Low-cost, High Accuracy GPS Timing

Thomas A. Clark, *NASA Goddard Space Flight Center, Greenbelt, Maryland*
Richard M. Hambly, *CNS Systems Inc., Severna Park, Maryland*
Reza Abtahi, *CNST, San Jose, California*

BIOGRAPHIES

Dr. Thomas A. Clark joined NASA's Goddard Space Flight Center in 1968 with research interests in developing the techniques of VLBI and GPS for high accuracy geodesy. His GPS "Totally Accurate Clock" ("TAC") has allowed the VLBI and Astronomy communities to achieve global time synchronization of atomic clocks at levels of better than 25 nsec. His research has also involved the characterization of geodetic GPS antenna performance at mm levels and the mitigation of site-specific multipath.

Dr. Clark has been author or co-author of more than 150 scientific and technical papers in many fields. He has received numerous awards including NASA's Medal for Exceptional Engineering Achievement, Goddard's Moe I. Schneebaum Memorial Award for Engineering and the CSVHFS John T. Chambers Memorial Award. He is a Fellow of the American Geophysical Union and the International Association of Geodesy. In addition to these research efforts, Dr. Clark was an Adjoint Professor of Physics and Astronomy at the Univ. of MD (1968-76) and a Visiting Professor at Chalmers Univ. in Sweden (1993).

Richard M. Hambly is president of CNS Systems, Inc., a consulting and manufacturing firm that provides communication, navigation and surveillance solutions for the commercial and military transportation industries. He has implemented advanced communications, navigation and surveillance systems for the aerospace industry and has experience in data networks, VHF voice and data communications, satellite communications, and GPS-based navigation, surveillance and precision time systems.

Prior to founding CNS Systems, Mr. Hambly was an Engineering Director at ARINC and an Engineering Manager for Harris/RF Communications. He holds both Bachelors and Masters degrees in Electrical Engineering from Cornell University.

Dr. Reza Abtahi is founder and general manager of Custom Navigation Systems Technology in Santa Clara, CA, which develops specialized hardware and firmware for GPS and other navigation applications. His specialty is the development of new algorithms used inside embedded systems. Prior to establishing CNST, he was with Ashtech Inc., where he was responsible for developing real-time signal processing, RTCM differential reference station and user equipment, GPS receiver remote control interfaces, and GPS integrity monitoring.

His education includes Bachelors and Masters degrees from E.N.S.E.E.I.H.T. in Toulouse, France and a Ph.D. in Electrical Engineering from the University of Sherbrooke in Sherbrooke, Canada.

ABSTRACT

This paper describes our long-term efforts to develop low-cost (under $1,000) timing systems for use at isolated locations that are accurate at levels of <50 nanoseconds. The initial application was at radio telescopes around the world used for geodetic and astronomical Very Long Baseline Interferometry (VLBI) measurements. In VLBI, wide bandwidth microwave noise signals from extragalactic radio sources are recorded on magnetic tape. The tapes are brought together days later and correlated coherently. To achieve coherence at microwave frequencies for hundreds of seconds, each VLBI station uses a Hydrogen Maser frequency standard. In order for the correlation process to proceed, the relative timing of the station clocks all around the world must be known at levels <100 nsec and rates <100 nsec/day (i.e. $<1:10^{12}$).

To meet the needs of VLBI, in 1994 the "Totally Accurate Clock" (TAC) was developed as a low-cost GPS-based solution based on off-the-shelf OEM GPS receivers. After evaluating the receivers from several manufacturers, we selected the Motorola PVT-6 and its successor, the ONCORE VP. With the VP ONCORE, we have been able to demonstrate ~20 nsec RMS timing on time scales from minutes to days.

The situation has recently changed. Motorola announced the discontinuance of the VP ONCORE receiver in 1999 because of component shortages. This left us with the lower cost (and reduced capability) UT+ receiver. This prompted us to begin reviewing an alternative prototype based on the SiRF chipset. And, to everyone's joy, in May 2000, the DoD removed the S/A (Selective Availability) clock "dither" making a significant improvement in timing performance of the GPS system.

Since S/A was turned off, data taken with ONCOREs show an improvement of short-term (time scales of minutes) to ~4 nsec RMS, but shows "glitches" that were formerly masked by S/A. This is compared to the SiRF-based receiver, which shows short-term noise at the ~660 psec level with very few "glitches". The performance of the best of the single frequency receivers (not surprisingly) shows uncalibrated ionospheric biases with diurnal signatures at the 10-20 nsec level. After filtering the ionosphere, the residuals agree to a few nsec with the $\text{UTC}_{(\text{USNO})}$ minus $\text{UTC}_{(\text{GPS})}$ offset values published daily on the USNO Web site.

1. A BRIEF INTRODUCTION TO VLBI

The time/frequency needs of community of Very Long Baseline Interferometry (VLBI) stations used for both Radio Astronomy and Geodesy pose some of the most stringent requirements on system timing. At some 40-50 remote sites all around the world, Hydrogen Masers are employed. To illustrate the reasons Masers are needed we note:

- To achieve ~10° signal coherence for ~1000 seconds at 10 GHz, the local oscillators at each end of the interferometer to maintain relative short-term stability of

$$\approx \frac{10^\circ}{360^\circ * 10^{10}\, Hz * 10^3 \sec} \approx 2.8 * 10^{-15} \ @1000 \sec$$

- To cross-correlate data acquired at 16Mb/s, station timing at relative levels ~50 nsec or better is needed. After a few days of inactivity, this requires long-term stability (or accuracy) of

$$\approx \frac{50 * 10^{-9}}{10^6 \sec} \approx 5 * 10^{-14} \ @10^6 \sec$$

- In Geodetic applications, the relative performance of station clocks are modeled with polynomials at levels ~30 psec (~1 cm of distance) over a 24 hour observation set, requiring the clocks to exhibit "smoothness" and "predictability" at levels of

$$\approx \frac{30 * 10^{-12}}{86400 \sec} \approx 3.5^{-16} \ @1\, day$$

- Finally, since astrometric measurements made with VLBI constitute the definition of UT1 at levels of <1 μsec, there is a need to control the network timing [$\text{UTC}_{(\text{USNO})}$ minus $\text{UTC}_{(\text{VLBI})}$] to an overall accuracy ~100 nsec or better over time scales of years.

These VLBI stations are truly remote, spanning all the continents in such locations as Antarctica, Spitzbergen (at 79° North), and the Xinjiang Province of western China. Each of these stations maintains their own Maser and hence needs to know the "health" and timing autonomously and in near-real-time. These requirements led to the development of the low-cost GPS timing clock, which we dubbed the TAC – "Totally Accurate Clock".

