A NIST Disciplined Oscillator

Speaker/Author: Michael A. Lombardi
Time and Frequency Division
National Institute of Standards and Technology
325 Broadway, Boulder, CO 80305
lombardi@nist.gov

Abstract: The National Institute of Standards and Technology (NIST) now offers a service that provides customers with an oscillator locked to UTC(NIST), the United States national standard for frequency and time. A NIST disciplined oscillator (NISTDO) works by utilizing both the Internet and "common-view" observations of Global Positioning System (GPS) satellites, and can serve as the primary frequency and time standard for a calibration or metrology laboratory. NISTDOs are directly referenced to the Coordinated Universal Time scale kept at NIST, known as UTC(NIST). This makes it easy for laboratories to establish traceability to the International System (SI) directly through NIST. Customers are provided with standard frequency outputs of 5 MHz and/or 10 MHz, as well as 1 pulse per second timing outputs. These outputs provide time accurate to within about ±20 ns (peak-to-peak variation) with respect to UTC(NIST) and provide frequency with an uncertainty near 5×10^{-14} when averaged over a 24-hour interval. This paper discusses the theory of operation of the NISTDO, and demonstrates the accuracy and stability of the device over both short and long time intervals.

1. Introduction

Signals broadcast by radio have long been used for time and frequency control, allowing clocks to be synchronized to a reference time and oscillators to be syntonized to a reference frequency. Oscillators whose frequency is controlled by an external reference signal are known as disciplined oscillators. Unlike free running oscillators, which need to be periodically adjusted to stay within specification, disciplined oscillators are frequency or phase-locked to a reference signal and never require manual adjustment. The best disciplined oscillators can generate local signals with nearly the same accuracy and stability as the remote reference.

The topic of transferring time and frequency from a reference oscillator to a local oscillator has been of interest for many years. Most modern disciplined oscillators employ signals from the Global Positioning System (GPS) satellites as their reference source [1], but devices referenced to radio signals from ground based transmitters appeared decades earlier. For example, John A. Pierce of Harvard University published accounts of disciplined oscillators locked to very low frequency (VLF) radio signals during the 1950s. Pierce first used VLF signals to measure the performance of oscillators, but quickly found that there "is an obvious relation between the measurement of the frequency of an oscillator and the automatic control of that frequency." [2]

Radio signals have also long been used to compare clocks and oscillators to each other via a measurement technique called common-view. The technique predates GPS [3], but during the past 30 years common-view has become synonymous with common-view GPS (CVGPS) [4], a method routinely used for international comparisons of oscillators. [5, 6] Although routinely used for measurements, CVGPS has rarely been suggested [7, 8] or implemented as a control technique. This is because CVGPS measurements normally do not generate a real-time "signal". The measurement requires data collected at two sites to be transferred and processed, and the results are delayed, sometimes by days, and are usually available only at irregular intervals. However, recently developed CVGPS systems such as those supplied by NIST to subscribers of its Time Measurement and Analysis Service (TMAS) [9] use the Internet to automate data transfer and processing. Thus, the TMAS can generate CVGPS data in real-time.

Real-time CVGPS data serves the same purpose as a reference signal received by radio and has made it possible to develop a new device known as a common-view disciplined oscillator (CVDO) that can in principle be locked to any reference time scale. [10] This paper describes a NIST disciplined oscillator (NISTDO), a CVDO locked to UTC(NIST), which is now offered as an optional add-on to the TMAS. [11]. This service makes it possible for any laboratory to have a frequency standard that closely tracks the performance of the United States national standard.

2. Theory of Operation

The NISTDO is based on the CVGPS technique, a simple but effective method for comparing two clocks. Ideally, a comparison between two clocks would be made by bringing them both to the same location and making a direct comparison. However, when the two clocks are located at different sites, the time difference between them can still be measured by simultaneously comparing both clocks to a signal that is in "common-view" of both sites. The difference between the two comparisons is the time difference between the two clocks. The common-view signal is simply a vehicle used to transfer time from one site to the other. Its accuracy is unimportant because it does not influence the final measurement result.

The CVGPS method involves a GPS satellite (*S*), and two receiving sites (*A* and *B*), each containing a GPS receiver and a local clock (Figure 1). The satellite transmits a signal that is received at both *A* and *B*, and *A* and *B* each compare the received signal to their local clock. Thus, the measurement at site *A* compares the GPS signal received over the path d_{SA} to the local clock, *Clock A – S*. Site *B* receives GPS over the path d_{SB} and measures *Clock B – S*.

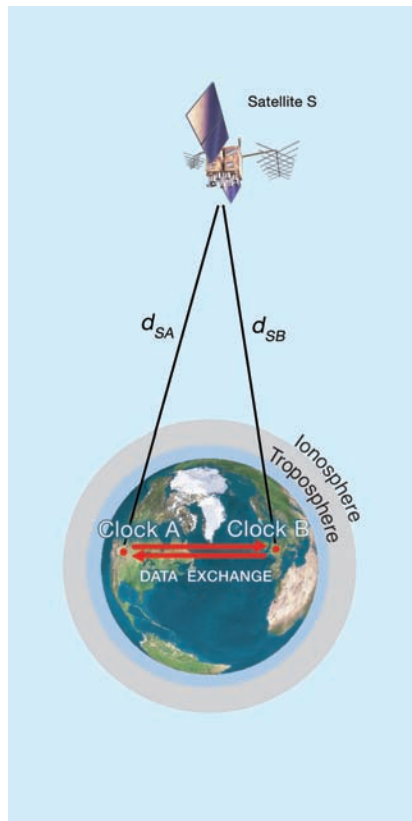

Figure 1. The common-view GPS measurement method.

