

HARDWARE DELAY MEASUREMENTS AND SENSITIVITIES IN CARRIER PHASE TIME TRANSFER

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Abstract

Precise time and frequency transfer experiments using GPS carrier phase with time stability less than one hundred picoseconds are now being reported. Strong daily variations in some of the data reported indicate temperature sensitivity in the measurement hardware. The environmental dependence of the instrumental delays of a commonly used carrier phase GPS receiver, its antenna, and several types of antenna cable are reported in this paper.

INTRODUCTION

Carrier phase GPS time and frequency transfer experiments are now showing the potential for 100 picosecond time transfer [1, 2] and frequency transfer to $1E-15$ for one-day integration time. To gain a better understanding of the error contributions of the GPS measurement hardware, we performed a series of experiments to determine their stability over a range of temperatures and through receiver resets and power cycles. Zero-baseline stability analysis of the receiving hardware will also be discussed in this paper, as briefly will absolute calibration issues and plans for future testing.

GPS ANTENNA AND ASSOCIATED ELECTRONICS

GPS antennas were not studied, but we note that many geodetic antennas are based on a Dorne & Margolin DM C146 broadband antenna. This antenna has a bandwidth of 425 MHz (1200 MHz – 1625 MHz) with a characteristic impedance of 50 ohms and a VSWR rating of 1.5:1. The wide bandwidth implies that the delay through the antenna is small (< 500 ps), and thus any change in delay due to temperature would also be small. In contrast, the electronics package within and immediately after the GPS antenna contain 20-MHz-wide filters so as to remove unwanted near-band interfering signals, and their delay is around 25 to 50 ns.

For this experiment we tested the antenna electronics of an Allen Osborne Associates (AOA) choke ring antenna, which is widely used in the geodetic community. We separated the antenna from its associated electronics and used a network analyzer to measure the delay through the electronics portion at both 1575.42 MHz (L1) and 1226.6 MHz (L2). We found a delay variation of tens of nanoseconds (ns) across the 20 MHz wide P-code bandwidth. The net delay at both L1 and L2 frequencies was measured to be approximately 30 ns +/- 5 ns. Because the entire GPS C/A and P-code spectrum must pass through these non-symmetrical filters, it may be incorrect to assume the net delays through these filters are the same as measured at precisely the L1 and L2 center frequencies. This effect should cause a smaller bias for the C/A code delay, because it occupies a smaller bandwidth over which the filter response is flatter.

We heated the antenna electronics assembly and observed a variation in the delay on the order of 4 to 16 ps/°C and also noted a slight change in the center frequency of the filter response. The test data also indicate that an L1, L2 bias may exist in this set of electronics, which will cause the receiver's ionosphere corrections estimates to be biased. Since the L1 and L2 filters may respond differently to temperature changes, this ionosphere bias may change slightly with temperature.

Additional experiments were also performed using an older AOA antenna electronics design that contained only a wide-band 600 MHz low noise amplifier with no filters. The variation in delay across the GPS L1 and L2 spectrum was only a few ns and the change in delay due to temperature was small. No measurable L1, L2 bias was observed.

GPS ANTENNA CABLE

As reported in [3, 4], the net changes in electrical delay due to temperature fluctuations in the GPS antenna cable can have a significant impact on the time and frequency transfer performance when using carrier phase to compare remote clocks. Measurements made the Astronomical Institute, University of Berne and the Swiss Federal Office of Metrology[4] of RG-213/U and RG-58 type cable showed a net electrical delay variation of about -0.42 ps/C/m between temperatures of -20 °C to $+40$ C. At higher temperatures ($+40$ C to $+70$ C) the electrical delay changed by an even greater amount, -1.38 ps/C/m. For a GPS receiver installation with 200 feet (60 meters) of exposed antenna cable, this error could amount to as much as 1 ns over the course of a 15 °C diurnal cycle, and seasonal fluctuations of several ns could be expected.

