# Replicating UTC(NIST) at Remote Sites

Michael A. Lombardi[1], Andrew N. Novick[1], Jose Mauricio López-Romero[2], and Rodrigo Ramos P.[3]

[1]National Institute of Standards and Technology (NIST), Boulder, Colorado, USA
*lombardi@nist.gov*, *novick@nist.gov*

[2]Centro Nacional de Metrología (CENAM), Querétaro, México
*jlopez@cenam.mx*

[3]University of Concepción, Concepción, Chile
*roramos@udec.cl*

**Abstract–The National Institute of Standards and Technology (NIST) is deploying disciplined oscillators that are referenced to the UTC(NIST) time scale through common-view observations of Global Positioning System (GPS) satellites. We present measurement results from four NIST disciplined oscillators (NISTDOs), three located in the United States, and one located in Concepción, Chile. These devices replicate the NIST time scale at remote sites, and uncertainties of less than 5 ns are demonstrated at all locations. The results were verified by utilizing the national time scale of Mexico as an independent check standard. Further verification was obtained by directly comparing a NISTDO to UTC(NIST) in Boulder, Colorado.**

## I. INTRODUCTION

Disciplined oscillators, first described by Pierce in 1957 [1], are essential instruments for frequency control and timekeeping. They allow accurate frequency and time signals, controlled by a common reference, to be simultaneously generated at multiple sites. A disciplined oscillator has at least three parts: a local oscillator (LO), a receiver that collects data transmitted from a reference source, and a frequency or phase comparator. The comparator measures the difference between the LO and the reference, and this difference is converted to a frequency correction that is periodically applied to the LO. By continuously repeating this process, an oscillator can be disciplined so that it replicates the performance of the reference.

To replicate the reference time, the LO output is divided to 1 pulse per second (pps) and synchronized with the reference on-time marker. To properly synchronize the 1 pps output signal, the delay of the entire signal path must be measured, and corrections must be made for the delays. The path delay is the interval required for the signal to travel from the transmitter to the receiver, and includes all cable and equipment delays. As is always the case with time transfer systems, the accuracy of the transferred time can be no better than the uncertainty of the path delay measurement [2].

To replicate the reference frequency, a disciplined oscillator must lock to the reference signal. As long as it remains locked, its accuracy and stability in the long term (weeks and months, for example) should be nearly identical to those of the reference. Its short-term stability, at intervals shorter than the correction interval, should be identical to the short-term stability of the free running LO. Its medium-term stability, at intervals longer than the correction interval but shorter than perhaps one month, is design dependent and influenced by many factors. These factors include the quality of the receiver and antenna, the stability of the LO, the resolution of the comparator, the correction method, the correction uncertainty, and the correction interval.

## II. DESCRIPTION OF THE NIST DISCIPLINED OSCILLATOR

Nearly all disciplined oscillators being sold today receive Global Positioning System (GPS) satellite signals, and are thus known as GPSDOs. The reference source for these instruments is UTC(USNO), the Coordinated Universal Time scale kept by the United States Naval Observatory [3]. Disciplined oscillators referenced to UTC(NIST) were once fairly common and worked by receiving 60 kHz signals from the NIST radio station WWVB [4]. However, they were made obsolete by the invention of the GPSDO and are no longer sold. Their performance was poor when compared to a GPSDO, with frequency uncertainties at least a factor of 10 larger (parts in $10^{12}$) and time uncertainties roughly a factor of 1000 larger (limited to about 100 µs). In addition, their coverage area was relatively small, limited to the continental United States. In an effort to deliver a low-uncertainty version of UTC(NIST) to its customers, NIST introduced the NISTDO service in 2010 [5]. A simplified diagram that illustrates the NISTDO concept is shown in Figure 1.

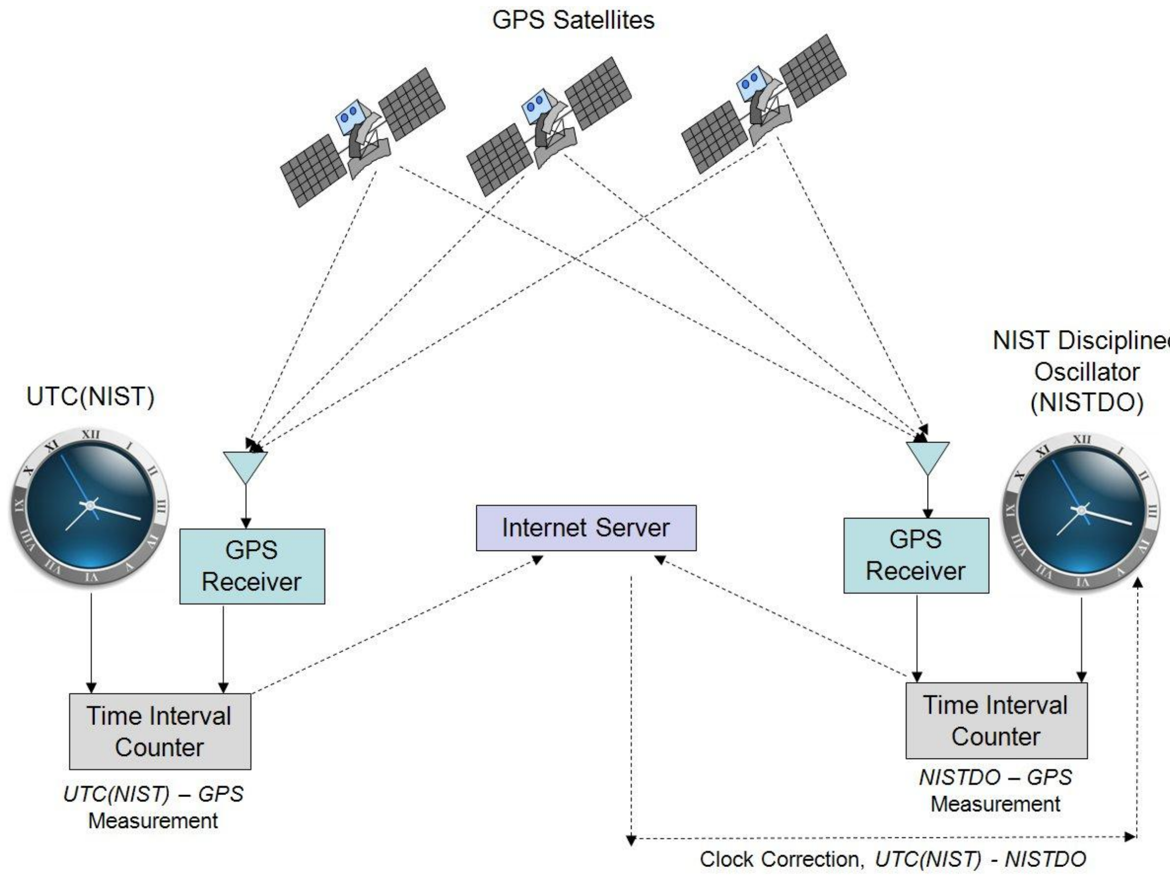


Figure 1. NIST disciplined oscillator system.

