Remote Calibration of a GPS Timing Receiver to UTC(NIST) via the Internet*

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Abstract

The timing pulse from a Global Positioning System (GPS) receiver is typically within 1 μs of Coordinated Universal Time (UTC) kept at NIST, called UTC(NIST), even if the receiver and antenna have not been calibrated for delays. However, it is not possible for most laboratories to make an accurate measurement of their GPS receiver's time offset with respect to UTC(NIST), or to monitor its continuous performance. This paper presents a method for remotely calibrating a GPS timing receiver at the customer's location with respect to UTC(NIST) using the common-view GPS technique and the Internet. We present data from a remote calibration of a GPS timing receiver located at Sandia National Laboratories in Albuquerque, New Mexico, about 561 km from the NIST Laboratories in Boulder, Colorado. The uncertainty of the calibration is shown to be less than 50 ns.

INTRODUCTION

There is a small but growing demand in the calibration community for laboratories to maintain an on-time 1 pulse per second (pps) reference with a known uncertainty. This timing reference can be used either as a time interval standard, or to synchronize or calibrate other devices. By far the easiest way to obtain accurate timing pulses is to use a Global Positioning System (GPS) receiver. A typical commercial GPS receiver will produce a timing signal within 1 μs of UTC(NIST), even if it has not been calibrated for delays. However, since measuring the actual time offset to UTC(NIST) is usually not an option, laboratories are often limited to using the number quoted on the manufacturer's specification sheet as their uncertainty figure.

This paper describes a measurement system that can remotely calibrate a GPS timing receiver and determine the actual time offset of the receiver with an uncertainty of < 50 ns. The Internet is used to exchange data and to display the measurement results.

GPS TIME

The time broadcast by the GPS satellites, called GPS time, is controlled by the United States Naval Observatory (USNO) from their alternate master clock facility collocated with the GPS Master Control Station at Schriever Air Force Base, located near Colorado Springs, Colorado. The on-time pulses broadcast by the satellites are in close agreement with both the UTC(USNO) and UTC(NIST) time standards. Figure 1 shows the average daily time offsets of GPS time –

UTC(USNO), GPS time − UTC(NIST), and an estimate of UTC(USNO) − UTC(NIST) for the month of October 2002. This data can be obtained from the USNO web site at http://tycho.usno.navy.mil/gps_datafiles.html and from the NIST web site at http://tf.nist.gov/service/gpstrace.htm. NIST and the USNO have agreed not to allow their time scales to differ by more than 100 ns, and as Figure 1 indicates, the recent average time offset between the two time scales has been less than 10 ns.

