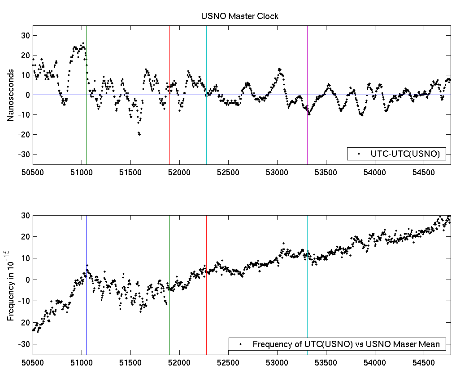

Figure 1. Interplay between the time and fractional frequency stability of the USNO Master Clock, from February, 1997 to the present.

The top plot of Figure 1 is UTC – UTC (USNO) from the International Bureau of Weights and Measure's (BIPM's) Circular T. The lower plot shows the fractional frequency difference of the Master Clock against the maser mean, derived by subtracting an arbitrary constant (for plot display) from the difference between the Master Clock and mean frequencies, measured in Hz and divided by the 5 MHz frequency of the signal-realization. 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. Hourly steers were implemented on 53307. Vertical lines indicate the times of these changes. UTC (USNO) has stayed within 5 ns rms of UTC for 5 years.

While the long-term stability of the Master Clock is set by steering to UTC, the exceptional stability of USNO's unsteered mean can also be used to attempt to diagnose issues involving the long-term stability of UTC itself. The dense purple line in Figure 2 shows the fractional frequency difference between our unsteered cesium average and EAL, which is the unsteered timescale generated by BIPM that is steered to primary frequency standards so as to create UTC.

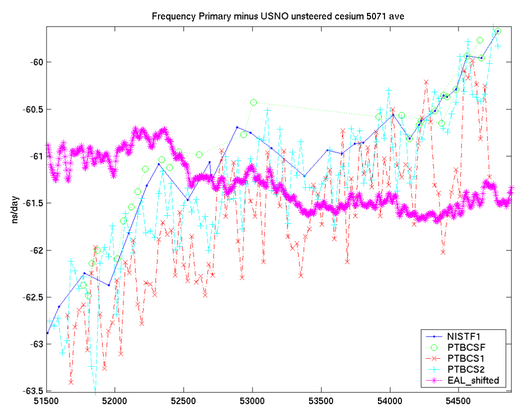

Figure 2. Fractional frequency of unsteered average of USNO-DC cesiums against that of EAL and also against several primary frequency standards. The frequencies have been shifted in the vertical direction for display, and the difference with the cesium average has been scaled to remove the contribution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

In order to improve timescale operations, USNO has a staff of five developing rubidium-based atomic fountains **[13]**.

III. TIME TRANSFER

The fastest-growing service is the Internet service Network Time Protocol (NTP). Until it levelled off at over 5000 requests/second, in 2005, the number of individual requests doubled every year since the program was initiated. The billions of requests correspond to at least several million users **[14]**.

Greater precision is required for two services for which USNO is the timing reference: GPS and LORAN. USNO monitors LORAN at its Washington, DC site. With some assistance from 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 crude check **[15]**, and USNO is pursuing a collaborative effort with the Loran Support Unit (LSU) to test an Enhanced Loran (eLORAN) receiver system.

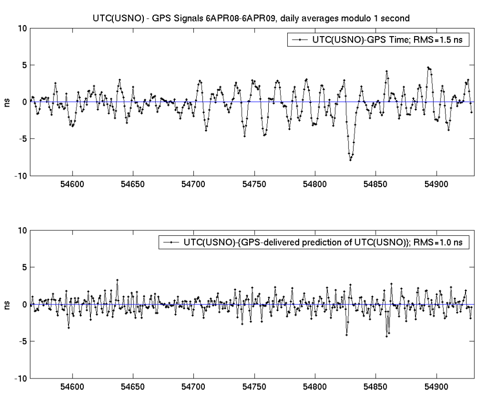

Figure 3. Recent daily averages of UTC (USNO) minus GPS Time and UTC minus GPS's delivered prediction of UTC (USNO).

