IMPROVING THE PERFORMANCE OF LOW COST GPS TIMING RECEIVERS

⌘**Thomas A. Clark**

NASA Goddard Space Flight Center (retired)

mailto:K3IO@verizon.net

⌘ **Richard M. Hambly**

CNS Systems, Inc. (http://cnssys.com & http://gpstime.com)

mailto:RICK@cnssys.com

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Why?

Our quest for low cost, high accuracy timing grew from the needs of Very Long Baseline Interferometry (VLBI) for astronomy and geodesy measurement programs.

What Timing Performance Does VLBI Need?

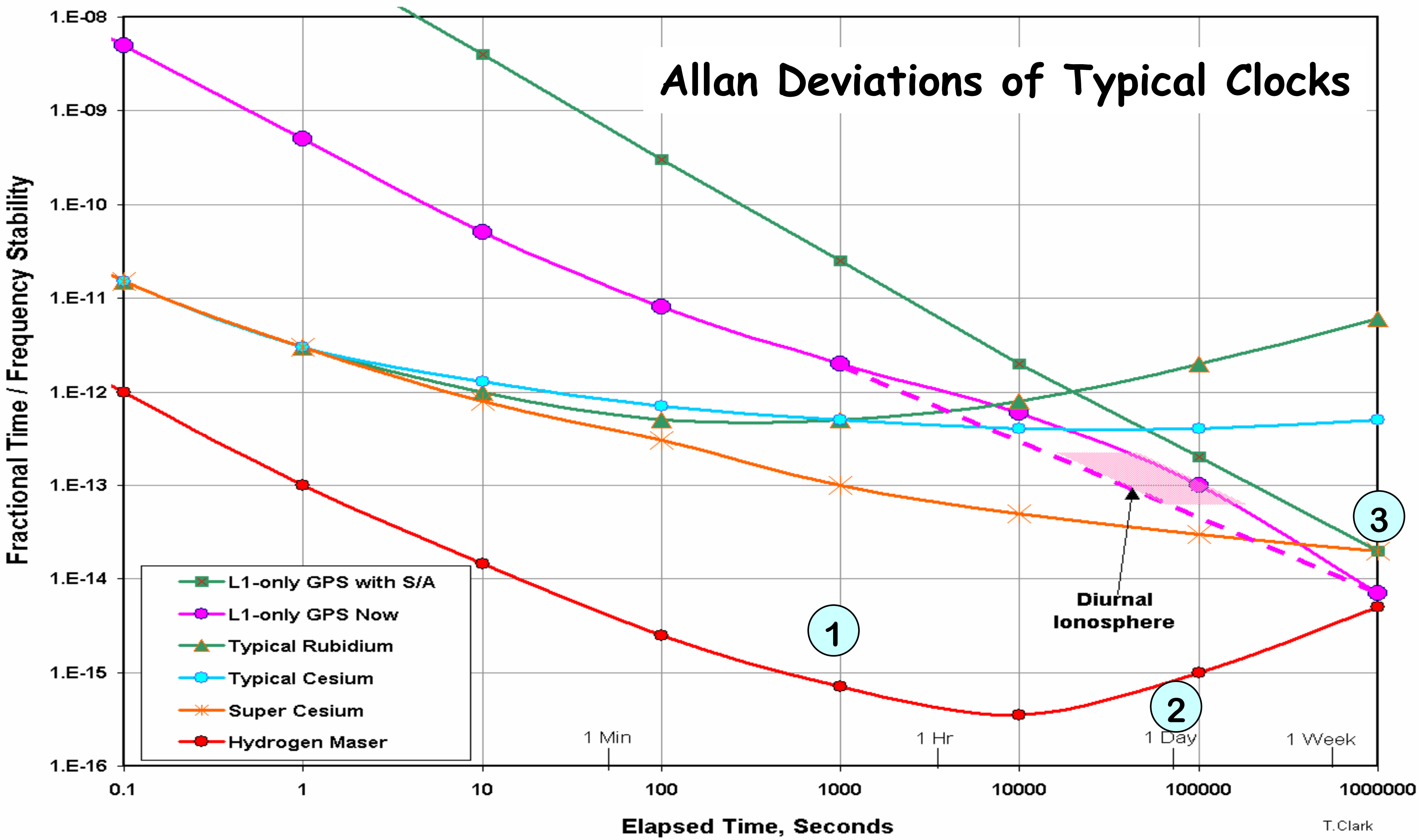
- The VLBI community (Radio Astronomy and Geodesy) uses Hydrogen Masers at 40-50 remote sites all around the world. To achieve ~10° signal coherence for ~1000 seconds at 10 GHz we need the 2 clocks (oscillators) at the ends of the interferometer to maintain relative stability of $\approx [10°/(360° \cdot 10^{10}\text{Hz} \cdot 10^{3}\text{sec})] \approx 2.8 \cdot 10^{-15}$ @ 1000 sec. 1

- In Geodetic applications, the station clocks are modeled at relative levels ~30 psec over a day $\approx [30 \cdot 10^{-12}/86400 \text{ sec}] \approx 3.5 \cdot 10^{-16}$ @ 1 day. 2

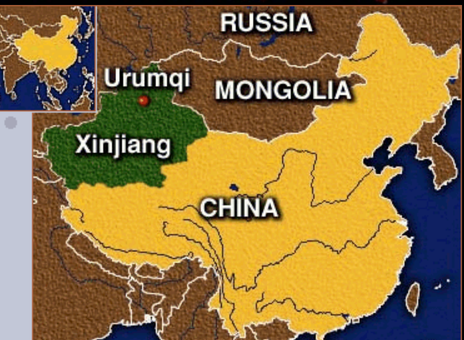
- To correlate data acquired at 16Mb/s, station timing at relative levels ~50 nsec or better is needed. After a few days of inactivity, this requires $\approx [50 \cdot 10^{-9}/ 10^{6} \text{ sec}] \approx 5 \cdot 10^{-14}$ @ 10^{6} sec 3

- Since VLBI now defines UT1, we need to control $[UTC_{(USNO)} - UTC_{(VLBI)}]$ with an ***ACCURACY*** of 100 nsec or better.

The Allan Deviation – A statistical look at clock performance

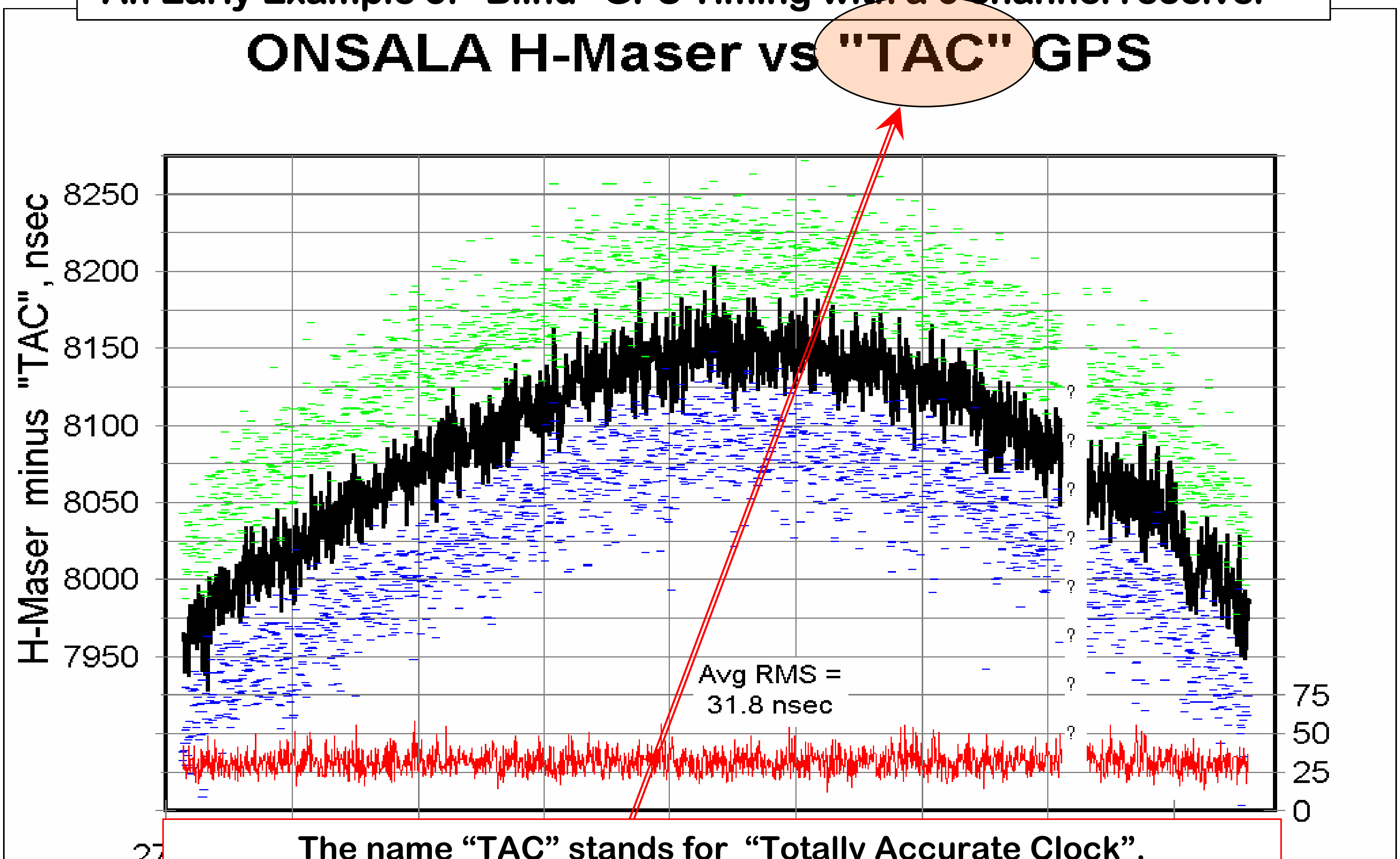


VLBI is one of the main users of H-Masers, even at very remote locations.