Since each station has an atomic clock "flywheel", we developed a number of "tricks" to improve the accuracy of GPS timing in the presence of Selective Availability (S/A). The essence of these "tricks" included:

- Instead of allowing the GPS receiver to use at least four satellites solve for a 3-D position + time, the receiver is "locked" in position (the "Zero-D" mode) and all available satellites are used to determine time. We determined that S/A is uncorrelated between the N different satellites in use, so this reduced S/A's effects by a factor $\approx \sqrt{N}$.

- The predominant error involved in S/A was determined to be a band-limited random clock "dither". The significant time scales were found to range from a few seconds to ~½ hour. Since each site has an atomic clock, the noise can be reduced by averaging measurements over many minutes.

Other error sources manifest themselves on times scales of 12 hours (satellite orbit and geometry errors and the repeatability of multipath biases), and one day (uncalibrated ionosphere, tropospheric water vapor, etc,). In trying to model long-term timing of an atomic clock, this leads to the fitting of multi-day data sets to determine a "paper clock" model for each station.

2. THE EARLY YEARS – 1994 to 1999

The earliest TACs used the Motorola PVT-6 “Six Gun” receiver, what was later became the first of the ONCORE series. About 50 copies of the original TAC (along with an early MSDOS control program named SHOWTIME) were supplied to the scientific community by NASA Goddard and many are still in use.

Figure 1 shows six weeks of data obtained in 1995 at the Onsala Space Observatory in Sweden. In this data set, the time-interval counter averaged 1PPS measurements for 30 seconds. Then 60 of these 30-second samples were combined into 30 minute averages and plotted. The average RMS of the samples in each 30 minute bin was 31.8 nsec over the entire six week period.

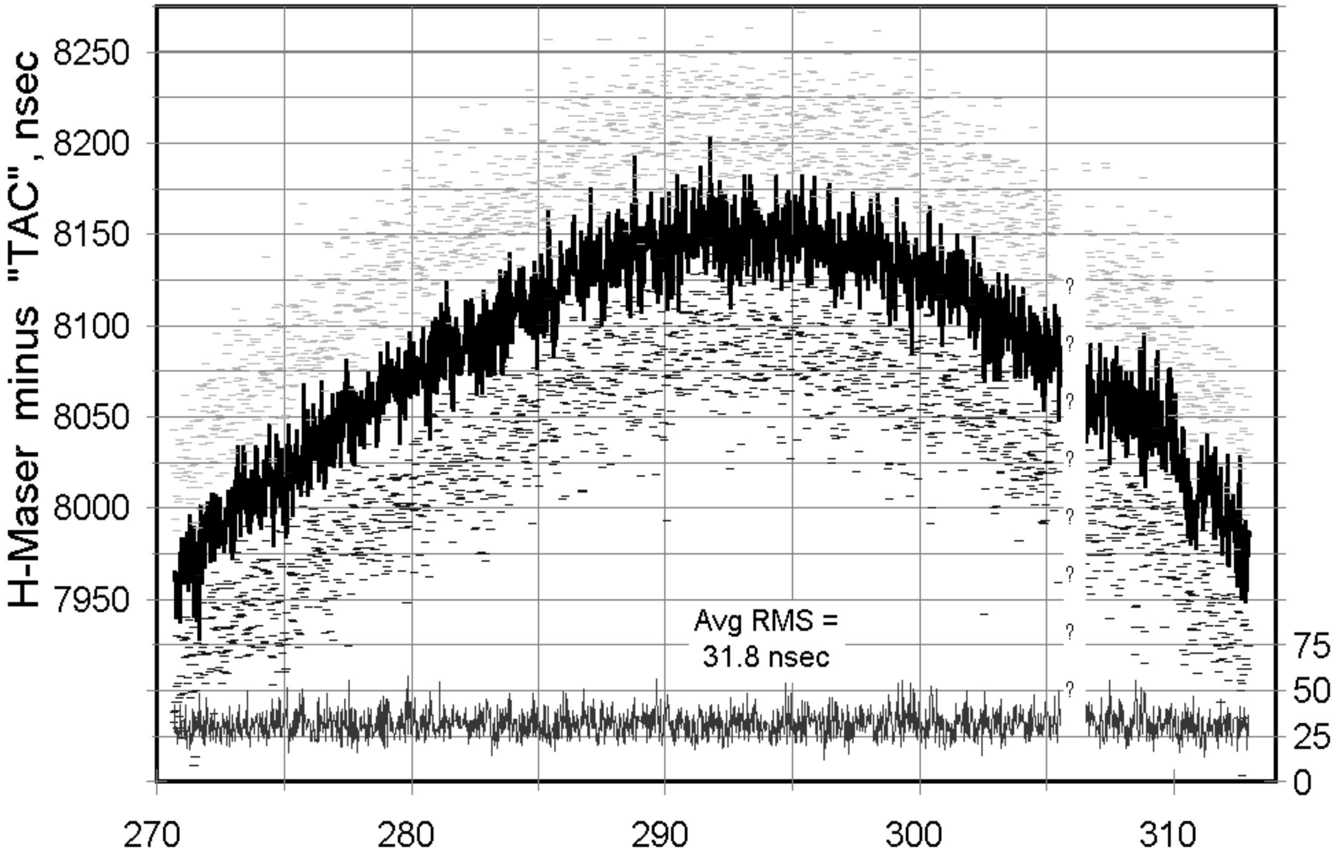


Figure 1. Six weeks of H-Maser vs. TAC data from the Onsala Space Observatory, Sweden in 1995

Also in 1995, we made a number of tests to verify the accuracy of the TAC. This included direct measurements against the USNO with travelling clocks and TV signals, and with common-view measurements between Arecibo, PR and NIST. At about the same time there were a number of requests for TAC clones that totally swamped the NASA/GSFC R&D group’s ability to supply the needs.

In 1994 Motorola introduced the 6-channel Oncore VP and in 1995 the 8-channel ONCORE VP. This led to the development of the improved TAC-2. The TAC-2 design was made available to the world by the not-for-profit Tucson Amateur Packet Radio (TAPR) group as a kit. This design was then adopted by CNS Systems as the CNS Clock. As best we can determine, more than 500 of the TAC-2/ TAPR/CNS clocks have been made.

