It’s About Time !!!!!

Timing for VLBI

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- and -

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MIT Haystack Observatory
May 9–12, 2011

The difference between Frequency and Time

Oscillators and Clocks

Oscillator

- Escapement Wheels & Pendulums
- Crystal Oscillators
- Cavity Oscillators
- Oscillator Locked to Atomic Transition
  - Rubidium (6.8 GHz)
  - Cesium (9.1 GHz)
  - Hydrogen Maser (1.4 GHz)

Events that occur with a defined

FREQUENCY

nsec -- minutes

Integrator and Display = Clock

- Gears
- Electronic Counters
- Real Clocks

Long-Term

TIMING

seconds - years

What “Clock” Performance Does VLBI Need?

1

- 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:
  - $\approx [10°/(360° * 10^{10}\text{Hz} * 10^{3}\text{sec})]$
  - $\approx 2.8 * 10^{-15}$ @ 1000 sec.

What "Clock" Performance Does VLBI Need?

2

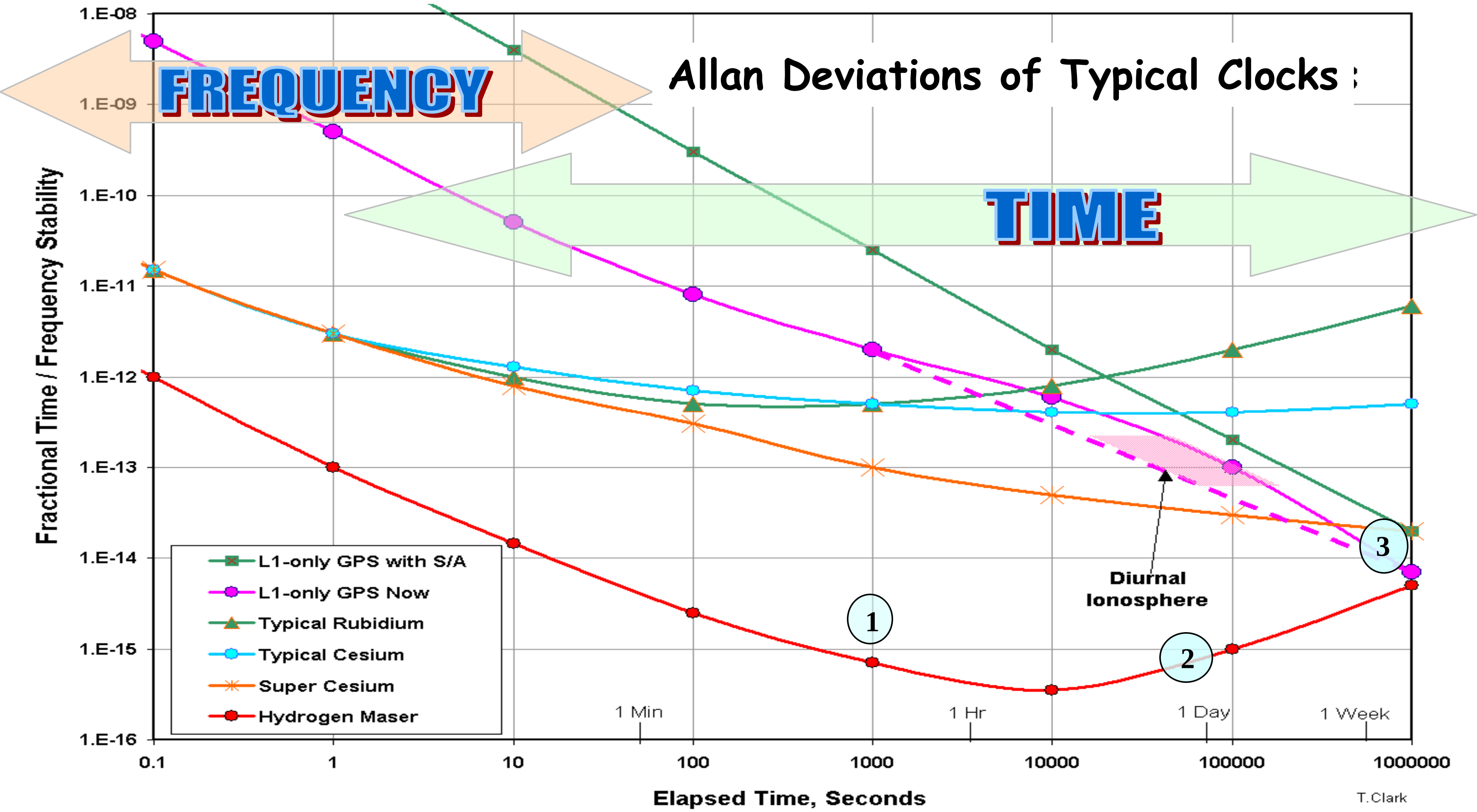
- In Geodetic applications, the station clocks are modeled at relative levels ~30 psec over a day:
  - $\approx [30 \cdot 10^{-12} / 86400 \text{ sec}]$
  - $\approx 3.5 \cdot 10^{-16}$ @ 1 day

What "Clock" Performance Does VLBI Need?

3

- 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:
  - ≈ [50 * 10^{-9} / 10^{6} sec]
  - ≈ 5 * 10^{-14} @ 10^{6} sec
- Since VLBI now defines UT1, VLBI needs to control [$UTC_{(USNO)}$ - $UTC_{(VLBI)}$] with an ***ACCURACY*** (traceable to USNO)
  - ≈ 100 nsec - 1 μsec
- To detect problems, VLBI should monitor the long-term behavior of the Hydrogen Masers (at least) every hour with ***PRECISION***
  - ≈10-50 nsec

Allan Deviation –
A graphical look at clock performance



Why do we need to worry about "Absolute Time" (i.e. Clock ***Accuracy***) in VLBI?

•The ***ONLY*** real reason for worrying about "absolute time" is to relate the position of the earth to the position of the stars:

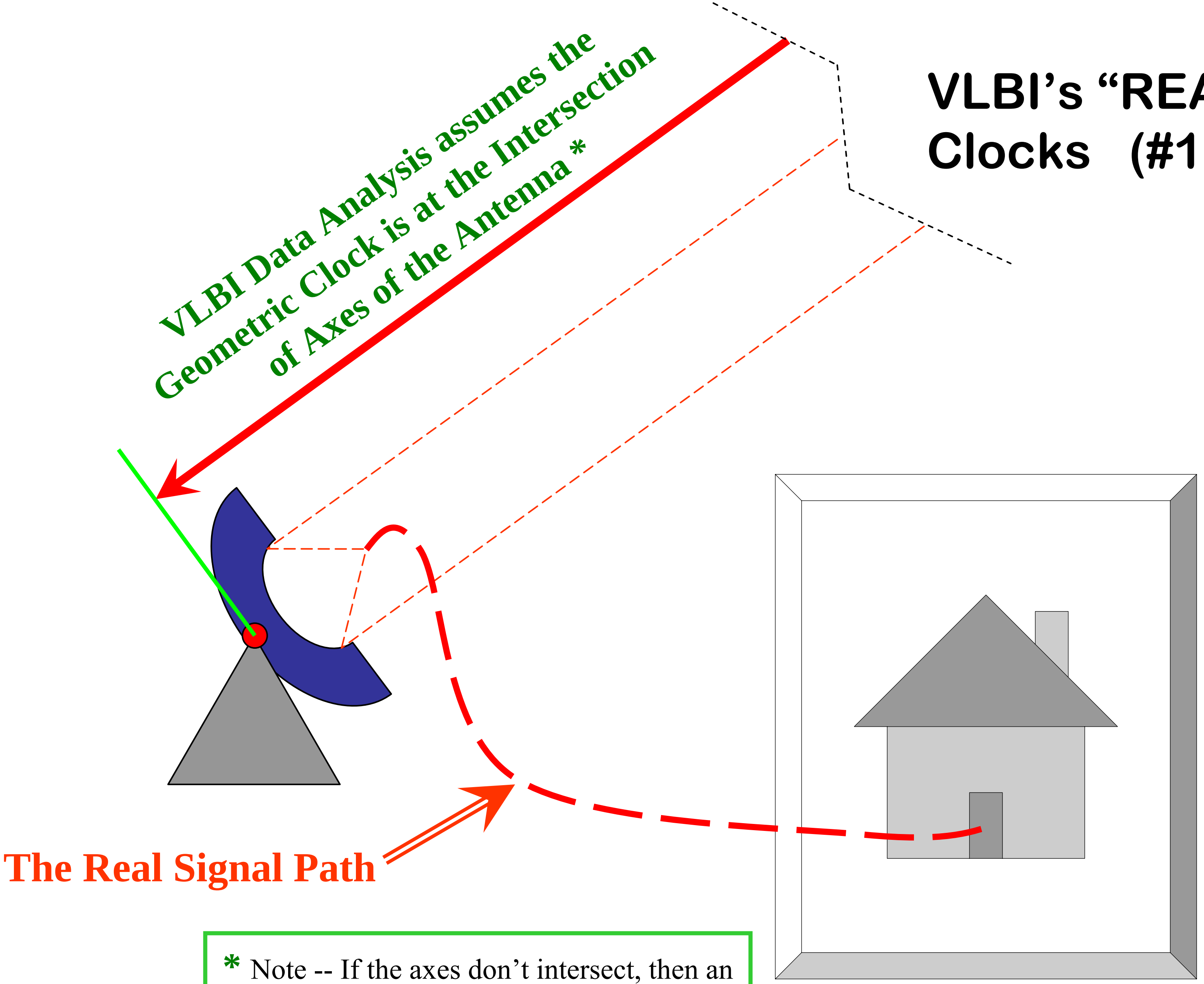
- Generating Sidereal Time to point antennas.
- Measuring UT1 (i.e. "Sundial Time") to see changes due to redistribution of mass in/on the earth over long periods of time (a.k.a. "The Reference Frame")
- Knowing the position of the earth with respect to the moon, planets and satellites.
- Making the correlation and Data Analysis jobs easier

Why do we need to worry about "Absolute Time" (i.e. Clock *Accuracy*) in VLBI?

At the stations this means that we will need to pay more attention to timing elements like

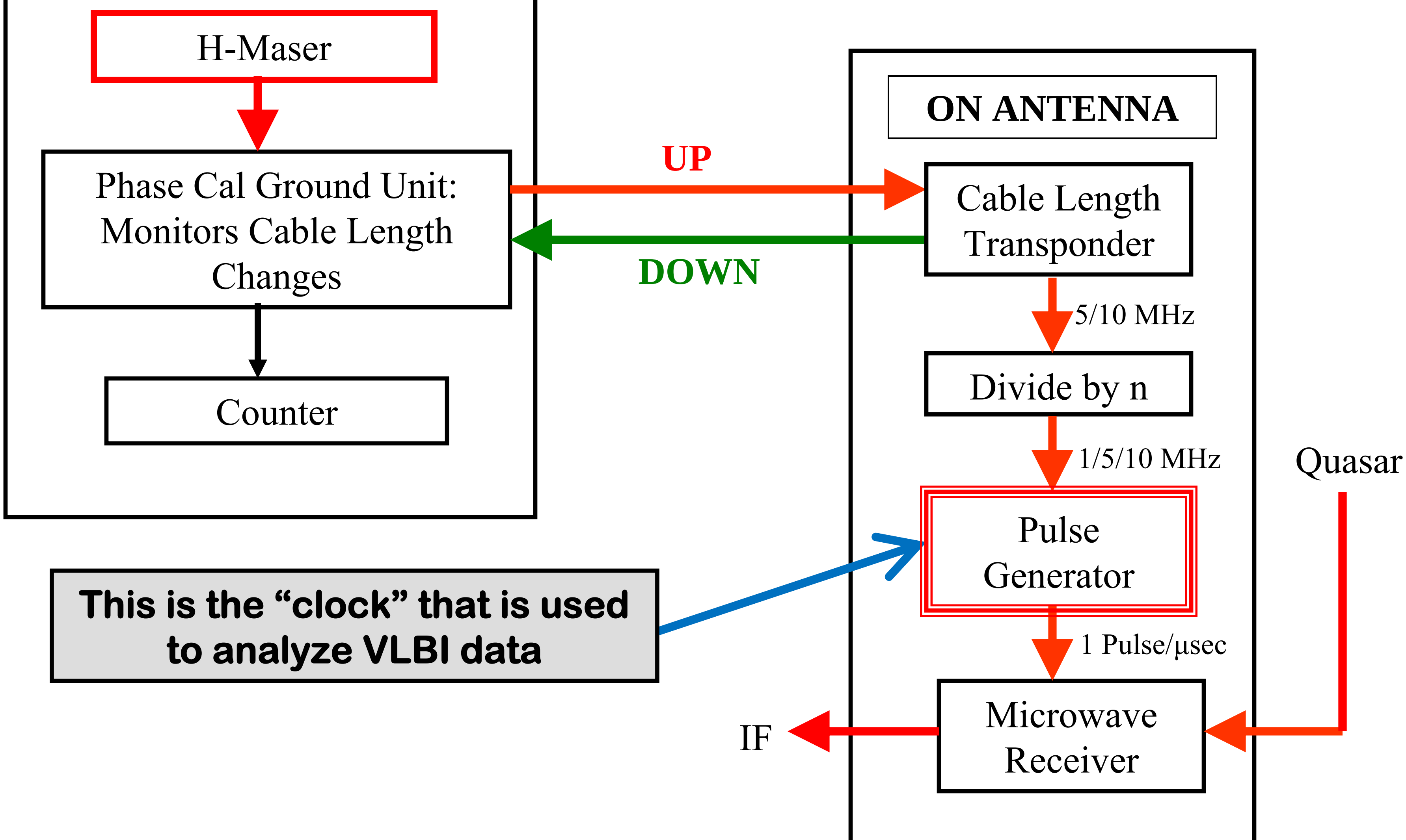
- Frequency Standard and Station Timing
- The lengths of all signal & clock cables
- The geometry of the feed/receiver to the antenna.
- Calibration of instrumental delays inside the receiver and backend. The development of new instrumentation is needed.
- The care with which system changes are reported to the correlators and the data analysts.

