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DELAY VARIATIONS IN SOME GPS TIMING RECEIVERS*

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Abstract

We report a number of studies of variations in the delay through GPS receivers used for timing at NIST. As a first study, the data from the receivers built at NIST in the early 1980's (called the NBS-type receiver) are compared over periods of many years to show variations in delay. These receivers vary of the order of 5 ns over a year, with the peak-to-peak variation of 10 ns over 6 years. A second study shows the temperature dependence of the antenna system and of the receiver unit of the NBS-type receiver. The antenna system of one receiver was held constant at 42 °C for the entire experiment. The antenna of another system was held at various fixed temperatures, and the relative delay through the two antennas was determined at each temperature. Similarly we varied the receiver temperature of one system, holding the antenna temperature constant. Though the delay varied 2 ns over the course of the experiment, this variation was not correlated with temperature. We next report the delay variation with temperature of a commercial multi-channel GPS receiver, which we are investigating for use in an alternative common-view receiver. We studied the temperature dependance of two receivers separate from the antenna. In one unit, we found a 2.3 ns a peak-to-peak variation of delay with temperature and a 4.3 ns peak-to-peak variation in the other, both over a range from 10 °C to 55 °C. The delay variation in both appears to be approximately quadratic over some range of temperature.

Introduction

Common-view time transfer using GPS signals has been used since the early 1980's as the best operational time transfer method. Early in its use it was believed to have an uncertainty of 10 ns globally [1]. In the last few years some timing laboratories which participate in the generation of International Atomic Time have adopted a goal of achieving an uncertainty of 1 ns worldwide. While there is considerable research into developing two-way satellite time and frequency transfer, which has the potential for increased accuracy and stability [2], the common view system will always have some advantages. The common-view method requires using only passive reception of signals; there is no transmission from the user station. Consequently, the receivers are less expensive, and the antenna systems smaller.

One barrier to achieving the goal of 1 ns

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uncertainty for GPS common-view time transfer is the stability of the receiver delay. For common-view time transfer we need only calibrate the delay of one receiver relative to another. However, any change in the delay between calibrations directly degrades the time transfer.

One design of GPS common-view receiver has been in use since the early 80's. That receiver was designed and originally built by what was then called the National Bureau of Standards (NBS), at the Time and Frequency Division in Boulder, Colorado, USA. This agency is now called the National Institute of Standards and Technology (NIST), but the receiver is still referred to as the NBS-type receiver. This is a single channel, C/A-code only receiver which tracks up to 48 satellites per day according to a schedule.

We present data from two studies of the delay in this NBS-type receiver. In one study we document the long term change in the differential delays among three receivers kept on-line continuously at NIST. A second study shows the change in differential delay as a function of temperature of both the antenna and front-end electronics which sit with the antenna outside, as well as of the receiver unit which sits in the lab.

We are currently developing a new GPS common-view time transfer system. We want to take advantage of the new multi-channel GPS technology to generate common-view data on a networked computer. This could then be accessed in near-real time. However, it is essential that the receiver delay be as stable as we can make it. We hope to achieve a stability under 1 ns over a year. We are studying the use a commercial GPS engine [3], a time interval counter and a personal computer (PC) to control them and the internet interface.

We have found that the major change in the delay through the commercial receiver system, from the L1 signal as received at the antenna to the 1 pulse-per-second (pps) out, is in the receiver box separate from the antenna. This box could typically be kept in the laboratory. We have been studying the change in delay due to temperature changes in this receiver box, in two such units. We will refer to them as receiver A and receiver B.

Long-Term Studies of NBS-Type Receivers

Using our stored GPS data, we compared differential delays among our three on-line receivers over several years. Since we keep three receivers on-line at all times and the receivers are driven by the same clock, we were able to study common-view common-clock data among them. The receiver systems consist of a front-end antenna and electronics on our roof in the outside environment, the antenna cable into the lab, and the receiver-microprocessor-counter which operates inside the building [4]. Variations in delay can come from any element of this system. While all three systems are driven by the same clock, the 1 pps reference cables vary in length from about 10 m to nearly 100 m, all running inside the building.