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 **[16]**. The standard setup includes temperature-stable cables and flat-passband, low-temperature-sensitivity antennas.

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 **[17]**. 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 **[18]**. 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 $\sqrt{2}$. 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 BIPM's relative calibration efforts for geodetic GPS receivers, and in particular are looking forward to comparisons with the multipath-free TWSTT calibrations.

USNO has been participating in discussions involving the interoperability of GPS, Galileo **[19]**, QZSS (Quasi-Zenith Satellite System), and GLONASS. In December of 2006, a Galileo monitor station was installed, and detailed plans have been made to monitor the GPS/GNSS timing offset (GGTO) [**19]** 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 **[20]**. 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 4) **[21].**

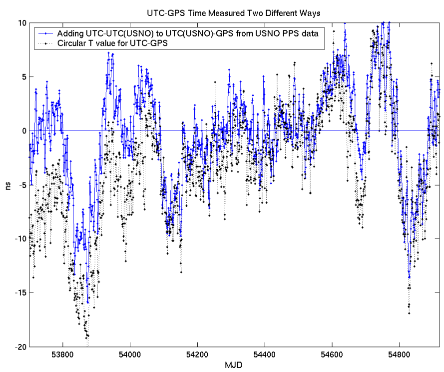

Figure 4. UTC – GPS as reported in the Circular T, and UTC – GPS inferred by subtracting UTC (USNO) – GPS from UTC – UTC (USNO). UTC (USNO) –GPS can be obtained from the satellite broadcasts, and is also measured directly at USNO.

The most accurate means of operational long-distance time transfer is TWSTT **[22-25]**. 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 **[26]**. For improved precision, we have made some efforts to develop carrier-phase TWSTT **[27]**, although it appears the most promising technology would include a frequency standard in the satellite **[28]** .

We have also actively pursued development of GPS carrier-phase time transfer, in cooperation with the International GPS Service (IGS). **[23, 29-31]**. 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. The receivers used at USNO and elsewhere have exhibited both sudden and gradual variations at the 1 ns level **[32]**, but we are experimenting with more modern components **[33]**. While several algorithms are insensitive to short-term variations of the receiver's pseudo-range calibration **[22, 34, 35]**, only human intervention in the form of calibration monitoring and recalibration can correctly account for non-transient receiver variations.

Frequency transfer has been shown to be achievable at a few parts in 10^{-16} or better, if receivers are kept environmentally stable, and one removes the discontinuities at day boundaries, which are largely due to instabilities in the pseudorange reception **[35, 36]**.

V. DISCLAIMER

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.

V. ACKNOWLEDGEMENTS

We thank the staff of the Time Service Department of the USNO for their skill and dedication in maintaining and improving the Master Clock.

REFERENCES

[1] L. A. Breakiron, 1992, *"Timescale Algorithms Combining Cesium Clocks and Hydrogen Masers,"* in Proceedings of the 23rd Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 3-5 December 1991, Pasadena, California, USA (NASA Conference Publication 3159), pp. 297-305.

[2] D. N. Matsakis, M. Miranian, and P. A. Koppang, 2000, *"Alternative Strategies for Steering the U.S. Naval Observatory (USNO) Master Clock,"* in Proceedings of the ION 56th Annual Meeting, 26-28 June 2000, San Diego, California, USA (Institute of Navigation, Alexandria, Virginia), pp. 791-795.

[3] D. N. Matsakis, M. Miranian, and P. A. Koppang, 2000, *"Steering the U.S. Naval Observatory (USNO) Master Clock,"* in Proceedings of 1999 ION National Technical Meeting, 25-27 January 2000, San Diego, California, USA (Institute of Navigation, Alexandria, Virginia), pp. 871-879.

[4] 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.

[5] P. Koppang, D. Johns, and J. Skinner, 2004, *"Application of Control Theory in the Formation of a Timescale,"* in Proceedings of the 35th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 2-4 December 2003, Long Beach, California, USA (U.S. Naval Observatory, Washington, D.C.), pp. 319-325.