The difference between the two measurements is an estimate of *Clock A – Clock B*. Delays that are common to both paths d_{SA} and d_{SB} cancel even if they are unknown, but uncorrected delay differences between the two paths add uncertainty to the measurement result. Thus, the basic equation for a CVGPS measurement is

$$(Clock\ A - S) - (Clock\ B - S) = (Clock\ A - Clock\ B) + (e_{SA} - e_{SB}). \quad (1)$$

The components that make up the ($e_{SA} - e_{SB}$) error term include delay differences between the two sites caused by ionospheric and tropospheric delays, multipath signal reflections, environmental conditions, or errors in the GPS antenna coordinates. These factors can be measured or estimated and applied as a correction to the measurement, or they can be accounted for in the uncertainty analysis. It is also necessary to calibrate the GPS receivers used at both sites and account for the delays in the receiver, antenna, and antenna cable.

There are several variations of the CVGPS measurement technique, and the magnitude of the error components depends upon the type and quality of the GPS equipment in use, and the way that the data is processed. For example, the differential ionospheric delay can be nearly eliminated by receiving both the L1 and L2 carrier frequencies, certain types of receivers are less sensitive to environmental changes, and certain types of antennas are more effective than others at mitigating multipath. The most sophisticated techniques and equipment can reduce the time uncertainty to a few nanoseconds or less, but the incremental performance gains obtained from the additional cost and effort are relatively small. Even when inexpensive GPS hardware and simple processing techniques are used (such as in the NISTDO system), the time uncertainty of a CVGPS measurement is often less than 10 ns.

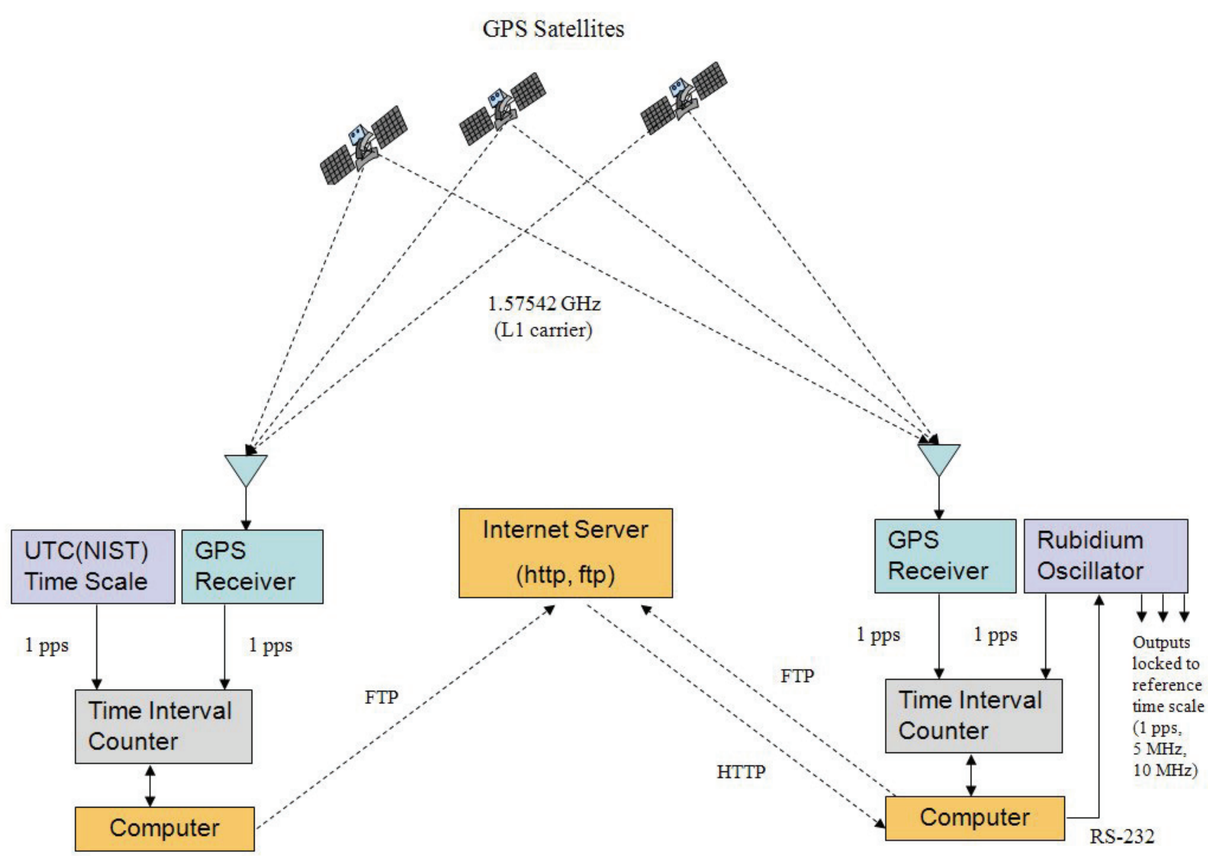

Figure 2. The NISTDO system.

Figure 2 is a diagram of the NISTDO system. One common-view GPS system is located at NIST, the second at the customer's facility. These systems are supplied by NIST to its TMAS customers. Each system includes an eight-channel GPS receiver (C/A code, L1-band) and a time interval counter. The NIST system compares a 1 pulse per second (pps) timing signal from the GPS receiver to the UTC(NIST) time scale. The customer's system compares a 1 pps signal from the GPS receiver to a rubidium oscillator that NIST supplies.