We look at NBS10; the primary receiver, NBS11, the secondary receiver since 1991; NBS05, our tertiary receiver from 1993-1996; and NBS08, our tertiary receiver since 1996. Figure 1 shows the delay of NBS10 minus that of NBS11 from 1991 to 1996. We see variations over one year of typically about 5 ns. There appears to be an annual period to the data, though not clearly deterministic.

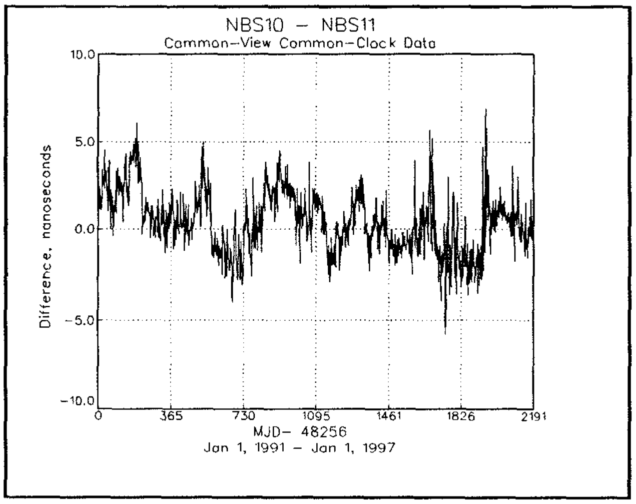

Figure 1 The delay of NBS10 minus NBS11 over a six year period

We studied the common-clock common-view NBS10-NBS05 difference over the years 1993-1996. The NBS05 receiver was used for a number of studies and experiments during this period. Hence there were a few uncalibrated jumps in delay due to equipment changes. To view the stability of the NBS05 receiver we estimated and removed the large time steps and a constant of 230 ns. Figure 2 shows the reultant values for NBS10 - NBS05.

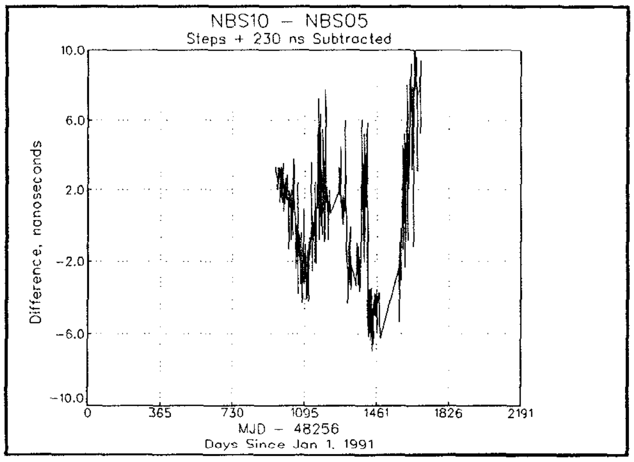

Figure 2 Residuals of NBS10 - NBS05 after removing estimated time steps.

NBS05 was taken off line in 1995 and replaced with NBS08. In Figure 3 we show the NBS10-NBS08 delays. Figure 3 shows a stability between NBS10 and NBS08 comparable to that between NBS10 and NBS11. We note an apparent diurnal variation of about 5 ns peak to peak.