The NISTDO is a common-view disciplined oscillator [5, 6, 7] that works by simultaneously comparing both UTC(NIST) and the NISTDO to signals broadcast by the GPS satellites. To achieve the smallest timing uncertainties, the GPS systems at both NIST and the remote site must be calibrated to account for delays in the receiver, antenna, and antenna cable, and the positions of the GPS antennas must be accurately determined.

The NISTDO systems include a low-cost L1 band GPS receiver (several different models have been successfully tested) and a time interval counter. The LO is a rubidium standard with a built-in distribution amplifier with several frequency (10 MHz) and time (1 pps) outputs. NIST customers can distribute these signals at their facilities. The noise floor of the LO, as estimated with the Modified Allan deviation, *Mod* $\sigma_y(\tau)$, is near $4 \times 10^{-13}$ at $\tau = 1$ hour. The stability is about a factor of five worse at $\tau = 1$ day, due to the effects of frequency drift and aging.

The measurements performed at NIST produce the time difference *UTC(NIST) – GPS*, and the measurements performed at the remote site produce *NISTDO – GPS*. The GPS signals are simply a vehicle used to transfer time from one site to the other, and when the two measurements are subtracted from each other, the result is an estimate of *UTC(NIST) – NISTDO*. The data are collected by having the measurement systems at both sites average time interval counter readings for 10 minutes. At the end of each 10-minute segment, the NIST system and the NISTDO systems simultaneously upload their measurements to a file transfer protocol (FTP) server. The use of FTP requires Internet access, and requires transmission control protocol (TCP) ports 20 and 21 to be left open on the local firewalls.

The NISTDO software includes an adaptive proportional-integral-derivative (PID) controller [8] that was implemented to discipline the LO. The purpose of a PID controller is to correct the error, *e*, between a measured process variable and a desired set point (*SP*). In this case, the desired value of *SP* is 0, because the goal is simply to lock the NISTDO to UTC(NIST). The process variable is *TD*, the last measured time difference between the LO and UTC(NIST). To obtain *TD*, the PID controller invokes common gateway interface (CGI) applets on the Internet server. These applets instantly process the data and send the results through TCP port 80, where the correction values are read with the hypertext transfer protocol (HTTP), using software that serves as a rudimentary web browser.

The NISTDO software allows the user to select one of two different applets to process the data. The first applet, called *CVDIFF*, implements the classic common-view method. It aligns and differences data from the individual satellite tracks, discards data collected from satellites that are not visible at both sites, and uses only the satellites visible at both locations to produce *TD*. A second applet, called *AVDIFF*, implements the "all-in-view" method, where the satellite tracks are not aligned and no tracks are discarded. Instead, *AVDIFF* collects the average time difference from all available satellites at both sites, and *TD* is simply the difference between the two averages. *CVDIFF* provides slightly better performance, but has a limited coverage area. At distances greater than about 5000 km from Boulder, Colorado, the number of common-view satellites will approach zero, and *CVDIFF* will become less effective or unusable. *AVDIFF* does not have these limitations, and allows a NISTDO to be deployed anywhere on Earth.

Once the PID controller obtains *TD*, it converts the measurement to a dimensionless frequency correction that is applied to the LO through an RS-232 interface. This "measure and correct" process is repeated every 10 minutes to keep the NISTDO locked to UTC(NIST).

The NISTDO software display indicates a lock condition when the LO is accurate to within 50 ns of UTC(NIST) and stable to within 5 ns as estimated with the time deviation, $\sigma_x(\tau)$, at $\tau = 10$ minutes. Internally, however, the software distinguishes between a "soft lock" based on the 50/5 criteria, and a "hard lock," which is reached when the accuracy is within 10 ns and the time deviation is less than 2 ns.

The NISTDO records the frequency corrections sent to the local oscillator. If the NISTDO loses lock due to an Internet or GPS outage, its 1 pps timing output can be quickly resynchronized to UTC(NIST), and its frequency can be quickly restored to the last recent "hard lock" condition after the outage ends. During this reacquisition procedure, the PID controller is disengaged until the LO reaches a steady state condition with respect to UTC(NIST), at which point frequency corrections are resumed. This technique avoids situations where overly aggressive corrections can cause the set point to be overshot multiple times, a condition that can last for many hours. Instead, an unlocked condition normally lasts for less than one or two hours once the Internet and GPS are both accessible [5].

## III. NISTDO PERFORMANCE

Four NISTDOs were deployed at remote sites and measured for this study. The location of each instrument is listed in Table 1. The three devices in the United States were disciplined using the common-view method, and the device in Concepción, Chile was disciplined using the all-in-view method, which was necessary due to its distance from NIST. Table 1 also lists the distance of each instrument from UTC(NIST) in Boulder, Colorado, and from UTC(CNM), the national frequency and time standard of Mexico, located at the Centro Nacional de Metrología in Querétaro. The UTC(CNM) time scale was utilized as an independent check standard to help evaluate the NISTDO performance.

Table 1. Location of NIST disciplined oscillators.

| Location | Country | Distance (km) | |
|---|---|---|---|
| | | From UTC(NIST) | From UTC(CNM) |
| **El Segundo, California** | United States | 1345.32 | 2308.49 |
| **Plymouth, Minnesota** | United States | 1116.58 | 2761.83 |
| **Weehawken, New Jersey** | United States | 2621.56 | 3306.47 |
| **Concepción** | Chile | 8358.55 | 6620.72 |

Before deployment, each NISTDO was calibrated for 10 days in Boulder by use of the common-view, common-clock method. The uncertainty of this calibration method has been demonstrated to be less than 2 ns [9]. The GPS antenna in Boulder and at the California site were surveyed using a dual-frequency receiver and a differential GPS correction service, and their horizontal and vertical coordinates are known to be within 20 cm. The antennas at the other three sites were surveyed either by averaging position fixes from the single frequency (L1 band) receiver for 24 hours, or by interpolating the position from previously surveyed antennas located nearby. In all three cases, their horizontal uncertainty is known to be less than 1 m, but the error in their vertical altitude estimate is unknown (likely to be larger than 1 m) and will bias the timing accuracy.