VLBI's "REAL" Clocks (#1)

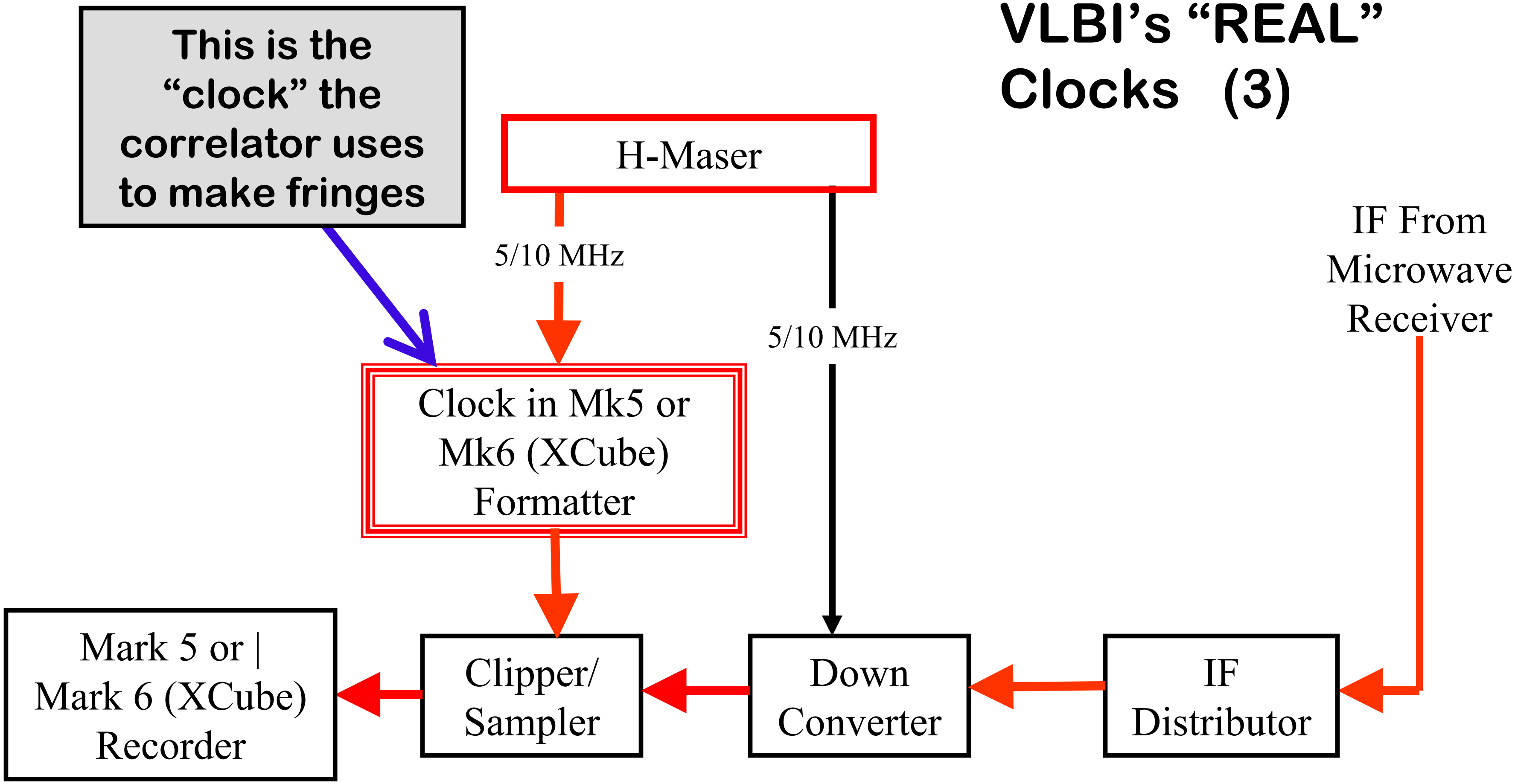


* Note -- If the axes don't intersect, then an "offset axis" model of the antenna is used

VLBI's "REAL" Clocks (#2)



VLBI's "REAL" Clocks (3)

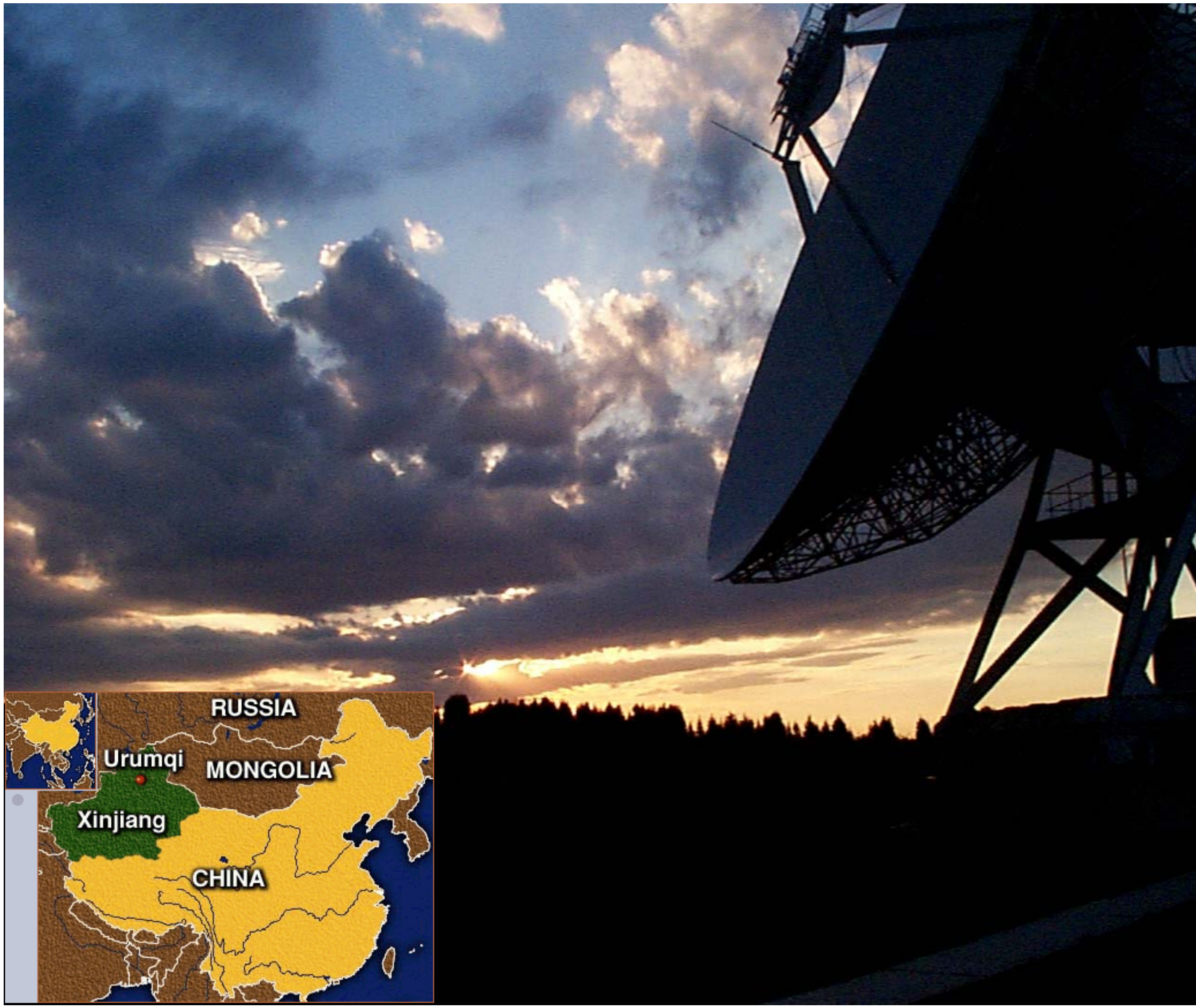


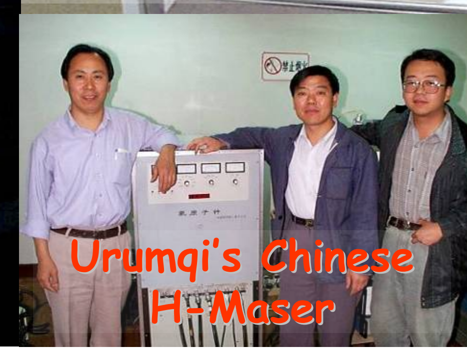
Setting VLBI Clock Time & Rate with GPS
-- 3 possible ways--

- **Compare two distant clocks by observing the same GPS satellite(s) at the same time** (also called **Common View**)
  - Requires some intervisibility between sites
  - Requires some near-Real-Time communication
  - Links you directly to the "Master Clock" on the other end at ~1 nsec level
- **Use Geodetic GPS receivers** (i.e. as an extension of the IGS network)
  - Requires high quality (probably dual frequency) receiver (TurboRogue, Z12, etc), but it's hard to gain access to the internal clock.
  - Requires transferring ~1 Mbyte/day of data from site
  - Requires fairly extensive computations using dual-frequency data to get ~300 psec results with ionosphere corrections
  - Allows Geodetic community to use VLBI Site (and H-Maser) for geodesy
  - Difficult to obtain "Real Time" clock pulses!

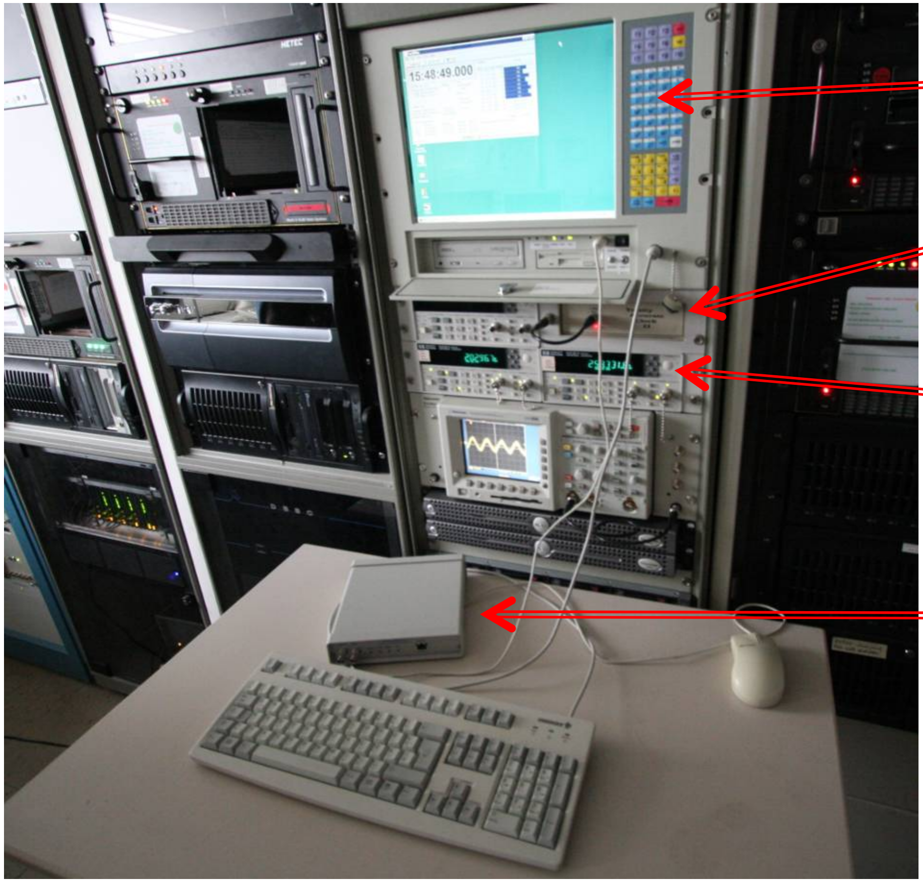
- **Blindly use the Broadcast GPS Timing Signals as a clock**
  - Yields "Real Time" ~10-30 nsec results with ~ $1000 hardware
  - Single Frequency L1 only (for now) causes ionospheric error

Timing at an Isolated, Remote VLBI Site -- Urumqi in Xinjiang Province, China





Old and New Timing Systems at Wettzell (2009)



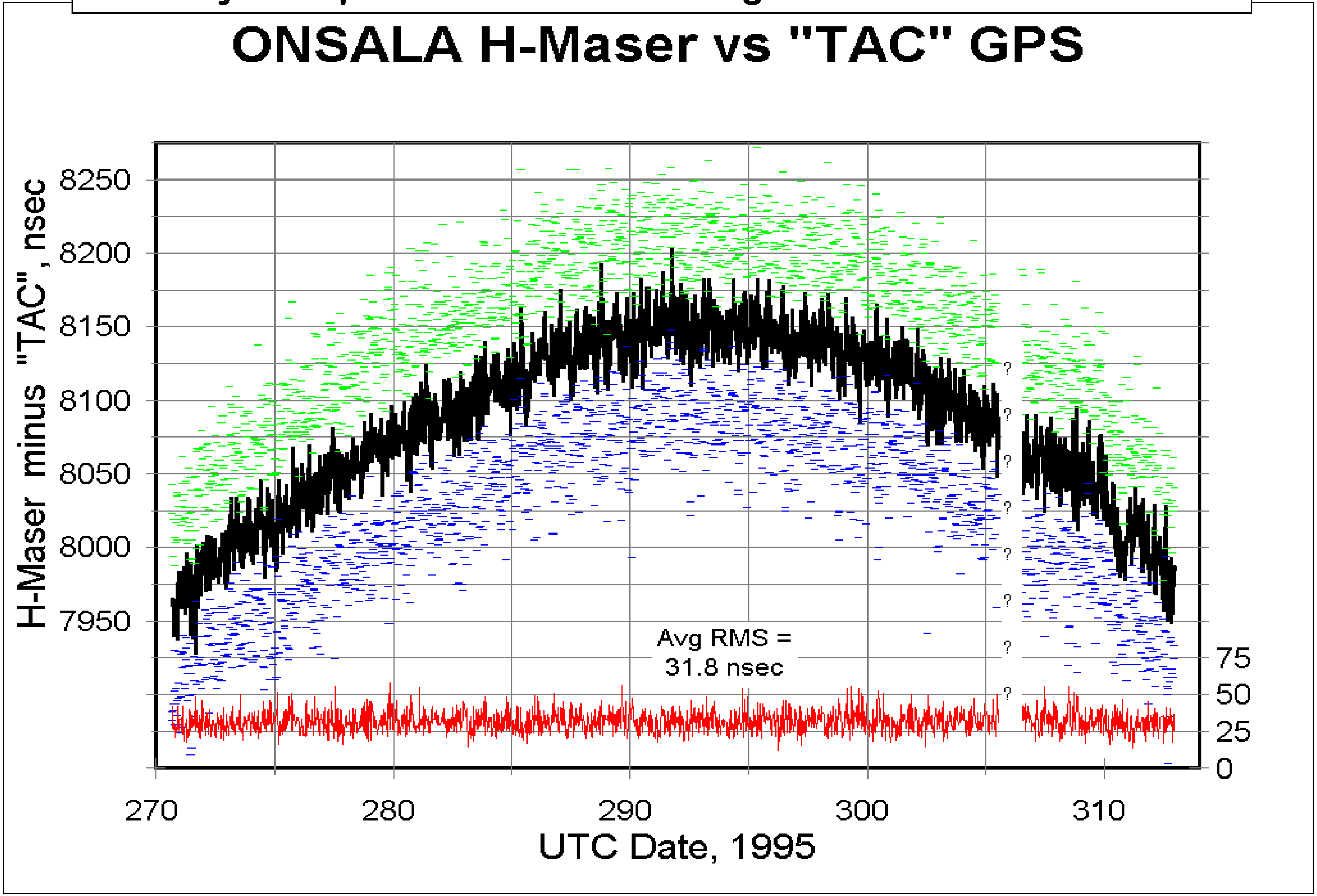
Rick's Tac32Plus Software

Tom's old 8 channel "TAC"

