It’s About Time !!!!

Timing for VLBI

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CNS Systems, Inc.

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IVS TOW Workshop

Haystack – April 30 - May 3, 2007

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 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)

Integrator and Display = Clock

- Gears
- Electronic Counters
- Real Clocks

Events that occur with a defined

FREQUENCY

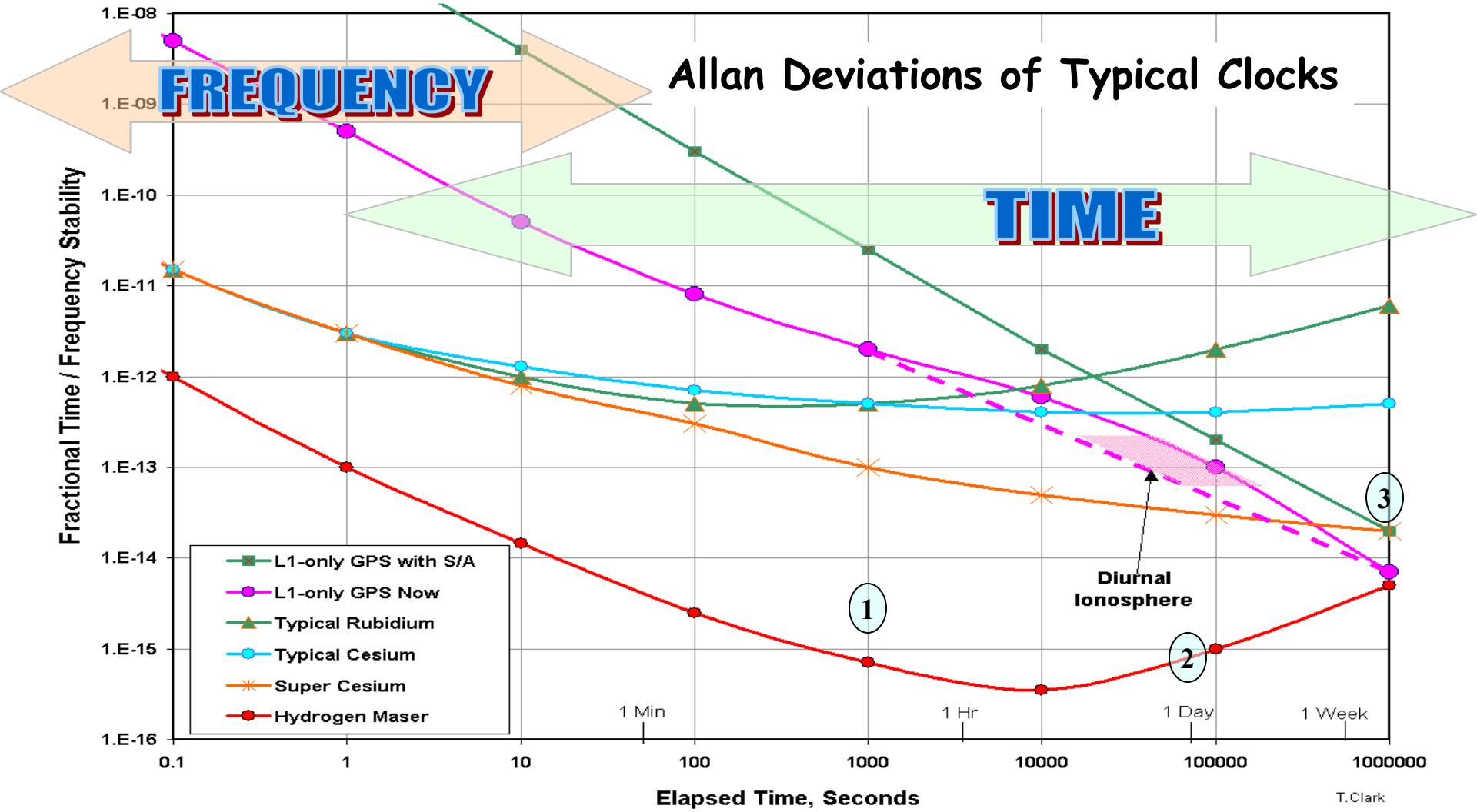
nsec -- minutes

Long-Term

TIMING

seconds - years

The Allan Deviation – A graphical look at clock performance



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

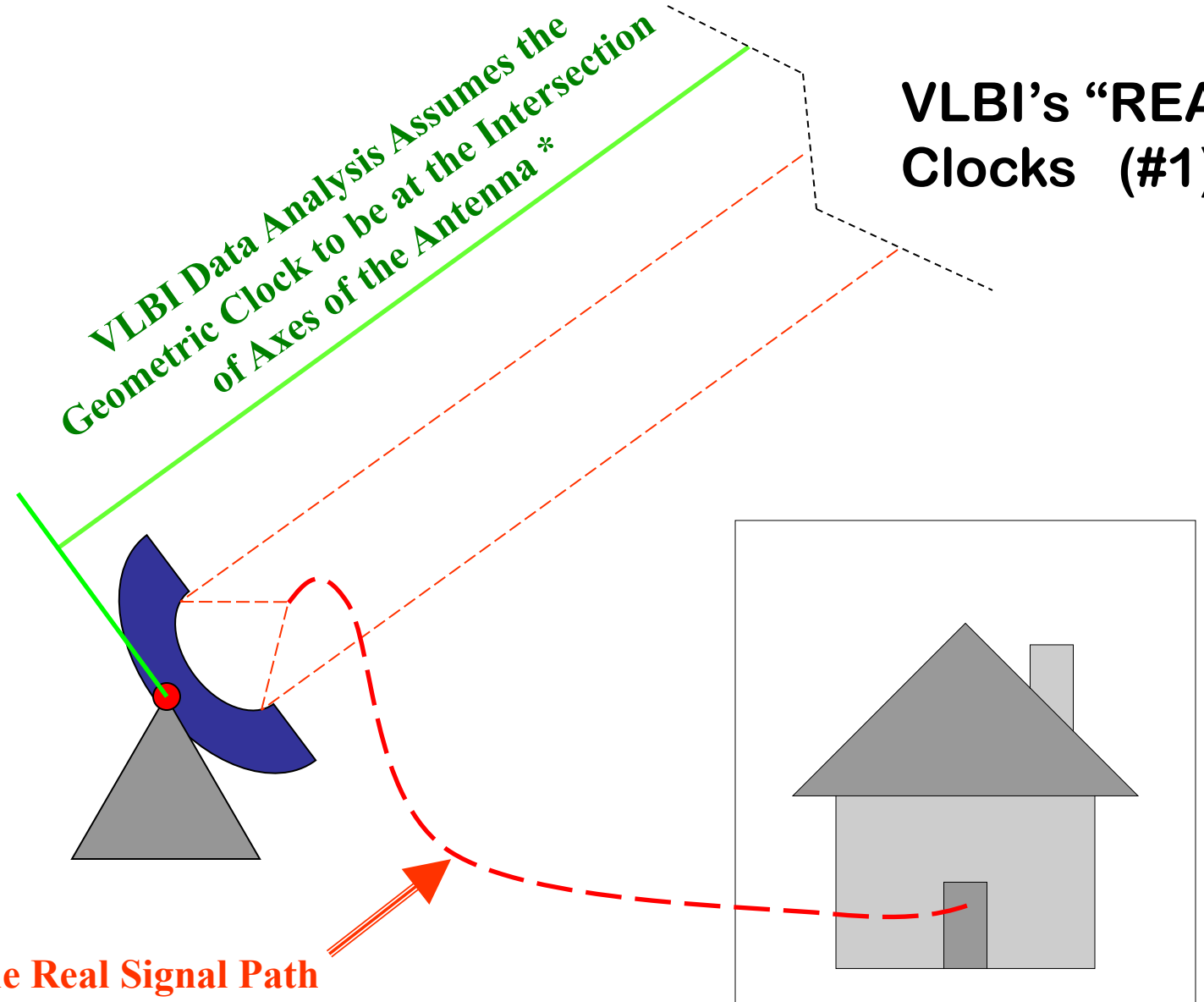
- The ***ONLY*** reason for worrying about "absolute time" is to relate the position of the earth to the position of the stars:
  - Generating Sidereal Time to point antennas.
  - Measuring UT1 (i.e. "Sundial Time") to see changes due to redistribution of mass in/on the earth over long periods of time.
  - 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. Clock Accuracy) in VLBI?

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

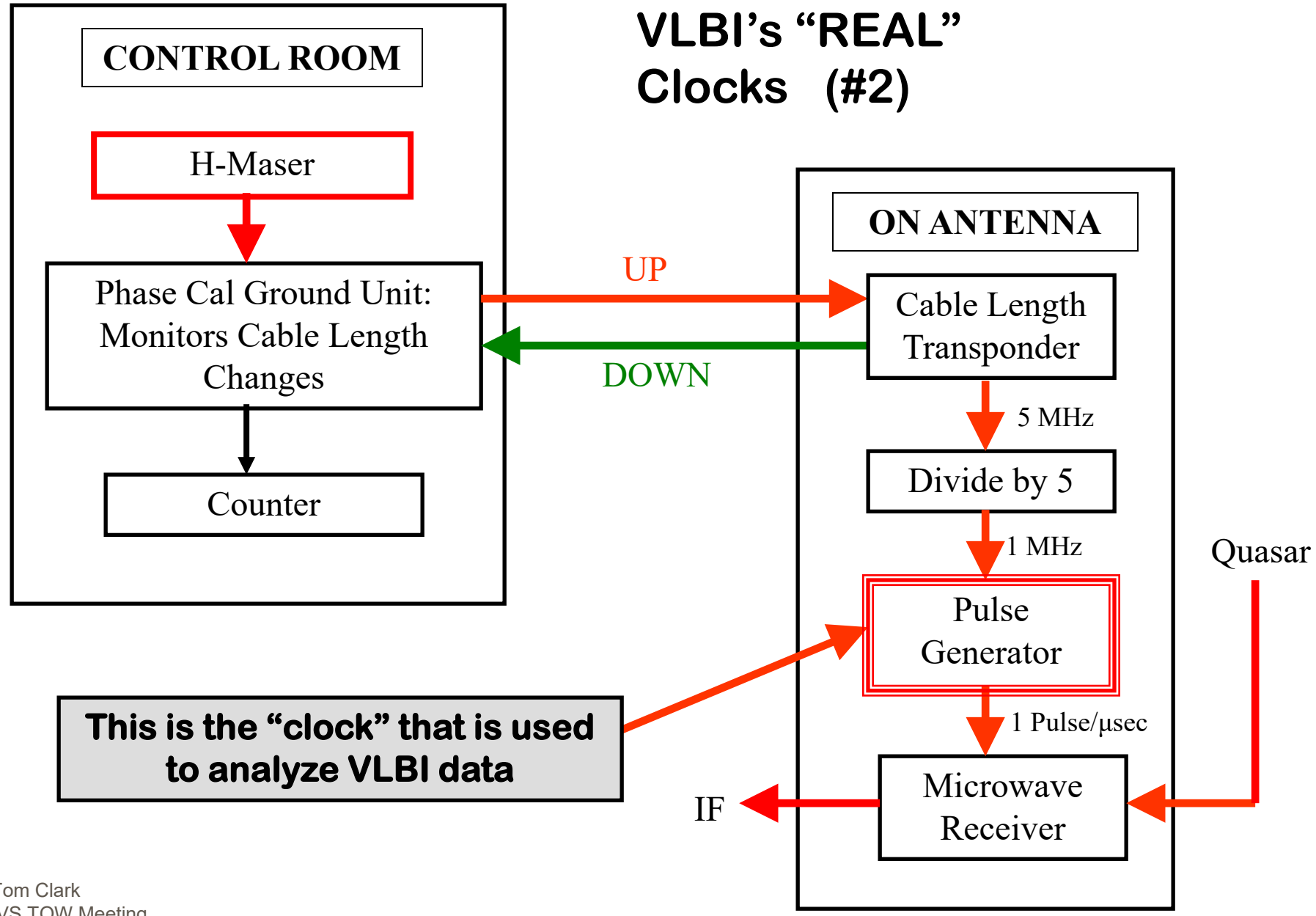
- Frequency Standard and Station Timing
- The lengths of cables
- The geometry of the feed/receiver to the antenna.
- Calibration of instrumental delays inside the receiver and backend. The development of new instrumentation is needed.
- The care with which system changes are reported to the correlators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

VLBI's "REAL" Clocks (#1)

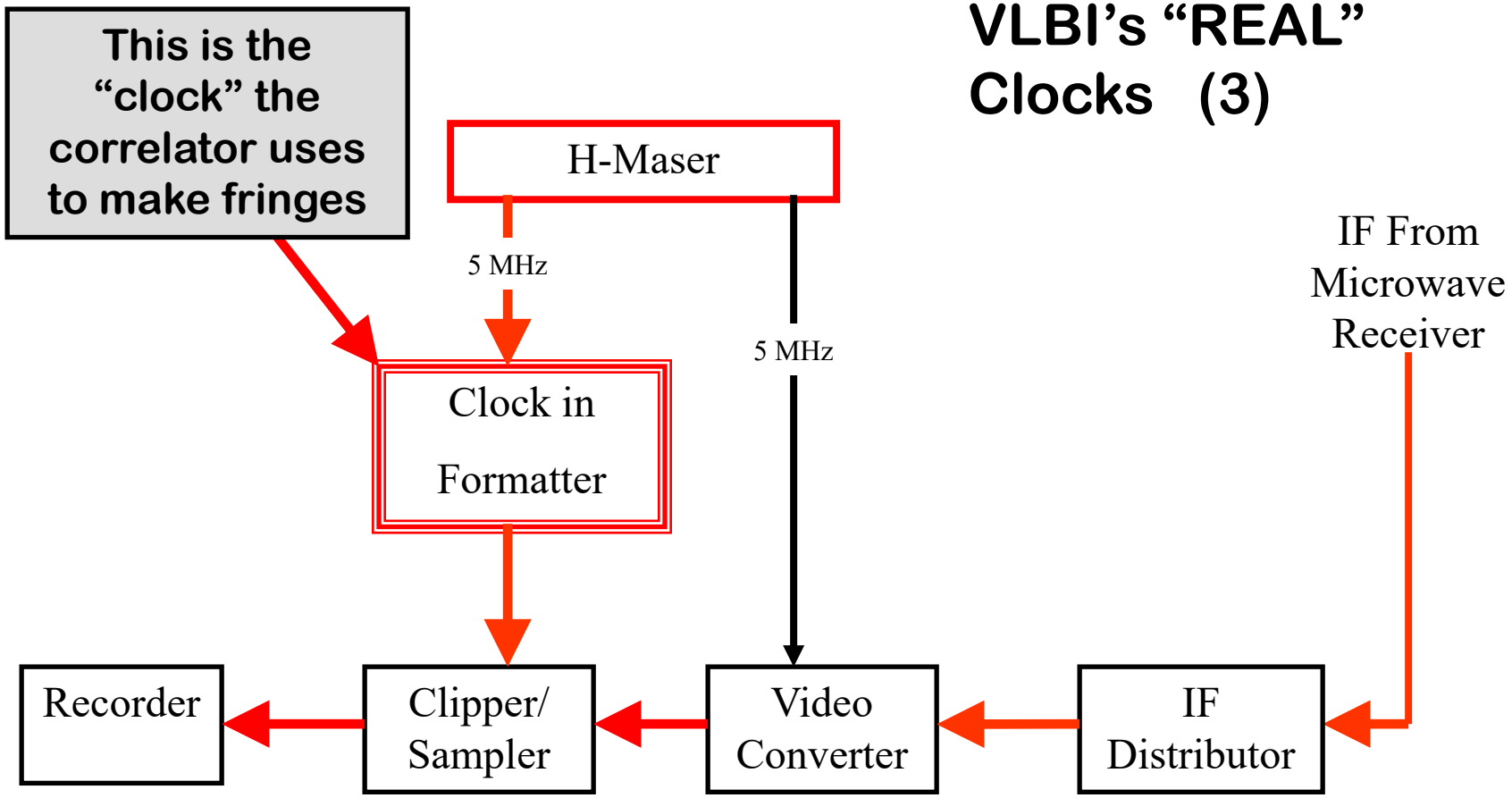


* Note -- If the axes don't intersect, then an "offset axis" model of the antenna is used

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** (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
  - Not "Real Time" !