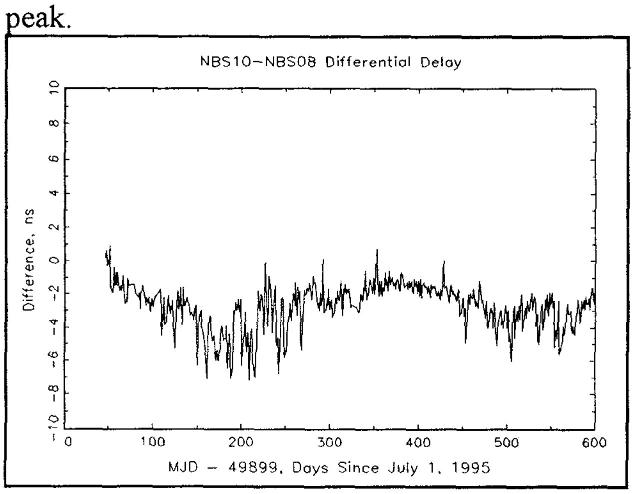

Figure 3 The delay of NBS10 minus NBS08.

Next we combine the NBS05 and NBS08 data, removing 230 ns from NBS05 data to give us a continuous reference to compare to NBS10, independent of NBS11. The results are shown in Figure 4.

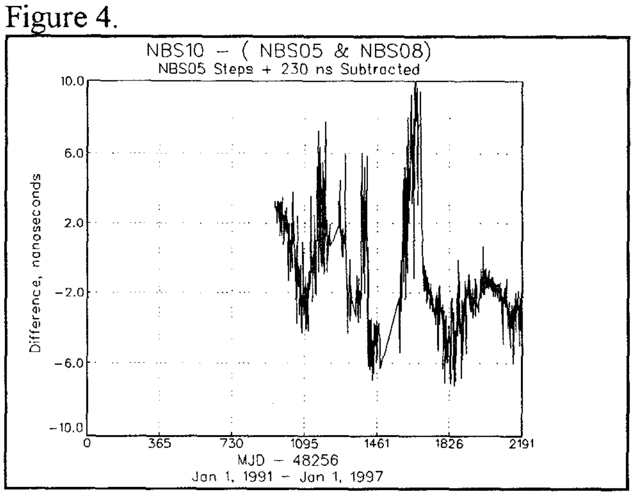

Figure 4 NBS10 minus the combined data from NBS05 and NBS08. The NBS05 data has had various steps removed, as above, and a constant 230 ns.

Comparing Figure 4 and Figure 1, we see similar diurnal swings. This suggests that a significant part of the diurnal variation may either be due to NBS10 or to a common-mode variation in the other receiver systems.

Temperature Effects on NBS-Type Receivers

The antenna systems of two NBS-type receivers, NBS08 and AOA57, were placed in temperature controlled chambers on the roof. NBS08 was the reference receiver with its antenna held at a constant temperature inside a chamber to 42 ±1 °C. The sensor for this measurement was on the mixer board inside the metal box holding the antenna's front-end electronics. Figure 5 shows the temperature logged from its chamber on the roof.

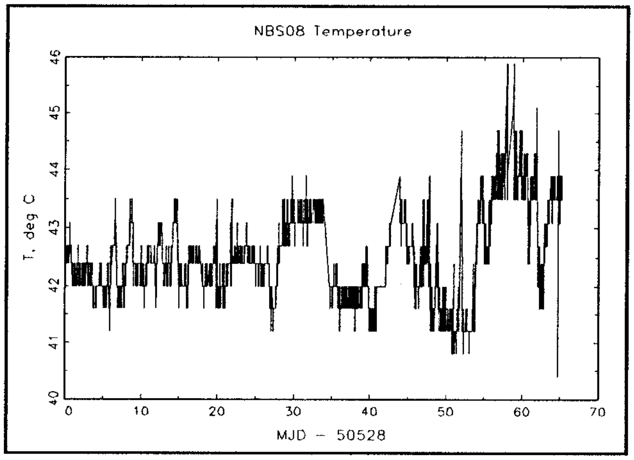

Figure 5 Temperature of NBS08 antenna system.

The NBS08 minus AOA57 differential delay is show in Figure 6 for the period of temperature control.