Figure 2 shows the results of comparisons of each of the four NISTDOs to UTC (NIST) over the 76-day interval from 06/27/2012 to 09/10/2012 (MJD 56105 to 56180). The time difference values were obtained by averaging for one day. There were a few periods of missing data due to losses of network connectivity when no frequency corrections could be sent to the NISTDOs. The device in New Jersey missed four days (MJD 56148 to 56151), and the devices in Chile (MJD 56157) and California (MJD 56162) each missed one day. In each of these cases, network connectivity was lost for more than several hours. This caused the NISTDO to lose lock, and each device required a short interval to relock once network connectivity was restored. Data recorded while the devices were unlocked have been removed.

Table 2 summarizes the accuracy and stability of the NISTDO comparisons with respect to UTC(NIST). The average time offset was within ±0.2 ns for all four devices The NISTDO in Chile had outliers that exceeded 2 ns, but the three devices located in the United States were always within ±1 ns, with the exception of one outlier for the California device (MJD 56141) when the average offset reached 1.3 ns. The stability, as estimated by the time deviation, $\sigma_x(\tau)$ at $\tau = 1$ day, was 0.5 ns or less for the three devices in the United States, and 1.1 ns for the NISTDO in Chile.

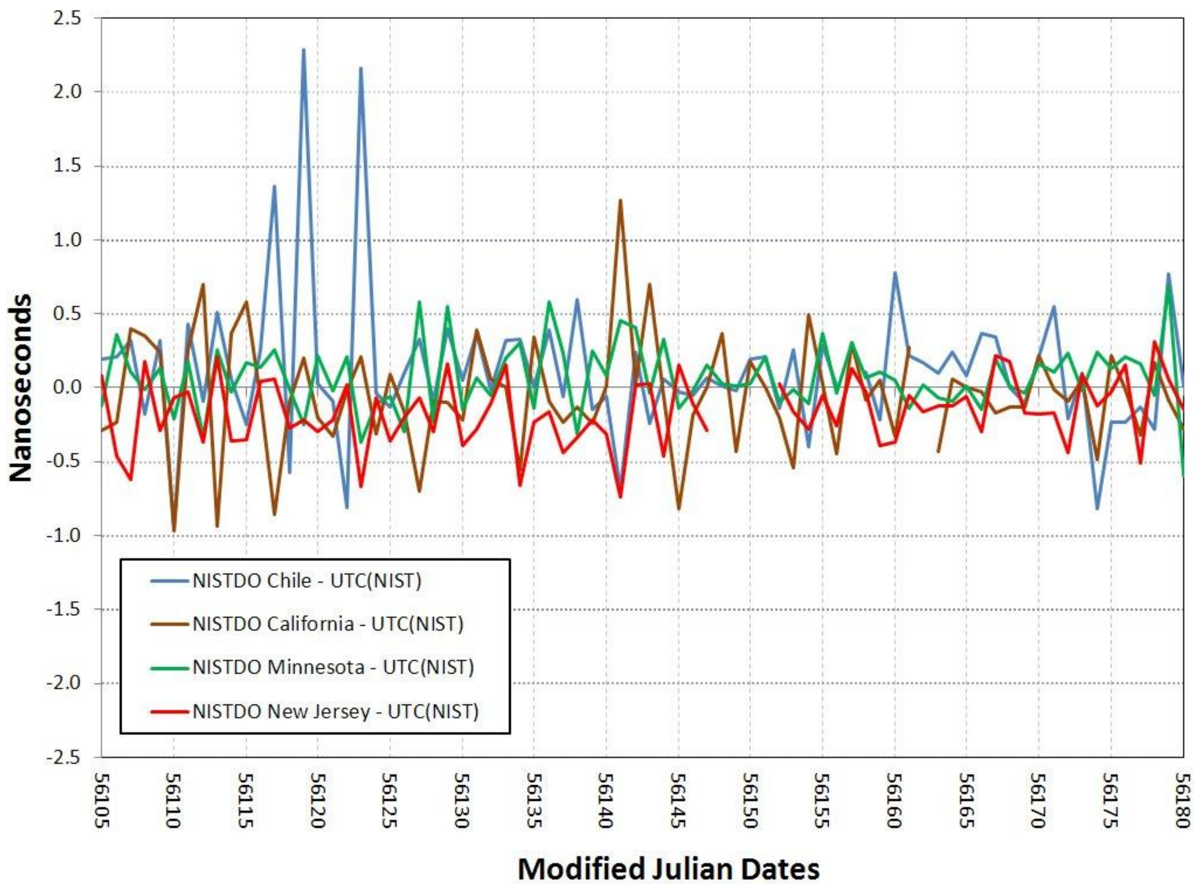


Figure 2. NIST disciplined oscillators compared to UTC(NIST).

Table 2. Time accuracy and stability of NIST disciplined oscillators.

| Measurement Results (ns) | | Location: El Segundo, California, USA | Plymouth, Minnesota, USA | Weehawken, New Jersey, USA | Concepción, Chile |
|---|---|---|---|---|---|
| **Accuracy (Average time offset)** | Direct to UTC(NIST), uncorrected | -0.1 | 0.1 | -0.2 | 0.2 |
| **Stability ($\sigma_x(\tau)$, $\tau$ = 1 day)** | Compared to UTC(NIST) | 0.5 | 0.3 | 0.3 | 1.1 |

The values shown in Table 2, however, do not necessarily reflect the "true" time difference between the NISTDO and UTC(NIST), because the PID will adjust the LO until *SP* = 0. This adjustment appears to remove biases (Type B uncertainties), including any errors in the NISTDO calibration or antenna position, but instead it simply compensates for the biases by "moving" the LO in the opposite direction. Thus, the biases are still present but no longer reflected in the time difference values. To better estimate the time difference between each NISTDO and UTC(NIST), the national time scale of Mexico, UTC(CNM), was utilized as an independent check standard.