The measurement systems at both sites average time interval counter readings for 10 minutes and then simultaneously upload their results to an Internet file transfer protocol (FTP) server. The use of FTP requires transmission control protocol (TCP) ports 20 and 21 to be left open on the local firewalls. After the data are uploaded, the NISTDO invokes a common gateway interface (CGI) applet on the Internet server that instantly processes the CVGPS data. This applet, called *CVDIFF*, aligns and differences data from the individual satellite tracks, and discards data collected from satellites that are not in common view at both sites. The average time difference, *TD*, between the clocks at the two sites is obtained by

$$TD = \frac{\sum_{i=1}^{N} (REFGPS_i(A) - REFGPS_i(B))}{N}, \qquad (2)$$

where N is the number of satellites tracked by both GPS receivers, $REFGPS_i(A)$ is the series of individual satellite tracks recorded at the customer's site, and $REFGPS_i(B)$ is the series of tracks recorded at NIST.

The server includes another applet, called *AVDIFF*, for use by customers that are located so far away from NIST that few if any satellites are in common-view. *AVDIFF* implements the "all-in-view" method, where the satellite tracks are not aligned and no tracks are discarded. Instead, the averages of the $REFGPS_i(A)$ and $REFGPS_i(B)$ data series are calculated, and the time difference *TD* is the difference between the two averages.

Both *CVDIFF* and *AVDIFF* send data through TCP port 80, where it can be read by the NISTDO by use of the hypertext transfer protocol (HTTP). Thus, the NISTDO can nearly instantly obtain the time difference between its local oscillator and the reference time scale, and apply this information to discipline the local rubidium oscillator.

A PID controller, the most common control loop feedback mechanism [12], was chosen to discipline the rubidium. Its purpose is simply to correct the error, *e*, between a measured process variable and a desired set point (*SP*). Here the process variable is *TD*, the last measured time difference between the local oscillator and UTC(NIST). Because the NISTDO is attempting to lock the local oscillator as closely as possible to UTC(NIST), the desired value of SP is 0.

The PID controller algorithm involves three terms. The *P*-term determines the reaction to the present error, the *I*-term determines the reaction based on the sum of recent errors, and the *D*-term determines the reaction to the rate of change of the error. The weighted sum of these three actions is used to calculate a correction that is applied to the process that is being controlled. The output of the PID controlled system is the manipulated variable (*MV*), calculated as

$$MV(t) = P_{out} + I_{out} + D_{out} \quad , \qquad (3)$$

where P_{out}, I_{out}, and D_{out} are the contributions to the output from each of the three terms, as defined below.

The *P*-term makes a change to the output that is proportional to the current error. The P-term is given by

$$P_{out} = K_p e(t) \quad , \tag{4}$$

where P_{out} is the proportional output, K_p is the proportional gain, e is the error (*TD*), and t is the time of the error.

The *I*-term makes a change to the output that is proportional to both the magnitude and duration of the error. By integrating the error, the PID controller can account for the accumulated time and frequency offset that should have been corrected previously. The *I*-term is given by

$$I_{out} = K_i \int_0^t e(\tau) d\tau \quad , \tag{5}$$

where I_{out} is the integral output, K_i is the integral gain, e is the error (*TD*), and τ is the time in the past that has contributed to the integral response.

The D-term is the rate of change of the process error. It can be calculated by determining the slope of the error over time (its first derivative with respect to time) and multiplying this rate of change by the derivative gain:

$$D_{out} = -K_d \frac{de(t)}{dt} \quad , \tag{6}$$

where D_{out} is the derivative output, K_d is the derivative gain, e is the error (*TD*), and t is the instantaneous time [12, 13, 14].

Shortly after a new value for *TD* is obtained (some delay time is allowed to account for slow network connections), the P, I, and D terms are updated, and *MV* (Equation 3) is converted to a steering correction that is sent to the local oscillator. The steering correction is always a dimensionless frequency correction, and time errors are corrected through frequency adjustments. To compensate for small oscillator frequency changes that occur slowly, the control loop requires a low natural frequency and a narrow bandwidth. Thus, once the NISTDO is locked, the control loop is dominated by the I-term. The bandwidth of the control loop is software-limited to match the approximate tuning range of the rubidium oscillator, or ±0.05 Hz at a nominal frequency of 10 MHz.

As shown in equations 4 through 6, each control term has an associated gain term (K_p, K_i, and K_d) that serves as a tuning parameter. Tuning the gain parameters changes the speed at which the PID controller responds to errors, the degree to which the controller overshoots the set point, and both the phase noise and stability of the NISTDO output. The current implementation of the

NISTDO software (Figure 3) allows each gain parameter to be changed so that further tuning can be done. However, because stable oscillators tend to behave in a predictable fashion, a simple tuning scheme has been shown to work well with rubidium oscillators, where K_p is set to a small value (~0.03, for example) and where $K_i = K_p / 2$ and $K_d = K_p / 4$. If K_d is set to 0, the controller becomes a PI controller, and there is no significant change in the NISTDO's long-term stability or accuracy. However, because the derivative action is based on the predicted future action of the process variable, its inclusion allows the controller to respond faster to errors or incorrect trends in the NISTDO output. This results in a slight improvement in short-term stability.

