Measurement of Transient Environmental Effects in GPS-Disciplined Clocks

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ABSTRACT

GPS-disciplined clocks (GPSDCs) are designed to optimize the accuracy and stability of their pulse-per-second (PPS) and frequency outputs by steering an internal oscillator to the timing solution from a GPS receiver based on the received satellite signals. The steering function uses either a frequency-lock or phase-locked loop (PLL), typically implemented with a proportional integral derivative (PID) controller. Ideally, a GPSDC will exploit the stability of its local oscillator for short intervals but derive its long-term accuracy and stability from the GPS system's delivered prediction of UTC(USNO), the Coordinated Universal Time (UTC) scale maintained by the United States Naval Observatory (USNO). The output frequency of both quartz and rubidium oscillators is affected by changes in external environmental conditions, primarily temperature. Therefore, it would not be expected that the optimal steering function in the steady state would also be optimal during rapid variations of environmental conditions surrounding the device. We report the observed behavior of several commercially available GPSDCs while they are subjected to rapid temperature variations and discuss potential modifications that might make them less sensitive to these variations.

1. INTRODUCTION

GPS-disciplined clocks (GPSDCs) are widely deployed as frequency and time standards and usually meet specifications without being calibrated. Most GPSDCs use proportional integral derivative (PID) control or similar techniques to balance the short-term stability of the local oscillator with the long-term stability and accuracy of GPS, as well as the ability to quickly respond to conditions that cause the frequency of the oscillator to change [1]. The PID setpoint represents an offset of 0 ns between the local oscillator and the received GPS signals, but a residual time offset will remain until the hardware delays in the device have been calibrated. When a GPSDC is calibrated, its frequency outputs cannot be adjusted, as the local oscillator frequency is always externally controlled by the received satellite signals. However, once the combined receiver, antenna, and antenna cable delays have been measured, its time outputs can be adjusted by applying a delay value to the GPSDC configuration to compensate for all delays. Delay calibrations can be obtained by sending a GPSDC to a national laboratory such as the National Institute of Standards and Technology (NIST), or by subscribing to a remote calibration service. An additional delay is added with height errors in the position determination. It is suggested that a dual-frequency GPS receiver or augmented geodetic receiver be used to determine more accurate coordinates than the GPSDC may establish. In most cases, this position can be entered manually into the GPSDC settings.

During most GPSDC calibrations, the temperature of the laboratory environment is usually carefully controlled, and therefore the effects that temperature variations might have on a GPSDC are usually not measured [2]. This paper shows how external temperature changes can affect the time outputs of a GPSDC. Because some commercial GPSDCs allow the user to adjust the parameters of the control loop, we will demonstrate a basic example where adjusting the gains of some parameters of the PID control can improve the device's response to temperature changes [3].

2. DATA COLLECTION

2.1 Experimental Setup

Using a programmable thermal chamber, the GPSDCs under test were subjected to temperature changes in several patterns to observe how the timing output varies and how it recovers back to a steady state condition. Figure 1 shows a block diagram of

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the measurement setup for this process. An L1 band antenna was mounted on an antenna platform on the roof of NIST in Boulder, Colorado. The poles on the platform have been surveyed with an augmented geodetic receiver and the antenna coordinates were manually entered into all of the devices under test used in this experiment. The GPSDCs were placed into a programmable thermal chamber, which was varied by ±15 °C from a middle-point around 22 °C. A time interval counter was used to compare the 1 pulse per second (pps) output of the GPSDCs to the 1 pps output of UTC(NIST) every second. The measurements were recorded with compensation applied for the cable delays.