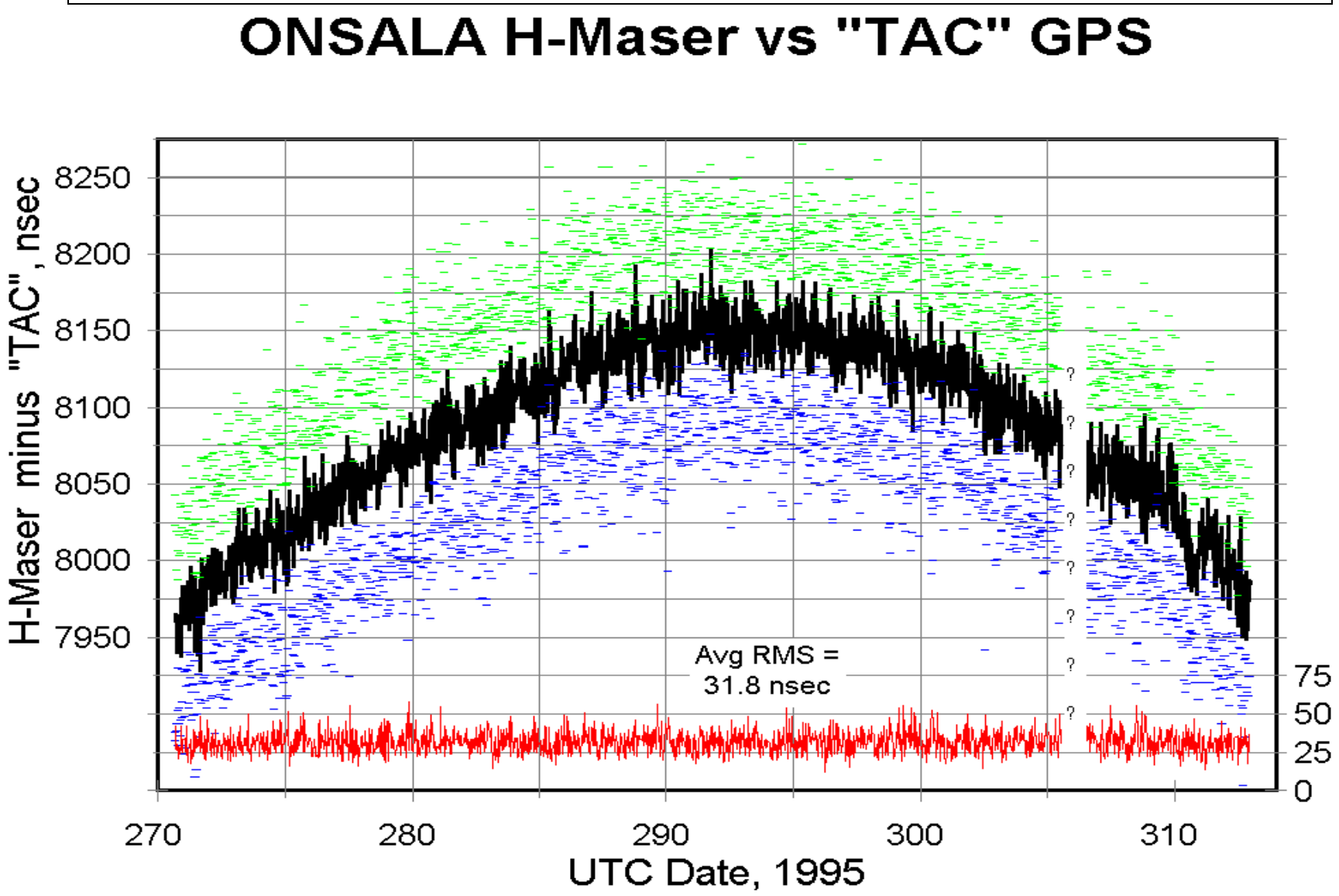
- **Blindly use the Broadcast GPS Timing Signals as a clock**
  - Yields "Real Time" ~10-30 nsec results with ~ $1000 hardware
  - Single Frequency L1 only (until 2008?) causes ionospheric error

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

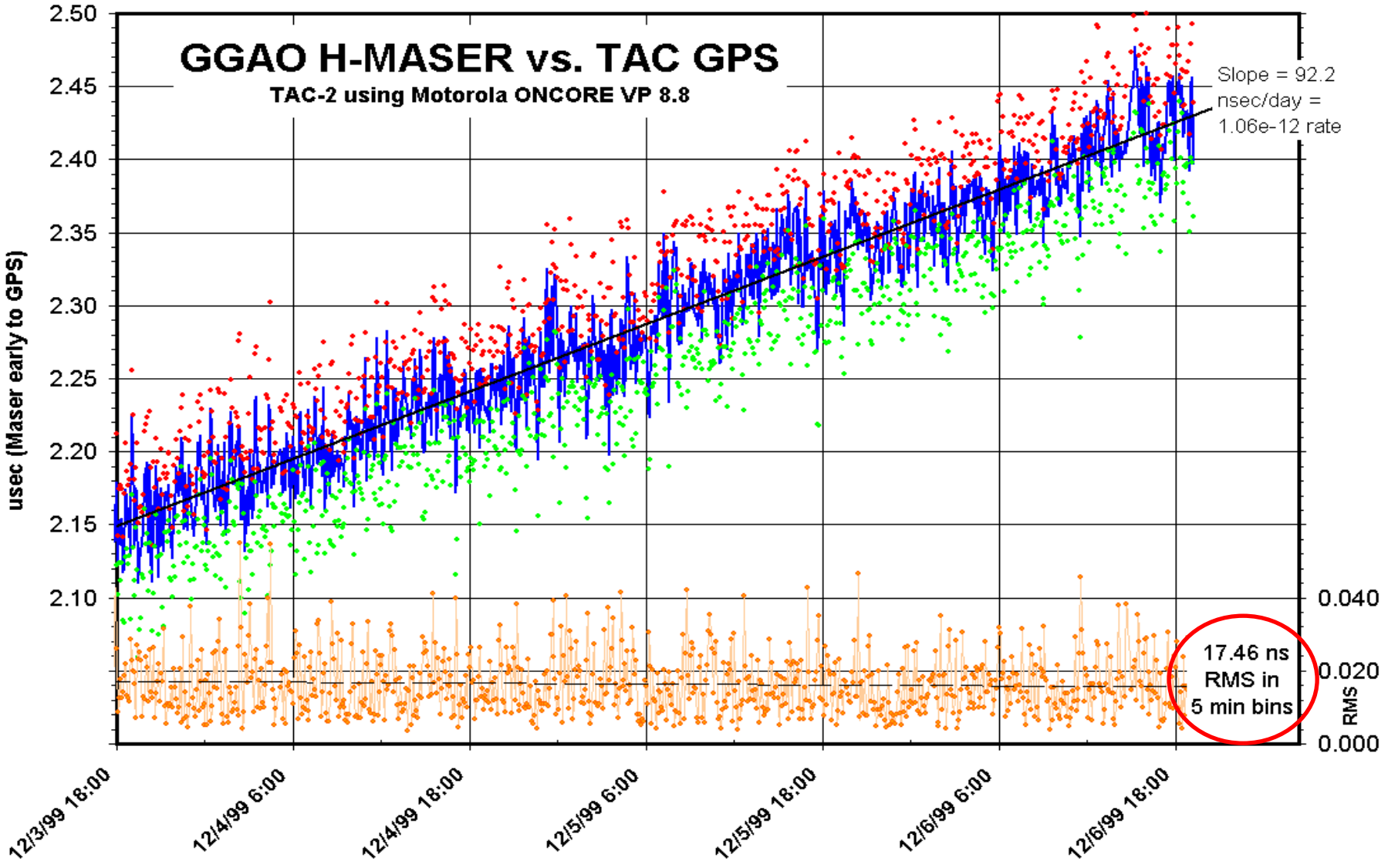
Urumqi's 6-channel NASA-built TAC

Urumqi's Chinese H-Maser

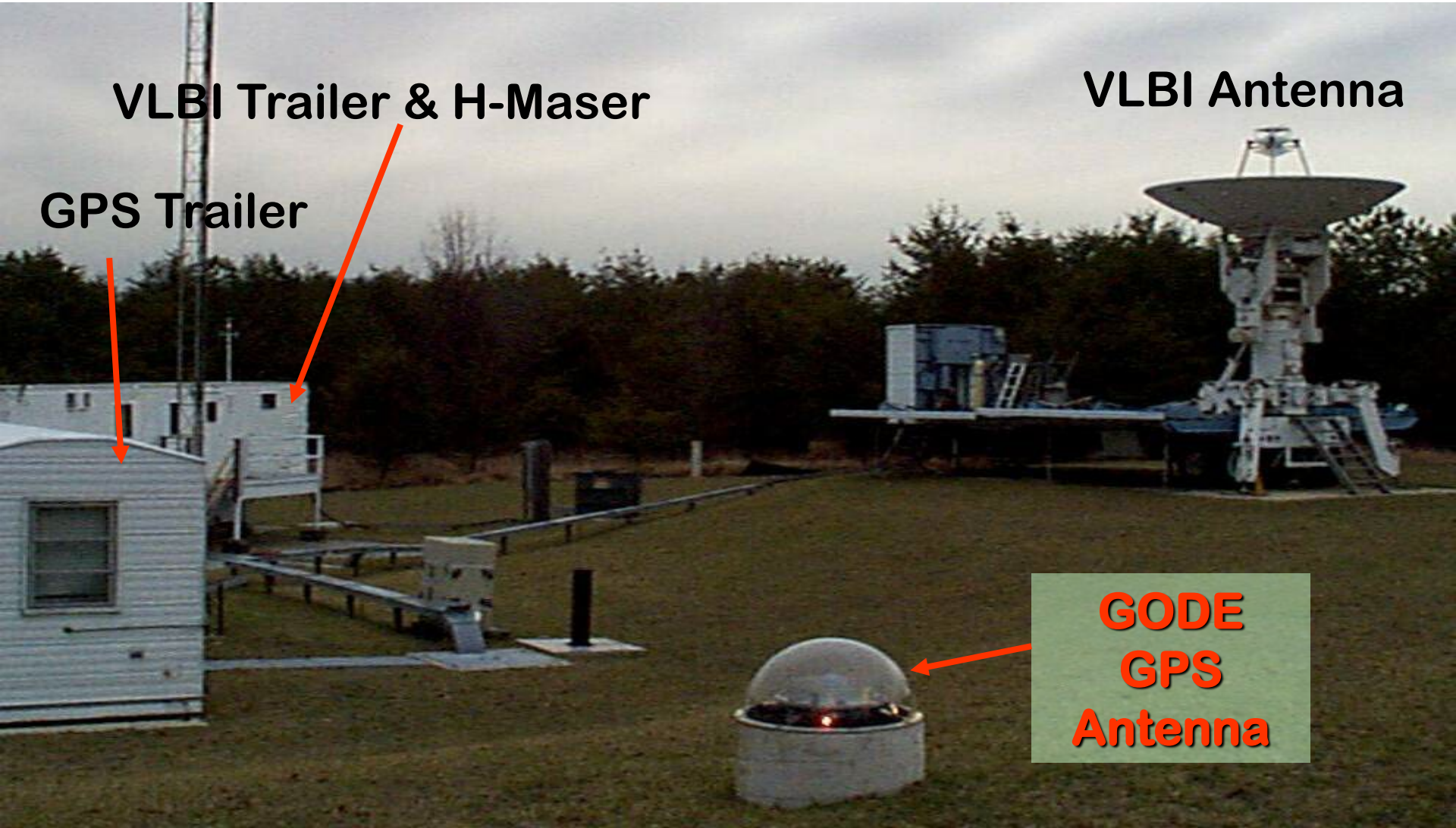
An Early Example of “Blind” GPS Timing with a 6 channel receiver



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



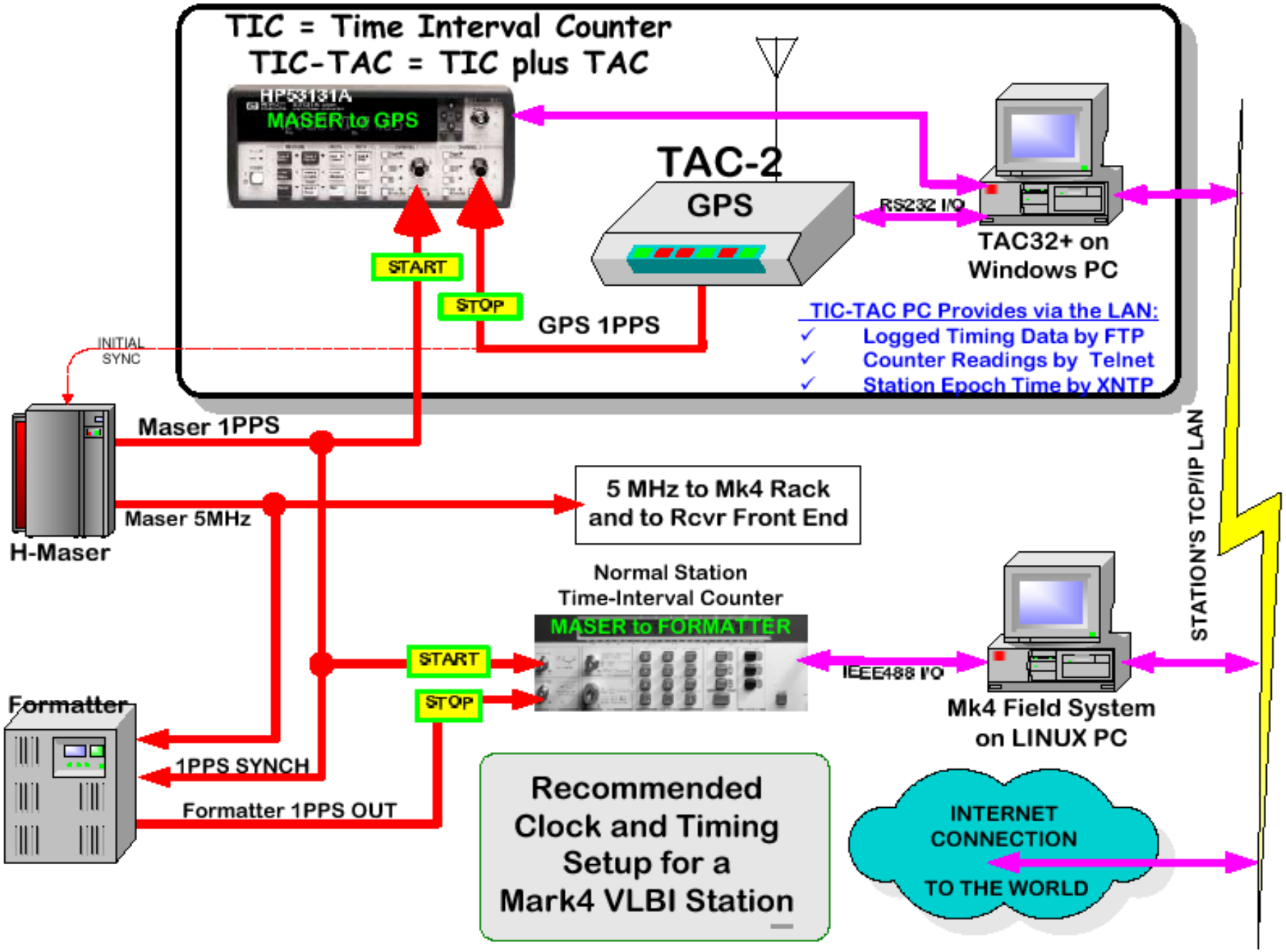
GGAO (Goddard Geophysical & Astronomical Observatory)



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.