Figure 3 shows five common-view comparisons of UTC(CNM), one directly to UTC(NIST), and one to each of the four NISTDOs over the same 76-day interval shown in Figure 1. All five measurements have similar phase signatures, indicating that all of the NISTDOs are locked and tracking UTC(NIST). The NISTDOs located in California and New Jersey agree to within ±0.3 ns to the actual UTC(NIST) comparison. This suggests that the uncertainty of their calibrations was small and that their antenna coordinates are correct. However, the NISTDOs located in Minnesota and Chile have a noticeable bias from the UTC(NIST) – UTC(CNM) comparison.

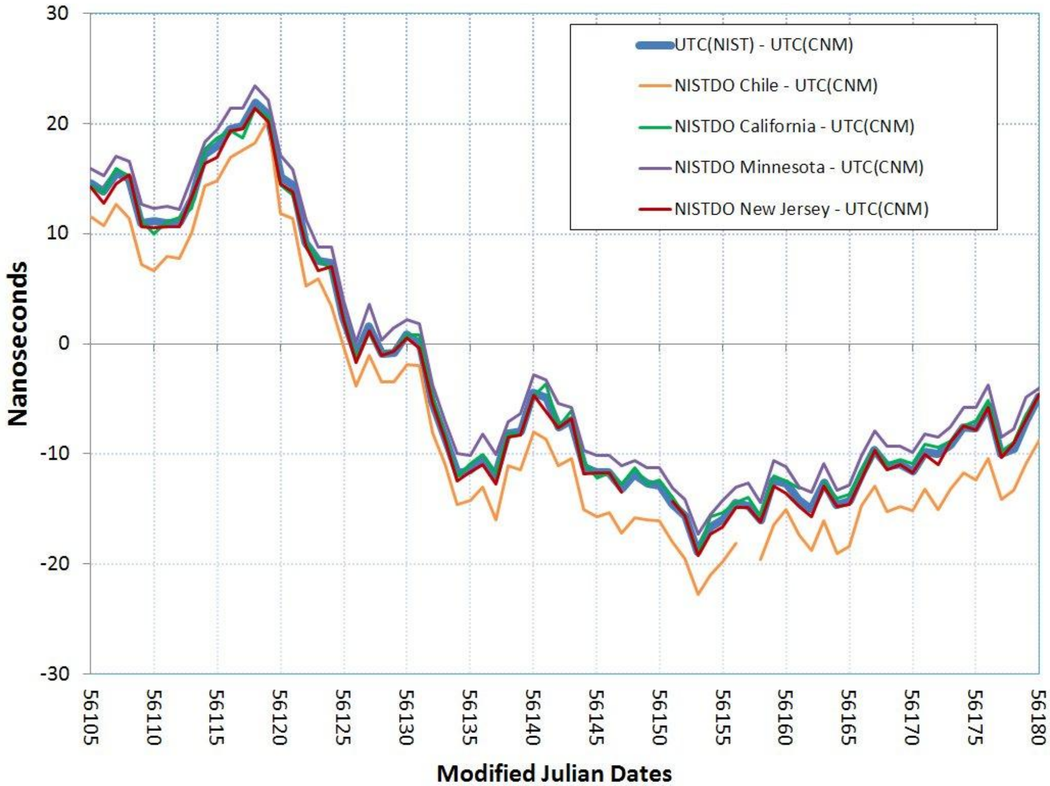


Figure 3. UTC(NIST) and NIST disciplined oscillators compared to UTC(CNM).

Figure 4 shows the bias more clearly by subtracting the results of the UTC(NIST) – UTC(CNM) comparison from each of the four NISTDO – UTC(CNM) comparisons. This is essentially a common-view measurement, where UTC(CNM) serves as the "satellite." The corrected results reveal the actual time difference of each NISTDO from UTC(NIST). The NISTDO in Minnesota is biased "low" by about 1.6 ns, probably due to an error in the antenna elevation, which was not independently surveyed. The NISTDO in Chile is biased "high" by about 3.4 ns, due to a combination of factors that likely includes calibration uncertainties, vertical coordinate errors, and the necessary use of the all-in-view technique over the very long baseline. Table 3 summarizes the results.

Table 3. Time accuracy of NIST disciplined oscillators (corrected).

| **Measurement Results (ns)** | | **Location** | | | |
|---|---|---|---|---|---|
| | | El Segundo, California, USA | Plymouth, Minnesota, USA | Weehawken, New Jersey, USA | Concepción, Chile |
| **Accuracy (Average time offset)** | With respect to UTC(NIST) after UTC(CNM) correction | -0.2 | -1.6 | 0.3 | 3.4 |