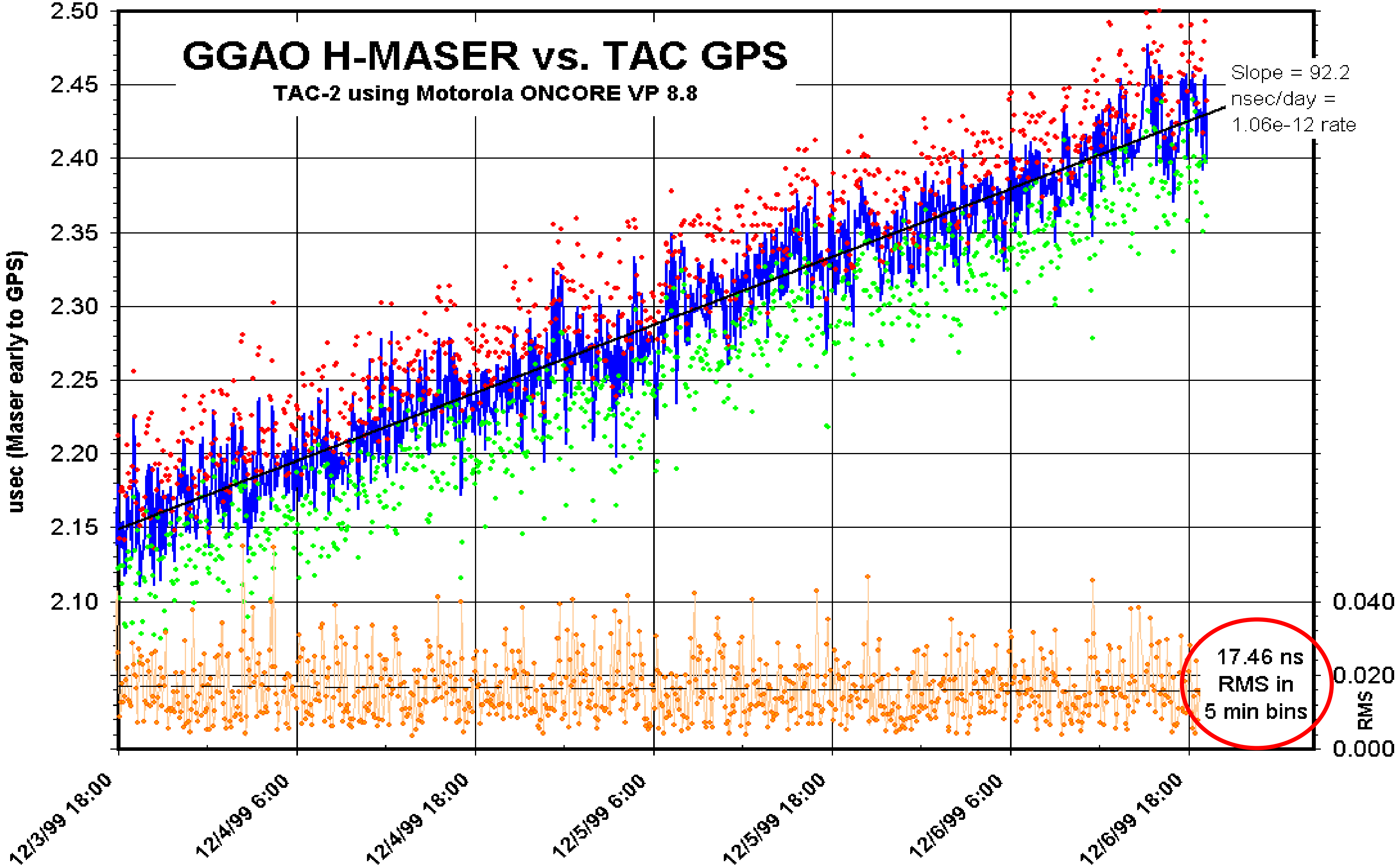
HP53132A Counters

Rick's New 12- channel "CNS Clock II"

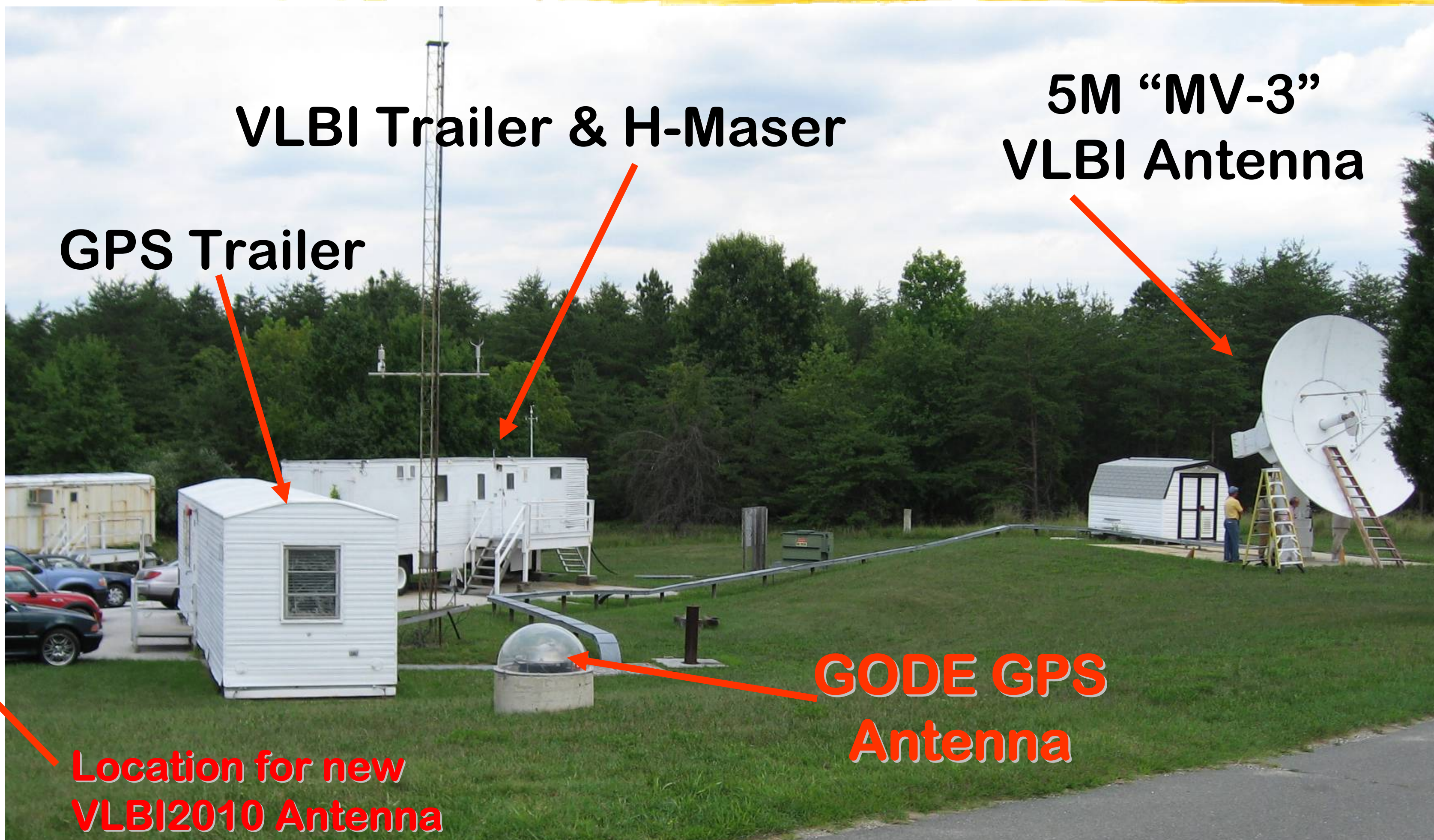
An Early Example of “Blind” GPS Timing with a 6 channel receiver



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



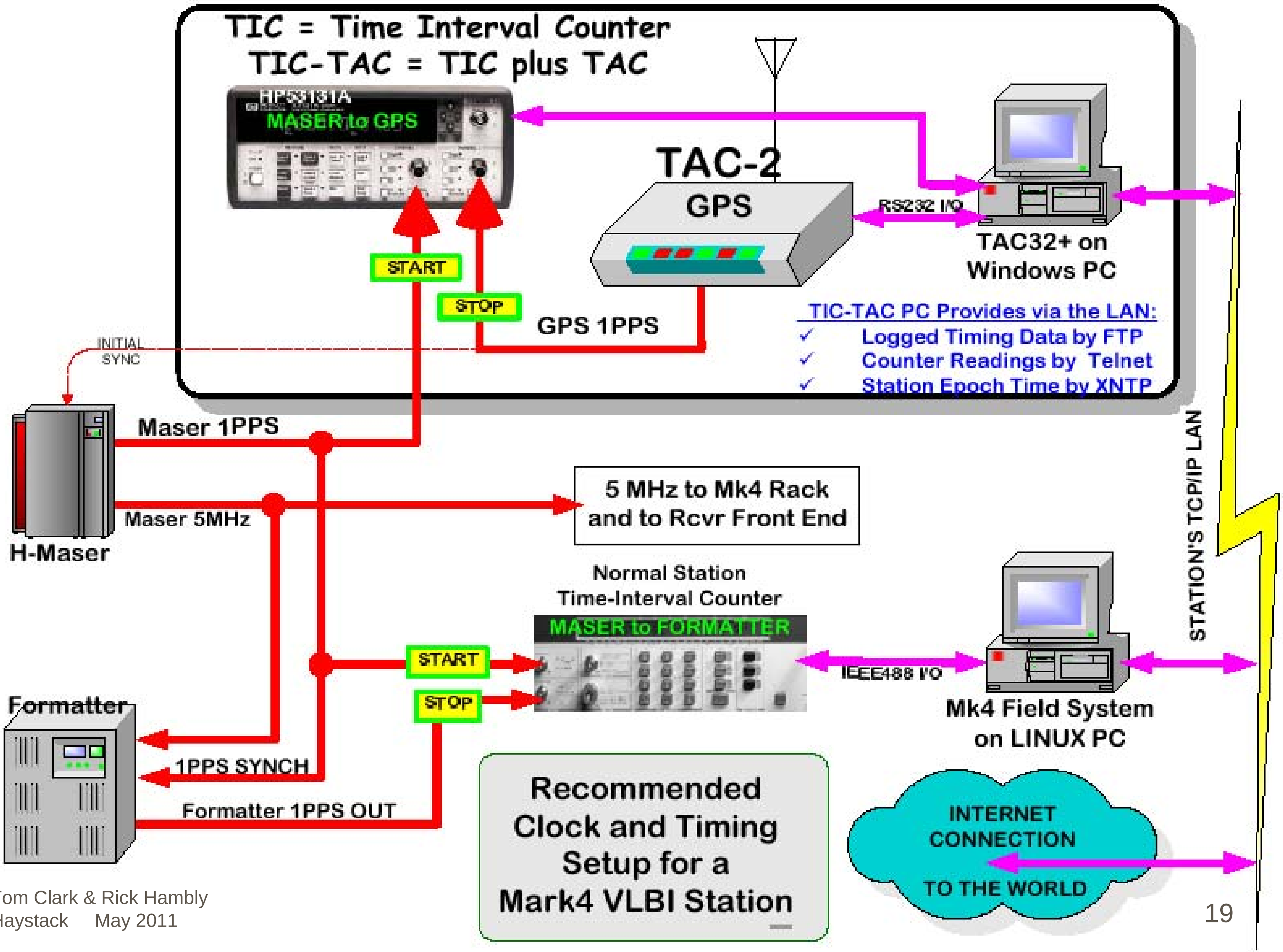
GGAO (Goddard Geophysical & Astronomical Observatory)



How we got ~30 nsec timing in 1995 *even with S/A*

- Start with a good timing receiver, like the Motorola ONCORE
- Average the positioning data for ~1-2 days to determine the station's coordinates. With S/A on, a 1-2 day average should be good to <5 meters. Or if the site has been accurately surveyed, use the survey values.
- Lock the receiver's position in "Zero-D" mode to this average.
- Make sure that your Time-Interval Counter (TIC) is triggering cleanly. Start the counter with the 1 PPS signal from the "house" atomic clock and stop with the GPS receiver's 1PPS.
- Average the individual one/second TIC reading over ~5 minutes.

- All these steps have been automated in my SHOWTIME and in CNS System's Tac32Plus Software using a barebones PC

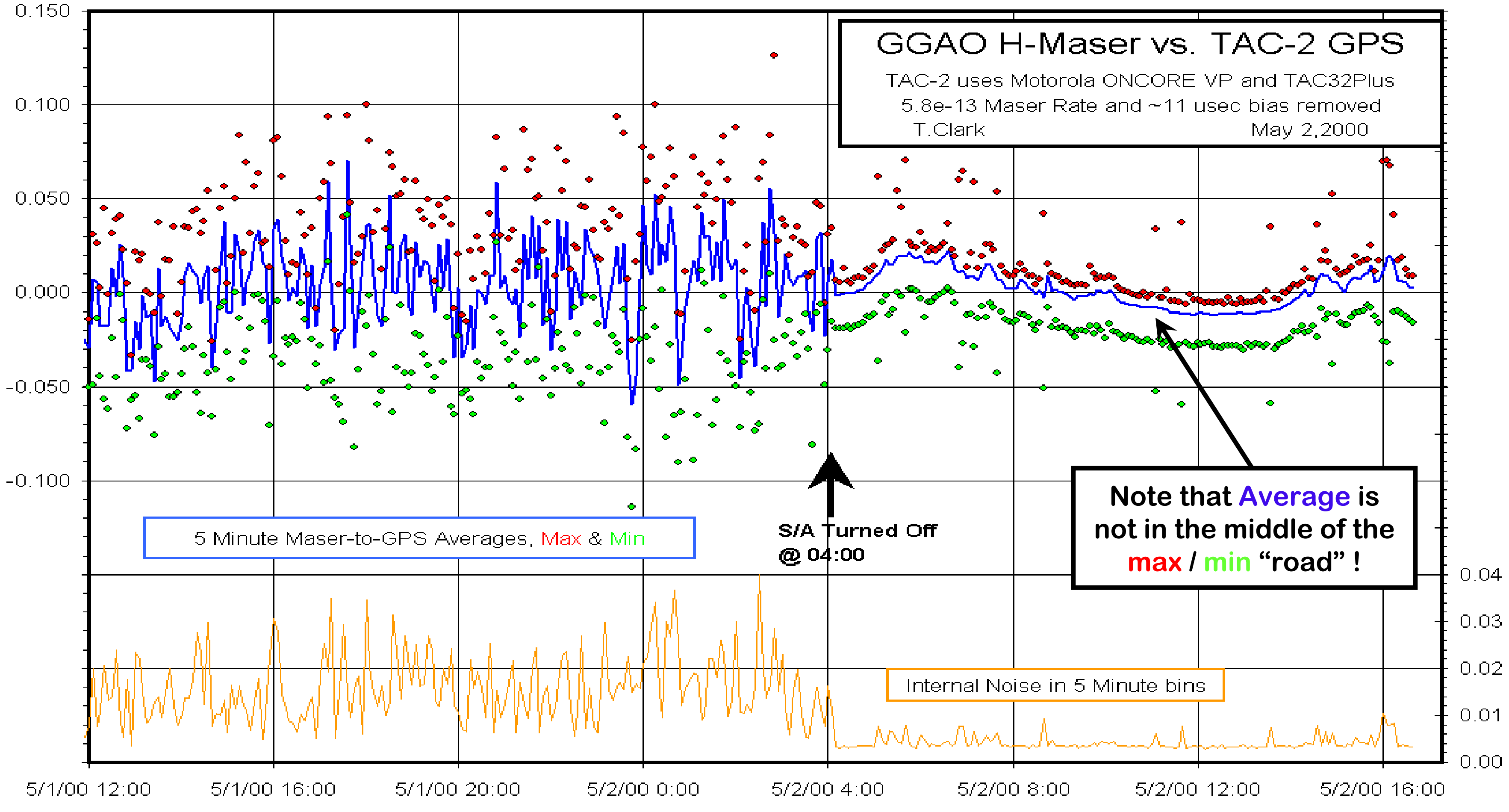

TIC = Time Interval Counter
TIC-TAC = TIC plus TAC
HP53131A
MASER to GPS
TAC-2
GPS
RS232 I/O
TAC32+ on
Windows PC
START
STOP
GPS 1PPS
TIC-TAC PC Provides via the LAN:
✓ Logged Timing Data by FTP
✓ Counter Readings by Telnet
✓ Station Epoch Time by XNTP
INITIAL
SYNC
Maser 1PPS
5 MHz to Mk4 Rack
and to Rcvr Front End
Maser 5MHz
H-Maser
STATION'S TCP/IP LAN
Normal Station
Time-Interval Counter
MASER to FORMATTER
START
STOP
IEEE488 I/O
Mk4 Field System
on LINUX PC
Formatter
1PPS SYNCH
Formatter 1PPS OUT
Recommended
Clock and Timing
Setup for a
Mark4 VLBI Station
INTERNET
CONNECTION
TO THE WORLD