Several cable types typically used as GPS antenna cables were studied. Thirty-meter lengths of RG-214/U, RG-217, RG-8A, and Andrew's FSJ1-50A cables were placed in a thermal chamber and their delay characteristics were measured over a range of temperatures. The thermal chamber was stepped in temperature by 20 °C from 5 °C to 45 °C and then back to 5 °C. Delay measurements were made using a network analyzer around both of the GPS frequencies of 1575 MHz and 1226 MHz, by sending a 1 PPS signal through the cables to a SRS620 time-interval counter and with a time-domain reflectometer. Close agreement between the time-interval counter 1 PPS measurements and the network analyzer measurements were obtained. As can be seen in Figures 1 and again summarized in Table 1, the Andrews FSJ1-50A phase stable HELIAX™ cables proved to be 15 to 30 times more thermally stable than the cables previously used at USNO. The FSJ1-50A cable is low loss and much lighter than solid dielectric cables. The main disadvantage of the FSJ1-50A cable is that it is more rigid and somewhat more fragile than standard coax cables.

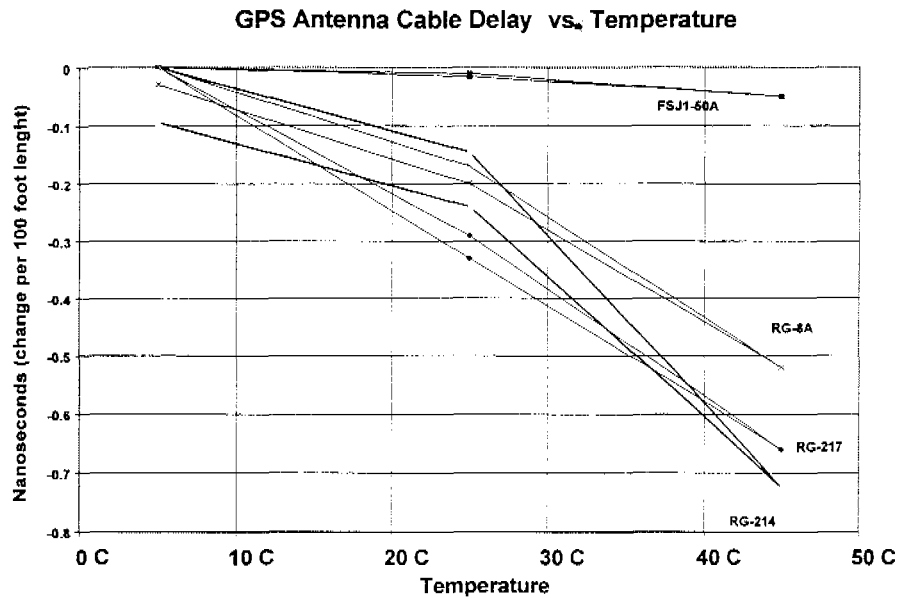


Figure 1 GPS Antenna Cable Delay versus Temperature

Table 1. GPS Antenna Cable Measured Properties

Cable Type	RG-217	FSJ1-50A	RG-214	RG-8A
Loss at L1/100 ft.	7.5 dB	7.5 dB	14 dB	11 dB
Loss at L2/100 ft.	6.5 dB	6.75 dB	12 dB	9 dB
Temp Coefficient	0.54 ps/C/m	0.03 ps/C/m	0.54 ps/C/m	0.45 ps/C/m
Velocity Factor	0.66	0.84	0.66	0.66

The low-loss foam dielectric used in Andrew's HELIAX™ cable has a dielectric constant that decreases with increasing temperature [5]. This causes an increase in the velocity of propagation within cable, which results in a decrease in electrical delay. For the Andrew's HELIAX™ cables the delay change due to thermal expansion and the change in dielectric constant are very similar in magnitude but of opposite signs, which allow these two effects to tend to cancel. In contrast, a typical solid dielectric cable experiences a greater delay change from dielectric constant variation than from the physical length change. Delay hysteresis is another problem that plagues most cable types. When solid or foam dielectric cables are subjected to thermal changes, their physical length and dielectric constant will change, and when the cable is returned to its original temperature the cable may not return to its original electrical length. Andrew uses a temperature cycling process to reduce the hysteresis effect.

GPS RECEIVER STABILITY

The temperature stability of two 12-channel AOA TurboRogue™ GPS receivers was measured in a zero-baseline experiment, during which two GPS receivers were operated from the same GPS antenna and shared a common clock. When data from the two receivers are differenced, the only error contribution that remains is from the GPS receiver.

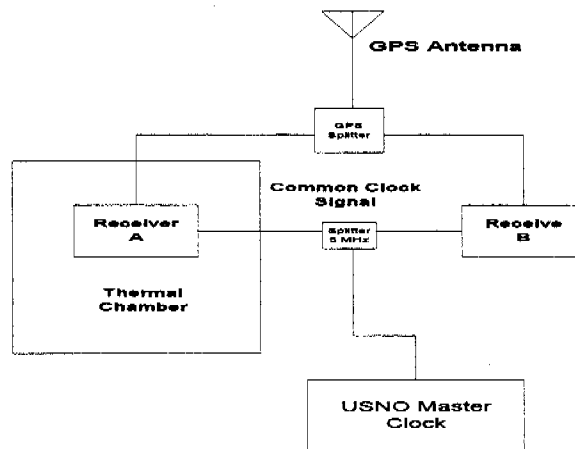


Figure 2 Zero-Baseline Experiment

As shown in Figure 2, one receiver was placed in a thermal chamber and subjected to temperature steps of 5 °C over a range from 20 to 35 °C. The second receiver was held at room temperature, which through most of the experiment was constant to about 1 °C. Later the experiment was repeated after exchanging the two receivers. The measurements were terminated prematurely when one of the receivers was needed operationally. The L1 CA code and L1 and L2 carrier measurements from each of the receivers were differenced and analyzed. We found that the code measurements tended to be approximately ten times more sensitive to the temperature than the carrier phase measurements. Tables 2 and 3 show the results of typical measurements for both GPS receivers, and Figure 3 shows the L1 carrier phase measurements.

Table 2 TurboRogue Temperature Sensitivity Receiver 245 (Uncertainty)

Receiver 245 Temperature	L1 CA Code	L1 Carrier Phase	L2 Carrier Phase	PPS Time Output
20 °C	0 ps (100 ps)	0 ps (50 ps)	0 ps (50 ps)	0 ps (50 ps)
25 °C	450 ps (100 ps)	25 ps (50 ps)	45 ps (50 ps)	250 ps (50 ps)
30 °C	1250 ps (100 ps)	115 ps (50 ps)	165 ps (50 ps)	540 ps (50 ps)
35 °C	1800 ps (100 ps)	200 ps (50 ps)	275 ps (50 ps)	900 ps

Table 3 TurboRogue Temperature Sensitivity Receiver 202 (Uncertainty)

Receiver 202 Temperature	L1 CA Code	L1 Carrier Phase	L2 Carrier Phase	PPS Time Output
20 °C	0 ps (100 ps)	0 ps (50 ps)	0 ps (50 ps)	0 ps (50 ps)
25 °C	200 ps (100 ps)	- 30 ps (50 ps)	- 40 ps (50 ps)	190 ps (50 ps)
30 °C	1200 ps (100 ps)	20 ps (50 ps)	25 ps (50 ps)	500 ps (50 ps)
35 °C	1700 ps (100 ps)	70 ps (50 ps)	120 ps (50 ps)	725 ps (50 ps)

At temperatures between (20 – 25) °C , receiver 202 exhibited the smallest thermal sensitivity with relative L1/L2 carrier phase measurement delays changing inversely to the code measurements, but

receiver 245's code and carrier phase measurements tended to change delays proportionally. It is not yet understood why the GPS code measurements tended to be ten times more sensitive to thermal changes than the carrier phase measurements.

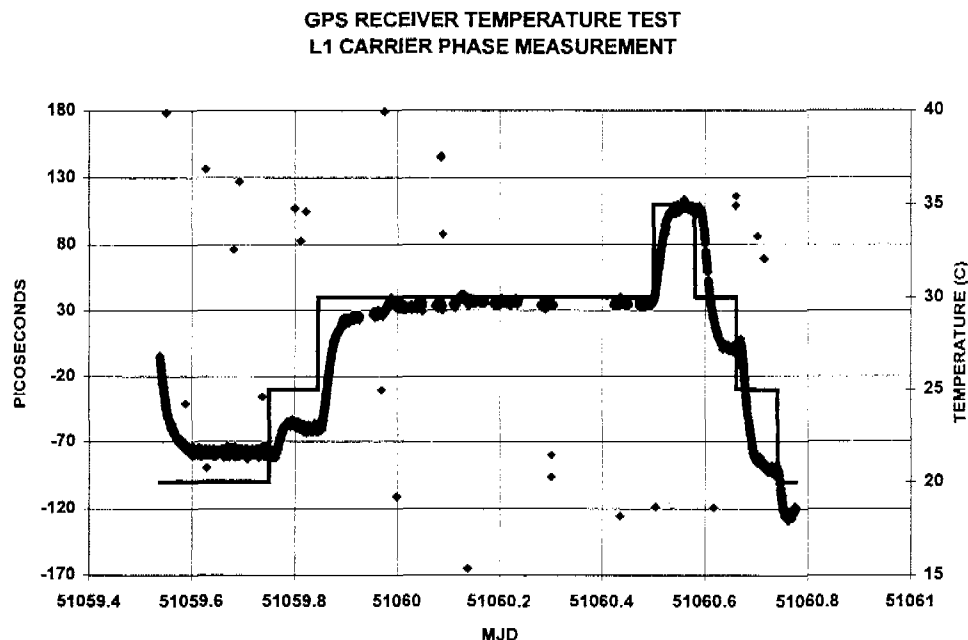


Figure 3 Zero-Baseline L1 Carrier Phase Temperature Testing

USING AN EXTERNAL CLOCK WITH THE TURBOROGUE™

In this section we will discuss the errors associated with locking the TurboRogue™ internal clock to an external frequency and time standard and how to correct for some of the errors that occur during this process.

All of the receiver's internal measurements are referenced to a common internal clock running at 20.456 MHz. This internal clock is phase-locked to an external 5 MHz frequency standard by dividing the external 5 MHz frequency reference (N) and the internal 20.456 MHz clock (M) down to common sub-multiples in the range of a few tens of kilohertz. These two sub-multiple frequencies are mixed and the resulting error signal is used to phase-lock the internal 20.456 MHz clock to the external frequency reference. The two N/M divider circuits used in the receiver's frequency synthesis chain are not synchronous. A receiver power cycle will reset this divider chain and the phase relationship between the internal frequency reference and the external frequency reference will be lost. This relationship is preserved in the event of software resets. Figure 4 shows a block diagram of the receiver's frequency synthesis chain and time base. The receiver outputs a one-pulse-per-second (1PPS) time output that is

divided down from the internal 20.456 MHz frequency reference. This 1 PPS is approximately synchronized to GPS time during the receiver's initial startup and is used internally by the receiver as a time mark for its GPS measurements. The jitter on this receiver's 1PPS is typically 125 ps, with one standard deviation being 45 picoseconds per 10 seconds average. As shown earlier in Tables 4 and 5, the 1 PPS output is sensitive to temperature changes at the level of 50 ps/C.

A TurboRogue™ can be used as a time transfer receiver if the 1PPS output from the receiver is measured against the local time reference. The internal receiver measurement of a GPS space vehicle's (SV) clock offset is referenced to the internal receiver's clock which is internally referenced to the receiver 1PPS, so the internal receiver clock can be subtracted out by subtracting the GPS SV clock offset measurements from the external time interval measurements (see Equations 1-3 below).

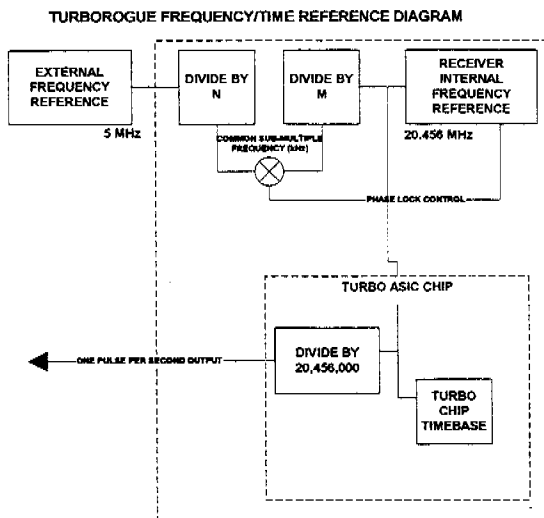


Figure 4 Block Diagram of TurboRogue™ Timing Architecture

$$A = \text{GPS SV clock offset} + \text{Receiver calibration bias} - \text{Receiver clock offset} \quad (1)$$

$$B = \text{User Local clock} - \text{Receiver clock offset} \quad (2)$$

$$A - B = \text{GPS SV clock offset} + \text{calibration bias} - \text{User Local clock offset} \quad (3)$$

This ability to subtract out the receiver internal clock allows the user to correct for jumps or resets in the internal receiver time base caused by either a power cycle or software reset.

Using the zero-baseline experimental setup described above, we periodically reset and power-cycled one of the two receivers used in the experiment. We found that the 1 PPS difference between these two receivers equaled the CA code measurement jumps to within a 200 ps measurement uncertainty (see Table 4).

Table 4 Results from Six Power Cycle Experiments

	CA Code Difference (NS)	One PPS Difference (NS)	Re-Calibration Difference (NS)
Power Cycle #1	-317.3	-317.5	0.2
Power Cycle #2	163.1	163.07	0.03
Power Cycle #3	-147.8	-147.6	-0.2
Power Cycle #4	-62.5	-62.62	0.12
Power Cycle #5	9.7	9.53	0.17
Power Cycle #6	-155.4	-155.54	0.14

We have also found that, after a receiver software reset and subsequent time re-synchronization the bias in the code range measurement will change by multiples of 24.4427 ns. This 24.4427 ns step size is one half the period of the receiver internal frequency reference (20.456 MHz). Substituting the closest multiple of this step seems to work in all cases except for power interruptions.

Working with Allen Osborne Associates, we developed a modified frequency synthesis chain has been developed that will accept an external 1PPS timing signal from the local clock to force the synthesis chain to return to its previous state after a power interruption. This could allow a TurboRogue™ receiver to be used as a timing receiver without the use of an external time-interval counter, but further investigation is needed. The additional data processing techniques that will be needed to resolve this 24.4427-ns ambiguity should be simple to develop if the external time reference is stable.

Table 5 Receiver Reset Correction Values for USNO(AMC) to USNO(DC)

MJD	GPS - Clock (ns)	Type of Reset	Number of 24.443 (ns) Cycles	Cycle Error (ns)	1 PPS - Clock (ns)	1 PPS Error (ns)
51020.0	782.35	Soft	32.008	0.17	782.23	0.1
51042.0	-1173.0	Soft	47.99	0.24	-1173.35	0.35
51047.6	1026.75	Soft	42.006	0.15	1026.39	0.36
51052.6	195.5	Soft	7.998	0.05	195.45	0.05
51061.6	-195.35	Soft	7.992	0.2	-195.63	0.28
51065.9	162.45	Power	6.646	8.65	161.98	0.47
51066.5	179.3	Power	7.336	8.06	179.67	-.375
51070.6	-31	Power	1.268	6.35	-30.47	-.53
51082.6	-97.3	Soft	3.981	0.45	-97.63	0.33

USNO operates two IGS reference stations, one at USNO Washington DC (IGS designation: USNO) and the other at the USNO Alternate Master Clock at the GPS Master Control Station in Colorado Springs (IGS designation: AMCT or AMC2). USNO also continuously measures each station's TurboRogue™ receiver's 1PPS error signals relative to the Master Clock at both locations. Using reduced data publicly available by the CODE [7], we have examined a series of nine resets of AMCT receiver and found that

the internal clock error after resets can be corrected to within the measurement noise of a few hundred picoseconds. Most of this uncertainty can be attributed to data processing errors in the geodetic software used. Table 5 shows the size of these nine jumps, the cause of each jump, and information on measured correction factors.

STABILITY OF CODE AND CARRIER PHASE MEASUREMENTS

The relative stabilities of two TurboRogue™ receivers are analyzed in this section. Figure 5 shows zero-baseline L1 CA code difference measurements from two receivers measuring PRN 26 from horizon to horizon. At low elevation angles the differential measurement noise approaches 1 ns, and at elevation angles above 25 degrees the noise drops to only a few hundred picoseconds. This is due to the much higher signal strength received at higher elevations due in large part to the antenna gain pattern. Zero-baseline L1-code measurements were typically 100 times noisier than the L1-carrier phase measurements. The L2 code-less carrier phase measurements were about five times noisier than the L1 carrier phase measurements. Figure 6 shows the relative frequency stability of these three observables.

FUTURE PLANS

Additional and more thorough testing is planned to better understand the delays in the antenna electronics and to design new antenna electronics. Further studies of the receiver's sensitivity to changes in RF power level, temperature changes, use of different antenna electronics and filters, power supply fluctuations, and multi-path are planned.

We also plan to investigate a more direct approach to eliminating many of the GPS receivers' sensitivities by use of a calibrated signal generator. Our approach would be to design an elementary L1 and L2 CA/P code signal generator (calibrator) that could work cooperatively with the GPS receiver. This calibrator would be clocked from the user's time reference in a well-controlled and calibrated manner. The signal from this calibrator would be injected directly after the first stage low noise amplifier but before any filters. This injection point would be calibrated such that the code transitions have known offsets from the local time reference [6]. The L1 and L2 carrier phases would be generated so that coherence would be preserved on restart after power cycles or through other hardware resets.

The GPS receiver firmware would need to be modified so that the receiver can track this calibration pseudolite signal. With the advent of WAAS and other pseudolite-based systems, these modifications may already be in the works. A PRN sequence would be chosen that is compatible with existing pseudolite signal structures. It would be important to try to replicate the present GPS signal structure shape so that the receiver's tracking loops would not be biased. The calibrator signal would be tracked continuously on one of the receiver's unused channels or the receiver could sequence through each channel to calibrate any receiver inter-channel and L1, L2 biases.

The main advantage to this approach is that the calibrator signal would travel through the same path as the normal GPS measurements, and any delay fluctuations due to thermal changes would cancel. The normal GPS receiver measurement would be referenced to the receiver clock, as will the calibrator measurements. Each of the GPS measurements would be subtracted from the calibrator measurements, thus re-referencing the measurements to the local time reference with zero calibration delay.

During the initial proof of concept stage we plan to use a STel Model 7200 calibrator as our signal generator. This signal generator is capable of transmitting a zero Doppler L1/L2 C/A and P-code signal that can be calibrated to 1 ns [7].

CONCLUSIONS

Carrier phase measurements have been shown to be very stable and useful for frequency comparisons, but questions still remain as to the absolute calibration of the carrier phase measurement and how accurately it can be related to the user clock.

To approach 100 picosecond long-term stability in a carrier phase time/frequency transfer system, minimizing the thermal sensitivities in the GPS receiver and associated hardware is required. Use of phase-stable antenna cable will be needed if more than a few meters are exposed to the extremes of outdoor temperature changes. Either thermally controlled antenna enclosures or antenna electronics designed to be thermally stable over wide temperature range will be needed. Thermally controlled enclosures, like those used for the Geodetic Time Transfer Terminal (GeTT) [4], will also be required for the GPS receiver.

Receivers like the TurboRogue™ and the Ashtech Z12-T have been shown to be capable of making very stable GPS code and carrier phase measurement with stability better than 100 picoseconds. Great care must be taken in relating the internal receiver clock to the external frequency reference. For the TurboRogue™, a time-interval counter can be used to relate the receiver's internal clock to an external frequency/time standard. Modifications to the TurboRogue™ frequency synthesis design have been made to simplify relating the internal clock to an external reference.

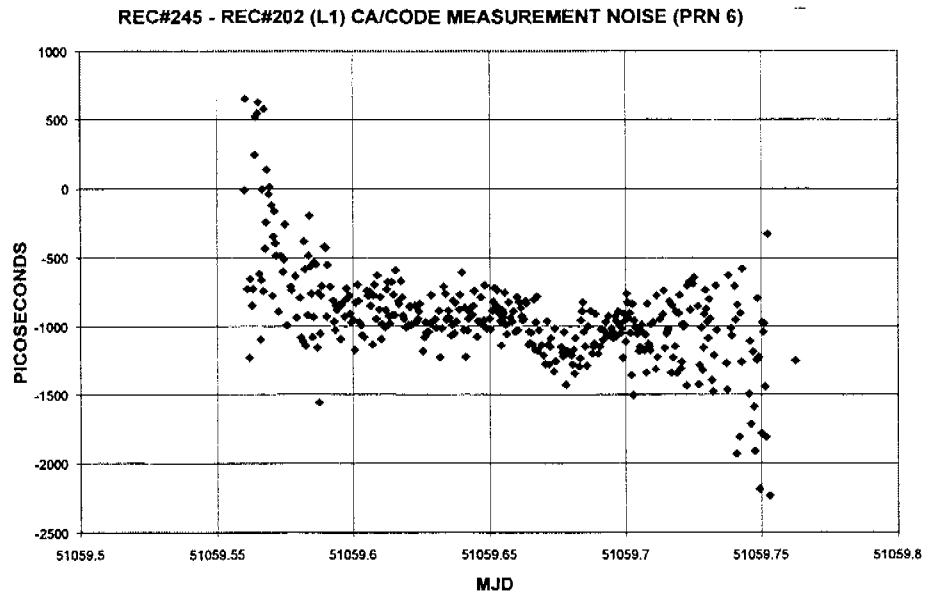


Figure 5 Zero-Baseline L1 CA-Code Measurement for a Complete Satellite Track

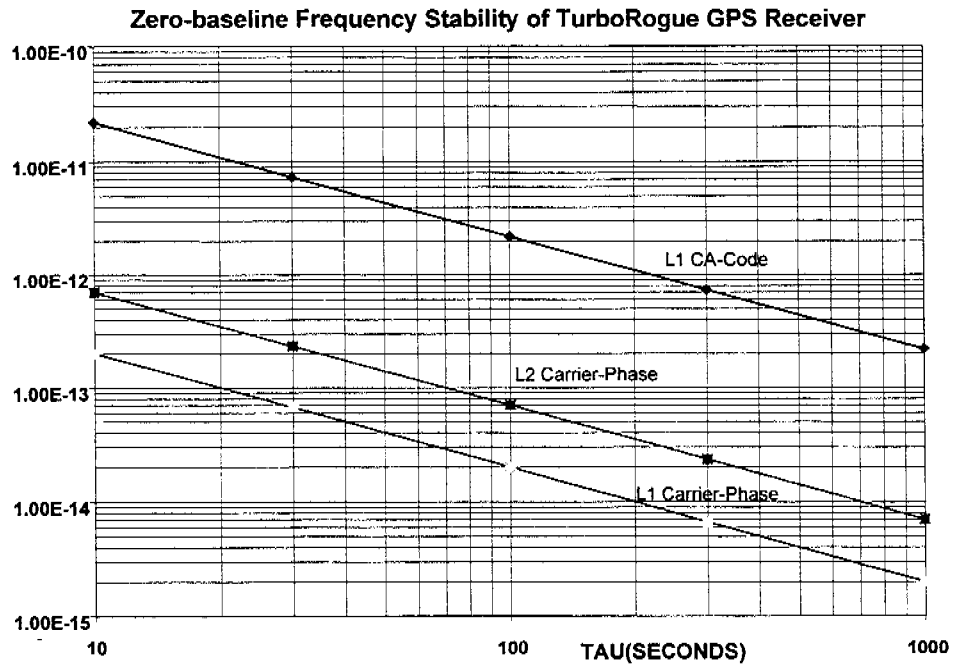


Figure 6 Stability of Receiver Measurement Noise

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Questions and Answers

JIM DeYOUNG (USNO): Ed, in the temperature plots that you were showing, the square waves – was that actually just showing the impulse time of the temperature change?

ED POWERS (USNO): It is just the impulse time. They actually look pretty close to a square wave. The response time in the chamber was pretty fast. You could see the slope, though, it did have a little corner. For simplicity's sake I just rounded it off.

JIM DeYOUNG: So, was there any evidence from the time of the impulse – in other words, was there a lag time in the reaction?

ED POWERS: Yes, I did see some in the first receiver I tested, If you shocked the receiver too hard, you might actually get a little impulse and a little overshoot.

THOMAS SCHILDNECHT (University of Berne): Am I correct that one of your conclusions is that the one PPS output of the TurboRogues can be used down to a level of 100 picoseconds to reconstruct the offsets during the power cycles resets?

ED POWERS: It does appear that way. I did not mention this, I meant to, but Demetrios has done some analysis of the data that you provided him, where he was able to correct them down to below the nanosecond level. I think the NIST group had similar results where they were able to eliminate the jumps below the nanosecond level. But the zero-baseline test allows me to do it without any noise, so it is much clearer to see.

THOMAS SCHILDKNECHT: Yes, because it is really the crucial point in the whole line. To be sure that this one PPS output is really traceable to the internal clock.

ED POWERS: When I say 100 picoseconds, that is in a controlled environment. You can see that the differential temperature coefficient between the one PPS and the code are going to give you maybe a 50-picosecond per degree Celsius sensitivity right there. So, if you are going to just run an open laboratory that goes up three or four degrees Celsius, you are not going to do it. If you change your temperature more than that amount, you certainly will not do it. So, stabilizing the hardware may be critical, like you have already found.

DEMETRIOS MATSAKIS (USNO): I know that these comments are going to appear at the end of the Proceedings. We want to put in our paper a table of the jumps that we have seen with co-data and just how well the PPS took it out. I would like to pass this discussion to Judah, who is analyzing some of data from the TurboRogues. Try to put that in your printed version too.

JUDAH LEVINE (NIST): All of our jump data is your data.

DEMETRIOS MATSAKIS: It is processed through GIPSY, so there is a processing noise in there.

JUDAH LEVINE: I understand. But the one PPS jump stuff is on your Web site.

ED POWERS: I think what Demetrios is looking for is just the plot or the difference between the jump-corrected data and the fit-corrected data.

SIGFRIDO LESCHIUTTA (IEN): I would like not to raise a question, but to make a couple of very general remarks concerning the very interesting sessions we had this afternoon. I think that we who work in the time and frequency community should congratulate the PTTI Executive Committee for offering us very interesting sessions in which 12 papers of this new technology was opened to some extent. That also brings to mind similar sessions we had in the past years concerning Loran-C and the first use of GPS codes.

I would like to make two statements, and the second one is just a matter of wording. Inside scientific unions, such as the International Union of Radio Science, the International Astronomical Union and similar bodies such as CCIR by tradition, for the word "time comparison" is meant as a comparison between two clocks. These are the reading of the clocks or clock against the time scale. So, I think we should be a bit cautious in speaking of a frequency comparison, phase comparison and, finally, time comparisons.