CNS Systems also adapted the algorithms of the original TAC SHOWTIME software to the 32-bit Windows world with Tac32. A subsequent version, Tac32Plus, integrated support for the HP/Agilent 53131A and 53132A time-interval counters to make an integrated time-interval measurement system that is now in operational use at many of the world’s VLBI and SLR stations. In addition, Tac32Plus allows the GPS timing receiver to be used as an NTP time server for the station. We use two of these measurement systems at the Goddard Geophysical and Astronomical Observatory (GGAO) R&D site, as shown in Figure 2, for most the measurements presented here.

By 1999, the newer 8-channel ONCORE was performing at the ~17 nsec level, as seen in the 3-day plot of the

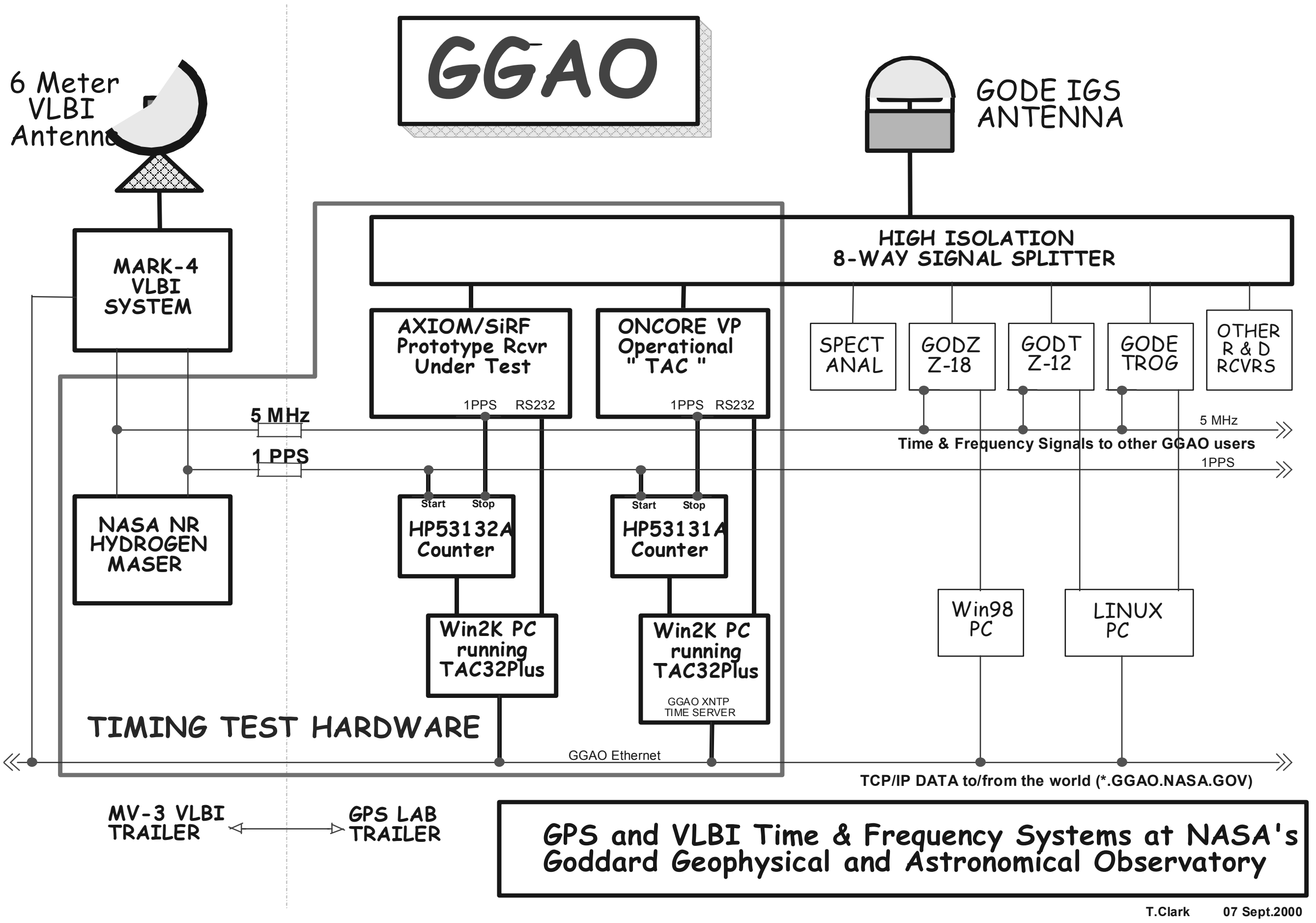


Figure 3 – The Tac32Plus-based Timing Measurement System used at GGAO

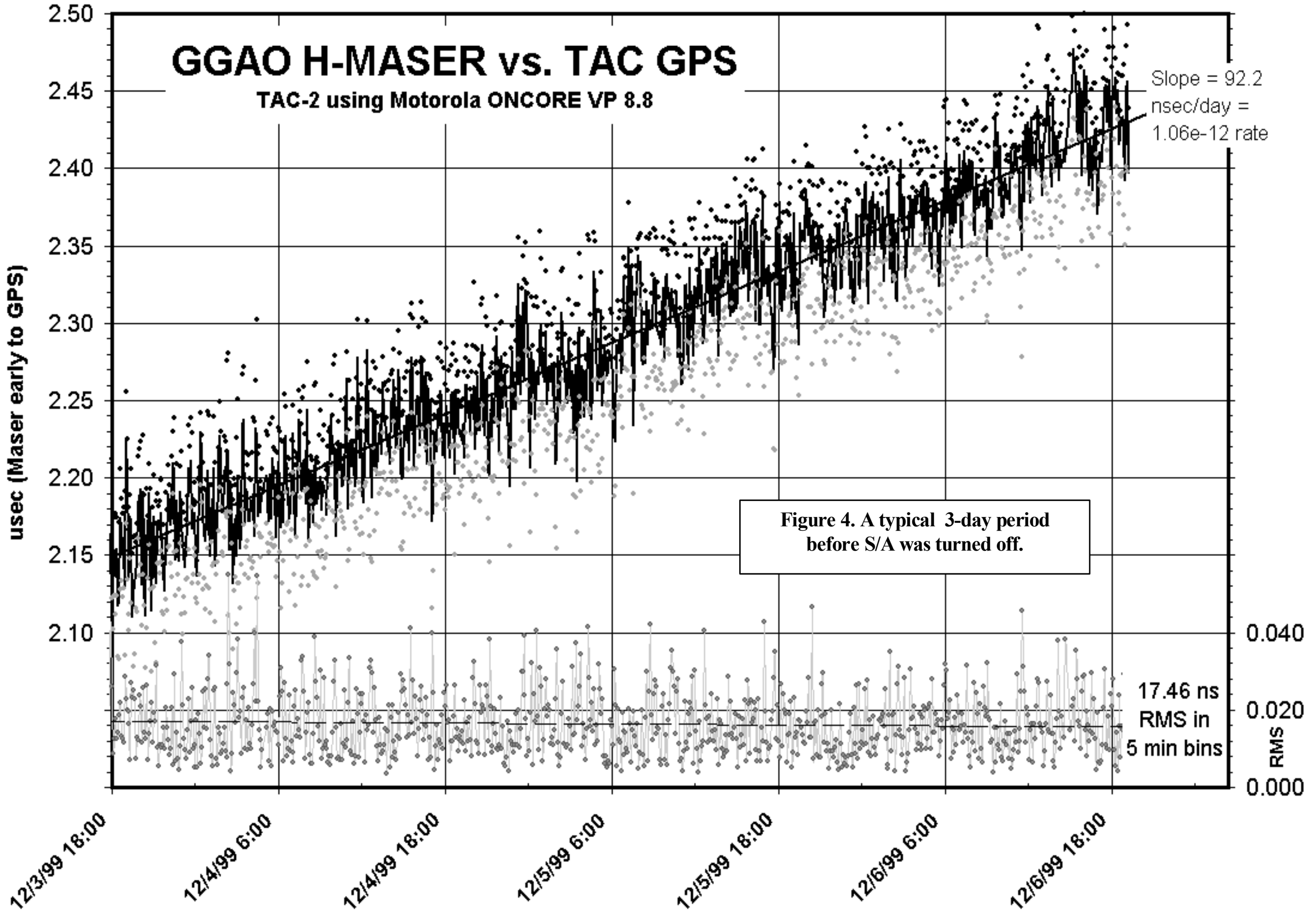


Figure 4. A typical 3-day period before S/A was turned off.

GGAO Maser/TAC combination in Figure 3. In this case, an H-Maser rate offset of $\sim 1{:}10^{12}$ is very obvious. The counter data has been averaged into 5 minute bins, and the internal noise of the 300 samples in the 5 minute bins averages about 17½ nsec.

3. INTO THE NEW MILLENIUM

The year 2000 brought some major changes in the low-cost timing arena. Three major events are noted:

- Motorola announced in late 1999 that they were discontinuing their ONCORE VP product. They advise users to change over to their improved version of the UT+ receiver.
- We learn in April that Reza Abtahi has developed timing firmware for the SiRFstar chipset. The code was ported to run on Axiom Navigation's Sandpiper OEM receiver board. As we learn more about the SiRF performance we begin a program to fine-tune its performance.
- On May 2nd, the White House announces that DoD is turning off S/A.. Fortunately we have both ONCORE and SiRF receivers running at the time!

In Figures 5 (Motorola ONCORE VP) and 6 (Axiom/SiRF prototype) we show the May 2nd transition. The change at 04:00 UTC is very obvious!

