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LONG TERM EFFECTS OF ANTENNA CABLES ON GPS TIMING RECEIVERS*

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ABSTRACT

We report efforts to minimize the effect of reflected signals in GPS antenna cables on the delay stability of common-view time-transfer receivers. The delay stability of interest is at long-term time intervals from five days to about one year. We measured cables for a commercial receiver with the signal transmitted from the antenna to the receiver at the L-band frequency. In a typical system the lock point of the receiver could change almost 60 ns with cable lengths and temperature variations. This would occur if the reflected signal was 25 dB below the direct signal, and the electrical length of the cable was 217 ns and changed 165 ps, or about 5 cm. By terminating the antenna cable with good 50 Ω matching, the reflection loss was 50 dB below the direct signal. This reflection loss, along with the use of phase-stable cables with delays under 120 ns, should keep the lock point change due to coherent reflections in the cable below 200 ps. A common-clock common-view experiment using 90 days of data showed stabilities of the differential delays below 100 ps for averaging times from 1 to 10 days. Whereas before the matching, stabilities were worse than 300 ps.

1. INTRODUCTION

This paper describes an effort to eliminate sources of instability in the total time delay through GPS receivers, particularly through the use of cabling systems that provide cable phase stability and good 50 Ω termination at both the receiver and antenna. We have also studied other sources of instabilities, with a goal of controlling all significant effects at the 1 ns level for averaging times of 1 d and longer.

Common-view GPS time transfer is still a primary method of comparison of the local version of Coordinated Universal Time (UTC) of labs throughout the world for the generation of International Atomic Time (TAI). TAI is relied on primarily for its long term stability, at time periods of months and years [1]. Any uncalibrated changes in the time or phase delay through GPS receivers used for the generation of TAI contribute noise to TAI. Receivers can be calibrated against each other by moving a traveling receiver from one lab to another, and performing common-clock common-view comparisons. Closure is achieved by re-calibrating the first lab at the end of the trip [2]. This needs to be done periodically through the network of receivers that contribute to TAI. At best this can be achieved annually. Hence, the instability of the delay of receivers out to at least one year is a contributor to the noise of TAI. Our goal is to attain a receiver instability of less than 1 ns out to one year.

Along with several other researchers, we have studied the temperature effects on a particular commercial GPS receiver [3]. Even without temperature stabilization the antennas do not add to instabilities greater than 500 ps. The receiver unit of this commercial system requires stabilization of both temperature and power-supply voltage. For the worst case we found a delay variation with temperature of 250 ps/°C. We have stabilized the temperature of our receivers to a peak-to-peak variation of 2 °C, implying a variation of no more than 500 ps. We have found a worst-case delay variation with voltage of 20 ps/mV. To address this sensitivity, we built power supplies that should vary no more than 5 mV per year.

Using a network analyzer we measured the impedance of several GPS antenna cables. We also measured the impedance of our commercial GPS receiver and antenna. Of particular interest for this work is the signal power reflected back from the receiver to the antenna, and then back to the receiver. After making several such measurements we designed a new cable system for our commercial system. This system uses an amplifier and attenuators to provide 50 Ω terminations at each end of a cable with increased phase stability with temperature.

In the next section, we discuss the theory of how cables can affect the delay through common-view receivers. In Section 3 we discuss cable systems for our commercial receivers and data recorded over several months.

2. THEORY

A pseudo-random noise (PRN) signal, such as a GPS signal, can exhibit large variations in the code-lock point due to small variations in the carrier phase of delayed coherent interference [4,5]. Such interference can occur due to reflections in an antenna cable.

The code in a GPS signal is bi-phase modulated on the carrier [6]. A receiver locks onto the code by correlating the received signal with a locally generated replica. A delayed copy of the signal added to the direct signal can pull

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the lock point if the delay is within the length of one bit or "chip" PRN code. Because the phase of the carrier determines the phase of the code chip, the relative phase of the reflected signal strongly affects the way the lock point is pulled. A change in the reflected carrier phase of half a cycle produces a maximum change in the lock point due to that multipath signal. For a GPS receiver with the L1 frequency coming down through the antenna cable, this requires a change in the delay of the reflected signal of about 330 ps. Since this reflected signal makes two extra passes through the antenna cable, a 330 ps change in delay could be caused by a 165 ps change in the electrical length of the cable, or about 5 cm.