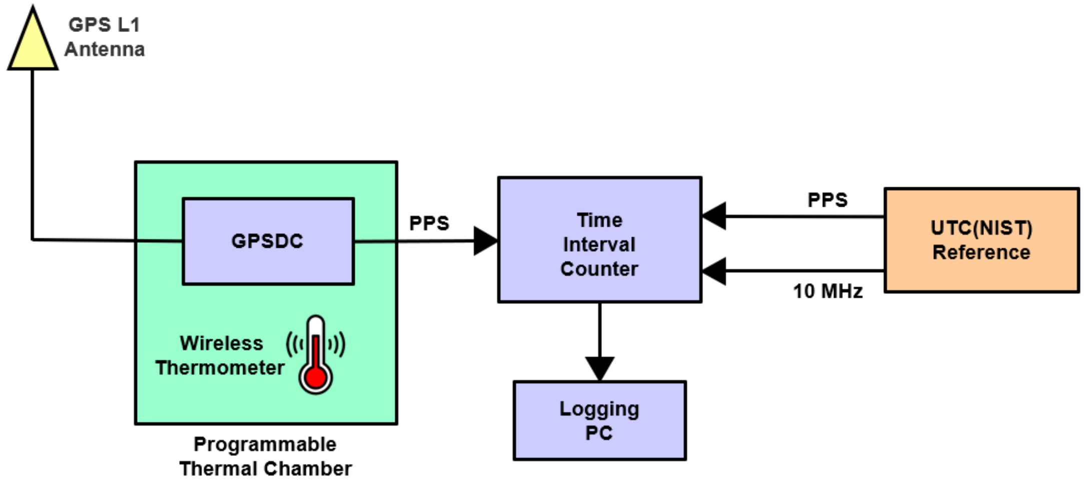

Figure 1. *Block diagram experimental setup to measure the time offset of a GPSDC in a thermal chamber at NIST.*

A wireless thermometer inside the thermal chamber recorded the temperature readings and relayed the data to an Internet server. Temperature readings were recorded and sent every five minutes, so five-minute averages were used to align the time measurements to the temperature readings. Control mechanisms that compensate for the temperature coefficient of the local oscillator have been included in some GPSDC designs for many years [4], and several of the GPSDCs that we tested did not have noticeable variations in their timing outputs even when they were subjected to rapid temperature variations. However, one model of GPSDC that was tested did produce large 1 pps time excursions that corresponded to temperature changes. The following data and analysis relate to this model which is based on an oven-controlled crystal oscillator (OCXO).

2.2 Temperature Changes

The temperature of the chamber was stabilized for several hours before and after the transient effects were introduced. Figure 2 shows a measurement run on December 12, 2022, where the temperature in the chamber was adjusted from a baseline of 22.3 °C up to 33.7 °C over a period of 40 minutes, down to 6 °C over 80 minutes, and then back to 22.3 °C over 40 minutes. This caused the GPSDC timing output compared to UTC(NIST) to shift from an average around -5 ns down to -59 ns and then up to 105 ns before returning to the original time offset. Note that the time offset does not change immediately with temperature changes, as the turnaround points lag the temperature changes by about 15 minutes.