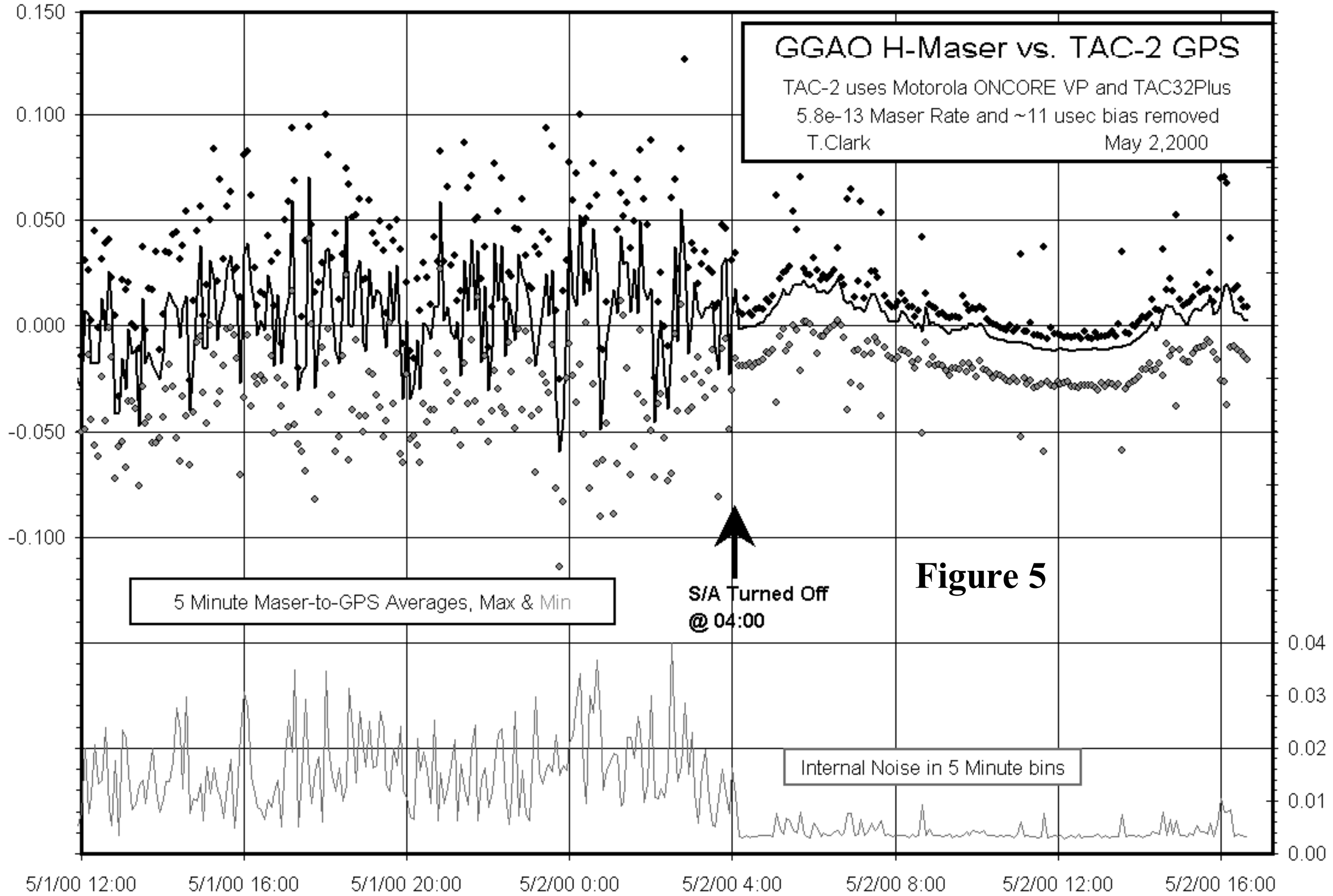


Figure 5

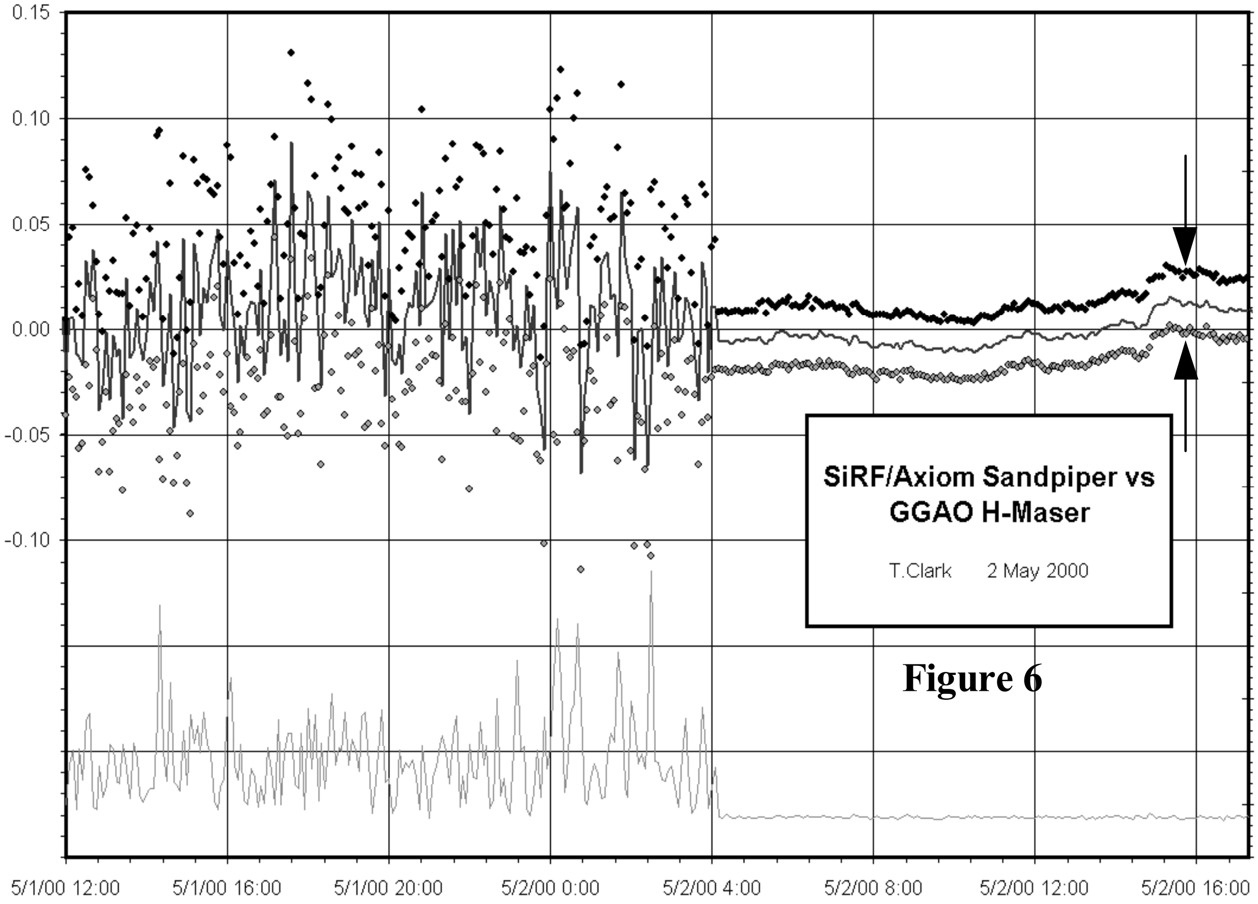


Figure 6

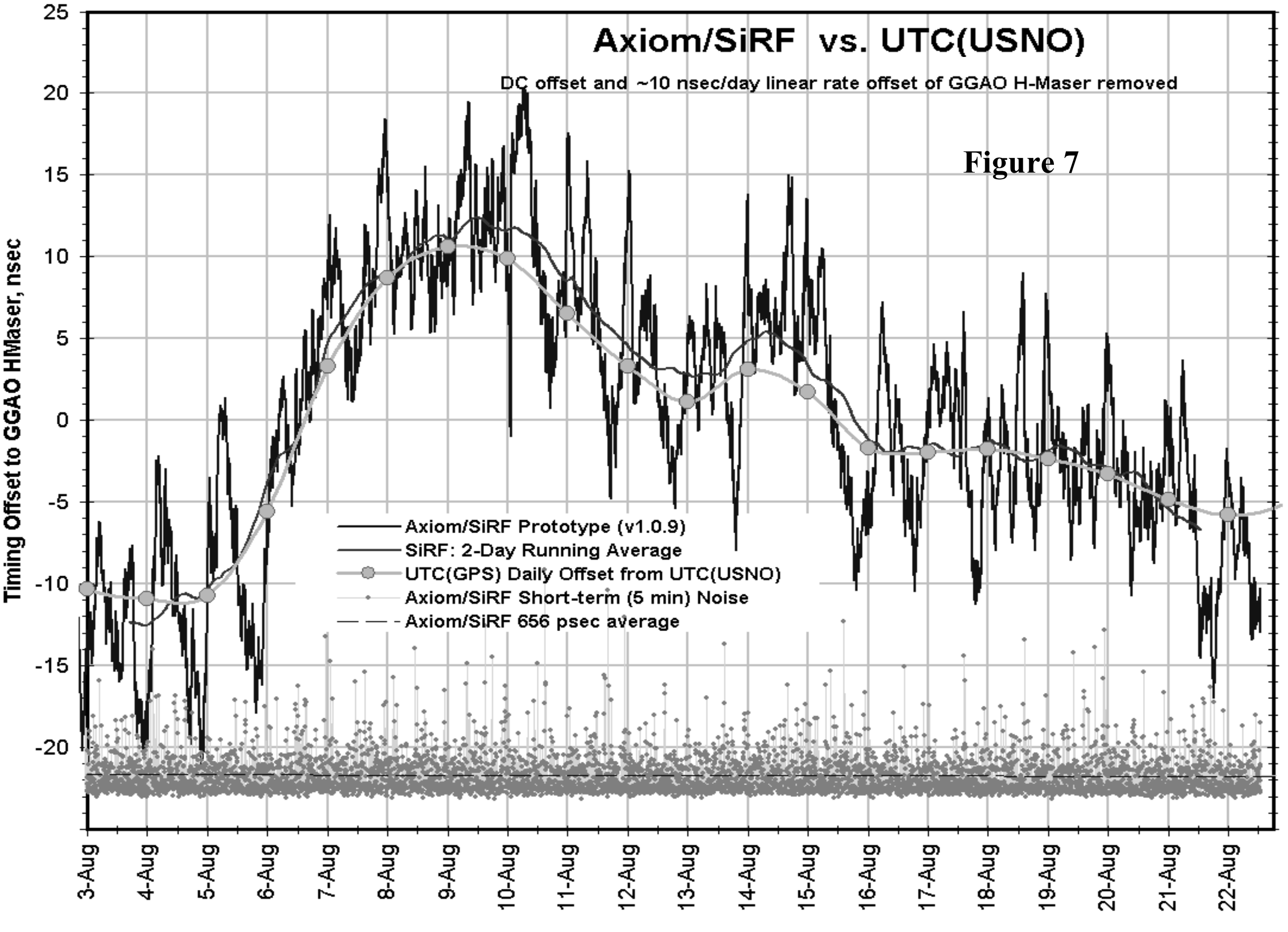


Figure 7

4. SOME RECENT RESULTS

Since S/A was turned off, we have continued to improve the performance of the SiRF-based timing receiver. Figure 7 shows Maser-to-GPS timing results from a three week period in August, 2000 after removing a ~12 μsec "DC" bias and linear ~10^{-13} (10 nsec/day) rate offset.

The timing data (after correcting for the ±13 nsec quantization sawtooth with data reported by the receiver) was averaged over a five minute windows, and the average short-term measurement noise in these bins was 656 psec over the entire period. We believe that this is the first time a small, single frequency timing receiver has demonstrated sub-nsec noise.