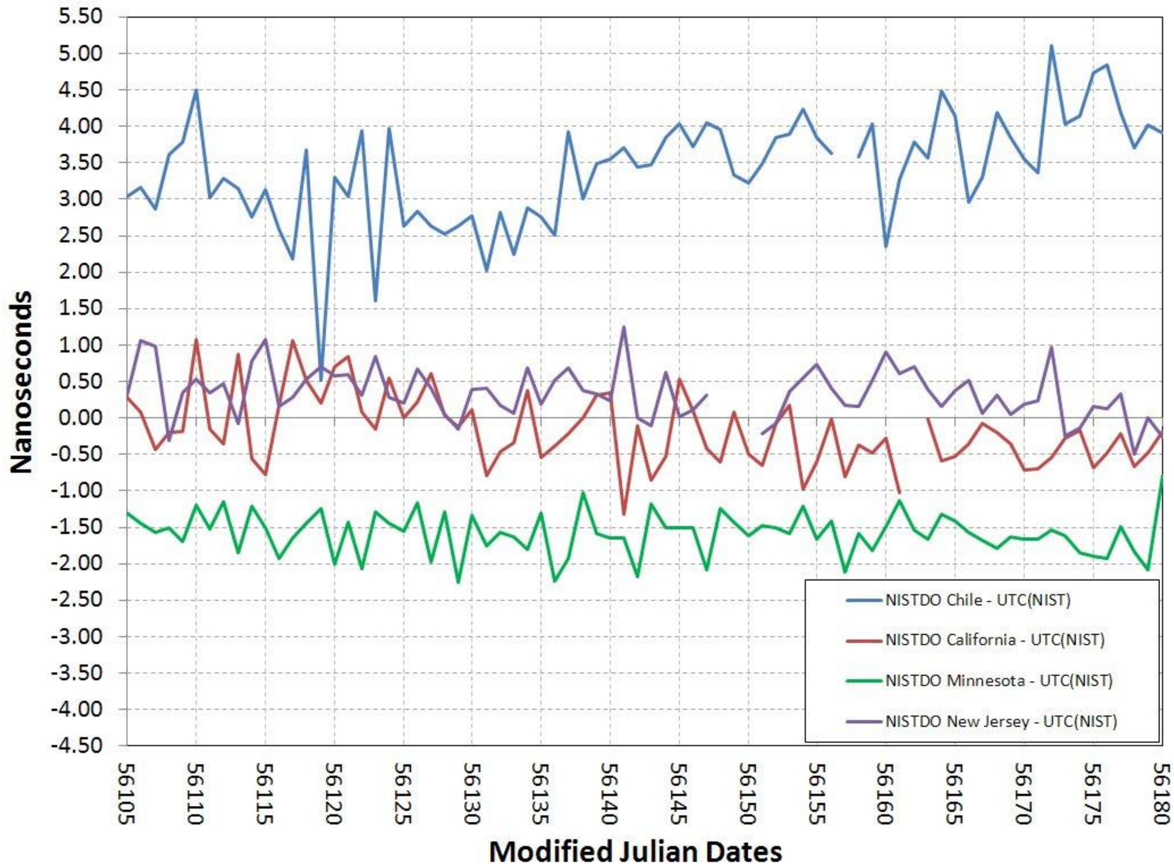


Figure 4. NIST disciplined oscillators compared to UTC(NIST) after CNM correction applied.

## IV. DIRECT COMPARISON OF NISTDO TO UTC(NIST)

The ultimate verification of a time transfer system would require bringing the two clocks being compared into the same laboratory, so that they could be directly compared to each other. This, of course, is impossible in the case of clocks separated by large distances, which is why time transfer links are implemented in the first place. However, if a direct comparison is possible, it provides the best possible measurement of the difference between the two clocks. A time transfer system, regardless of how well it is designed, cannot improve upon those results. The best that can be hoped for is to equal the results of a direct comparison. Equaling the result of a direct clock comparison can be achieved only if there are no systematic errors (biases) in the time transfer system calibration, and if the amount of transfer noise is smaller than the amount of clock noise.

Because a NISTDO is located within the NIST laboratories in Boulder, Colorado, we had the rare opportunity to verify its uncertainty by directly comparing it to its reference source. This was done by comparing the NISTDO 1 pps output to the 1 pps output of the UTC(NIST) time scale, using calibrated cables and a time interval counter. The results of this test may represent the practical limit of how well the current NISTDO design can perform when deployed at a remote site.

Figure 5 shows the measurement configuration for the direct comparison. The two GPS antennas were each located on the roof of the NIST laboratories, separated by a baseline of 42.3 m. The NISTDO was located on the fourth floor of the NIST laboratories and the UTC(NIST) time scale was located on the second floor. A calibrated cable was run from the time scale through a distribution amplifier to a time interval counter located on the fourth floor near the NISTDO. The total delay from UTC(NIST) to the time interval counter, including cables and distribution amplifiers, was 428.6 ns. Another calibrated cable, with a delay of 39.4 ns, connected the NISTDO to the same time interval counter. A 5 MHz signal from UTC(NIST) served as the time interval counter's time base. The time interval readings were collected every second and corrected by software to account for cable and distribution amplifier delays.

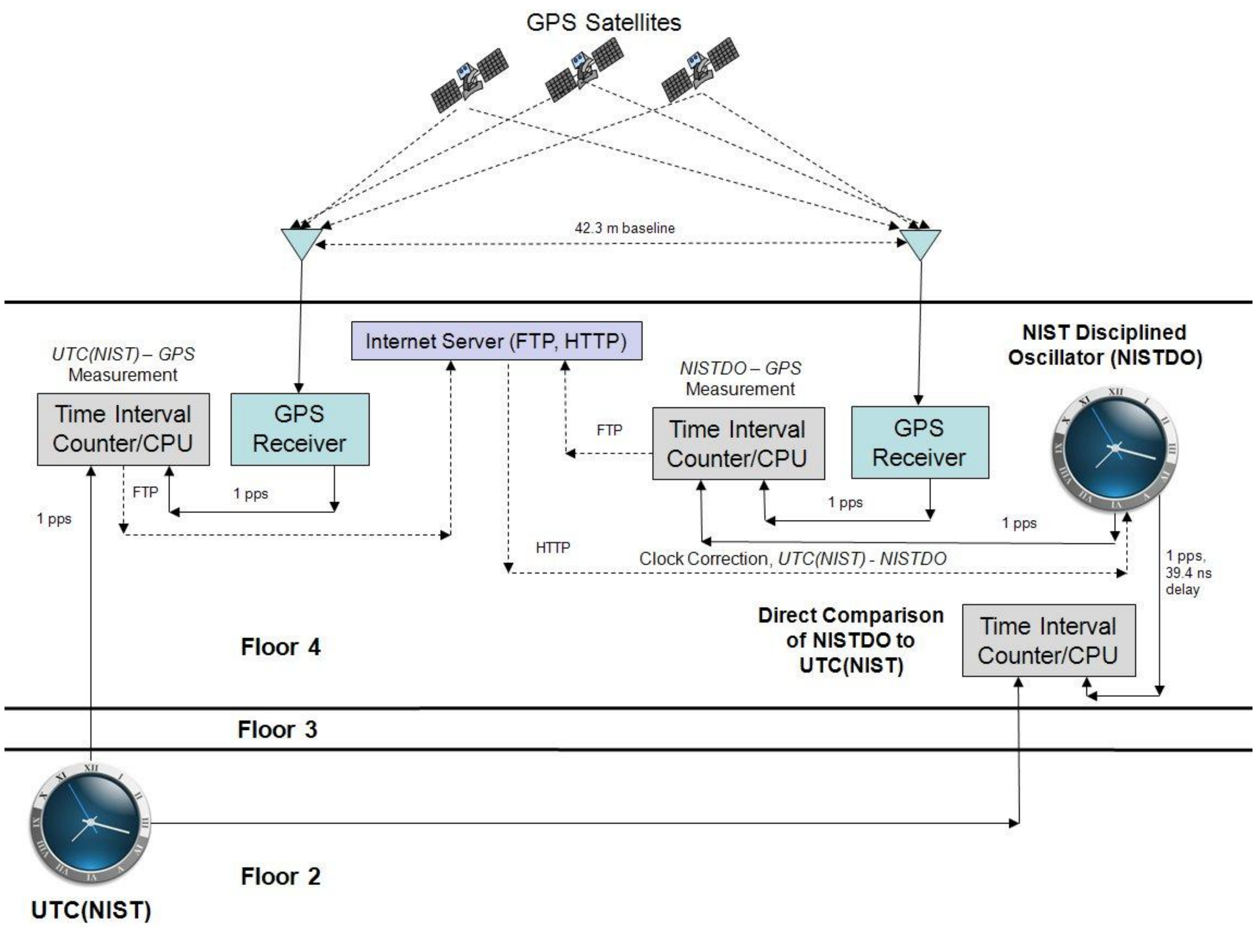


Figure 5. Measurement configuration for direct comparison of NISTDO to UTC(NIST).