- All these steps were automated in my SHOWTIME and CNS System's TAC32+ Software using a barebones PC

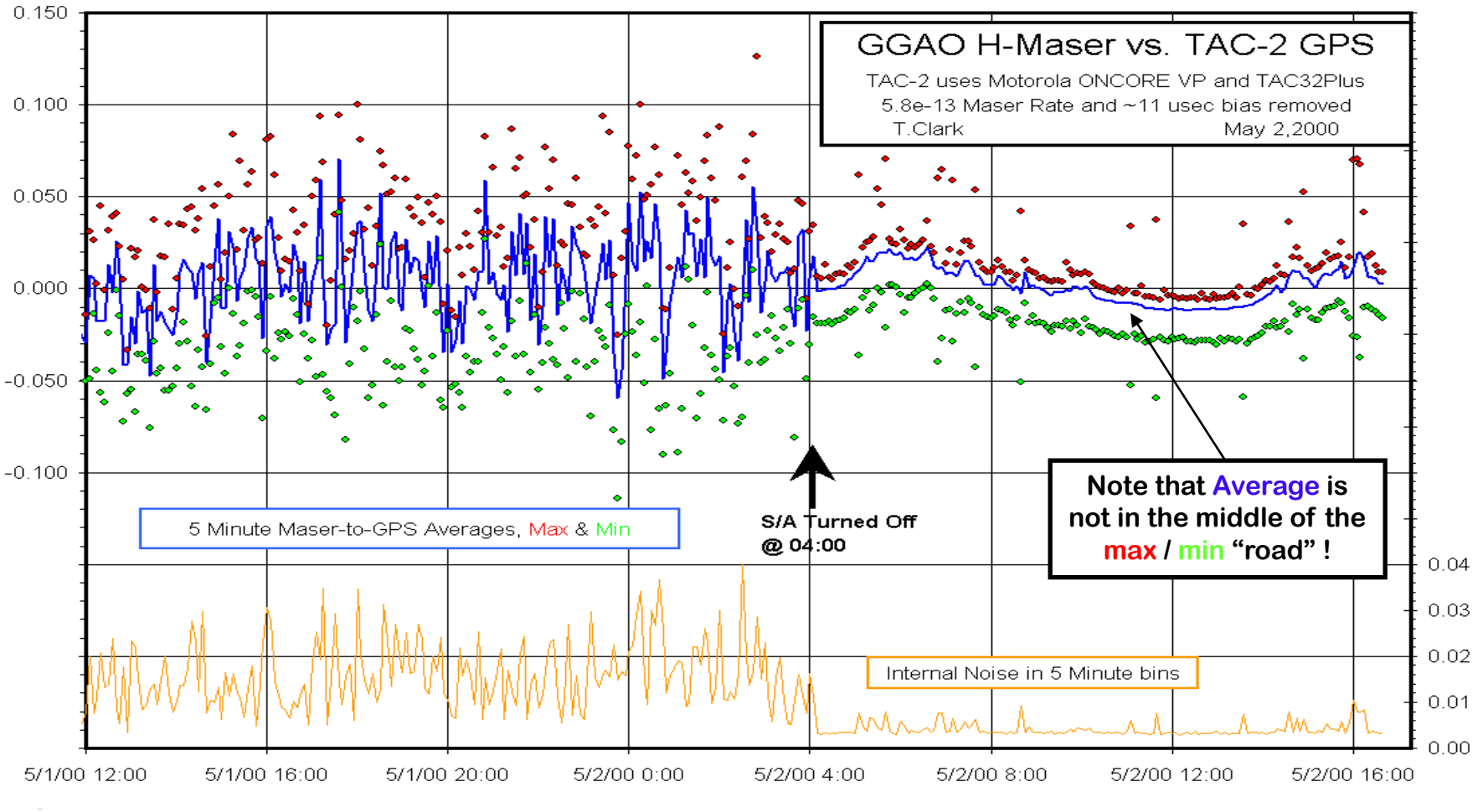

TIC = Time Interval Counter
TIC-TAC = TIC plus TAC
HP58131A
MASER to GPS
TAC-2
GPS
RS232 I/O
TAC32+ on
Windows PC
START
STOP
GPS 1PPS
INITIAL
SYNC
TIC-TAC PC Provides via the LAN:
✓ Logged Timing Data by FTP
✓ Counter Readings by Telnet
✓ Station Epoch Time by XNTP
Maser 1PPS
Maser 5MHz
H-Maser
5 MHz to Mk4 Rack
and to Rcvr Front End
Normal Station
Time-Interval Counter
MASER to FORMATTER
START
STOP
IEEE488 I/O
Mk4 Field System
on LINUX PC
STATION'S TCP/IP LAN
Formatter
1PPS SYNCH
Formatter 1PPS OUT
Recommended
Clock and Timing
Setup for a
Mark4 VLBI Station
INTERNET
CONNECTION
TO THE WORLD

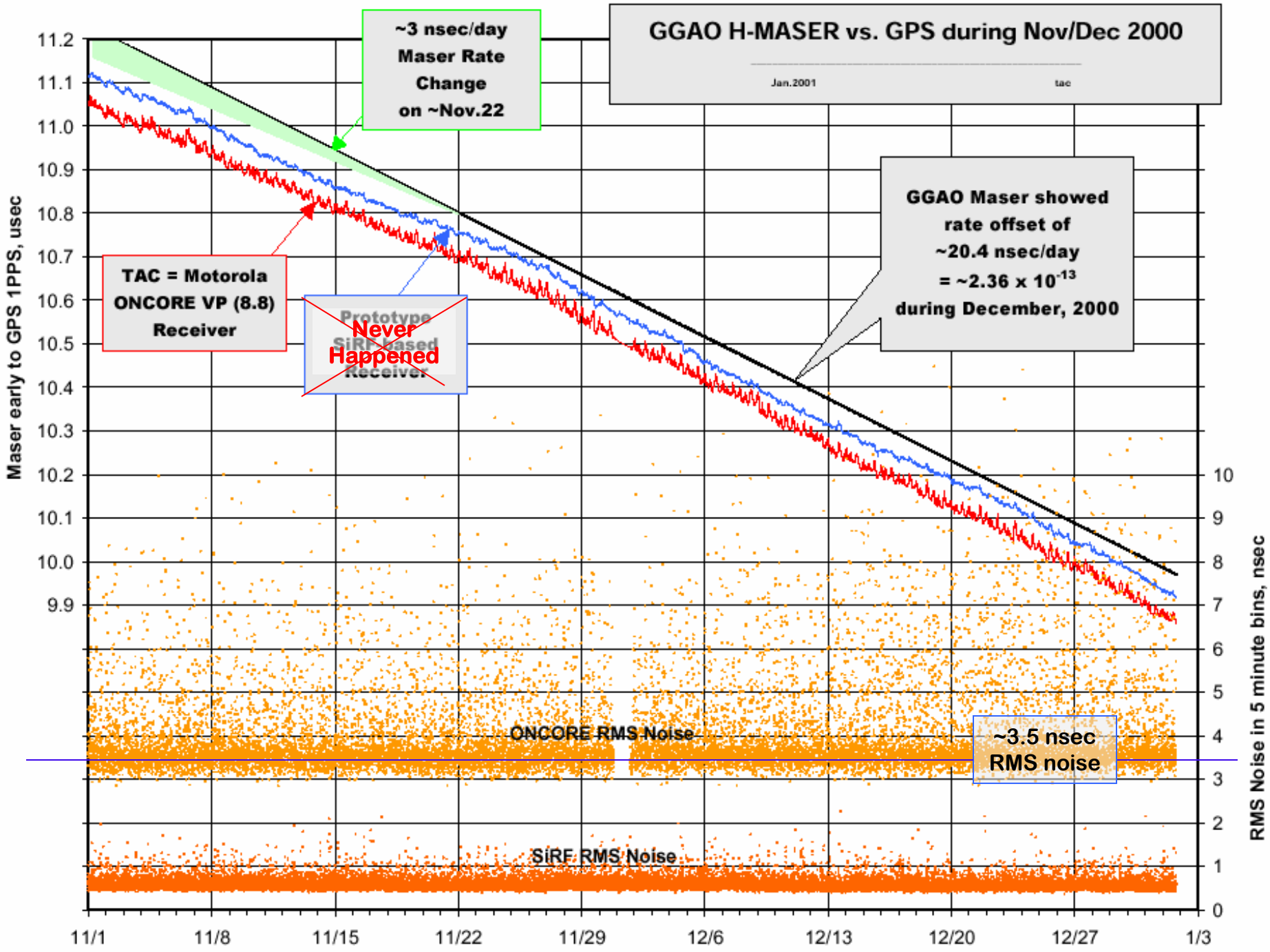
Let Us Now Discuss . . .

- 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+)

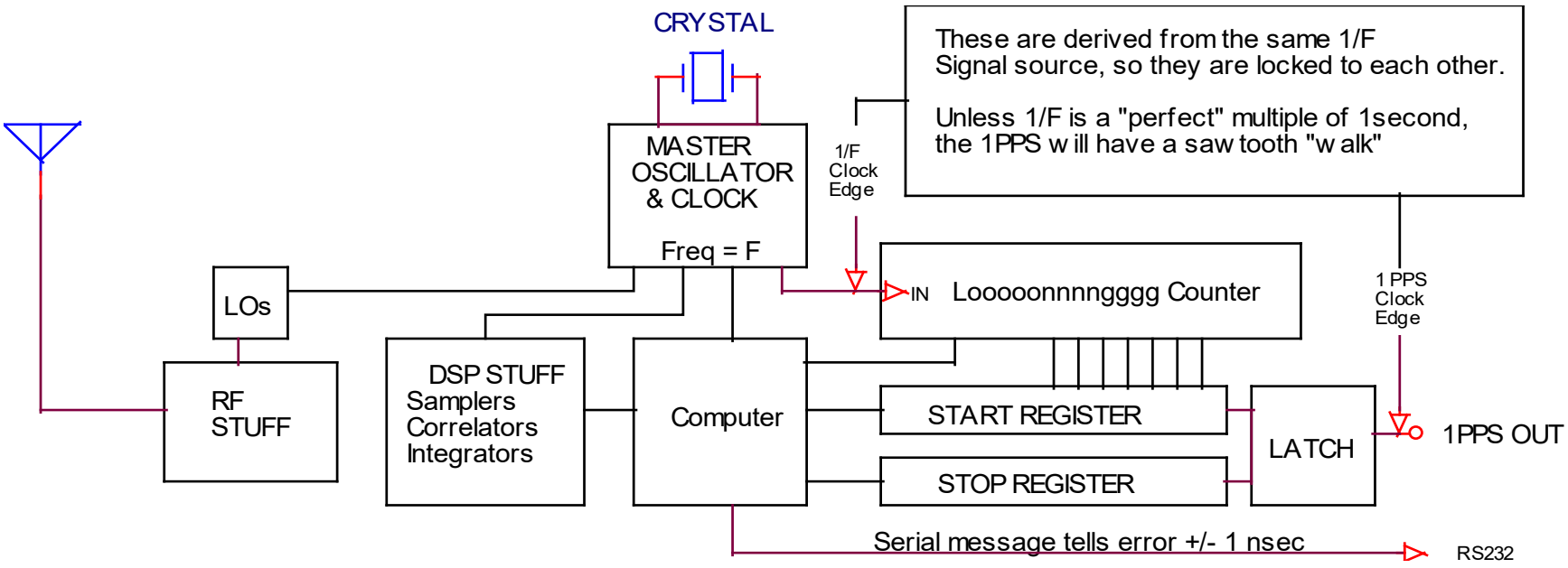
What happened when S/A went away?

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

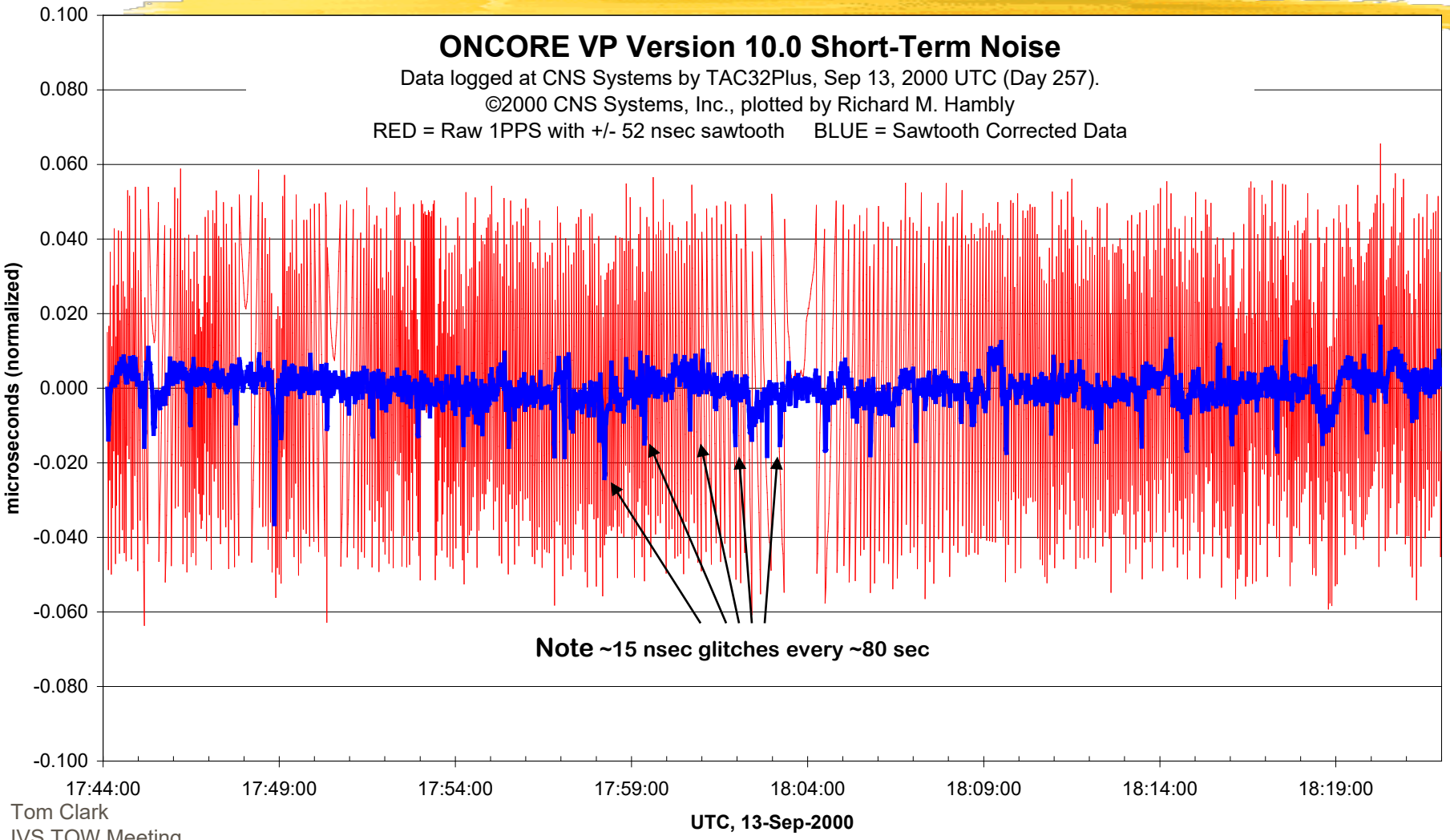
What is the sawtooth effect ????



- 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).

