It’s About Time !!!!!

Timing for VLBI

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IVS TOW Meeting

Haystack – May 9-12, 2005

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 two 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

- 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

- 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

- Since VLBI defines UT1, we need to control $[UTC_{(USNO)} - UTC_{(VLBI)}]$ to an accuracy ~100 nsec or better.

The difference between Frequency and Time

Oscillators and Clocks

Oscillator

- Pendulum
- Escapement Wheel
- Crystal Oscillator
- 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

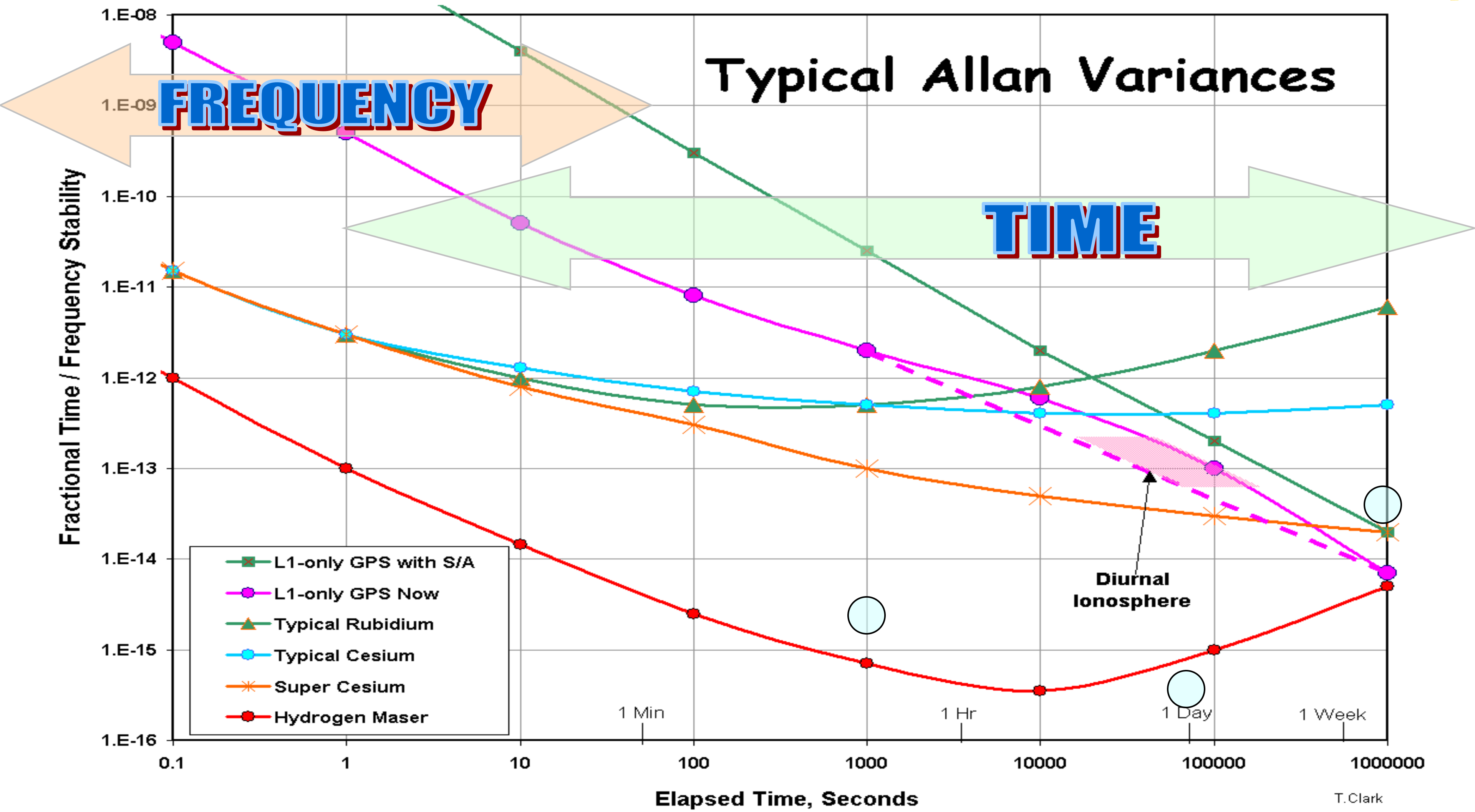
- Gears
- Electronic Counters
- Real Clocks

Long-Term

TIMING

seconds - years

The Allan Variance – A graphical look at clock performance



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

- To get the correlators to line up for efficient processing, the relative time between stations needs to be known to ~ 100 nsec.
- The correlators maintain their "magic tables" that relates the GPS timing data reported by different stations to each other.
- In the past, geodetic and astronomical VLBI data processing has been done by fitting the data with "station clock polynomials" over a day of observing, and then discarding these results as "nuisance parameters" that are not needed for determining baseline lengths, source structure, etc.
- The uncalibrated and unknown offsets now range from 1-10 usec at many VLBI stations.

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

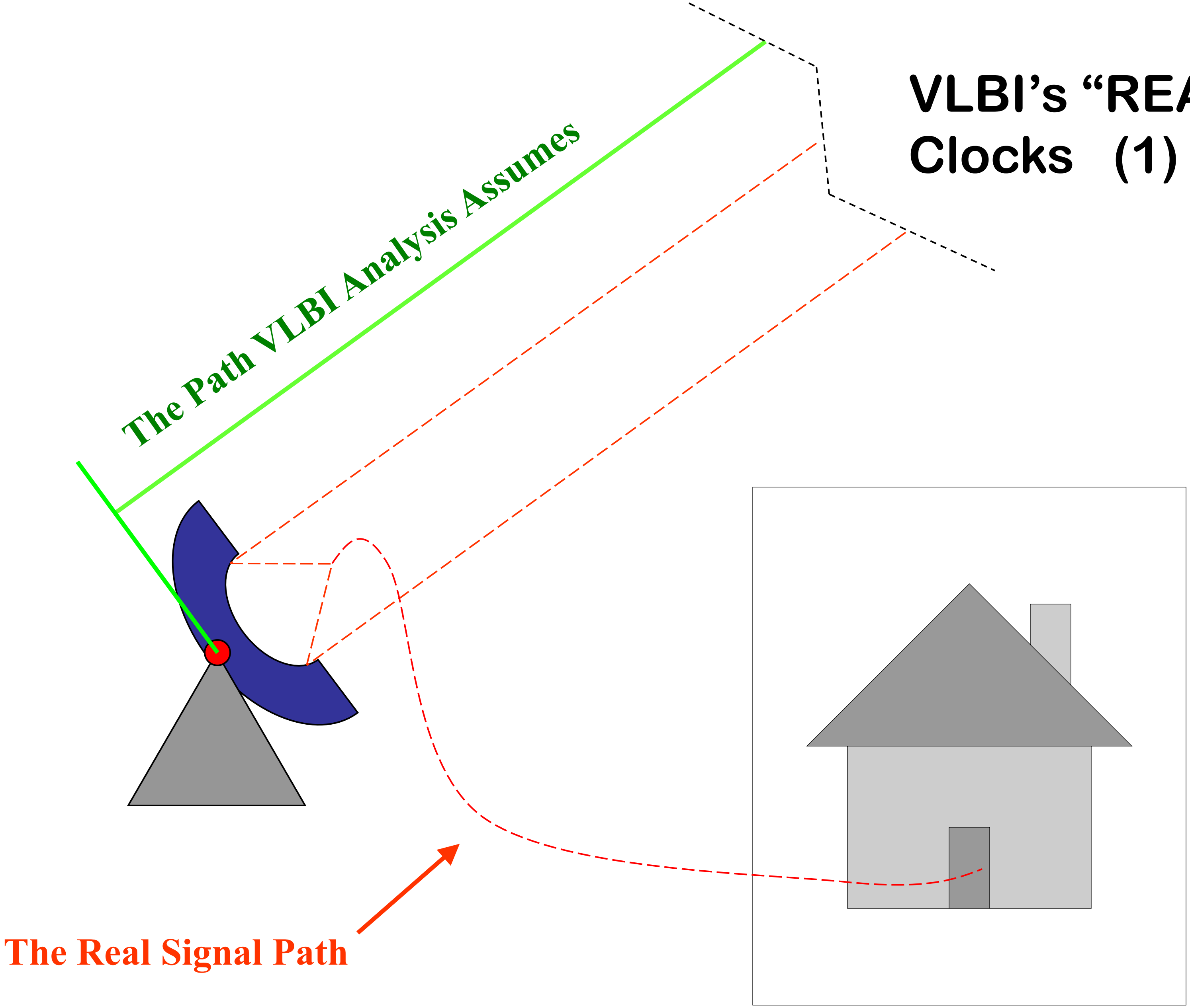
- The ***ONLY*** reason for worrying about "absolute time" is to relate the position of the earth to the position of the stars:
  - Generating Sidereal Time to point antennas.
  - Measuring UT1 (i.e. "Sundial Time") to see changes due to redistribution of mass in/on the earth over long periods of time.
  - Knowing the position of the earth with respect to the moon, planets and even the the GPS satellites.

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

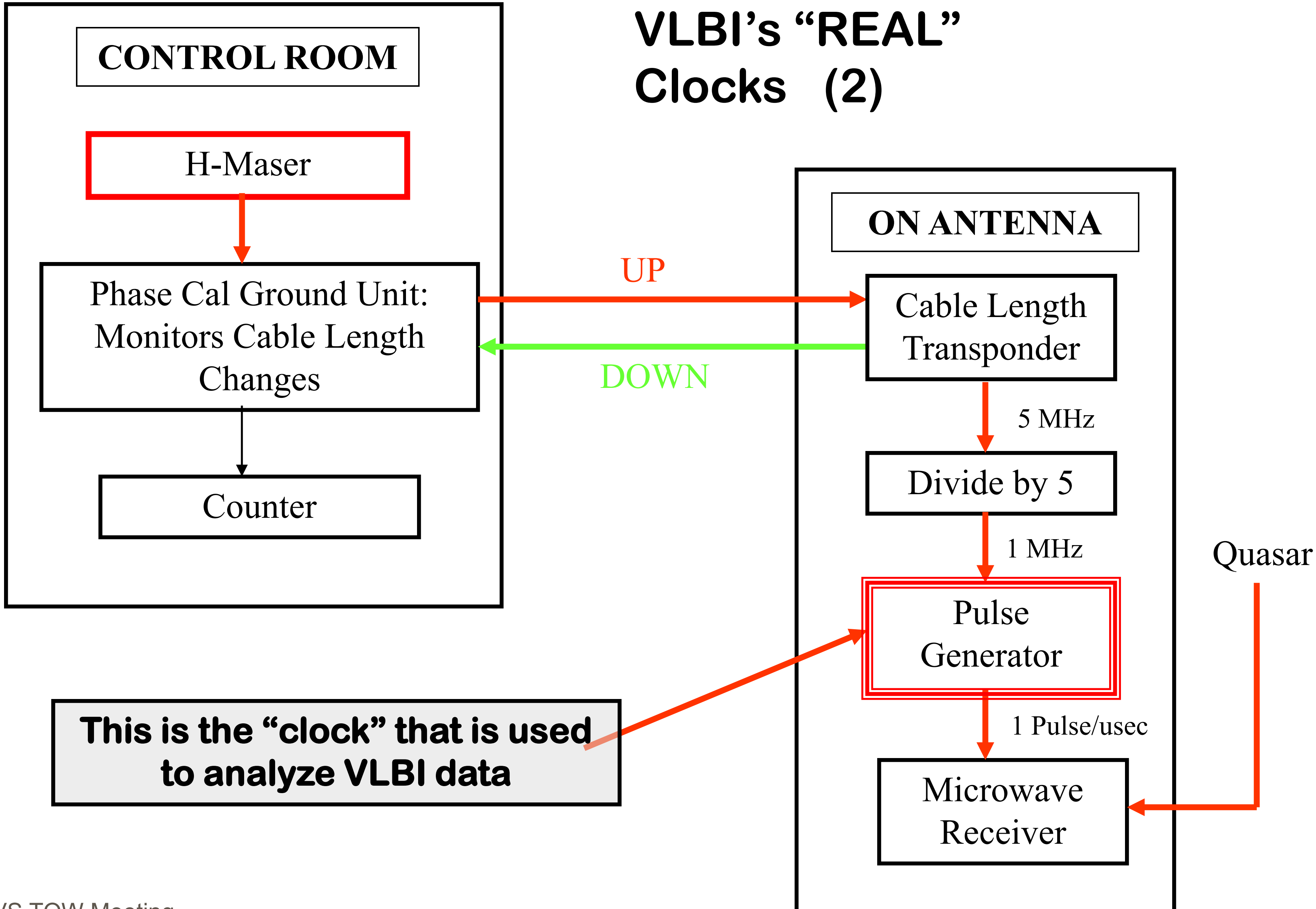
At the stations this means that we will need to pay more attention to timing elements like

- Frequency Standard and Station Timing
- The lengths of 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.

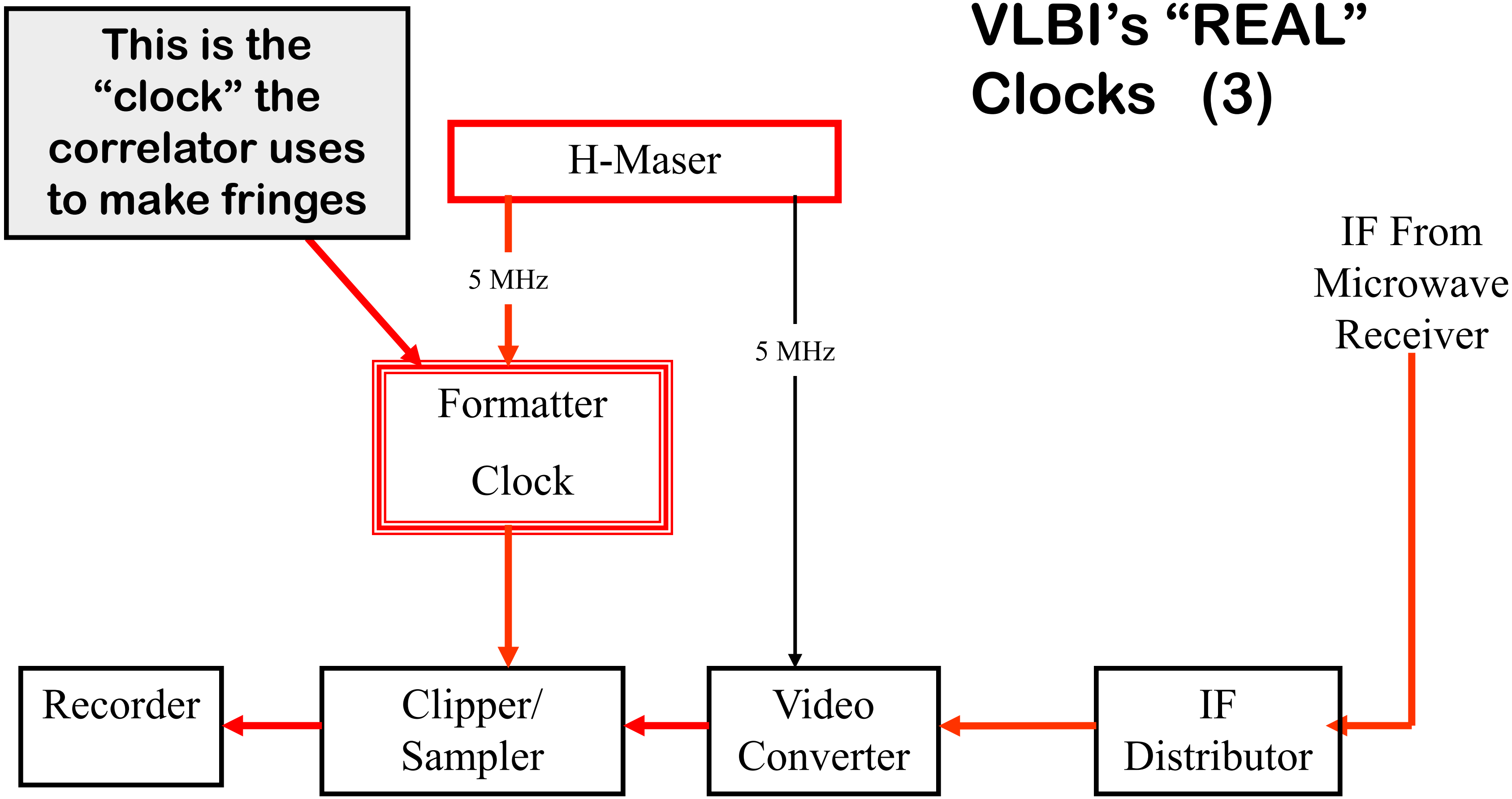
VLBI's "REAL" Clocks (1)