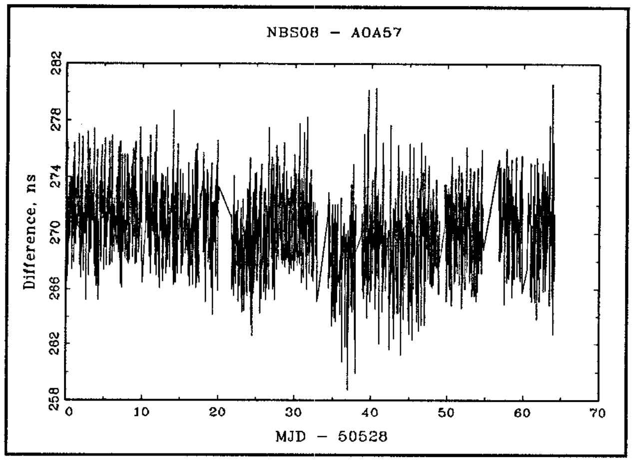

Figure 6 The difference in delays between two NBS-type receivers with temperature controlled antennas. The NBS08 antenna was kept constant at 42°C. The AOA57 antenna temperature varied.

Figure 7 shows the temperature of the AOA57 antenna system.

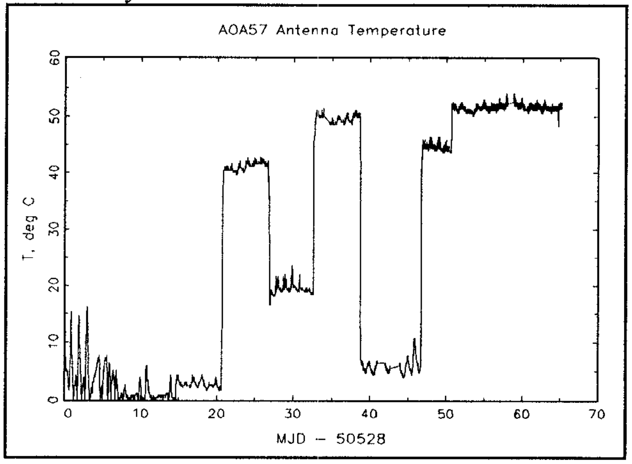

Figure 7 The temperature of the AOA57 antenna system.

Averaging common-view common-clock differences for NBS08 minus AOA57 data for each interval of relatively constant antenna temperature, we plot the AOA57 delay as a function of antenna temperature in Figure 8. The error bars are one standard deviation of the mean, the standard deviation divided by the square root of the number of points.

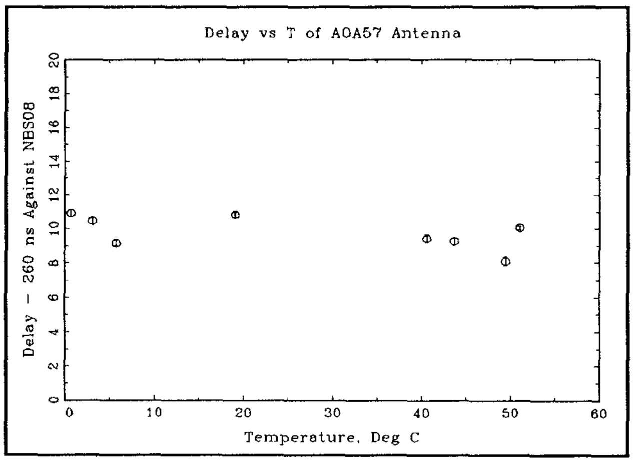

Figure 8 The AOA57 system delay as a function of antenna temperature determined against NBS08 while its receiver temperature was relatively constant. Error bars are one standard deviation of the mean.

A linear fit to the data in Figure 8 yields a coefficient of -0.03 ns/°C. Over the range of temperatures measured this implies a total change of -1.5 ns. With variations in delay of order 2 ns when repeating the maximum and minimum temperatures, we have little confidence in this temperature coefficient.