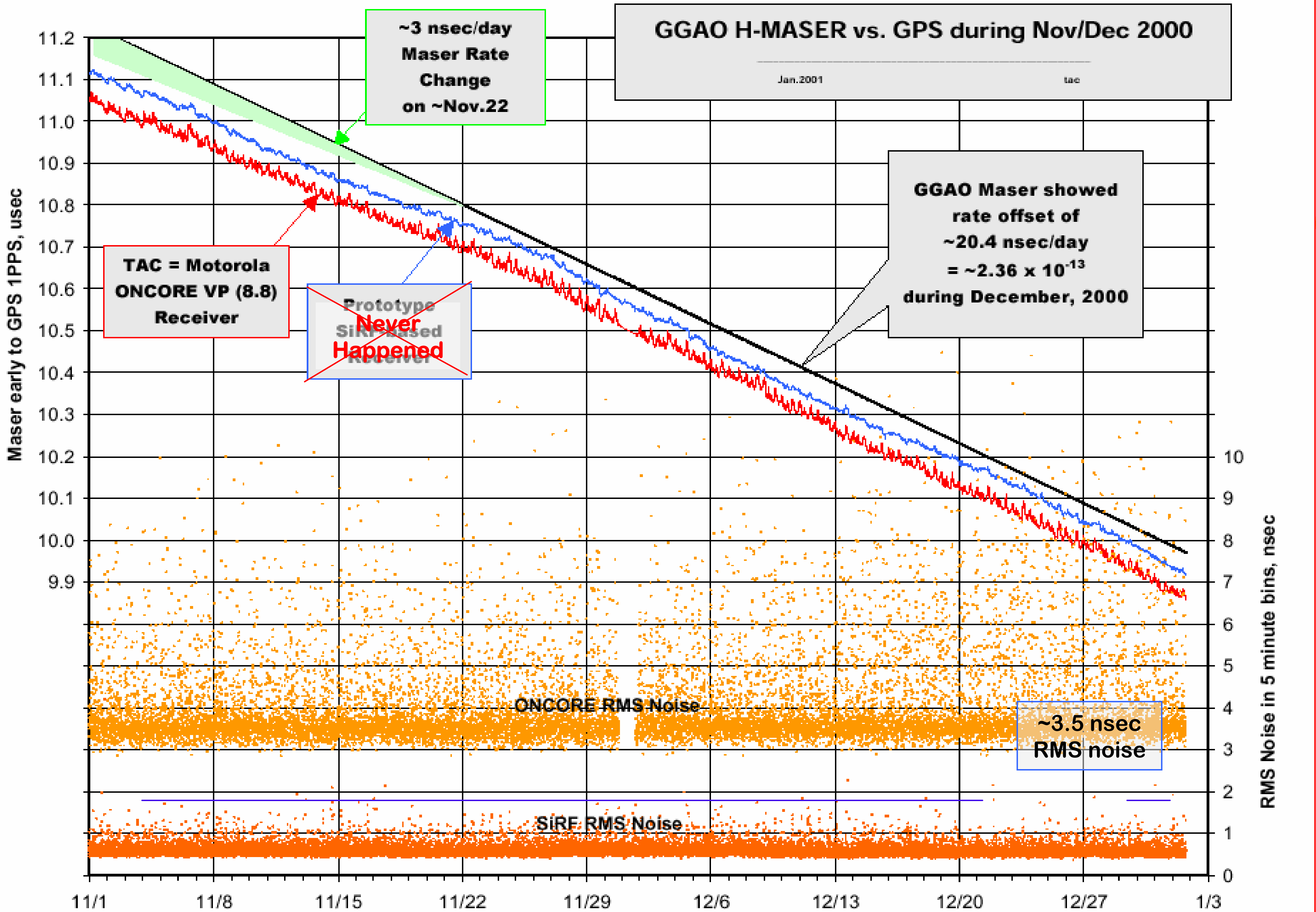
All that is ancient history. In the new millennium, let's now discuss . . .

- What happened when the DoD turned off S/A on May 2, 2000.
- Sawtooth and Glitches – Some Receiver Defects
- Some results obtained with Motorola's newer low cost timing receiver, the M12+ and M12M
- "Absolute" Receiver Calibration
- The post-Motorola era & new developments

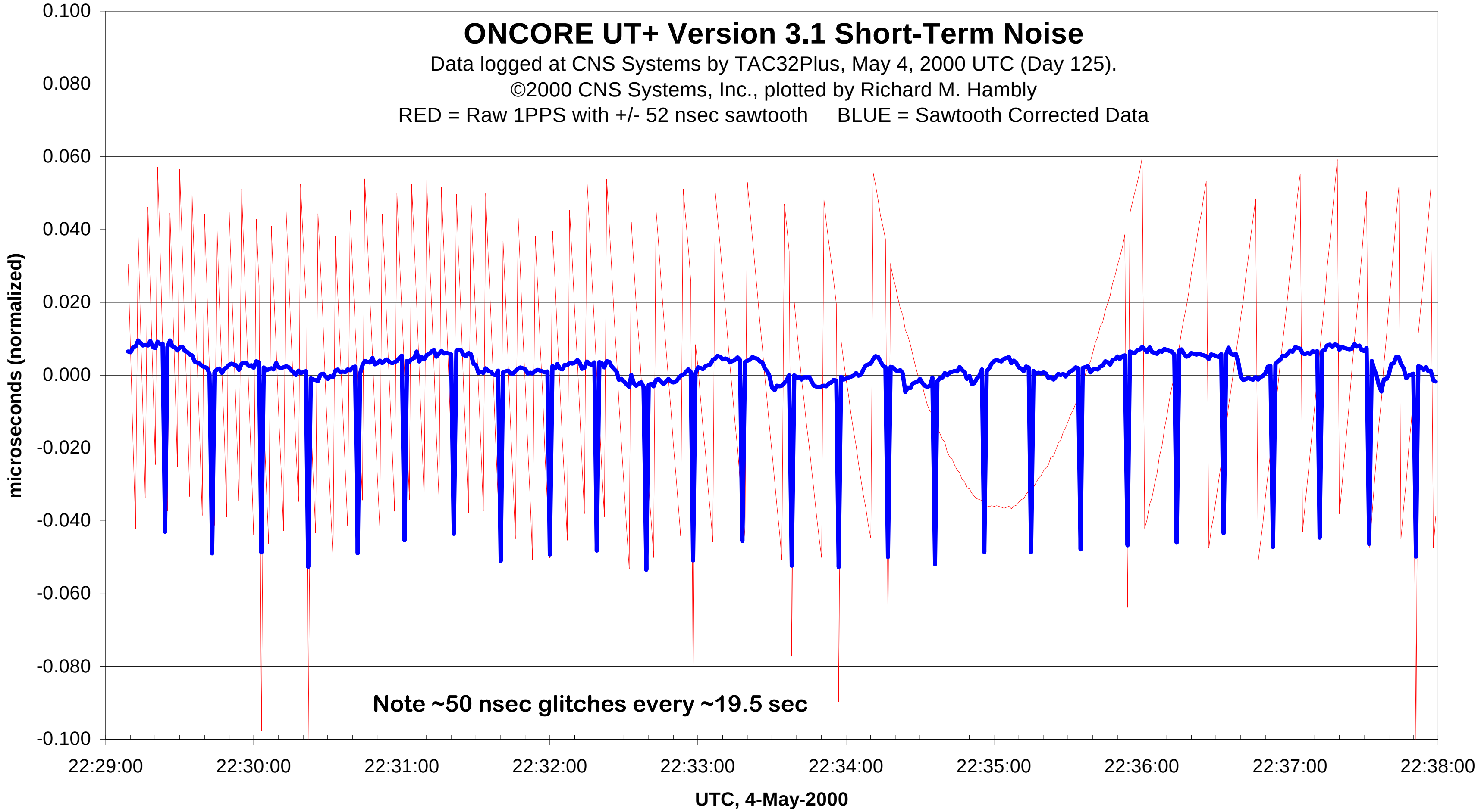
What happened when S/A went away?

Using 8-channel Motorola ONCORE VP Receiver . . .



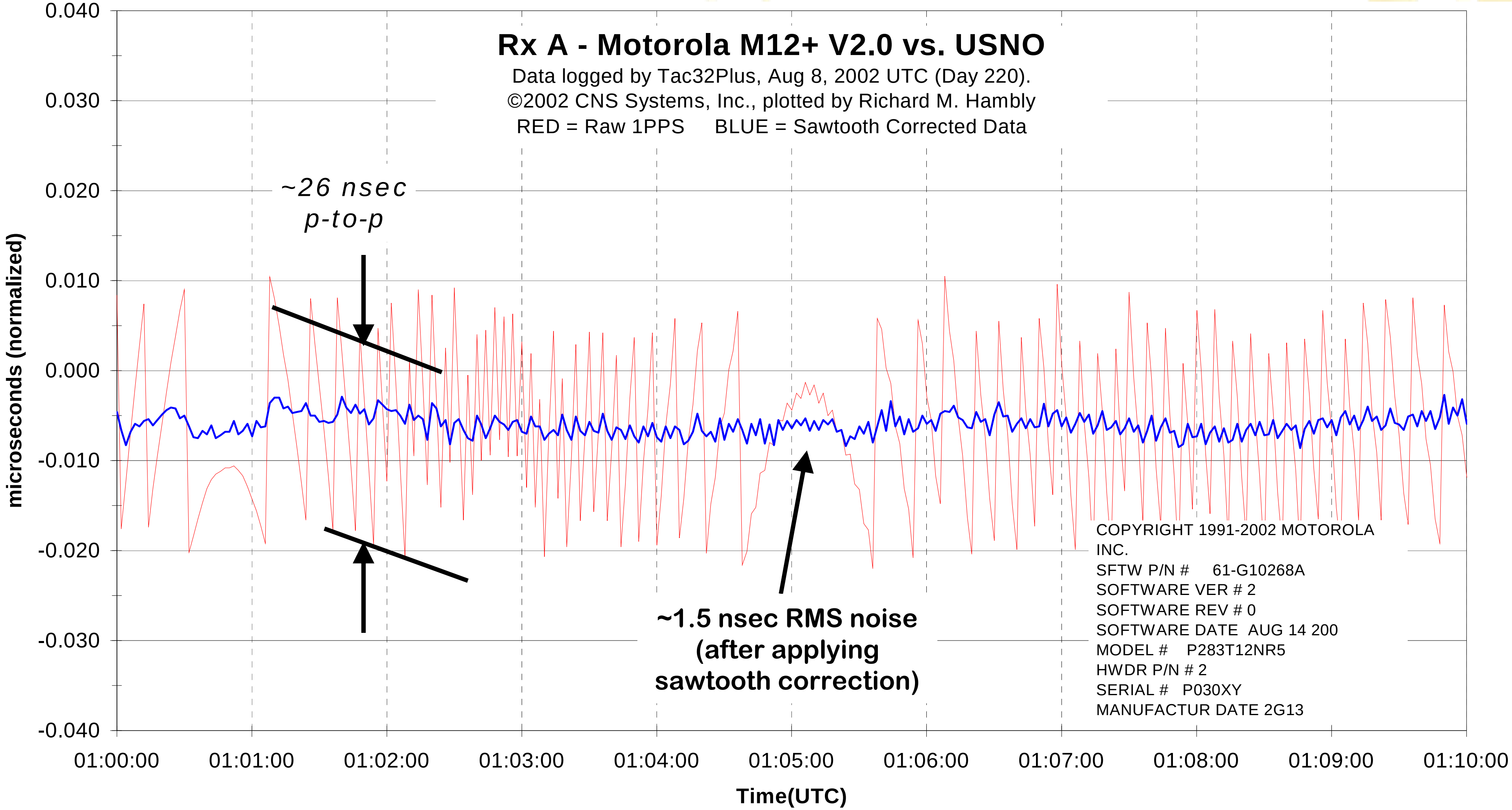

GGAO H-MASER vs. GPS during Nov/Dec 2000
Jan.2001
tac
~3 nsec/day
Maser Rate
Change
on ~Nov.22
GGAO Maser showed
rate offset of
~20.4 nsec/day
= ~2.36 x 10^-13
during December, 2000
TAC = Motorola
ONCORE VP (8.8)
Receiver
Prototype
SiRF-based
Receiver
Never
Happened
ONCORE RMS Noise
~3.5 nsec
RMS noise
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

An example of 1PPS Sawtooth & Bad Glitches Motorola's low cost UT+ Oncore (v3.1)

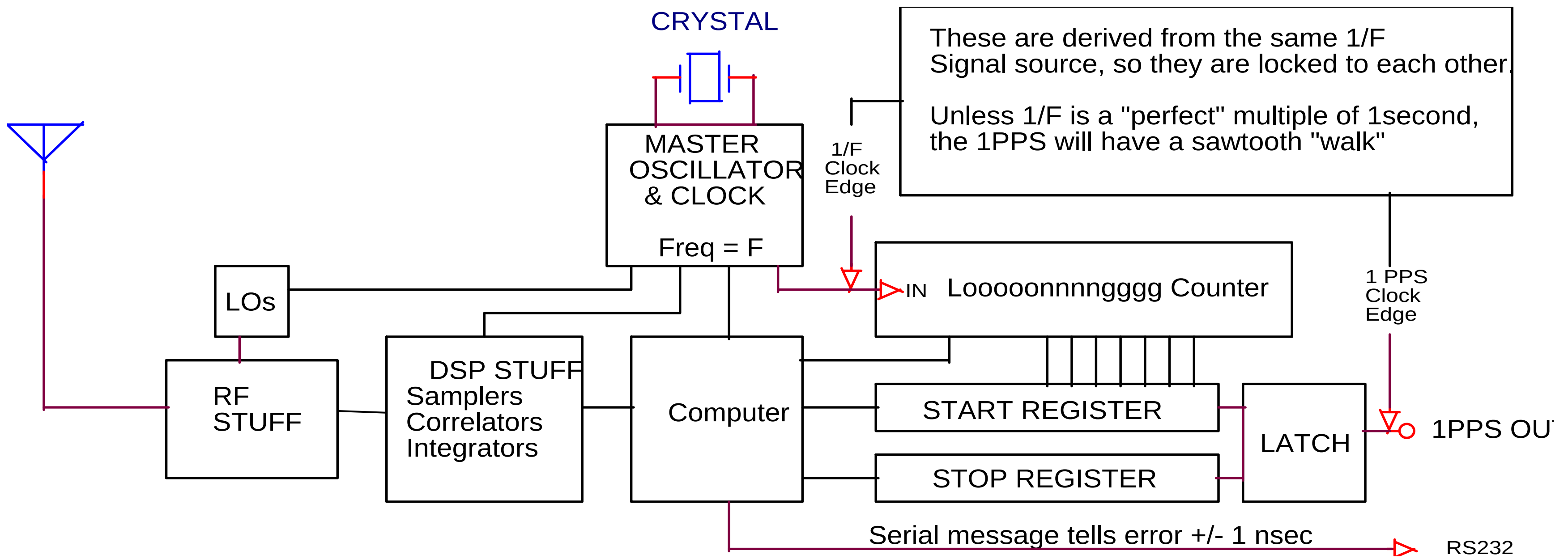


An example of 1PPS sawtooth

with Motorola's 12-channel M12+ receiver



What is the sawtooth effect ????



•**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 newer M12+ & M12M have F ≈ 40 MHz, so the sawtooth has been reduced to +/- 13 nsec (26 nsec).**

VLBI's annoying problem caused by the sawtooth timing error

- When the formatter (Mark 5 sampler) needs to be reset, you have to feed it a 1PPS timing pulse to restart the internal VLBI clock. After it is started, it runs smoothly at a rate defined by the Maser's 5/10 MHz.
- The ***AVERAGE*** of the 1pps pulses from the GPS receiver is "correct", but any single pulse can be in error by ±13 nsec (or ±52 nsec with the older VP & UT Oncore receivers) because of the sawtooth.
- Once you have restarted the formatter with the noisy 1 PPS signal, you then measure the actual (GPS minus Formatter) time that you actually achieved.