VLBI's "REAL" Clocks (2)



VLBI's "REAL" Clocks (3)

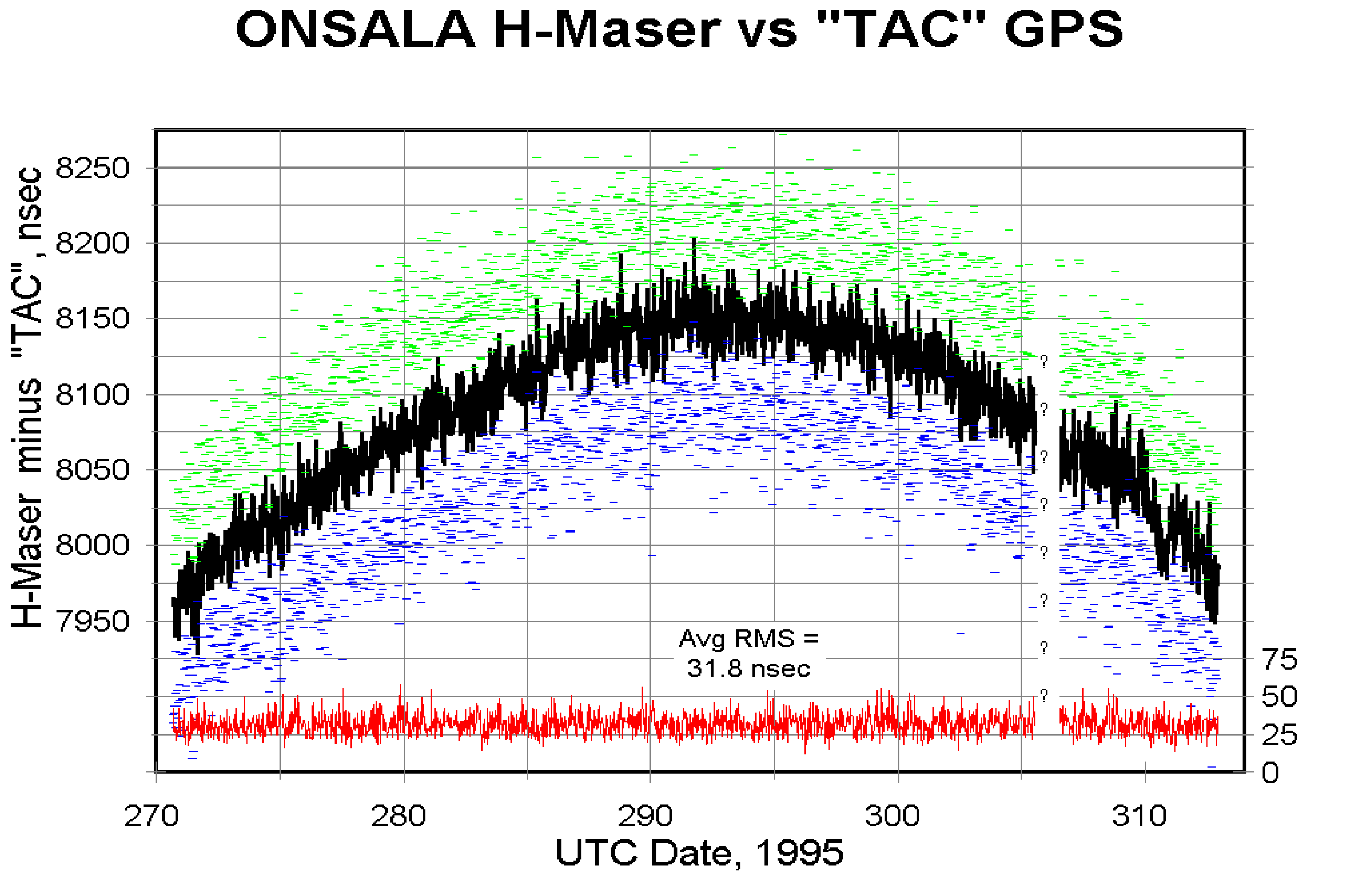


Setting VLBI Clocks Time & Rate with GPS
-- 3 possible ways--

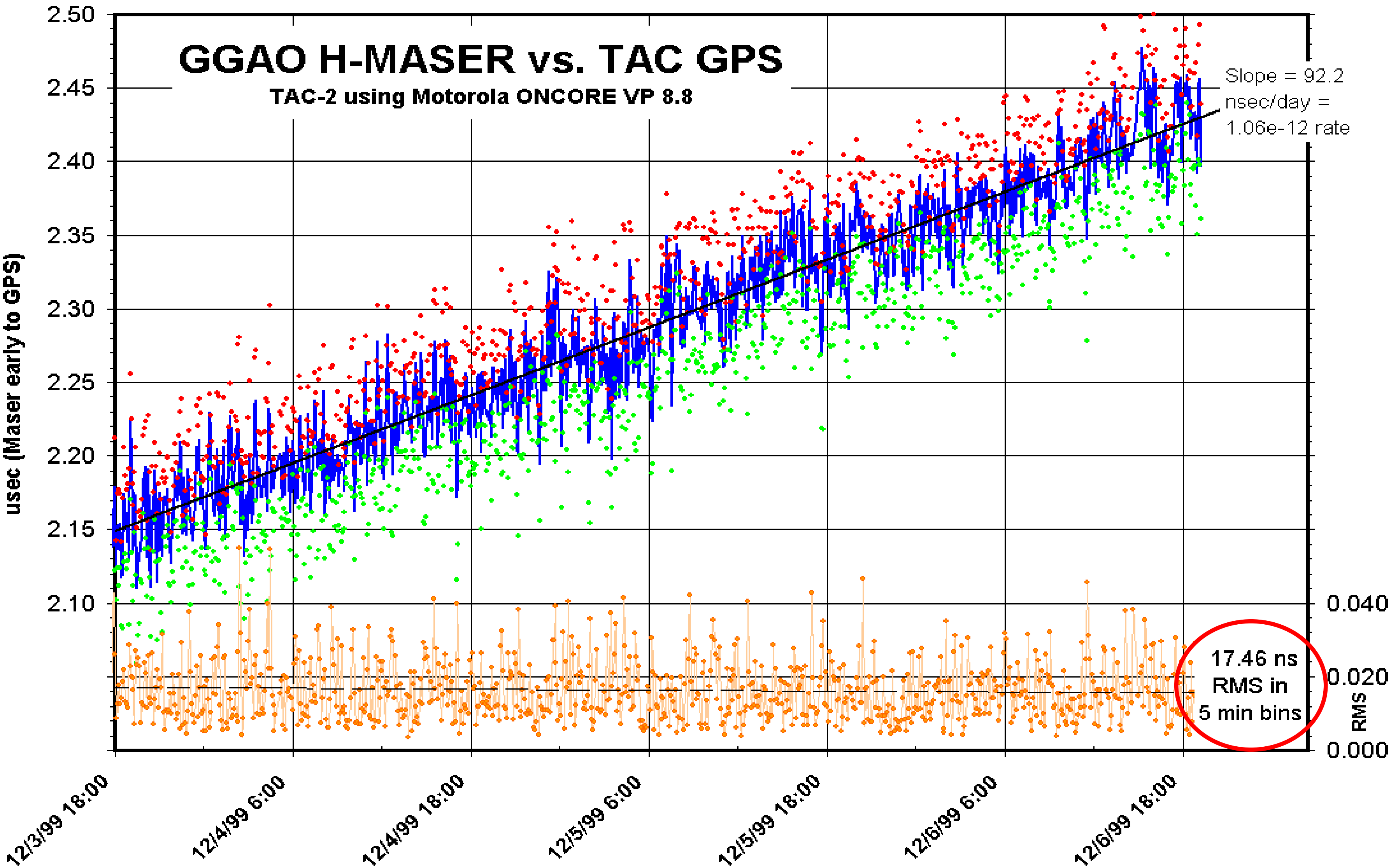
- Compare two distant clocks by observing the same GPS satellite(s) at the same time (called Common View)
  - Requires some intervisibility between sites
  - Requires some near-Real-Time communication
  - Links you directly to the "Master Clock" on the other end at ~1 nsec level
- Use Geodetic GPS receivers (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 for geodesy & ionosphere network
- **Blindly use the Broadcast GPS Timing Signals as a clock**
  - **Single Frequency L1 only (until 2004)**
  - **Yields ~10 nsec results with < $1000 hardware**

An Isolated, Remote VLBI Site -- Urumqi in Xinjiang Province, China

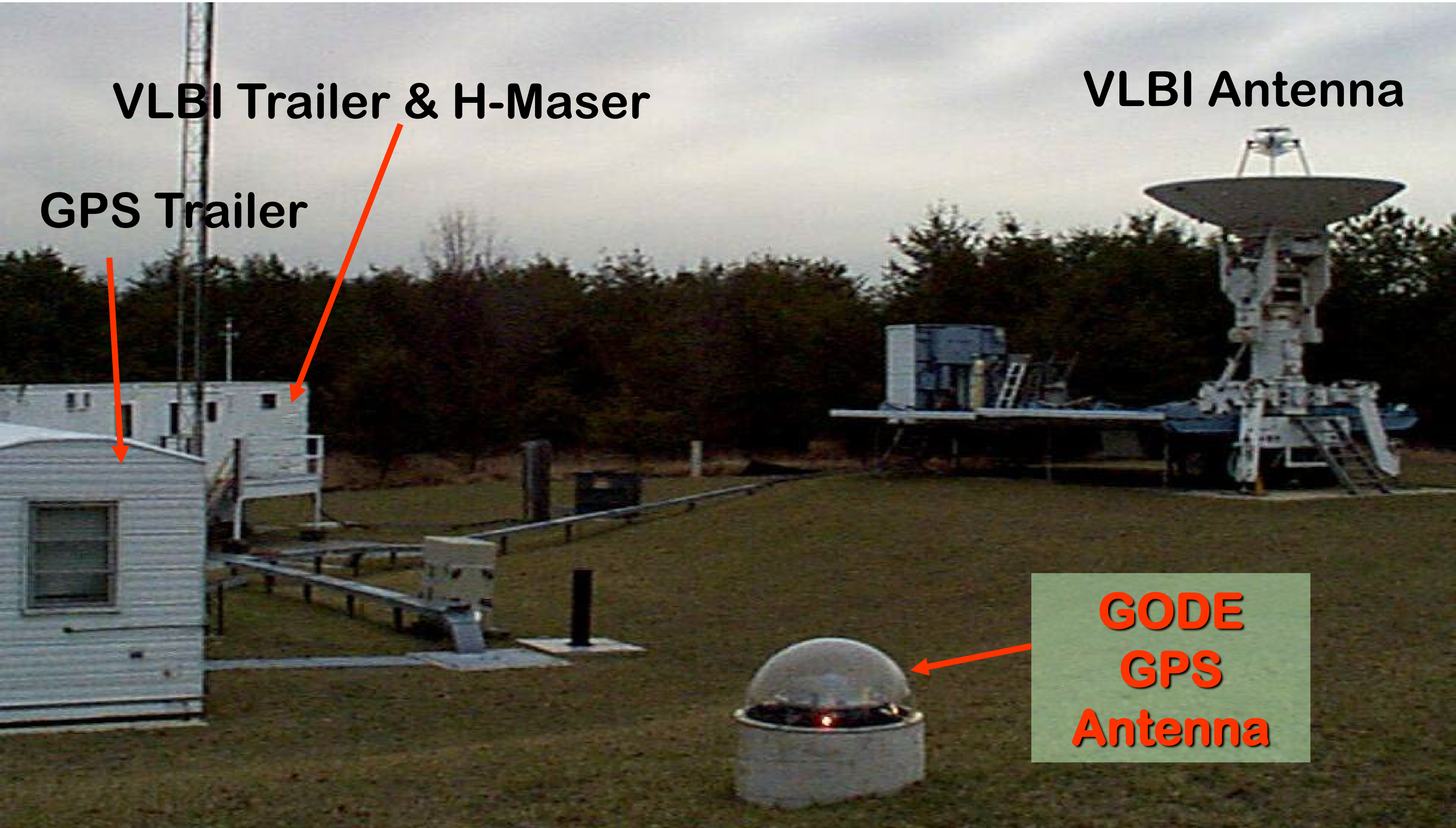
An Early Example of "Blind" GPS Timing with a 6 channel receiver



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



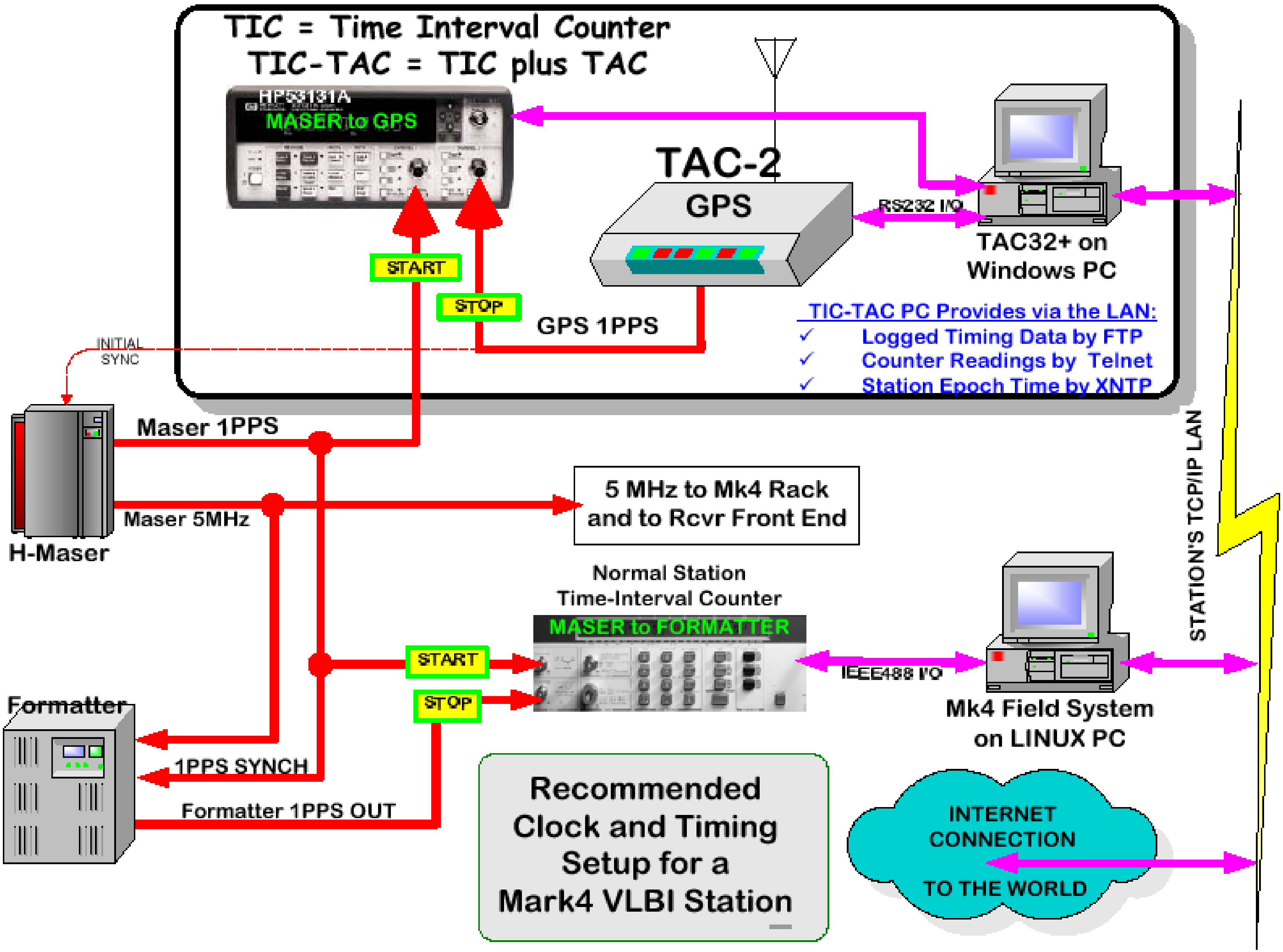
GGAO (Goddard Geophysical & Astronomical Observatory)



How we got ~30 nsec timing 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.