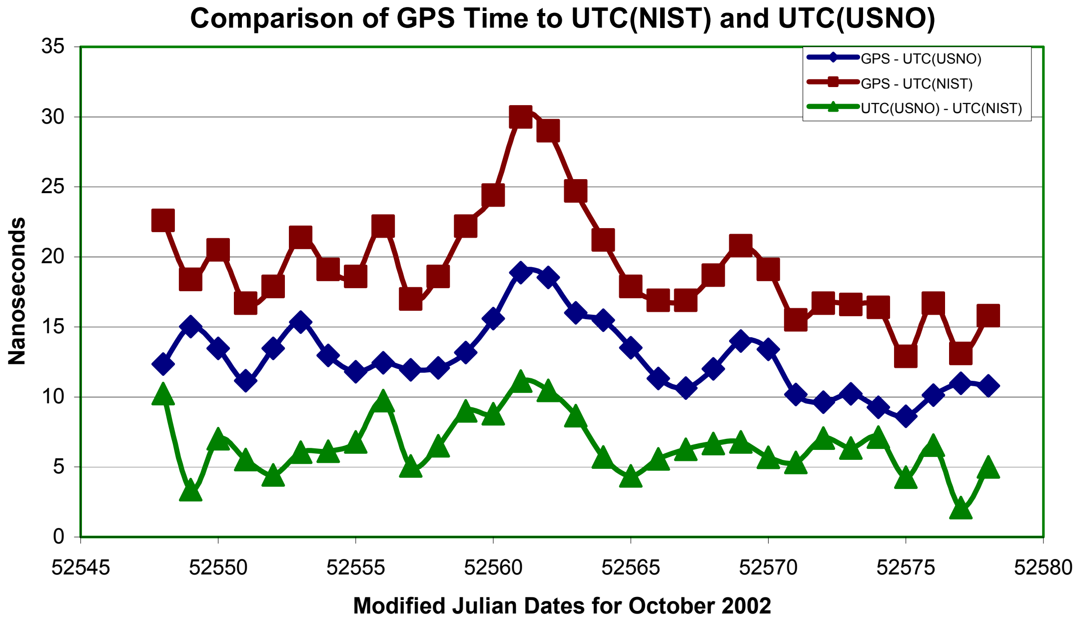

Figure 2. Comparison of GPS Time to UTC(NIST) and UTC(USNO).

Although GPS time as broadcast is in close agreement with UTC(NIST), the equipment used to receive the GPS signal can increase the uncertainty of the received time. The receiver hardware, firmware, antenna, and antenna cable introduce intrinsic delays and uncertainties. Varying propagation delays through the ionosphere and troposphere, multipath delays caused by GPS signals bouncing off other objects before they reach the antenna, and uncertainties in the estimate of the receiving antenna's position also increase the overall uncertainty of the received time.

A GPS receiver and its antenna and cable can be sent to NIST or another laboratory for a delay calibration. This type of calibration does a thorough job of measuring the receiver's intrinsic delays, but cannot account for the environmental delays the receiver encounters while operating at its assigned location. A remote calibration has the advantage of calibrating the receiver at its normal location, without removing it from service. Remote receiver calibrations use the common-view GPS technique. This technique involves sending a measurement system to the customer's site that includes a NIST-characterized GPS receiver.

Common-view GPS measurements began at NIST shortly after the first GPS satellite was launched in 1978 [1], and calibration services based on this technique have existed for years at NIST and other national metrology institutes [2]. The common-view technique also plays a central role in the international calculation of UTC performed by the International Bureau of Weights and Measures (BIPM) [3]. The technique is based on the concept that two laboratories can measure the time difference between their local clocks by each comparing their local clock to the same reference at the same time. The laboratories record and exchange their measurements, and the difference between the measurements is the difference in the time kept by the two clocks.

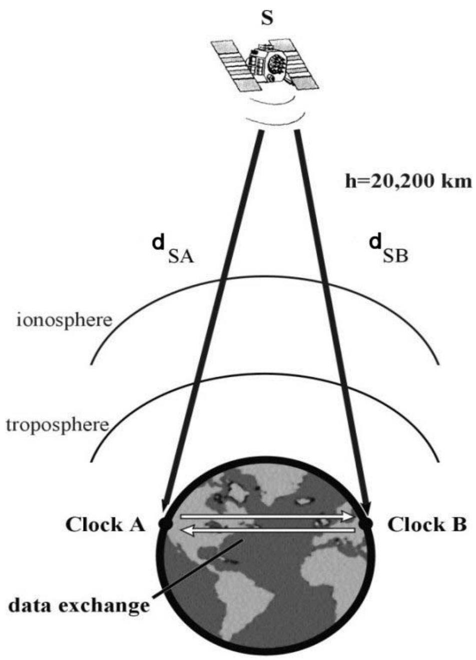

Figure 2. Common-View GPS.

To visualize how the common-view technique works, imagine two people living at opposite ends of town who want to compare the time on the grandfather clocks in their living rooms. This would be an easy problem to solve if they could get the clocks together in the same place and compare them side by side. However, moving the clocks is not possible. Therefore, each person agrees to write down the time displayed by their clock when the fire whistle (located midway between them) blows in their town, an event that happens each day around noon. They then call or email each other and exchange the time readings. If the first clock read 12:01:35 and the second clock read 12:01:47, then simple subtraction tells them that the second clock was 12 seconds ahead of the first clock when the fire whistle blew. Whether the fire whistle blew exactly at noon or not is unimportant. It only matters that it was heard at the same time at both locations. If so, the measurement reveals the difference between the two clocks, and the comparison is successful.