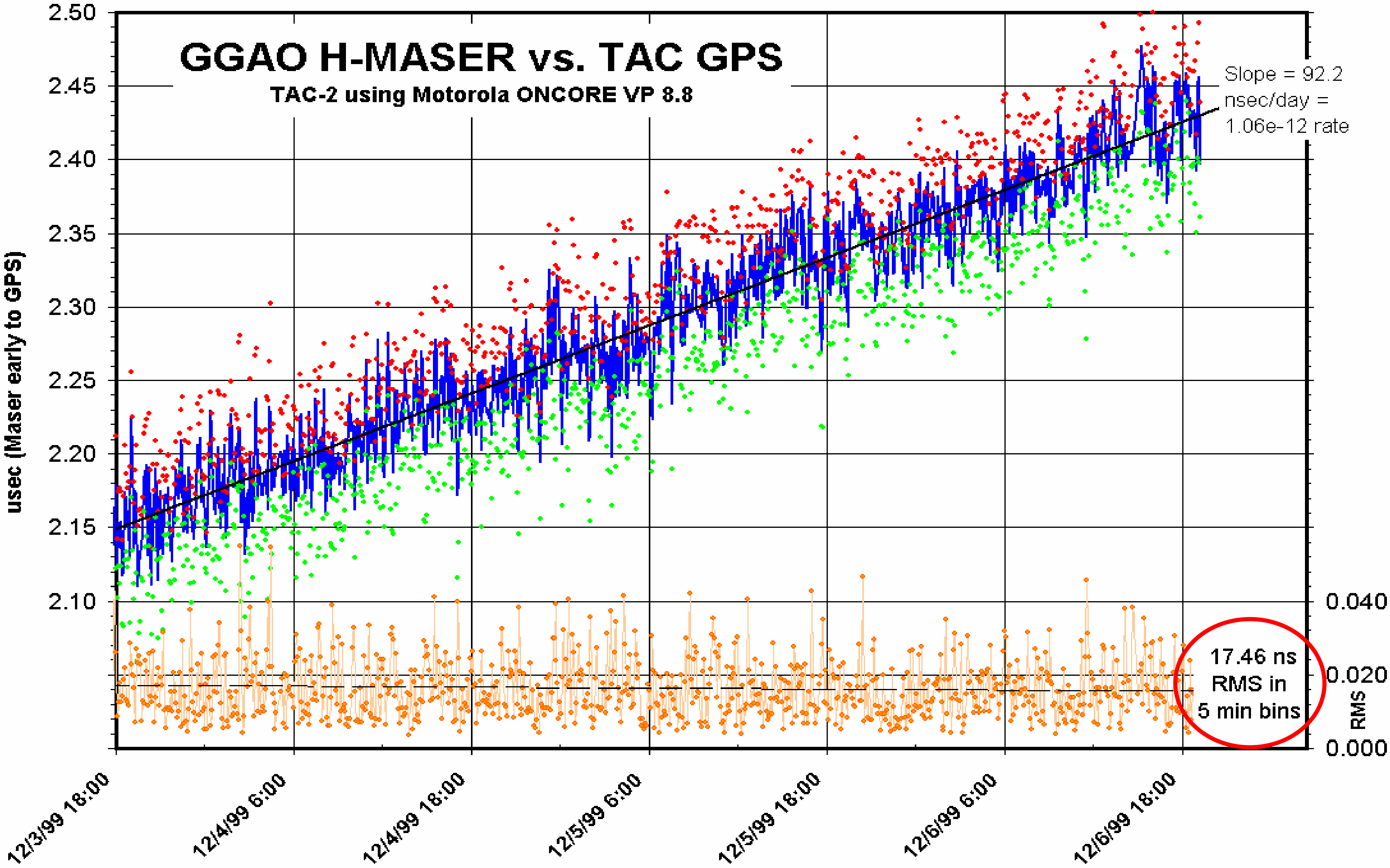
This is a 25m radio telescope near Urumqi, in China's Xinjiang Province. Low-cost, stand-alone GPS Timing Receivers are used to meet VLBI's Time/Frequency needs.

An Early Example of "Blind" GPS Timing with a 6 channel receiver



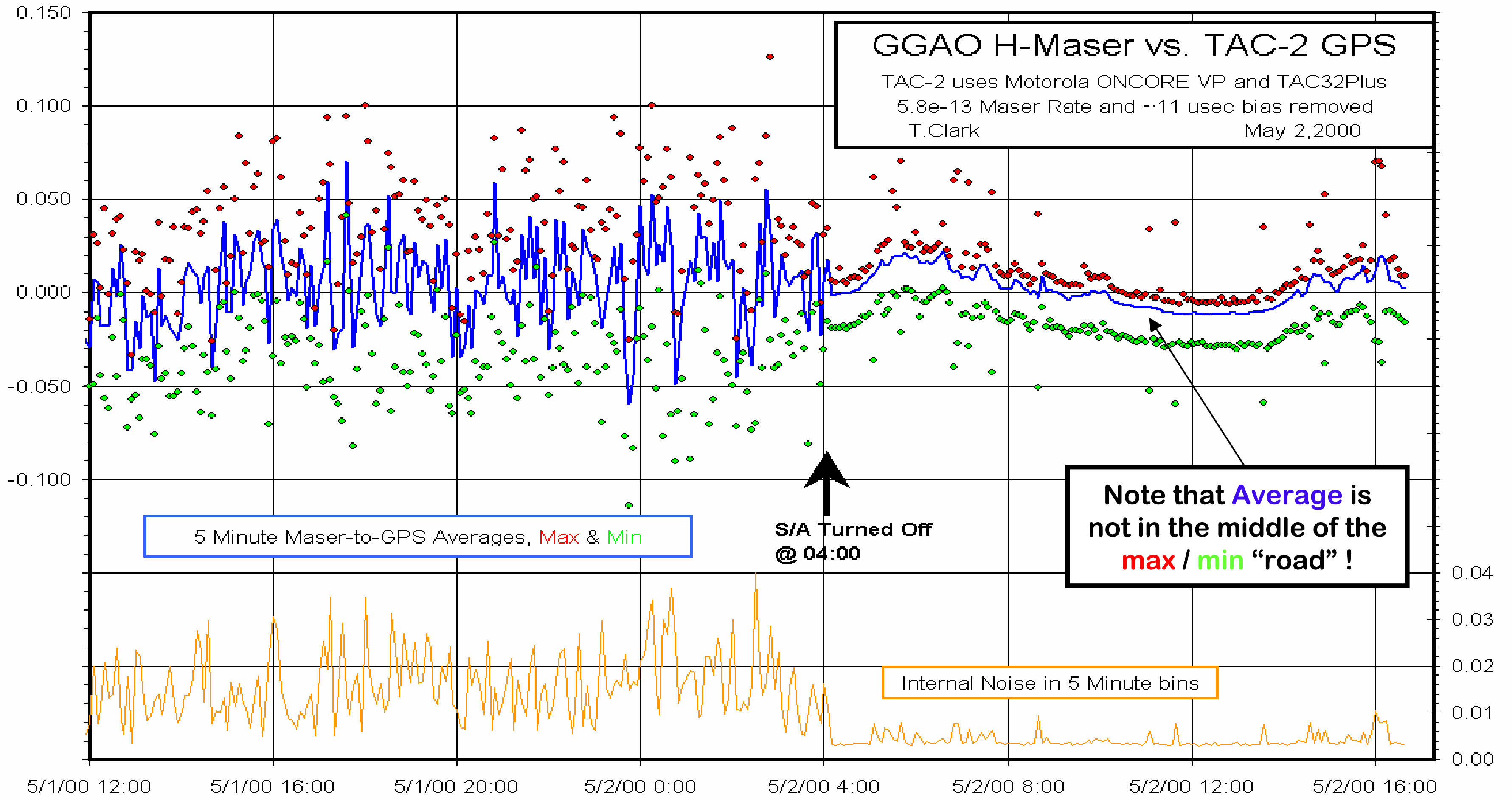
The name "TAC" stands for "Totally Accurate Clock".
The "TAC-2" Clock is basically the same as the "CNS Clock-I".
☺ The letters "TAC" are also my initials. ☺

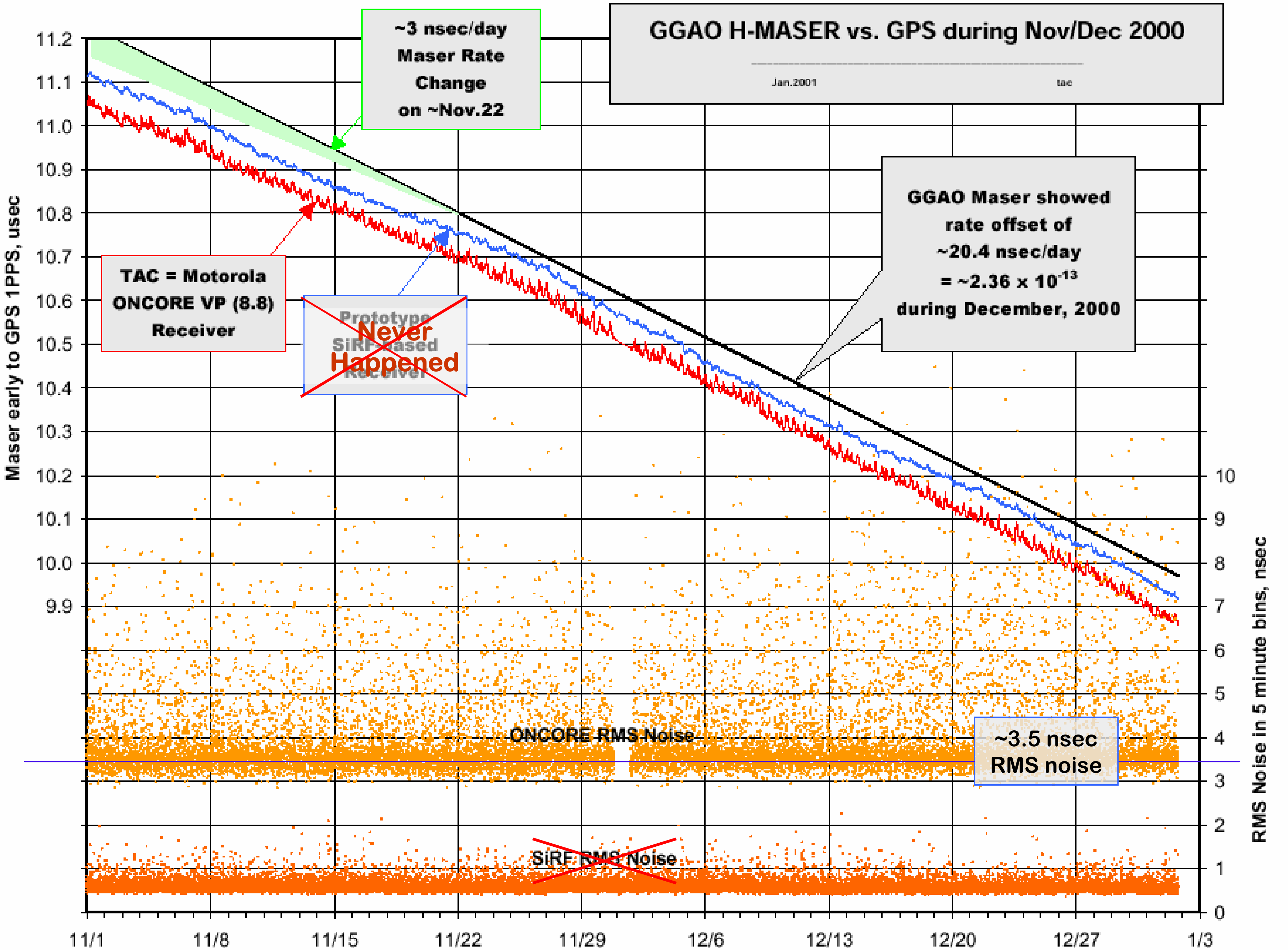
Before S/A was turned off (8-channel) . . .



