Timing for VLBI

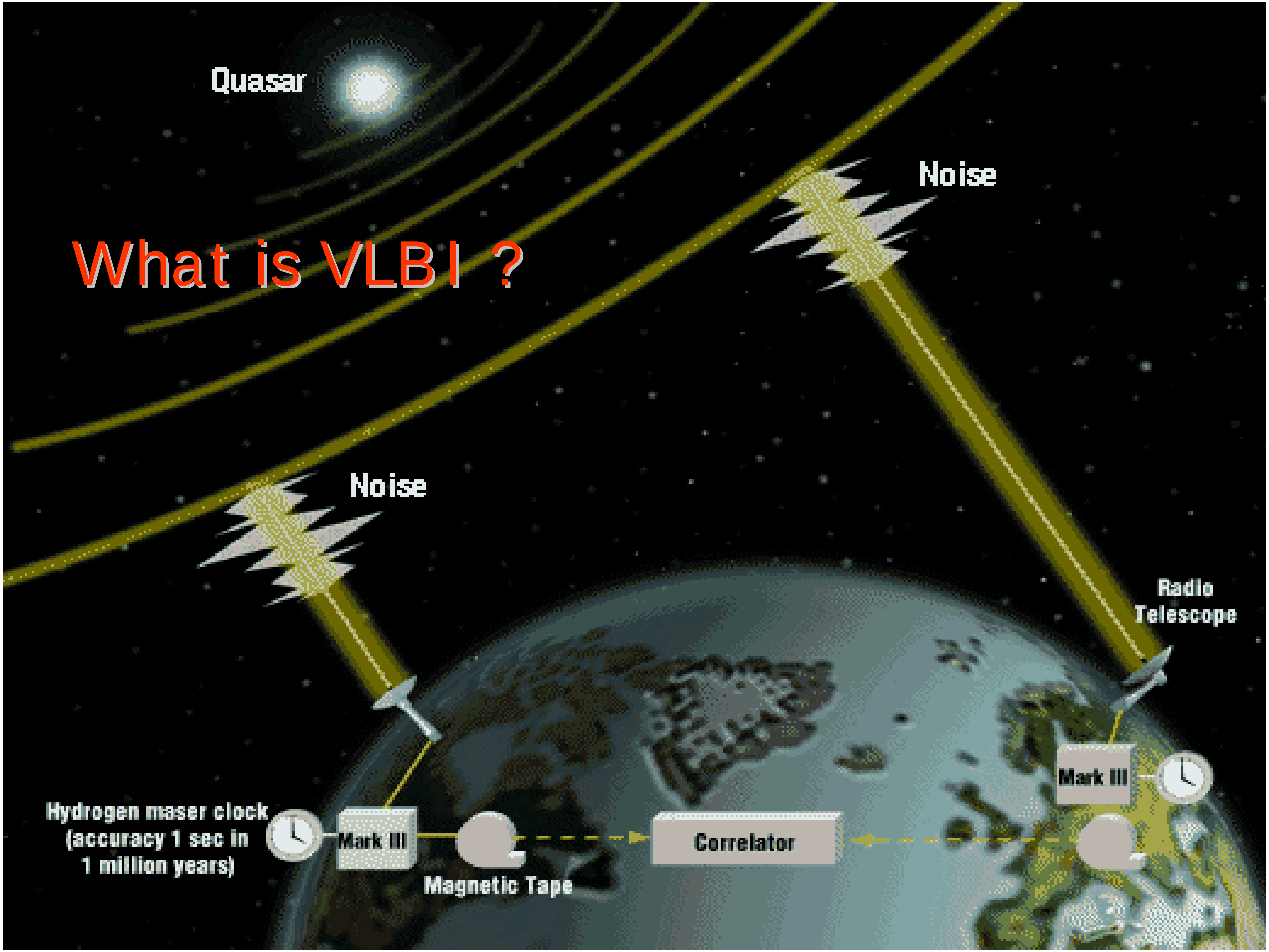
- **Tom Clark**

NASA Goddard Space Flight Center

Greenbelt, MD

IVS TOW Meeting

Haystack -- March 12, 2001


Quasar
What is VLBI ?
Noise
Noise
Radio Telescope
Mark III
Hydrogen maser clock (accuracy 1 sec in 1 million years)
Mark III
Magnetic Tape
Correlator

Oscillators and Clocks

Frequency and Time

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 occuring at a defined FREQUENCY

nsec -- minutes

Integrator and Display

- Gears
- Electronic Counters

Long-Term TIME

seconds - years

What Timing Performance Does VLBI Need?

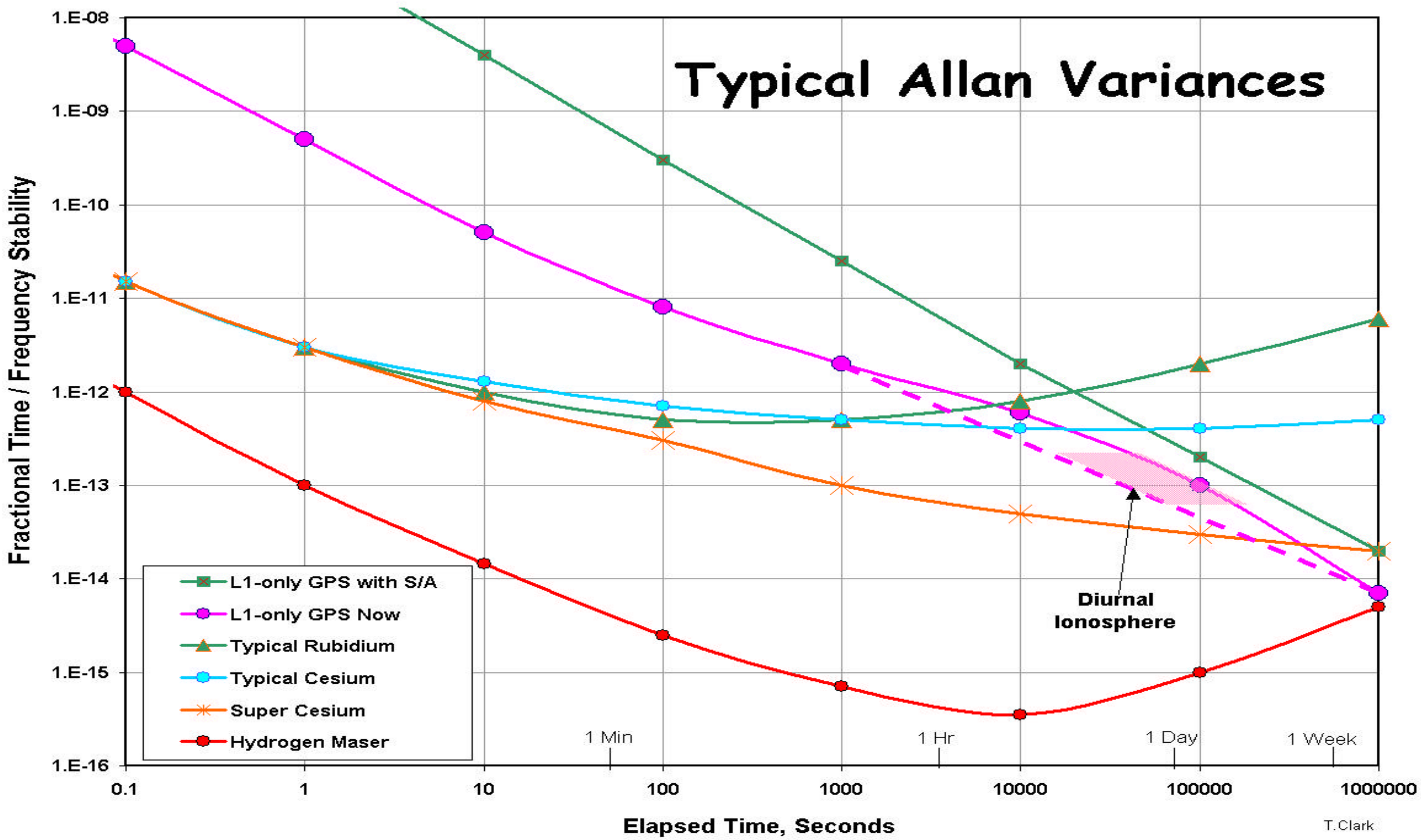
- The VLBI community (Radio Astronomy and Geodesy) uses Hydrogen Masers at 40-50 remote sites all around the world. To achieve ~10° signal coherence for ~1000 seconds at 10 GHz we need the two oscillators at the ends of the interferometer to maintain relative stability of $\approx [10° / (360° \bullet 10^{10} \text{Hz} \bullet 10^{3} \text{sec})] \approx 2.8 \bullet 10^{-15}$ @ 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 $\approx [50 \bullet 10^{-9} / 10^{6} \text{ sec}] \approx 5 \bullet 10^{-14}$ @ 10^{6} sec

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

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

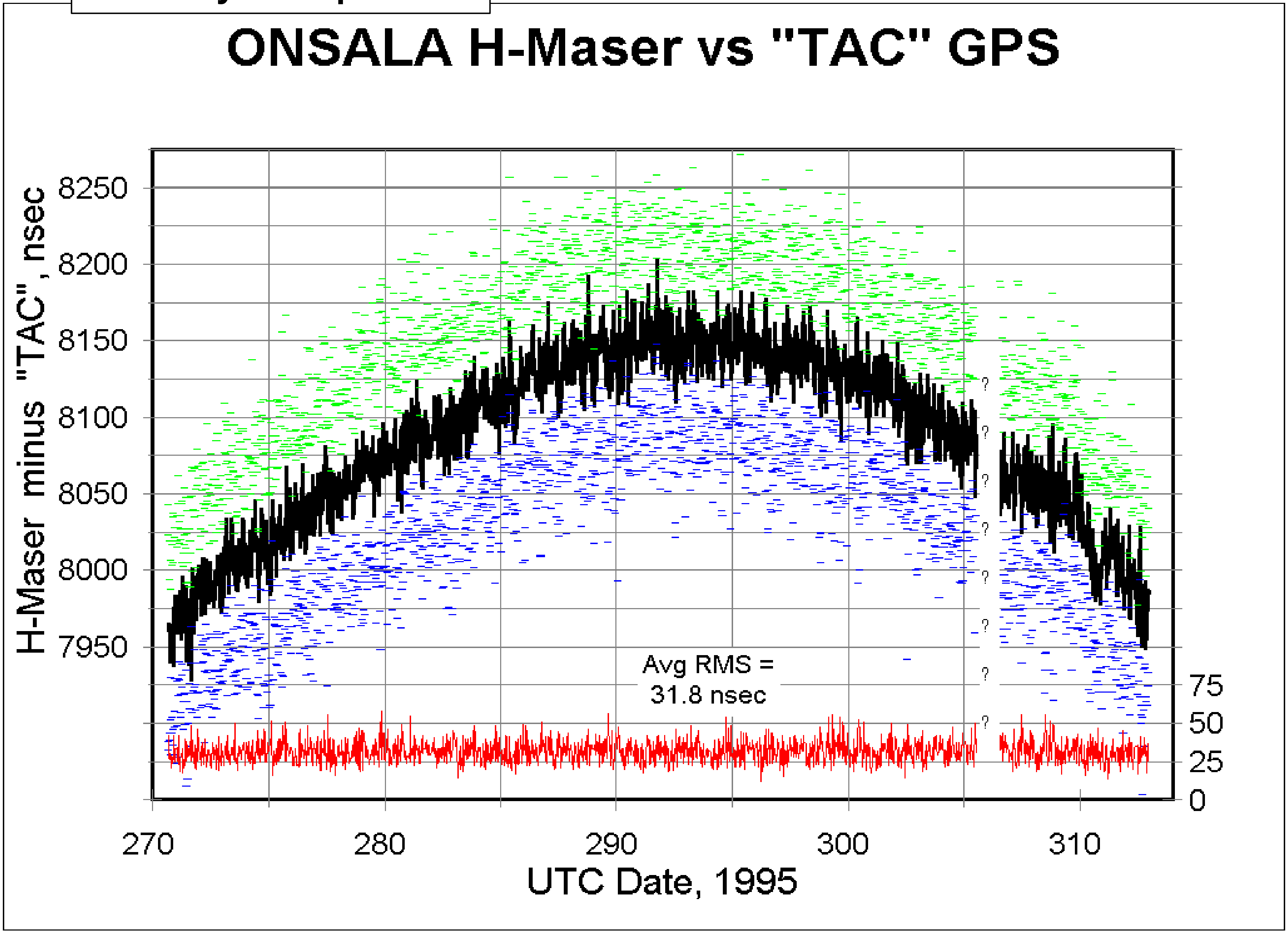
Clock Performance --The Bottom Line . . .



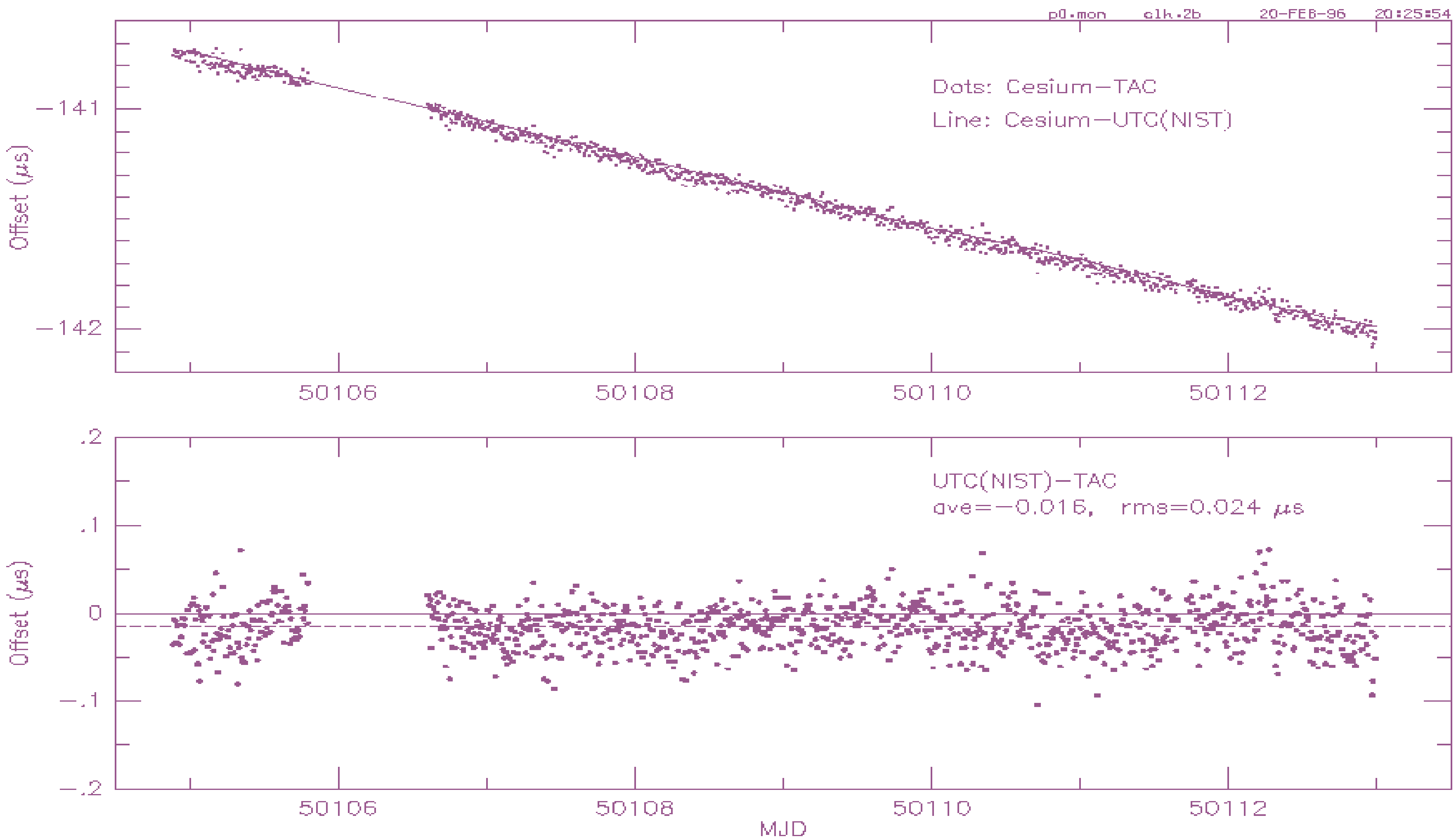
Setting VLBI Clocks Time & Rate with GPS

- **Compare two distant clocks by observing the same GPS satellite(s) at the same time (called <u>Common View</u>)**
  - 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 <u>Geodetic GPS receivers</u>** (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
  - Allows Geodetic Community to use VLBI Site and provides you Ionosphere data
- **<u>Blindly use the Broadcast GPS Timing Signals</u>** **(much like WWVB)**
  - **Single Frequency L1 only (until 2004)**
  - **Yields ~10 nsec results with < $1000 hardware**

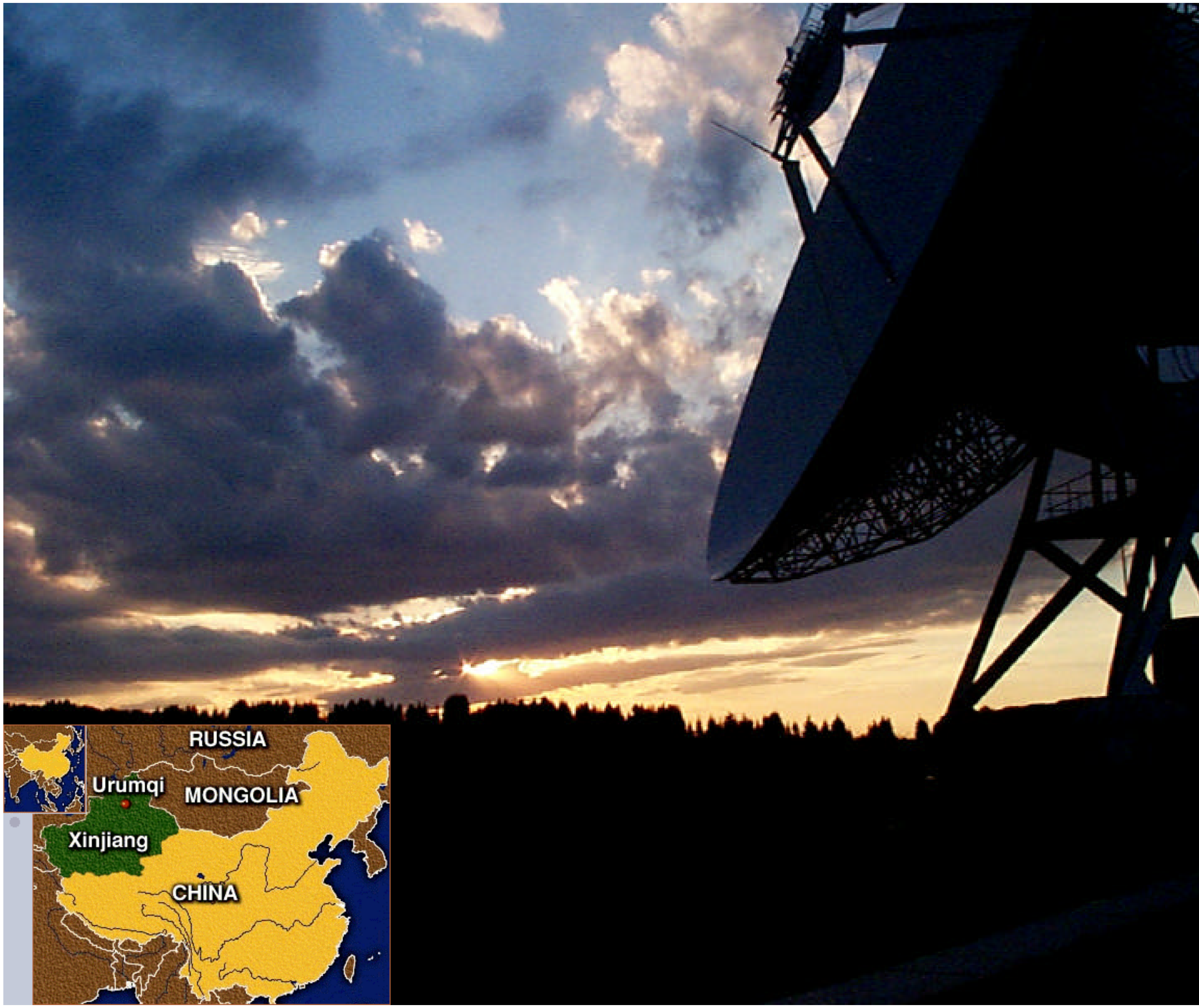
An Early Example - - -



Joe Taylor tests TAC Accuracy at Arecibo



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



Urumqi's 6-channel NASA-built TAC

Urumqi's Chinese H-Maser

How to get ~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.

Some Things about my "TAC" have changed in the Past 2 Years . . .

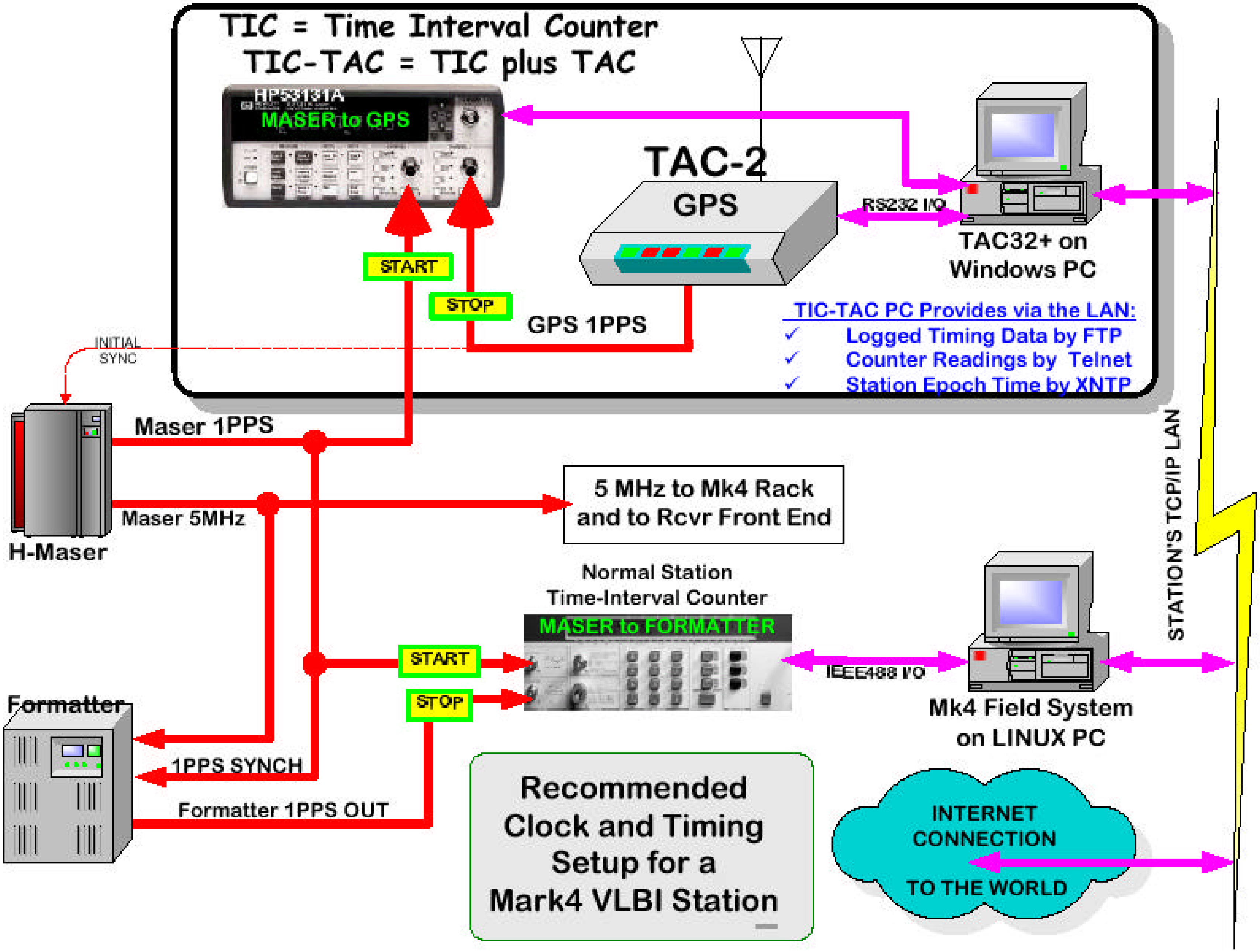
- Based on the GPS "W1K" (August 21, 1999) scare, we got NASA to implement TACs (and their commercial clone, the CNS Clock) at NASA VLBI + SLR stations. This included our developing the new TAC32Plus Windoze support software, deploying new WIN98/2000 computers and HP53131A Time-Interval counters, and integrating the package with the LINUX VLBI PCFS. With this setup, we routinely were getting ~15-20 nsec RMS timing even with S/A turned on.

-- AND --

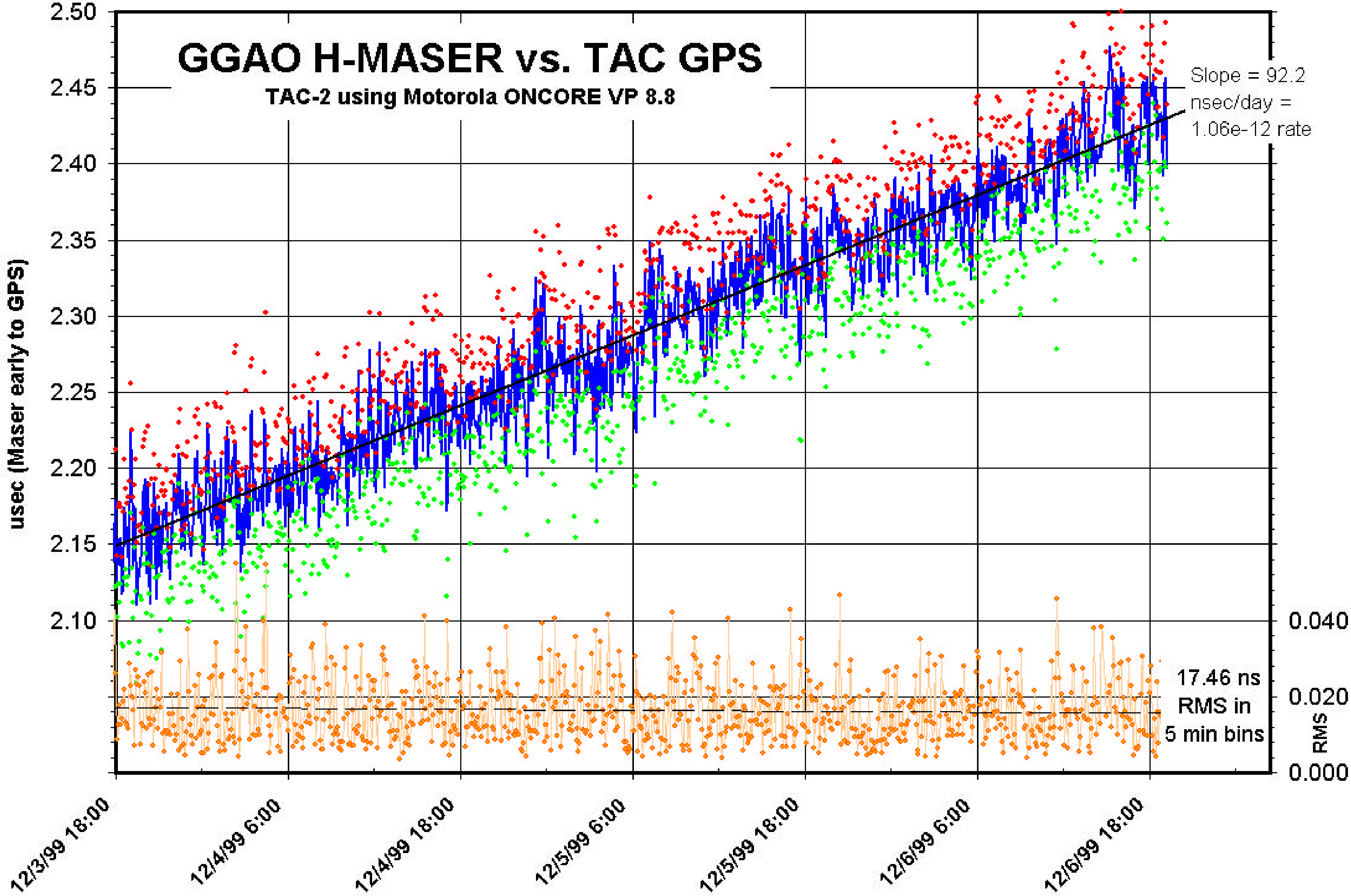
- DoD turned off S/A in May, 2000

-- AND --

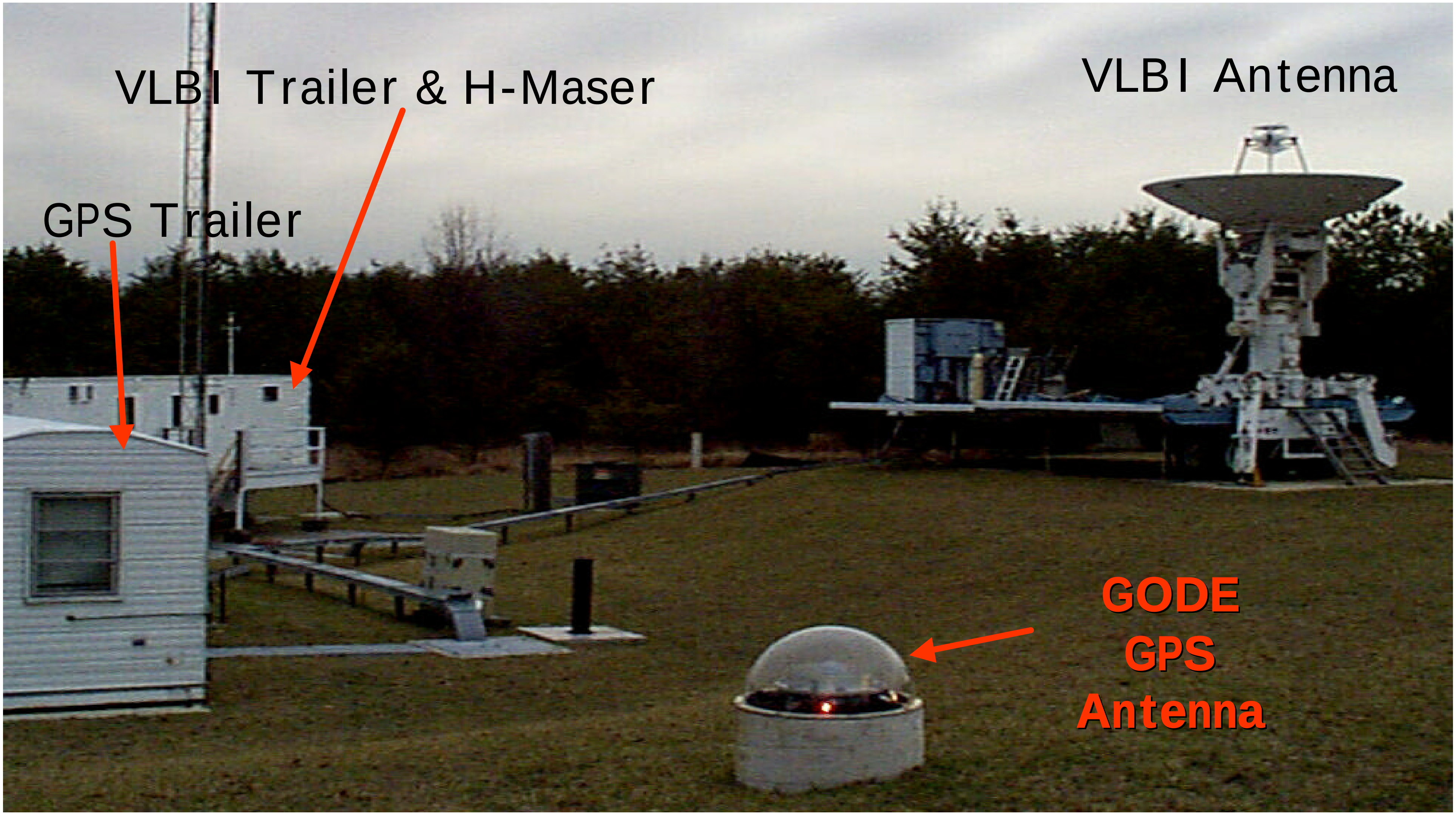
- Motorola discontinued the ONCORE VP receiver in late 1999

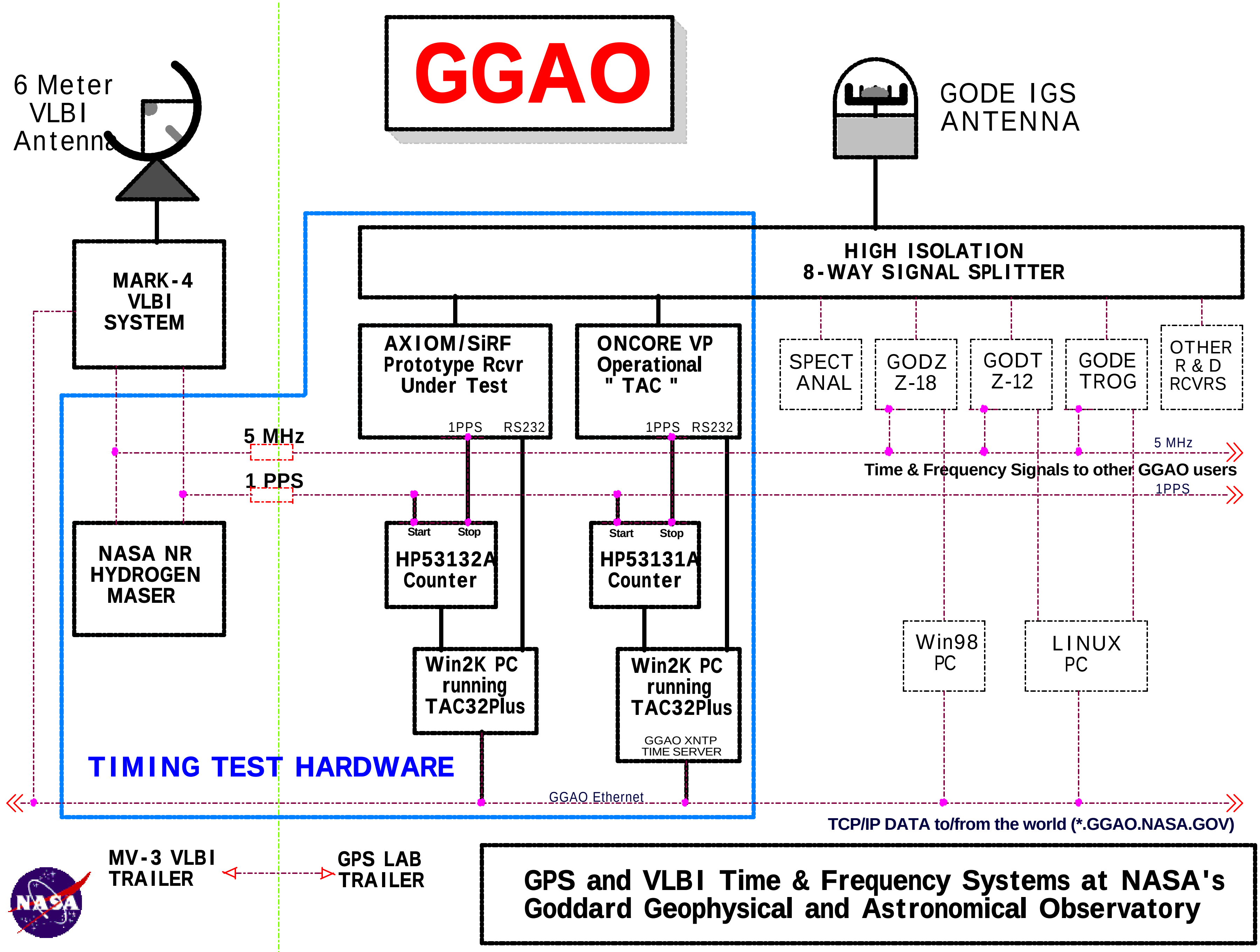

TIC = Time Interval Counter
TIC-TAC = TIC plus TAC
HP53131A
MASER to GPS
TAC-2
GPS
START
STOP
GPS 1PPS
RS232 I/O
TAC32+ on Windows PC
TIC-TAC PC Provides via the LAN:
Logged Timing Data by FTP
Counter Readings by Telnet
Station Epoch Time by XNTP
INITIAL SYNC
Maser 1PPS
Maser 5MHz
H-Maser
5 MHz to Mk4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

Before S/A was turned off . . .



GGAO (Goddard Geophysical & Astronomical Observatory)





GPS and VLBI Time & Frequency Systems at NASA's Goddard Geophysical and Astronomical Observatory

T.Clark 07 Sept.2000

Let Us Now Discuss . . .

- What happened when S/A was turned off.
- Some recent results obtained with prototypes of a new, low cost timing receiver:

OEM Chipset: SiRFStar 1

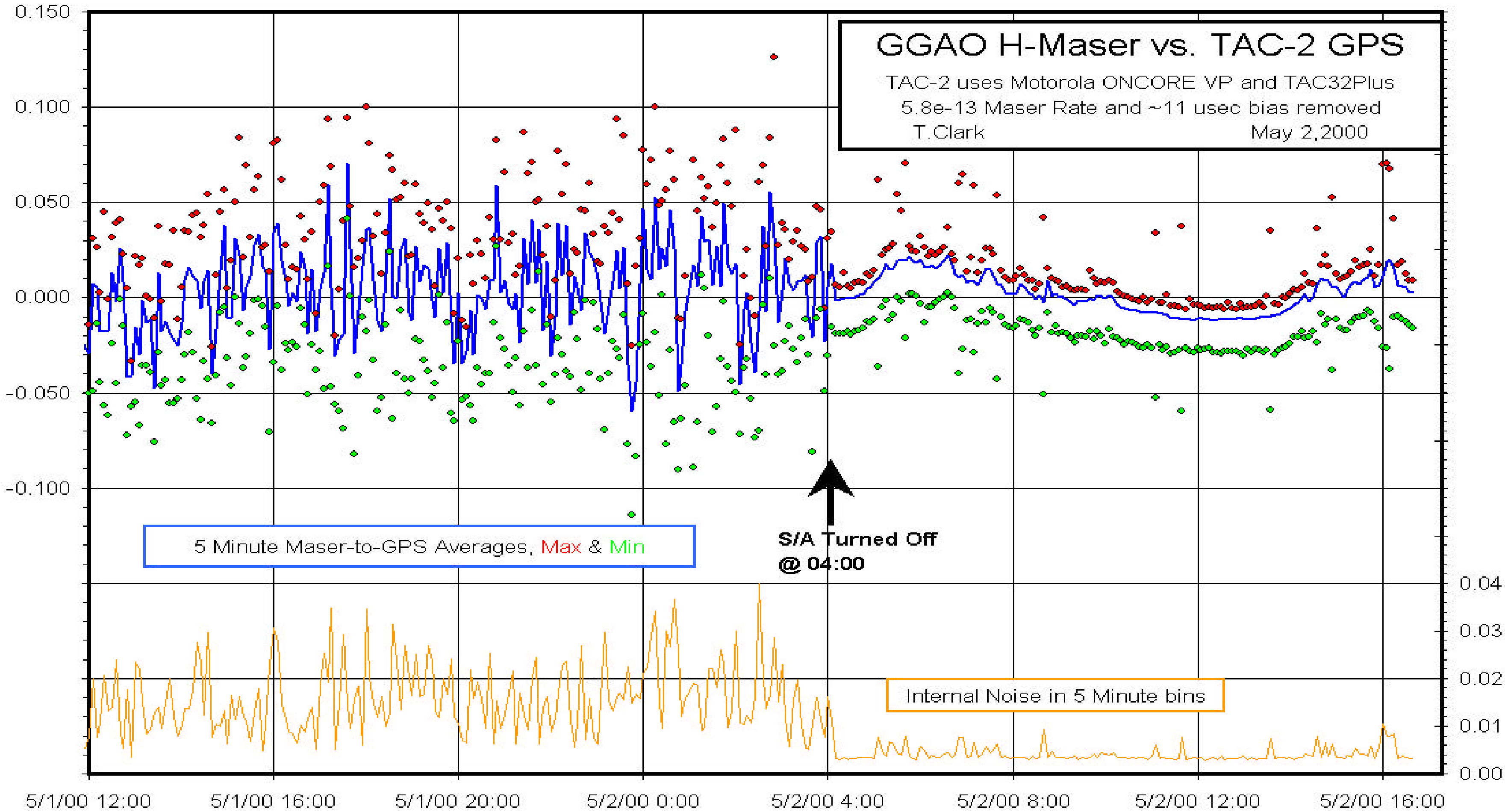
Receiver Hardware: Axiom Navigation's Sandpiper with Custom Firmware by Reza Abtahi/CNST

- A comparison of the new SiRF-based receiver with the venerable Motorola VP receiver.
- A discussion of the timing accuracy that can be obtained with single-frequency receivers now that S/A is off.

On May 2, 2000
at 04:00 UT,
DoD Turned
S/A OFF ! !

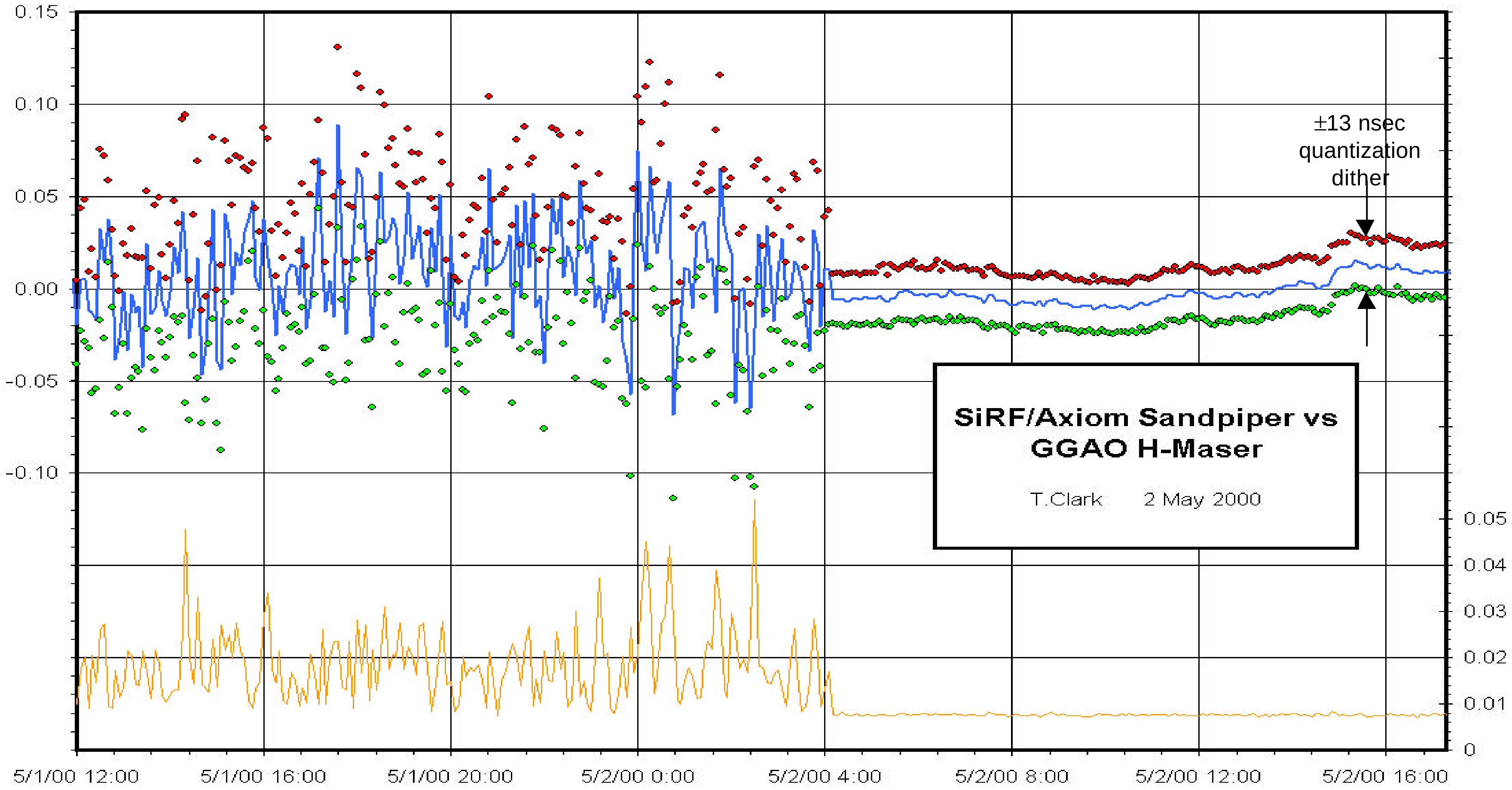
What happened when S/A went away?

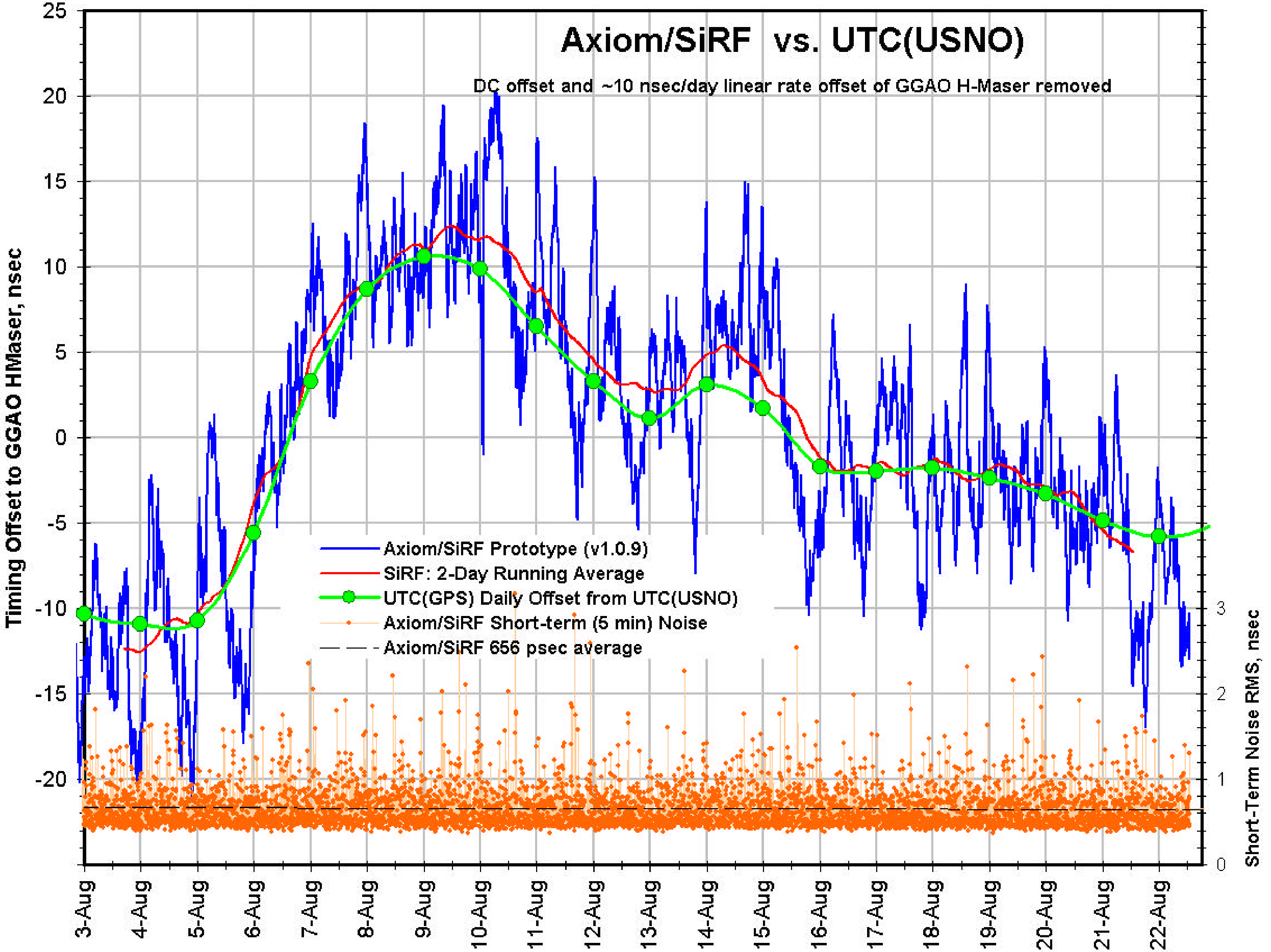
The Motorola ONCORE VP Receiver . . .



What happened when S/A went away?

The SiRF/Axiom prototype receiver . . .





Axiom/SiRF vs. UTC(USNO)
DC offset and ~10 nsec/day linear rate offset of GGAO H-Maser removed
Timing Offset to GGAO HMaser, nsec
Short-Term Noise RMS, nsec
Axiom/SiRF Prototype (v1.0.9)
SiRF: 2-Day Running Average
UTC(GPS) Daily Offset from UTC(USNO)
Axiom/SiRF Short-term (5 min) Noise
Axiom/SiRF 656 psec average
25
20
15
10
5
0
-5
-10
-15
-20
3
2
1
0
3-Aug
4-Aug
5-Aug
6-Aug
7-Aug
8-Aug
9-Aug
10-Aug
11-Aug
12-Aug
13-Aug
14-Aug
15-Aug
16-Aug
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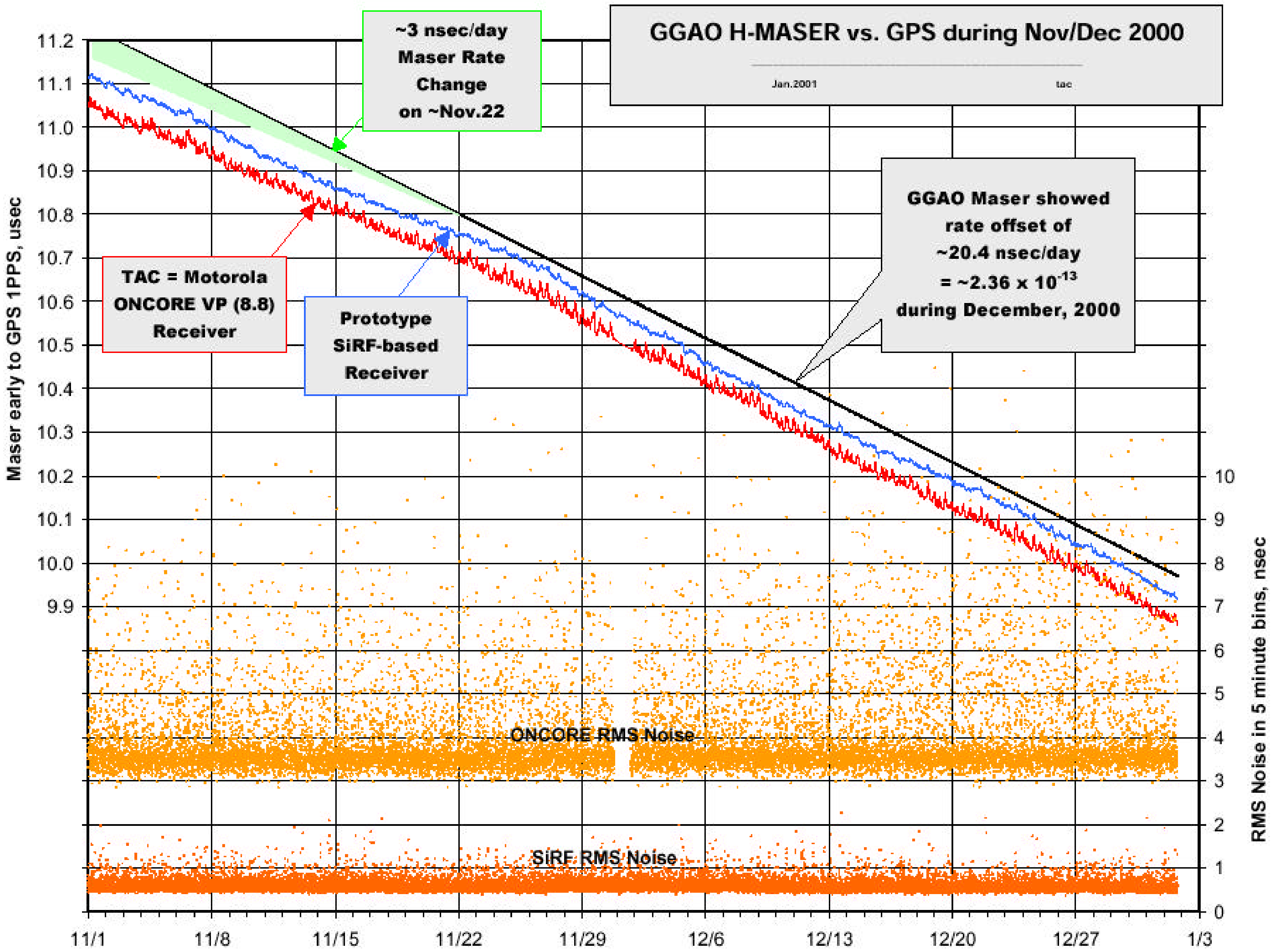
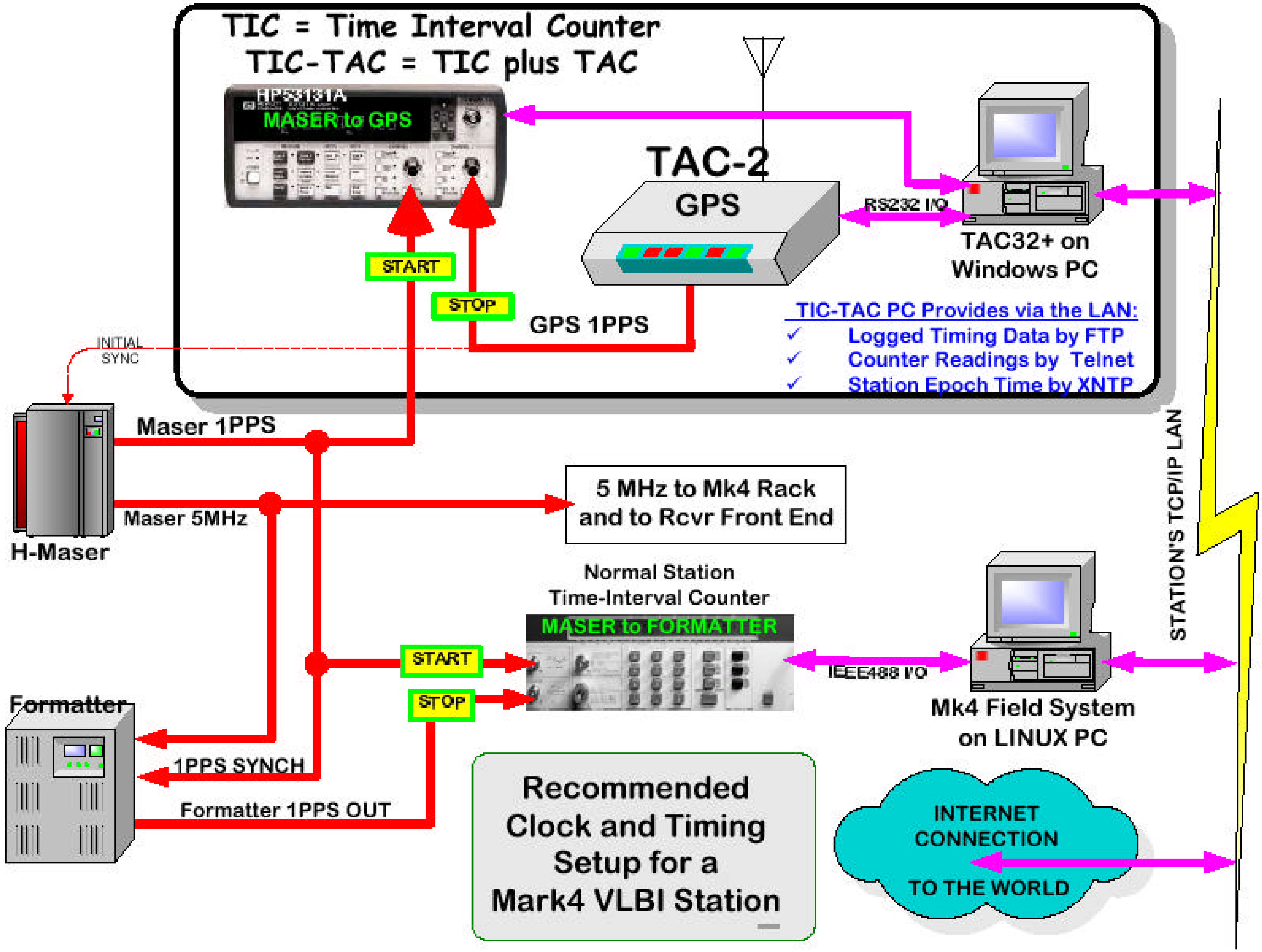
18-Aug
19-Aug
20-Aug
21-Aug
22-Aug



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
ONCORE 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



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
H-Maser
Maser 5MHz
5 MHz to Mk4 Rack
and to Rcvr Front End
Normal Station
Time-Interval Counter
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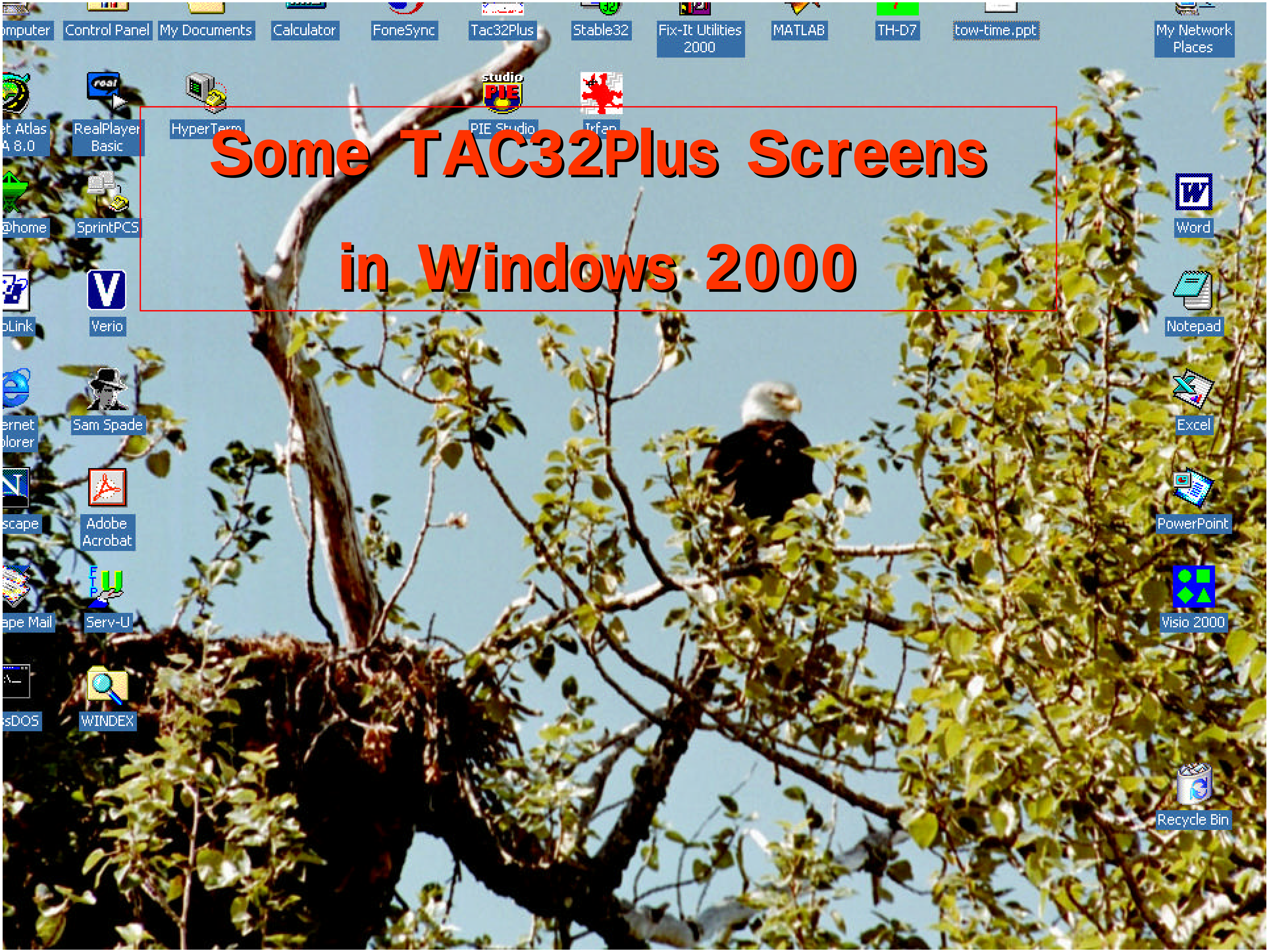
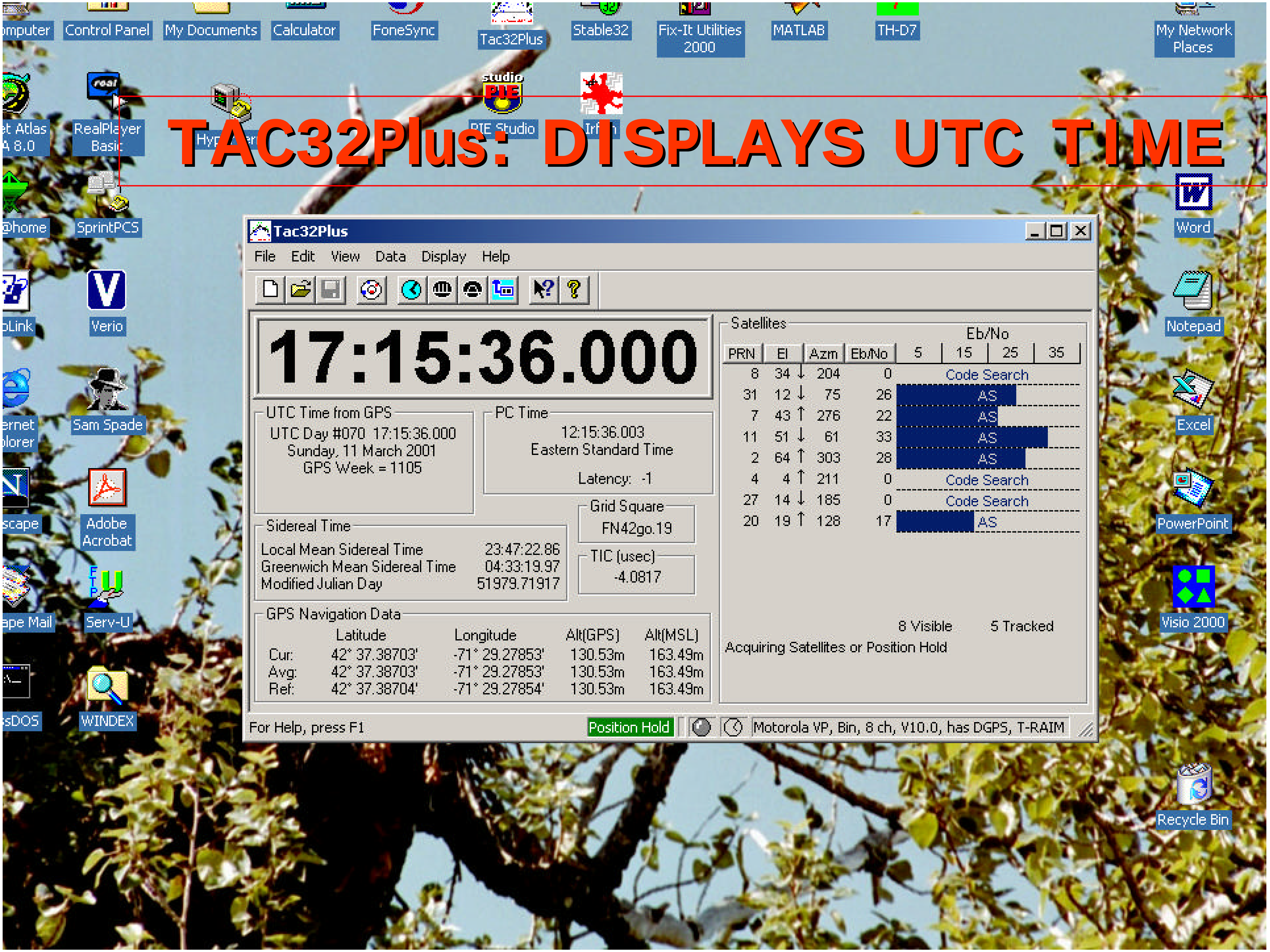
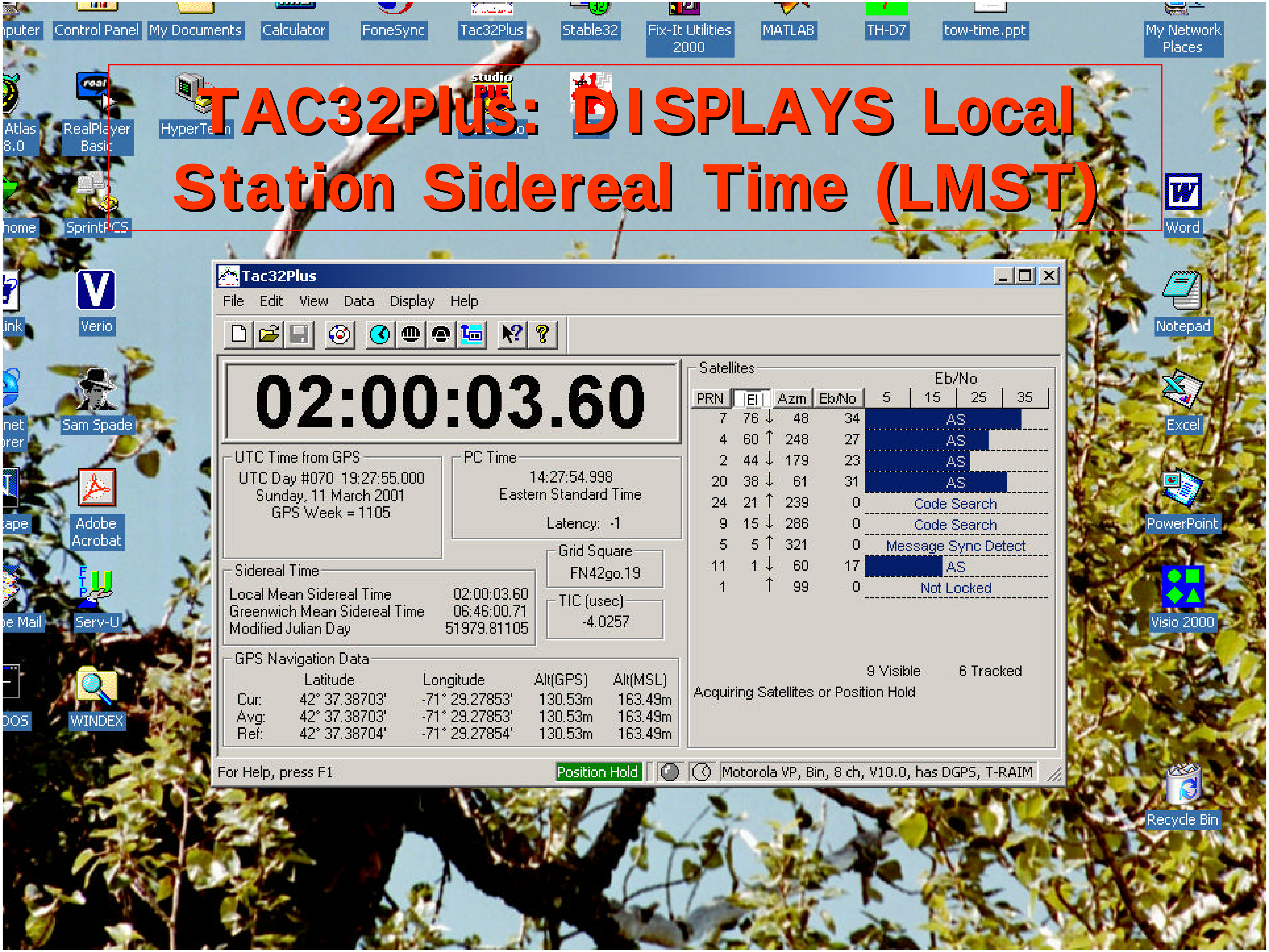

Some TAC32Plus Screens
in Windows 2000
Control Panel
My Documents
Calculator
FoneSync
Tac32Plus
Stable32
Fix-It Utilities 2000
MATLAB
TH-D7
tow-time.ppt
My Network Places
RealPlayer Basic
SprintPCS
Verio
Sam Spade
Adobe Acrobat
Serv-U
WINDEX
Word
Notepad
Excel
PowerPoint
Visio 2000
Recycle Bin

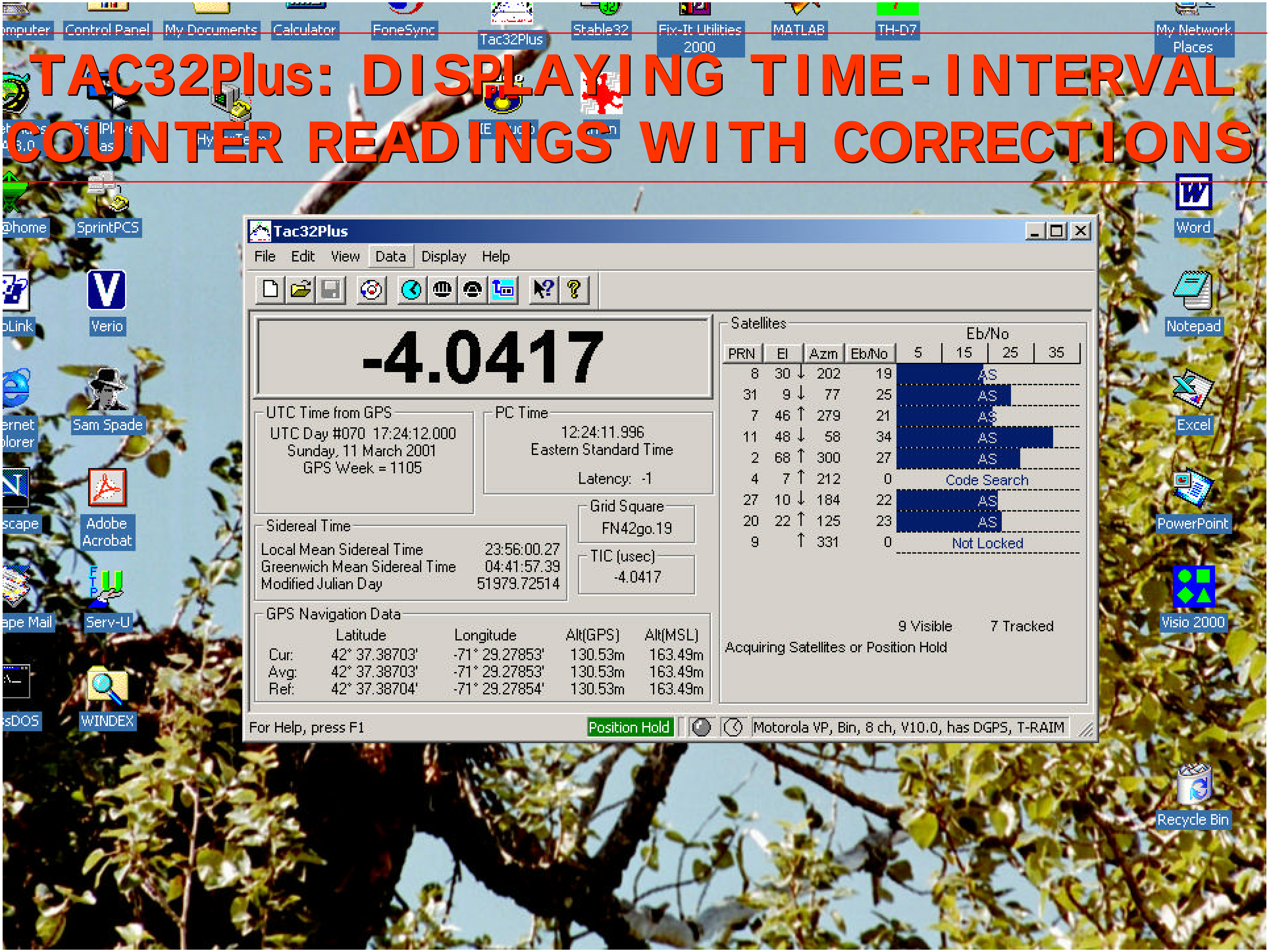
TAC32Plus: DISPLAYS UTC TIME

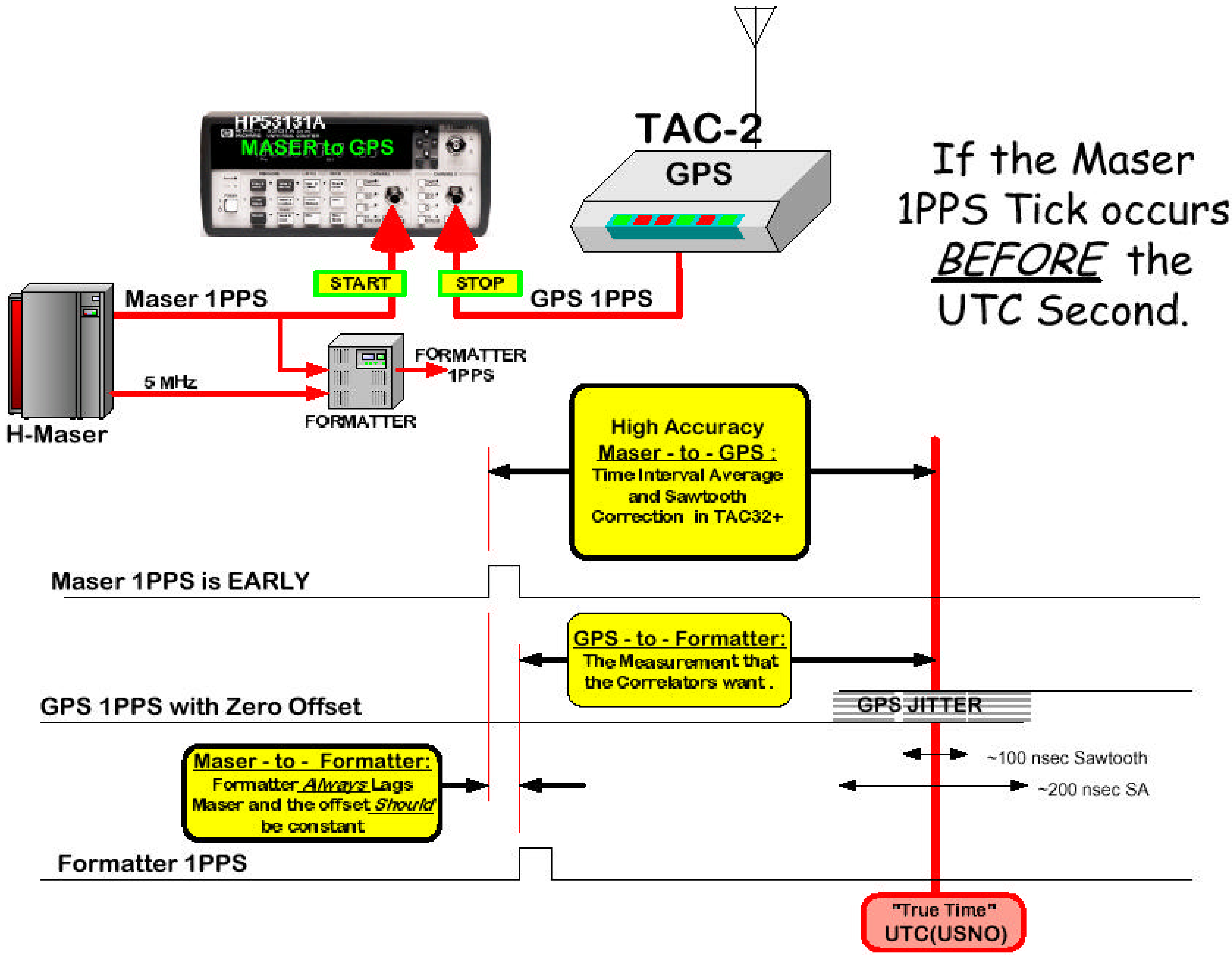


TAC32Plus: DISPLAYS Local Station Sidereal Time (LMST)

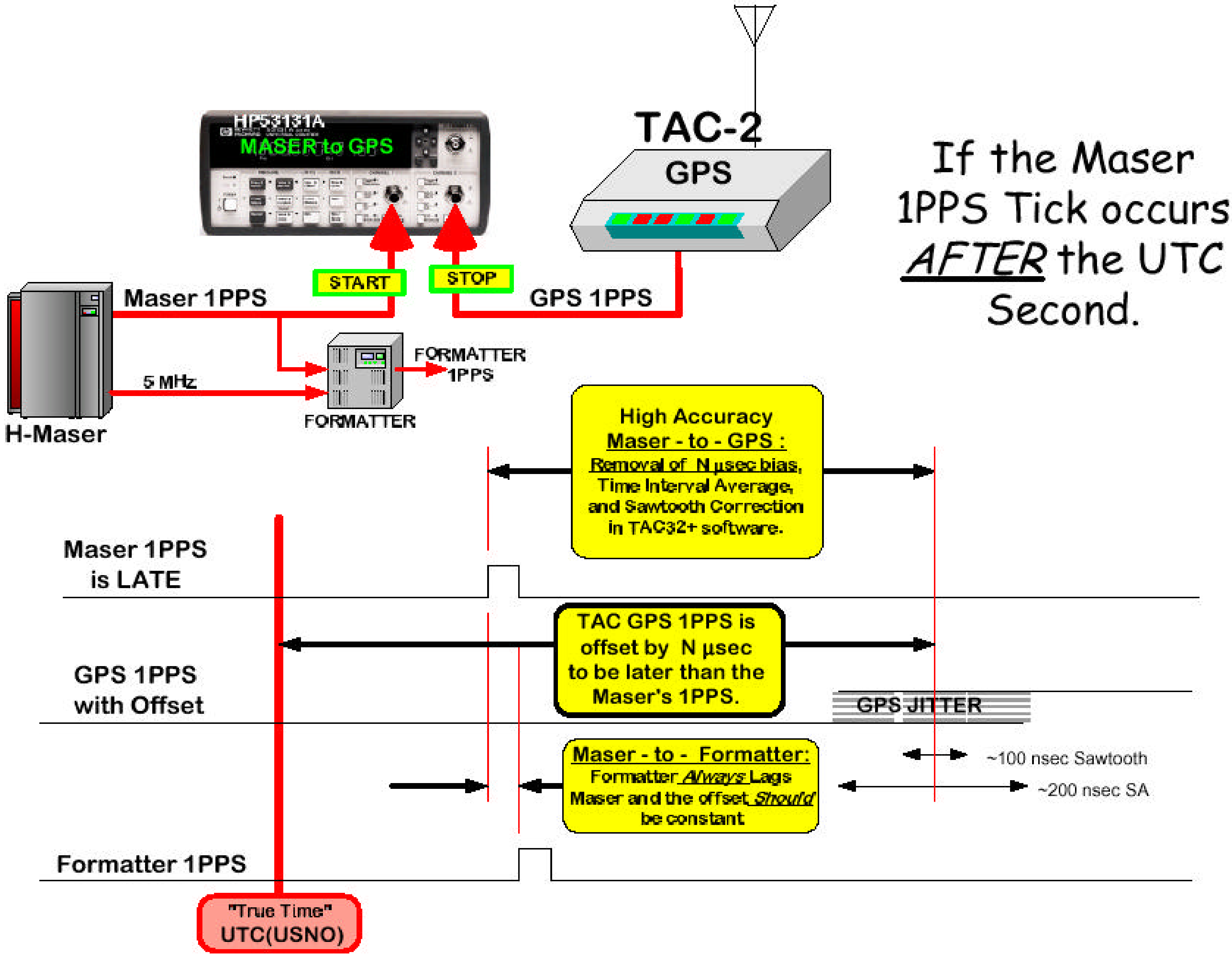


TAC32Plus: DISPLAYING TIME-INTERVAL COUNTER READINGS WITH CORRECTIONS





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 1PPS with Zero 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)


If the Maser 1PPS Tick occurs AFTER the UTC Second.
HP53131A
MASER to GPS
TAC-2
GPS
START
STOP
Maser 1PPS
GPS 1PPS
5 MHz
H-Maser
FORMATTER 1PPS
FORMATTER
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)

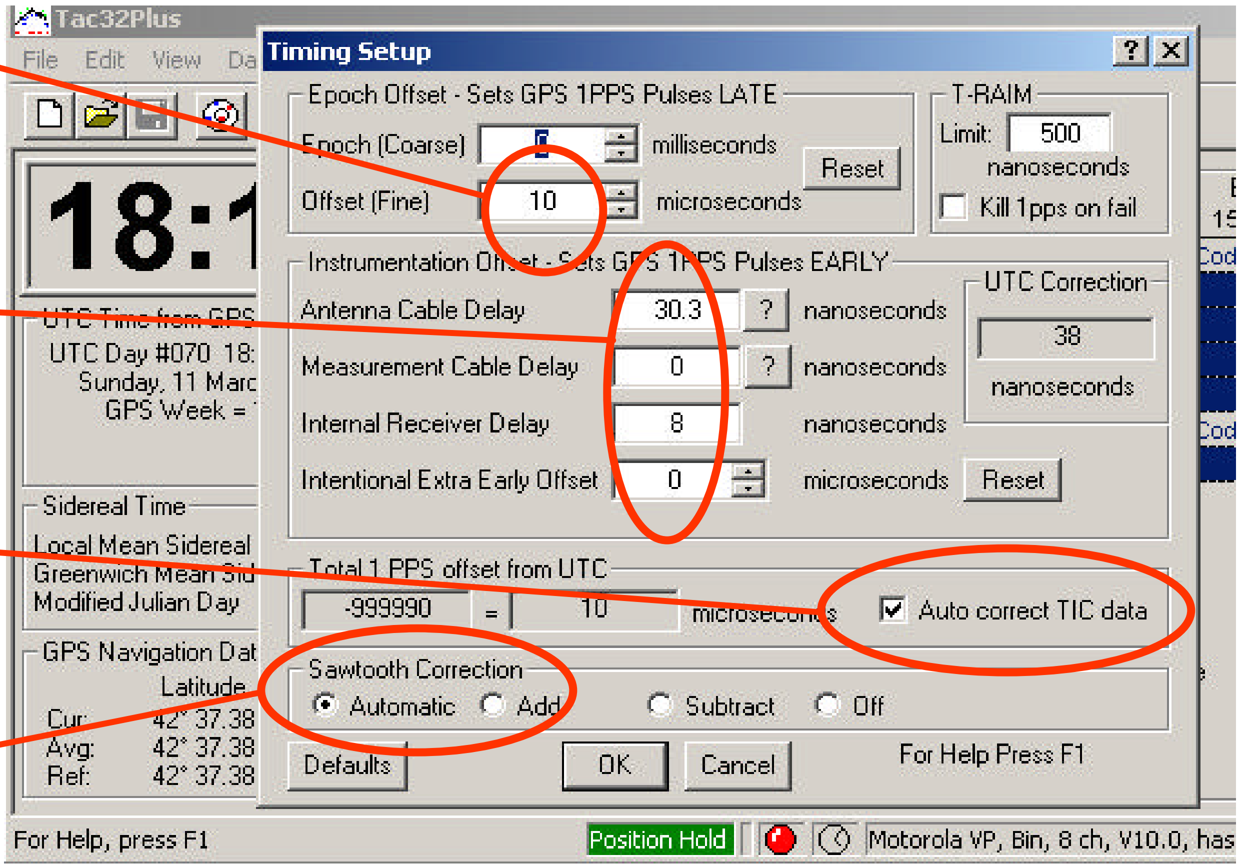
To Make Sure TAC32 is Logging the "true" Maser-to-GPS Time Interval:

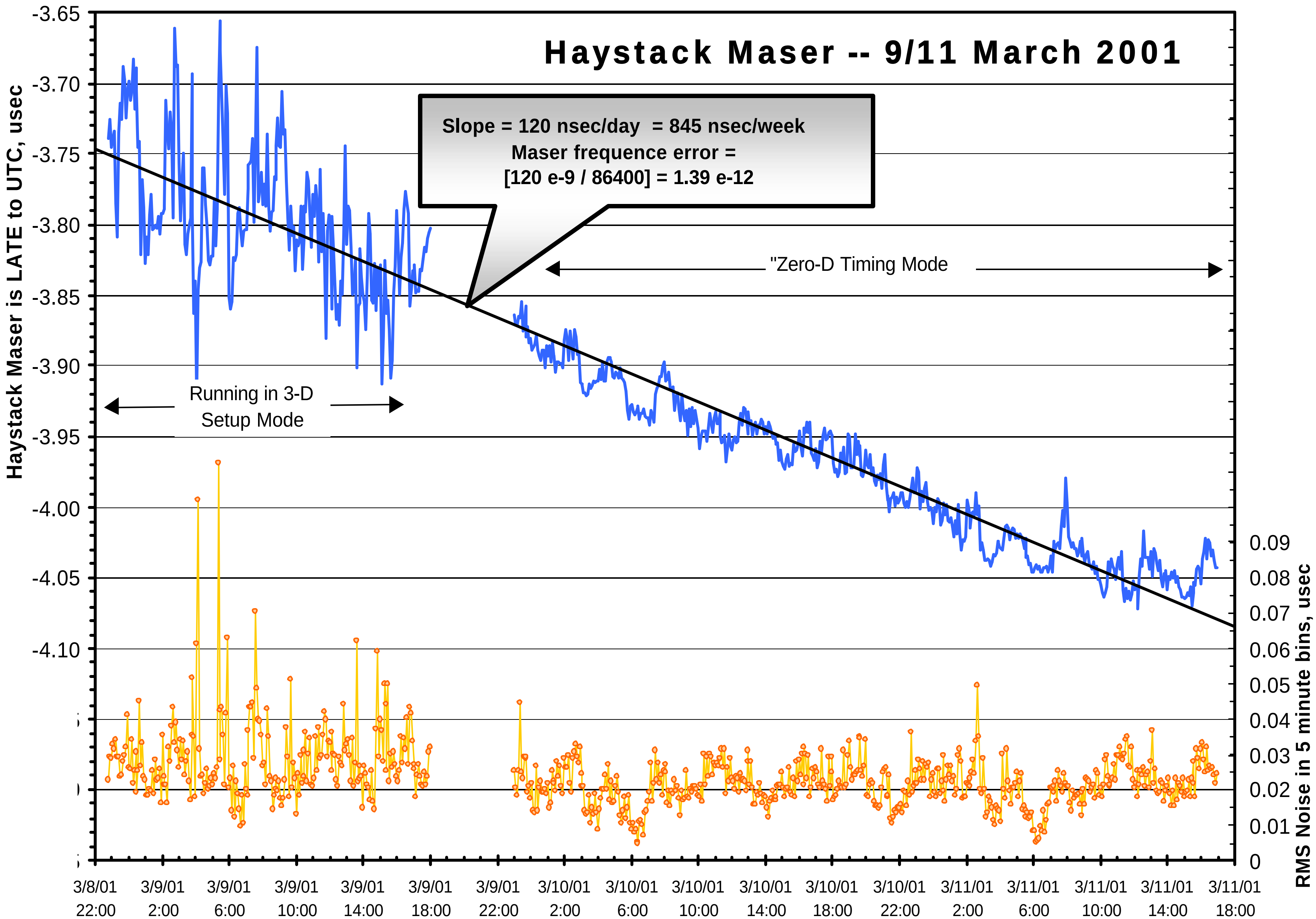
Offset GPS LATE if needed to be certain that GPS 1PPS is later than Maser 1PPS.

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




Haystack Maser -- 9/11 March 2001
Slope = 120 nsec/day = 845 nsec/week
Maser frequence error =
[120 e-9 / 86400] = 1.39 e-12
"Zero-D Timing Mode
Running in 3-D
Setup Mode
Haystack Maser is LATE to UTC, usec
RMS Noise in 5 minute bins, usec
-3.65
-3.70
-3.75
-3.80
-3.85
-3.90
-3.95
-4.00
-4.05
-4.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
3/8/01 22:00
3/9/01 2:00
3/9/01 6:00
3/9/01 10:00
3/9/01 14:00
3/9/01 18:00
3/9/01 22:00
3/10/01 2:00
3/10/01 6:00
3/10/01 10:00
3/10/01 14:00
3/10/01 18:00
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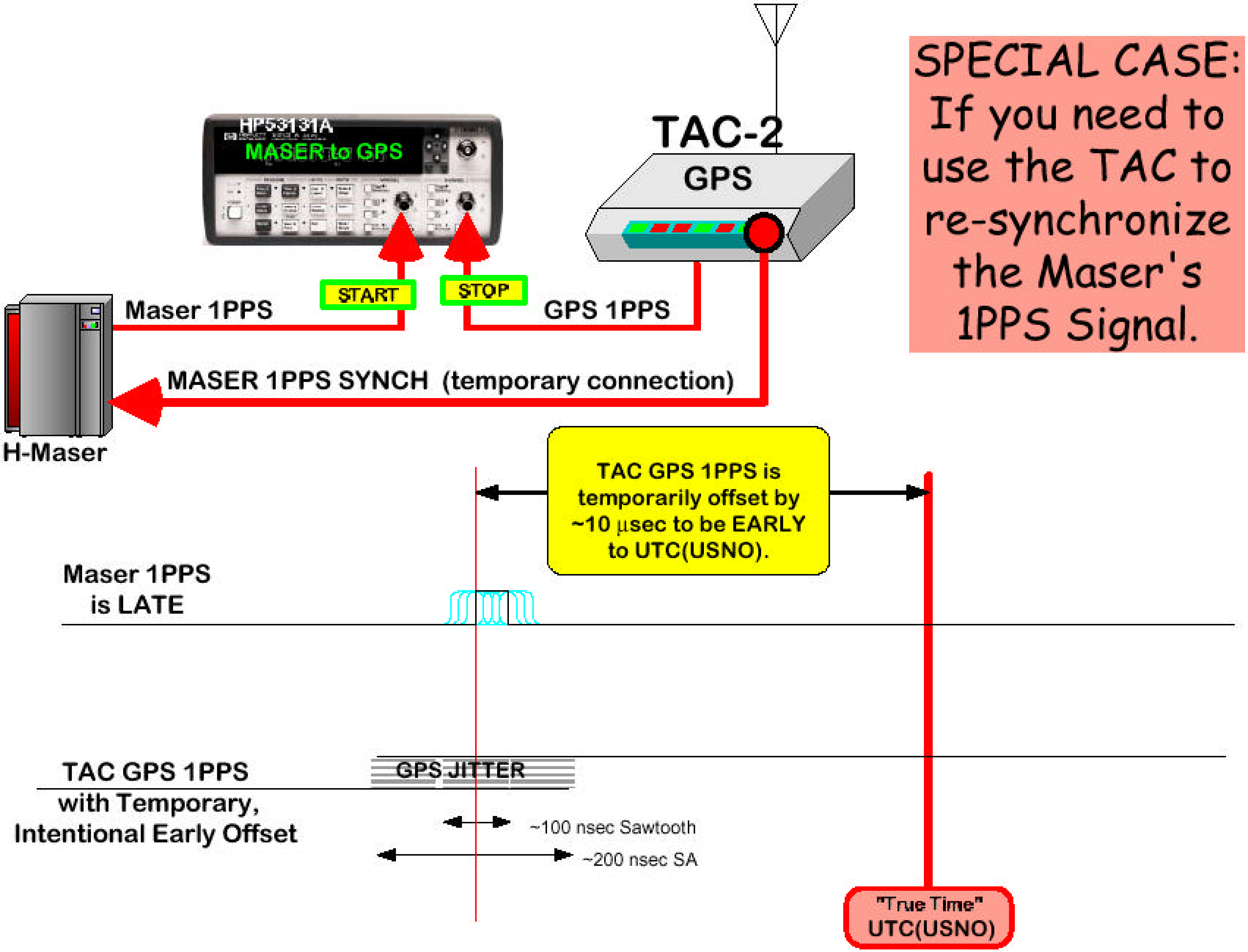
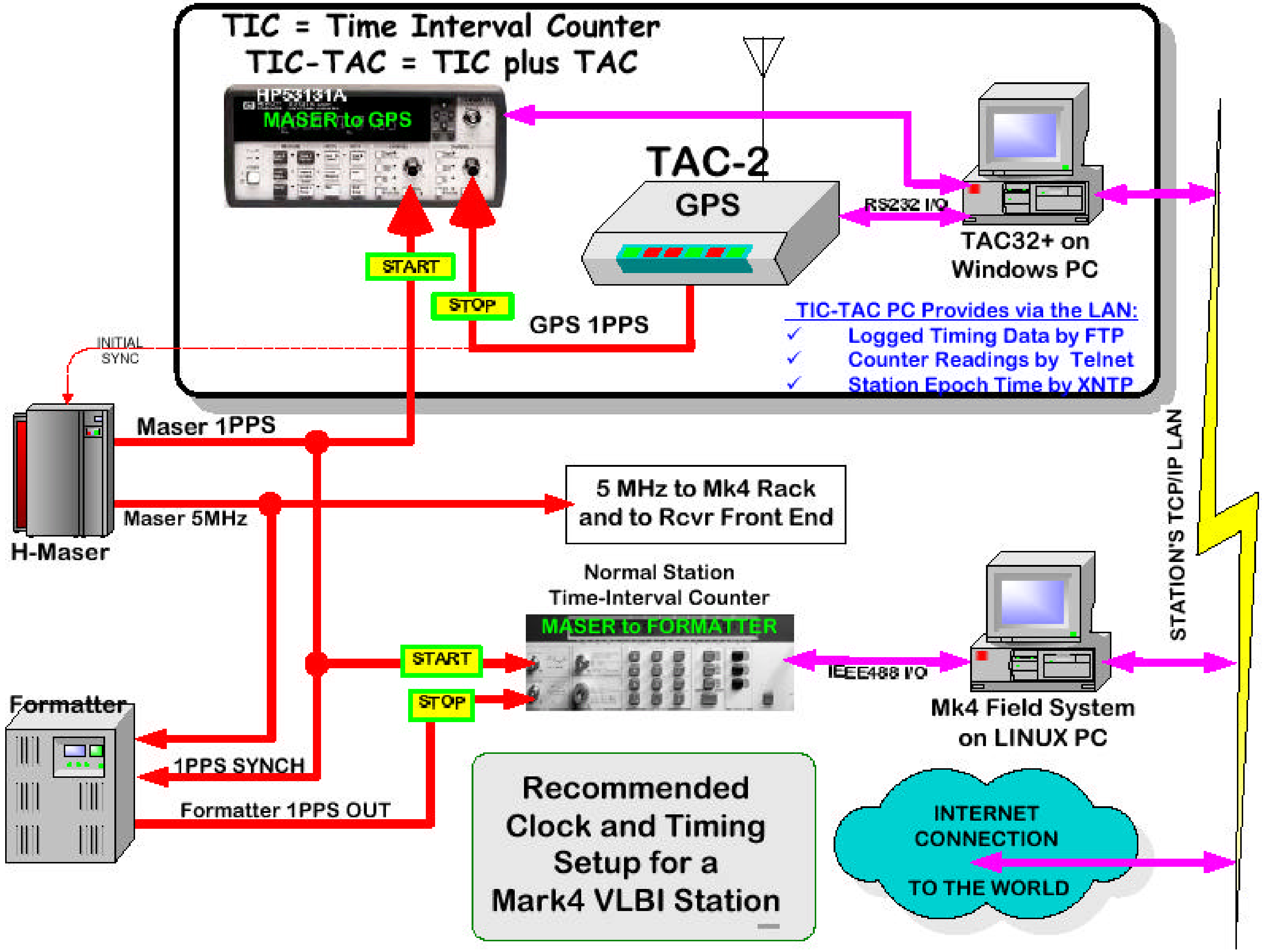
3/11/01 6:00
3/11/01 10:00
3/11/01 14:00
3/11/01 18:00


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)



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TIC-TAC PC Provides via the LAN:
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✓ Station Epoch Time by XNTP
INITIAL
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Maser 1PPS
H-Maser
Maser 5MHz
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
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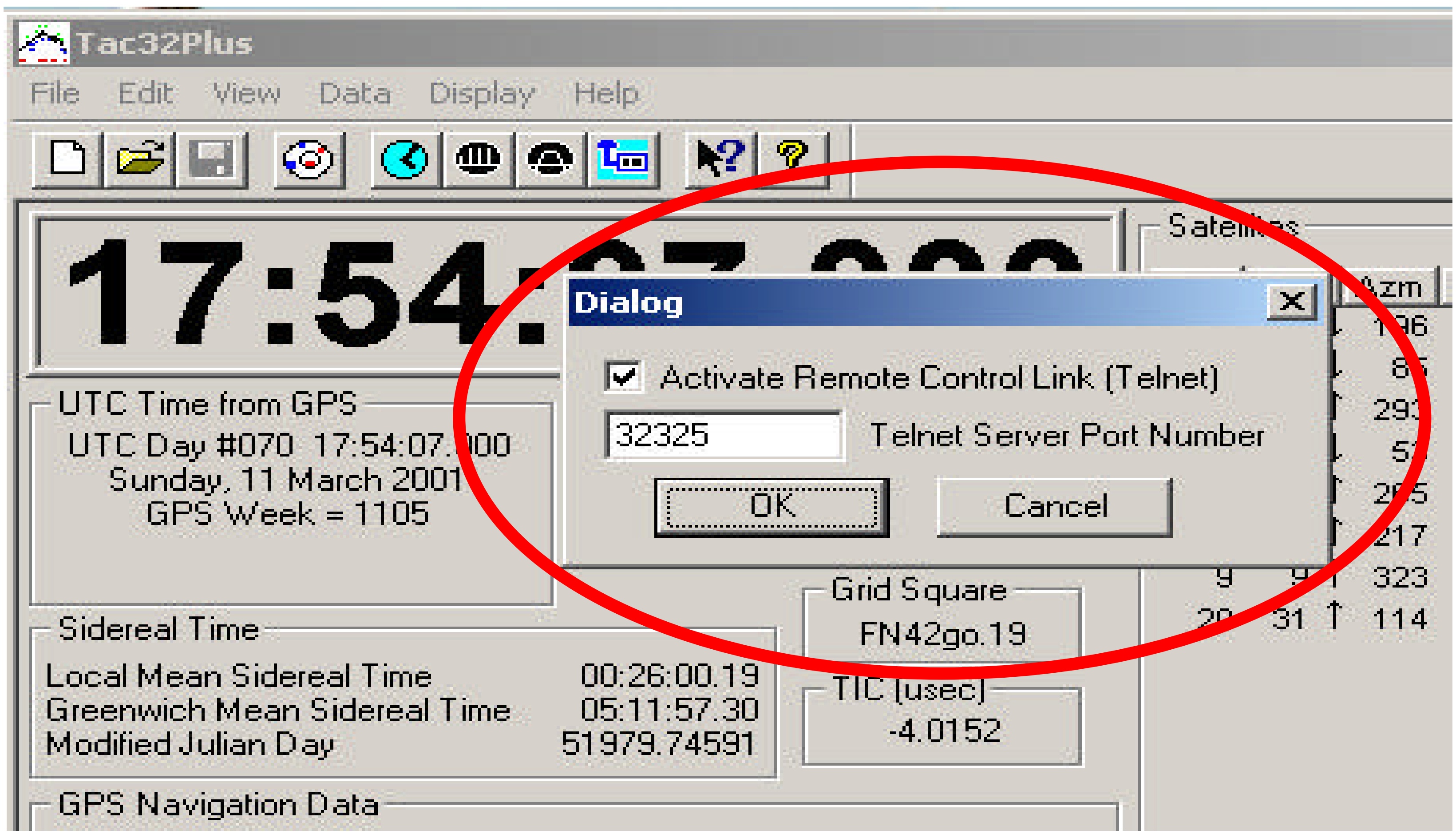
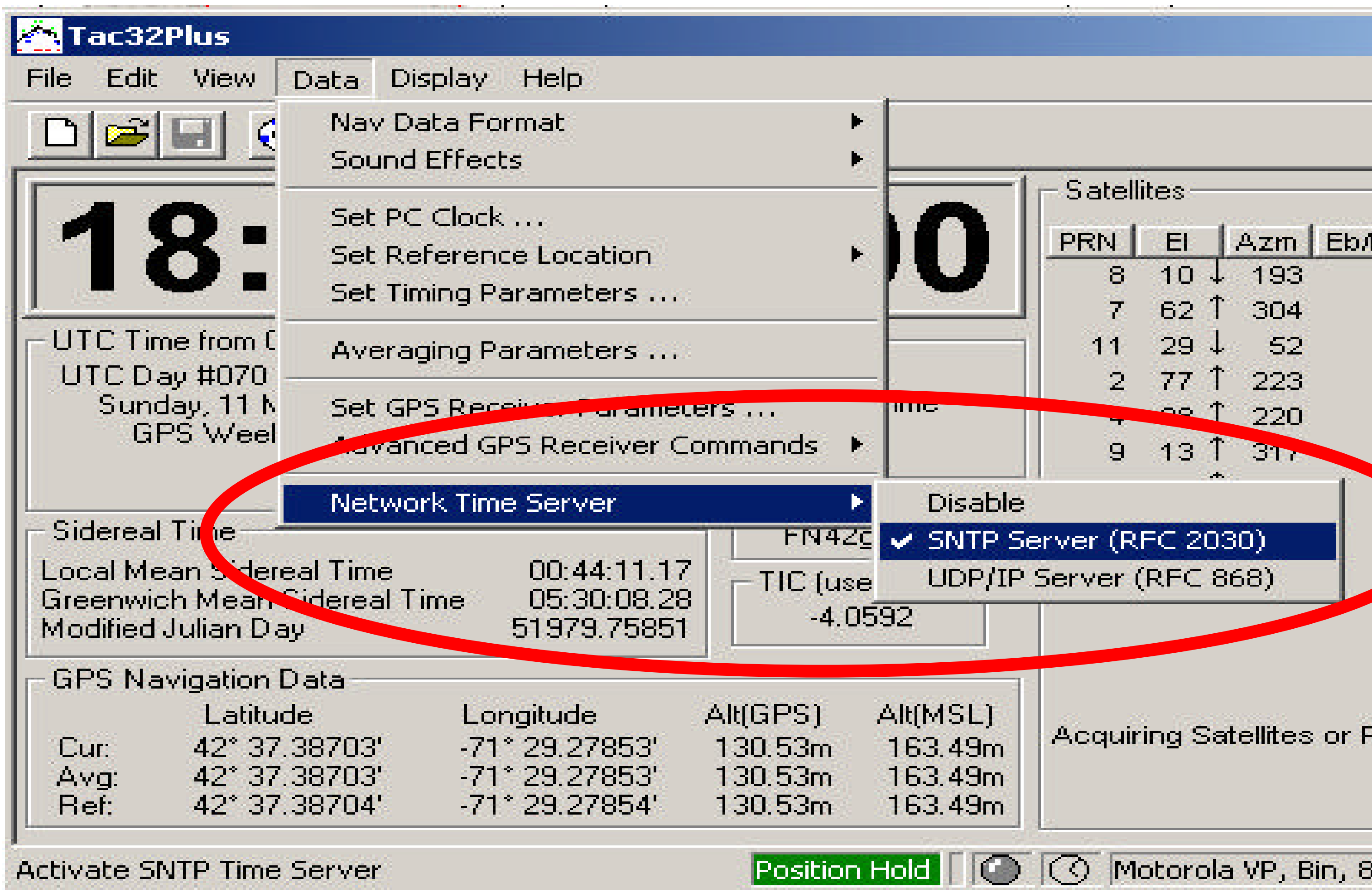
To Activate the Telnet Link between TAC32Plus and the LINUX PC Field System, Hit Control-T:

Then Click on the check-box and the OK button



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



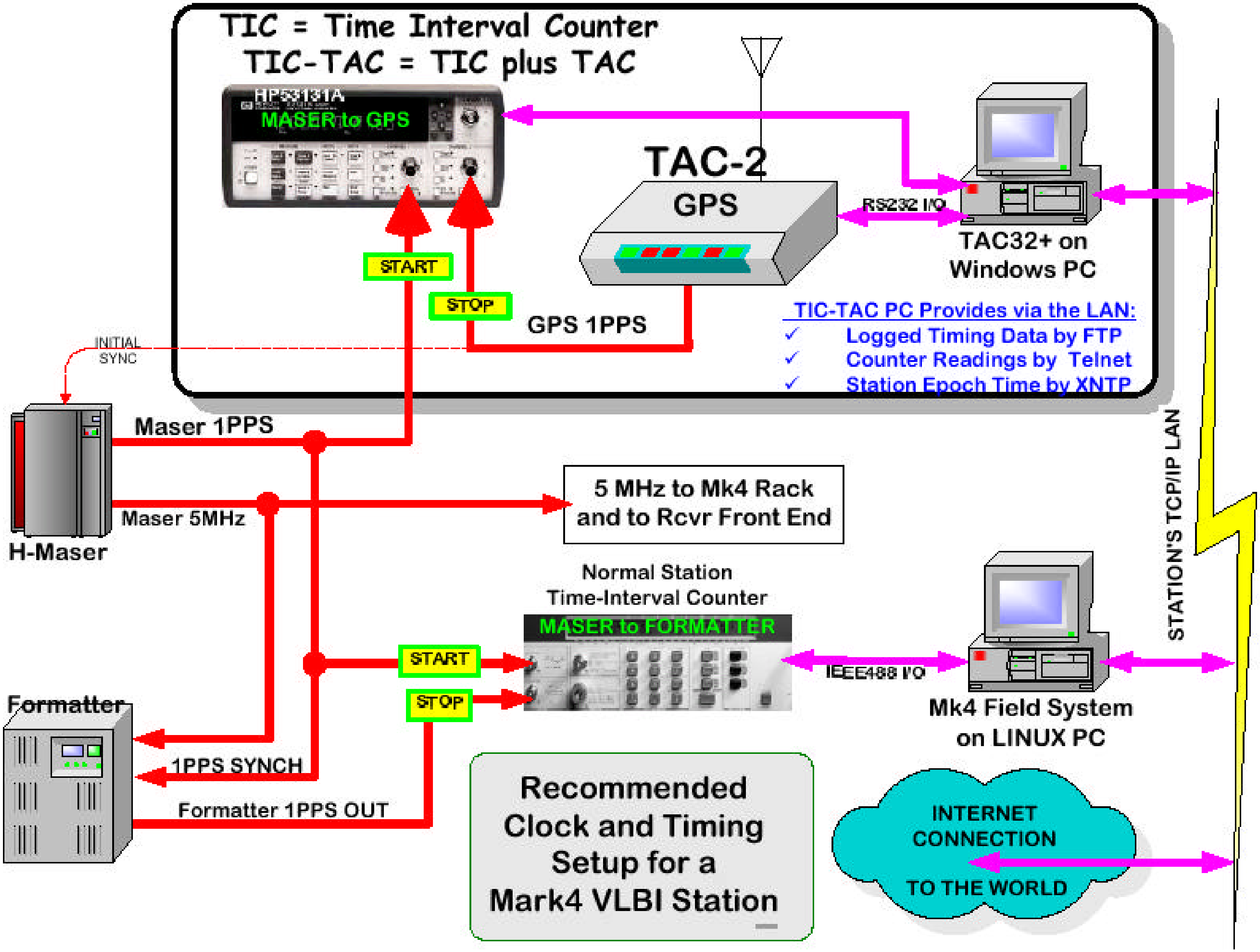
Why do we need to worry about "Absolute Time" (i.e. Accuracy) in VLBI?

•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 "magictables" 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 mny VLBI stations.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HP53131A
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START
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✓ Logged Timing Data by FTP
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✓ Station Epoch Time by XNTP
INITIAL
SYNC
Maser 1PPS
Maser 5MHz
H-Maser
5 MHz to Mk4 Rack
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STATION'S TCP/IP LAN
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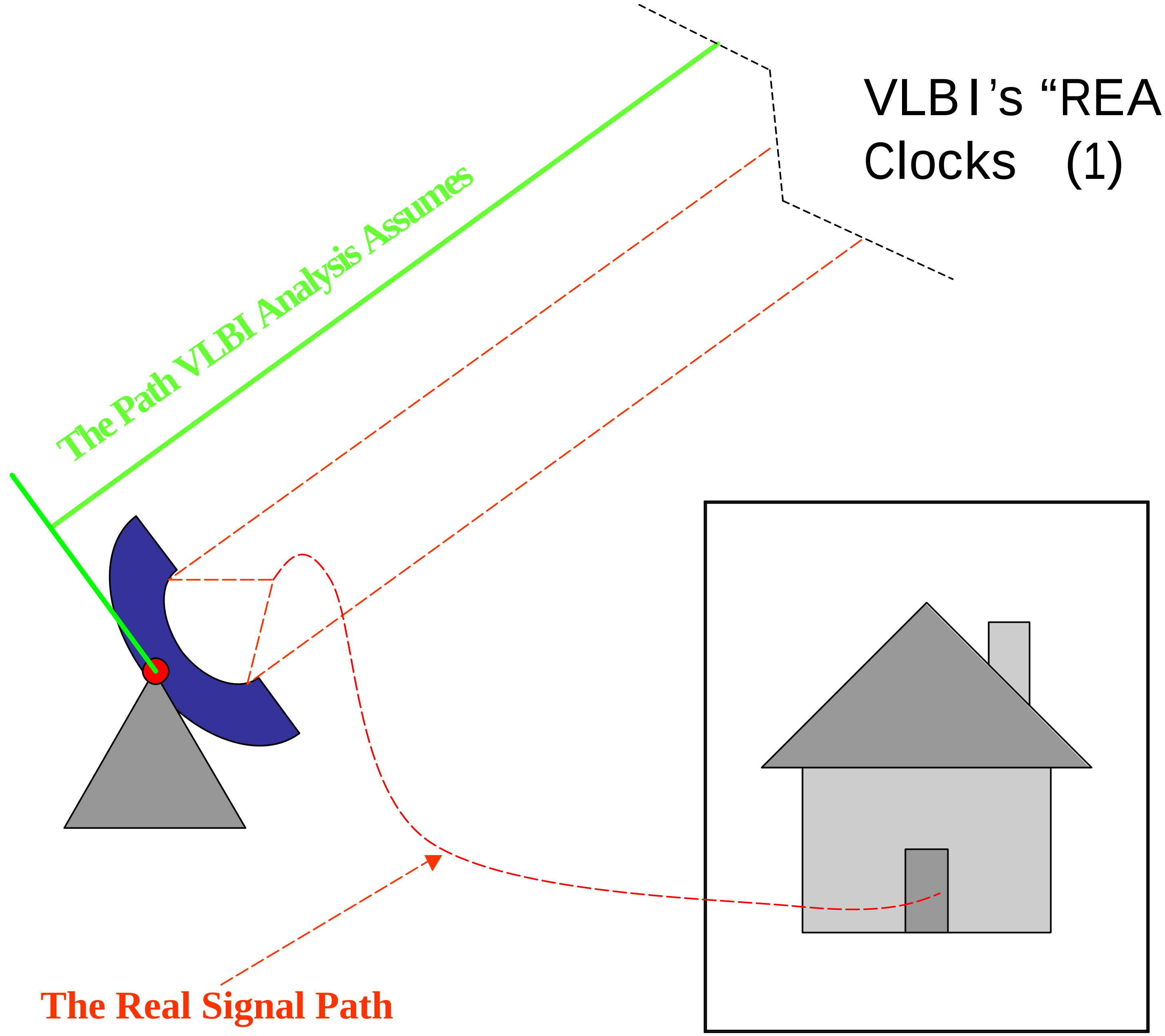
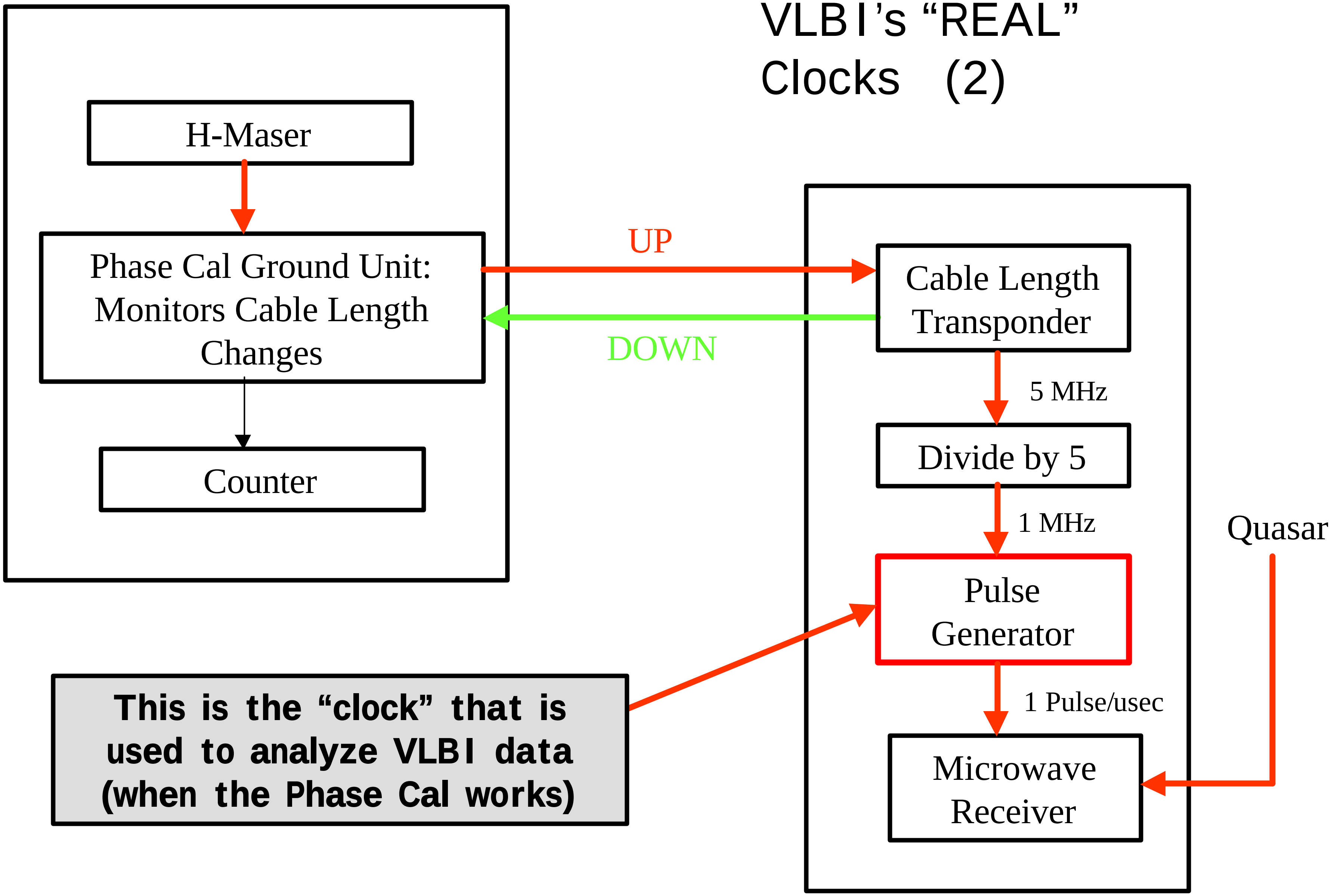
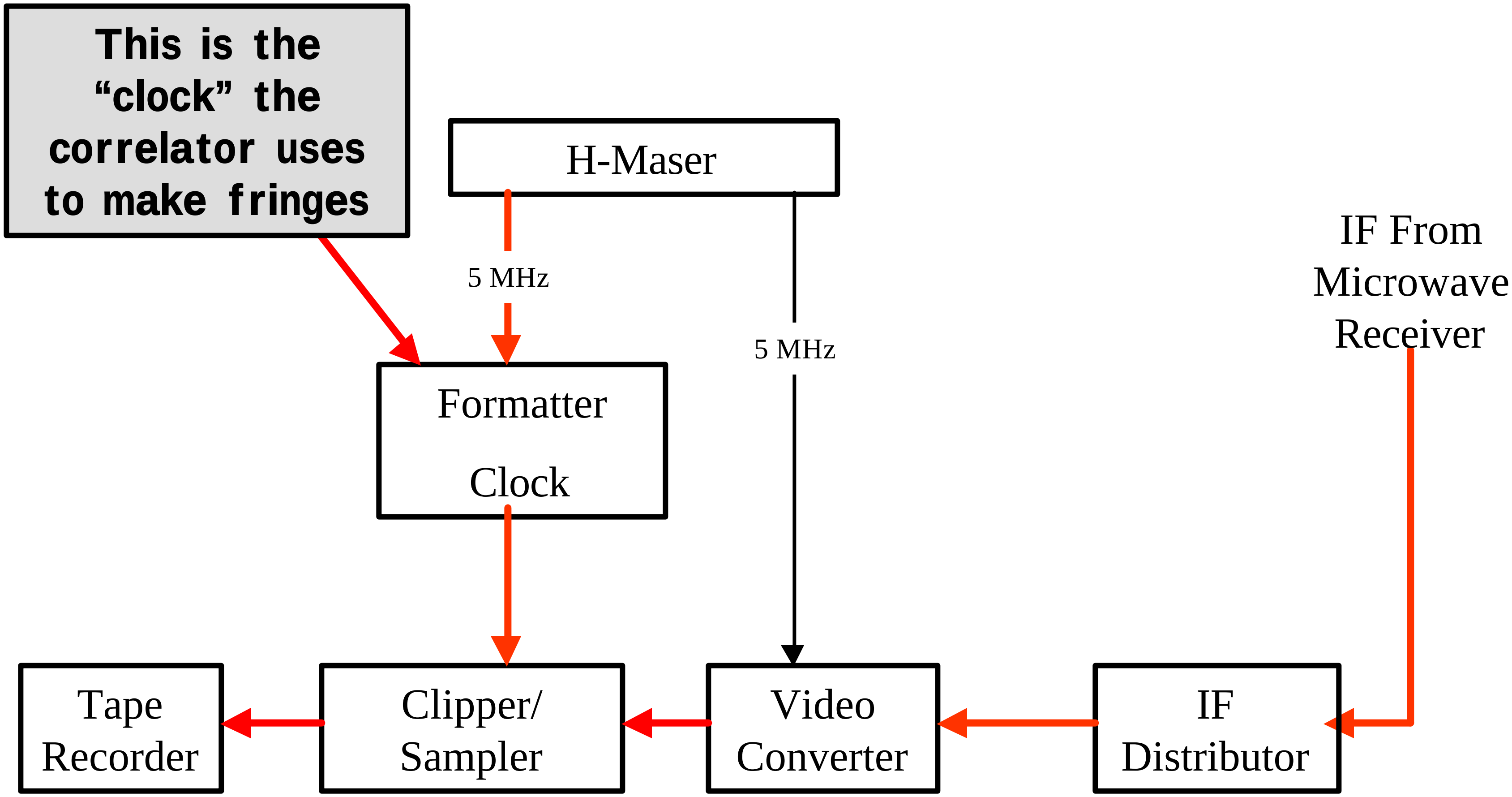
VLBI's "REAL" Clocks (1)



VLBI's "REAL" Clocks (2)





VLBI's "REAL" Clocks (3)

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

•The ***<u>ONLY</u>*** 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.

We have solved the mysteries of Plate Tectonics and have left it to GPS to clean up the details. Our new major challenge is involved $tudies of Earth Rotation and the orientation of the earth with respect to the starts and planets.

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.

Where to get information?

- These Slides and related material:

  ftp://aleph.gsfc.nasa.gov/pub/IVS_TOW/

  and our Salt Lake City ION 2000 paper:

  http://gpstime.com

- Information on Rick Hambly's CNS Clock, a commercial clone of my TAC-2:

  http://www.cnssys.com

- A kit form version of my TAC-2 is still available from TAPR:

  http://www.tapr.org

- To try a TAC2/TAC32+ xntp Network Time Server running in Win2K (the same receiver that produced the ONCORE results presented here):

  tac.ggao.nasa.gov

  - ditto for the prototype SiRF Timing receiver shown here:

    tomcat.ggao.nasa.gov

  - and for ONCORE TAC-2 receiver on a LINUX xntp server:

    gpstime.com