Instead of a fire whistle, common-view GPS comparisons use one or more GPS satellites as the common-view reference (Figure 2). There are several variations of the technique [4], but all have the same objective, to compare clocks or oscillators at remote locations. The common-view method involves a satellite (S) and two receivers (A and B). The satellite transmits a time signal that is simultaneously received by both receivers. Both receivers compare the received signal to their local clock and record the data. Receiver A receives the signal over the path d_{SA} and compares the reference to its local clock (S - Clock A). Receiver B receives the signal over the path d_{SB} and records (S - Clock B). The two receivers then exchange and difference the data. Delays that are common to both paths d_{SA} and d_{SB} cancel out, but delays that aren't common to both paths contribute uncertainty to the measurement. The result of the measurement is (Clock A - Clock B) with an error term of ($d_{SA} - d_{SB}$). This error term can be estimated and applied as a correction to the measurement.

The $d_{SA} - d_{SB}$ term not only includes delays from the satellite to the receiving antennas, but also includes equipment delays that take place after the signal is received. Therefore, a key to a successful common-view measurement is to have equal delays at each site. Prior to a measurement, the common-view systems should be calibrated so that their relative delays are as close to zero as possible.

DESCRIPTION OF MEASUREMENT SYSTEM

The measurement system sent to the customer's site includes a time interval counter (TIC) with an integrated GPS receiver [5]. The TIC and an 8-channel GPS receiver are both contained on a single Industry Standard Architecture (ISA) bus card designed at NIST for use in a standard PC. The TIC has a single shot resolution of < 30 ps, and a 2σ stability of <100 ps at an averaging time of one day. The TIC requires a 1, 5, or 10 MHz external time base oscillator. The system at the customer's site compares the 1 pps output from the GPS receiver under test to the 1 pps output of the integrated GPS receiver, and collects and stores one reading per second. An identical system at NIST uses a 1 pps output reference signal from UTC(NIST) instead of a signal from the receiver under test.

The measurement system is controlled using a standard Windows computer with a software application written at NIST. The software that controls the receivers does not use a tracking schedule. It simply collects and stores data from all available satellites in view (limited in some instances by the 8 satellite capacity of the receiver). Every satellite is measured for the entire amount of time it is visible above a 10° elevation angle. On average, about 400 minutes of data are collected from each satellite per day. This means that even though a GPS satellite completes slightly more than two Earth orbits per day, it is still visible from a single fixed position on Earth more than 25 % of the time. The receiver has the ability to apply the broadcast ionospheric and tropospheric correction to the measurements, and this feature is activated.

The software makes a time interval measurement between the GPS pulse and the local clock every second. It uses information supplied by the receiver to produce a time offset reading for each individual satellite, and stores 10-minute averages for each satellite. The data from a complete day is stored in a daily file as a 32 column × 144 row matrix. The 32 columns represent the possible number of GPS satellites (27 GPS satellites were usable throughout most of this experiment), with each satellite's data stored in the column whose number equals its psuedo random noise (PRN) code. The 144 rows represent the number of 10-minute segments in 1 day. The collected data is uploaded to an Internet server using the file transfer protocol (FTP). During the remote calibration, this upload is performed every 24 hours, but the software can be modified to upload more frequently. All data graphing, reduction, and analysis is performed by web-based applications developed at NIST that are hosted on the Internet server.

TESTING THE MEASUREMENT SYSTEM

We performed a test by collocating two identical systems, and connecting a 1 pps signal from the same source to both systems. This common-clock test reveals noise introduced by the measurement system. Common-clock tests were performed with two different receivers (type 1 and type 2) by collecting 10-minute averages over an approximately 30-day interval (Figure 3).