What happened when S/A went away?

Using 8-channel Motorola ONCORE VP Receiver . . .





GGAO H-MASER vs. GPS during Nov/Dec 2000
Jan.2001
tae
~3 nsec/day
Maser Rate
Change
on ~Nov.22
GGAO Maser showed
rate offset of
~20.4 nsec/day
= ~2.36 x 10^-13
during December, 2000
TAC = Motorola
ONCORE VP (8.8)
Receiver
Prototype
SiRF-based
Receiver
Never
Happened
ONCORE RMS Noise
~3.5 nsec
RMS noise
SiRF RMS Noise
Maser early to GPS 1PPS, usec
RMS Noise in 5 minute bins, nsec
11.2
11.1
11.0
10.9
10.8
10.7
10.6
10.5
10.4
10.3
10.2
10.1
10.0
9.9
10
9
8
7
6
5
4
3
2
1
0
11/1
11/8
11/15
11/22
11/29
12/6
12/13
12/20
12/27
1/3

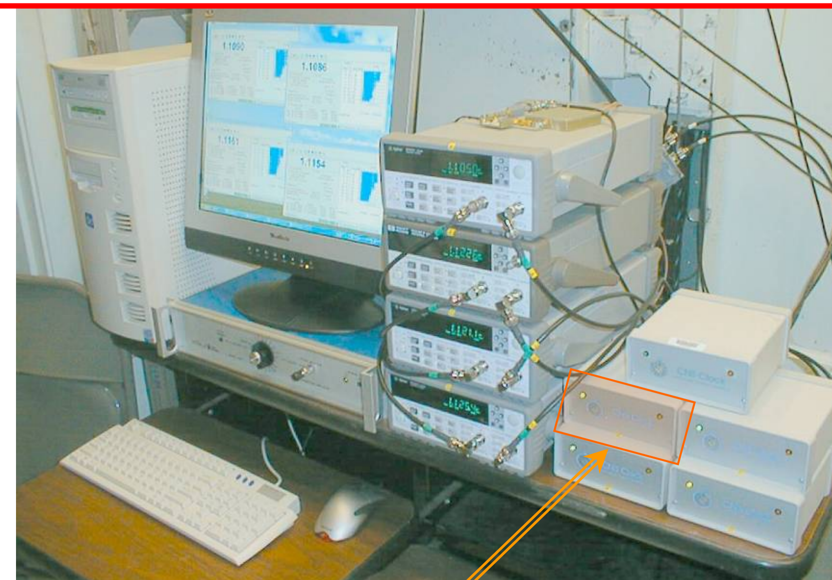
CNS Systems' Test Bed at USNO

Calibrating the "DC" Offset of M12+ receivers with 2.0 Firmware in 2002

We have observed that the ONCORE firmware evolution from 5.x ⇒ 6.x ⇒ 8.x ⇒ 10.x has been accompanied by about 40 nsec of "DC" timing offsets.

Motorola tasked Rick to make the new M12+ receiver be correct.

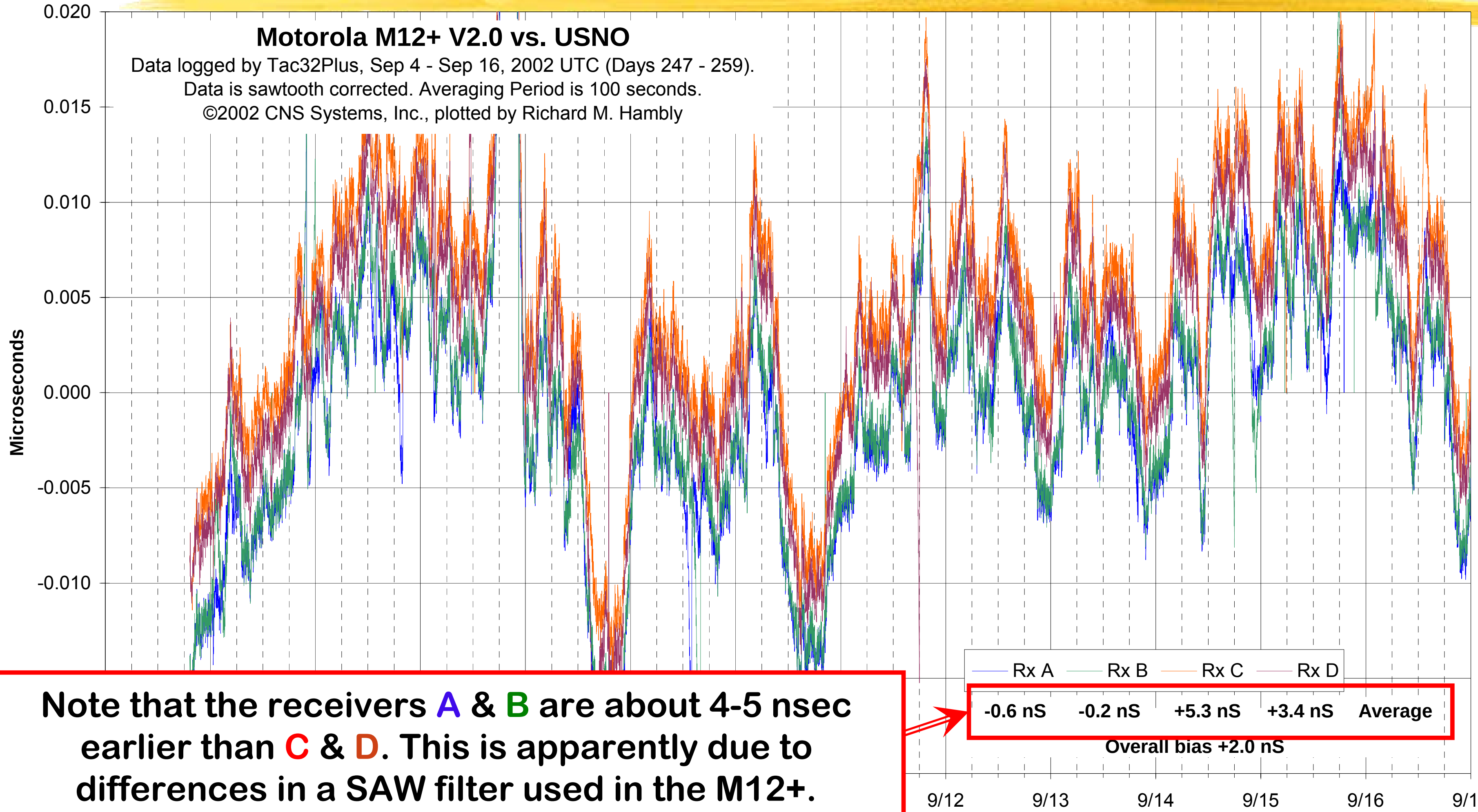
Tac32Plus software simultaneously processes data from four Time Interval Counters and four CNS Clocks, writing 12 logs continuously.



Time Interval Counters compare the 1PPS from each CNS Clock (M12+) against the USNO's UTC time tick.

This is the "Gold Standard" "A" receiver that we used for subsequent calibrations.

Comparing four M12+ Timing Receivers

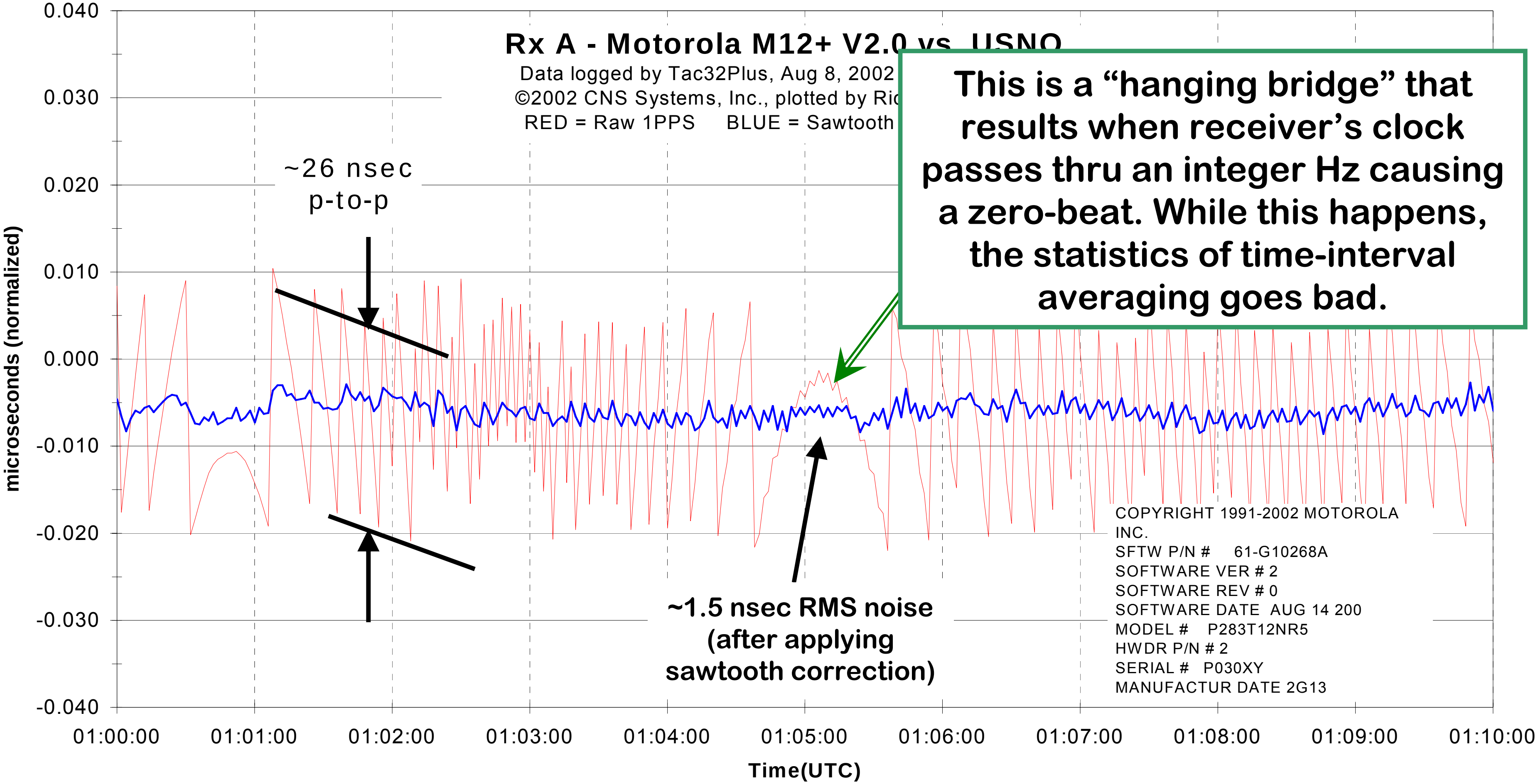


Note that the receivers A & B are about 4-5 nsec earlier than C & D. This is apparently due to differences in a SAW filter used in the M12+.

Rcvr A is now used as our "Gold" transfer standard.

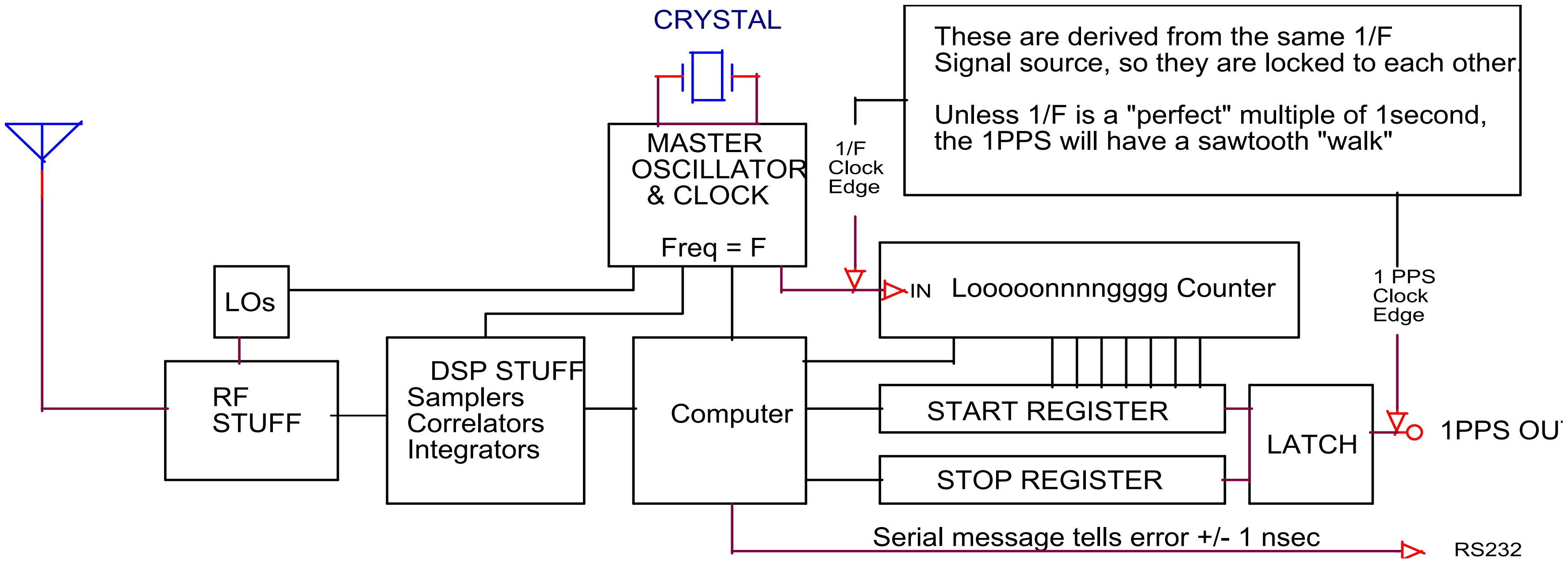
An example of 1PPS sawtooth

with the Motorola M12+ receiver



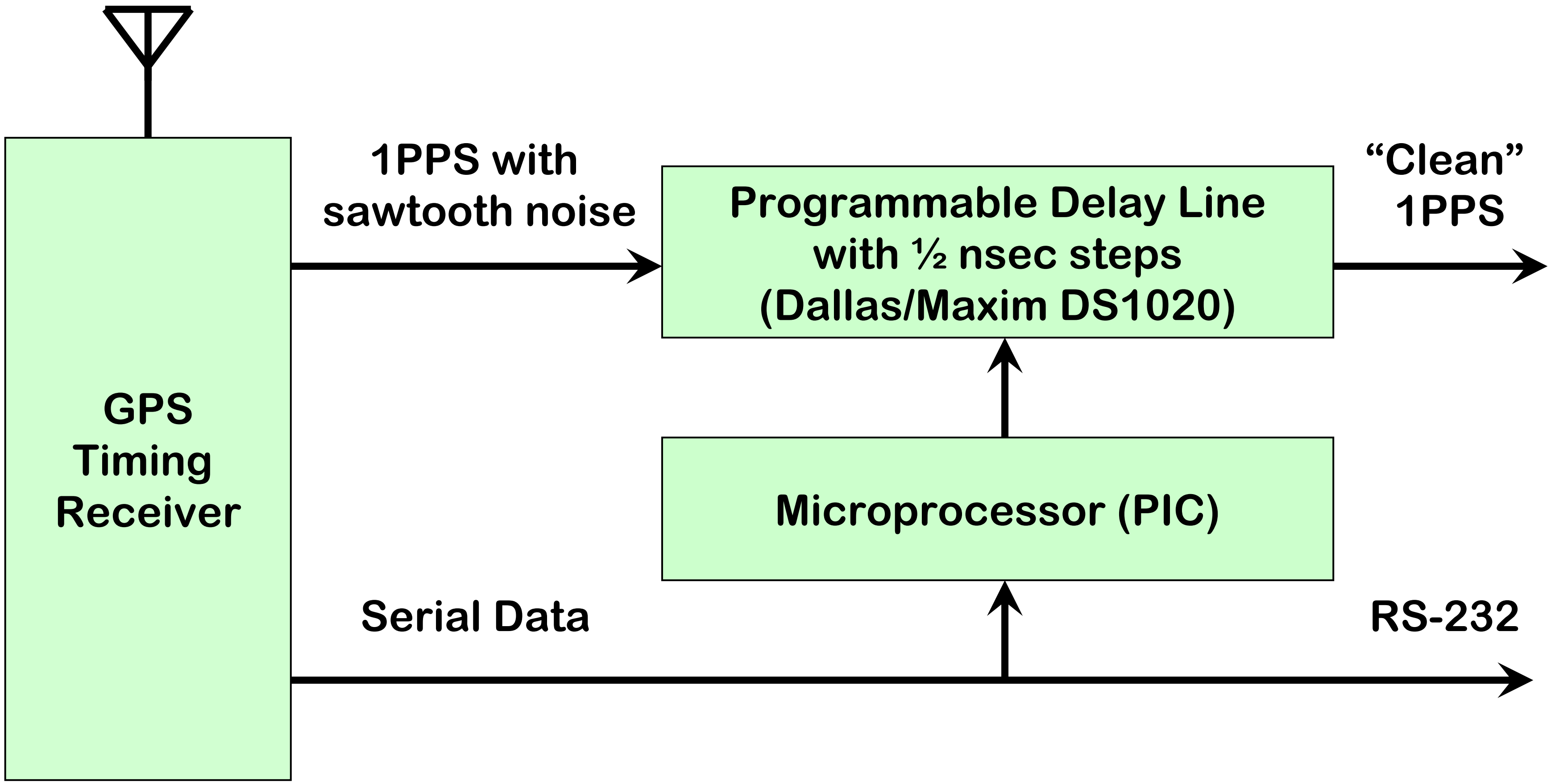
What causes the sawtooth effect ???

(in the Motorola timing receivers)



- For the older Oncore, F=9.54 MHz, so the 1/F sawtooth has a range of +/- 52 nsec (104 nsec peak-to-peak)
- The new Oncore M12+ has F $\approx$ 40 MHz, so the sawtooth has been reduced to +/- 13 nsec (26 nsec peak-to-peak).

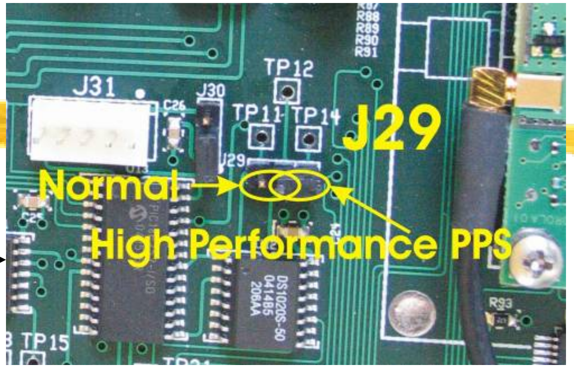
How could the sawtooth noise be eliminated ???



The Future is here now!
The CNS Clock II

1994 - 2004

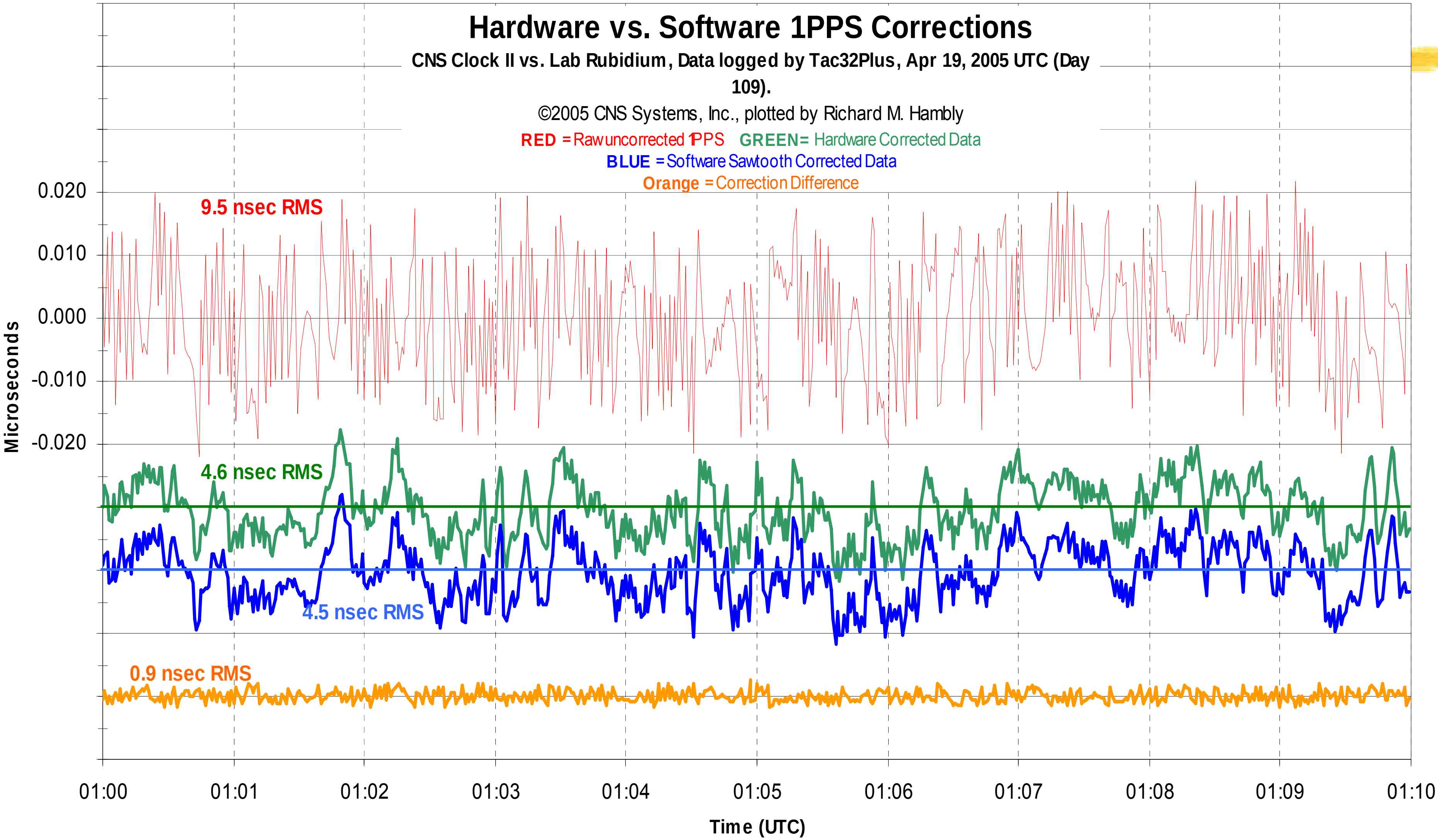
1PPS Sawtooth
Correction
Option



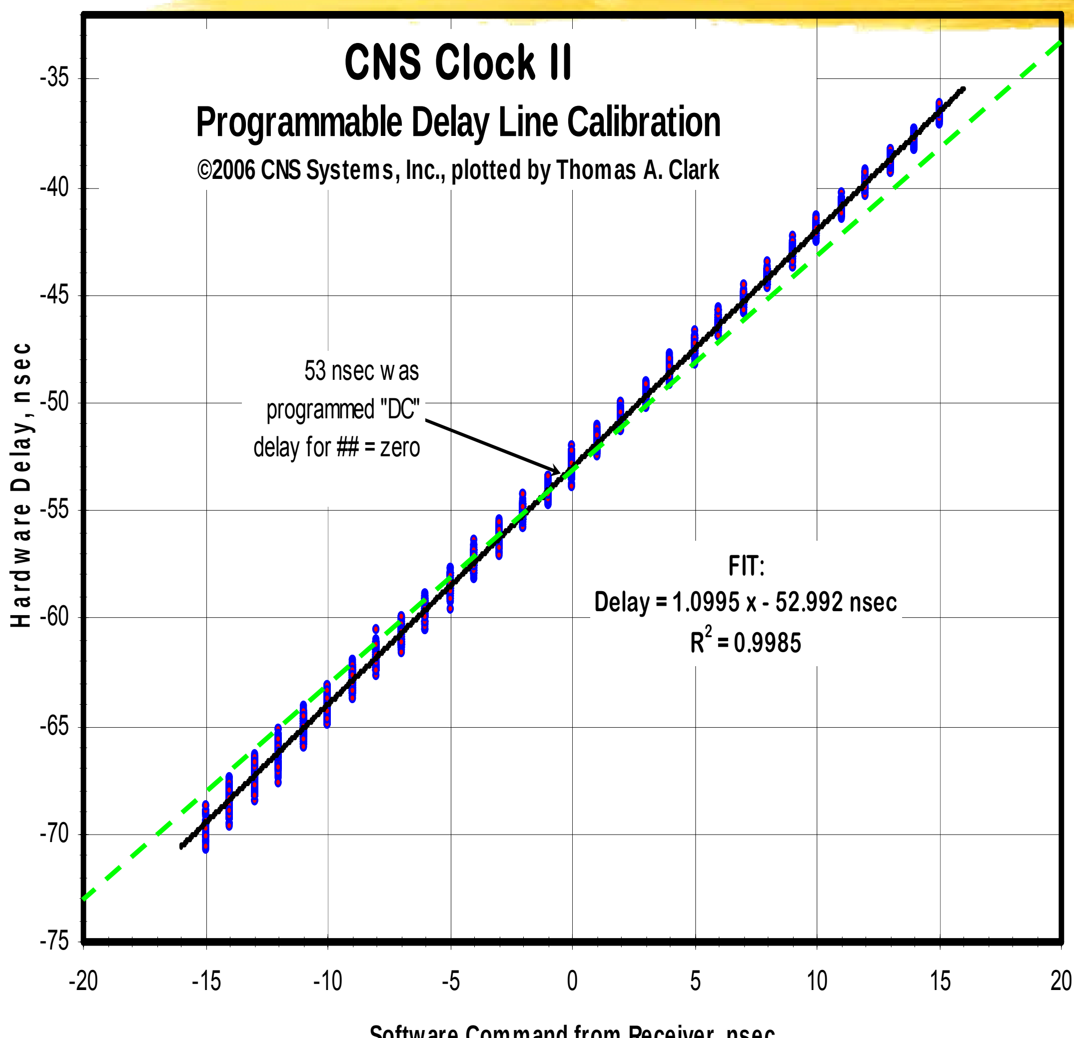
Available January 2005

- RS-232 & USB 2.0 Control Ports
- NTP Time Server for LAN
- TNC(F) Antenna Connector
- Buffered 1 PPS output
- Two buffered 1/100 PPS outputs
- 10 MHz (GPS disciplined) output
- 2 Bidirectional RS-485 ports
- Bipolar (AC/DC) solid state relay
- Power = 9-30 volts @ 500ma
- Options:
  Sequencer output.
  IRIG-B output (modulated,
  PWM or Manchester).

Hardware vs. Software 1PPS Sawtooth Corrections



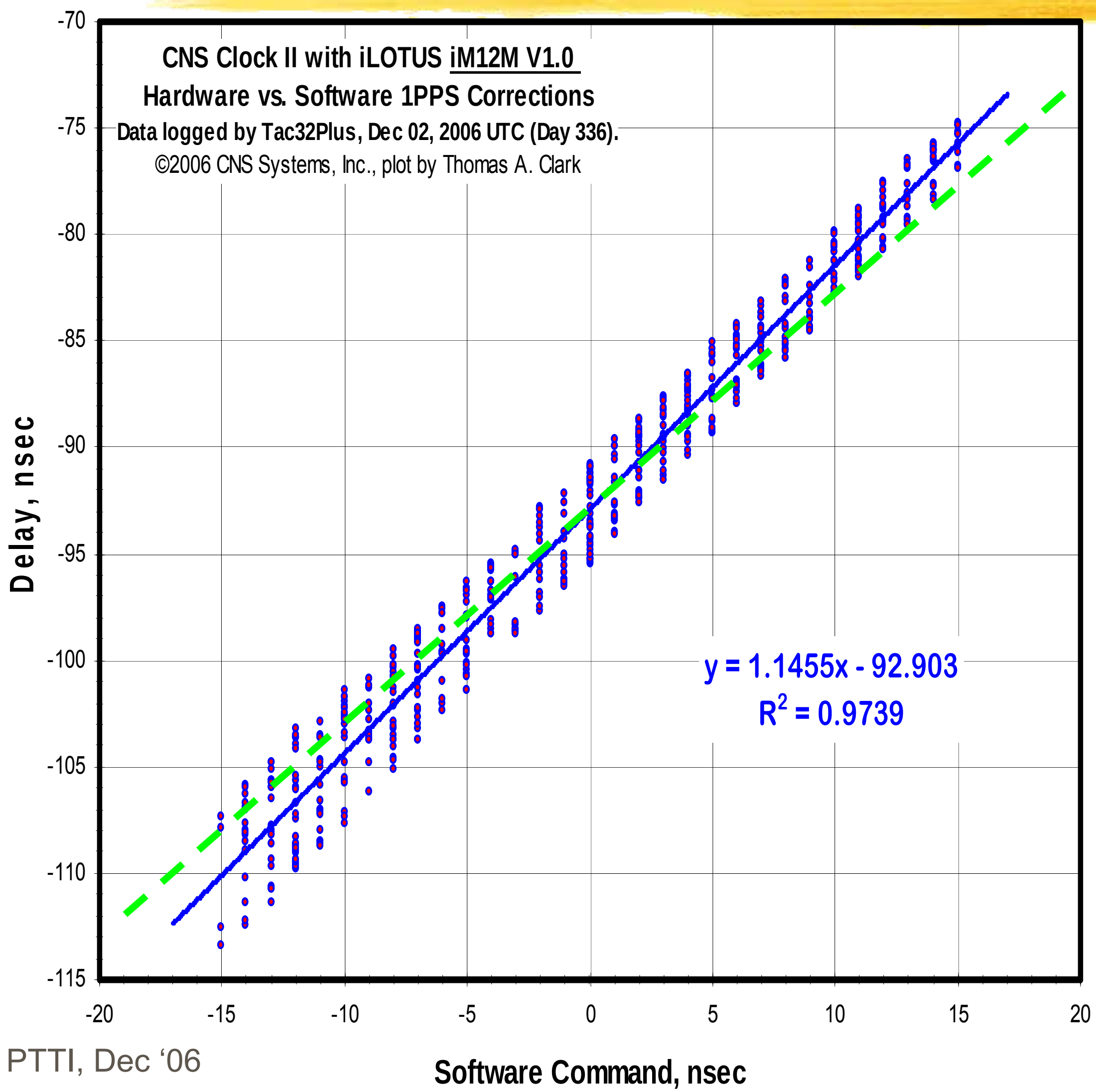
How Effective is the Programmable Delay Line ?



THIS SAMPLE (April 2005):

- Delay Line reproduces the intentional 53 nsec "DC" offset
- Delay Line over-corrects by about 10%
- Delay Line adds ~ 1 nsec of noise
- The 10% Scale Error could be corrected in firmware.
- Statistical problems that affect GPSDO (GPS Disciplined Oscillator) due to "Hanging Bridges" are removed

How Effective is the Programmable Delay Line (Second Sample) ?



THIS SAMPLE (Nov. 2006):

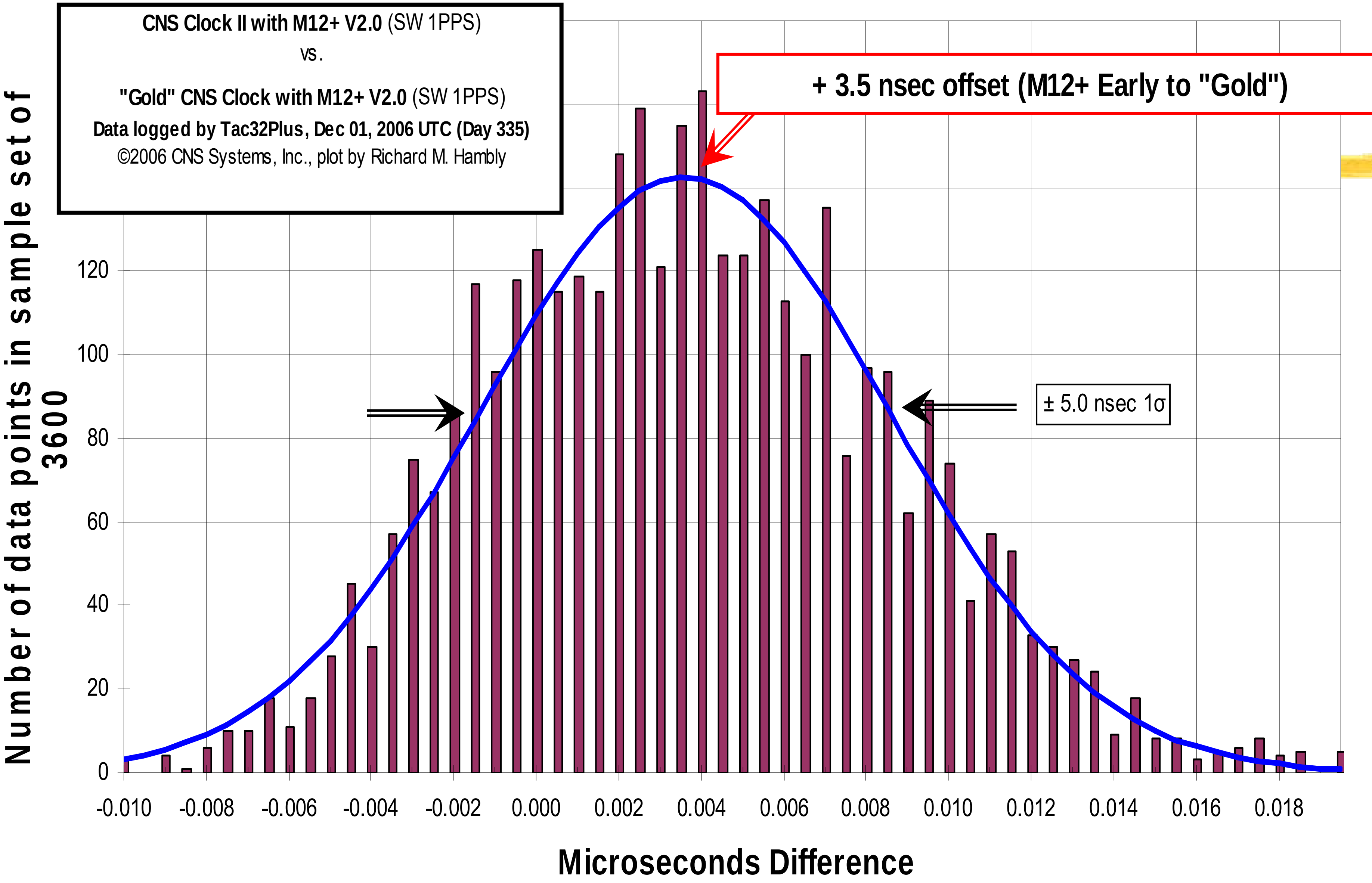
- Delay Line reproduces the intentional 93 nsec "DC" offset
- Delay Line over-corrects by about 14½%
- Delay Line adds ~ 3 nsec of noise (which is larger for the negative corrections)
- The 14½% Scale Error could be corrected in firmware.
- Statistical problems that affect GPSDO (GPS Disciplined Oscillator) due to "Hanging Bridges" are removed