[6] J. Skinner, D. Johns, and P. Koppang, 2005, *"Robust Control of Frequency Standards in the Presence of Systematic Disturbances,"* in Proceedings of the 2005 Joint IEEE International Frequency Control Symposium and the 37th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 29-31 August 2005, Vancouver, Canada (IEEE Publication 05CH37664C), pp. 639-641.

[7] J. G. Skinner and P. A. Koppang, 2002, *"Effects of Parameter Estimation and Control Limits on Steered Frequency Standards,"* 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. 399-405.

[8] L. A. Breakiron and D. N. Matsakis, 2001 *"Performance and Characterization of USNO Clocks,"* in Proceedings of the 32nd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 28-30 November 2000, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 269-288

[9] J. Skinner, D. Johns, and P. Koppang, 2009, *"Statistics of Modeling Errors in an Ensemble Mean,"* Proceedings of the 40th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 2-4 December 2008, Reston, Va.

[10] P. A. Koppang, J. G. Skinner, and D. Johns, 2007, *"USNO Master Clock Design Enhancements"*, in Proceedings of the 38th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 5-7 December 2006, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 185-192.

[11] J. G. Skinner and P. A. Koppang, 2007, *"Analysis of Clock Modeling Techniques for the USNO Cesium Mean"*, in Proceedings of the 38th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 5-7 December 2006, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 373-378

[12] G. Petit, 2007, *"The Long Term Stability of EAL and TAI (Revisited),"* in Proceedings of TimeNav'07, the 21st European Frequency and Time Forum (EFTF) Joint with 2007 IEEE International Frequency Control Symposium (FCS), 29 May-1 June 2007, Geneva, Switzer-land (IEEE Publication CH37839), pp. 391-394.

[13] C. S. Peil, S. Crane, T. Swanson, and C. Ekstrom, 2005, *Design and Preliminary Characterization of the USNO Rubidium Fountain,* in Proceedings of the 2005 Joint IEEE International Frequency Control Symposium and the 37th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 29-31 August 2005, Vancouver, Canada (IEEE Publication 05CH37664C), pp. 304-307.

[14] R. Schmidt, 2005, *"Reflections on Ten Years of Network Time Service,"* 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. 123-137.

[15] D. Matsakis and H. Chadsey, 2003, *"Time for Loran,"* in Proceedings of the 31st Annual Convention and Technical Symposium of the International Loran Association, 27-30 October 2002, Washington, D.C., USA (International Loran Association, Santa Barbara, California), *http://www.loran.org/Meetings/Meeting2002/ILA2002CDFiles/A-Index/ HTMLBrowserIndex.htm*

[16] M. Miranian, E. Powers, L. Schmidt, K. Senior, F. Vannicola, J. Brad, and J. White, 2001, *"Evaluation and Preliminary Results of the New USNO PPS Timing Receiver,"* in Proceedings of the 32nd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 28-30 November 2000, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 79-90.

[17] J. White, R. Beard, G. Landis, G. Petit, G., and E. Powers, 2001, *"Dual Frequency Absolute Calibration of a Geodetic GPS Receiver for Time Transfer,"* in Proceedings of the 15th European Frequency and Time Forum (EFTF), 6-8 March 2001, Neuchatel, Switzerland (Swiss Foundation for Research in Microtechnology, Neuchâtel), pp. 167-172.

[18] P. Landis and J. White, 2003, *"Limitations of GPS Receiver Calibration,"* in Proceedings of the 34th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 3-5 December 2002, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 325-332.

[19] J. Hahn and E. Powers 2006, "Implementation of the GPS to Galileo Time Offset (GGTO)", in Proceedings of the 2005 Joint IEEE International Frequency Control Symposium and the 37th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 29-31 August 2005, Vancouver, Canada (IEEE Publication 05CH37664C), pp. 33-37.

[20] 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.

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

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

[23] L. A. Breakiron, A. L. Smith, B. C. Fonville, E. Powers, and D. N. Matsakis, 2005, *"The Accuracy of Two-Way Satellite Time Transfer Calibrations,"* 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. 139-148.

[24] 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.