Next we held the antenna system temperaure constant at 50 °C and varied the receiver temperature in a chamber in the laboratory. The results for delay as a function of receiver temperature are presented in Figure 9. The slope of a linear fit through these data is also -0.03 ns/°C. Since the one standard deviation of the mean error bars are bigger than this, we conclude that this is insignificant.

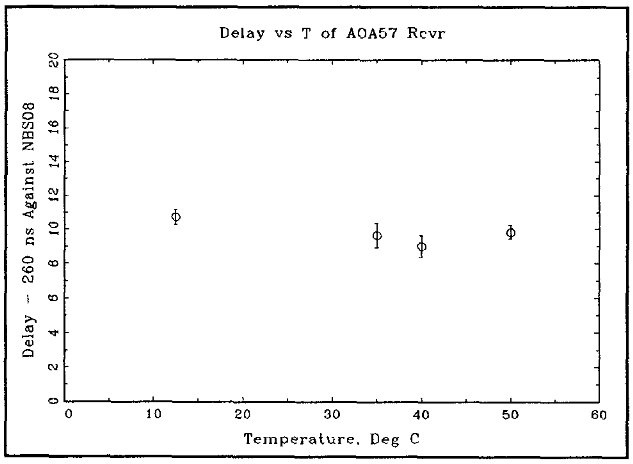

Figure 9 The AOA57 system delay as a function of receiver temperature determined against NBS08 while its antenna temperature was held constant. Error bars are one standard deviation of the mean.

<u>A Multi-Channel Commercial Receiver</u>
We next report on the stability of a commercial multi-channel GPS receiver "engine." We have taken two identical models of a commercial GPS receiver[3], combined with a NIST time-interval counter [5], and controlled by a PC running NIST-developed software. We measure the 1 pps out of the receiver against our local UTC(NIST) [6] 1 pps, using the time interval counter. The PC controls the counter and communicates with the receiver board through an RS232 interface. The receiver board itself communicates data with TTL logic, and both receiver units had TTL to RS232 converters. Both GPS receiver engines were placed in the same system and measured against the same local reference. We will refer to these systems as receivers A and B.

The NIST counter has been shown to be accurate to better than 300 ps. The software runs the receivers in a single channel mode, duplicating somewhat the data-taking process of the NBS-type receivers. We take measurements between the 1 pps output of the receiver locked to GPS time and our local reference, the same reference clock as used for NBS08 and several other receivers. We also correct for the granularity in the steering of the 1 pps output of the commercial receivers. It is steered in 50 ns steps, but data are available from the receiver through the RS232 interface to correct for the receiver's estimate of GPS time with a 1 ns resolution. The receiver also supplies data to allow users to estimate GPS time from individual satellites when the receiver is locked to multiple satellites. In order to accomplish multi-channel common-view time transfer, such corrections are essential. It appears, however, that when tracking only one satellite at a time these corrections for separating effects of different satellites are not valid. They add biases that change with each satellite. Hence, for this report since we are tracking in single-satellite mode, we use only the 1 pps signal and the corrections for steering granularity from the receivers.

We start the counter with the local 1 pps and stop with the 1 pps from the receiver locked to GPS on only one satellite, then correct each second for the steering granularity using the data from the receiver. This give us a reference-GPS measurement each second. We take 780 of these matching the international tracking schedule, do a linear fit to the entire set, and use the mid-point for common-view time transfer with various NBS-type receivers.

The antenna we used for this report was not the one which came with the receiver. Rather we purchased one from an independent manufacturer, as well as a cable which was designed to be low-loss at the L1 frequency. We were unable to detect a dependence of delay on antenna temperature. This is consistent with the manufacturer's specification of a total delay of about 10 ns.