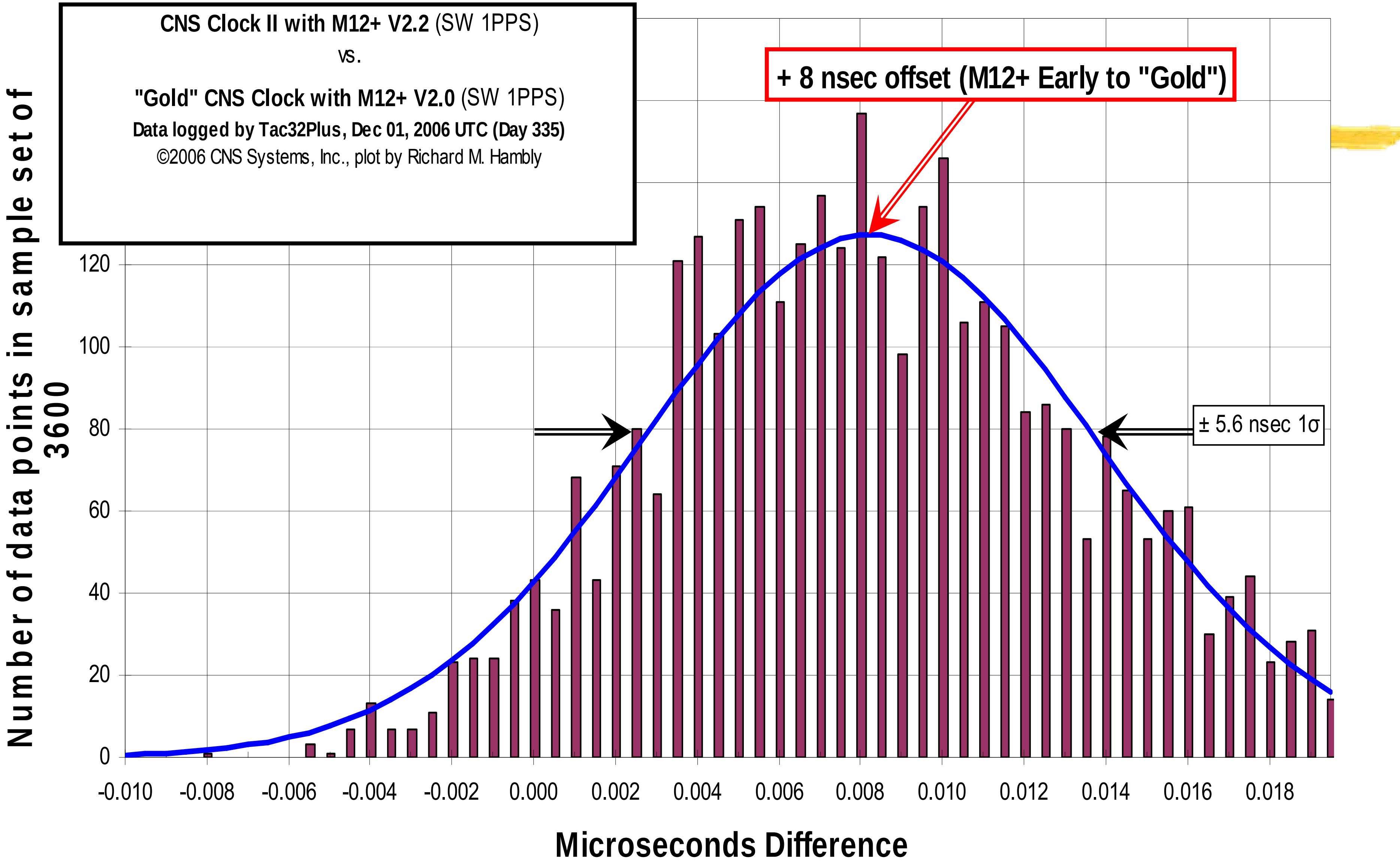
Delay Line – Work to be done

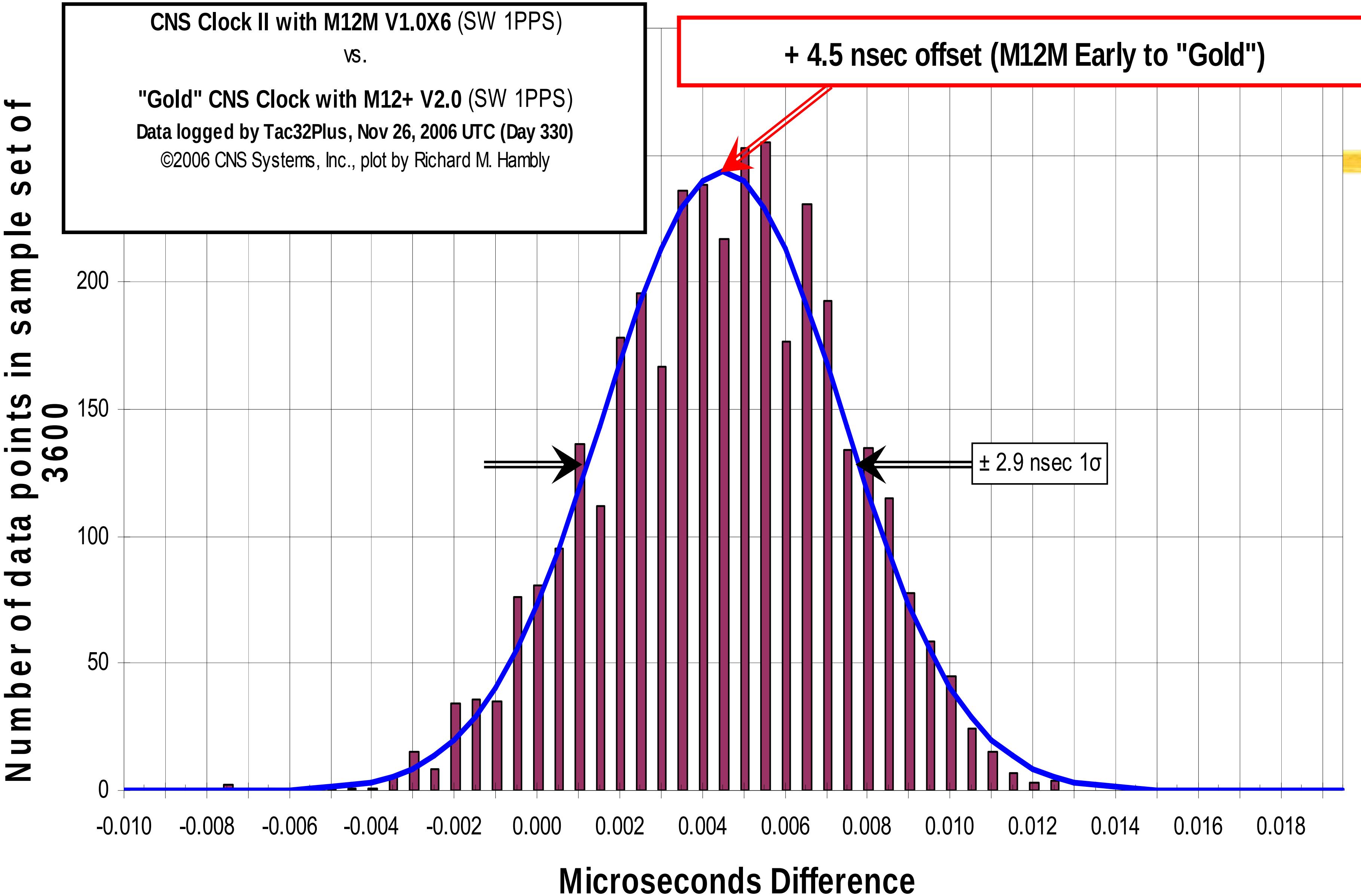
- Figure out why some DS1020 samples seem to have more noise than others.
- Investigate possible delay line temperature sensitivity.
- Develop firmware calibration procedure to minimize scale biases for customers needing higher accuracy.

Calibrating the new M12 Receivers

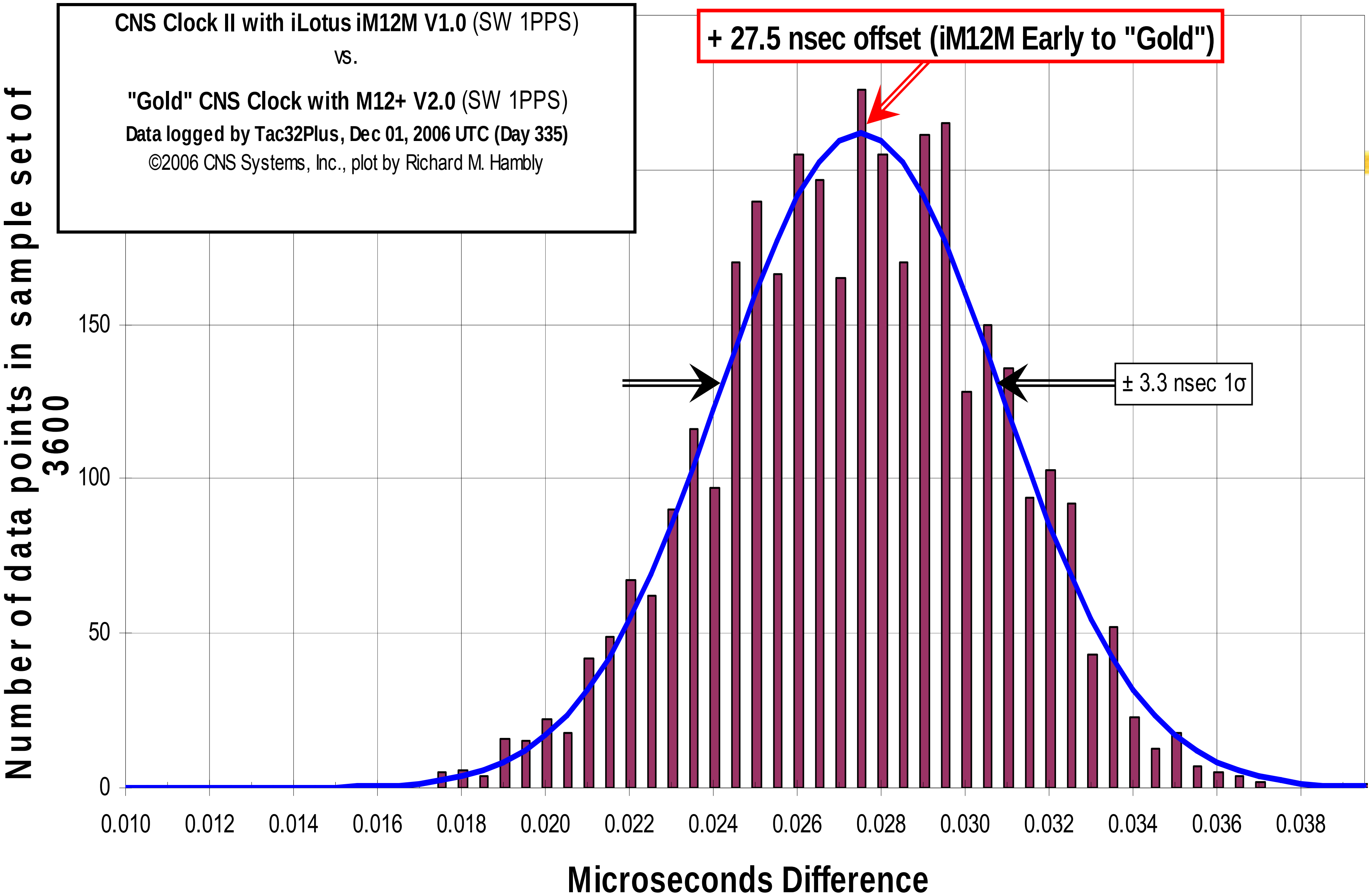
- **This work is based on the 2002 calibrations reported in the PTTI paper:**
  "Critical Evaluation of the Motorola M12+ GPS Timing Receiver vs. the Master Clock at the United States Naval Observatory" **available at http://www.gpstime.com**
- **One of the four Motorola M12+ receivers (firmware v2.0) that was tested at USNO has been retained as our "Gold Standard"**
- **New receivers tested:**
  - **Motorola M12+ with v2.0 firmware**
  - **Motorola M12+ with v2.2 firmware**
  - **Motorola M12M (with new RFIC)**
  - **iLotus M12M (Motorola transferred production offshore)**


CNS Clock II with M12+ V2.0 (SW 1PPS)
vs.
"Gold" CNS Clock with M12+ V2.0 (SW 1PPS)
Data logged by Tac32Plus, Dec 01, 2006 UTC (Day 335)
©2006 CNS Systems, Inc., plot by Richard M. Hambly
+ 3.5 nsec offset (M12+ Early to "Gold")
± 5.0 nsec 1σ
Number of data points in sample set of 3600
0
20
40
60
80
100
120
-0.010
-0.008
-0.006
-0.004
-0.002
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
0.016
0.018
Microseconds Difference


CNS Clock II with M12+ V2.2 (SW 1PPS)
vs.
"Gold" CNS Clock with M12+ V2.0 (SW 1PPS)
Data logged by Tac32Plus, Dec 01, 2006 UTC (Day 335)
©2006 CNS Systems, Inc., plot by Richard M. Hambly
+ 8 nsec offset (M12+ Early to "Gold")
± 5.6 nsec 1σ
Number of data points in sample set of 3600
0
20
40
60
80
100
120
-0.010
-0.008
-0.006
-0.004
-0.002
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
0.016
0.018
Microseconds Difference



CNS Clock II with M12M V1.0X6 (SW 1PPS)
vs.
"Gold" CNS Clock with M12+ V2.0 (SW 1PPS)
Data logged by Tac32Plus, Nov 26, 2006 UTC (Day 330)
©2006 CNS Systems, Inc., plot by Richard M. Hambly
+ 4.5 nsec offset (M12M Early to "Gold")
± 2.9 nsec 1σ
Number of data points in sample set of 3600
0
50
100
150
200
-0.010
-0.008
-0.006
-0.004
-0.002
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
0.016
0.018
Microseconds Difference



CNS Clock II with iLotus iM12M V1.0 (SW 1PPS)
vs.
"Gold" CNS Clock with M12+ V2.0 (SW 1PPS)
Data logged by Tac32Plus, Dec 01, 2006 UTC (Day 335)
©2006 CNS Systems, Inc., plot by Richard M. Hambly
+ 27.5 nsec offset (iM12M Early to "Gold")
± 3.3 nsec 1σ
Number of data points in sample set of 3600
0
50
100
150
0.010
0.012
0.014
0.016
0.018
0.020
0.022
0.024
0.026
0.028
0.030
0.032
0.034
0.036
0.038
Microseconds Difference

M12 Receiver Calibration Results

- All the varieties of M12+/M12M receiver show similar performance.
- All the Motorola samples (including the 4 receivers in the 2002 test) agree with UTC(USNO) to better than ±10 nsec.
- One sample of the new “offshore” iLotus M12M receiver shows a bias ~30 nsec.
  - It is not clear if this is a hardware or firmware bias.