[25] Matsakis, D., Breakiron, L, Bauch, A., Piester, D., and Jiang, Z, 2009, "*TWSTT Calibration Constancy from Closure Sums,"* Proceedings of the 40th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 2-4 December 2008, Reston, Va.

[26] D. Piester, A. Bauch, J. Becker, T. Polewka, A. McKinley, and D. Matsakis, 2004, *"Time Transfer Between USNO and PTB: Operation and Results,"* 2004, in Proceedings of the 35th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 2-4 December 2003, Long Beach, California, USA (U.S. Naval Observatory, Washington, D.C.), pp. 93-102.

[27] B. Fonville, D. Matsakis, W. Shäfer, and A. Pawlitzki, 2005, *"Development of Carrier-Phase-Based Two-Way Satellite Time and Frequency Transfer (TWSTFT),"* 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. 149-164.

[28] Y. Takahashi, M. Imae, T. Gotoh, F. Nakagawa, M. Fujieda, H. Kiuchi, M. Hosokawa, H. Noda, and K. Sano, 2004, "*Development of Time Comparison Equipment for ETS-VII Satellite,"* in Proceedings of the Conference on Precision Electromagnetic Measurements, 27 June-2 July 2004, London, England, UK (IEEE Publication), pp. 232-233.

[29] K. Senior, P. A. Koppang, D. Matsakis, and J. Ray, 2001, *"Developing an IGS Time Scale,"* in Proceedings of the 2001 IEEE & PDA Exhibition International Frequency Control Symposium, 6-8 June 2001, Seattle, Washington, USA (IEEE Publication 01CH37218), pp. 211-218.

[30] E. Powers, K. Senior, Y. Bar-Server, W. Bertiger, R. Muellerschoen, and D. Stowers, 2003, *"Real Time Ultra-Precise Time Transfer to UTC Using the NASA Differential GPS System,"* in Proceedings of the 16th Annual European Frequency and Time Forum (EFTF), March 2002, St. Petersburg, Russia.

[31] F. Lahaye, P. Collins, P. Héroux, M. Daniels, and J. Popelar, 2002, *"Using the Canadian Active Control System (CACS) for Real-Time Monitoring of GPS Receiver External Frequency Standards,"* in Proceedings of ION-GPS 2001, 11-14 September 2001, Salt Lake City, Utah, USA (Institute of Navigation, Alexandria, Virginia), pp. 2220-2228.

[32] D. Matsakis, M. Lee, R. Dach, U. Hugentobler, and Z. Jiang, 2006, *"GPS Carrier Phase Analysis Noise on the USNO-PTB Baselines,"* in Proceedings of the 2006 IEEE International Frequency Control Symposium, 5-7 June 2006, Miami, Florida, USA (IEEE Publication), pp. 631-636.

[33] B. Fonville, E. Powers, and F. Vannicola, 2008, *"Evaluation of Carrier Phase GNSS Timing Receivers for TAI Applications,"* in Proceedings of the 39th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 26-29 November 2007, Long Beach, California, USA (U.S. Naval Observatory, Washington, D.C.).

[34] C. Hackman and J. Levine, 2006, *"Towards Sub-10^{-16} Transcontinental GPS Carrier-Phase Frequency Transfer: a Simulation Study,"* in Proceedings of the 2006 IEEE International Frequency Control Symposium, 5-7 June 2006, Miami, Florida, USA (IEEE Publication), pp. 779-787.

[35] R. Dach, T. Schildknecht, U. Hugentobler, L.-G. Bernier, and G. Dudle, 2006, "*Continuous Geodetic Time Transfer Analysis Method*," **IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, UFFC-53,** 1250-1259.

[36] C. Hackman J. Levine, T. E. Parker, D. Piester, and J. Becker, 2006, *"A Straightforward Frequency-Estimation Technique for GPS Carrier-Phase Time Transfer,"* **IEEE Transactions on Ultrasonics, Ferroelectronics, and Frequency Control, UFFC-53,** 1570-1583.

[37] Walls, W., 2009, *"The Master Clock Building and USNO Infrastructure,"* Proceedings of the 40th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 2-4 December 2008, Reston, Va.