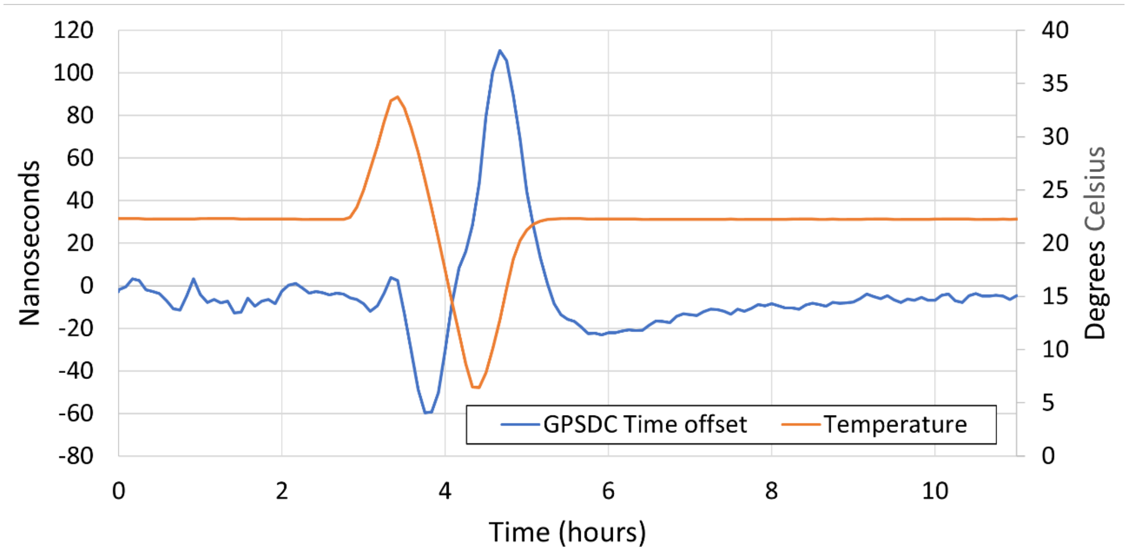

Figure 2. *Variations of the time offset of a GPSDC in a thermal chamber reacting to rapid changes in temperature.*

In rugged conditions, for example when GPSDC units are operated outdoors in a telecom installation, large and rapid temperature changes such as shown in Figure 2 are possible. However, in a laboratory setting, a GPSDC is unlikely to ever experience such large swings in temperature. Changes of only a few degrees are more likely in a laboratory, so a different temperature variation pattern was implemented to better understand the effects of small temperature changes on the timing output.

Instead of a temperature increase and an immediate temperature decrease, small increases in temperature were made to see if the time offset would change and then remain at its new value. Figure 3 shows data recorded on December 22-24, 2022, where the temperature was increased in steps of 2 °C, with a four hour interval of constant temperature in between steps, and then transitioned from 29.7 °C back to 22.3 °C. The small temperature changes caused short-term shifts in the time outputs, but the GPSDC's control loop then returned the output to the same setpoint. The large temperature transition back to the 22.3 °C baseline caused an approximate 110 ns time step that required about two hours for the control loop to remove, but afterwards the GPSDC still returned to the same setpoint as before, after a small overshoot.

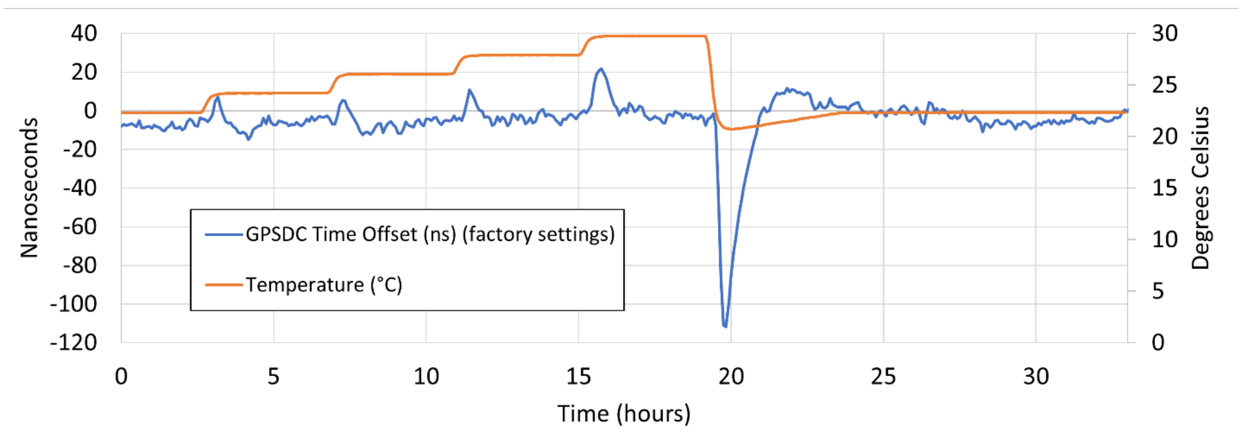

Figure 3. *Variations of the time offset of GPSDC reacting to stair-step changes in temperature.*

Because the time offset of this GPSDC always returns to the setpoint as long the temperature during a given period remains constant, then a delay calibration value applied to this device should remain valid even if the temperature of its local environment changes. However, the large time fluctuations that occur when the temperature is changing indicate that a delay calibration should not be performed unless the environment is stable.

2.3 Steering Changes

The GPSDC under test has some adjustable PID gain settings that provide an opportunity to tune the parameters and measure the effects. In this case, the adjustable parameters are not defined specifically in the reference manual as proportional, integral or derivative, but it does indicate parameters which are related to the P and I terms, so these parameters can be adjusted as a ratio with respect to the factory defaults. The P and I parameters were doubled, and the same chamber temperature sequence previously run with the factory PID settings was started again with the new settings. Figure 4 shows the results aligned with the previous graph to compare the difference in effects.

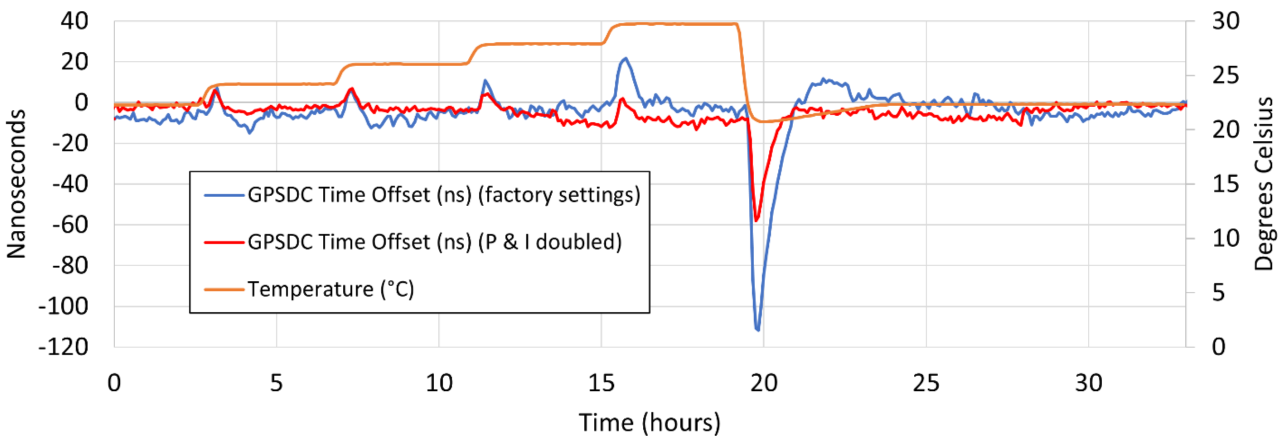

Figure 4. *Variations of the time offset of GPSDC with varying PID settings reacting to stair-step changes in temperature.*

With the P and I parameters doubled, the changes in temperature cause a maximum time fluctuation that was about half as large as the one obtained with the factory settings, and the average time offset is closer to zero as well. This is only a singular result and other factors, such as steering during startup or holdover, may be adversely affected by altering the factory settings. Much more experimentation should be done regarding the effects of PID changes and their response to varying environmental conditions.

3. SUMMARY AND CONCLUSION

With a commercial GPSDC product, it is difficult to characterize the internal changes caused by changing the environment. In other words, changes in temperature may affect more than one aspect of how the product operates. For instance, an external temperature change could be affecting the frequency of the oscillator and also the oven it is housed in (which may be controlled by a separate PID). Some GPSDCs contain a double oven to help mitigate the effects of external temperature changes but this adds to both the power consumption and cost.

Our measurements have shown that temperature changes can significantly affect the time outputs of a GPSDC, and this may not be revealed during a calibration in a laboratory environment. Adjusting the control loop parameters, if possible, might be beneficial for devices operated in unstable environmental conditions.

4. ACKNOWLEDGMENTS

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5. REFERENCES

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