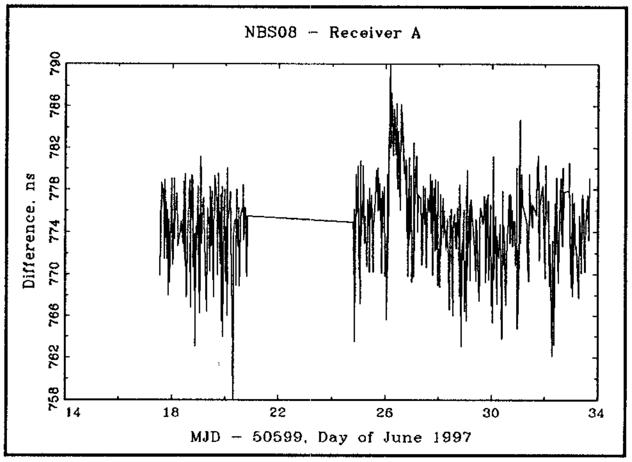

Figure 10 Common-view common-clock difference of NBS08 minus the commercial receiver A during the period of temperature control of the receiver. The receiver was off-line during the period of missing data.

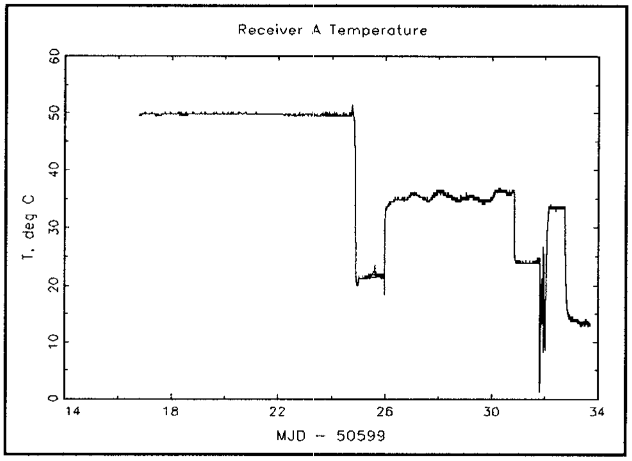

Figure 11 The temperature of the commercial receiver A during the testing period.

We measured the dependence of delay on temperature for receiver A by placing the receiver engine in a temperature controlled chamber in the laboratory. Common-view, common-clock data from this receiver against NBS08 are shown in Figure 10. There appears to be a step of about 15 ns which slowly decays back over a day. This step appears to have happened about 2 h after the receiver temperaure was changed from 22 °C to 35 °C. The temperature remained constant at 35 °C during the decay period. This event remains an unexplained anomaly. Such behavior must be avoided to meet a design goal of 1 ns for a common-view time transfer receiver. We have rarely seen such effects. We will continue to test several such commercial receivers. We have been running this receiver in a single-channel mode. Most users would rarely do so; it may be that this effect does not appear in multi-channel operation.

Figure 11 shows the temperautre of receiver A in the chamber in which it was tested. Figure 12 shows the differential delay as a function of the temperature. For this Figure the data during the anomalous time step have not been used.

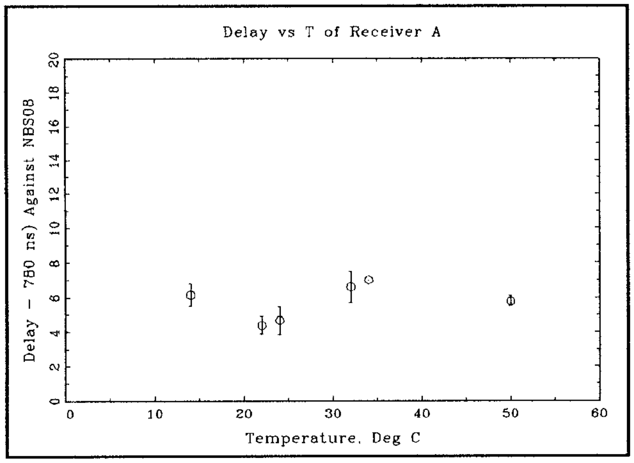

Figure 12 The mean of the common-view difference of the receiver A minus NBS08 for each of the periods of constant receiver A temperature. Error bars are one standard deviation of the mean.