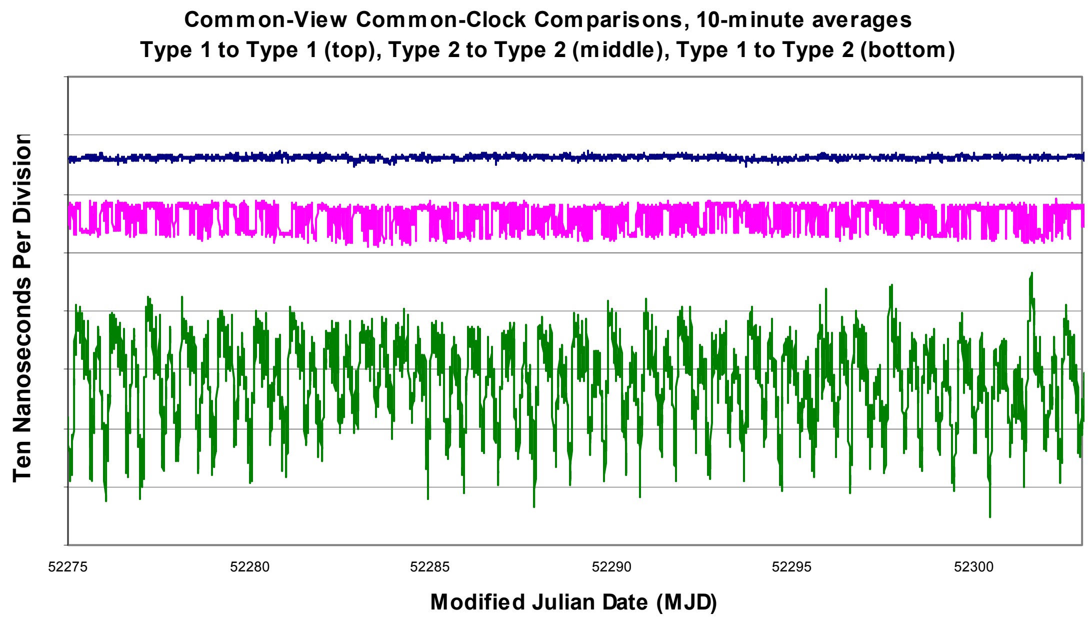

Figure 3. Results of Common-Clock Comparison using two different receivers.

The three traces on Figure 3 are separated for clarity. The time scale on the y-axis is 10 ns per division. The three traces have different amplitudes due to receiver noise. As expected, the data show no significant trend or frequency offset. The peak-to-peak variation of a common-clock comparison using two type 1 receivers (top trace on the graph) is just 1.3 ns with a standard deviation of about 0.3 ns. The type 2 receivers contribute more measurement noise. The common-clock comparison using type 2 receivers had a peak-to-peak variation (middle trace on the graph) of 6.4 ns with a standard deviation of about 2.1 ns. Unfortunately, the noisier type 2 receivers were the ones available to us for the remote calibration described here. However, the receiver noise has a Gaussian distribution, which results in an insignificant contribution to the uncertainty when a long averaging time (such as 1 day) is used.

The bottom trace on Figure 3 shows a common-clock comparison between a type 1 and a type 2 receiver. In this case, the errors do not cancel (at least in the short term) and the measurement is noisy, with a peak-to-peak variation of about 40 ns, and a standard deviation of about 7 ns. This indicates that when possible, two receivers of the same type should be used.

THE REMOTE CALIBRATION

One measurement system was installed at NIST in Boulder, Colorado, and connected to a 1 pps output from the UTC(NIST) time scale and to the Internet. We will call this system CV-NIST. An identical measurement system, called CV-Sandia, was sent to Sandia National Laboratories in Albuquerque and connected to a 1 pps output from the GPS receiver under test (RUT) and to the Internet. The CV-NIST antenna position was calculated from known coordinates, while the 3D position of the CV-Sandia antenna (latitude, longitude, and altitude) was “self-surveyed” to within 10 m by averaging GPS position data for 10000 s. The baseline (distance) between CV-NIST and CV-Sandia is about 561 km (Figure 4).