The NISTDO in Boulder utilized a common-view GPS system that had not been calibrated since April 2008. Thus, prior to beginning the measurement, we recalibrated its common-view system via the common-view, common-clock method [9] during the 10-day period from 07/27/2012 to 08/05/2012 (MJD 56135 to 56144). The new calibration differed by only 0.1 ns from the April 2008 calibration. We then restarted the NISTDO, allowed it to reacquire and achieve a "hard lock" condition, and began a direct comparison of the NISTDO to UTC(NIST). The comparison ran for 40 days, from 08/07/2012 to 09/15/2012 (MJD 56146 to 56185), with the results shown in Figure 6.

For the 40-day interval, the average value of NISTDO – UTC(NIST) was -0.1 ns for the common-view comparison, and 1.3 ns for the direct comparison, a difference of 1.4 ns. The range of the common-view comparison was about 1.5 ns as opposed to 2.3 ns for the direct comparison. The small time difference between the two comparisons is probably due to biases introduced by the uncertainty of the common-view system calibrations, and the uncertainty of the cable and distribution amplifier calibrations. However, it seems likely that the variations in the difference could be reduced by better temperature control. The outdoor temperature was high in Boulder during the months of August and September when the test was conducted (occasionally exceeding 38 ºC), and the temperature in the laboratory where the NISTDO is located is not monitored and poorly controlled. The temperature variations affect both the rubidium LO and the common-view GPS receivers.

The common-view comparison generally produces smaller fluctuations than the direct comparison because the PID, as noted earlier, adjusts the local oscillator until *SP* = 0, providing compensation that hides real biases. In addition, all corrections are based on past measurements, and can lag behind environmental effects such as rapid changes due to temperature. In some cases, the corrections may overcompensate for environmental effects. The 1.5 ns phase shift in the direct comparison that began around MJD 56178 appears to be the result of overcompensation.

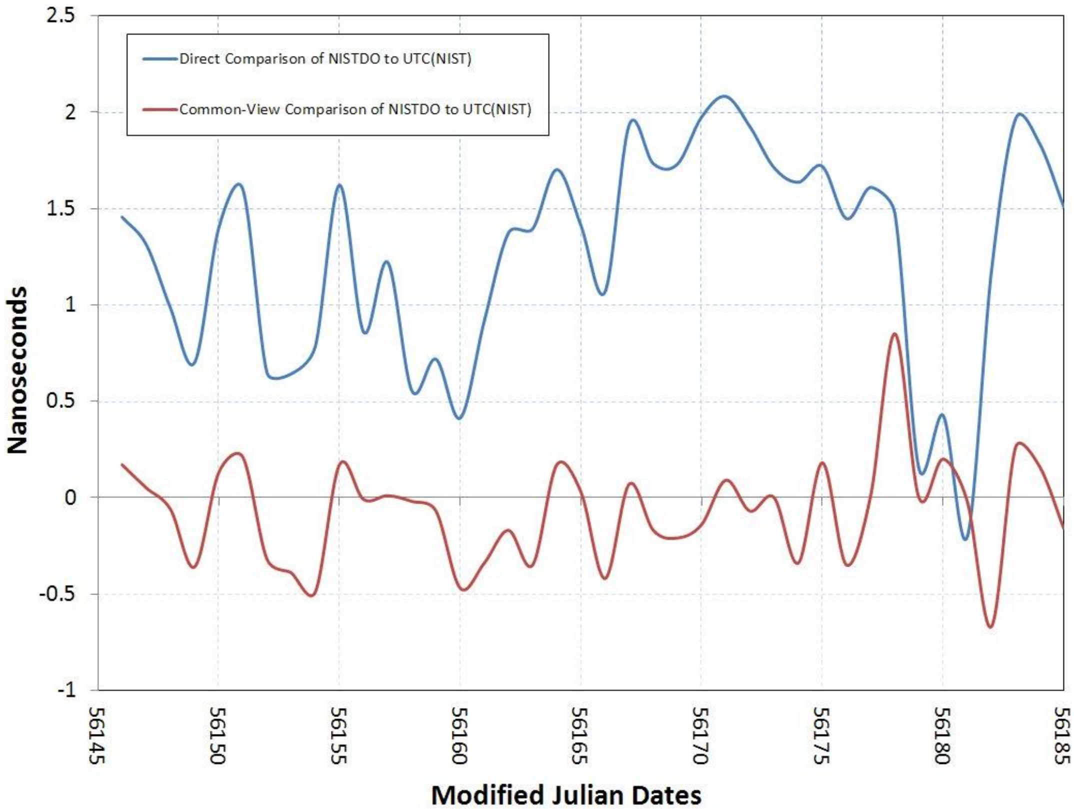


Figure 6. Direct and Common-View Comparisons of a NISTDO located in Boulder.

The direct comparison verifies the accuracy of the NISTDO in a way that provides more confidence than any type of mathematical analysis. It demonstrates that a NISTDO can deliver an on-time pulse to a remote site with an accuracy near 1 ns with respect to UTC(NIST). This is far greater accuracy than that provided by any previous NIST service.