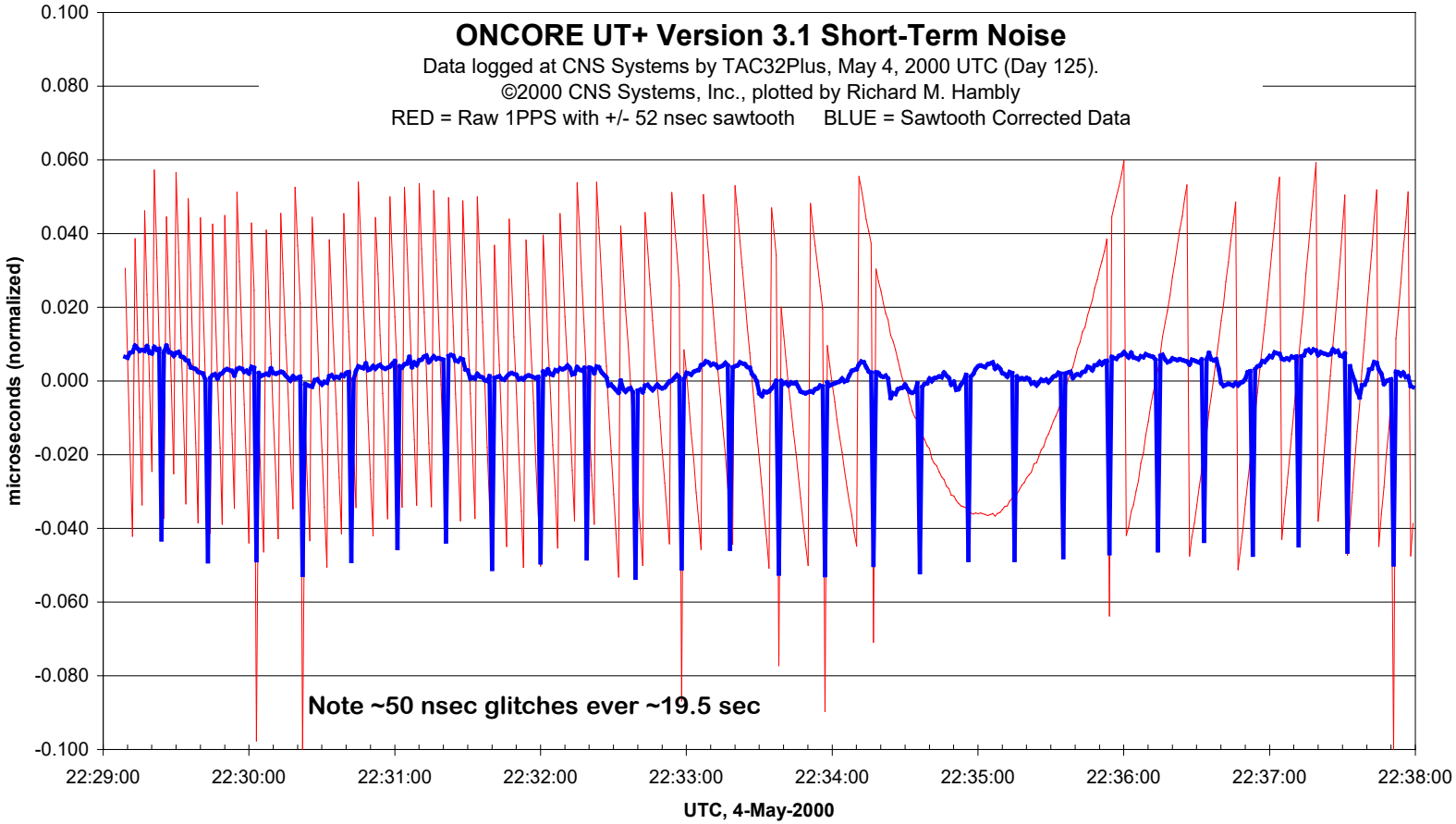
An example of 1PPS sawtooth

8-channel Motorola VP Oncore (v10.0)



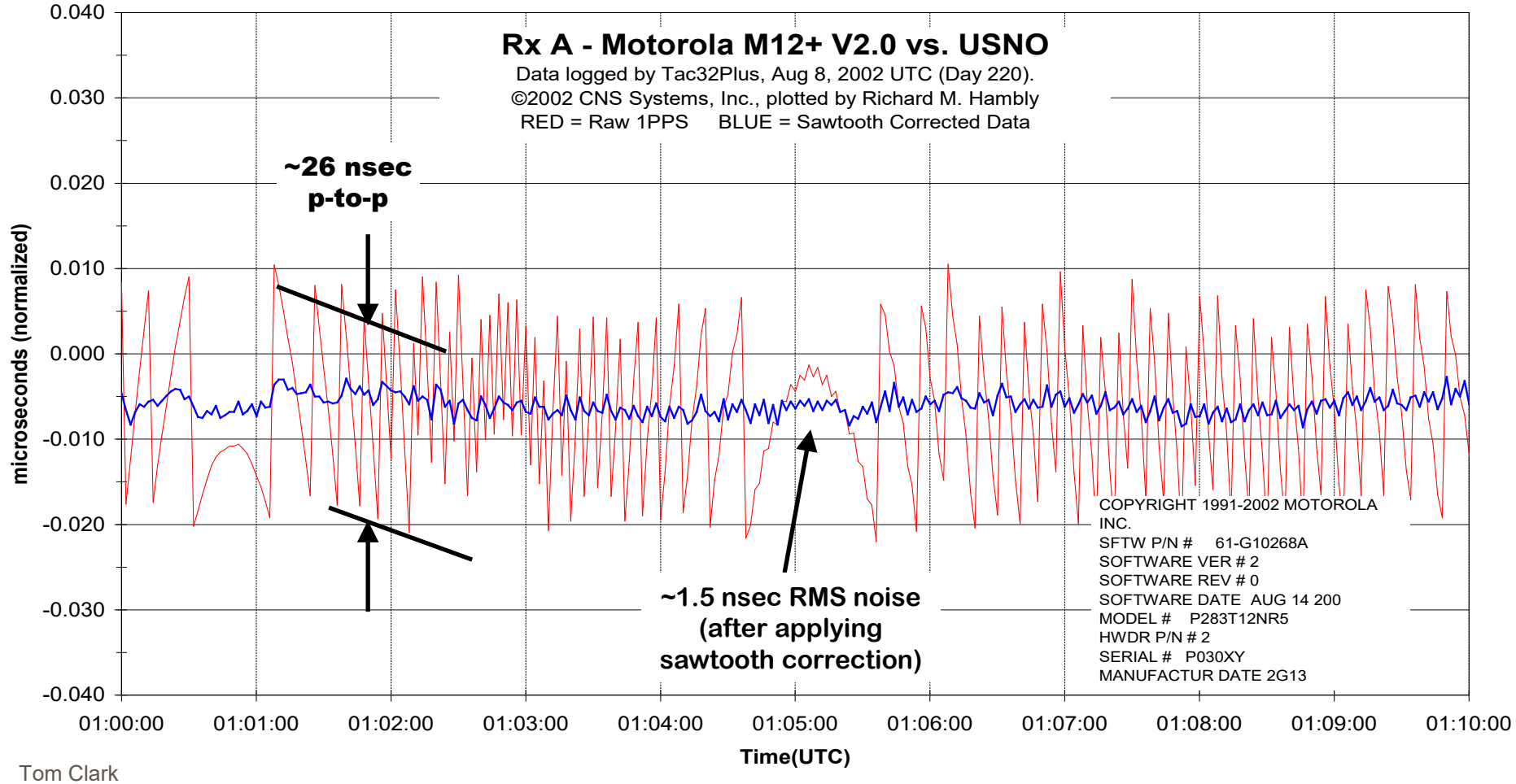
An example of 1PPS sawtooth

Motorola UT+ Oncore (v3.1)



An example of 1PPS sawtooth

with the new Motorola M12+ receiver



VLBI's annoying problem caused by the sawtooth timing error

- When the formatter needs to be reset, you have to feed it with a timing pulse to start the VLBI clock. After it is started, it runs smoothly at a rate defined by the Maser.

- 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.

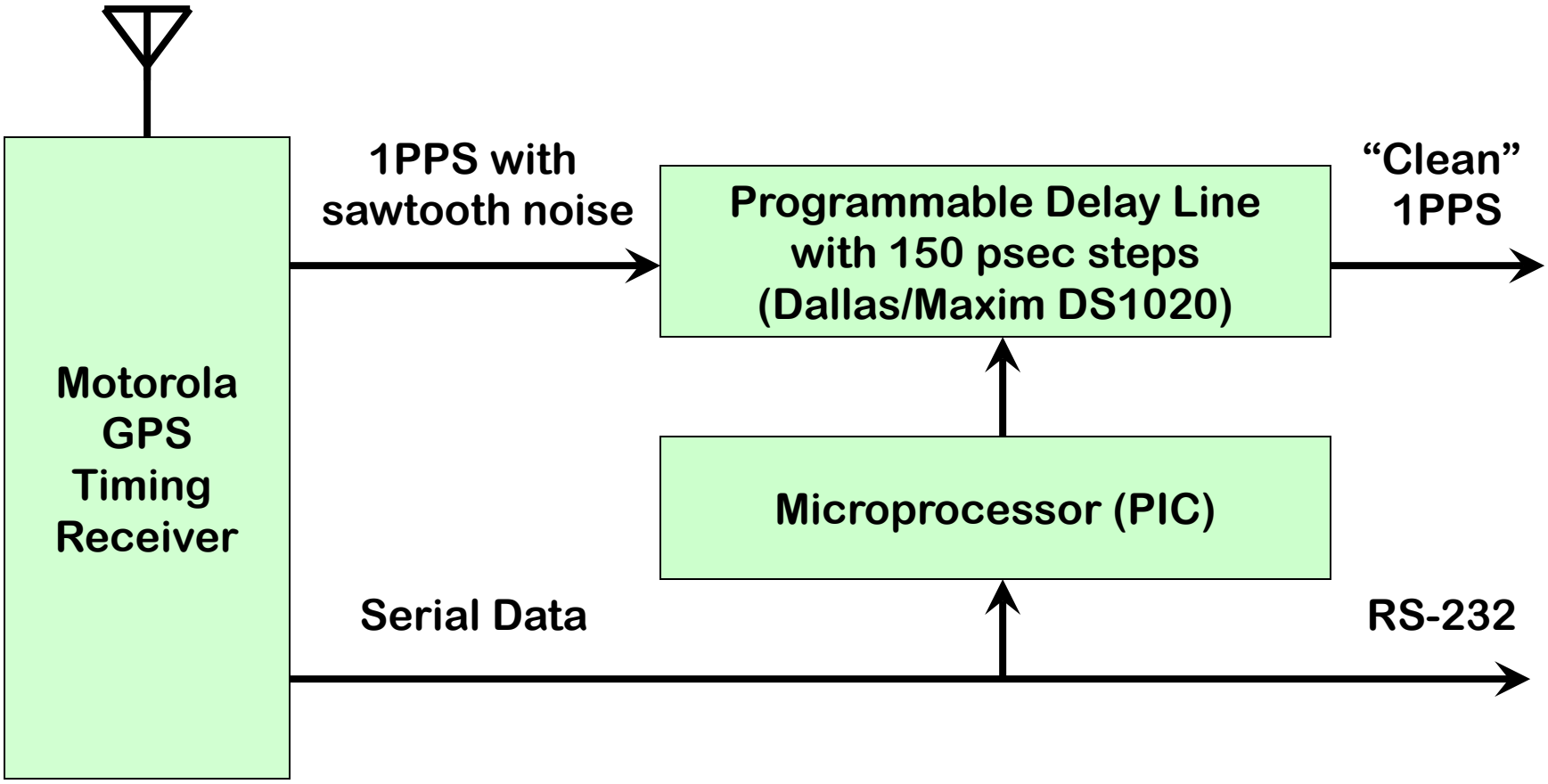
- Once you have restarted the formatter with the noisy 1 PPS signal, you must measure the actual (GPS minus Formatter) time that you actually achieved.

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.
- TAC32 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?

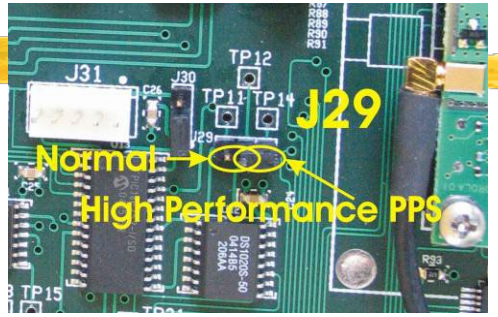
How could the sawtooth noise be eliminated ???



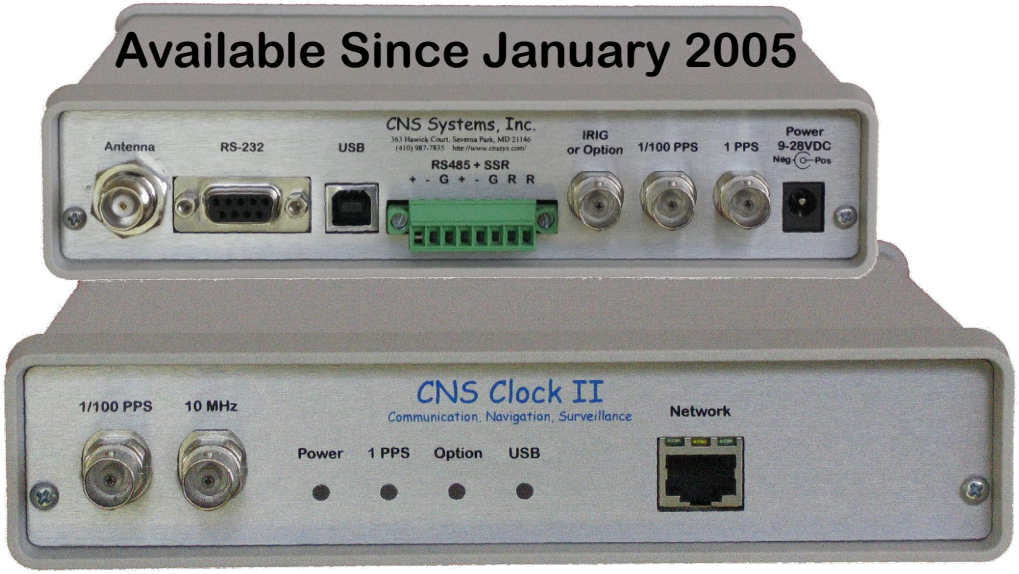
The Future is here now!
The CNS Clock II