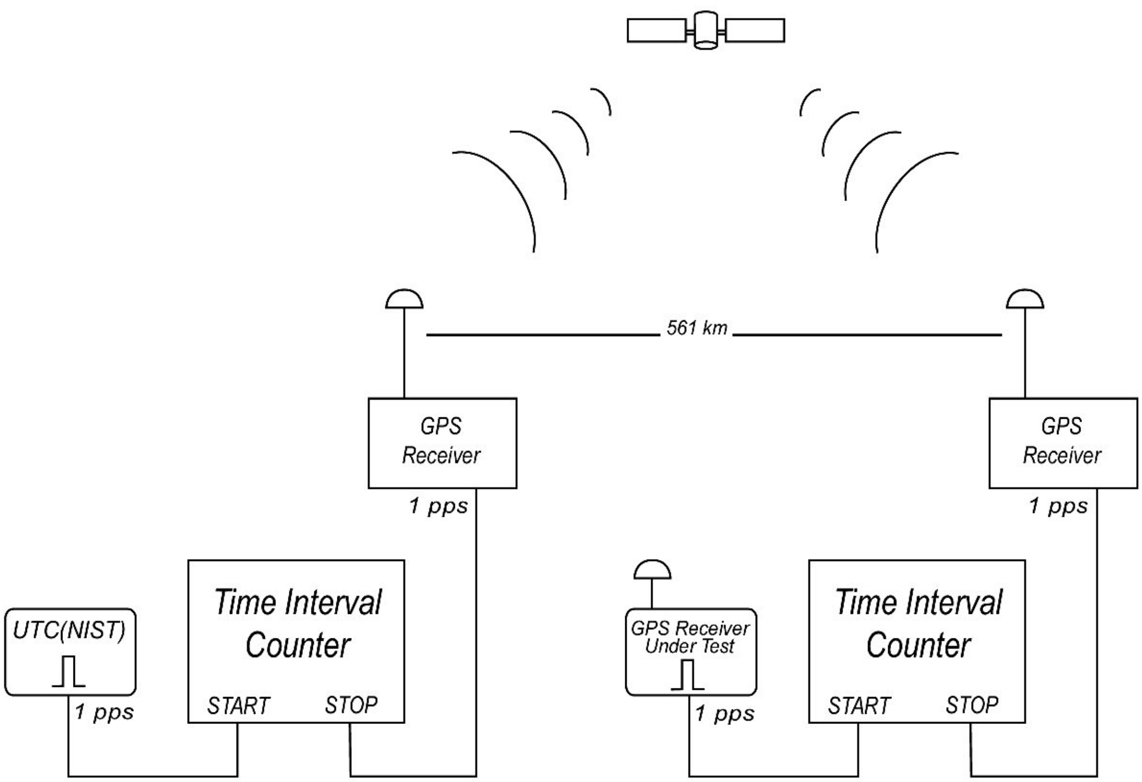

Figure 4. Common-View GPS Measurement Configuration.

Once the systems were running at both sites, each system began uploading data to a NIST Internet server once each day for processing. Both NIST and Sandia personnel can access the data reduction and analysis software that runs on the server using a standard web browser. The web software was developed as a common gateway interface (CGI) application for a Windows 2000 server. The CGI application was written using a combination of a compiled BASIC scripting language, and a Java graphics library. It can load up to 200 days of 10-minute averages (28800 data points) from two common-view receivers, align the data sets, perform the A minus B subtraction, graph the results and calculate both the time deviation $\sigma_x(\tau)$ and Allan deviation $\sigma_y(\tau)$ of the data set. In addition, both sides of the common-view track recorded from any individual GPS satellite can be viewed, and tabular data can be copied from the web page and pasted into a spreadsheet or other application for further analysis.

Ideally, a calibrated GPS antenna and cable would be shipped to the customer's site along with the measurement system. Two delay numbers are entered into the software. One, known as the clock delay, D_{clock}, is the cable delay between the reference clock and the measurement system. During pre-shipment tests at NIST, both CV-NIST and CV-Sandia were connected to signals from the UTC(NIST) time scale. There is a long cable run and a distribution amplifier between the UTC(NIST) time scale and the room where the test was conducted, and D_{clock} was measured at 408 ns. Once CV-Sandia was installed in Albuquerque, a short cable was used to connect to the RUT. This cable was calibrated at Sandia, and the D_{clock} parameter was set to 9 ns.