The timing offset in the GPS code lock due to a multipath reflection will depend on both the delay in the reflected signal and its signal power. If there is a reflected signal 25 dB below the direct signal, the code lock point can be pulled almost 0.03 of a chip (see Figure 1). For the 1.023 MHz chip rate of GPS this implies an offset of almost 30 ns. For a signal at -35 dB relative to the direct signal, the maximum error in lock is just under 10 ns, as shown in Figure 2. This maximum error corresponds to an envelope which grows linearly with the delay of the reflected signal out to about 435 ns. Since the reflected signal makes two passes more than the direct signal through the cable, a cable with a delay of 217 ns could produce the worst effect. If the relative phase of the carrier for the reflected signal moves by half a cycle, the resultant code lock point will change by twice the envelope as shown in Figures 1 and 2. Thus, with a 435 ns delayed signal at -25 dBc, a change in the reflected phase of 330 ps would produce a change in the apparent received signal of almost 60 ns. Figure 2 illustrates how a change in the phase of the reflected carrier can cause variations in the code-lock point.

The phase of the received GPS signal must remain stable to achieve good time stability. If there are cable reflections but they never change, then the system can be calibrated and will remain stable. Multipath reflections outside of the antenna also pull the code lock, but the amount of pulling tends to vary with the geometry of the relationships among the antenna, the satellite, and the reflectors. Since the satellites have repeating ground tracks each day, the effects of multipath outside of the antenna can average down somewhat over a day. For receivers contributing to TAI, the worst problem occurs when the lock point is slowly pulled over weeks or months.

3. A COMMERCIAL GPS RECEIVER

Using a network analyzer, we measured reflected power in a commercial GPS receiver, antenna, and antenna cable. In this case the signal comes from the antenna at the L1 frequency. We estimate that for this receiver and cables, the delayed coherent interference due to cable reflections was about 30 dB below the direct signal.

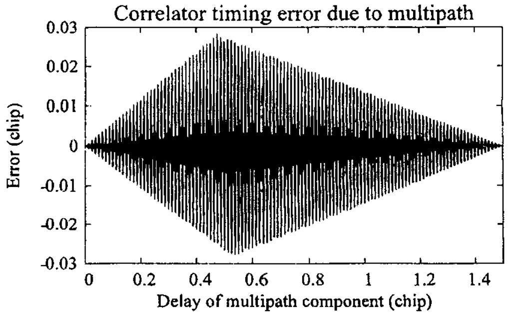

Figure 1 GPS correlator timing error due to a multipath signal 25 dB below the direct signal as a function of the delay.

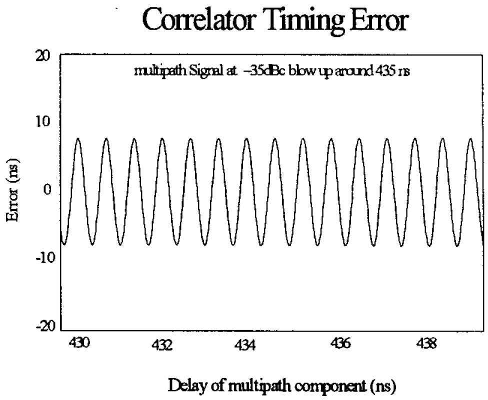

Figure 2 GPS L1 correlator timing error due to a multipath signal 35 dB below the direct signal. This window shows the interval of maximum variation.