## V. FREQUENCY STABILITY COMPARISON OF NISTDO TO GPSDOS

NIST periodically measures the frequency stability of GPSDOs with respect to UTC(NIST) when providing calibration services to its customers. Figure 7 compares the frequency stability of a NISTDO and two GPSDOs with respect to UTC(NIST), with $\tau_0$ = 1 hour. Based on past calibrations conducted at NIST, we have found that approximately half of the GPSDOs we have tested can reach a stability, *Mod* $\sigma_y(\tau)$, of $1 \times 10^{-13}$ at $\tau = 1$ day. The devices that miss this mark are usually no worse than about $4 \times 10^{-13}$. The best devices are about one order of magnitude more stable than the worst devices, reaching stabilities near $4 \times 10^{-14}$. The GPSDO measurements shown in Figure 7 represent the two extremes [10]. The measured NISTDO was the device located in Minnesota. Measurements were made continuously over a 125-day interval from 05/05/2012 to 09/06/2012 (MJD 56052 to 56176).

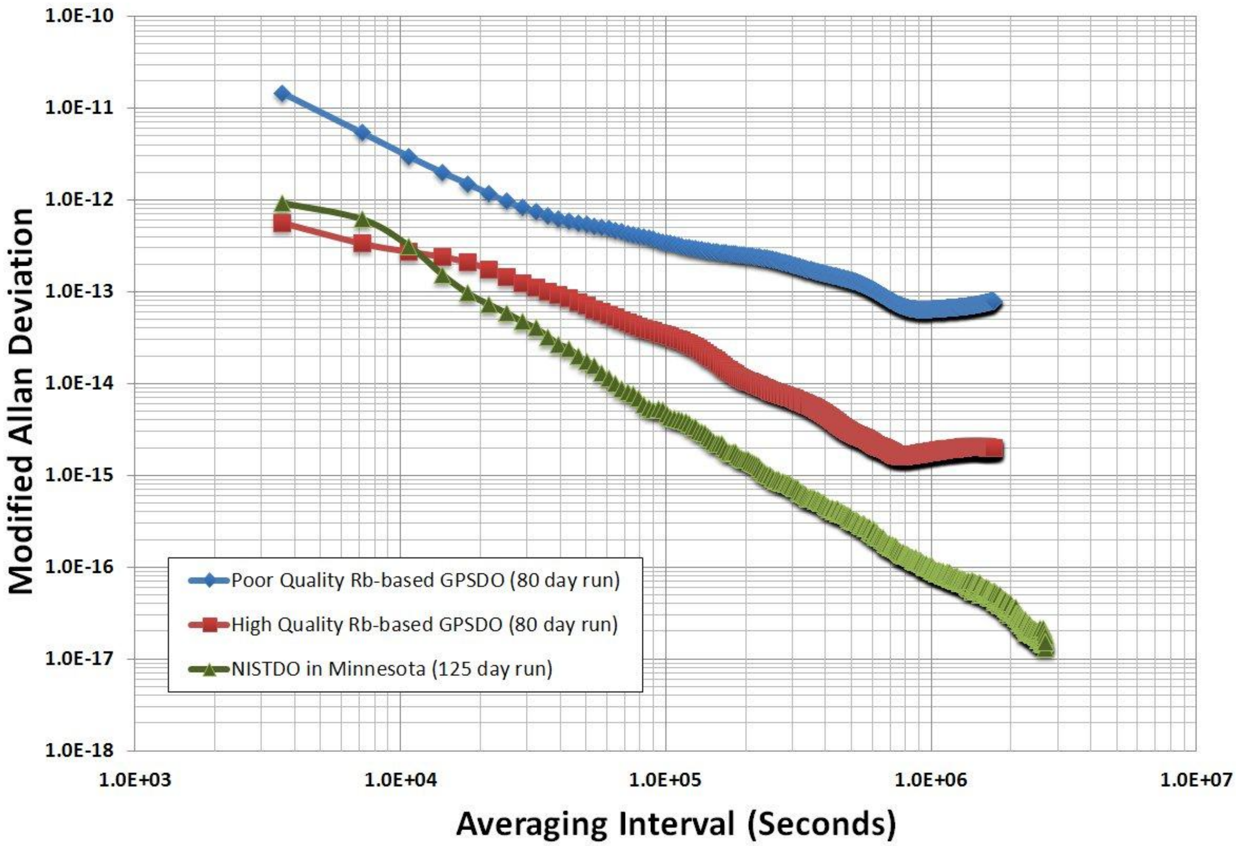


Figure 7. Frequency stability of a NISTDO and two GPSDOs with respect to UTC(NIST).

The NISTDO was slightly less stable than the "best" GPSDO at averaging intervals of less than 4 hours. This can be attributed to several factors: the speed at which the NISTDO responds to frequency fluctuations is limited because the correction interval for the common-view method can be no shorter than 10 minutes, the NISTDO utilizes a rubidium LO that is less stable than those used in the best GPSDOs, and the adaptive PID correction method has limitations that could be improved upon. Despite these factors, the long term stability of the NISTDO was nearly one order of magnitude better than the "best" GPSDO, reaching about $5 \times 10^{-15}$ at $\tau = 1$ day.

To put these results into context, consider that the reference for the Figure 7 measurements was UTC(NIST), and that GPSDOs are controlled by UTC(USNO). Thus, in the case of the NISTDO stability estimates, there is correlation between the device under test and the reference, which gives the NISTDO an advantage in this comparison. Comparing a NISTDO to UTC(NIST) is similar to comparing a GPSDO to UTC(USNO), after the UTC(USNO) correction from subframe 4 of the GPS broadcast has been applied [11].

Disciplined oscillators issue corrections to the LO to compensate for changes in frequency with respect to the reference; thus, the only factor that limits their stability is the uncertainty of the corrections. In the case of the NISTDO, the uncertainty of the corrections is continually reduced when averaged over long intervals and the stability of the device continues to improve. Ideally, statistical tests such as *Mod* $\sigma_y(\tau)$ should be used to estimate the stability of free running, rather than disciplined oscillators. Even so, they are still useful for indicating that the frequency of the NISTDO is in very close agreement with its reference, which is the desired result.

As shown in Figure 7, the frequency stability of a NISTDO, *Mod* $\sigma_y(\tau)$, with respect to UTC(NIST) reaches $1 \times 10^{-16}$ at $\tau$ = 10 days and a few parts in $10^{17}$ after 20 days of averaging. The time stability, $\sigma_x(\tau)$, drops below 100 ps at about $\tau$ = 4 days, and below 30 ps after about 20 days of averaging (Figure 8). These results demonstrate that the goal of replicating NIST frequency and time at remote sites has been realized.