- **These steps were automated in the SHOWTIME and TAC32Plus Software.**



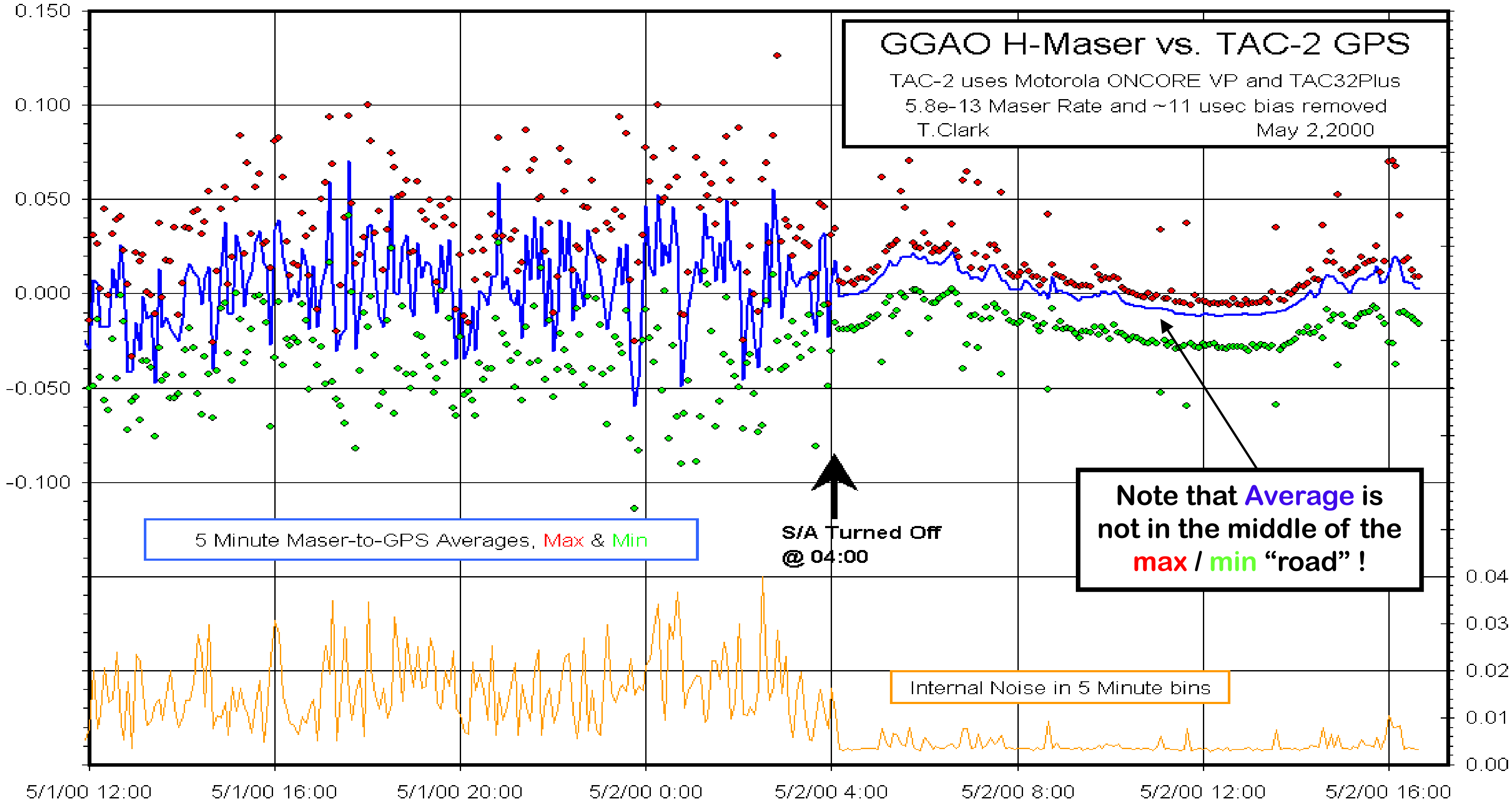
TIC = Time Interval Counter
TIC-TAC = TIC plus TAC
HP53131A
MASER to GPS
TAC-2
GPS
RS232 I/O
TAC32+ on
Windows PC
START
STOP
GPS 1PPS
INITIAL
SYNC
TIC-TAC PC Provides via the LAN:
✓ Logged Timing Data by FTP
✓ Counter Readings by Telnet
✓ Station Epoch Time by XNTP
Maser 1PPS
Maser 5MHz
H-Maser
5 MHz to Mk4 Rack
and to Rcvr Front End
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

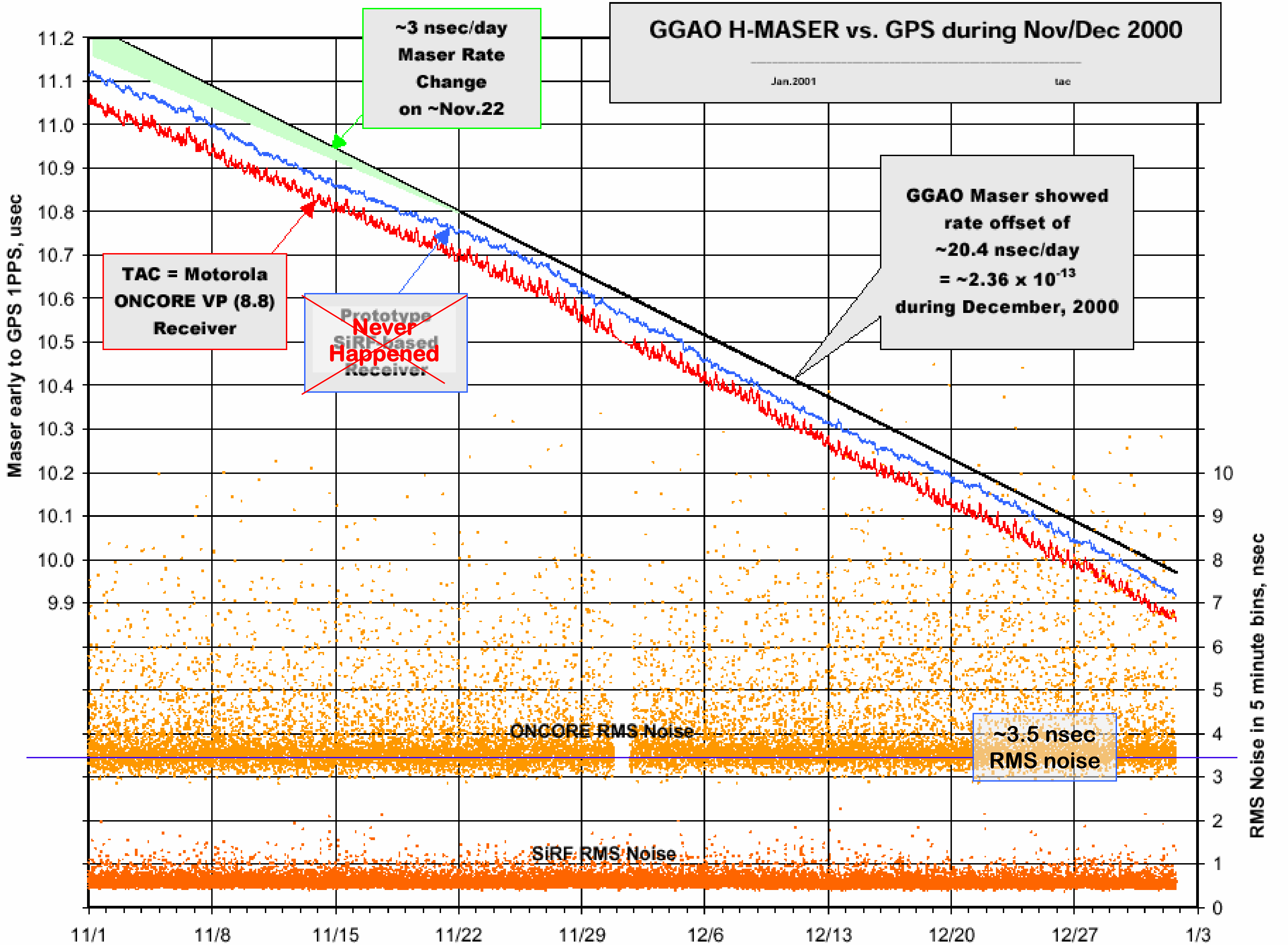
Let Us Now Discuss . . .

- What happened when S/A was turned off on May 2, 2000.
- Sawtooth and Glitches
- Some recent results obtained with Motorola's newest low cost timing receiver (the M12+)

What happened when S/A went away?

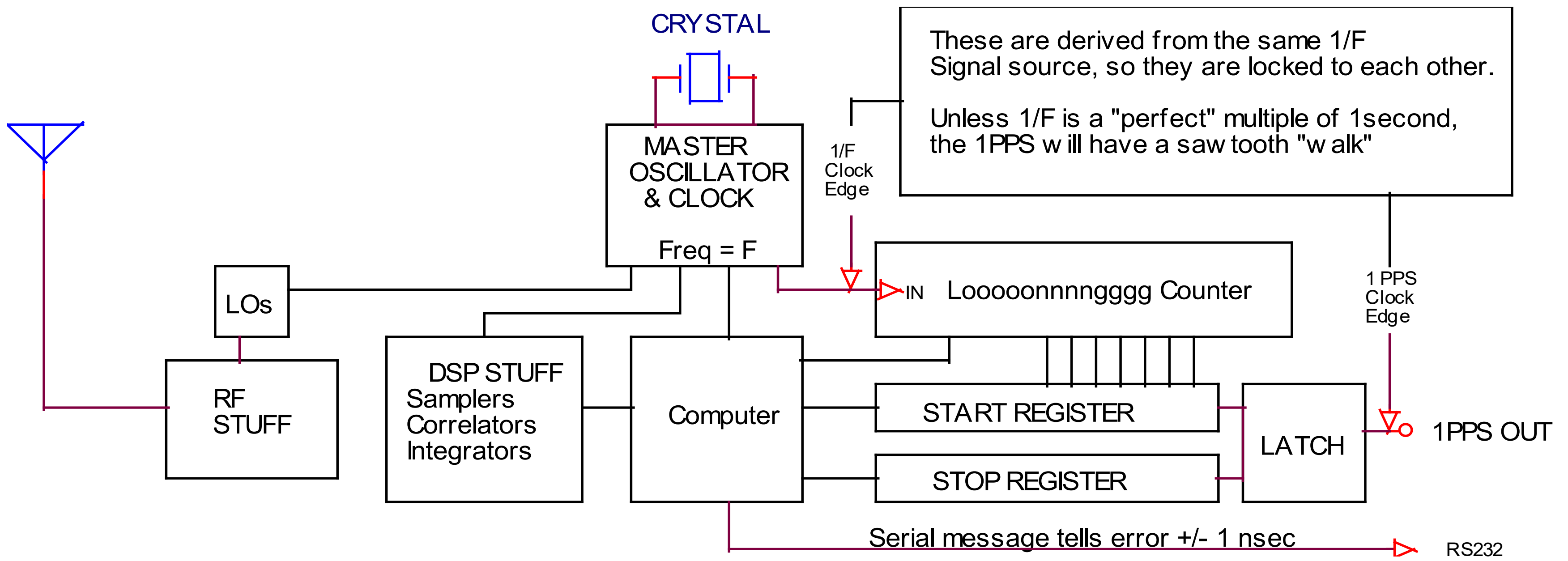
Using 8-channel Motorola ONCORE VP Receiver . . .





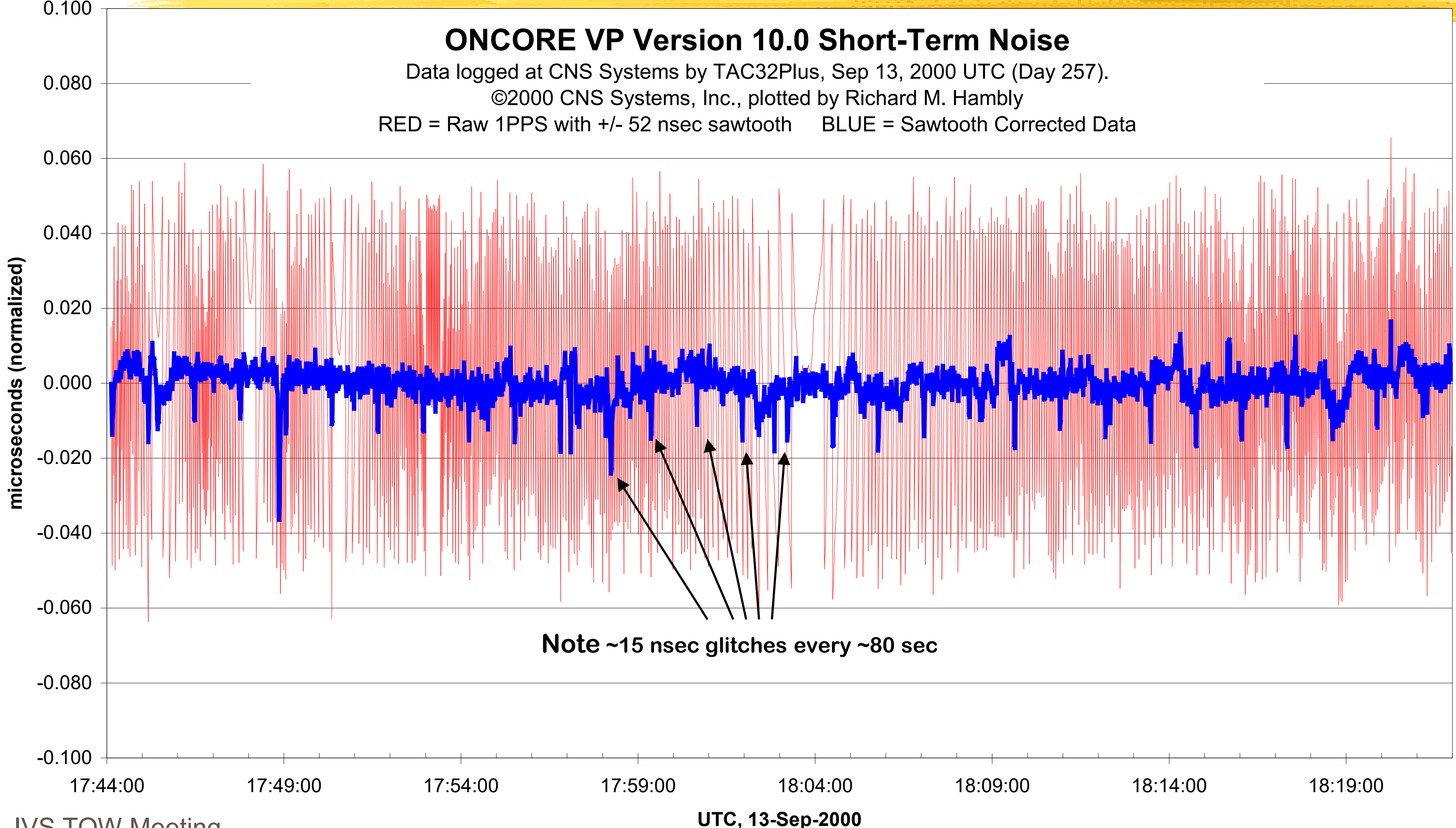
GGAO H-MASER vs. GPS during Nov/Dec 2000
Jan.2001
tac
~3 nsec/day
Maser Rate
Change
on ~Nov.22
GGAO Maser showed
rate offset of
~20.4 nsec/day
= ~2.36 x 10^-13
during December, 2000
TAC = Motorola
ONCORE VP (8.8)
Receiver
Prototype
SiRF based
Receiver
Never
Happened
ONCORE RMS Noise
~3.5 nsec
RMS noise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

What is the sawtooth effect ????



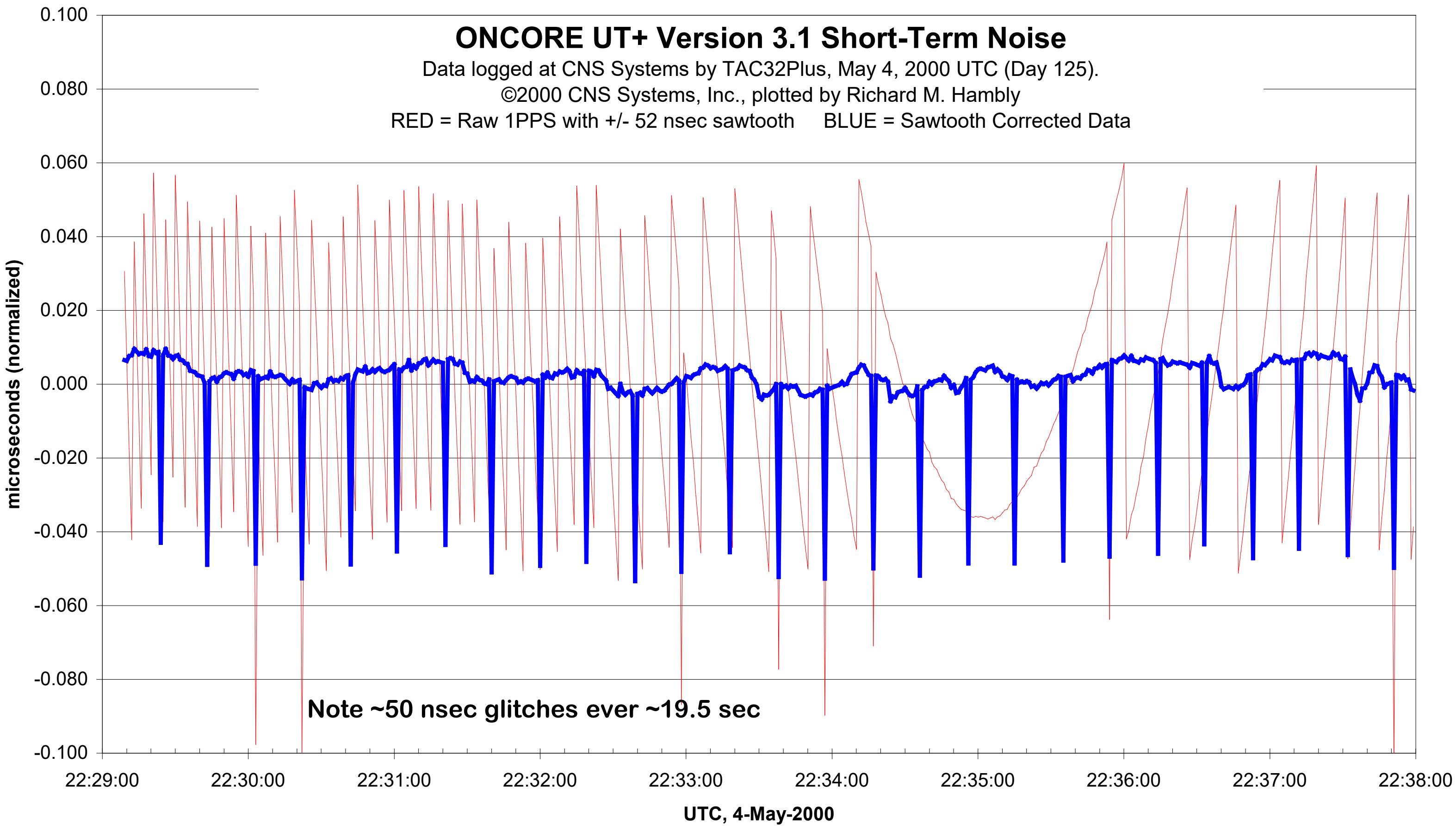
- For the older Oncore, F=9.54 MHz, so the 1/F sawtooth has a range of +/- 52 nsec (104 nsec peak-to-peak)
- The new Oncore M12+ has F ≈ 40 MHz, so the sawtooth has been reduced to +/- 13 nsec (26 nsec).

An example of 1PPS sawtooth
Motorola VP (10.0)



An example of 1PPS sawtooth

Motorola UT+ (3.1)



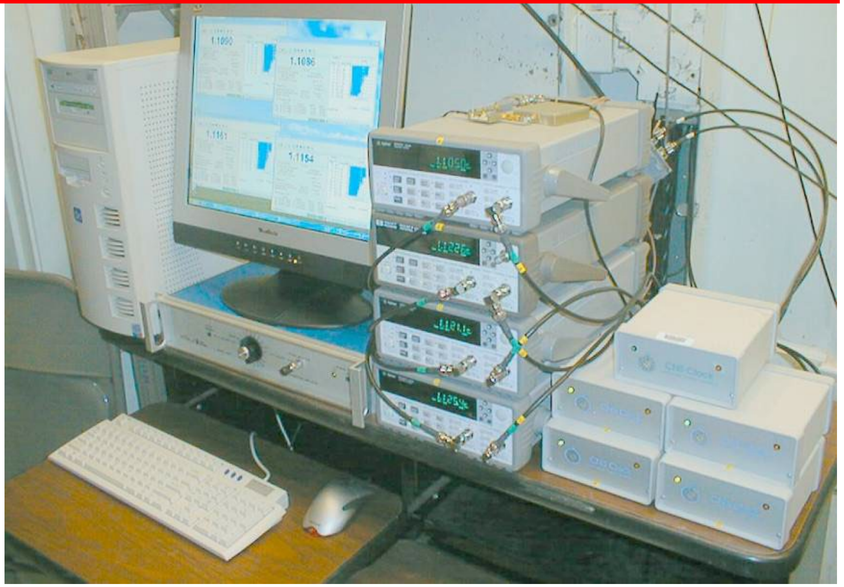
CNS Systems' Test Bed at USNO

Calibrating the "DC" Offset of the new M12+ receiver.

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.

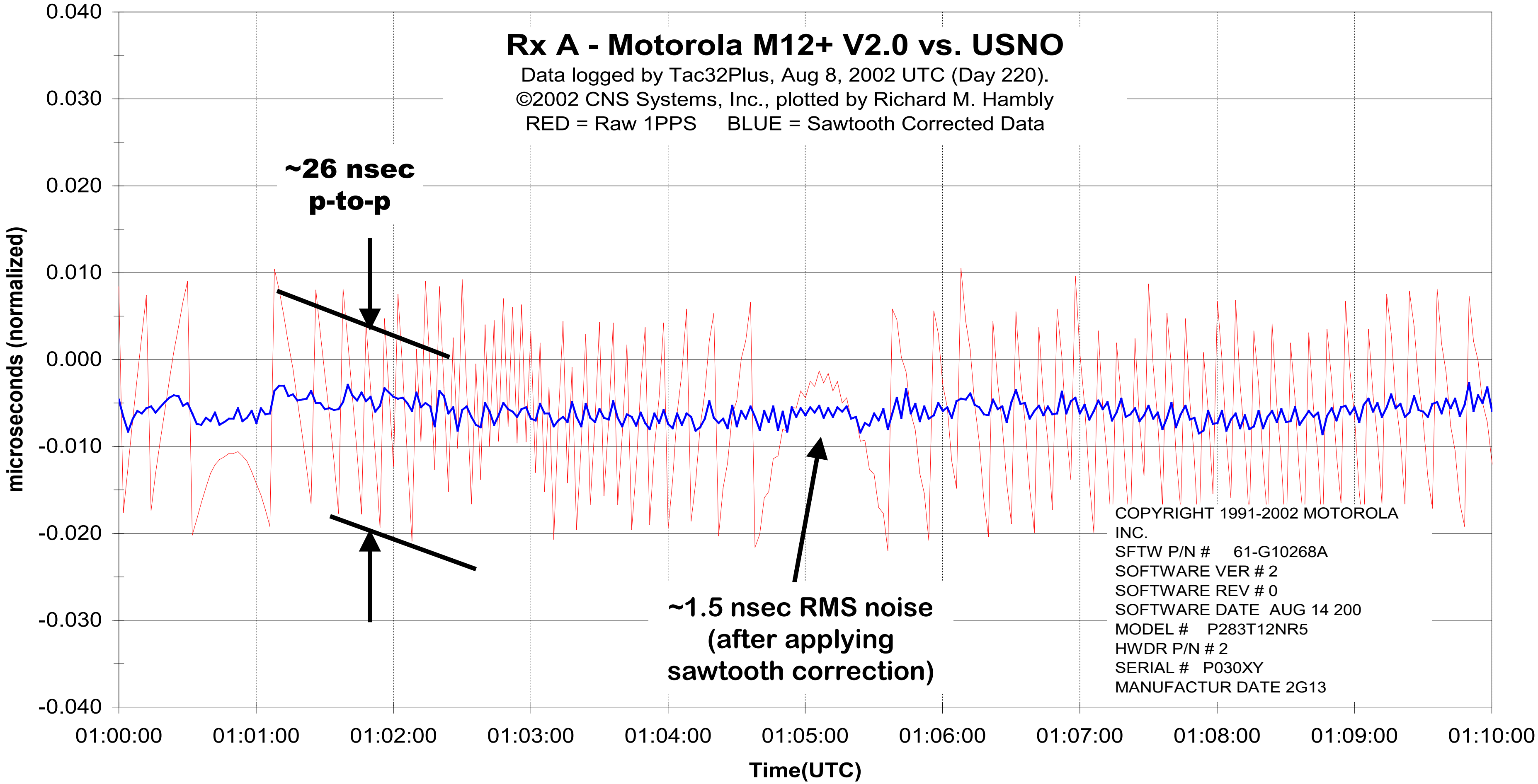
Tac32Plus software simultaneously processes data from four Time Interval Counters and four CNS Clocks, writing 12 logs continuously.



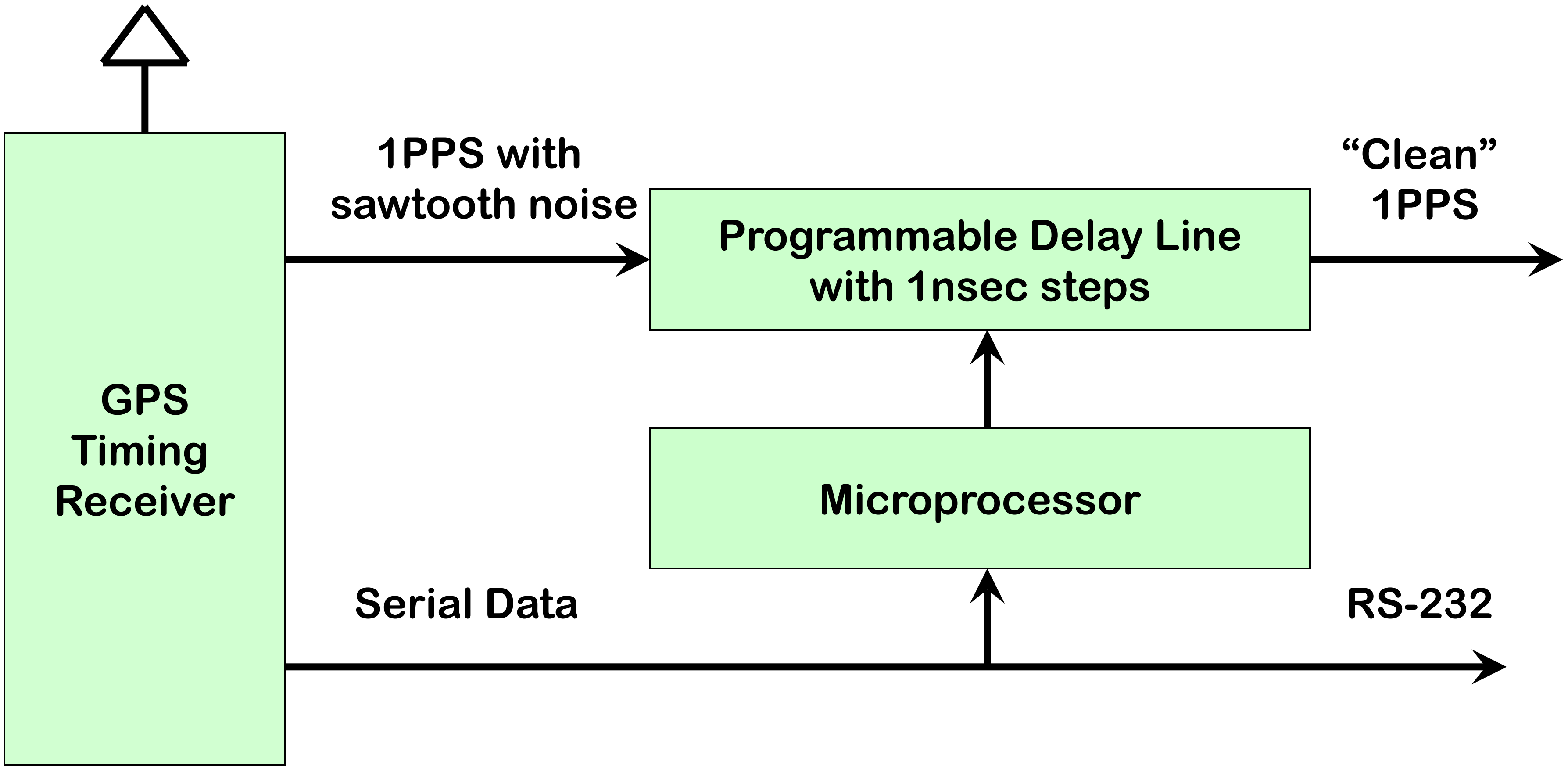
Time Interval Counters compare the 1PPS from each CNS Clock (M12+) against the USNO's UTC time tick.

An example of 1PPS sawtooth

with the new Motorola M12+ receiver



How could the sawtooth noise be eliminated ???

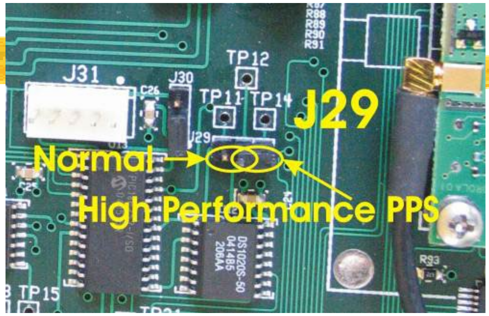


In 2003 we showed this potential solution …

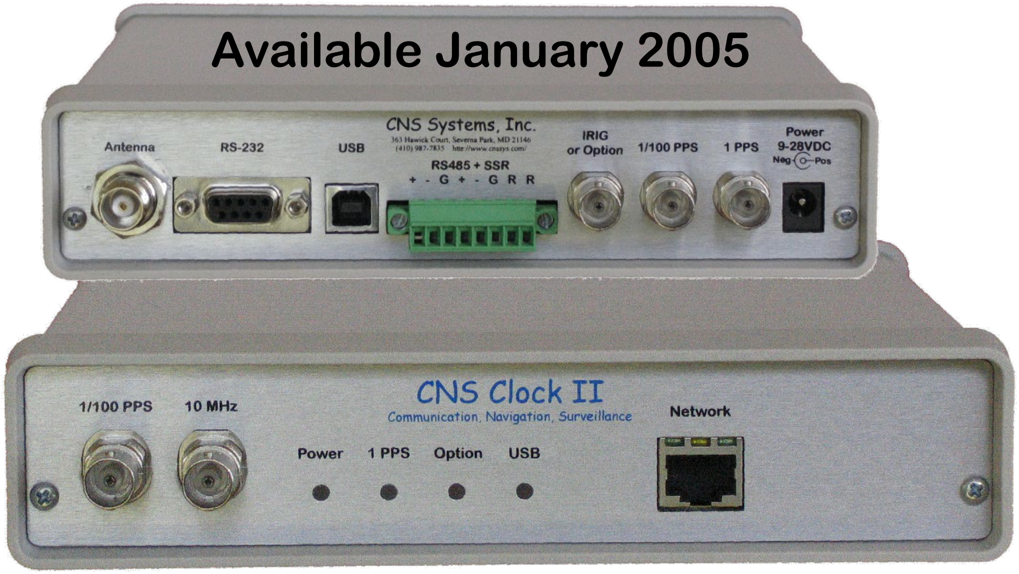
The Future is here now!
The CNS Clock II

1994 - 2004

1PPS Sawtooth
Correction
Option →

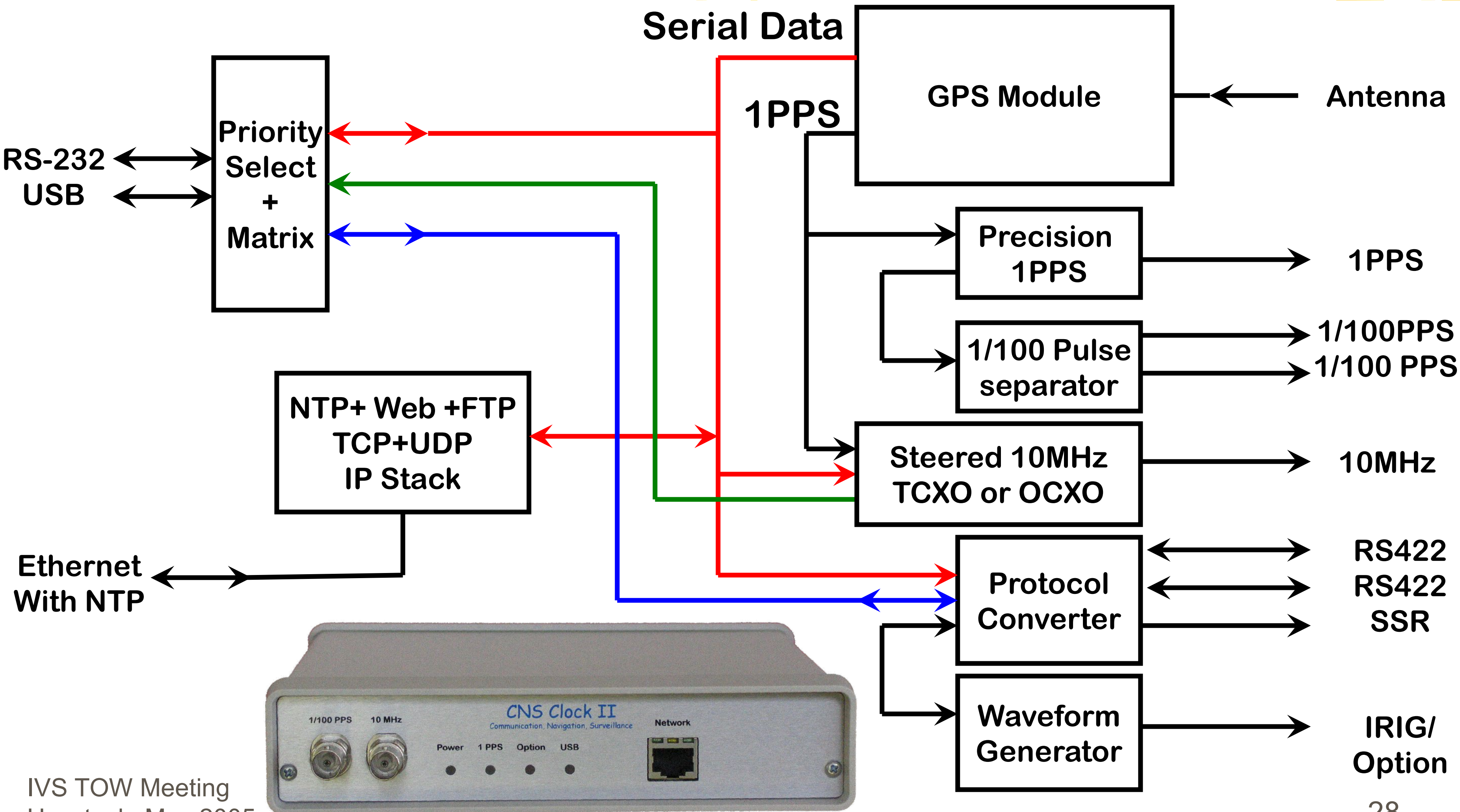


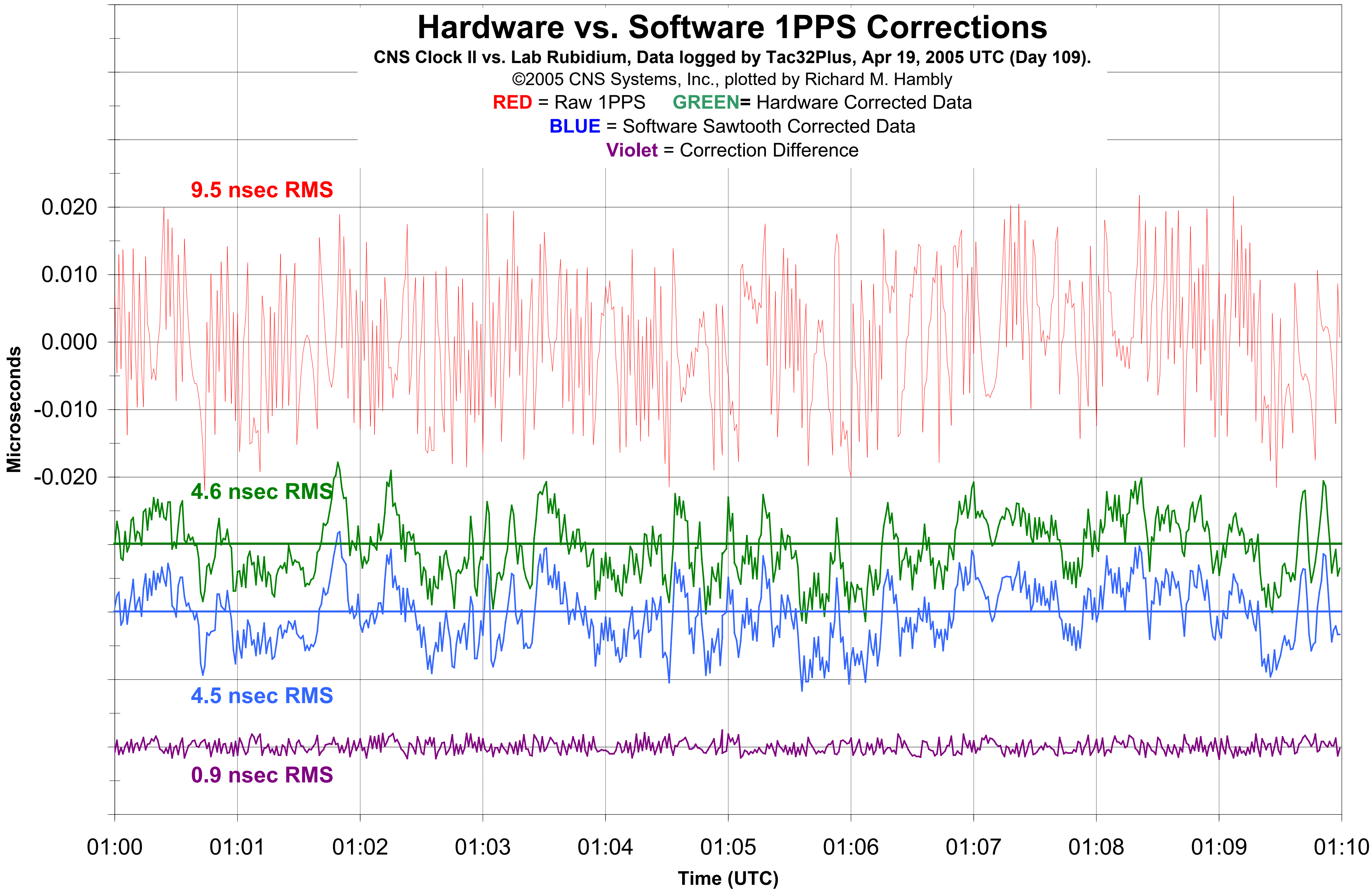
Available January 2005



RS-232 Serial Port
USB 2.0 Port
TNC(F) Antenna Connector
Buffered 1 PPS output
Two buffered 1/100 PPS outputs
10 MHz output
2 bidirectional RS-485 ports
Bipolar (AC/DC) solid state relay out
Power 9-30 volts @ 500ma
Options:
- Tx Sequencer output.
- IRIG-B output (modulated, PWM or Manchester).