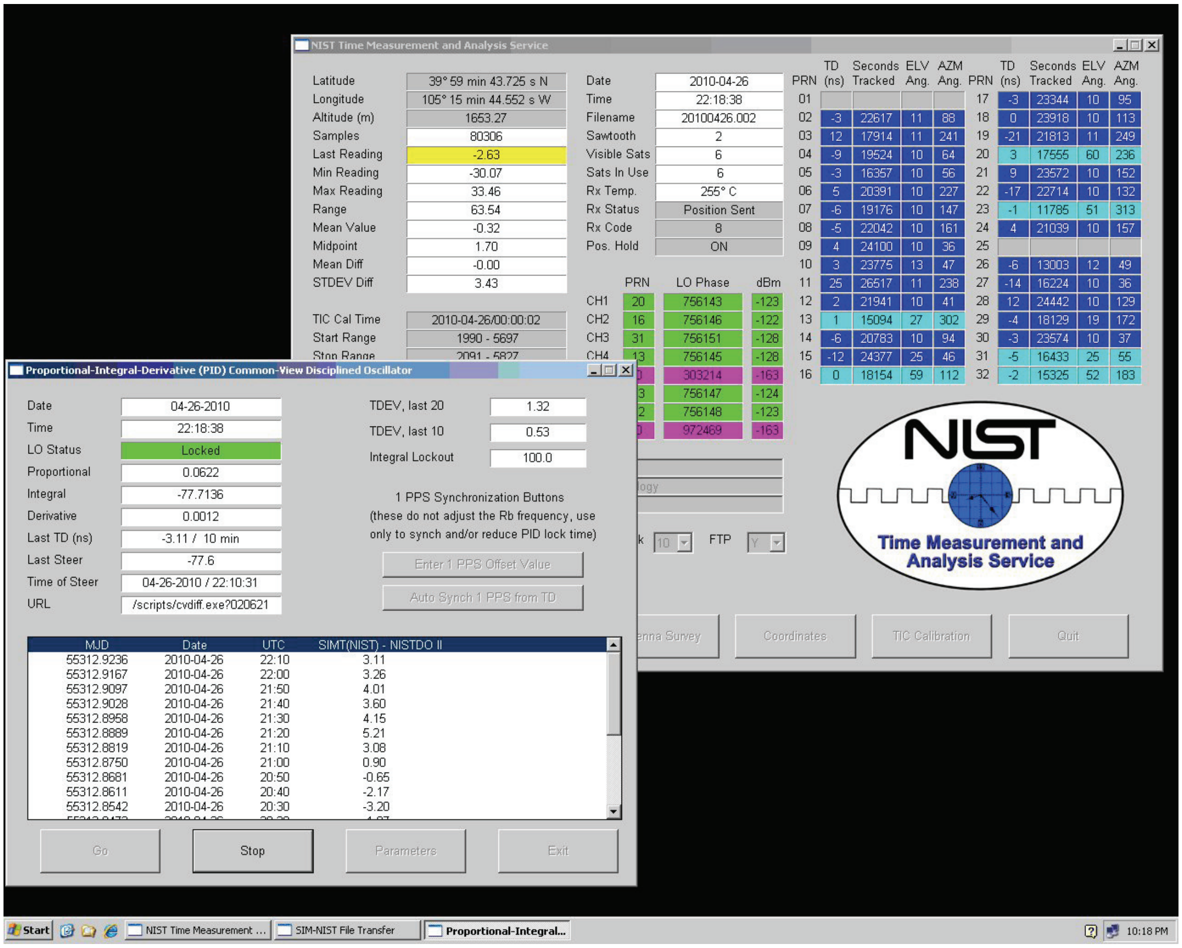

Figure 3. NISTDO software running on a TMAS system.

The NISTDO is considered to be locked if its output is both accurate and stable with respect to the reference. Two criteria must be met to satisfy the lock condition: the most recent time difference must be less than 50 ns (accuracy) and the time deviation [15, 16], $\sigma_x(\tau)$, of a series of the recent time differences must be less than 10 ns at τ = 10 minutes (stability). The time deviation is a metric for time stability based on the modified Allan deviation, *Mod* $\sigma_y(\tau)$, and is computed as

$$\sigma_x(\tau) = \frac{\tau}{\sqrt{3}} Mod\ \sigma_y(\tau) \quad . \tag{7}$$

The PID controller was designed to perform differently when the NISTDO is locked or unlocked. When the NISTDO is locked, *TD* values that are considered measurement outliers are filtered to prevent a condition known as integral windup [12, 13, 14] that can cause the system to be unstable, and in some cases, be unable to return to its set point. However, when the NISTDO is unlocked, the filtering is turned off. This allows it to quickly find its set point and lock.

The NISTDO records all steering corrections sent to the local oscillator, as well as the lock status at the time of each correction. If the NISTDO loses lock, its 1 pps timing output can be quickly resynchronized to the reference by stepping the phase of the divider output, and its frequency parameters can be restored to the last known lock condition. During this reset procedure, the PID controller is disengaged until the local oscillator reaches a steady state condition with respect to the reference, at which point frequency steering is resumed. This technique avoids typical PID behavior where overly aggressive corrections result in a damping effect where the set point is “overshot” multiple times until the process stabilizes; a condition that can last for many hours. Instead, an unlocked condition normally lasts for less than one hour if the Internet and GPS are both accessible.

3. NISTDO Performance

The rubidium oscillator incorporated into the NISTDO design has a built-in distribution amplifier with six outputs. One 1 pps output is required for the common-view measurements. The other five outputs can be configured to produce any combination of 5 MHz or 10 MHz frequency signals and 1 pps timing signals. The frequency stability of the rubidium, *Mod* $\sigma_y(\tau)$, reaches a noise floor near 4×10^{-13} at $\tau = 1$ hour, but is near 2×10^{-12} at $\tau = 1$ day, due to the effects of frequency drift and aging. The rubidium is more stable than the reference frequency transferred through the CVGPS channel for intervals up to about one hour. Thus, the NISTDO software can be configured to allow steering corrections at intervals of as long as one hour or as short as 10 minutes, the period of the CVGPS updates. A 10-minute update period provides the quickest response to an unlocked condition and minimizes the deviation from the set point. For most applications, this advantage outweighs the slight increase in phase noise caused by the additional steering.

Figure 4 is a phase plot of a NISTDO compared to UTC(NIST) for the 75-day period ending on April 25, 2010. The NISTDO was located near the UTC(NIST) time scale in Boulder, Colorado, and the two GPS antennas were separated by just 36.8 m.

The data points in Figure 4 are 1-hour averages. Note that the average time offset of the NISTDO with respect to UTC(NIST) was near zero (0.07 ns) with only a few outliers falling more than 15 ns from the mean. The phase plot has essentially no slope or trend and thus the frequency offset is negligible, less than 1×10^{-17}.