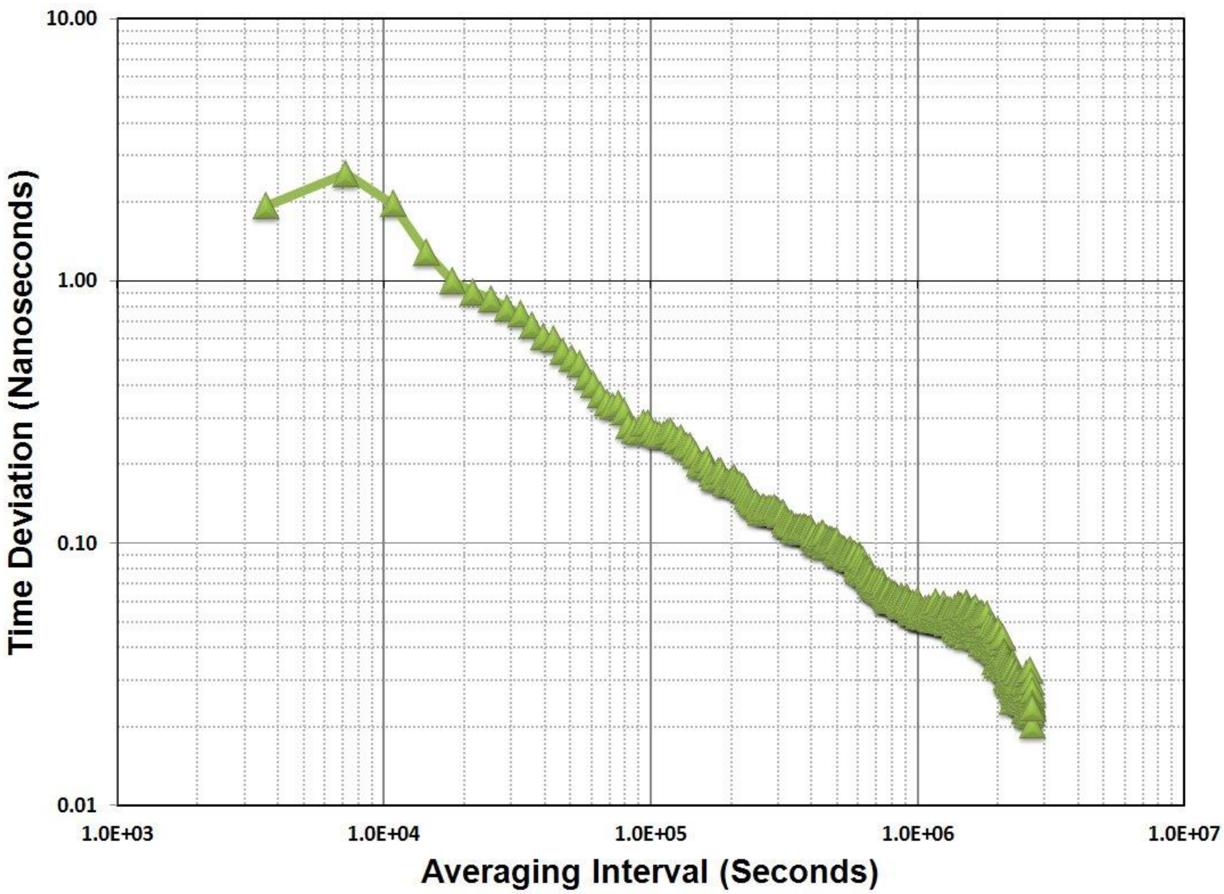


Figure 8. Time stability of a NISTDO with respect to UTC(NIST).

## VI. Summary

A NISTDO provides NIST customers with a replica of the UTC(NIST) time scale that resides within their laboratory. The measurements and verification tests described in this paper demonstrate that the frequency uncertainty of a NISTDO is less than $1 \times 10^{-14}$ after one day of averaging, and the time uncertainty is less than 5 ns, each with respect to UTC(NIST). These uncertainties were verified by direct comparisons to UTC(NIST) and can be achieved over very long baselines, as demonstrated by the performance of the NISTDO in Chile.



## References

[1] J. A. Pierce, 1957, "Intercontinental Frequency Comparison by Very Low-Frequency Radio Transmission," Proceedings of the IRE, 45, 794-803.

[2] J. L. Jespersen, 1970, "A Survey of Time and Frequency Dissemination Techniques," in Proceedings of the 1970 Frequency Control Symposium, 27-29 April 1970, pp. 322-324.

[3] M. Miranian, 1995, “UTC dissemination to the Real-Time User: The Role of USNO,” in Proceedings of the 27th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 29 November–1 December 1995, San Diego, California, USA, 75-85.
[4] R. E. Hesselberth, T. P. Danaher, and J. E. Sandahl, 1985, “Disciplined Oscillator System with Frequency Control and Accumulated Time Control,” United States Patent 4,525,685, filed May 31, 1983, granted June 25, 1985.
[5] M. A. Lombardi, 2010, “A NIST Disciplined Oscillator: Delivering UTC(NIST) to the Calibration Laboratory,” NCSLI Measure: The Journal of Measurement Science, 5(4), 46-54.
[6] M. A. Lombardi and A. P. Dahlen, 2008, “Locking a Rubidium Oscillator to a Remote Time Scale Using Real-Time Common-View GPS Measurements,” in Proceedings of the 40th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 1-4 December 2008, Reston, Virginia, USA, 527-542.
[7] M. Imae, et al., 2010, “Development of a GPS Common-view Terminal for Time and Frequency Remote Calibration Service,” in Proceedings of 2010 International Symposium on GPS/GNSS, 26-28 October 2010, Taipei, Taiwan, 1-5.
[8] K. Åström and T. Hägglund, 1995, PID Controllers: Theory, Design, and Tuning (Instrument Society of America, Research Triangle Park, North Carolina).
[9] M. A. Lombardi, et al., 2011, “The SIM Time Network,” Journal of Research of the National Institute of Standards and Technology, 116(2), 557–572.
[10] M. A. Lombardi, 2008, “The Use of GPS Disciplined Oscillators as Primary Frequency Standards for Calibration and Metrology Laboratories,” NCSLI Measure: The Journal of Measurement Science, 3(3), 56-65.
[11] S. Hutsell, M. Forsyth, and C. B. MacFarland, 2002, “One-Way GPS Time Transfer: 2002 Performance,” in Proceedings of the 34th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 3-5 December 2002, Reston, Virginia, USA, 69-76.