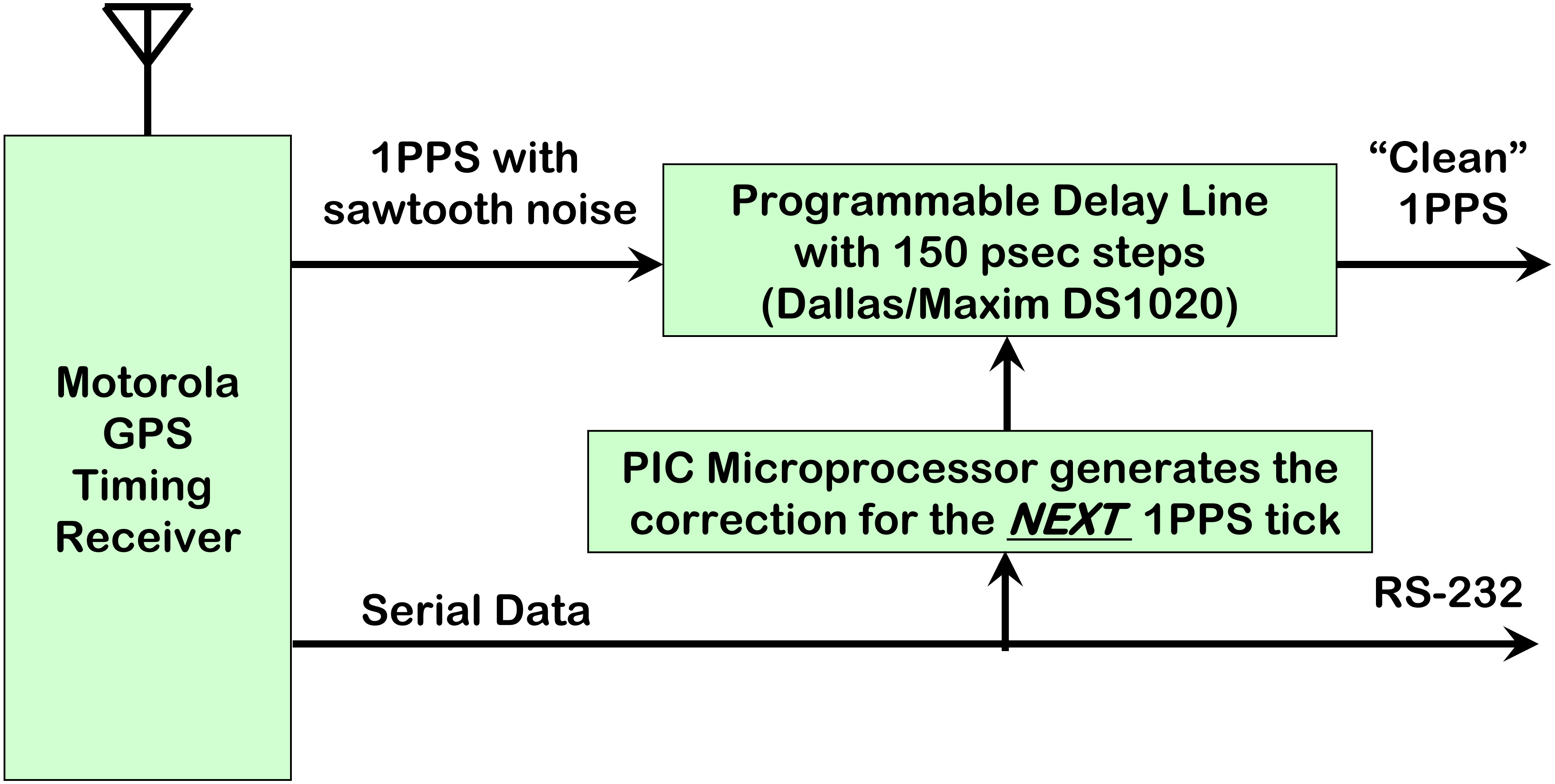
- Or, you can use the 1PPS from a new CNS Clock II which has the sawtooth "dither" removed.

Errors due to the sawtooth do not compromise VLBI data quality

- All the Motorola receivers report the error on the ***next*** 1 PPS pulse with a resolution of ~1 nsec as a part of the serial data message.
- Tac32Plus reads the HP53131/2 counter and the GPS data message and corrects the answer.

But, wouldn't it be good if the GPS receiver didn't have any sawtooth error, and that every 1 PPS pulse could be trusted?

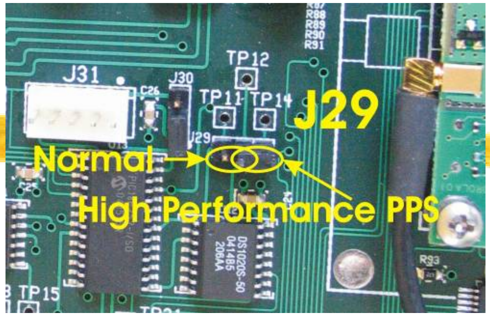
How can the Sawtooth noise be eliminated ???



The Future is here now!
The CNS Clock II

1994 – 2004: the TAC

1PPS Sawtooth Correction Option

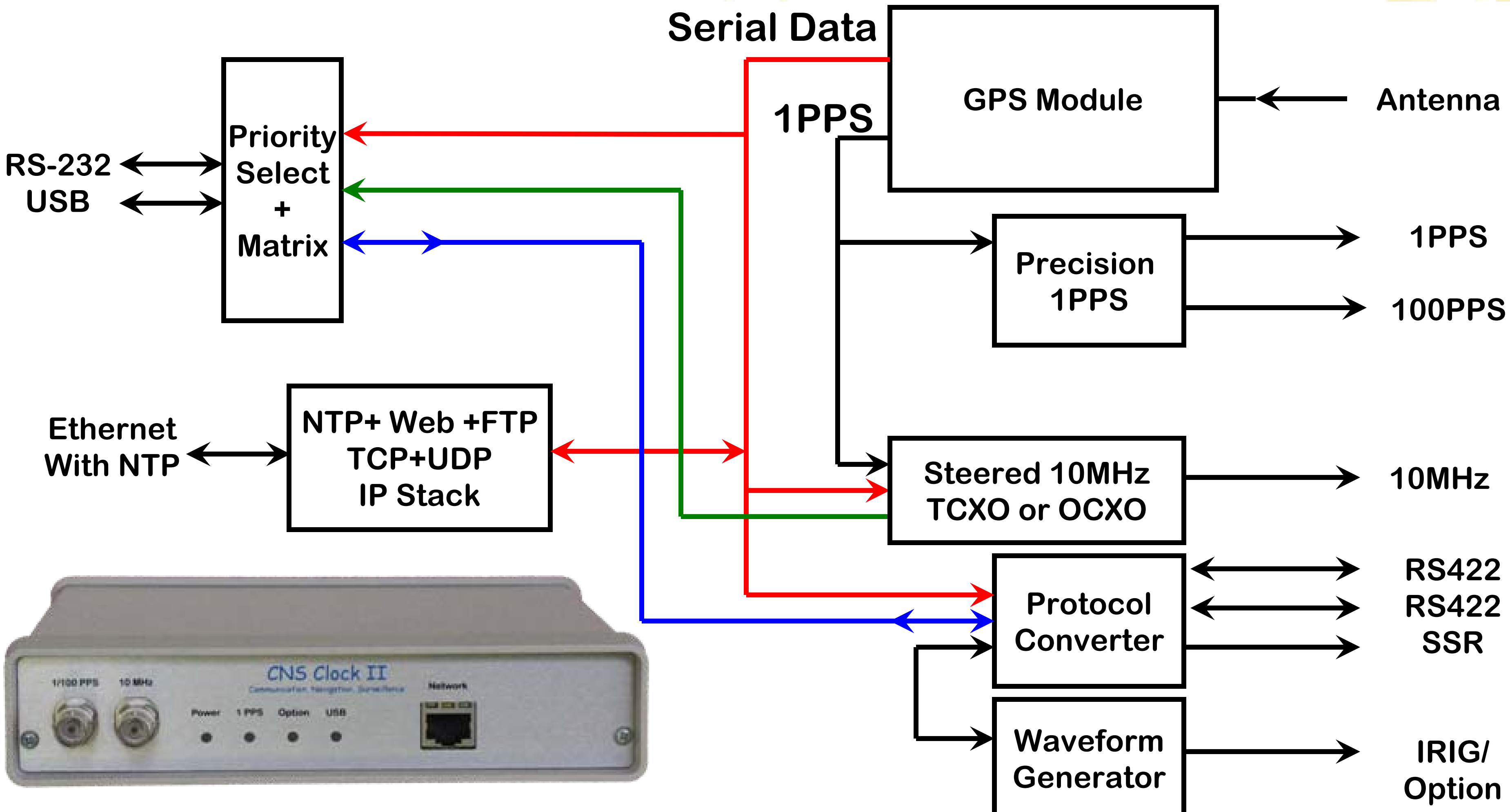


Available Since January 2005

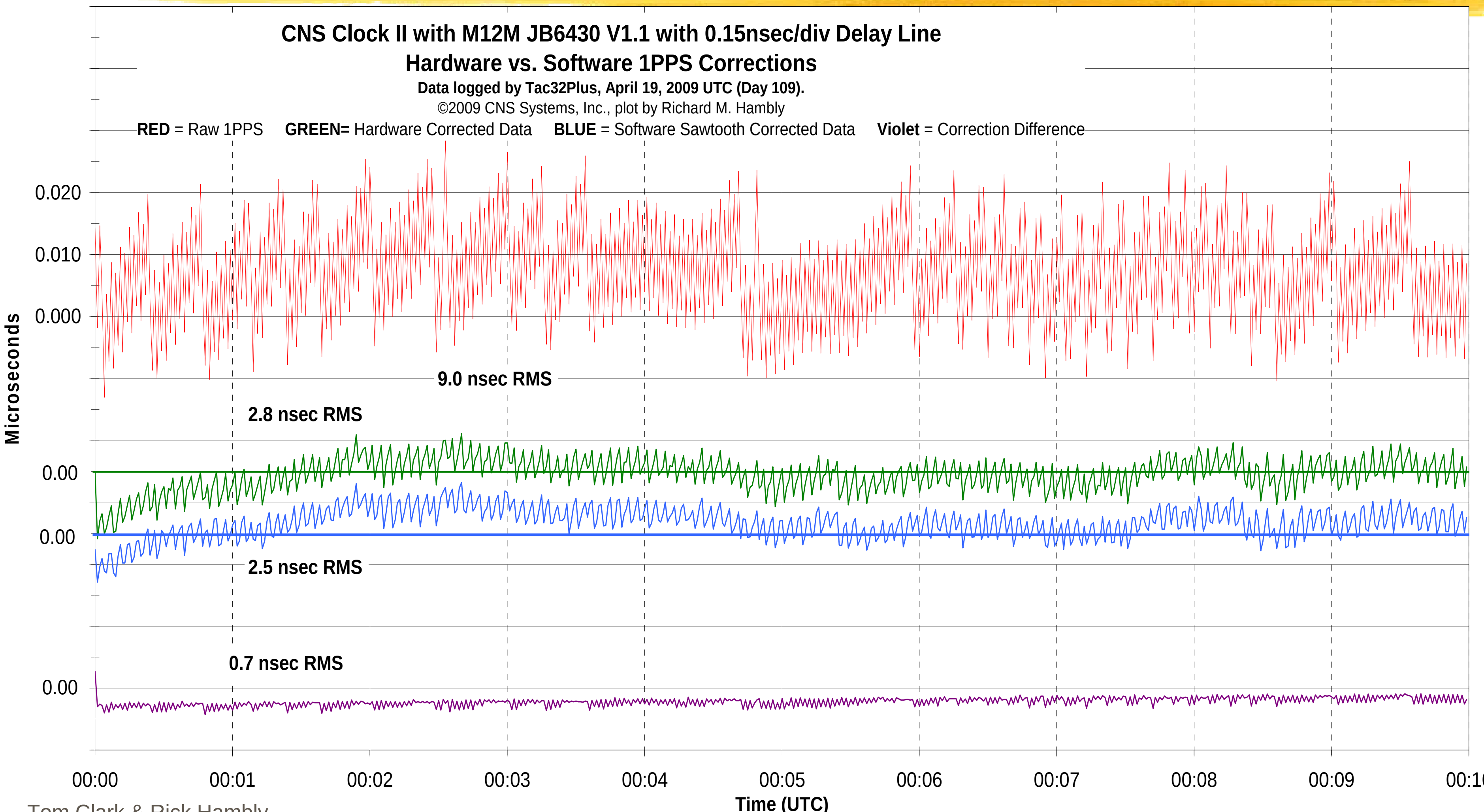
Data available on RS-232, USB 2.0, Ethernet LAN, RS-485 and solid state relay Ports
Ethernet NTP Server for your LAN
TNC GPS Antenna Connector
Buffered 1 PPS outputs
GPSDO 10 (or 5) MHz output
High Performance PPS
Steered TCXO
Steered Oscillator Utility Functions

Many Options: IRIG-B, Sequencer, Genisys, RS-485 RFID Timecode, Steered OCXO, and Event Recorder Interface.

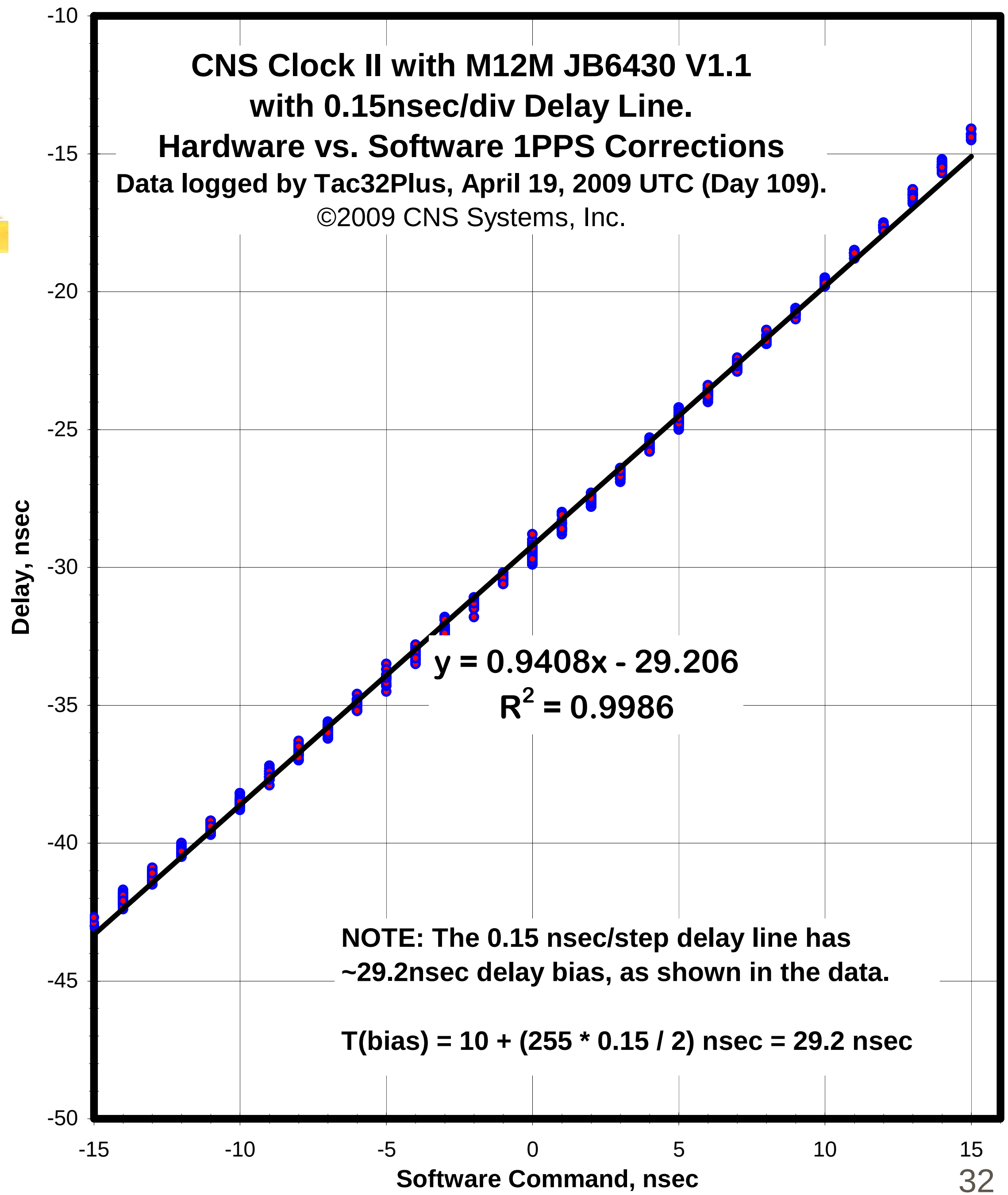
CNS Clock II Block Diagram



Does the hardware 1PPS correction work?