Figure 5 shows the frequency and time stability, *Mod* $\sigma_y(\tau)$ and $\sigma_x(\tau)$ respectively, of the NISTDO’s 1 pps output with respect to UTC(NIST) at intervals of 10 minutes and longer. The frequency stability reaches 1×10^{-12} after less than two hours of averaging and drops to 6×10^{-15} at $\tau = 1$ day. The time stability is near or below 1 ns after a few hours of averaging. After about 10 days of averaging, the frequency stability is near 1×10^{-16}.

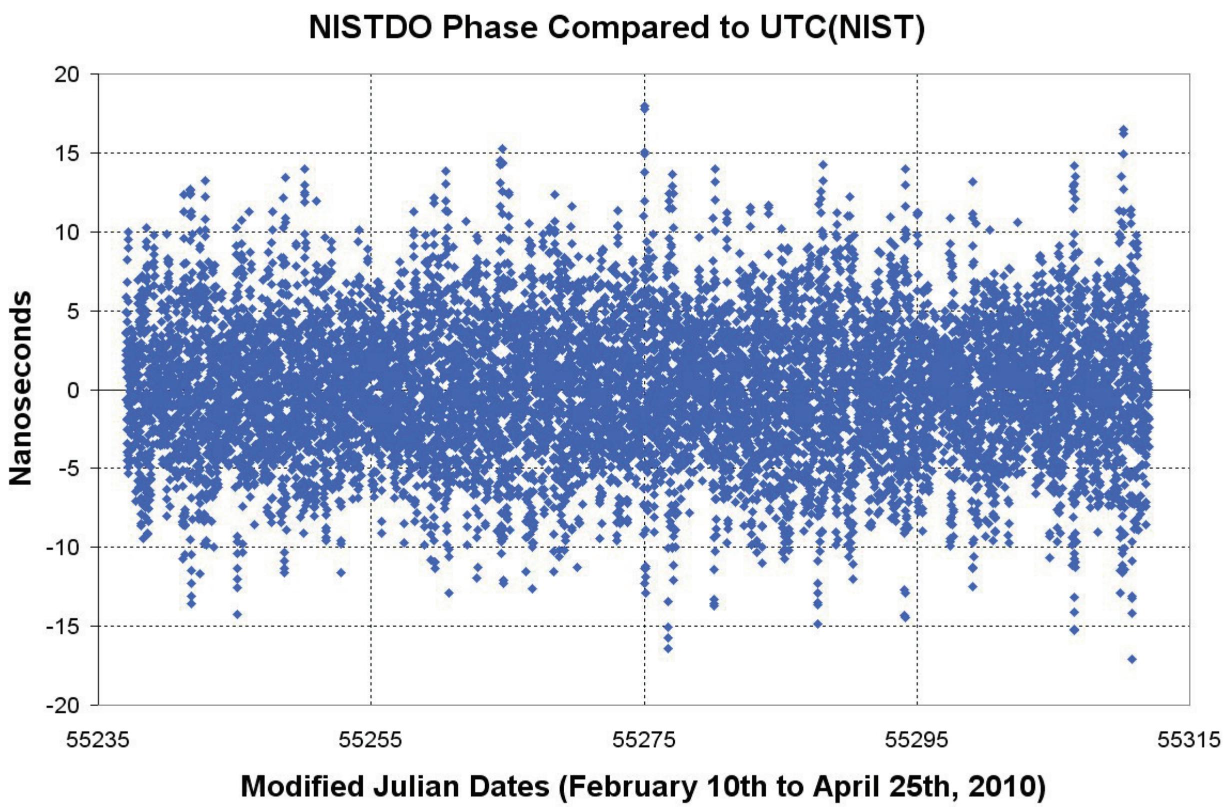

Figure 4. NISTDO phase compared to UTC(NIST).