1994 – 2004: TAC and

1PPS Sawtooth Correction Option →



Available Since January 2005

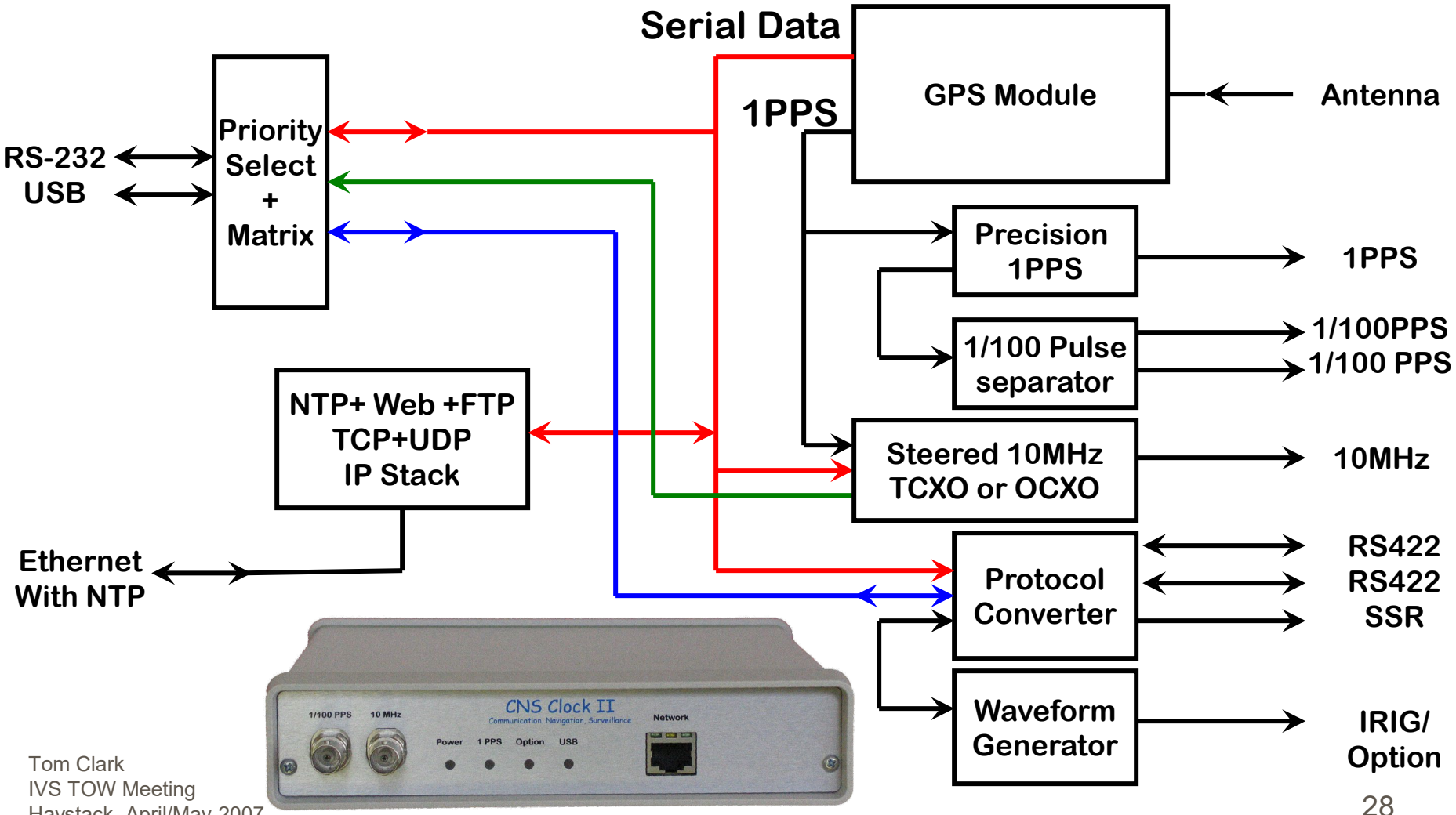


Data available on RS-232, USB 2.0, Ethernet LAN and RS-485 Ports
Full NTP Server for your LAN
TNC(F) GPS Antenna Connector
Buffered 1 PPS outputs
GPSDO 10 MHz output

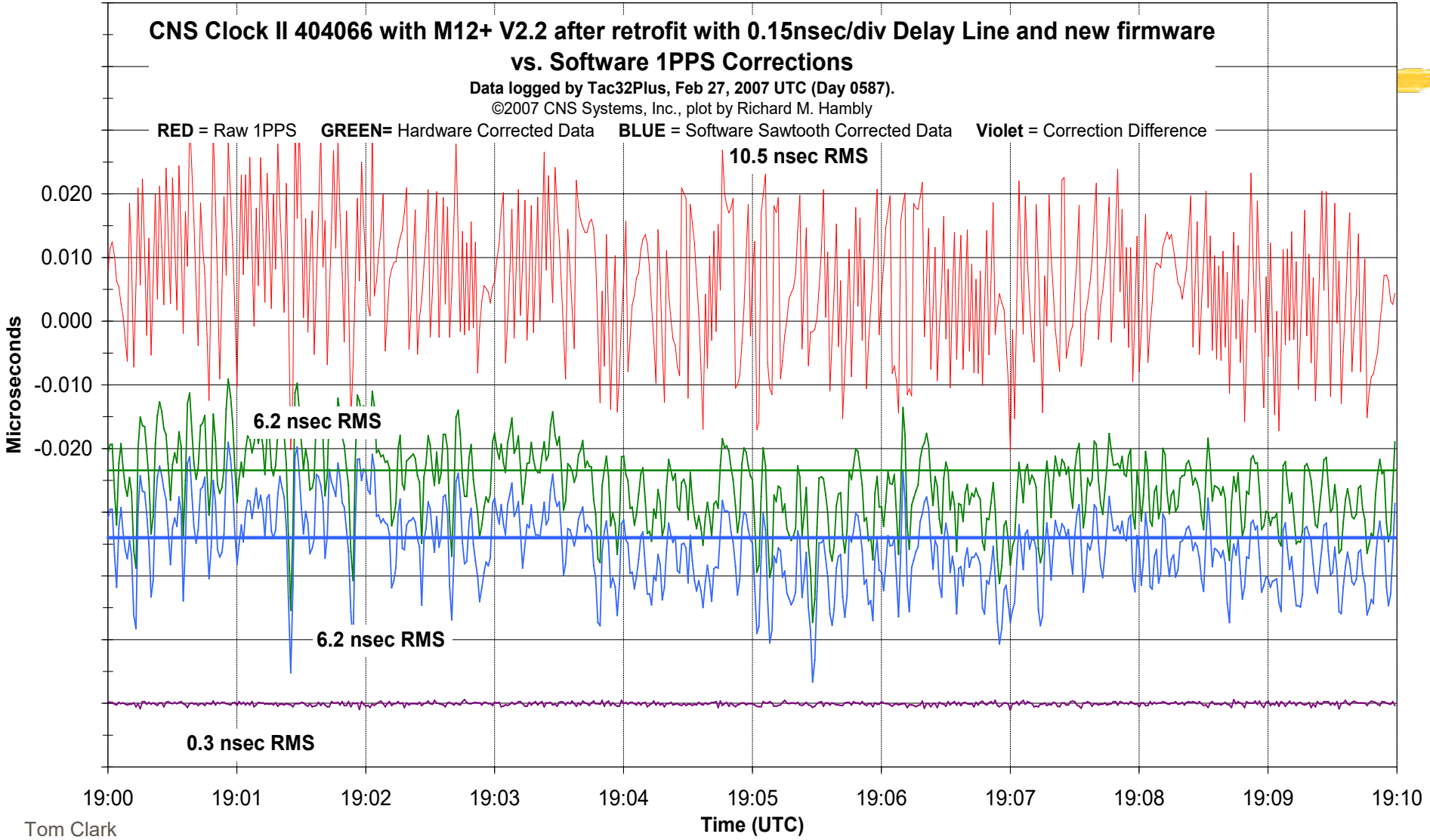
Power 9-30 volts @ 500ma

Options include:
- Tx Sequencer with (AC/DC) solid state relay output.
- IRIG-B output (modulated, PWM or Manchester).

CNS Clock II Block Diagram

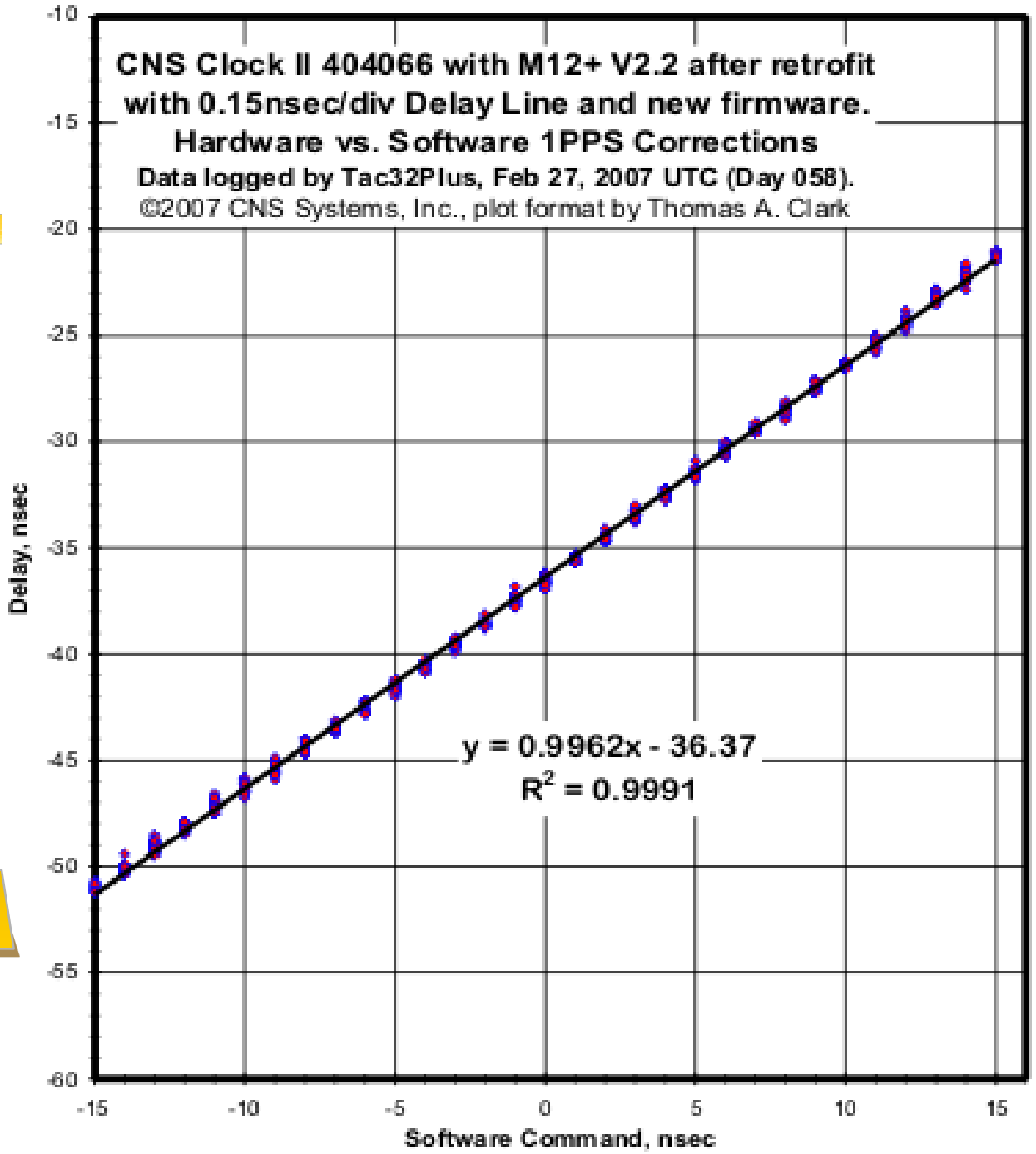


Does the hardware 1PPS correction work?



Does the hardware 1PPS correction work?

YES !!



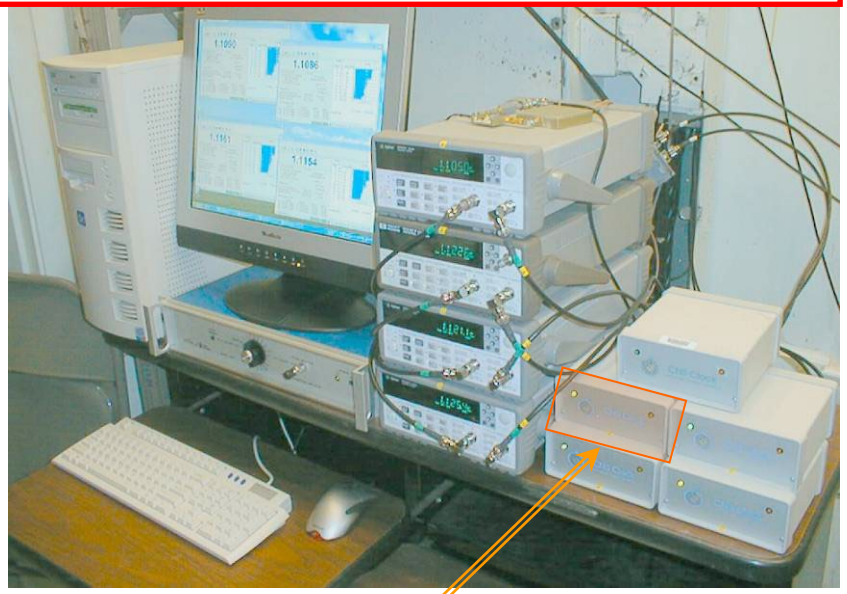
CNS Systems' Test Bed at USNO

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.

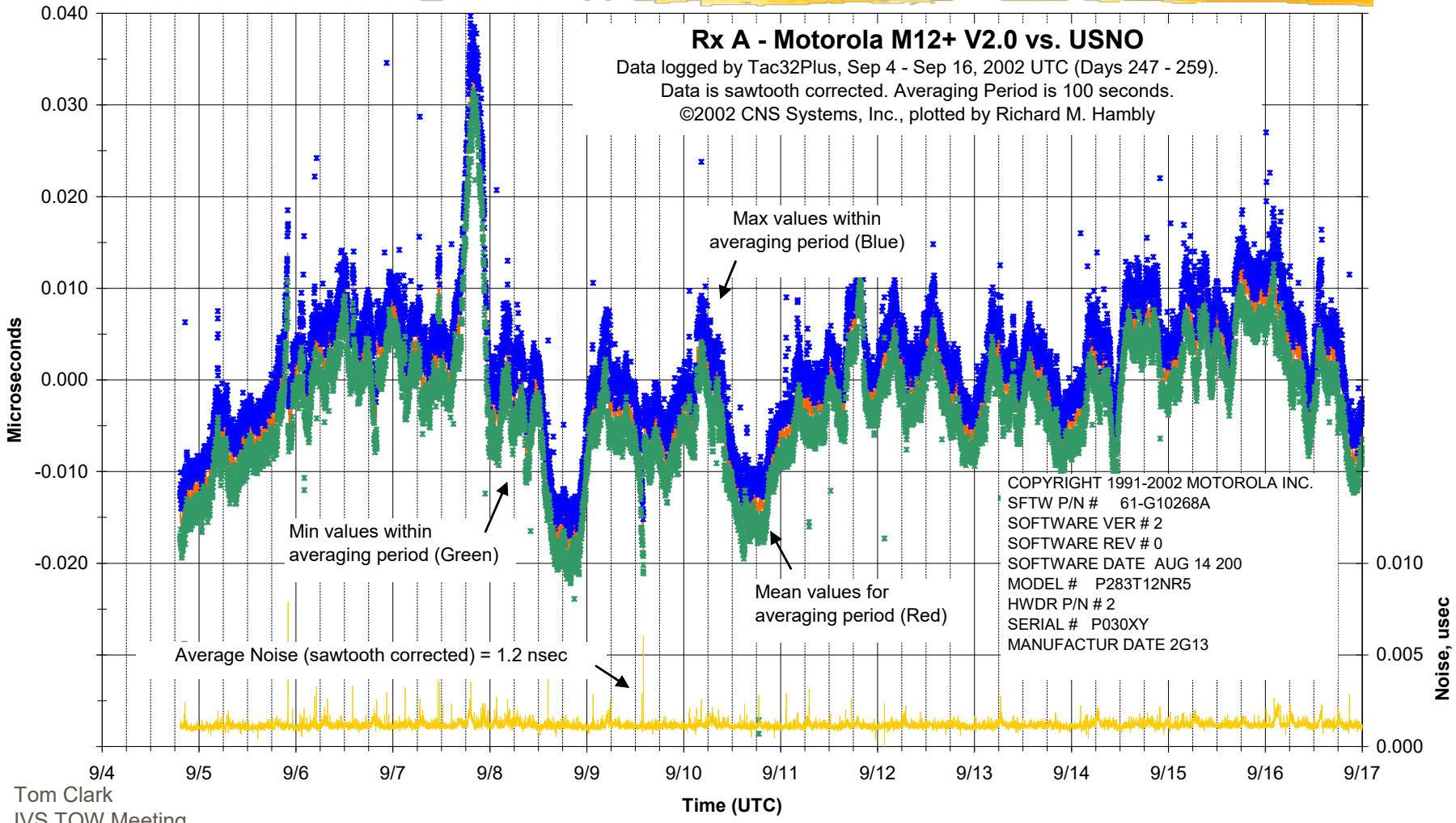


Time Interval Counters compare the 1PPS from each CNS Clock (M12+) against the USNO's UTC time tick.