At -30 dB, a reflecting multipath signal would pull the signal about half of what we see in Figure 1. The existing low-loss cables had delays of 60, 82, and 100 ns, implying potential reflected signals with 120, 164, and 200 ns delays. These lie on the envelope of Figure 1 where the potential change in code lock would be 15, 22, and 26 ns, respectively. That is, a reversal in phase of the reflected signal would change the lock point by the preceding amounts. A reversal of phase of the carrier would occur with a 330 ps change in the total delay of the reflected signal through the cable. This would occur if the cable delay changed by half of that, 165 ps, or the electrical length changed by about 5 cm. Over months, the cables could experience a change of about 20° C in temperature. For a 30 m length of cable, and a temperature variation of 20° C over the cable, we would need a temperature coefficient of 83 ppm/°C to see an effect of this magnitude. Ascarrunz measured temperature coefficients of 70 ppm/°C for RG-58 cables, and 7 ppm/°C for the new phase-stable cables[7].

In previous work we reported short term results from improvements which reduced the reflected power [8]. For that work we did three things: (1) cables had an impedance closer to 50 Ω, (2) cables had a lower temperature coefficient, and (3) the termination was closer to 50 Ω for the cables at both the antenna and the receiver. This system yielded a delayed signal approximately 40 dB below the direct signal, an improvement of about 10 dB. We now report more long term results after a further improvement. We further improved the terminations at each end of the cable by building DC-pass 10 dB attenuators. The DC-pass is required to supply power to the active elements in the antenna.

At -40 dB the envelope for maximum loss at a delay of 435 ns would be under 3 ns, implying a potential 6 ns change in code lock with a reversal of reflected phase. With the new attenuators, we measured a reflected signal 50 dB below the direct signal. At this attenuation, variations at a delay of 435 ns would be under 1 ns, implying a potential 2 ns change in code lock with a reversal of reflected phase. Since our cable delays are below 120 ns, the reflected signal would be delayed less than 240 ns from the direct signal. This would yield a maximum change of under 1 ns for the code lock with a reversal of phase. Further, with a temperature coefficient of 7 ppm/°C we would expect a change in phase of under 0.1 cycle with a 20 °C change in temperature. Thus, any change in lock point due to this effect should now be below 200 ps.

4. DATA

We measured the common-view common-clock difference among several receivers at NIST, all from the same commercial manufacturer. The best results were between two receivers with the new DC-pass attenuators. The receiver N03 compared to the N02 showed time deviation (TDEV) stabilities below 100 ps from 1 to 10 d. These data are displayed in figures 3 and 4. N03 compared to N01, a receiver with the same configuration as N02 and N03, showed occasional excursions of a few ns from the more stable performance. This degraded the stability of the N03-N01 data to a TDEV of 200 ps or below from 1 to 10 d. See figures 5 and 6. We suspect there was some intermittent failure in the N01 receiver or the associated electronics.

Unfortunately, the commercial receiver used for N01, N02, and N03 is no longer available. We have a number of them in stock, so it is possible we could use them for special situations. However, the manufacturer has replaced this model with another. We show common-view common-clock data between the N03 and this new model which we call here the U01 receiver. We found that the U01 receiver occasionaloly had severe departures in the 15 s average data which we had stored. After removing those anomalies, the TDEV staility drops to about 200 ps at 1 d. See figures 7 and 8.

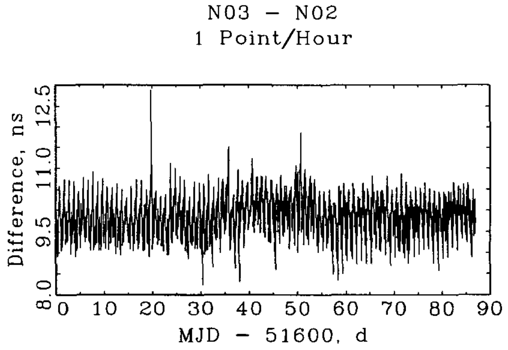

Figure 3 Common-clock common view comparison between two commercial receivers, which are no longer manufactured.

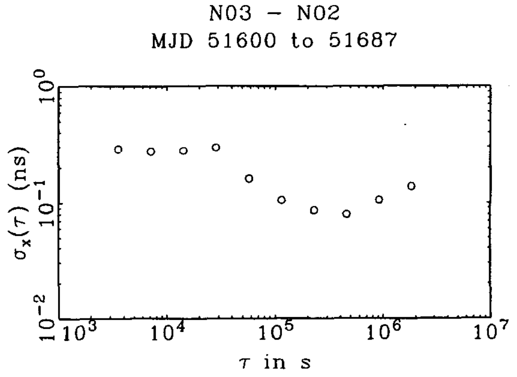

Figure 4 TDEV of the data in figure 4.

5. Conclusion

We conclude that the discontinued commercial receiver may be useful for special situations where we want to get the best possible common-view time transfer. For example, we might choose to use this receiver when comparing primary frequency standards which currently have accuracies of about 10^{-15}. The newer commercial receiver may be useful operationally in support of TAI, though significant numbers of bad points will have to be removed.

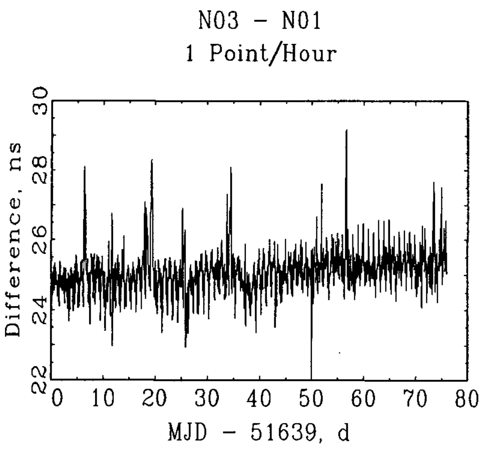

Figure 5 Common-clock common view comparison between two commercial receivers, which are no longer manufactured.

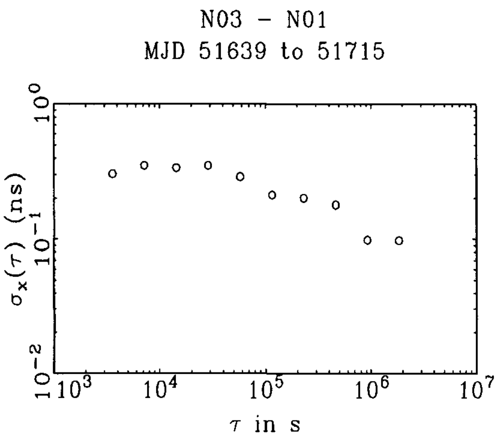

Figure 6 TDEV of the data in figure 5

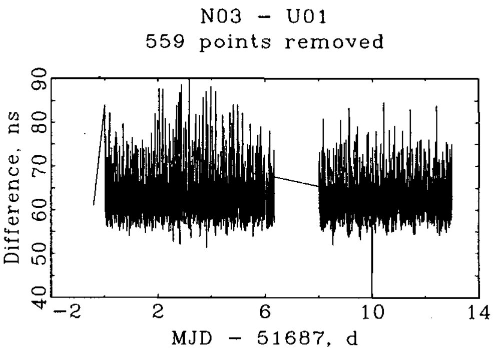

Figure 7 Common-clock common-view difference between a discontinued commercial receiver (N03) and its new replacement (U01)

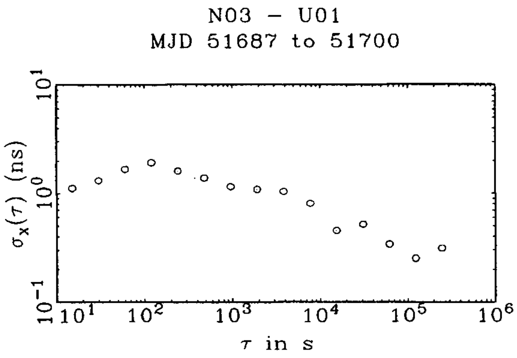

Figure 8 TDEV of the data in figure 7.

6. REFERENCES

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