Where to get information?

These Slides and related material:

http://gpstime.com

Information on the CNS Clock and the CNS Clock II:

http://www.cnssys.com

For ONCORE/TAC-2 receiver used as a LINUX xntp server: http://gpstime.com

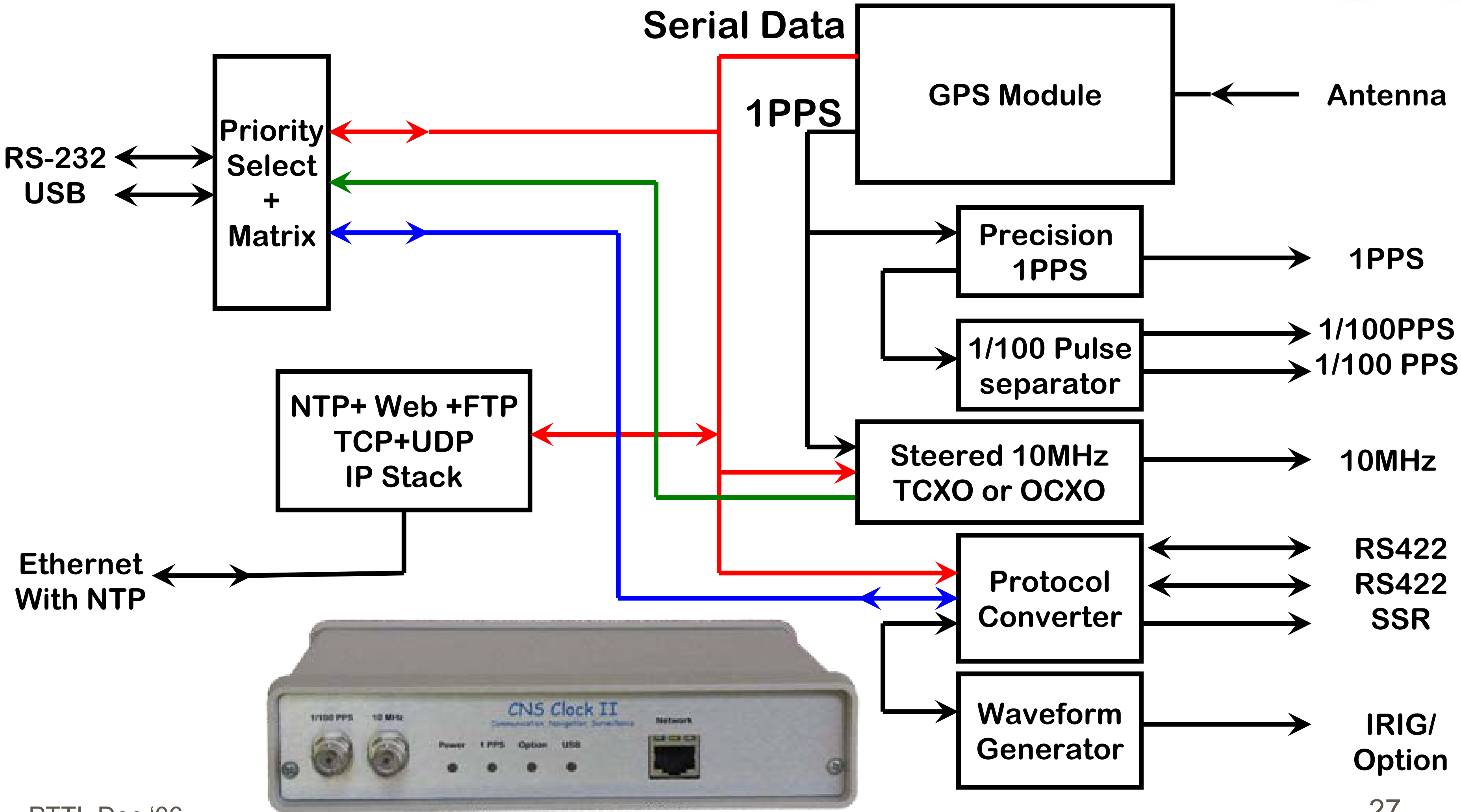
To contact Tom: mailto:K3IO@verizon.net

To contact Rick: mailto:RICK@cnssys.com

Backup Slides

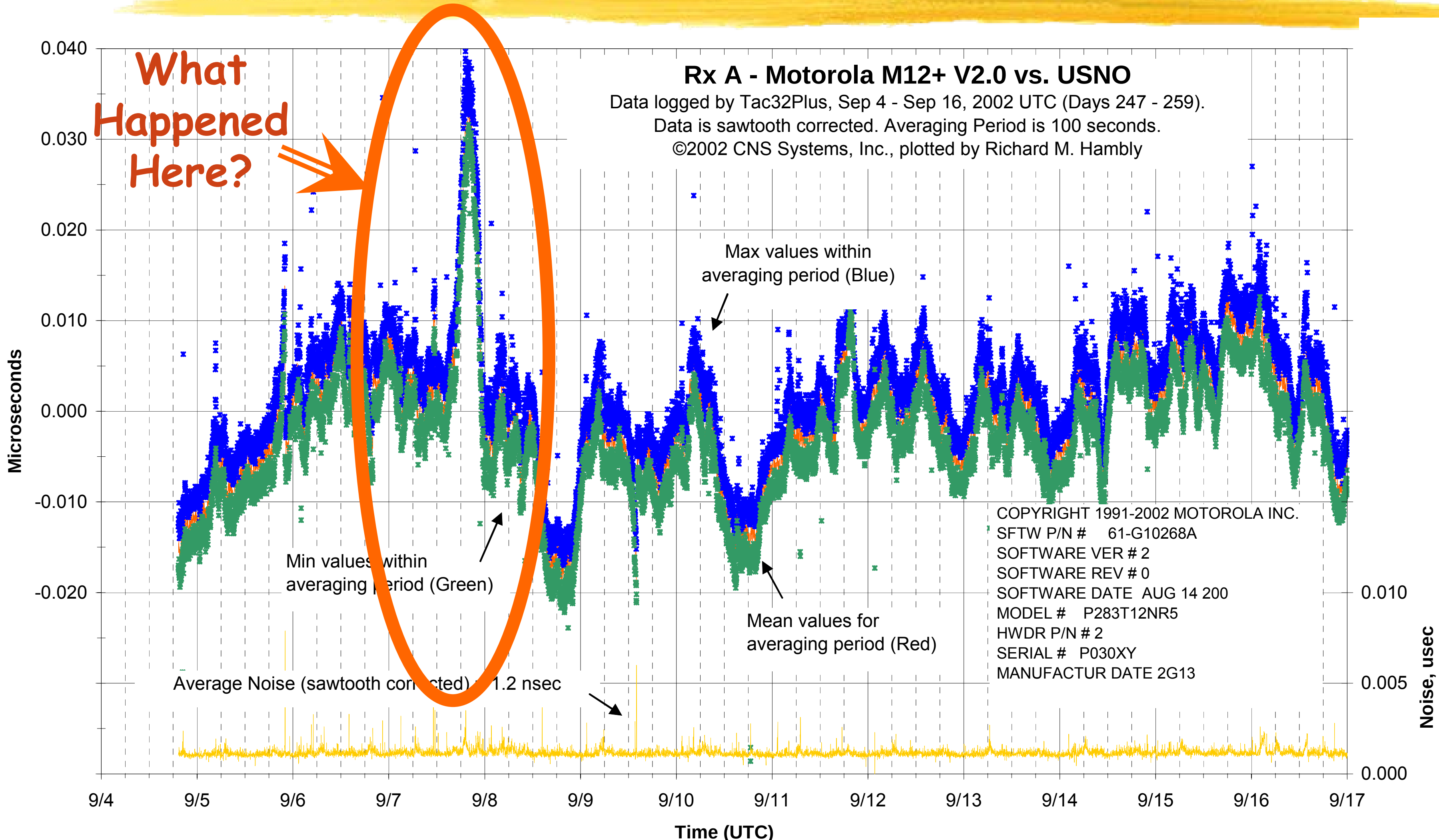
- Not shown in presentation

CNS Clock II Block Diagram



Individual M12 Clock Performance

Receiver (A) average "DC" offset = -0.6 ns



What Happened on 9/7/02 ?

September 7, 2002.

This picture is a two hour composite of 85 different photos spanning 21:07 thru 23:10 EDT on Sept. 7th (01:07 thru 03:10 UTC Sep. 8).

September 8, 2002.

This picture is a four hour composite of 140 different photos spanning 20:00 thru 24:00 EDT on Sept. 8th (00:00 thru 04:00 UTC Sep. 9).

Each picture was an 87 second exposure with 3 seconds between frames. The trails on the picture are all due to airplanes. The bright loop is from a plane on final approach into BWI airport. Camera = Canon D60 shooting Hi Resolution JPEG at ISO 100 with TC-80 timer. Lens = Sigma f/2.8 20-40 mm set to 20 mm @ f/4.5

Short Baseline Test (USNO to NASA GGAO)

Comparing two new Motorola M12+ GPS Timing Receivers over the 21.5 km baseline between the US Naval Observatory (USNO) and the NASA Goddard Geophysical & Astronomical Observatory (GGAO).

Both data sets compare the GPS timing receiver to a local Hydrogen Maser clock.
On both, a linear fit to remove constant clock offset and drift has been applied.