Receiver B, was placed in a temperature chamber in the laboratory as for receiver A, and the temperature varied. The data taken during this period are shown in Figure 13. The receiver temperature in the chamber is shown in Figure 14. The dependence of delay on temperature resulting from this experiment is shown in Figure 15.

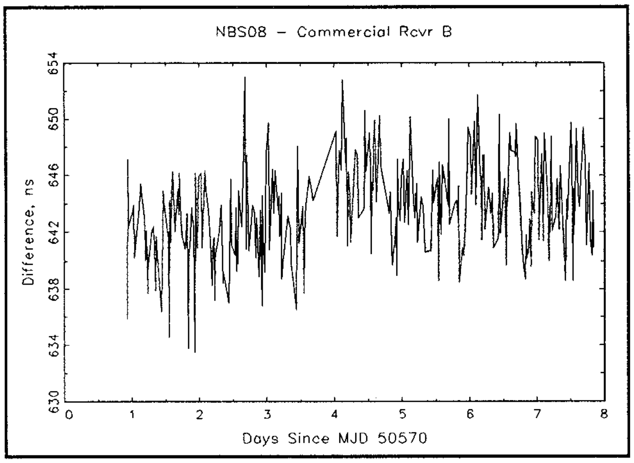

Figure 13 Common-view common-clock data of NBS08 minus the commercial receiver B.

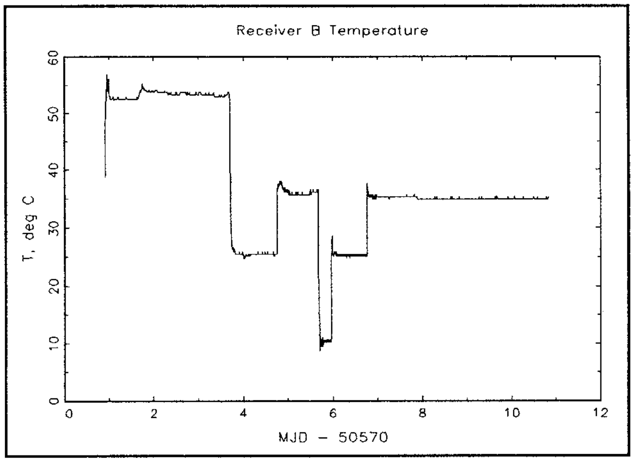

Figure 14 Temperature of the commercial receiver B in the chamber.

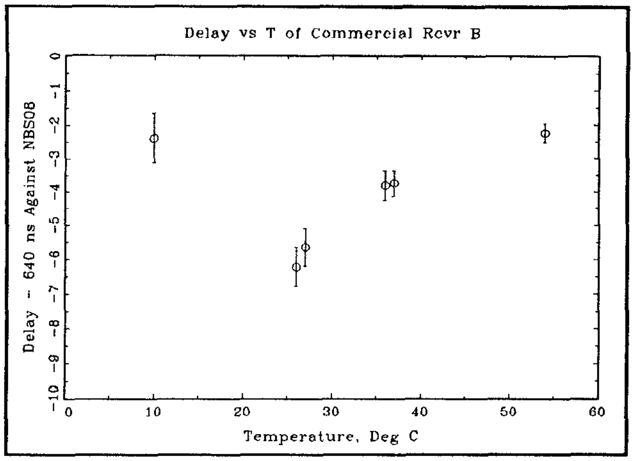

Figure 15 Receiver B delay as a function of temperature. Error bars are one standard deviation of the mean.