The second delay number is known as D_{Rx}, and refers to the total receiver delay, including the delay in the receiver itself, the antenna, and the antenna cable. Values for D_{Rx} were measured at NIST for both CV-NIST (D_{NRx}) and CV-Sandia (D_{SRx}) by calibrating both units against UTC(NIST). D_{NRx} was measured at 180 ns and this value was used throughout the calibration. A similar D_{SRx} value was obtained, and prior to shipment, the average delay between CV-Sandia and CV-NIST was known to within a few nanoseconds, which is the desired objective.

At this point, the ideal situation would have been to send CV-Sandia to Albuquerque with the same antenna and cable used during the receiver delay measurement, and with D_{SRx} already entered into the CV-Sandia software. However, installing a new antenna at Sandia was not an option, since only a fixed number of cable conduits exist between the calibration laboratory and the roof. Therefore, an existing antenna (fortunately the same model used by CV-NIST) with an unknown cable delay was used. Since it was not possible to remove the antenna cable at Sandia and measure the delay, we made a coarse estimate of D_{SRx} without the benefit of an actual measurement. Since the same model of GPS receiver and the same model of antenna were used by both CV-NIST and CV-Sandia, we assumed that these delays (and the delays introduced by cable connectors at both sites) were equivalent. We then made our estimate based on the difference in length between the two antenna cables, and the type of cables used. The CV-NIST antenna cable is approximately 39 m in length, and uses a cable type with an estimated delay of 4.13 ns/m. This cable delay (161 ns) accounts for most of D_{NRx}. The CV-Sandia antenna is connected to two sections of cable having different delays. The main section has an estimated delay of 391.6 ns, based on an estimated length of 107 m, and a cable type with an estimated delay of 3.66 ns/m. There is also an approximately 4 m cable with an additional delay of about 16.5 ns, making the total cable delay about 408 ns. Therefore, the differential delay between the two antenna cables (408 – 161) was estimated at 247 ns, and a value of 427 ns ($D_{SRx} = D_{NRx}$ + differential delay) was entered as D_{SRx} into the CV-Sandia software (Figure 5). Even after the differential delays are entered, we estimate that our systematic (type B) uncertainty could still be as large as 40 ns. This estimate allows for differential errors in the cable delay estimates (< 20 ns), differential errors in the antenna altitude coordinates (< 15 ns), and relative propagation delay differences between Boulder and Albuquerque (< 5 ns).

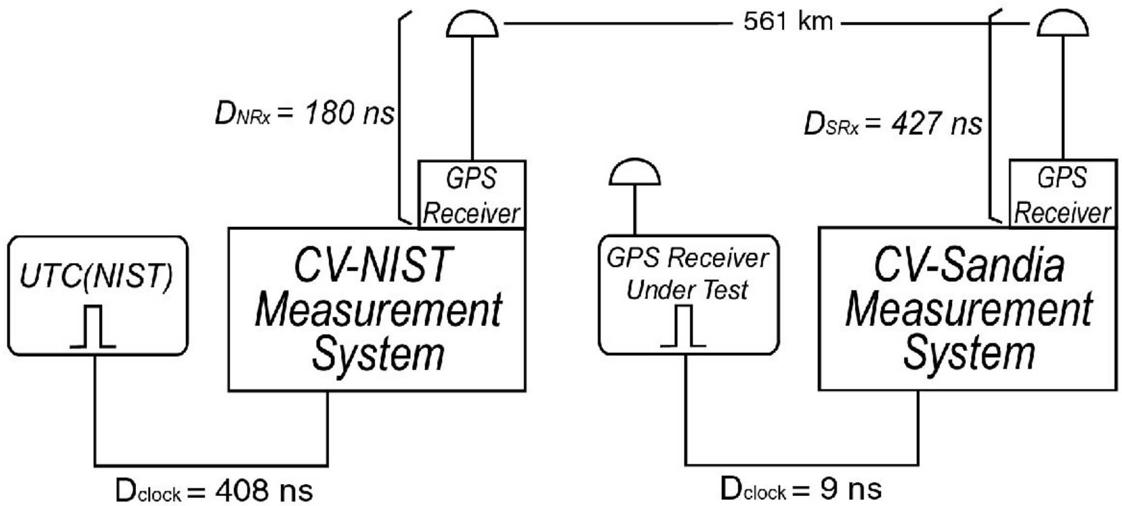

Figure 5. Block diagram of comparison with delay values entered.