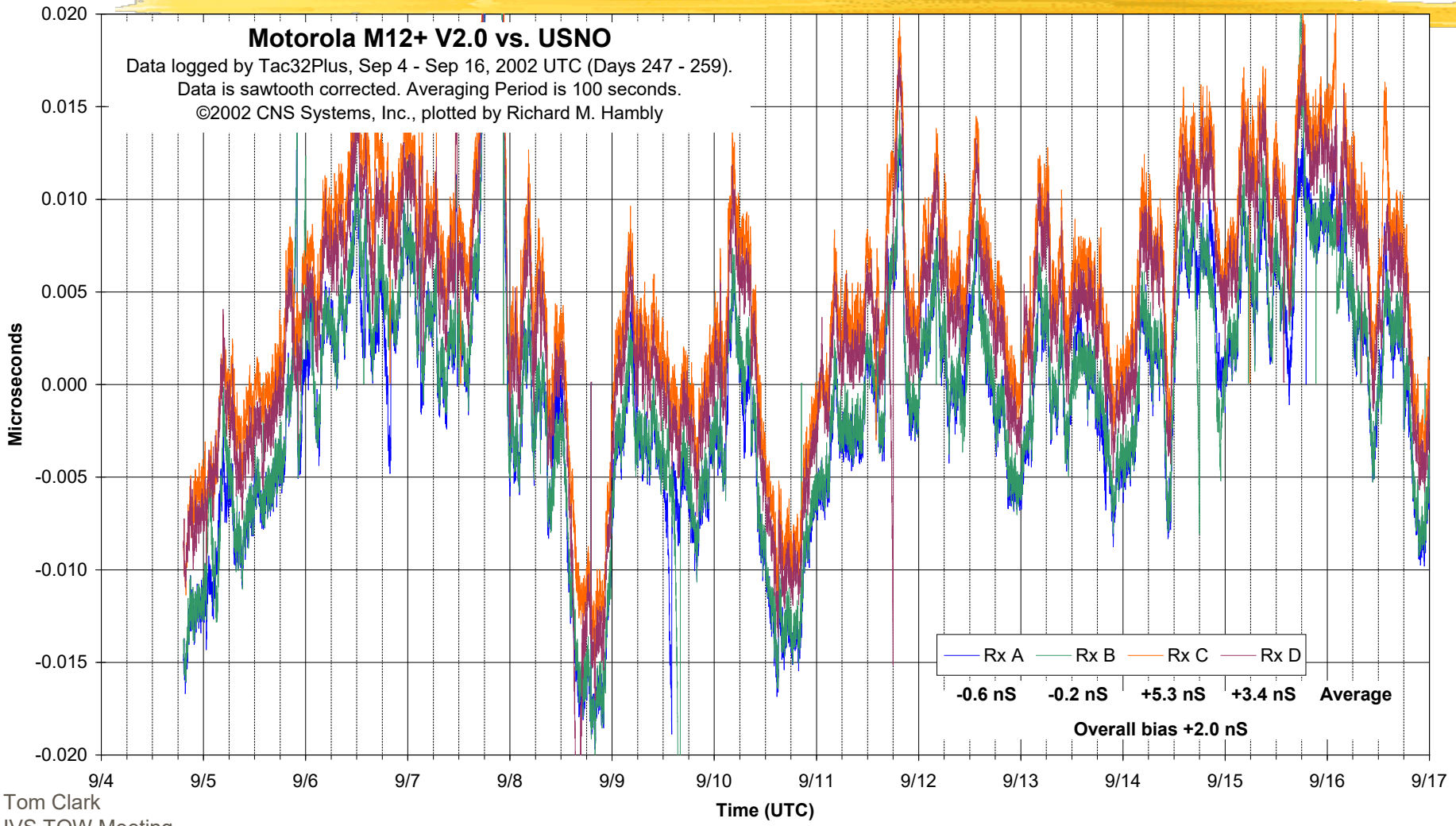
This is the "Gold Standard" "A" receiver that we used for subsequent calibrations.

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.

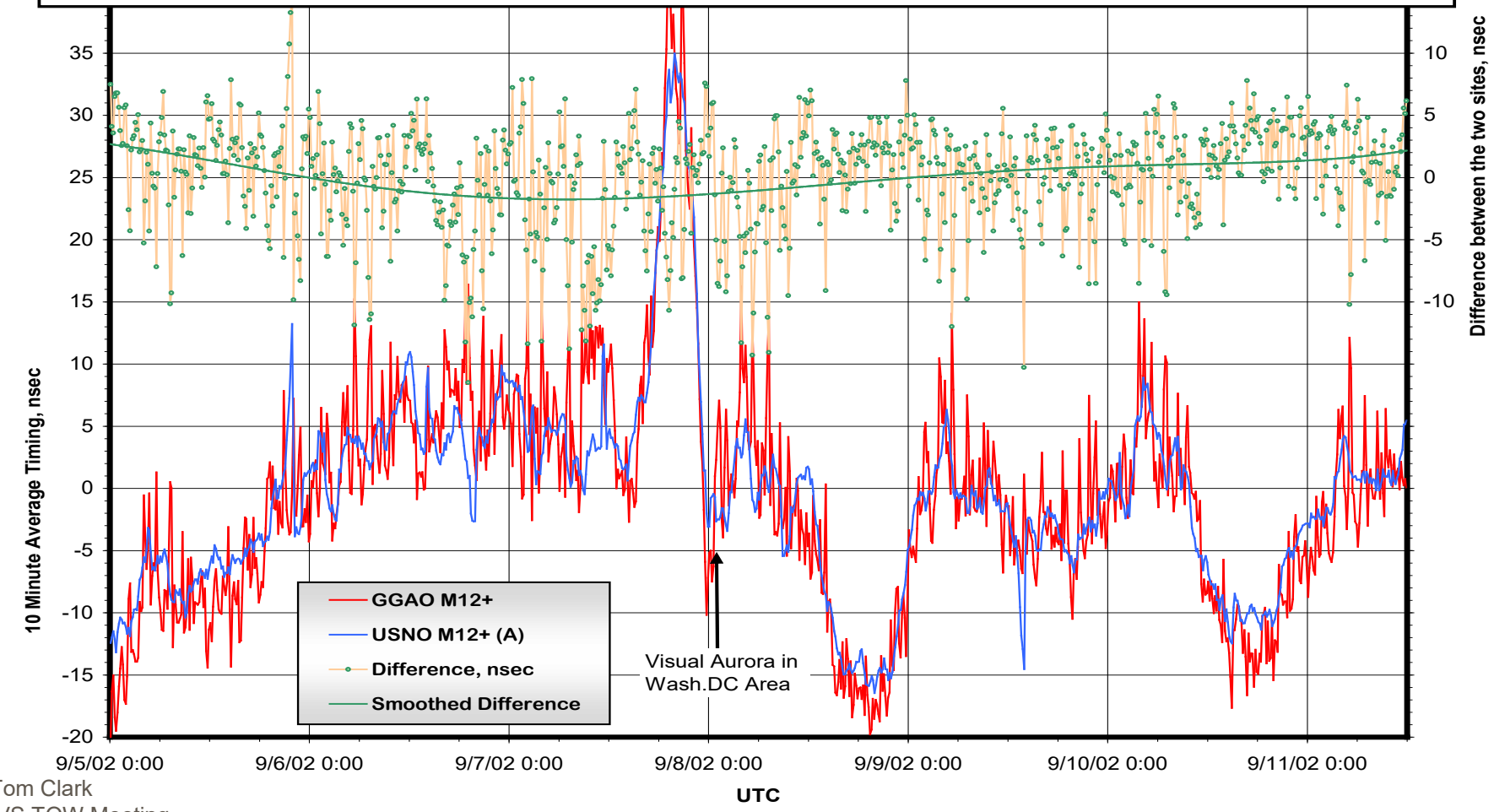
This picture is a four hour composite of 140 different photos spanning 20:00 thru 24:00 EDT on Sept. 8th (00:00 thru 04:00 UTC Sep. 9).

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 the varieties of the Motorola M12+/M12M timing receiver show similar performance.
- All the Motorola samples (including the 4 receivers in the 2002 test) appear to agree with UTC(USNO) to better than ±10 nsec.
- Motorola has made a business decision to get out of the GPS timing business.
  - The M12M timing receiver is now being manufactured by **iLotus LTD** in Singapore. For information see:
    http://www.synergy-gps.com/content/view/20/34/
  - The one sample of the iLotus M12M that we have seen shows a bias error of ~30 nsec as compared with our "Gold" reference Motorola receiver.
  - The reason for the bias (Hardware? Firmware?) is unknown.

What Else is New ?

- The **CNS Clock II** now is a fully functioning NTP Time Server for your LAN.
- CNS Systems is delivering the **CNS Clock II** with "genuine Motorola" M12+ receivers and the sawtooth remover. After the M12+ stock is depleted, M12Ms will be used.
- Rick continues to support the Windows-based **TAC32** PC software.
- **RSN** (**R**eal! **S**oon! **N**ow!) there will be an open source, GPL Linux version of TAC32 !

(This is the result of a collaboration between Rick and an un-named US Government organization)

Where to get information?

These Slides and related material:

http://gpstime.com

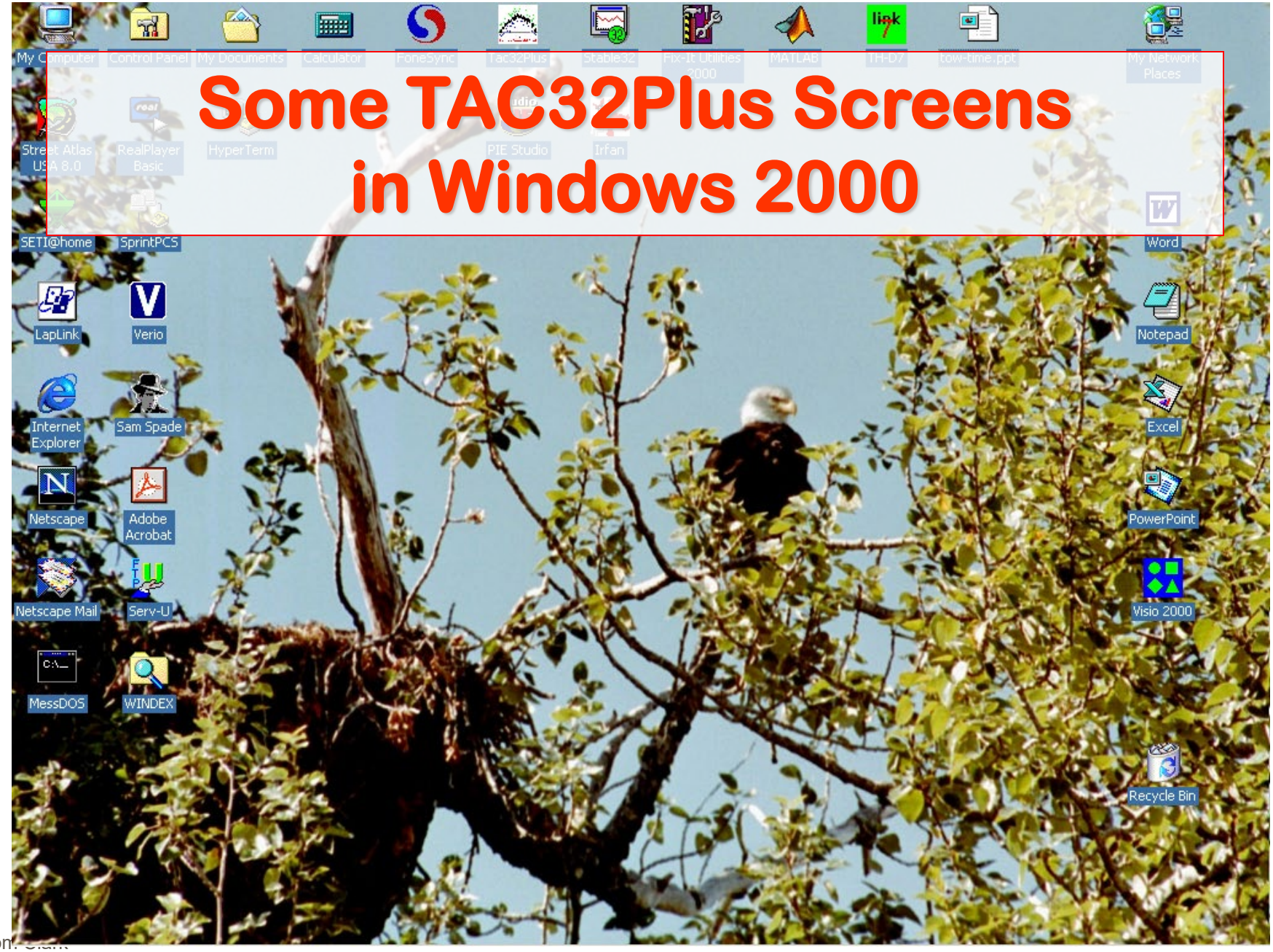
Information on the CNS Clock and the CNS Clock II:

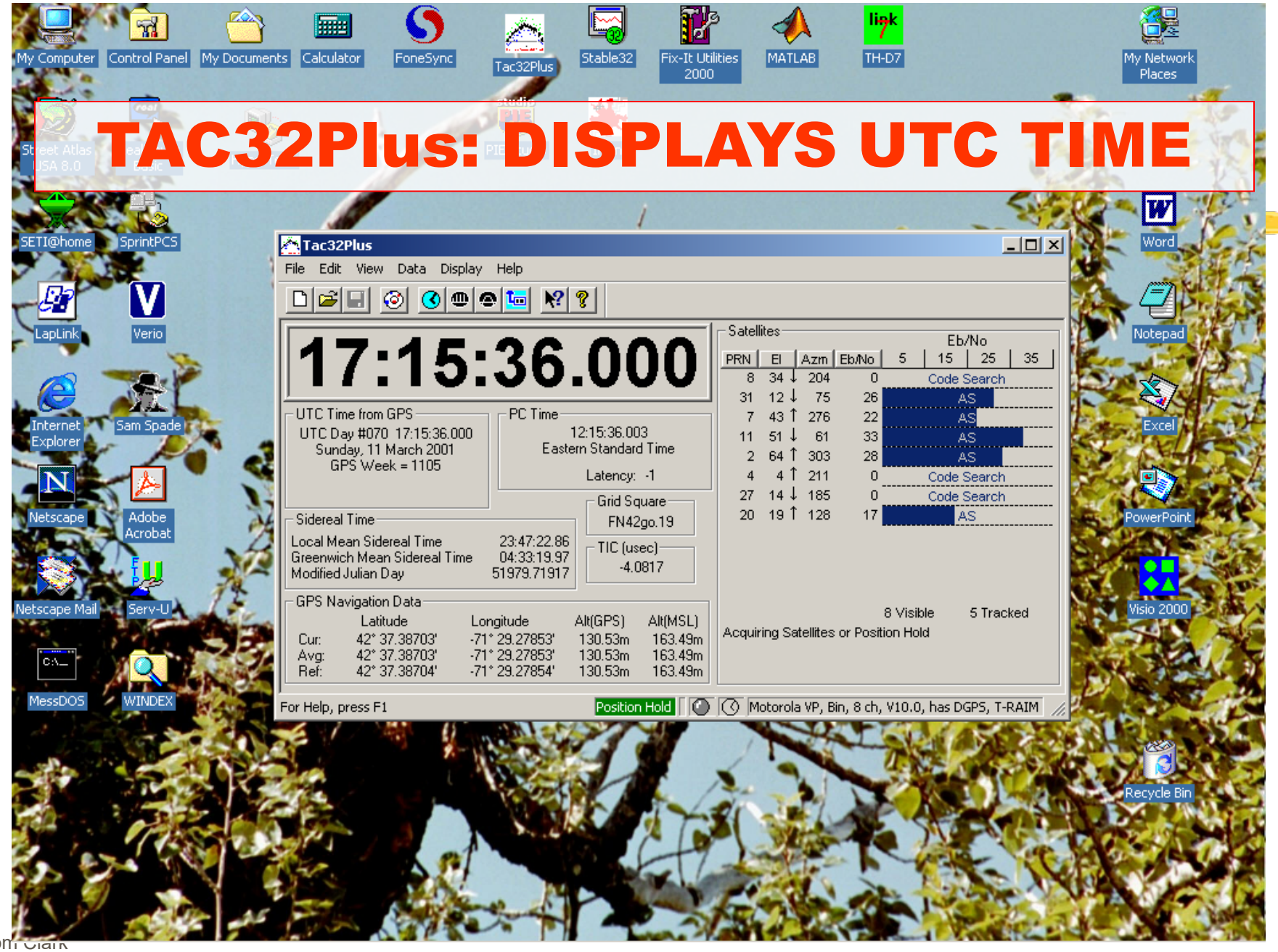
http://www.cnssys.com

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

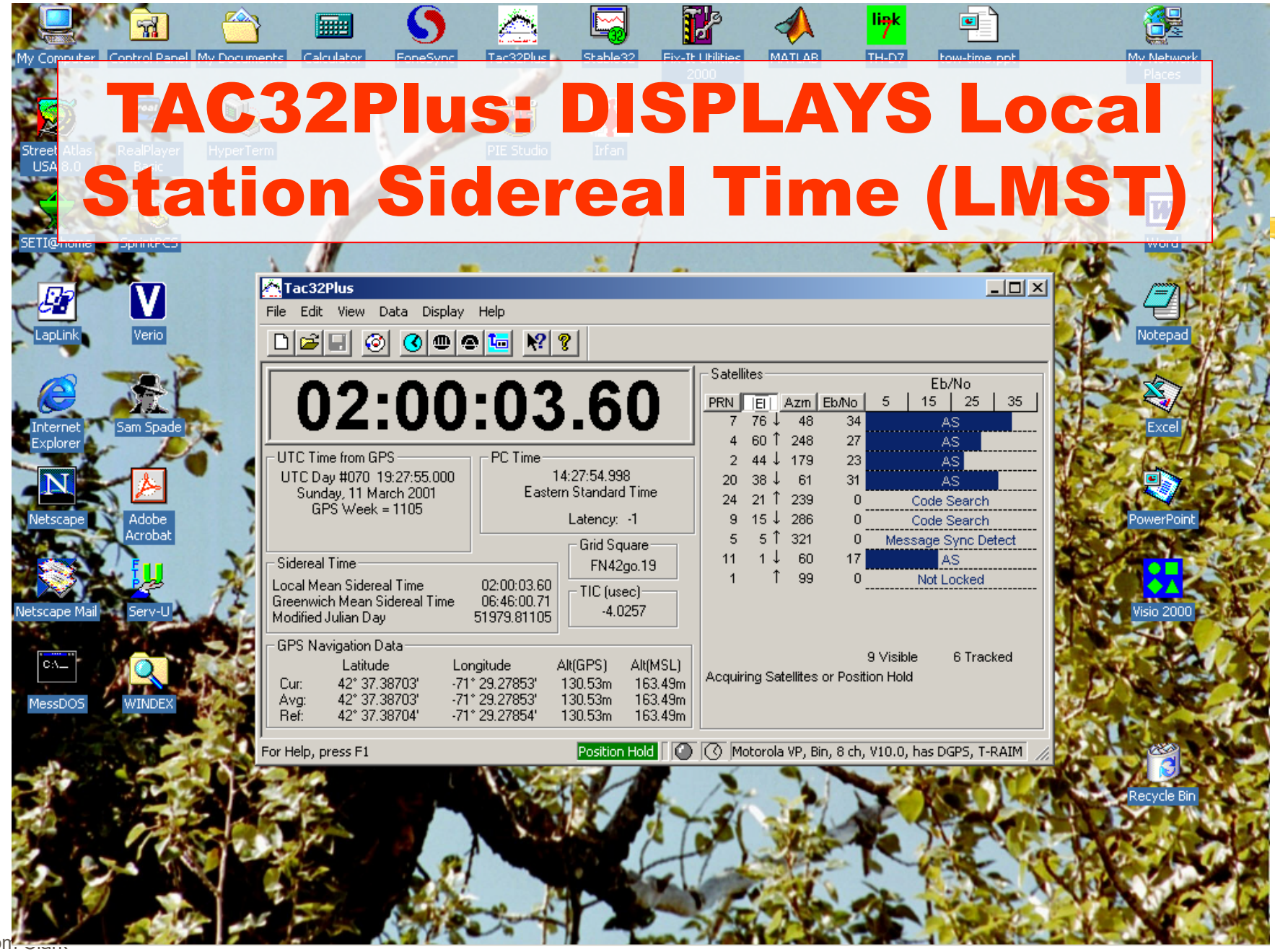
To contact Tom: mailto:K3IO@verizon.net

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

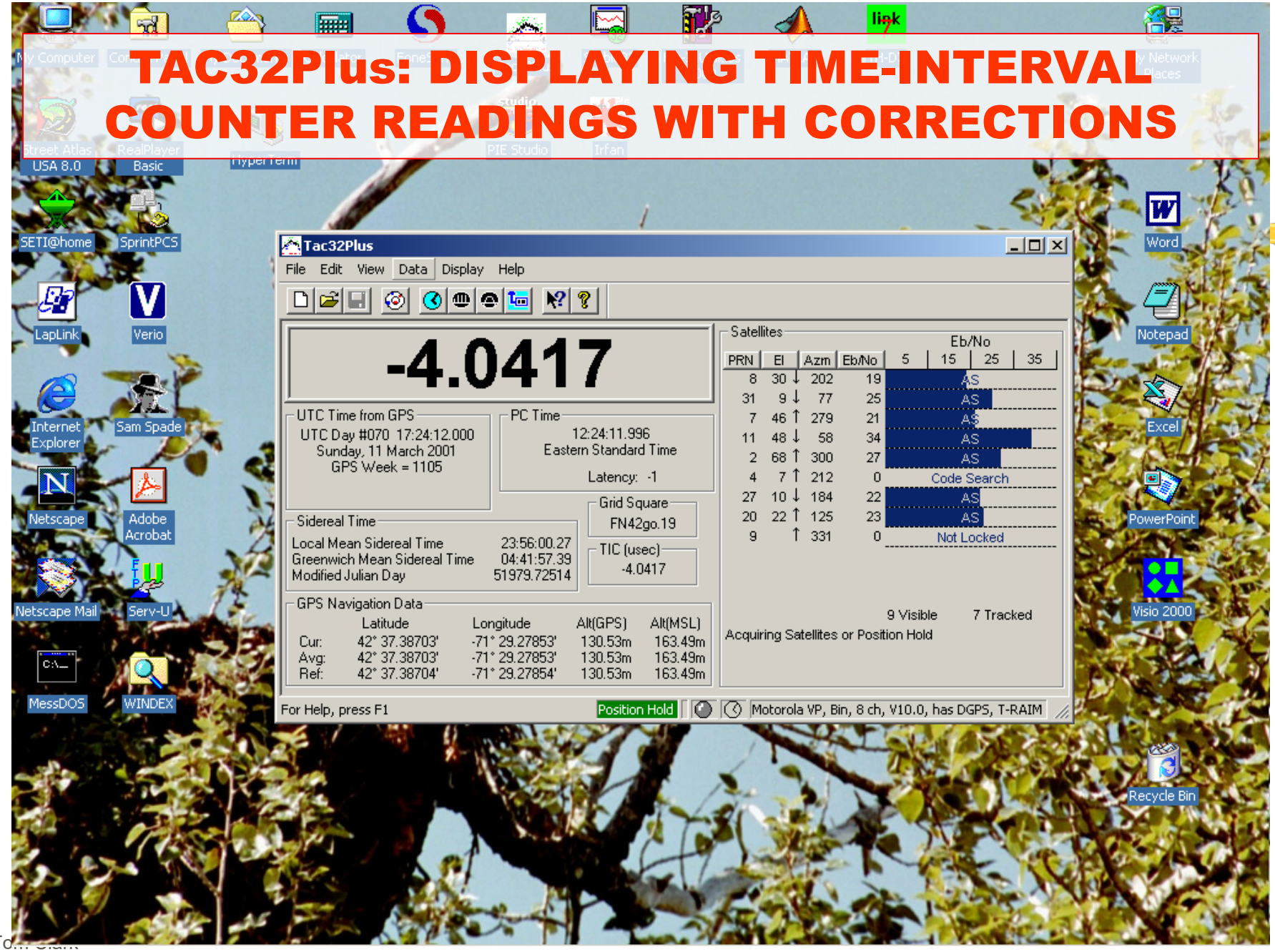

Some TAC32Plus Screens
in Windows 2000
My Computer
Control Panel
My Documents
Calculator
FoneSync
Tac32Plus
Stable32
Fix-It Utilities 2000
MATLAB
TH-D7
tow-time.ppt
My Network Places
Street Atlas USA 8.0
RealPlayer Basic
HyperTerm
PIE Studio
Irfan
SETI@home
SprintPCS
Word
LapLink
Verio
Notepad
Internet Explorer
Sam Spade
Excel
Netscape
Adobe Acrobat
PowerPoint
Netscape Mail
Serv-U
Visio 2000
MessDOS
WINDEX
Recycle Bin

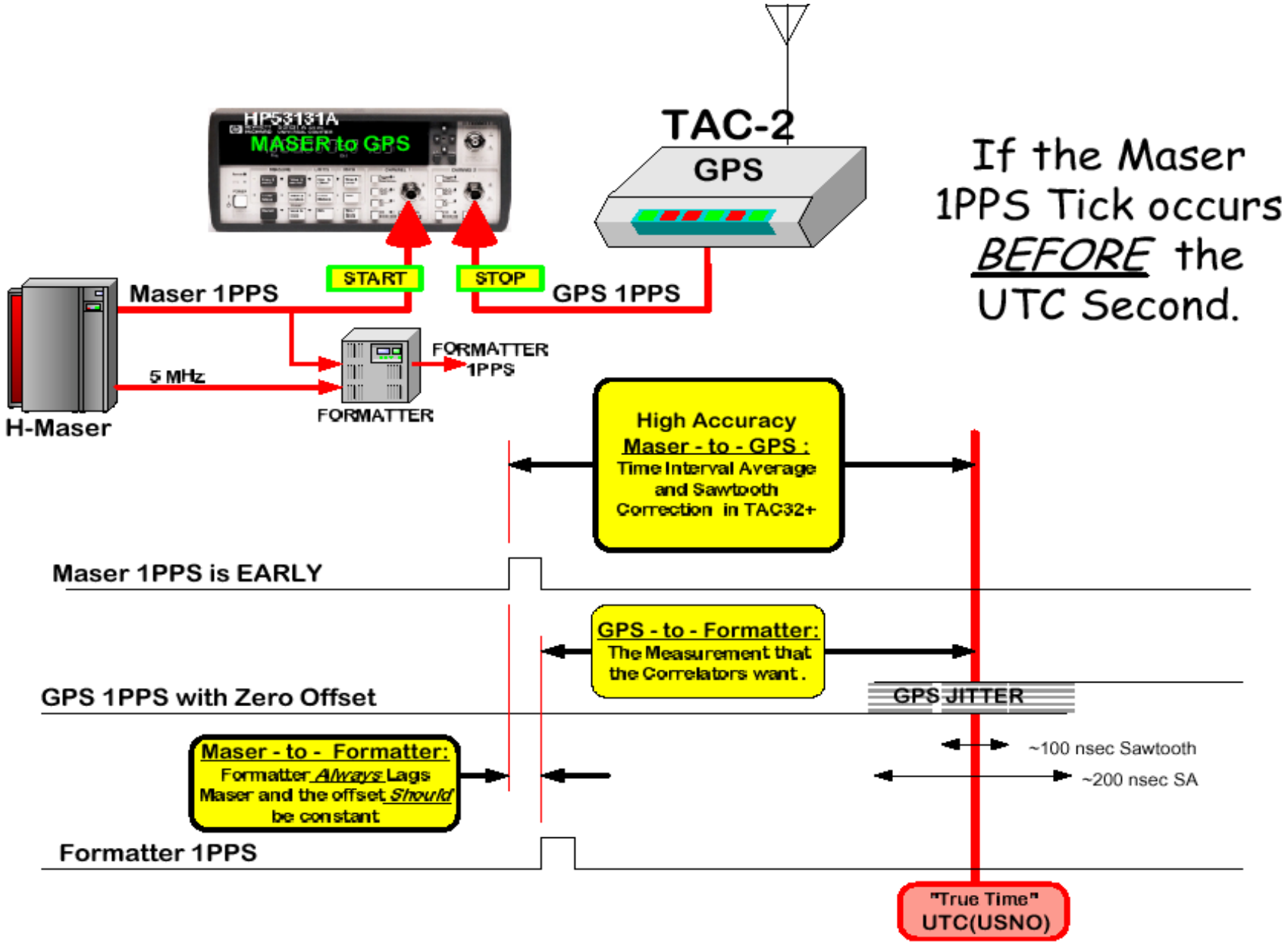

TAC32Plus: DISPLAYS UTC TIME
Tac32Plus
File Edit View Data Display Help
17:15:36.000
UTC Time from GPS
UTC Day #070 17:15:36.000
Sunday, 11 March 2001
GPS Week = 1105
PC Time
12:15:36.003
Eastern Standard Time
Latency: -1
Grid Square
FN42go.19
TIC (usec)
-4.0817
Sidereal Time
Local Mean Sidereal Time 23:47:22.86
Greenwich Mean Sidereal Time 04:33:19.97
Modified Julian Day 51979.71917
GPS Navigation Data
Latitude Longitude Alt(GPS) Alt(MSL)
Cur: 42° 37.38703' -71° 29.27853' 130.53m 163.49m
Avg: 42° 37.38703' -71° 29.27853' 130.53m 163.49m
Ref: 42° 37.38704' -71° 29.27854' 130.53m 163.49m
Satellites
Eb/No
PRN El Azm Eb/No 5 15 25 35
8 34 204 0 Code Search
31 12 75 26 AS
7 43 276 22 AS
11 51 61 33 AS
2 64 303 28 AS
4 4 211 0 Code Search
27 14 185 0 Code Search
20 19 128 17 AS
8 Visible 5 Tracked
Acquiring Satellites or Position Hold
For Help, press F1
Position Hold
Motorola VP, Bin, 8 ch, V10.0, has DGPS, T-RAIM