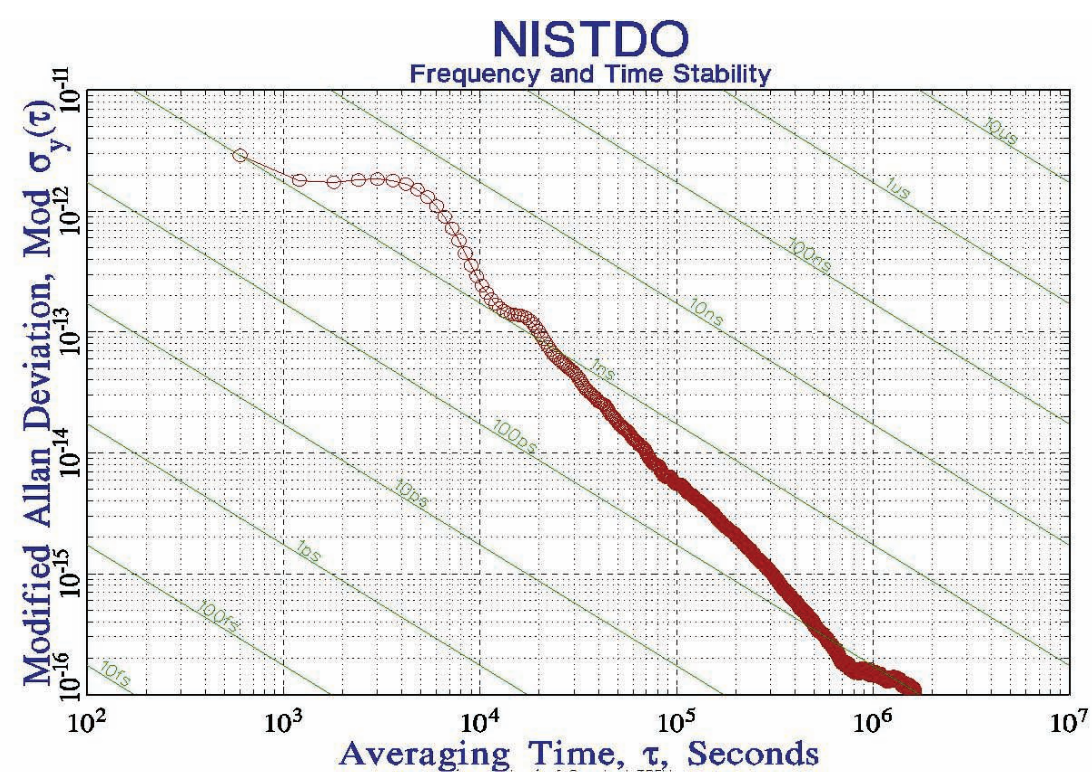

Figure 5. Frequency stability and time stability (diagonal lines) of NISTDO with respect to UTC(NIST).

To estimate the NISTDO's frequency stability at intervals shorter than 10 minutes, its 10 MHz output was measured at one-second intervals with a high resolution dual mixer time difference system [16]. The same measurement system was then used to measure the undisciplined 10 MHz output of the rubidium oscillator. Both measurements were made with respect to UTC(NIST). The results of the two tests are shown in the *Mod* $\sigma_y(\tau)$ graph in Figure 6. Note that the NISTDO stability becomes slightly worse at averaging times ranging from 10 minutes (the period of the steering corrections) to about one hour. This "bump" in the stability graph is typical of disciplined oscillators (a similar "bump" is visible in Figure 5). It indicates that the steering corrections are unable to completely compensate for the frequency drift and aging of the local oscillator at certain averaging times. This is due to the period of the steering corrections, and to a lesser extent, to their resolution and accuracy. However, even during these intervals, the NISTDO stability is less than 1×10^{-12}. At averaging times greater than one hour, the frequency stability rapidly improves, because the steering corrections keep the NISTDO in continuous agreement with UTC(NIST). In contrast, the undisciplined rubidium reaches a noise floor of ~4.5×10^{-13} near τ = 10 minutes and then rapidly deviates from the frequency of UTC(NIST) due to the effects of uncompensated frequency drift and aging. The "crossover point" where the disciplined oscillator diverges from the undisciplined oscillator is near τ = 1 hour.

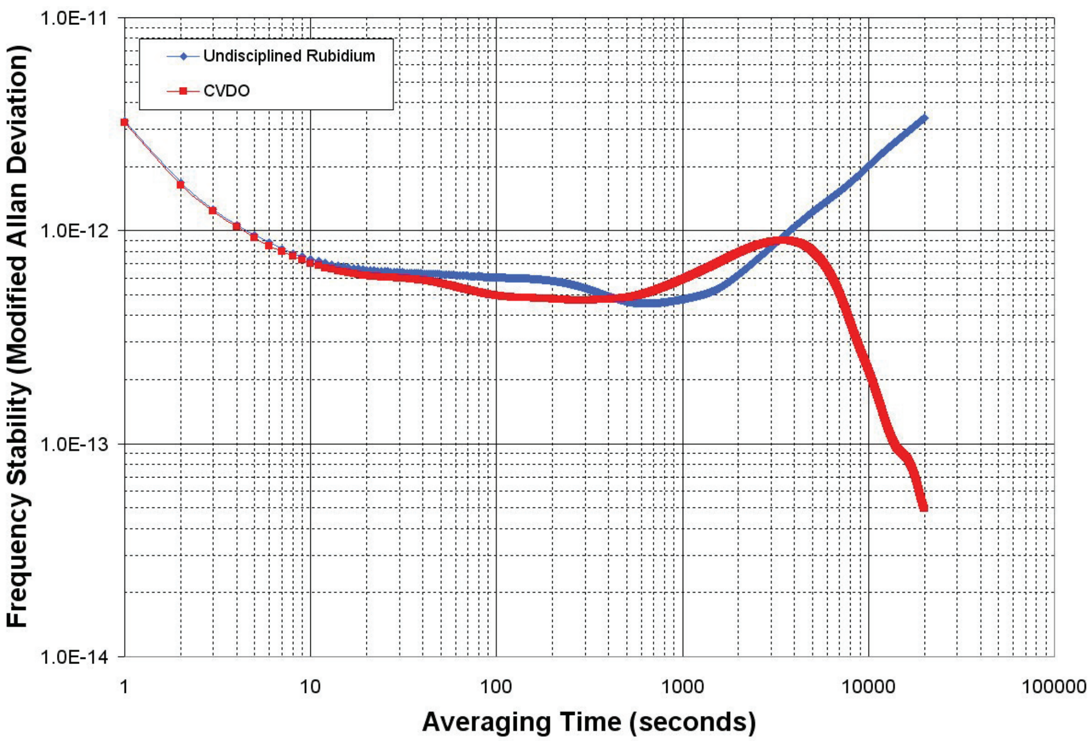

Figure 6 – Frequency stability of NISTDO compared to undisciplined rubidium oscillator.

The NISTDO software is versatile, and can be configured to lock to other reference time scales that make real-time CVGPS data available on the Internet. To demonstrate this, the software was configured to lock the rubidium to UTC(CNM), the national time scale of Mexico located at the Centro Nacional de Metrología in Querétaro City, a distance of 2199 km from NIST. UTC(NIST) was then simultaneously compared to UTC(CNM) and the rubidium locked to

UTC(CNM). Figure 7 shows a phase plot comparing 1-day averages obtained from both measurements during a 45-day interval (MJD 55158 to 55202).

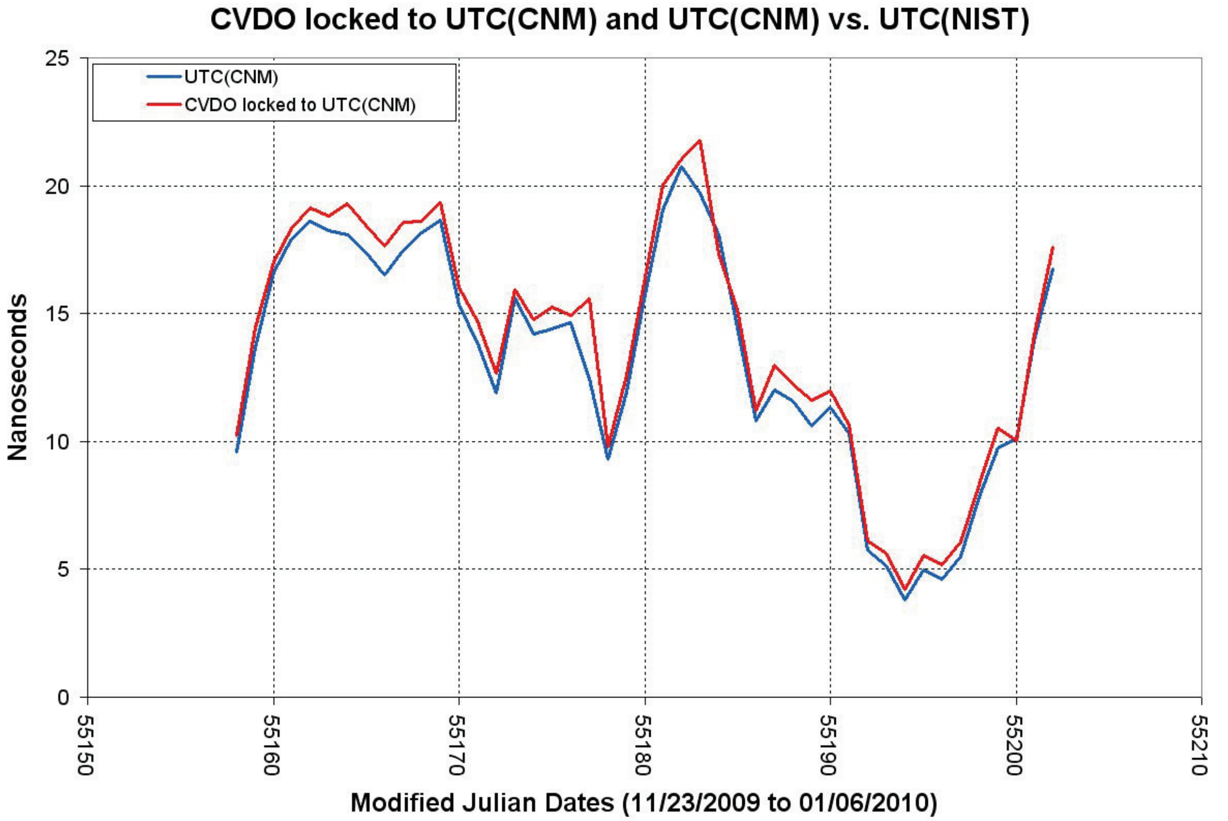

Figure 7. Phase comparison between UTC(CNM) time scale and rubidium locked to UTC(CNM).

The results shown in Figure 7 show very close agreement, and at first glance, the performance of the UTC(CNM) “emulator” appears to be nearly equivalent to UTC(CNM) itself. However, Figure 8 reveals that the disciplined oscillator is less stable than its reference at short averaging times, as estimated with *Mod* $\sigma_y(\tau)$. For example, at $\tau = 1$ hour the stability difference is nearly a factor of five, 0.5×10^{-12} for the reference time scale as opposed to 2.4×10^{-12} for the disciplined oscillator. This limitation in short-term stability with respect to the reference time scale is primarily due to three factors: the time transfer noise over the 2199 km path between Boulder and UTC(CNM), the ten-minute steering interval, and the resolution of the frequency corrections sent to the rubidium oscillator, which are limited by the hardware to 2×10^{-12}.

Figure 8 reveals that factors which influence the short-term stability have very little effect on the long-term stability. For example, at $\tau = 1$ day there is only marginal improvement; UTC(CNM) is stable to 1.9×10^{-14} with respect to UTC(NIST), as opposed to 2.2×10^{-14} for the “emulator”. At averaging times longer than one day, the two stability estimates are essentially identical. This same type of performance can be expected of NISTDOs deployed long distances away from Boulder. Over intervals longer of one day or longer, there will be very little difference between the performance of a NISTDO and the performance of UTC(NIST).