CNS Clock II Block Diagram

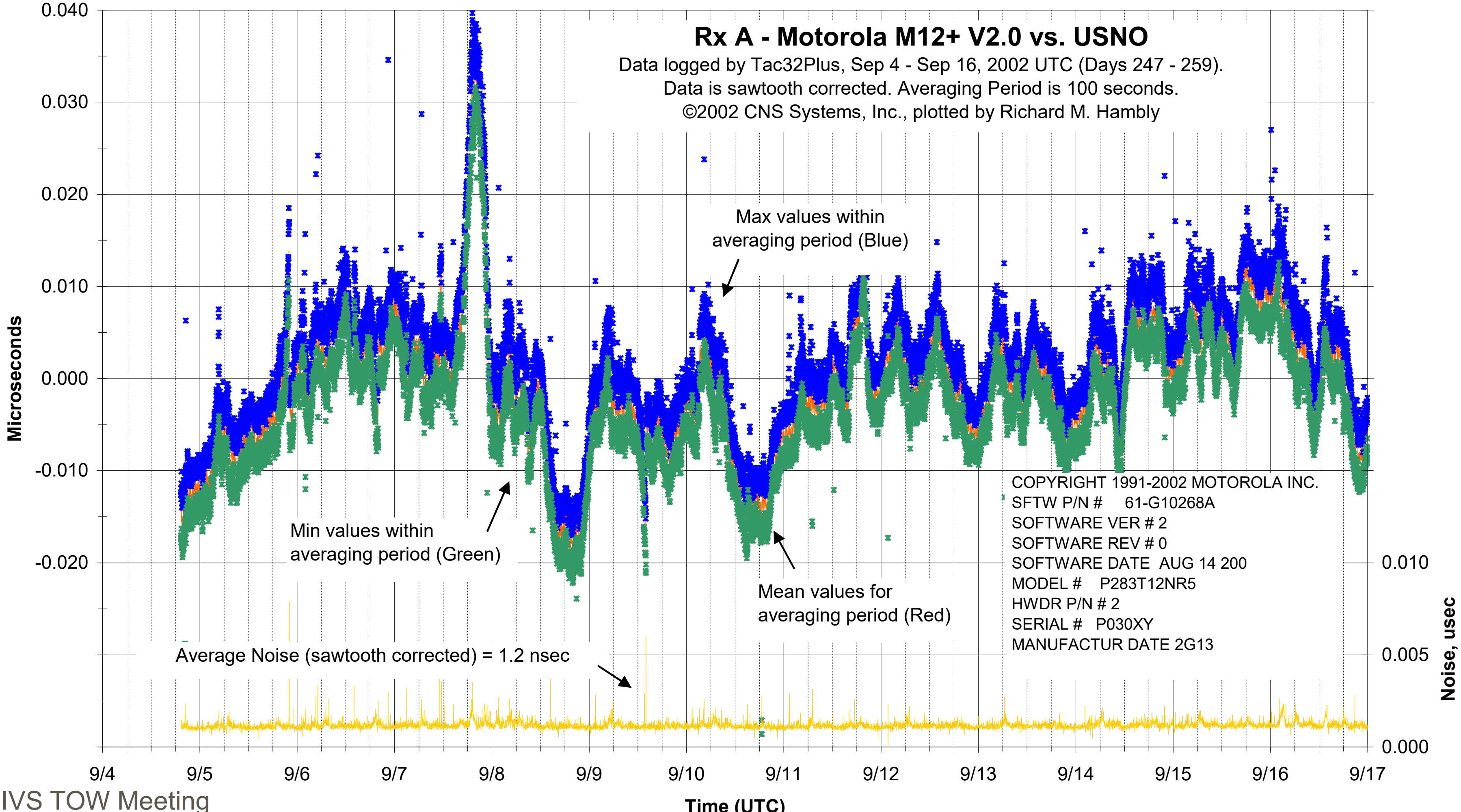




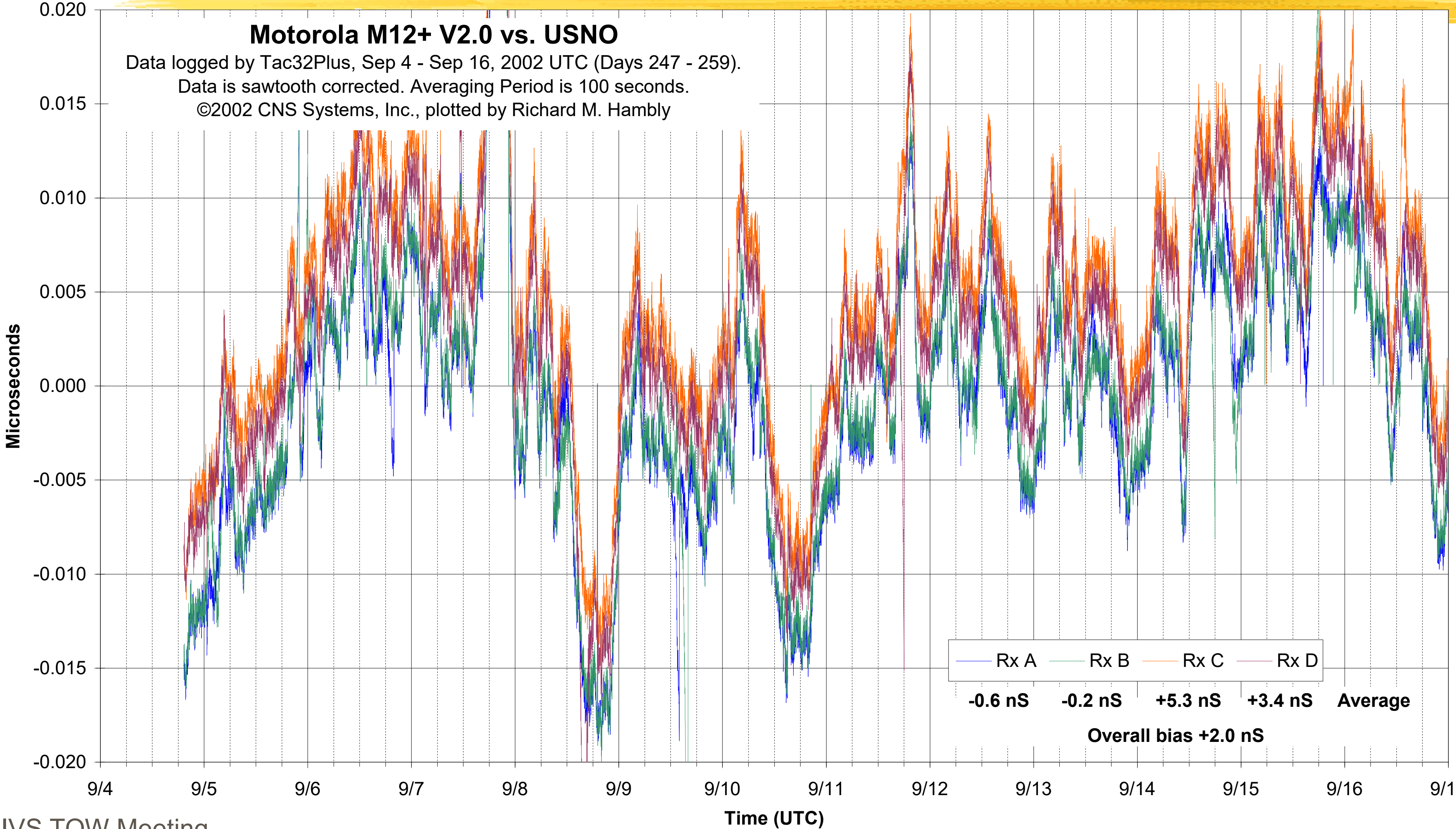
Hardware vs. Software 1PPS Corrections
CNS Clock II vs. Lab Rubidium, Data logged by Tac32Plus, Apr 19, 2005 UTC (Day 109).
©2005 CNS Systems, Inc., plotted by Richard M. Hambly
RED = Raw 1PPS
GREEN= Hardware Corrected Data
BLUE = Software Sawtooth Corrected Data
Violet = Correction Difference
9.5 nsec RMS
4.6 nsec RMS
4.5 nsec RMS
0.9 nsec RMS
Microseconds
0.020
0.010
0.000
-0.010
-0.020
01:00
01:01
01:02
01:03
01:04
01:05
01:06
01:07
01:08
01:09
01:10
Time (UTC)

Individual M12 Clock Performance

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.

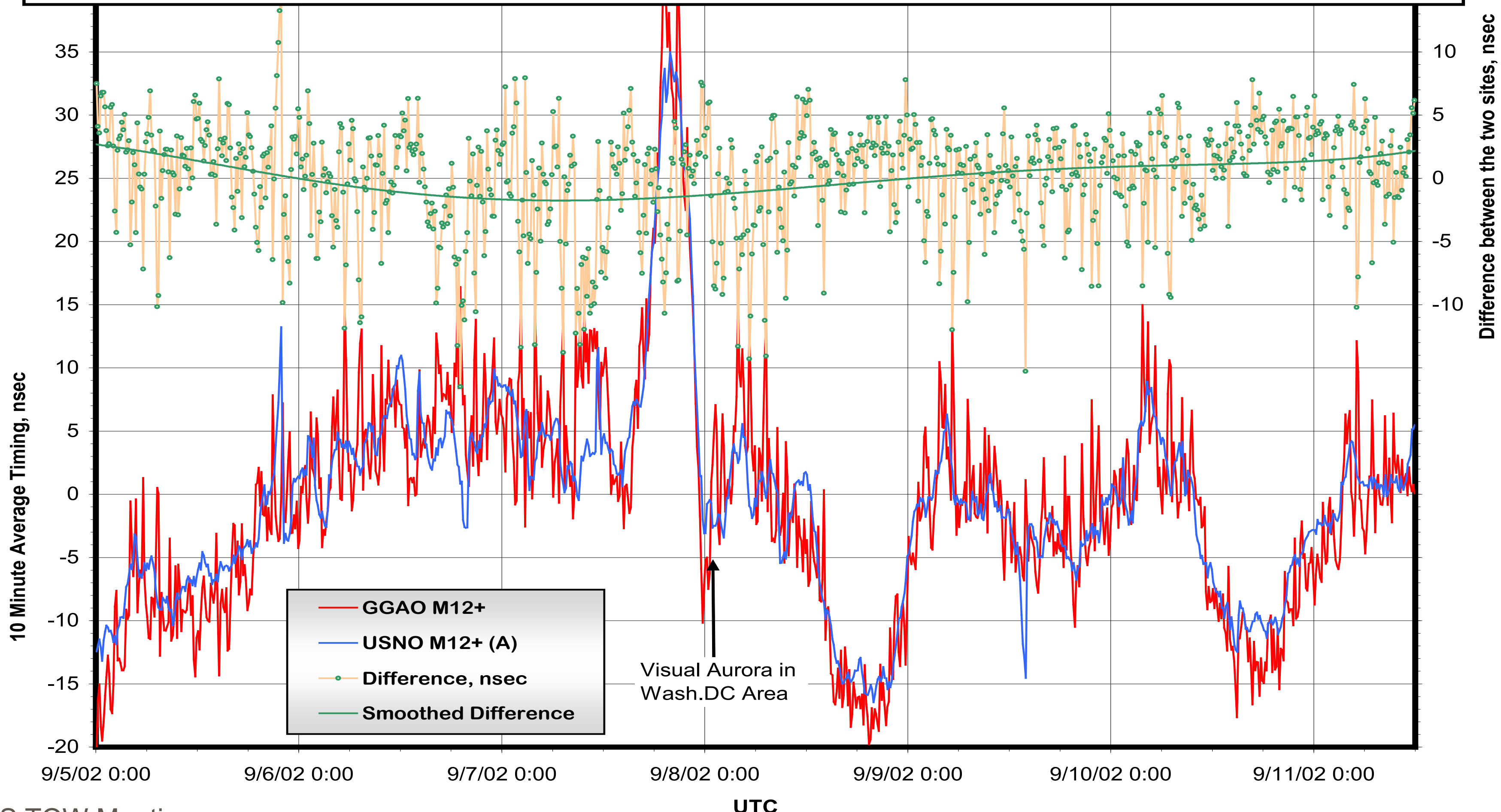
This picture is a four hour composite of 140 different photos spanning 20:00 thru 24:00 EDT on Sept. 8th (00:00 thru 04:00 UTC Sep. 9).

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.



Where to get information?

These Slides and related material:

http://gpstime.com

Information on the CNS Clock and the CNS Clock II:

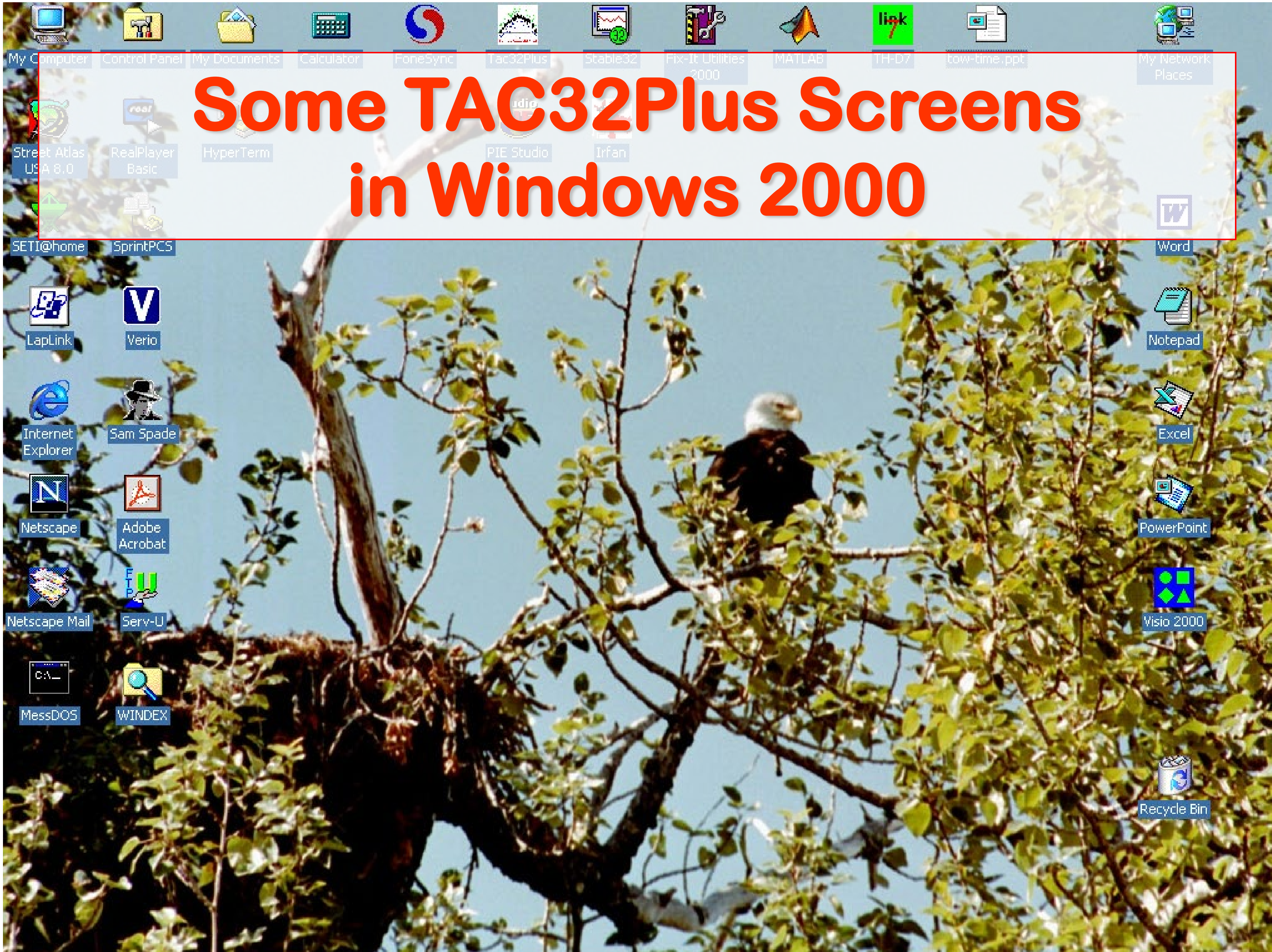
http://www.cnssys.com

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

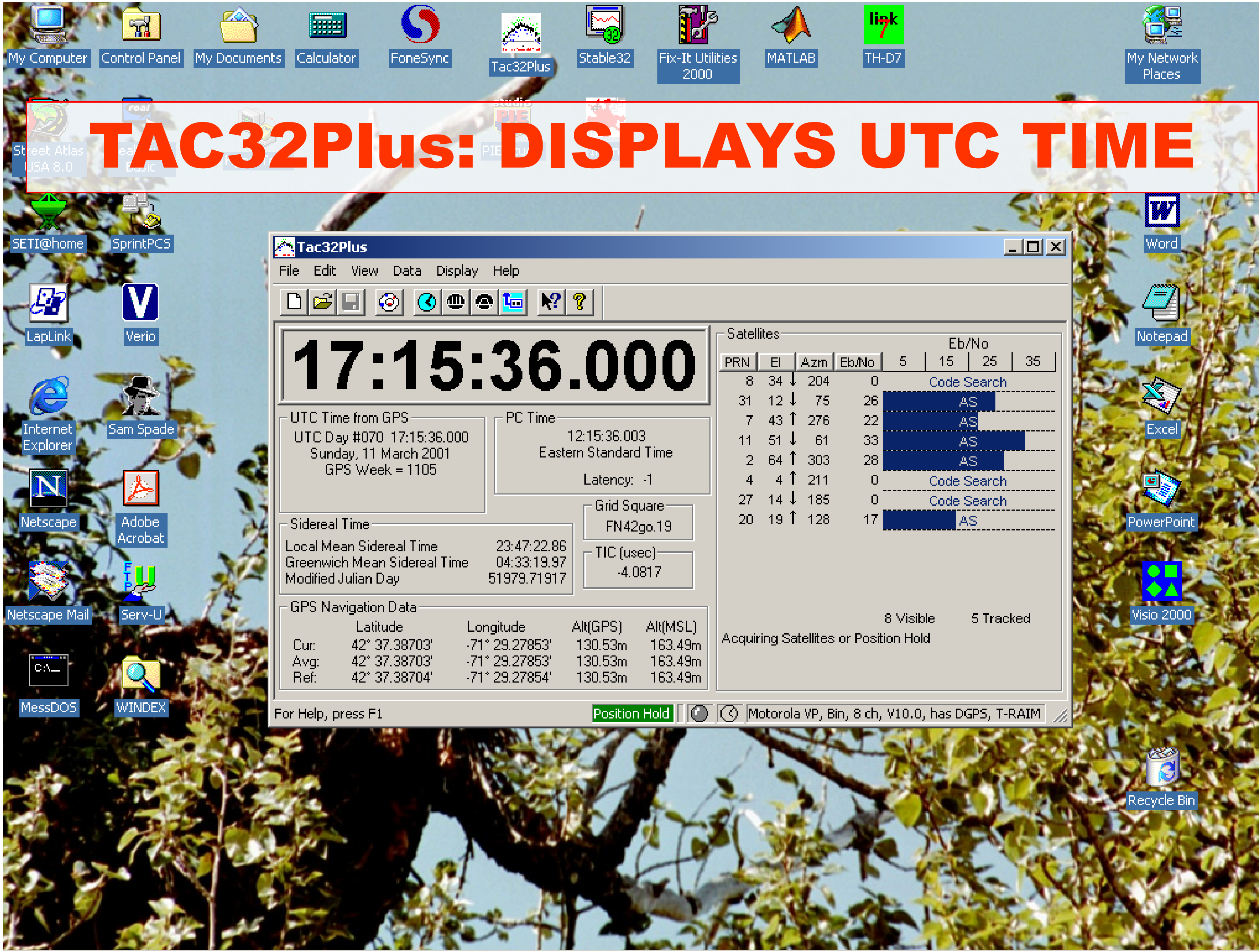
To contact me: mailto:w3iwi@toad.net

To contact Rick: mailto:rick@cnssys.com

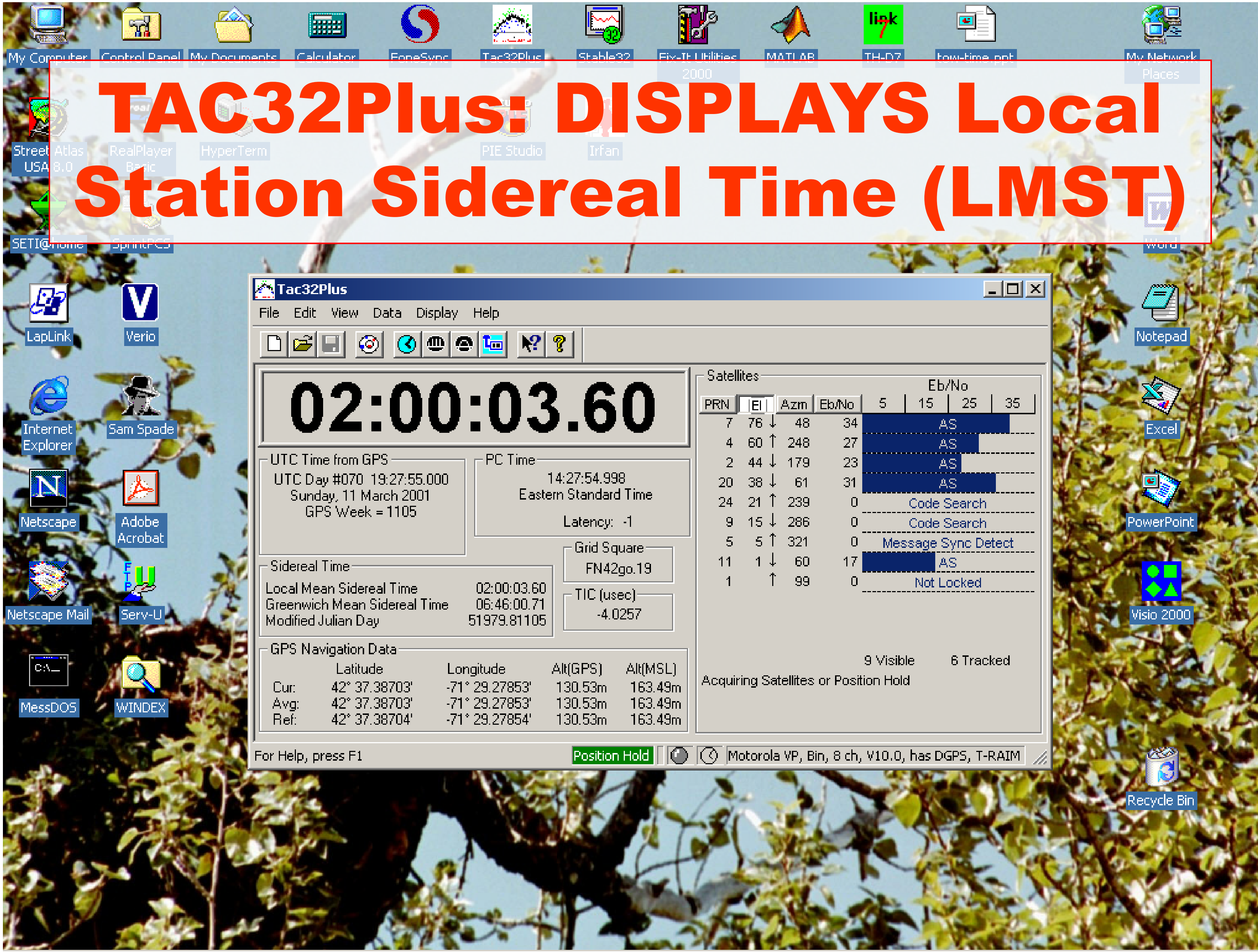
Some TAC32Plus Screens in Windows 2000



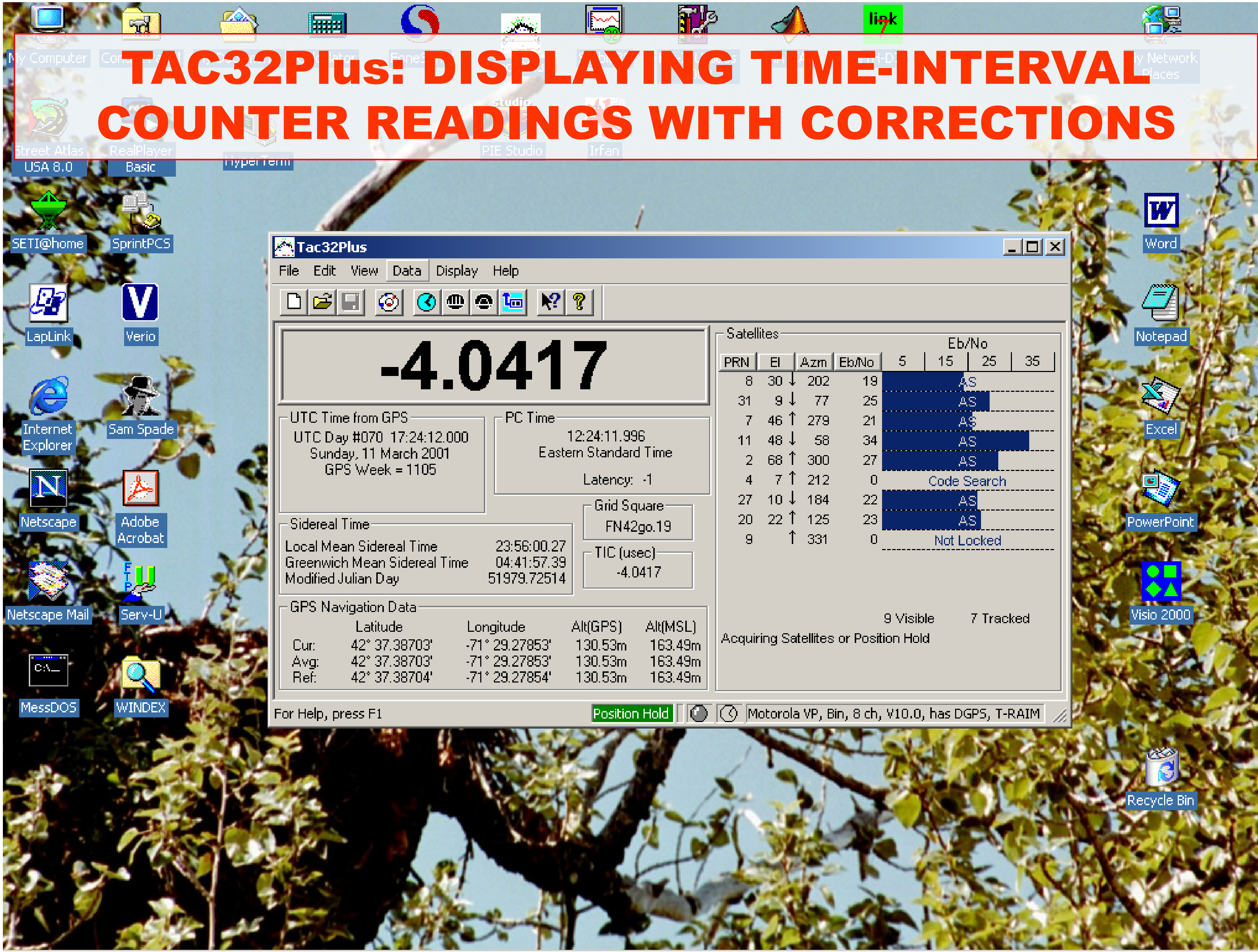
TAC32Plus: DISPLAYS UTC TIME

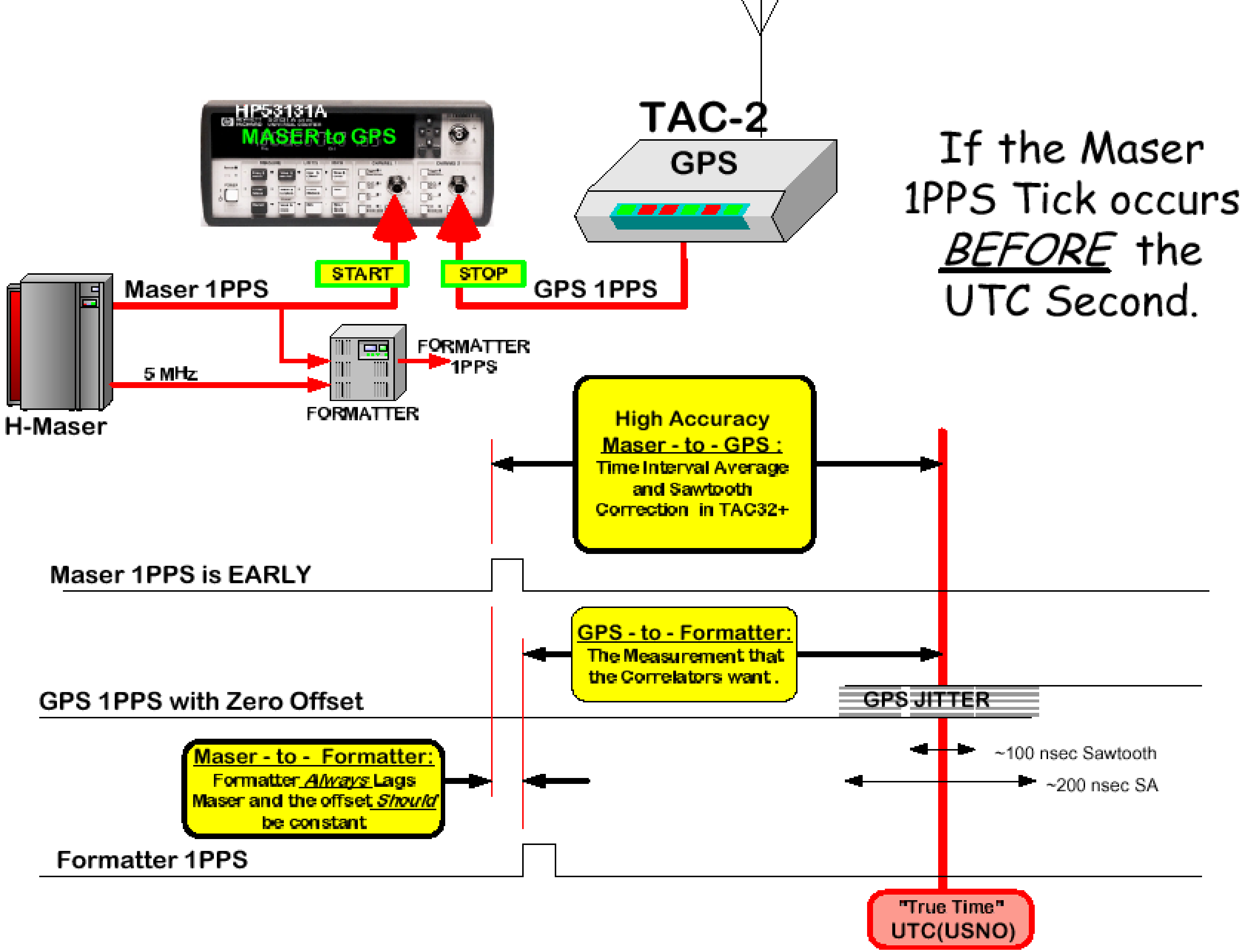


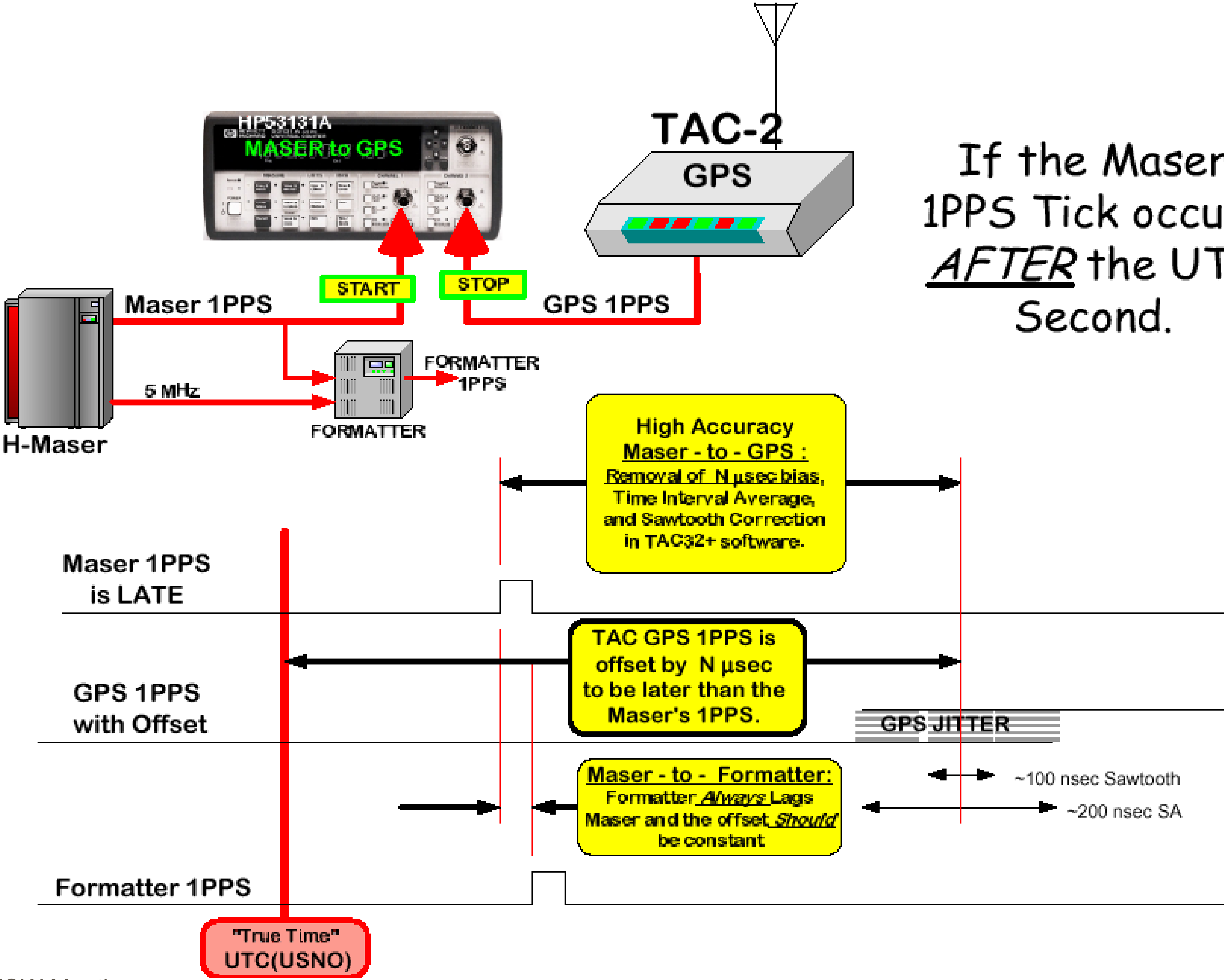
TAC32Plus: DISPLAYS Local Station Sidereal Time (LMST)



TAC32Plus: DISPLAYING TIME-INTERVAL COUNTER READINGS WITH CORRECTIONS




HP53131A
MASER to GPS
TAC-2
GPS
If the Maser 1PPS Tick occurs BEFORE the UTC Second.
START
STOP
Maser 1PPS
GPS 1PPS
5 MHz
FORMATTER 1PPS
FORMATTER
H-Maser
High Accuracy
Maser - to - GPS :
Time Interval Average and Sawtooth Correction in TAC32+
Maser 1PPS is EARLY
GPS - to - Formatter:
The Measurement that the Correlators want.
GPS JITTER
GPS 1PPS with Zero Offset
~100 nsec Sawtooth
~200 nsec SA
Maser - to - Formatter:
Formatter Always Lags Maser and the offset Should be constant
Formatter 1PPS
"True Time"
UTC(USNO)



If the Maser 1PPS Tick occurs *AFTER* the UTC Second.