Does the hardware 1PPS correction really work?



YES !!

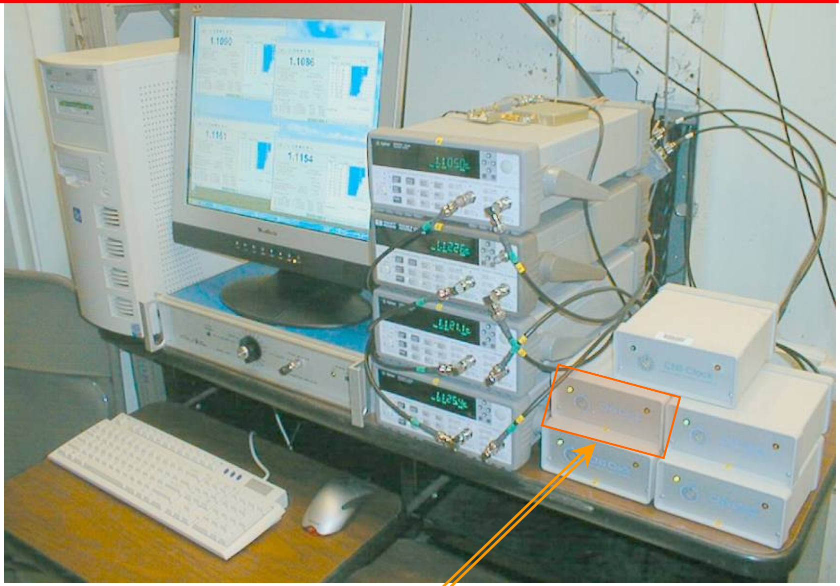
CNS Systems' Test Bed at USNO

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.

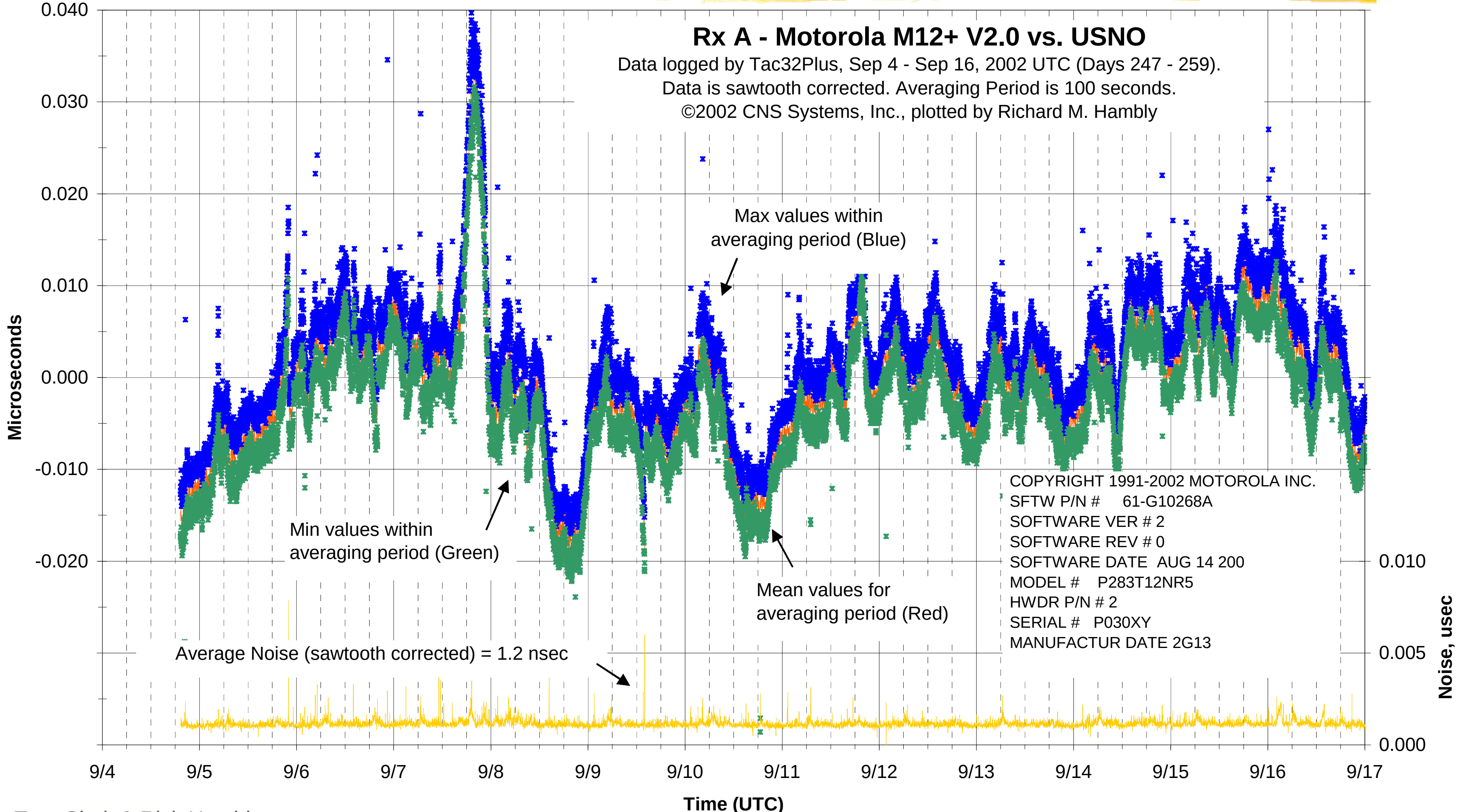


Time Interval Counters compare the 1PPS from each CNS Clock (M12+) against the USNO's UTC time tick.

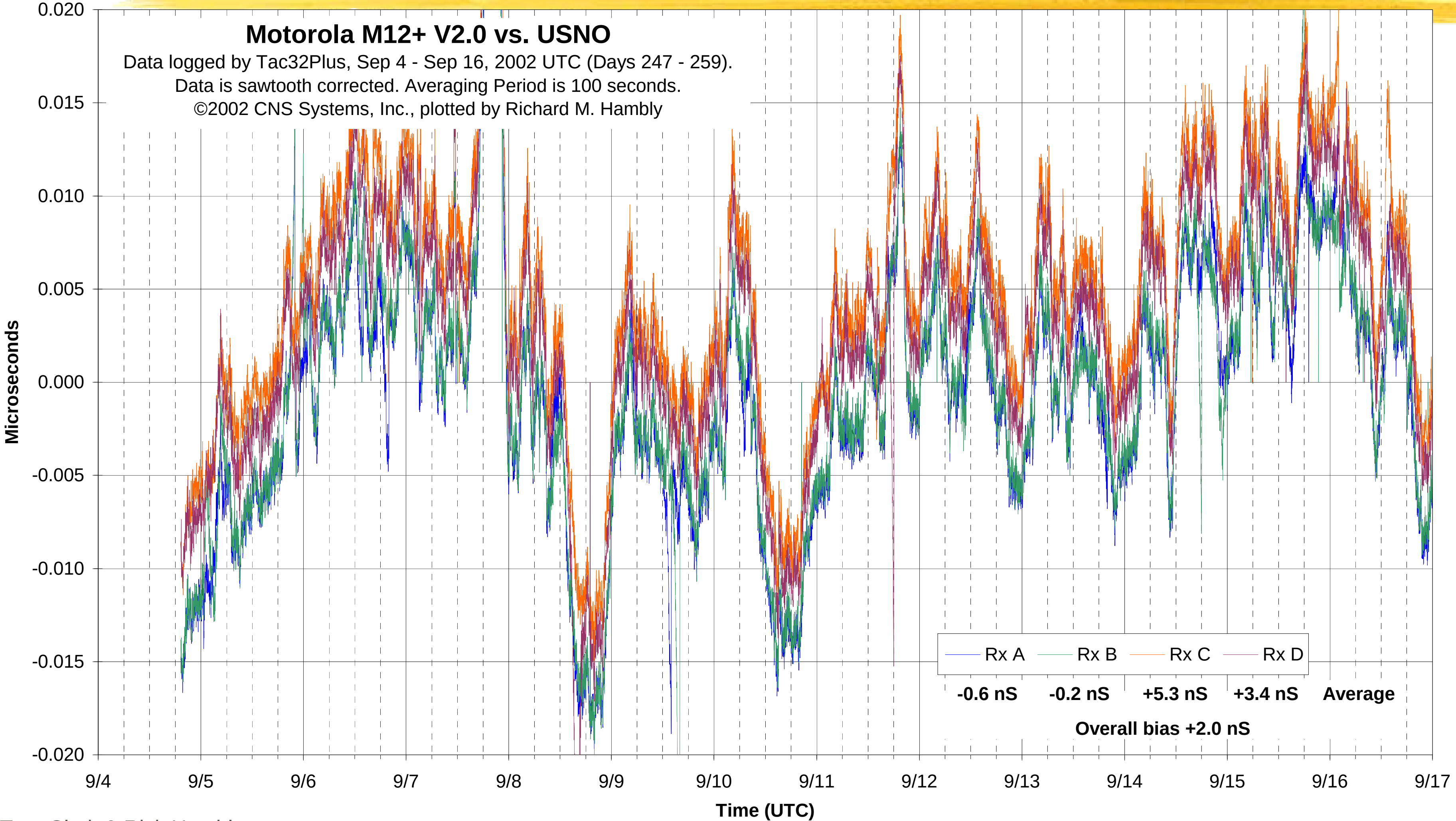
This is the "Gold Standard" "A" receiver that we used for subsequent calibrations.

Individual M12 Clock Performance

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



Comparing four M12+ Timing Receivers



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.

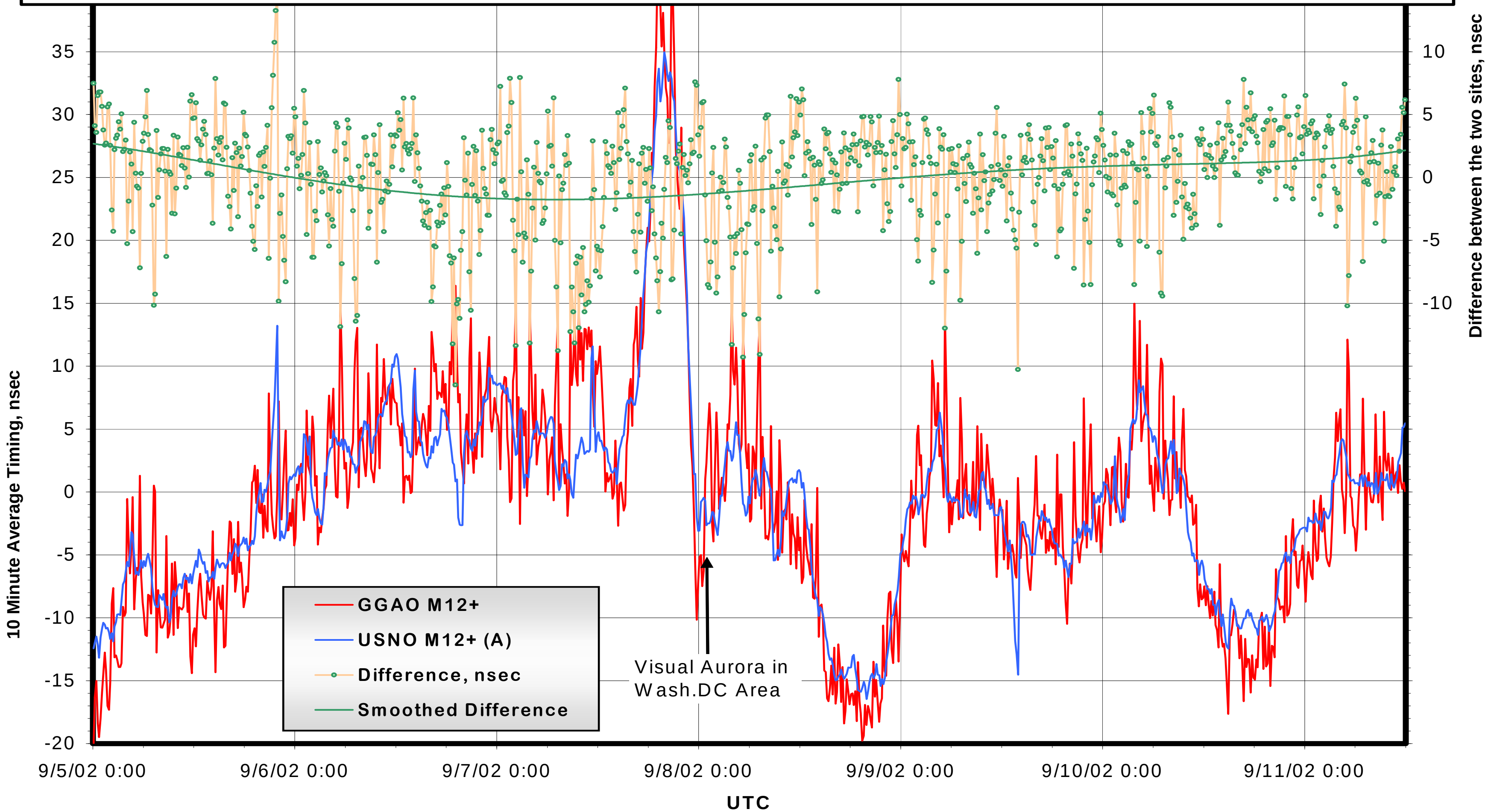
This picture is a four hour composite of 140 different photos spanning 20:00 thru 24:00 EDT on Sept. 8th (00:00 thru 04:00 UTC Sep. 9).

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.



Current M12 Receiver Status

- All varieties of the M12+ and M12M show similar performance.
- All the M12+ receivers, including the 4 receivers in the 2002 test, appear to agree with UTC(USNO) to better than ±10 nsec.
- Motorola made a decision to get out of the GPS business.
  - The M12M is now being manufactured by **iLotus LTD** in Singapore.
  - GPS performance of the M12M is better than the M12+
  - The M12Ms show a bias errors up to ~30 nsec as compared with our "Gold" reference Motorola receiver.
  - The reasons for the biases (Hardware? Firmware?) are unknown.

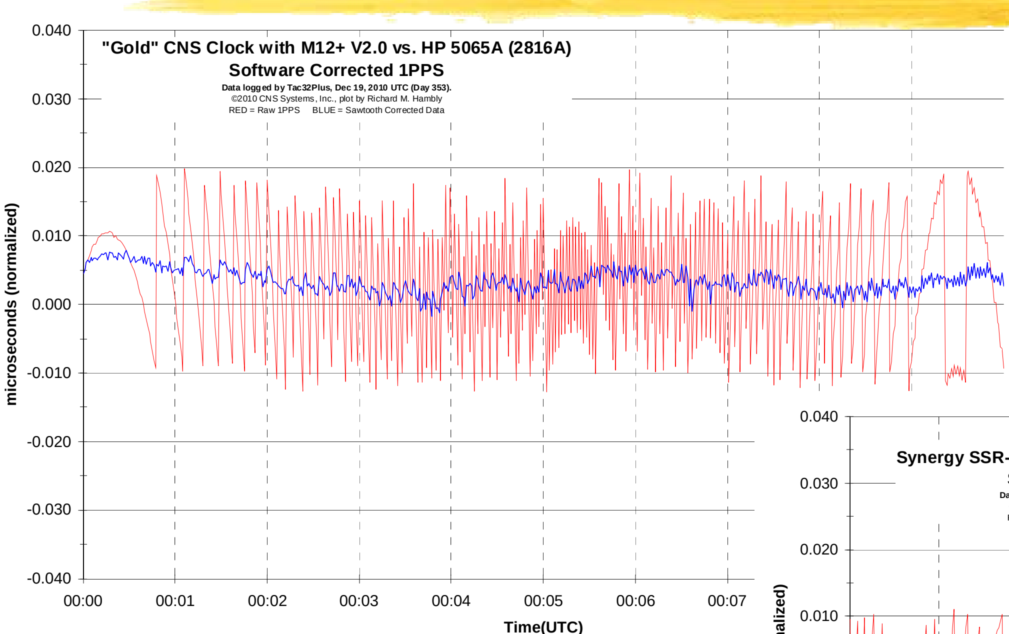
What Else is New ?

- **CNS Clock II** includes these standard features:
  - The latest M12M timing receiver
  - Ethernet / NTP Time Server
  - Hardware Sawtooth Correction
  - Steered TCXO with 10MHz or 5MHz output
  - Steered Oscillator Utility Functions
- Options include:
  - Steered OCXO with 10MHz or 5MHz output
  - IRIG-B
  - Other specialized and custom timing related outputs.
- New version of **Tac32Plus** is available.

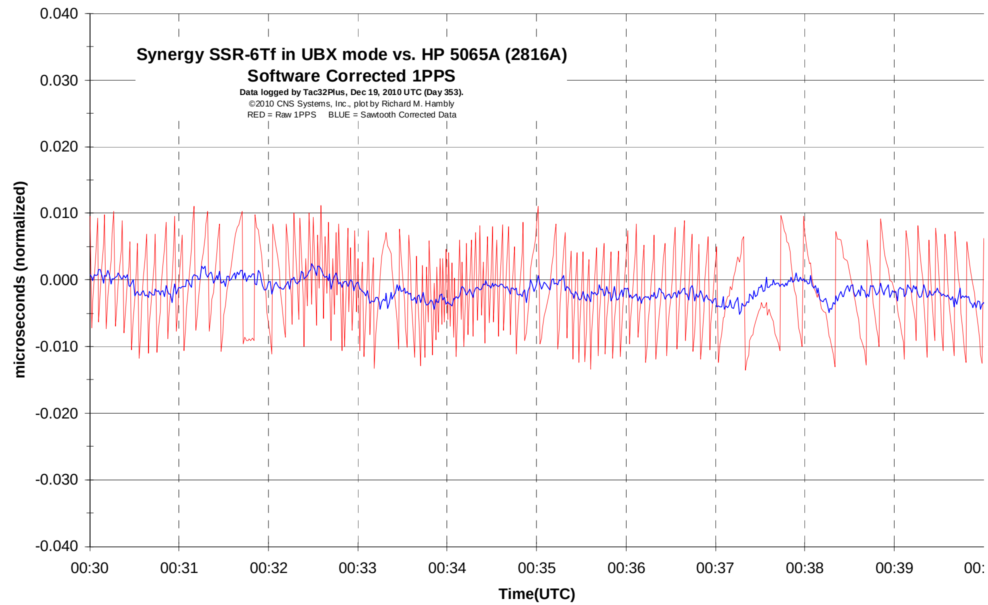
What is Coming Soon ?

- **CNS Clock II** will include new standard features:
  - The u-blox LEA-6T or LEA-7T 50 channel timing receiver with over 2 million effective correlators.
  - New 100/10 BASE-T Ethernet / NTP Time Server with auto crossover detection.
  - Improved Hardware Sawtooth Correction.
  - Improved Steered TCXO with 10MHz or 5MHz output.
  - 10/5 MHz output will become a sine wave at +7dbm nominal. It can be configured between 0 and +10 dbm.
- Options will include:
  - A programmable PPS output between 1PPS and 100K pps.
- Linux version of **Tac32Plus** (using QT? Help?).

The new u-blox timing receiver



- M12M short term noise
  - Red => Raw 1PPS
  - Blue = Sawtooth corrected 1PPS



- U-blox LEA-6T short term noise
  - Raw 1PPS = 2/3 of the M12M
  - Sawtooth corrected 1PPS = slightly better

Where to get information?

These Slides and related material:

http://gpstime.com

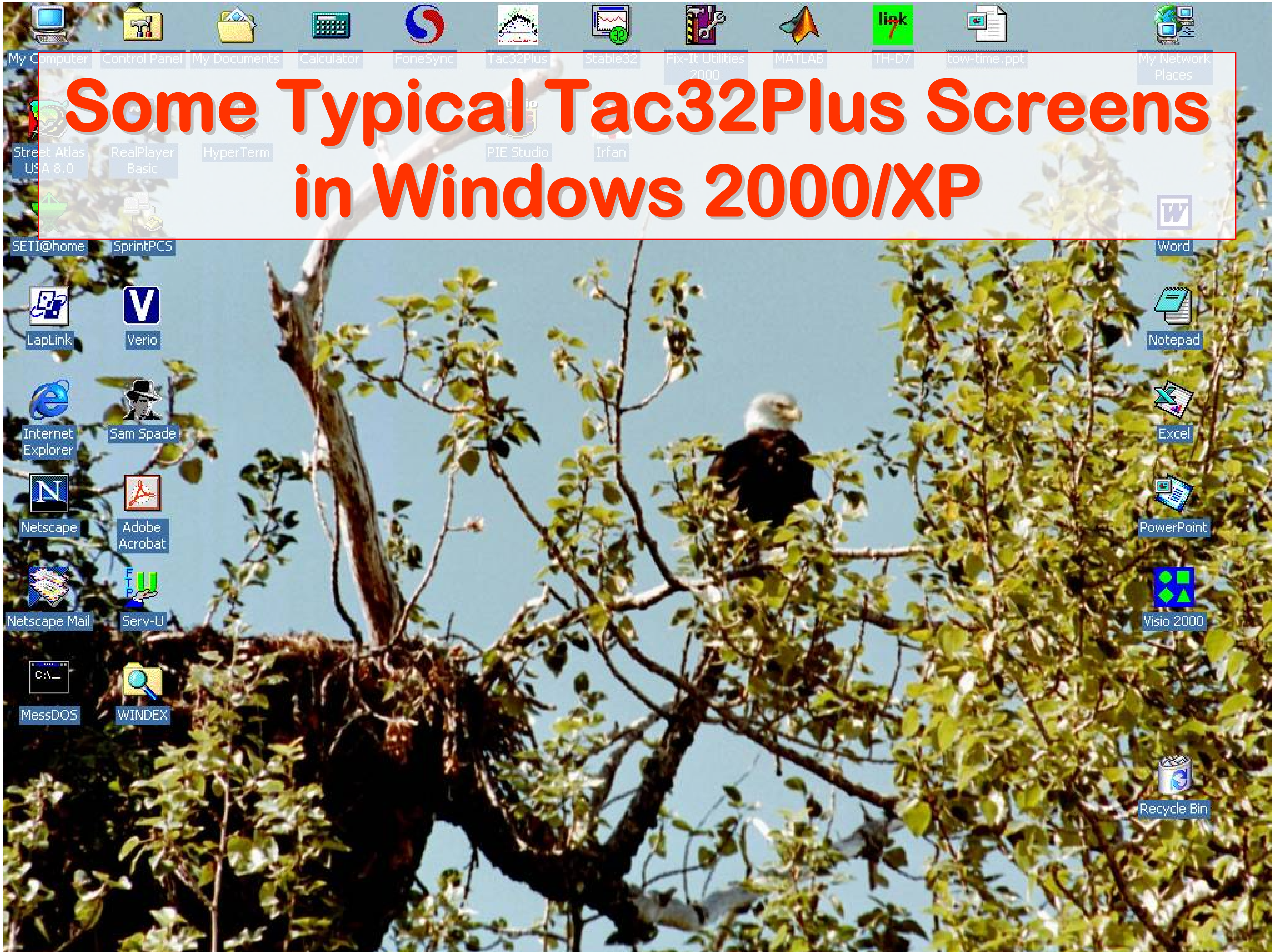
Information on the CNS Clock and the CNS Clock II:

http://www.cnssys.com

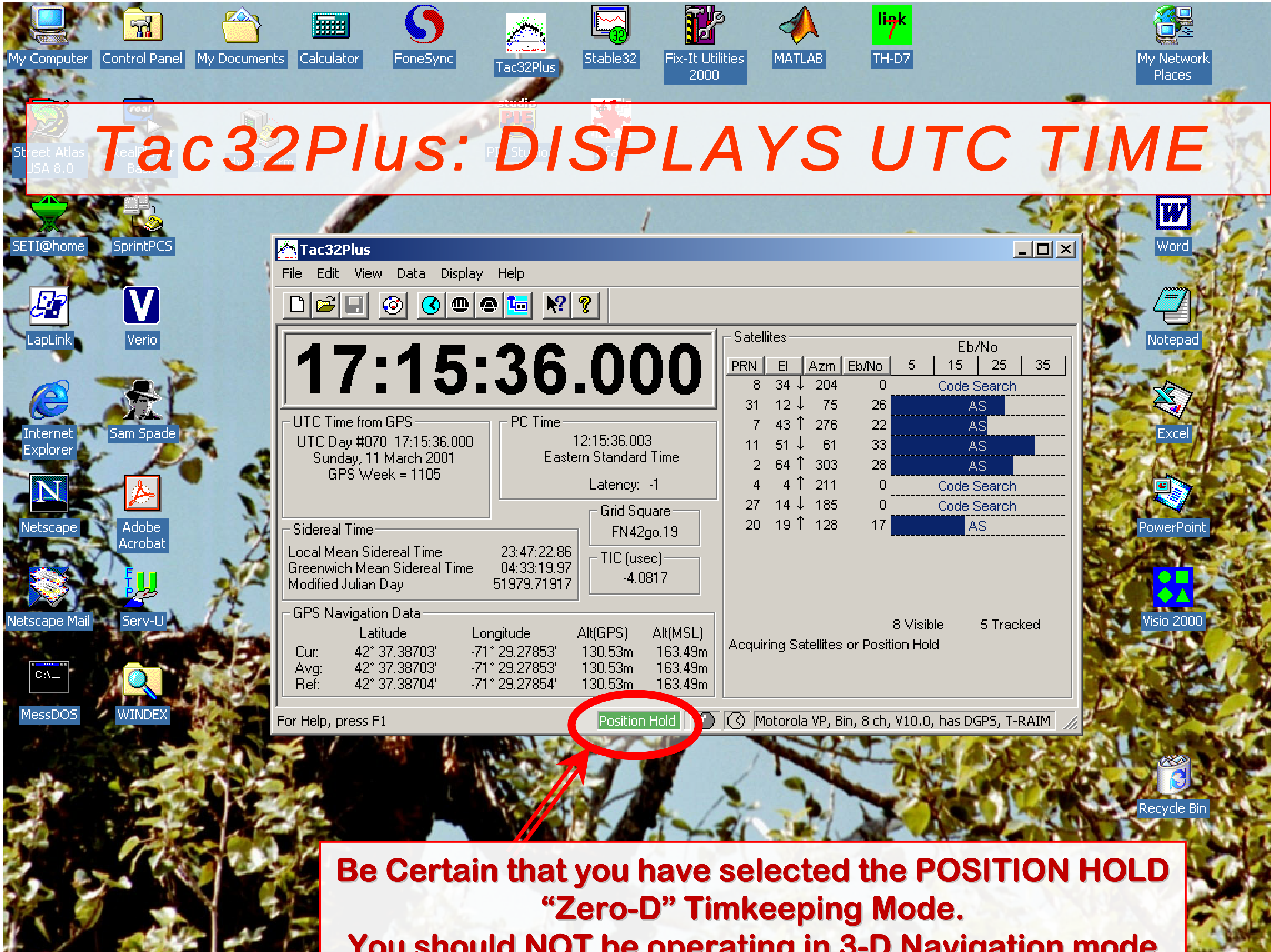
To contact Tom: mailto:K3IO@verizon.net

To contact Rick: mailto:Rick@cnssys.com, 410-987-7835

Some Typical Tac32Plus Screens in Windows 2000/XP

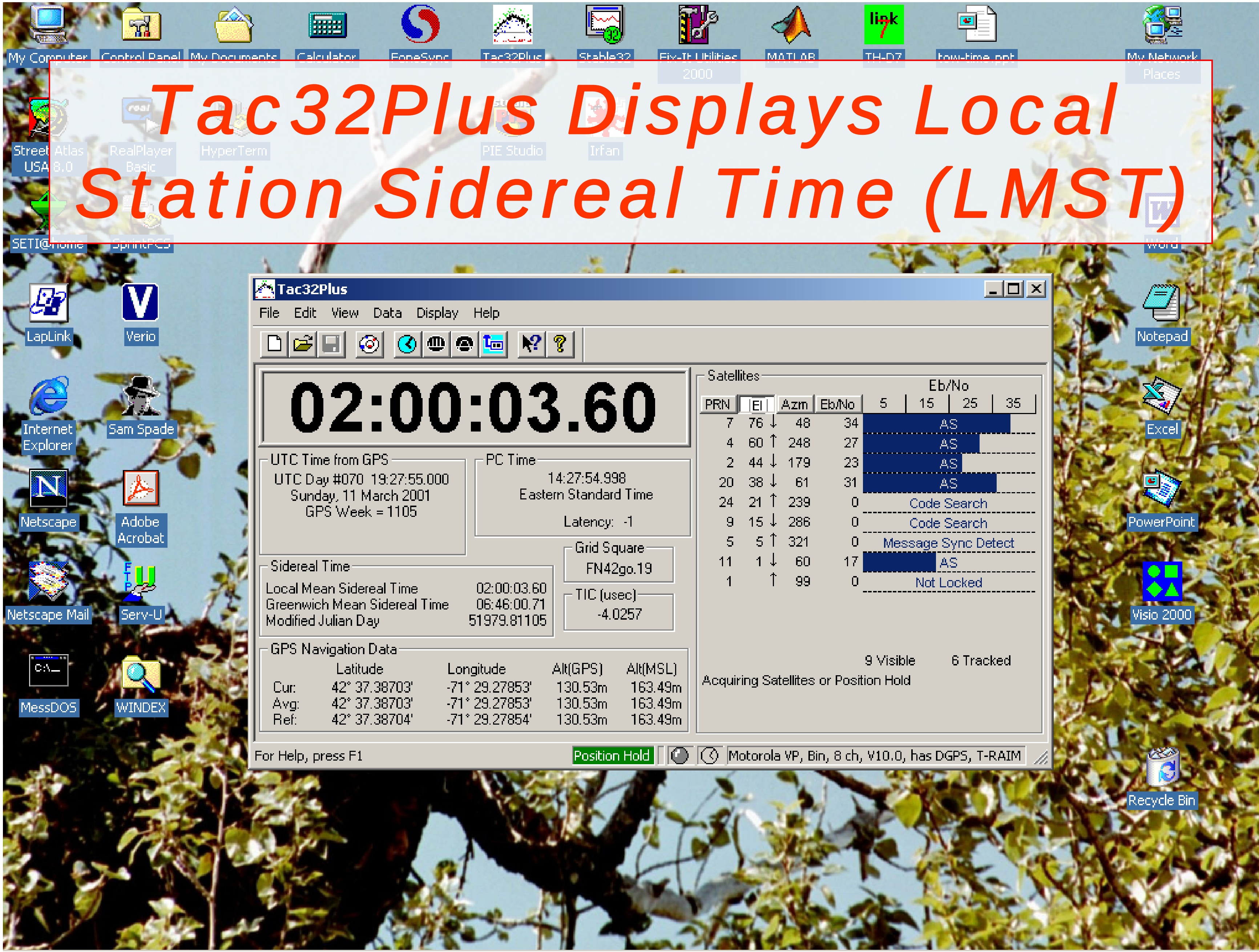


Tac32Plus: DISPLAYS UTC TIME

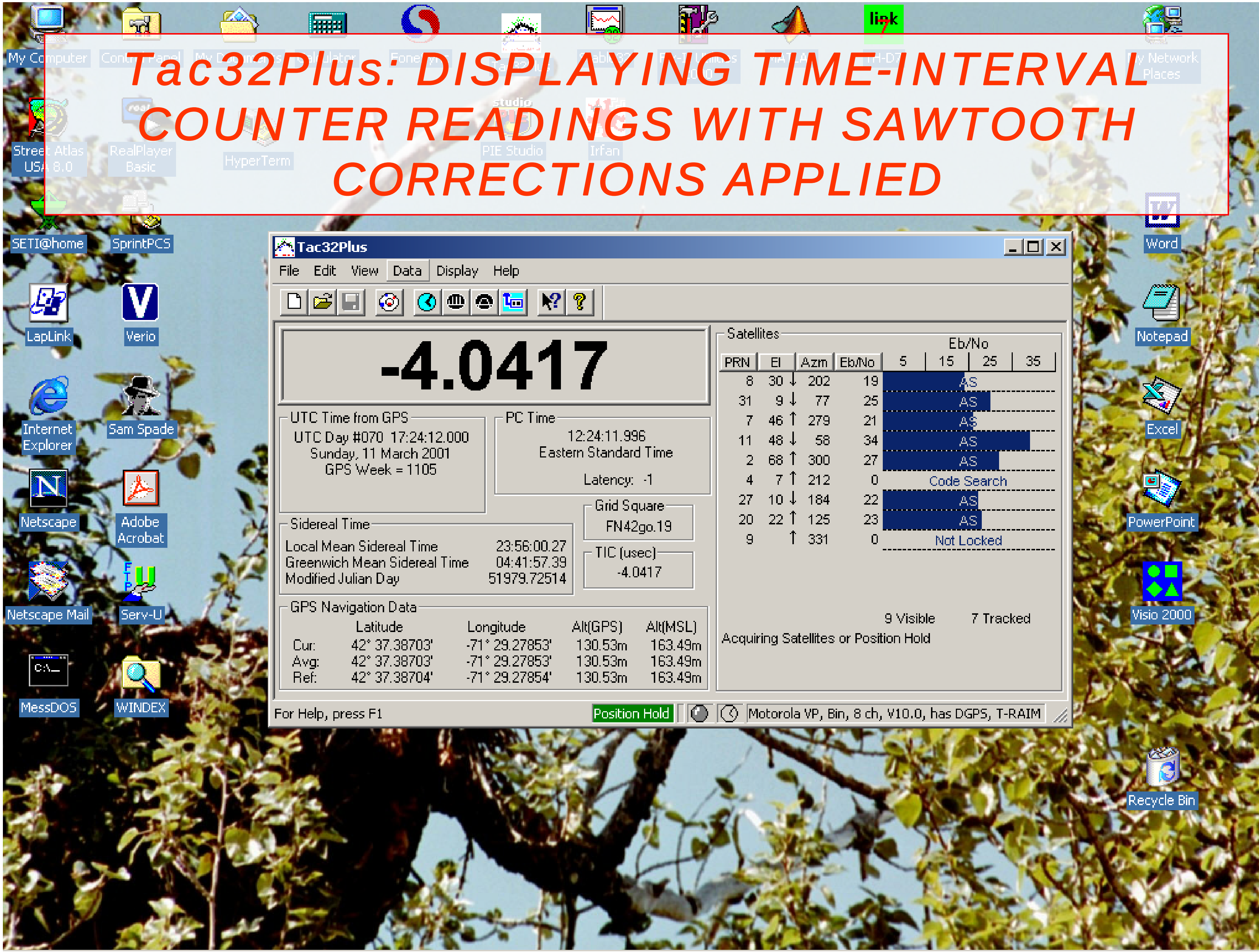


Be Certain that you have selected the POSITION HOLD "Zero-D" Timkeeping Mode.
You should NOT be operating in 3-D Navigation mode !!

Tac32Plus Displays Local Station Sidereal Time (LMST)



Tac32Plus: DISPLAYING TIME-INTERVAL COUNTER READINGS WITH SAWTOOTH CORRECTIONS APPLIED



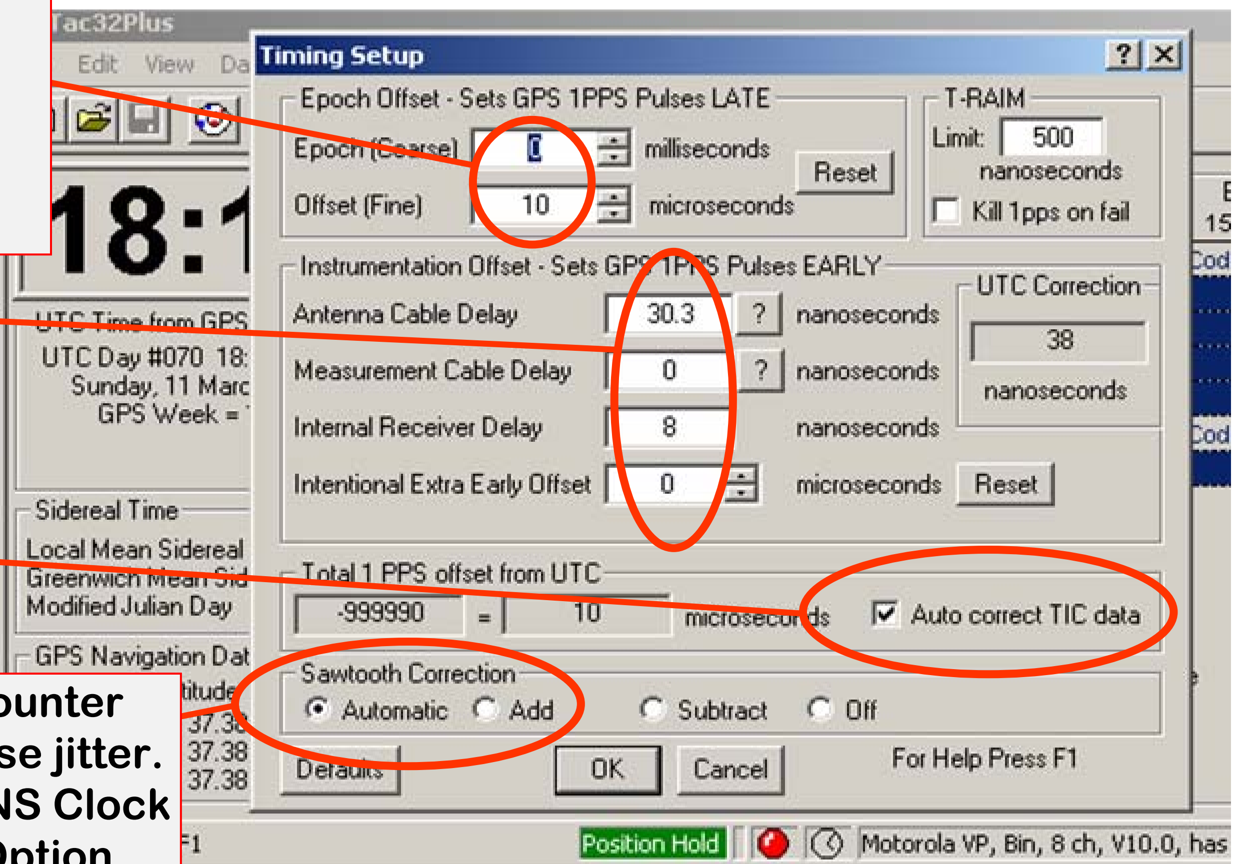
To Make Sure Tac32Plus is Logging the "true" Maser-to-GPS Time Interval:

Offset GPS LATE if needed to be certain that the actual GPS 1PPS is AFTER the Maser's 1PPS. Tac32Plus will do the arithmetic to make the log data be correct.

Be certain to account for the lengths of all coax cables.

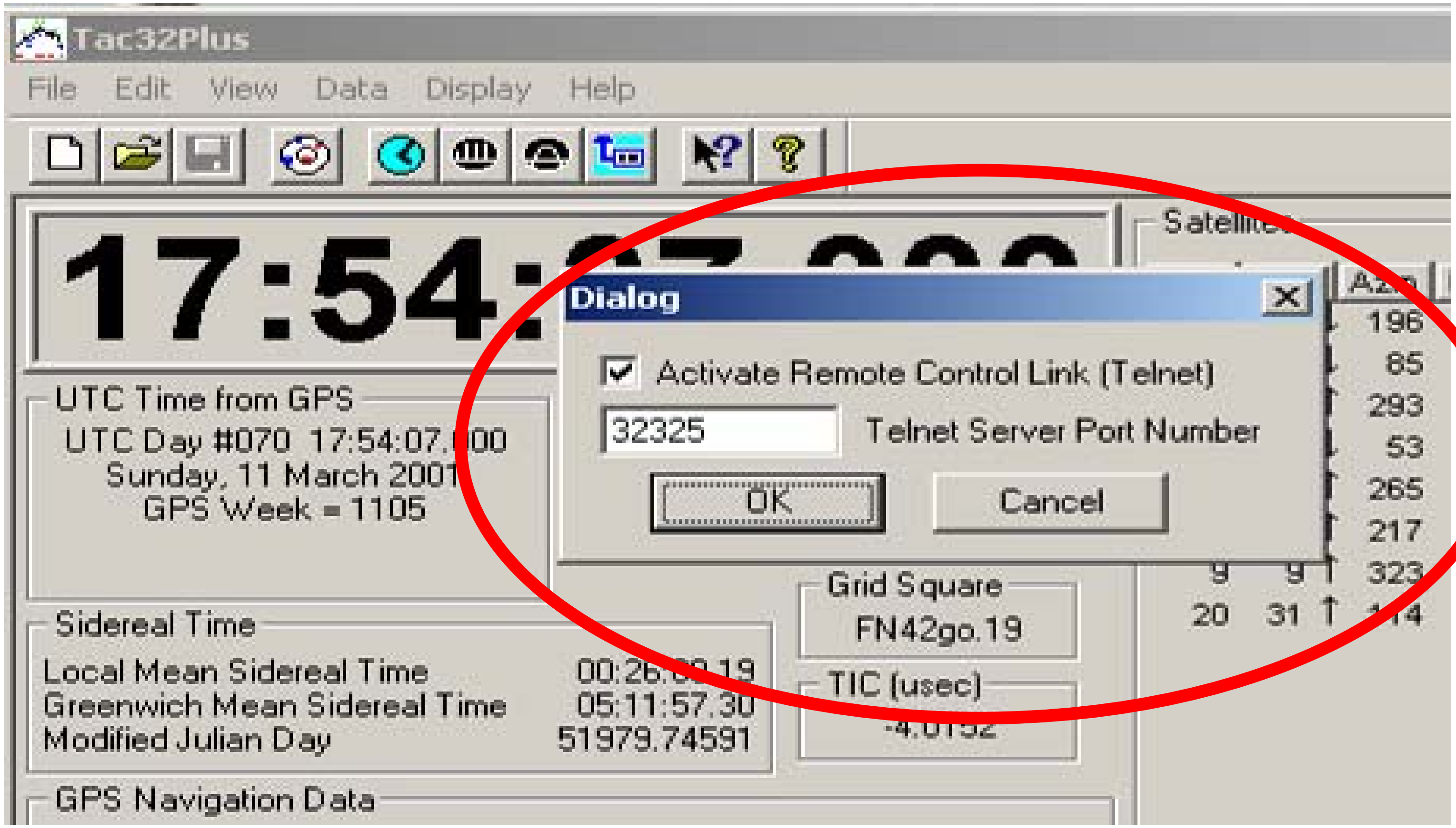
Allow the Tac32Plus software to correct for all timing offsets.

Allow software to correct counter reading for 1PPS pulse-to-pulse jitter. Select "OFF" if using a new CNS Clock II with the Precision 1 PPS Option.

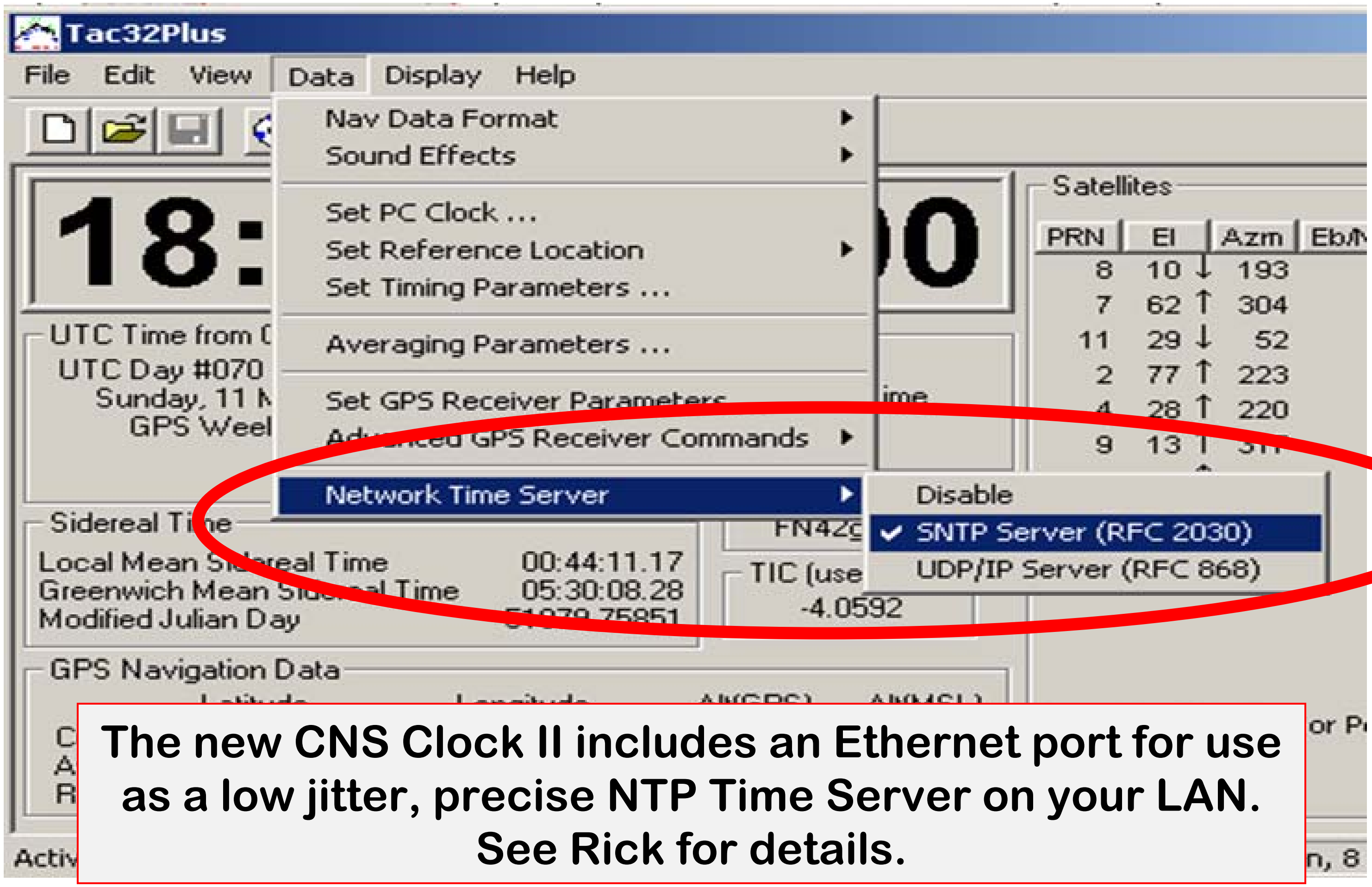


To Activate the LAN Telnet Link between Tac32Plus and the LINUX PC Field System, <u>Hit Control-T</u>:

Then Click on the check-box and the OK button



To Use Tac32Plus PC as your Station's SNTP Network Timer Server:



The new CNS Clock II includes an Ethernet port for use as a low jitter, precise NTP Time Server on your LAN. See Rick for details.