On longer time scales, the data in Figure 7 shows two obvious signatures. One clearly exhibits a diurnal signature with a peak-to-peak amplitude of 10-15 nsec. We identify this with ionospheric effects not removed by the ionosphere model contained in the GPS data message. As a simple test of this idea, we assume that the H-Maser is perfectly modeled with an offset and rate and then pass a two-day symmetric low-pass filter (a running average) over the SiRF timing data.

This running average is then compared with the daily constellation-wide [$UTC_{(USNO)}$ minus $UTC_{(GPS)}$] values posted by the USNO on their web site. The resulting peak difference [$UTC_{(SiRF)}$ minus $UTC_{(GPS)}$] is under 3 nsec for the entire three-week period.

Based on our original TAC experience when S/A was active, and our most recent results, Figure 8 presents an estimate of the Allan Variance that can be obtained with small, low-cost GPS timing receivers and a comparison with conventional atomic clocks. The shaded area denotes the region where diurnal (primarily ionospheric) effects will dominate. At multi-day time scales, the GPS curve assumes that the daily constellation offsets published by the USNO are applied to the observations.

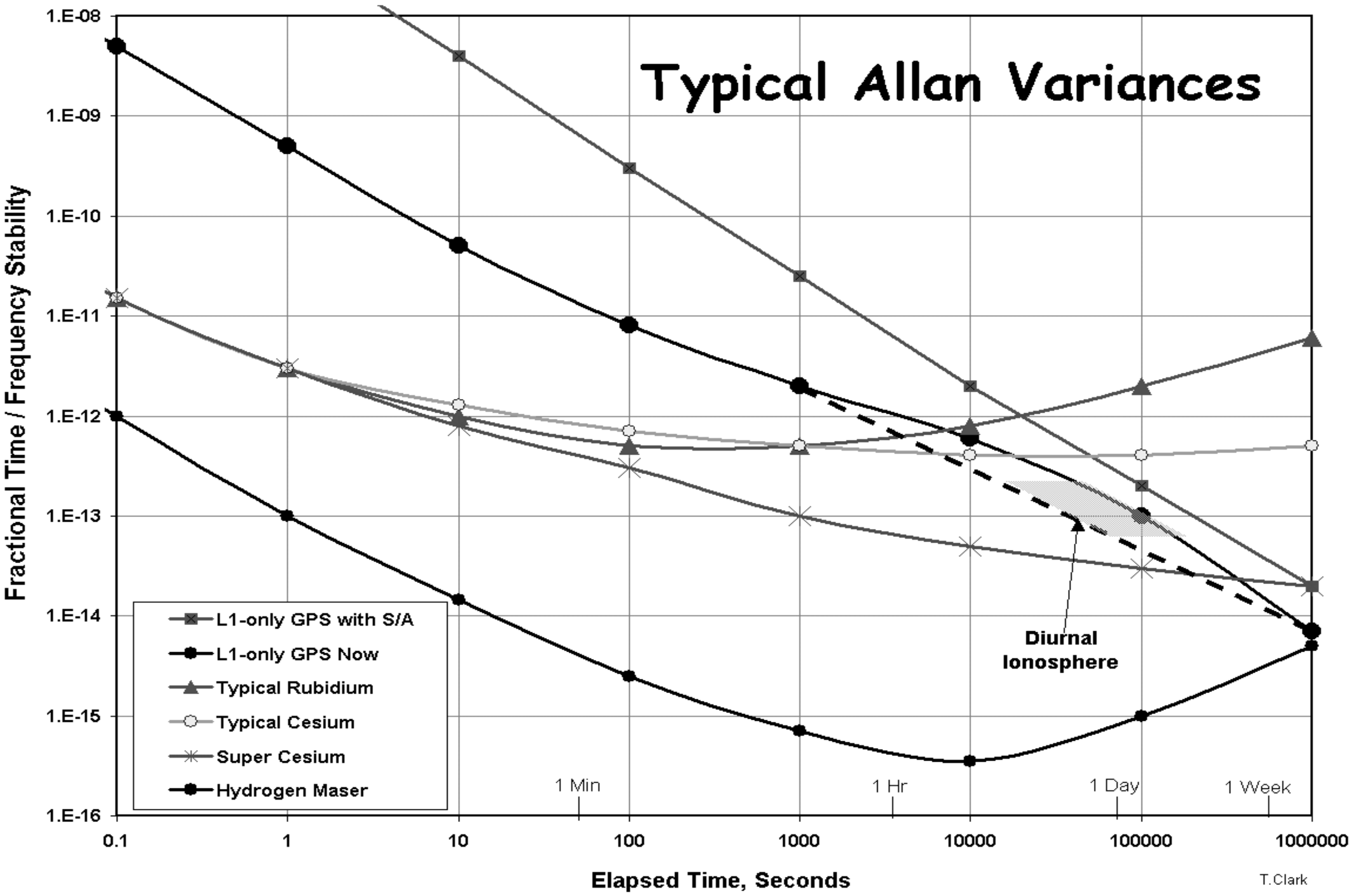


Figure 8. Typical Allan Variance of L1 GPS Receivers compared with typical atomic clocks.