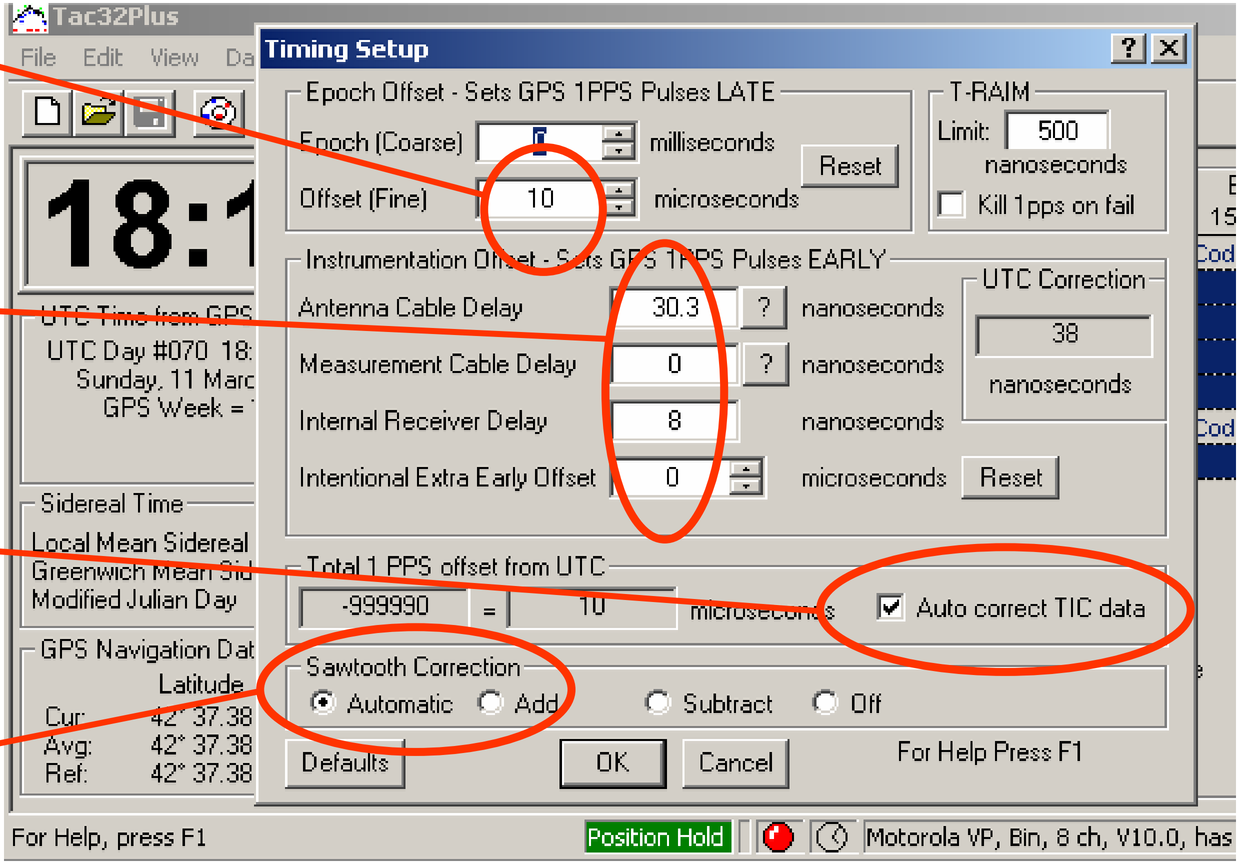
To Make Sure TAC32 is Logging the "true" Maser-to-GPS Time Interval:

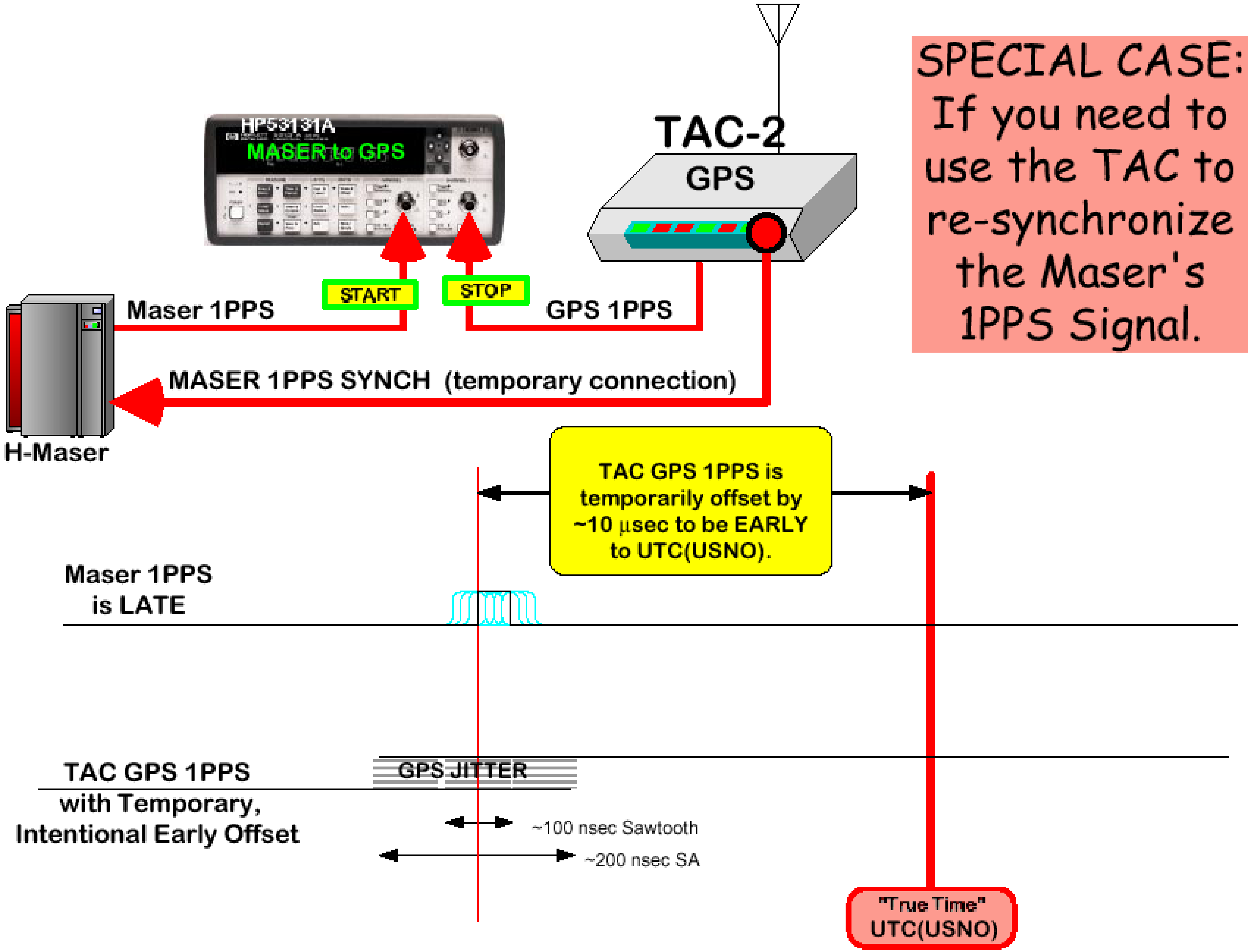
Offset GPS LATE if needed to be certain that GPS 1PPS is later than Maser 1PPS.

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

Allow the software to correct for all timing offsets.

Allow software to correct the 1PPS pulse-to-pulse jitter

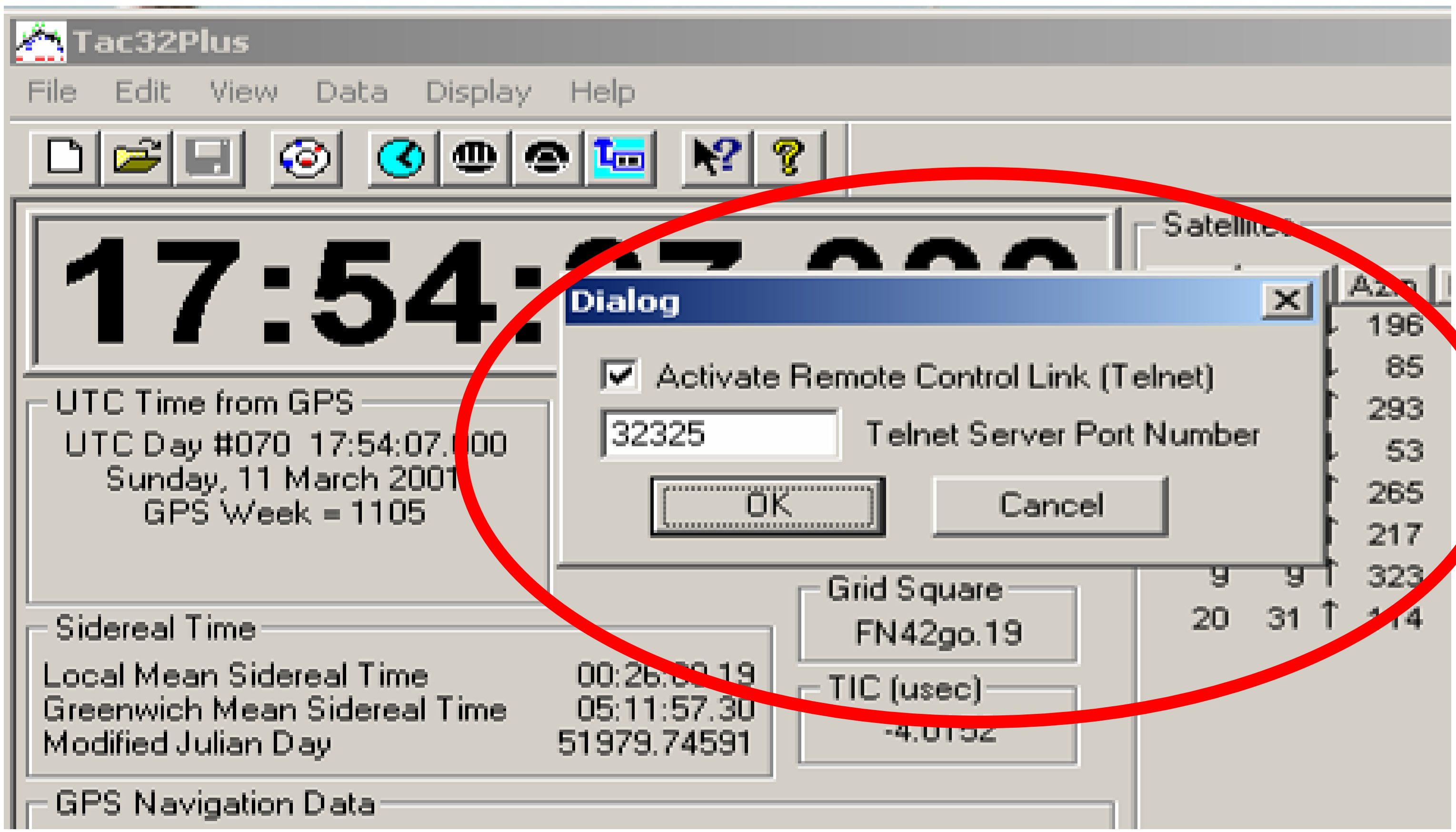




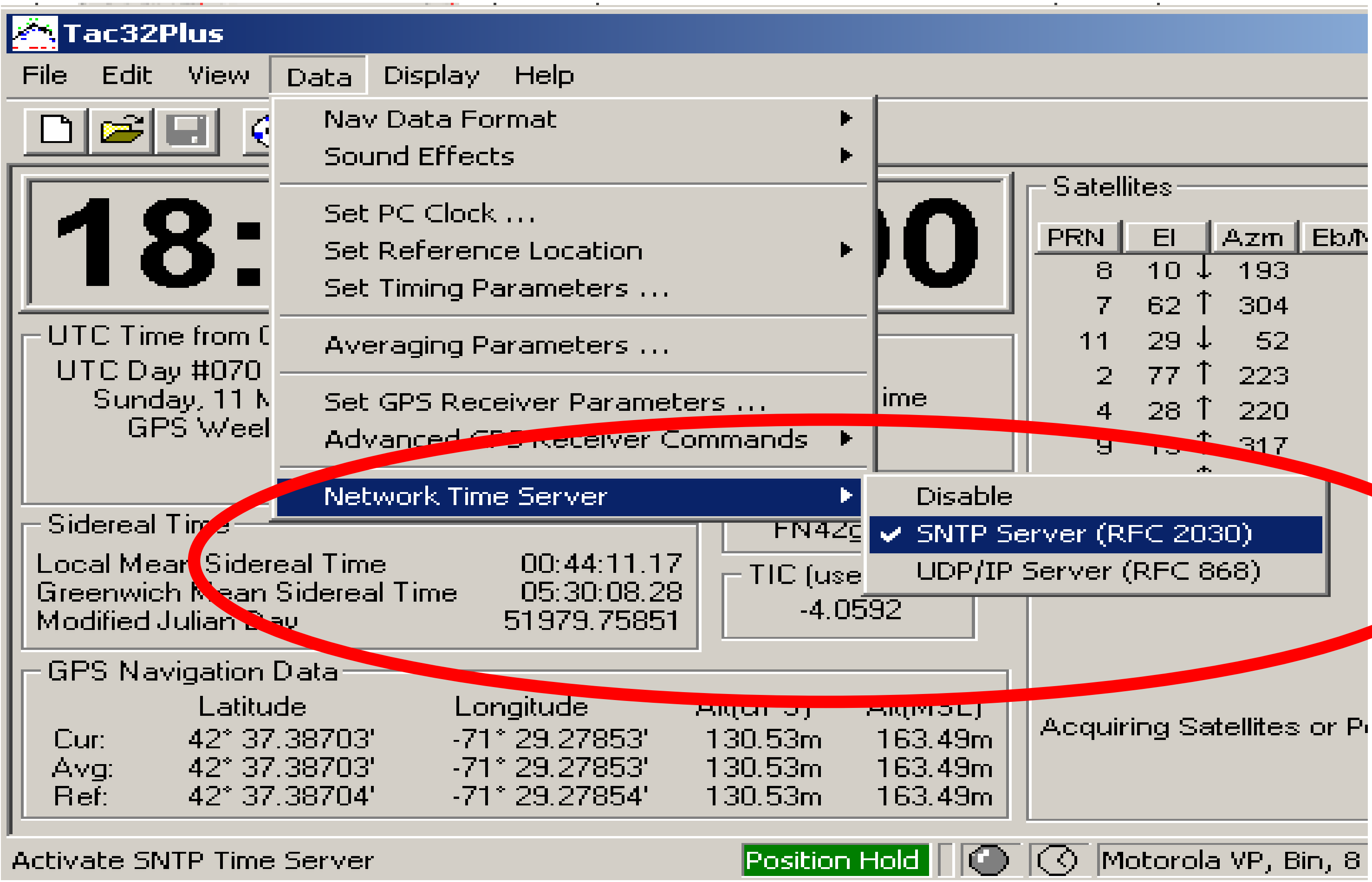
HP53131A
MASER to GPS
TAC-2
GPS
SPECIAL CASE: If you need to use the TAC to re-synchronize the Maser's 1PPS Signal.
START
STOP
Maser 1PPS
GPS 1PPS
MASER 1PPS SYNCH (temporary connection)
H-Maser
TAC GPS 1PPS is temporarily offset by ~10 µsec to be EARLY to UTC(USNO).
Maser 1PPS is LATE
TAC GPS 1PPS with Temporary, Intentional Early Offset
GPS JITTER
~100 nsec Sawtooth
~200 nsec SA
"True Time" UTC(USNO)

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 as your Station's SNTP Network Timer Server:



APPENDIX B
TEXT MATERIAL

-- **Field System Documentation for tacd**

-- **Ed Himwich's documentation for gpsoff**

-- **David Holland's HP53131 setup notes**