Figure 6 shows the average daily time offsets for a 40-day remote calibration (October 8 to November 16, 2002). The variation of the daily time offset (2σ) is 8.4 ns, and represents the statistical (type A) uncertainty of the measurement. The average time offset between the RUT and UTC(NIST) is –352.1 ns across the entire measurement period (the RUT time is late with respect to UTC(NIST)). Entering a delay constant into the RUT could compensate for this time offset. The measurement uncertainty is calculated as < 50 ns, obtained by combining the systematic and statistical uncertainties.

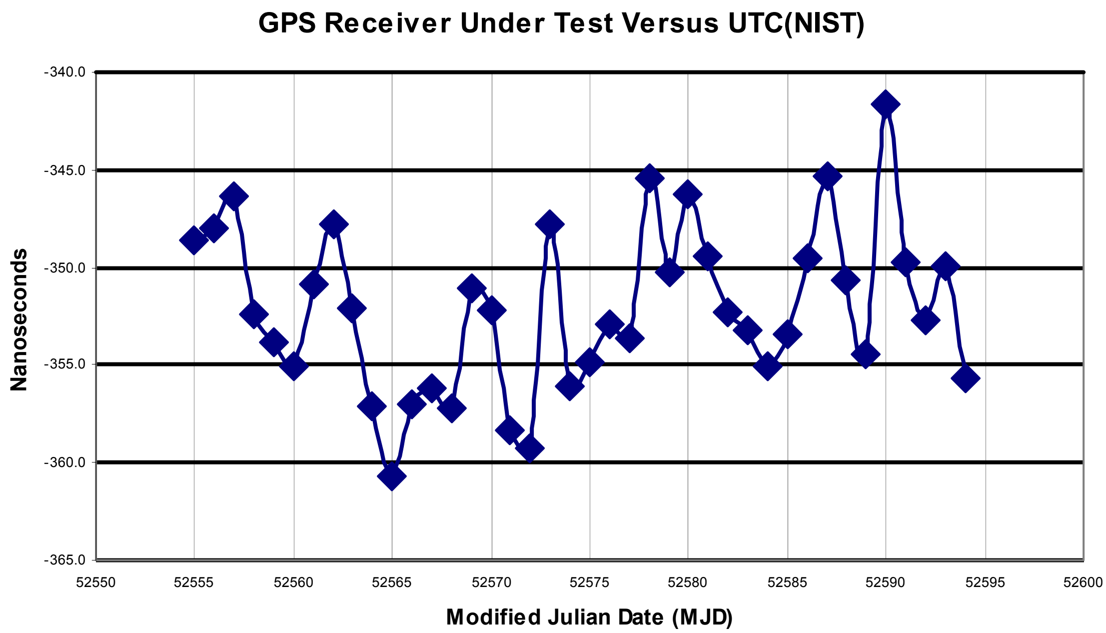

Figure 6. Results of 40-day remote calibration of GPS timing receiver.

SUMMARY AND CONCLUSION

We have described a remote calibration of a GPS timing receiver. The calibration uses the Internet for data exchange and processing. The combined measurement uncertainty (< 50 ns) described here will meet the requirements of many potential calibration laboratory customers, but can easily be reduced. Most of the systematic (type B) uncertainty could be eliminated with better knowledge of the relative delay between the two common-view systems, and a better survey of the receiving antenna altitude at Sandia. Using a lower-noise GPS receiver could also reduce the statistical (type A) uncertainty at short averaging times.

The authors thank Victor Zhang of NIST for many helpful discussions and for his review of this manuscript.

** Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

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