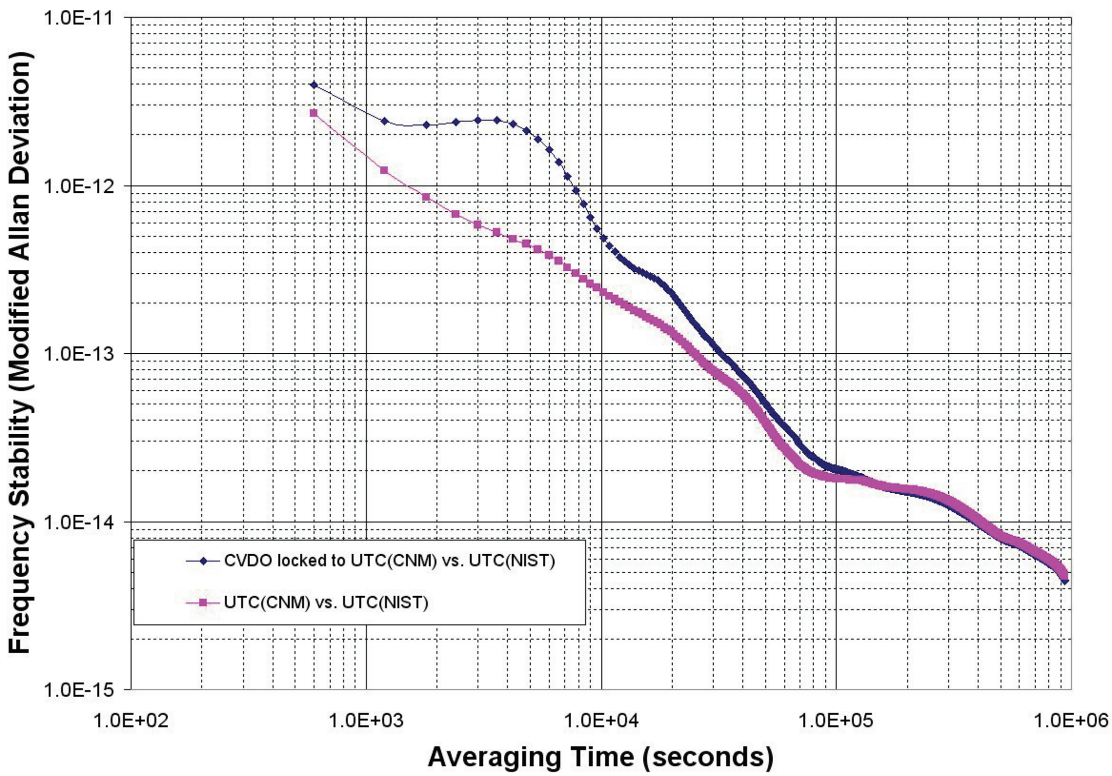

Figure 8. Stability comparison between UTC(CNM) time scale and rubidium locked to UTC(CNM).

4. NISTDO Failure Modes

Several situations can cause a NISTDO to fail or become unlocked. Like a GPS disciplined oscillator (GPSDO), a NISTDO is vulnerable to GPS outages due to local interference or other causes. The problem is more pronounced with a NISTDO, however, because a GPS failure either at NIST or at the customer's site can cause a failure. In addition, a NISTDO is vulnerable to Internet outages at either NIST or the customer's site.

If an Internet or GPS outage is long enough it will eventually cause the NISTDO to fail. However, short outages are normally not a problem. The rubidium oscillator is tuned very close to its nominal frequency while locked, and will continue to keep accurate time without steering corrections for a reasonably long interval. Internet and/or GPS outages of up to about one hour should not be noticeable, and time can be kept within a few microseconds of UTC(NIST) for one day or longer even if both the Internet and GPS are unavailable.

5. Summary

A NIST disciplined oscillator (NISTDO) is a unique new instrument that makes it possible for calibration and metrology laboratories to maintain a standard that is both synchronized and syntonized to UTC(NIST), the national standard for time and frequency in the United States.

The NISTDO is now available as an optional add-on to the NIST Time Measurement and Analysis Service.

6. Acknowledgements

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References

[1] M. A. Lombardi, "The Use of GPS Disciplined Oscillators as Primary Frequency Standards for Calibration and Metrology Laboratories," *Measure: The Journal of Measurement Science*, vol. 3, no. 3, pp. 56-65, September 2008.

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

[3] J. Tolman, V. Ptacek, A. Soucek, and R. Stecher, "Microsecond Clock Comparison by Means of TV Synchronizing Pulses," *IEEE Transactions on Instrumentation and Measurement*, IM-16, No. 3, pp. 247-254, September 1967.

[4] D. W. Allan and M. A. Weiss, "Accurate Time and Frequency Transfer During Common-View of a GPS Satellite", *Proceedings of the 1980 Frequency Control Symposium*, May 1980, pp. 334-346.

[5] W. Lewandowski, J. Azoubib, and W. Klepczynski, "GPS: Primary Tool for Time Transfer", *Proceedings of the IEEE*, vol. 87, no. 1, January 1999, pp. 163-172.

[6] T. E. Parker and D. Matsakis, "Time and Frequency Dissemination: Advances in GPS Transfer Techniques," *GPS World*, vol. 15, pp. 32-38, November 2004.

[7] D. W. Allan and J. Levine, "A Rubidium Frequency Standard and a GPS Receiver: Remotely Steered Clock System with Good Short-Term and Long-Term Stability," *Proceedings of the 44th Annual IEEE Frequency Control Symposium*, pp. 151-160, May 1990.

[8] K.–Y. Tu, F.-R. Chang, C.-S. Liao, and L.-S. Wang, "Frequency Syntonization Using GPS Carrier Phase Measurements," *IEEE Transactions on Instrumentation and Measurement*, vol. 50, no. 3, pp. 833-838, June 2001.

[9] M. A. Lombardi and A. N. Novick, "Remote Time Calibrations via the NIST Time Measurement and Analysis Service," *Measure: The Journal of Measurement Science*, vol. 1, no. 4, pp. 50-59, December 2006.

[10] M. A. Lombardi and A. P. Dahlen, "A common-view disciplined oscillator," *Review of Scientific Instruments*, vol. 81, no. 5, May 2010.

[11] The TMAS and the NISTDO option are described at: http://www.nist.gov/physlab/div847/grp40/tmas.cfm

[12] K. Åström and T. Hägglund, *PID Controllers: Theory, Design, and Tuning*, 2nd ed. (Instrument Society of America, Research Triangle Park, North Carolina, 1995).

[13] A. Visioli, *Practical PID Control* (Springer-Verlag, London, 2006).

[14] D. W. St. Clair, *Controller Tuning and Control Loop Performance*, 2nd ed. (Straight-Line, Newark, Delaware, 1993).

[15] IEEE, "Standard Definitions of Physical Quantities for Fundamental Frequency and Time Metrology - Random Instabilities," *IEEE Standard 1139*, 1999.

[16] W. J. Riley, Handbook of Frequency Stability Analysis, *NIST Special Publication 1065*, July 2008.