Conclusions

We have seen that the differential delay between pairs of NBS-type receivers has typically varied about 5 ns over a year. This study was between pairs of receivers at the same location in nearly identical external and internal environments. In this case the 5 ns change seemed to be an annual variation. Controlled temperature experiments between two antenna systems from NBS-type receivers showed no clear systematic variation with temperature. Unfortuneately, the receivers in the long term experiment were not tested for temperature dependance of their delays. Differential delays varied by about 2 ns over the experiment, but did not seem to correlate with either antenna or receiver temperature. However, though the confidence on the antenna delay temperature coefficient of 0.03 ns/°C was poor, such a coefficient could contribute 1.5 ns over a 50 °C variation. 50 °C is not unreasonable for the winter-summer variation on the roof at NIST. If two receivers had a temperature coefficient somewhat larger than this with opposite signs, that could account for what we see.

Differential delays were measured between a commercial multi-channel GPS receiver in single channel mode held at various temperatures and an NBS-type receiver with antenna temperature held at constant temperature. Two units, A and B, of the same commercial make and model were tested against NBS08. There appear to be systematic changes in delay through the commercial receiver as a function of receiver temperature, though these changes are not linear with temperaure. They seem to be quadratic over some range, with a 2.3 ns peak-to-peak variation for receiver A, and a 4.3 ns peak-to-peak variation for receiver B. It seems that this could be controlled well since the component whose delay varies with temperature could be kept inside the lab. Still some temperature control of the receiver should be done. The anomalous 15 ns step and decay in receiver A is of concern. If such events are rare or associated with use in single-channel mode, our tests thus far would indicate that this commercisl receiver has promise for multi-channel, common-view time transfer at the 1 ns level.

Acknowledgements

We wish to thank Ken Webster of the University of Colorado in Greeley for writing the code that controlled the comercial receivers in this study. We also wish to thank Robin Giffard of HP labs, Santa Clara, for many fruitful discussions and for the loan of our commercial receiver B. Acknowledgements are due also to the readers, Claudine Thomas of the BIPM, and Thomas Parker, Don Sullivan, and Matt Young of NIST for their help in editing this contribution.

References

[1] D.W. Allan, D.D. Davis, M.A. Weiss, A. Clements, B. Guinot, M. Granveaud, K. Dorenwendt, B. Fischer, P. Hetzel, S. Aoki, M-K. Fujimoto, L. Charron, N. Ashby, "Accuracy

of International Time and Frequency Comparisons Via Global Positioning System Satellites in Common-View," IEEE Trans. on Instrum. and Meas., Vol. IM-34, no. 2, pp.118-125, June 1985.

[2] J.A. Davis, W. Lewandowski, J.A. DeYoung, D. Kirchner, P. Hetzel, G. de Jong, A. Söring, F. Baumont, W. Klepczynski, A. McKinley, T. Parker, K.A. Bartle, H. Ressler, R. Robnik, L. Veenstra, "Preliminary Comparison of Two-Way Satellite Time and Frequency Transfer and GPS Common-View Time Transfer During the Intelsat Field Trial," *Proc. of the 27th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, San Diego, CA, pp.347-353, Nov. 29-Dec. 1, 1995.

[3] Motorla VP Oncore 8-channel GPS receiver. Trade names are mentioned for researc purposes only. No endorsement or critique by NIST is implied.

[4] D.D. Davis, M.A. Weiss, A.C. Clements, D.W. Allan, "Constructin and Perfromance Characteristics of a prototype NBS/GPS receiver," *Proc. of the 35th Annual Symposium on Frequecny Control*, pp. 546-552, May 27-29, 1981.

[5] V.S. Zhang, D.D. Davis, M. Lombardi, "High Resolution Time Interval Counter," *Proc. of the 26th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, Reston VA, pp. 191-200, Dec. 6-8, 1994.

[6] T.E. Parker, J. Levine, "Recent Improvements in the Performance of the NIST AT1 Time Scale," *Proc. of the 50th Annual Symposium on Frequecny Control*, pp. 1131-1136, June 5-7, 1996.