5. NOISE AND GLITCHES

The 1PPS signals from the ONCORE and the SiRF receiver running Reza Abtahi's firmware are quantized at times defined by their internal clocks. This results in the individual 1PPS pulses exhibiting a sawtooth "dither". The period of this error is typically 5-10 seconds. The relevant oscillator frequencies and the resulting sawtooth signal amplitudes are

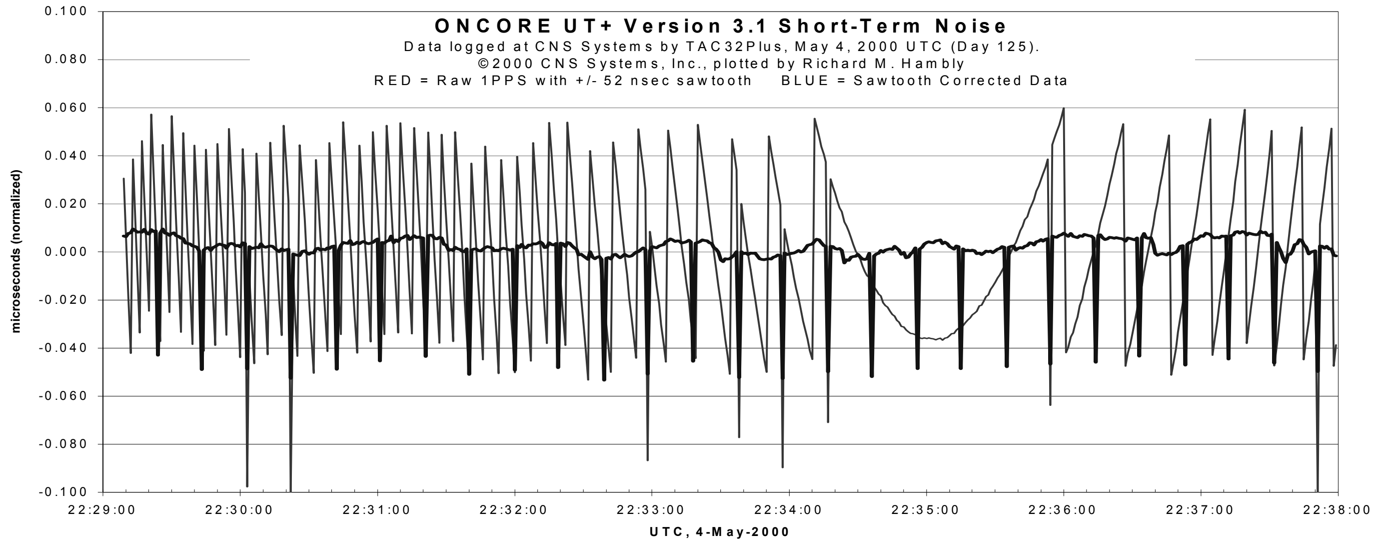
ONCORE:	9.54 MHz	⇒ ±52 nsec sawtooth
SiRF:	38.192 MHz	⇒ ±13 nsec sawtooth

Both receivers report the magnitude of the sawtooth error that should be applied to correct the *next* 1PPS pulse in their serial data stream. For the ONCORE, the magnitude is reported in integer nsec, while the SiRF reports the correction with a resolution of 10 psec. The Tac32Plus software continually reads data from both GPS receiver and Time Interval Counter and applies the sawtooth correction before generating data logs and averaging the counter readings.

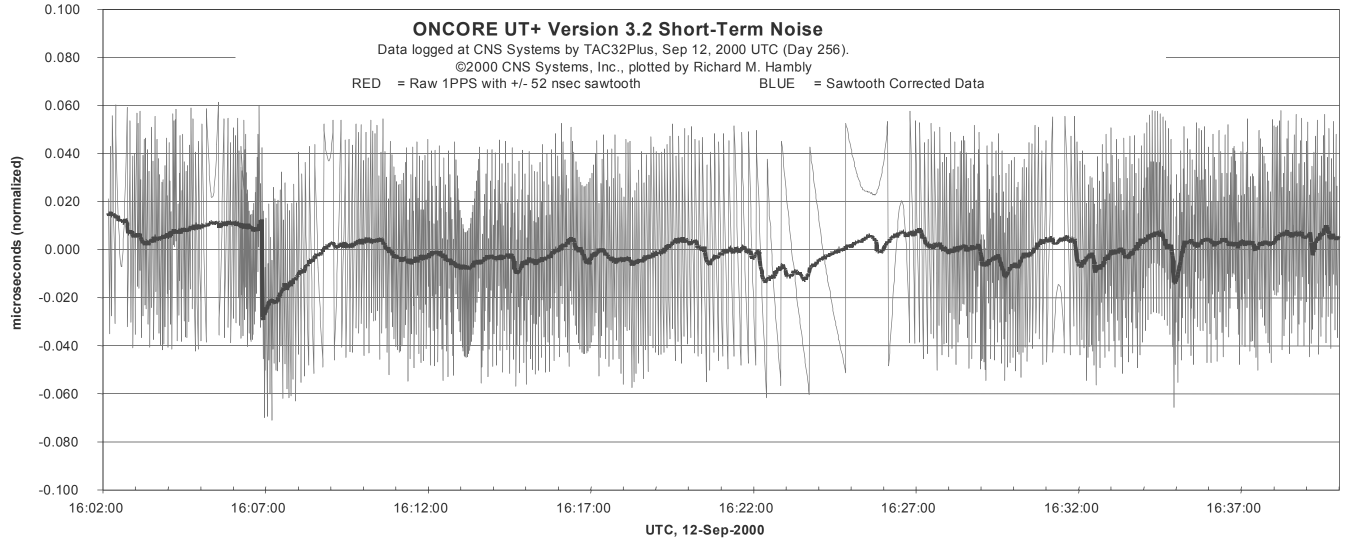
The magnitude of S/A errors was such that it masked any "glitches" in the generation of the 1PPS signals and in the sawtooth correction report. Now that S/A has been turned off, we have explored this issue.

Figure 9 shows some of these glitches in the ONCORE UT+ running Version 3.1 firmware. This figure shows ~50 nsec excursions alternately every 19 and 20 seconds. This means that the *average* error is only 50/19.5 = ~2.56 nsec but they could be annoying in critical applications.

Figure 10 shows a similar receiver running an early release of the Version 3.2 firmware. It appears that Motorola has found and corrected the 19.5-second problem.



Figures 9 and 10 – Timing "glitches in the UT+ ONCORE with two different firmware releases.



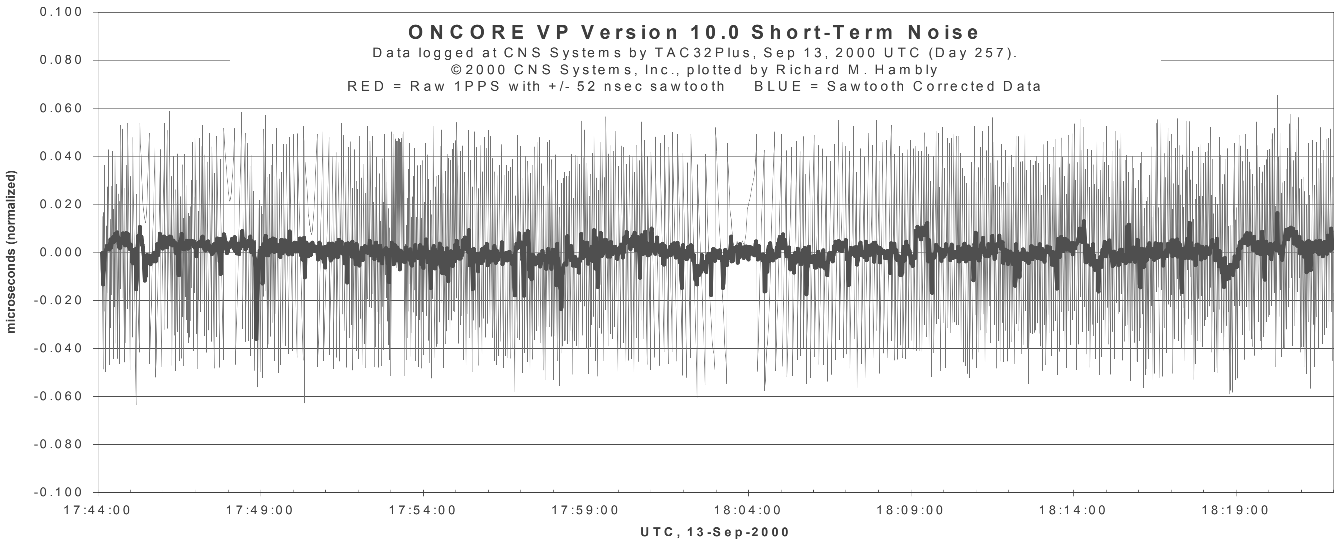


Figure 11 – Timing “glitches in the ONCORE VP with Version 10.0 firmware

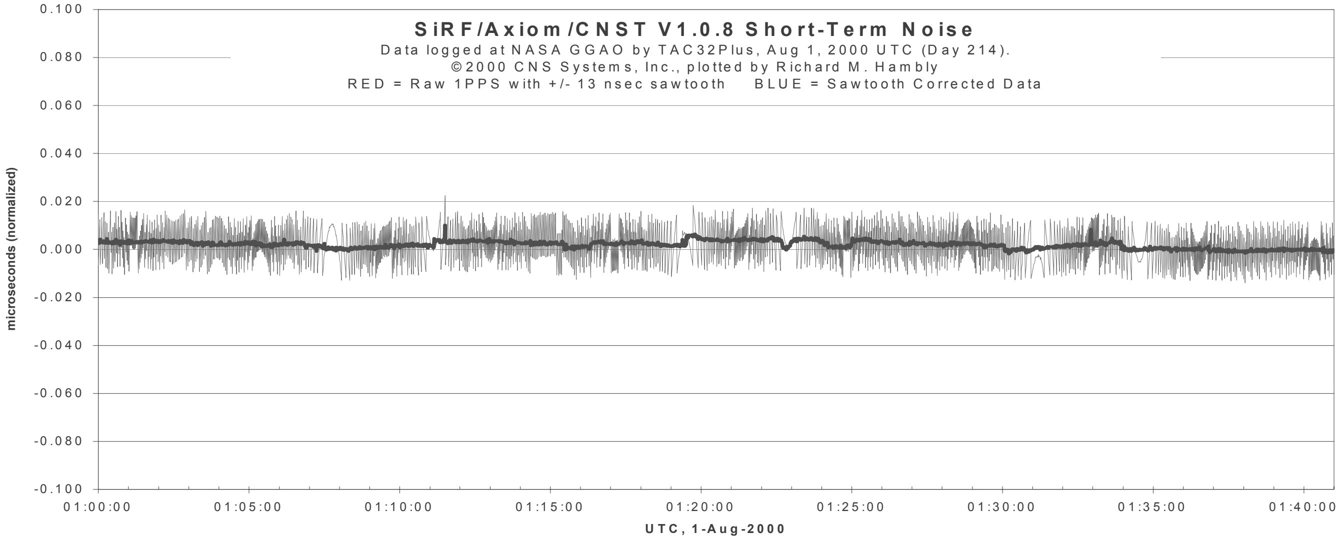


**Figure 12. Short-term timing noise from the Axiom/SiRF prototype receiver.
Note that the uncorrected sawtooth is smaller than for the Motorola receivers.**

In Figure 11, we see a similar plot for the (now discontinued) ONCORE VP with Version 10.0 firmware. Every 78-79 seconds, the receiver’s output pulse is in error by ~12 nsec. This same error is seen in Figure 5 where the 5-minute average is not symmetrically distributed between the max/min points. Figure 12 shows similar data for the prototype Axiom/SiRF receiver.

6. ACKNOWLEDGMENTS

The NASA portion of this measurement program is funded under the Solid Earth and Natural Hazards (SENH) NASA Research Announcement (NRA) to improve the inherent accuracy of GPS measurements used in Earth Science research. Chuck Kodak was most helpful in keeping the numerous PCs, counters, receivers and Internet connections functioning at the GGAO site.

Jim Read of Hyperfine and David Allan of AllansTime offered valuable encouragement and advice on numerous occasions.

We offer special thanks to Dave Smith and Gary Stormer (Axiom Navigation) and Art Sepin (Synergy Systems, LLC) for supplying some of the hardware for testing and for insuring the smooth flow of firmware updates.