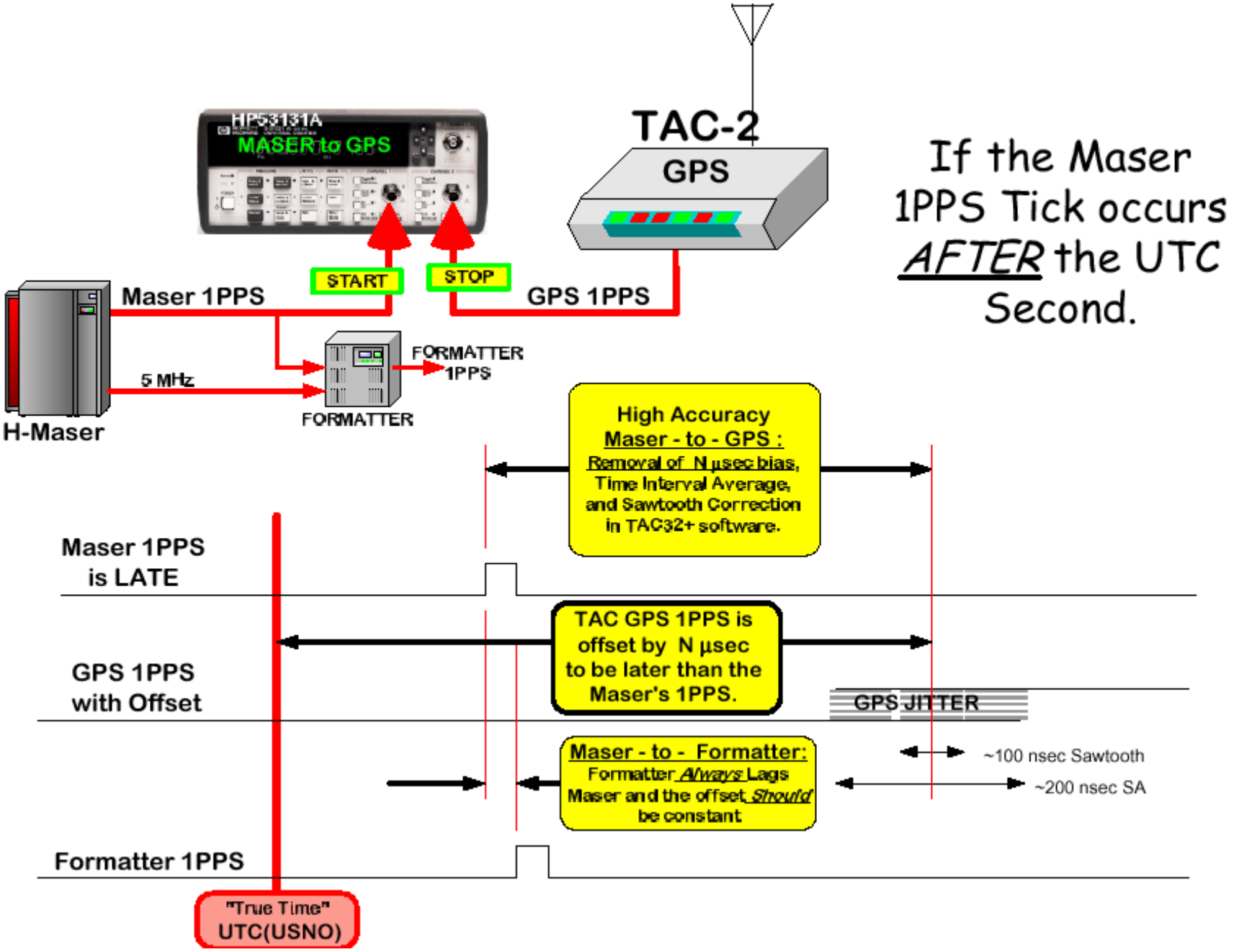
TAC32Plus: DISPLAYS Local Station Sidereal Time (LMST)



TAC32Plus: DISPLAYING TIME-INTERVAL COUNTER READINGS WITH CORRECTIONS




HP53131A
MASER to GPS
TAC-2
GPS
START
STOP
GPS 1PPS
Maser 1PPS
5 MHz
H-Maser
FORMATTER
FORMATTER 1PPS
If the Maser 1PPS Tick occurs BEFORE the UTC Second.
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 1PPS with Zero Offset
GPS JITTER
~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)


HP53131A
MASER to GPS
TAC-2
GPS
START
STOP
Maser 1PPS
GPS 1PPS
5 MHz
FORMATTER
1PPS
FORMATTER
H-Maser
If the Maser 1PPS Tick occurs AFTER the UTC Second.
High Accuracy
Maser - to - GPS :
Removal of N µsec bias,
Time Interval Average,
and Sawtooth Correction
in TAC32+ software.
Maser 1PPS
is LATE
TAC GPS 1PPS is
offset by N µsec
to be later than the
Maser's 1PPS.
GPS 1PPS
with Offset
GPS JITTER
Maser - to - Formatter:
Formatter Always Lags
Maser and the offset Should
be constant
~100 nsec Sawtooth
~200 nsec SA
Formatter 1PPS
"True Time"
UTC(USNO)

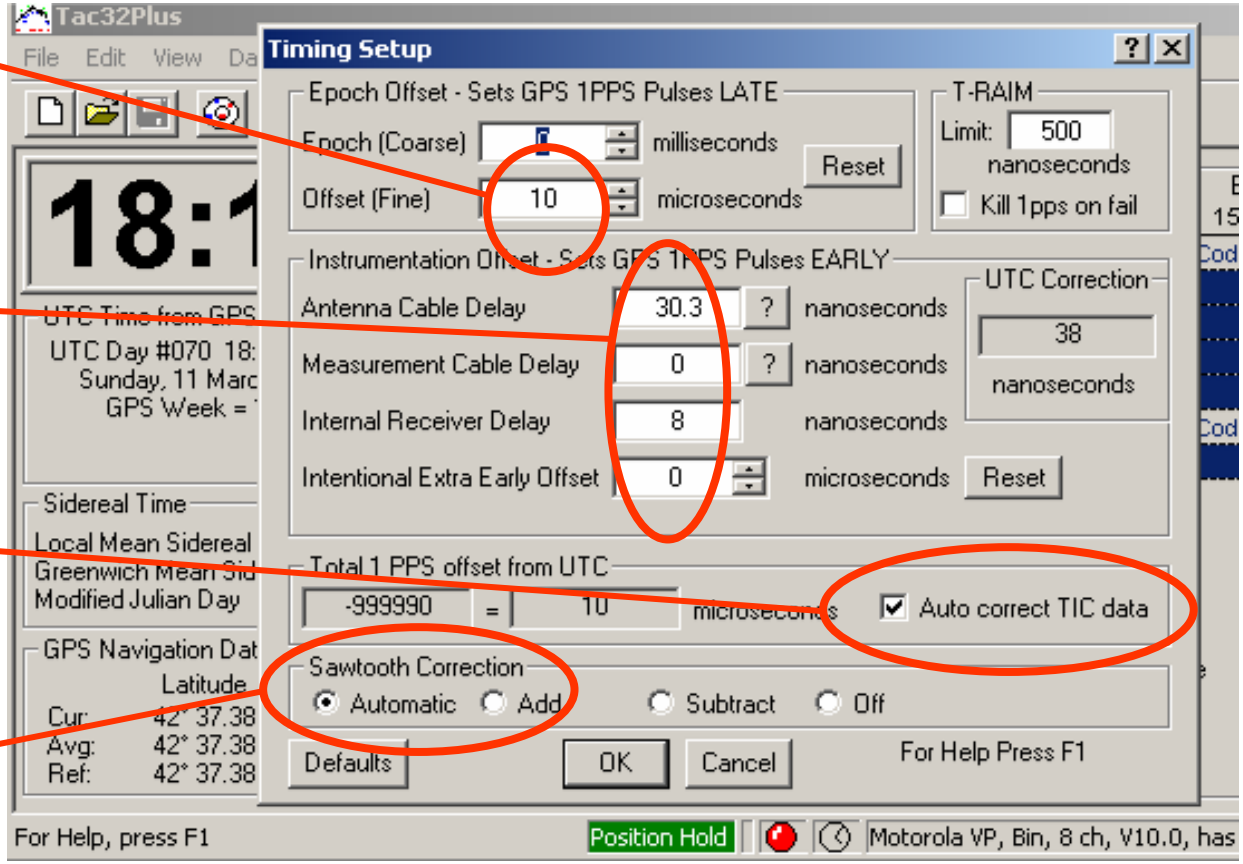
To Make Sure TAC32 is Logging the "true" Maser-to-GPS Time Interval:

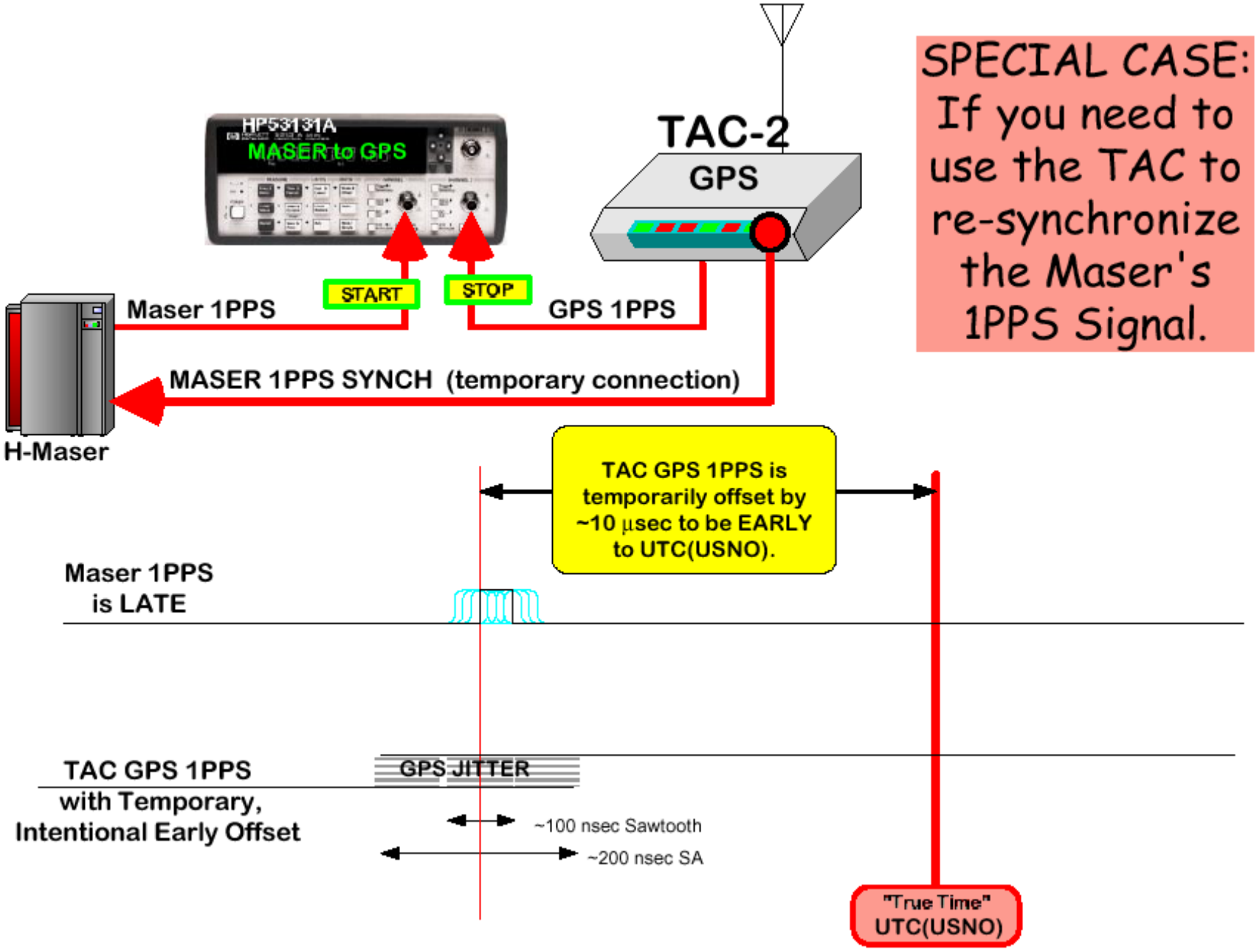
Offset GPS LATE if needed to be certain that GPS 1PPS is later than Maser 1PPS.

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

Allow the software to correct for all timing offsets.

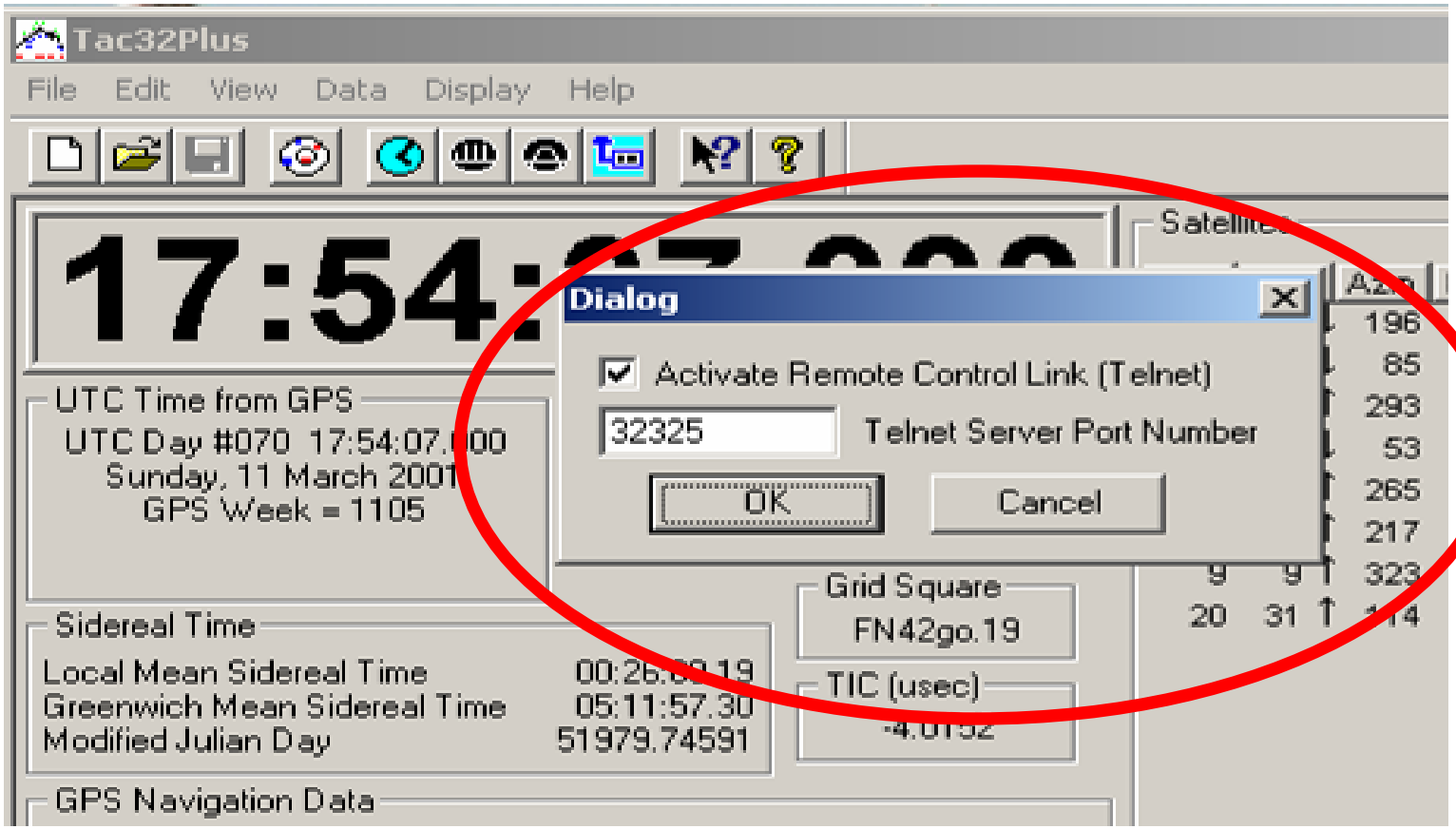
Allow software to correct the 1PPS pulse-to-pulse jitter




SPECIAL CASE:
If you need to use the TAC to re-synchronize the Maser's 1PPS Signal.
HP53131A
MASER to GPS
TAC-2
GPS
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, Hit Control-T:

Then Click on the check-box and the OK button



To Use TAC32Plus as your Station's SNTP Network Timer Server: