High-accuracy Time and Frequency in VLBI

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TOW 2017 April 30 – May 4
MIT Haystack Observatory

Agenda

Background – Rick Hambly

- Oscillators and Clocks
- What “Clock” Performance Does VLBI Need?
- “Absolute Time” (i.e. Clock Accuracy)

The Hydrogen Maser - Katie Pazamickas

- Maser Outputs
- Data/Frequency Monitoring
- Troubleshooting/Routine Maintenance

GPS Time - Rick Hambly

- Week rollover may mean retiring old GPS receivers
- GPS receiver’s quantization error
- “Absolute” Receiver Calibration
- New developments

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

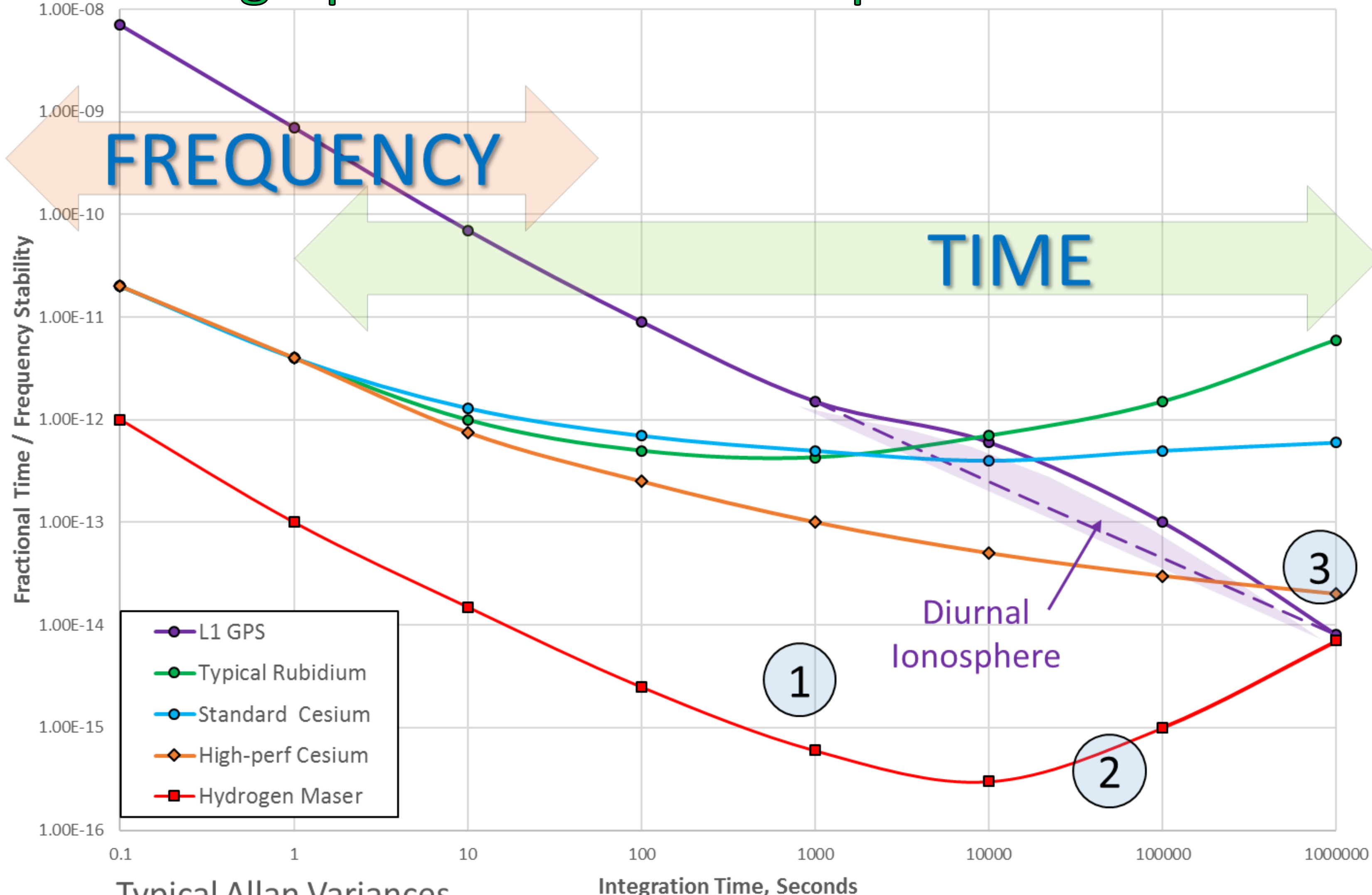
- Gears
- Electronic Counters
- Real Clocks

Long-Term

TIMING

seconds - years

Allan Variance –
A graphical look at clock performance



Typical Allan Variances

What “Clock” Performance Does VLBI Need?

The VLBI community (Radio Astronomy and Geodesy) uses Hydrogen Masers at 40-50 remote sites all around the world. 1

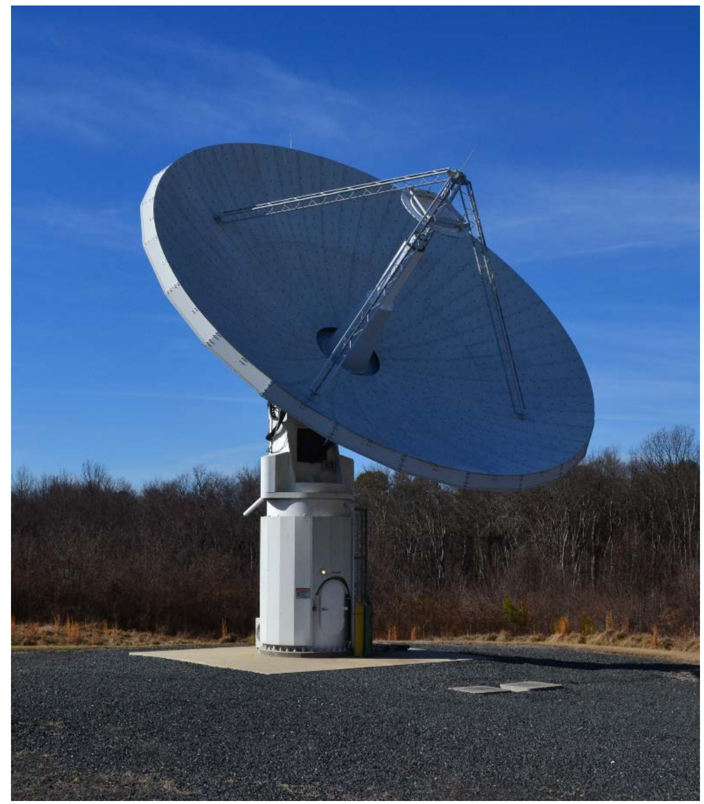
To achieve ~10° signal coherence for ~1000 seconds at 10 GHz we need the 2 clocks (oscillators) at the ends of the interferometer to maintain relative stability of:

- $\approx [10°/(360° * 10^{10}\text{Hz} * 10^{3}\text{sec})]$
- $\approx 2.8 * 10^{-15}$ @ 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:
  - $\approx [30 \blacklozenge 10^{-12} / 86400 \text{ sec}]$
  - $\approx 3.5 \blacklozenge 10^{-16}$ @ 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:

- $\approx [50 * 10^{-9} / 10^{6}$ sec]
- $\approx 5 * 10^{-14}$ @ 10^{6} sec

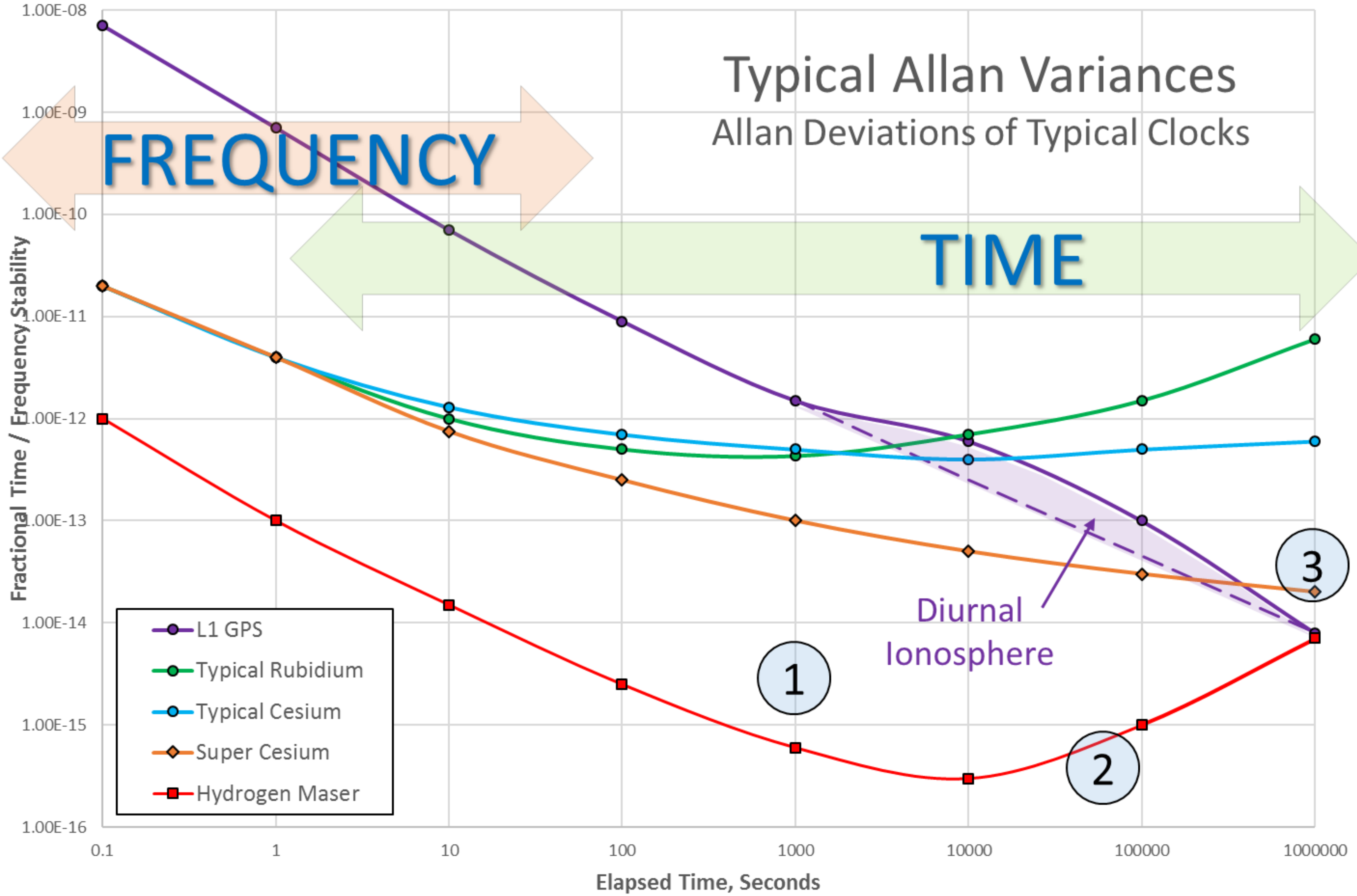
Since VLBI now defines UT1, VLBI needs to control [$UTC_{(USNO)}$ - $UTC_{(VLBI)}$] with an ***ACCURACY*** (traceable to USNO)

- ≈ 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:

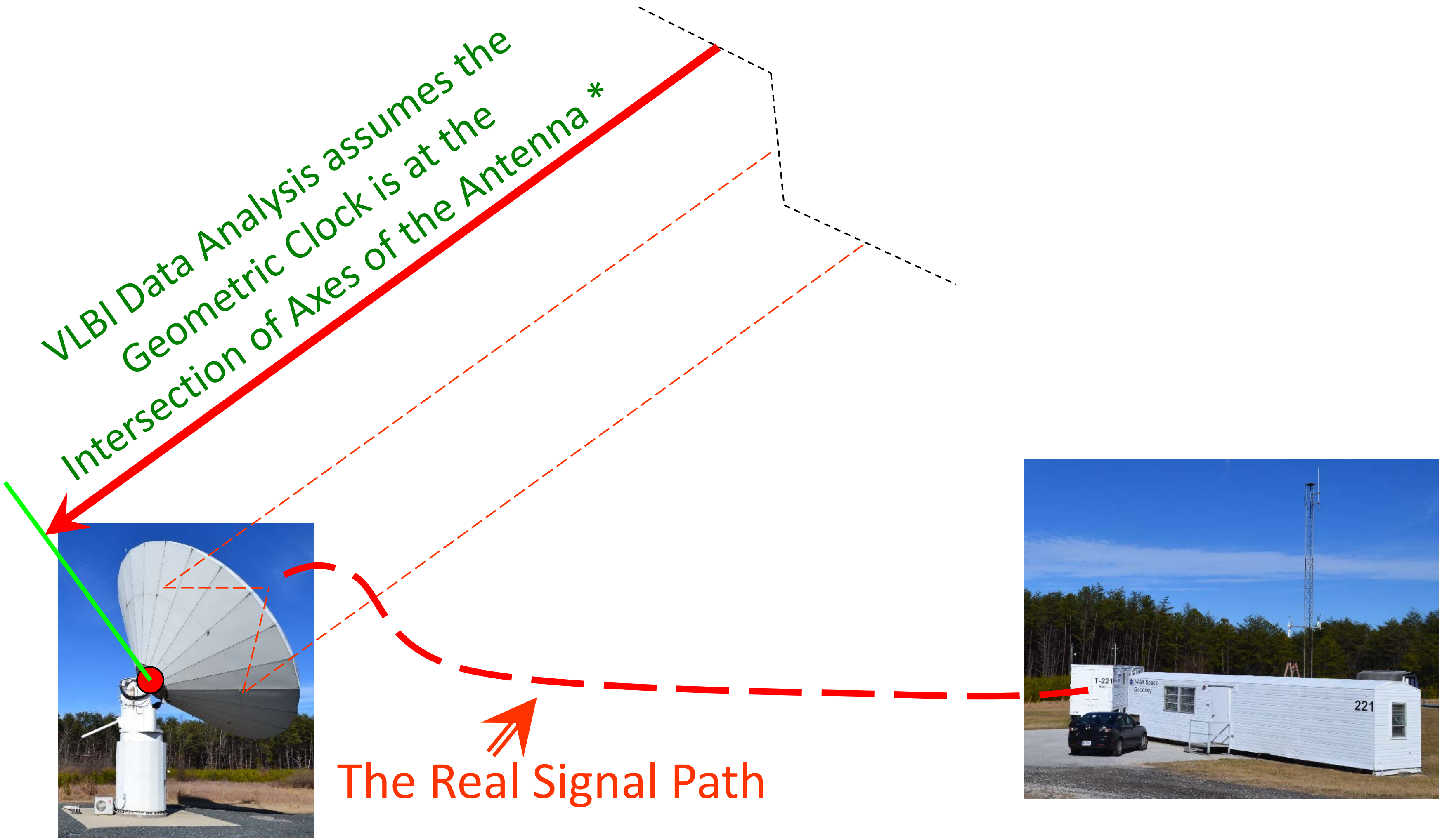
- Generating Sidereal Time to point antennas.
- Measuring UT1 (i.e. "Sundial Time") to see changes due to redistribution of mass in/on the earth over long periods of time (a.k.a. "The Reference Frame")
- Knowing the position of the earth with respect to the moon, planets and satellites.
- Making the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

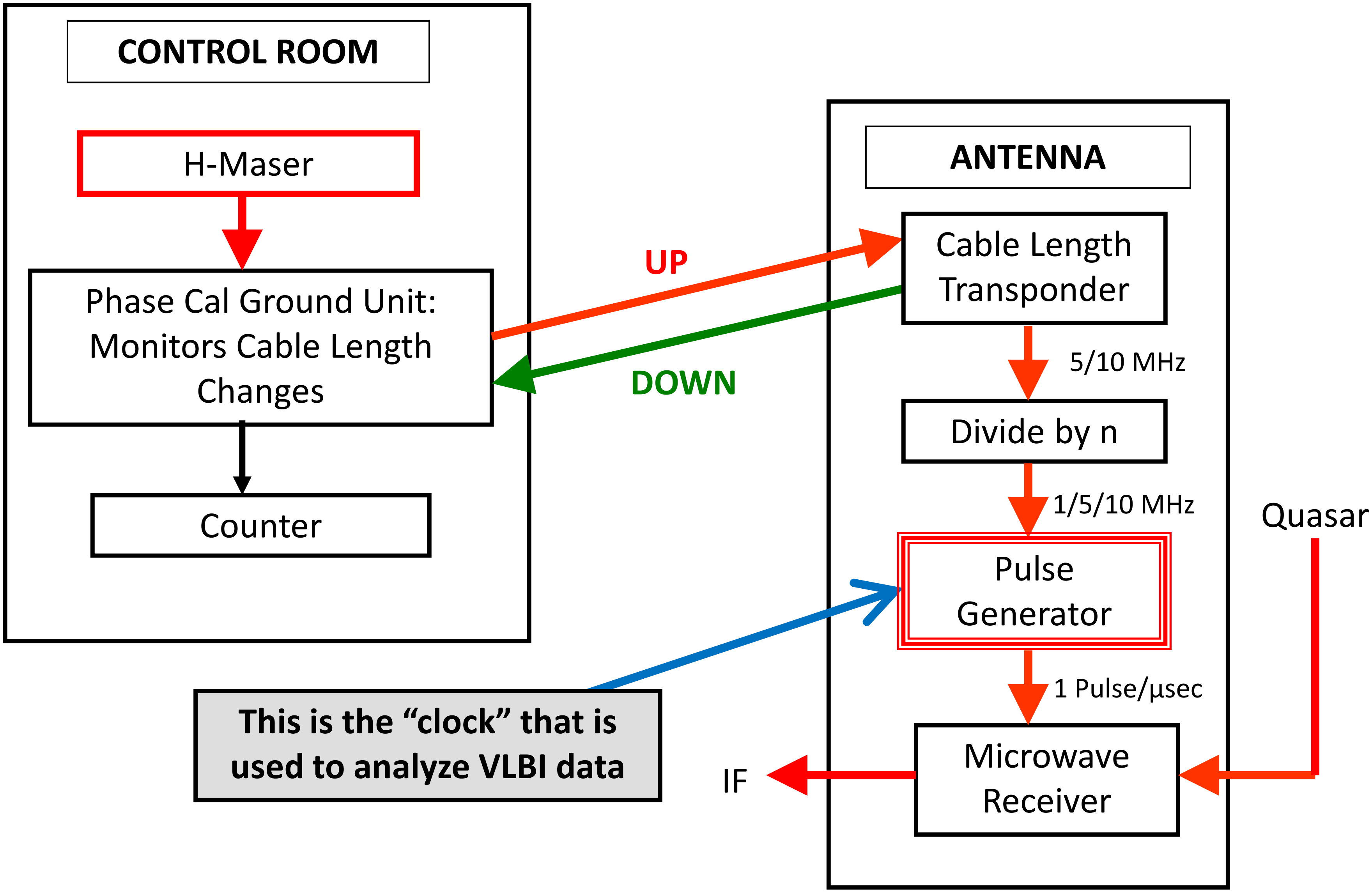
- Frequency Standard and Station Timing
- The lengths of all signal & clock cables
- The geometry of the feed/receiver to the antenna.
- Calibration of instrumental delays inside the receiver and backend.
- The care with which system changes are reported to the correlators and the data analysts.

VLBI's "REAL" Clocks (#1)

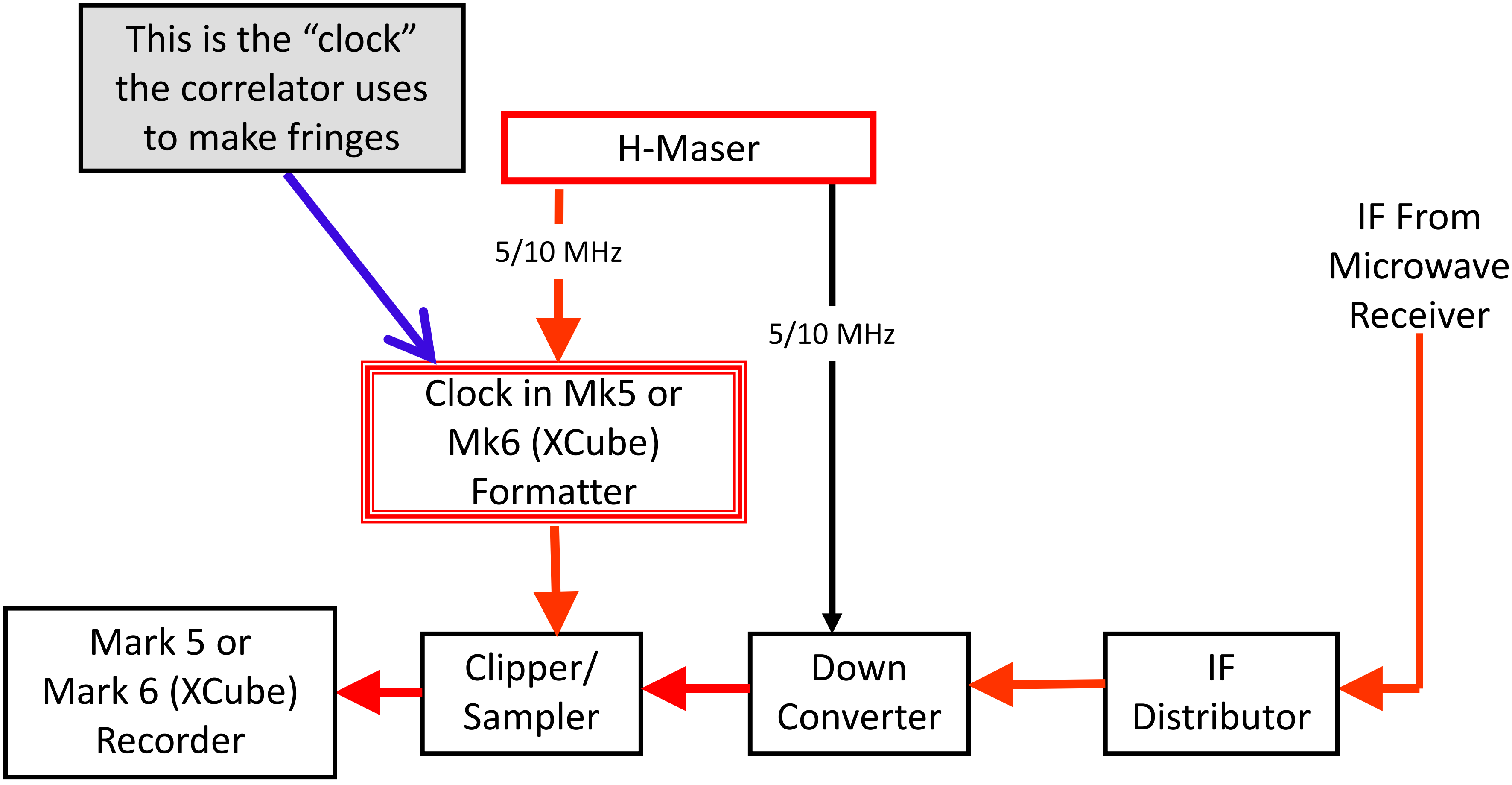


* Note -- If the axes don't intersect, then an "offset axis" model of the antenna is used

VLBI's "REAL" Clocks (#2)



VLBI's "REAL" Clocks (#3)



Setting VLBI Clock Time & Rate with GPS

- **Compare two distant clocks by observing the same GPS satellite(s) at the same time** (also called **Common View**)
  - Requires some inter-visibility 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 but it's hard to gain access to the internal clock.
  - Requires transferring ~1 MB/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!
- **Use the Broadcast GPS Timing Signals as a clock**
  - Yields "Real Time" ~10-30 nsec results with ~ low cost hardware
  - Single Frequency L1 only (for now) suffers from ionospheric error

How we get less than 5 nsec 1-sigma timing

- Start with a good timing receiver, like the Motorola Oncore or the Synergy SSR (uBlox).
- Average the positioning data for ~1-2 days to determine the station's coordinates. This should be good to <5 meters. Or if the site has been accurately surveyed, use the survey values.
- Lock the receiver's position 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 readings over ~5 minutes (300 seconds).
- **These steps have been semi-automated in Tac32Plus.**

IVS Recommended Maser Timing Practices

From: Roberto Ambrosini, Tom Clark, Brian Corey, and Ed Himwich
To: All IVS Stations
Date: 1 May 2014

We recommend the following practices for management of the 1 PPS derived from the Maser and used as the station 1 PPS. Its synchronization with UTC as derived from the GPS 1 PPS offers a common timing reference for all VLBI stations worldwide. We refer to the difference in the epochs of the Maser and GPS 1 PPS signals, as measured by a counter, as the Maser/GPS offset, regardless of which signal occurs later.

Because it is evident that crossing zero time for the Maser/GPS offset should be carefully avoided (the counter would read the complement of one second of the desired delay, arithmetic processing of data by the counter not being recommended), we recommend keeping the offset at a small but significant distance from zero and its drift rate positive.

We also recommend keeping the time and frequency retuning of the Maser at a minimum, typically no more than once in a year.

This procedure offers: less work at the station, better modelling of the long term drift of the Maser, and a better chance to identify jumps in the offset.

Here follow some practical recommendations for the Maser/GPS offset:

(1) Either the Maser 1 PPS or GPS 1 PPS can occur first.

(2) The offset should be significantly, at least a few microseconds, different from zero.

(3) The offset should not be too large, a useful upper limit might be on the order of 100 microseconds.

(4) The offset should be growing slowly, typically less than 0.1 microseconds/day.

(5) The offset should not be adjusted unnecessarily, no more often than once per year if possible.

(6) Items (2)-(5) are only recommendations and may not be feasible in some situations and do not need to replace existing successful practice at any station. However to the extent it is reasonable, stations should align themselves with these practices.

IVS Recommended Maser Timing Practices

Recommendation (1) is a recognition that different stations have different preferences on which 1 PPS occurs first: Maser or GPS.

Recommendations (2)-(4) are intended to minimize both the need to re-tune the Maser and the chances of the offset going through zero.

Recommendation (5) is intended to make it easier to relate the offset data from one experiment to another.

For completeness, the following requirements (as opposed to recommendations) are listed for the FS log recorded offset between GPS and formatter 1PPS signals, the "GPS/FM offset". These requirements are necessary to allow correct interpretation of the offset data downstream. Please note that these requirements deal with the GPS/FM offset, which is related to, but different from Maser/GPS offset discussed above. In addition to the GPS/FM offset, stations can, and are encouraged to, record (appropriately labelled) additional available clock offset data, including the Maser/GPS offset, in their FS logs or separately.

The requirements for the GPS/FM offset recorded in the FS logs:

(7) The offset is positive and small, i.e. close to (but not too close to) zero and NOT close to one second. If the recommendations (2)-(4) for the Maser/GPS offset above are used for that offset, they are likely to also be true for the GPS/Maser offset as well. In any event, the GPS/FM offset should not cross zero.

(8) The offset is recorded with either of two possible commands depending on how the counter is connected. The connections should be chosen to agree with (7) and:
(A) If the counter is started by the GPS 1 PPS, use the "gps-fmout" command. This should be the case if the formatter output 1 PPS (usually determined by the Maser) is late.
(B) If the counter is started by the fmout 1 PPS, use the "fmout-gps" command. This should be the case if the GPS 1 PPS is late.
It will be necessary to change which command is used if which signal is late changes. This should not be needed if recommendations (2)-(4) for the Maser/GPS offset are followed.

(9) The offset counter does not use arithmetical processing. It just reports the "raw" difference in time between the start and stop signal. So for example, the small positive offset in (7) is not achieved by subtracting the raw difference from 1 second.

(10) The offset counter does not use averaging. This allows immediate detection of jumps. Averaging can be applied in post processing of the data.

(11) The offset must be measured at least once per scan in MIDOB. Additional measurements are acceptable as well.

Hydrogen Masers

Physics Package

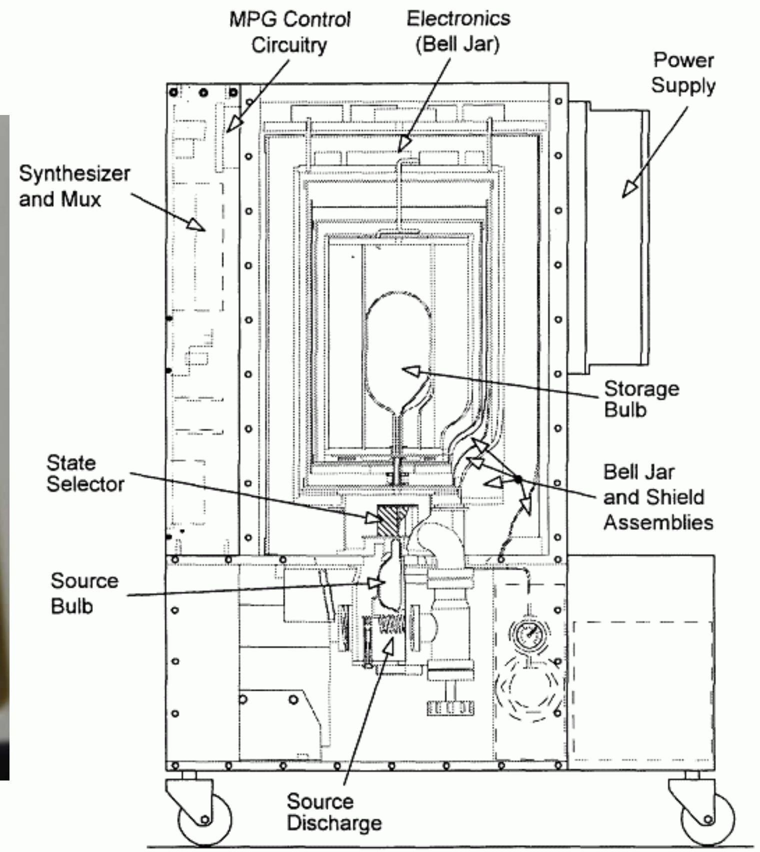


Figure 4. Hydrogen Maser, Physics Layout and Identification.

Credit: Microsemi MHM2010 Manual

Sigma Tau/NR Masers

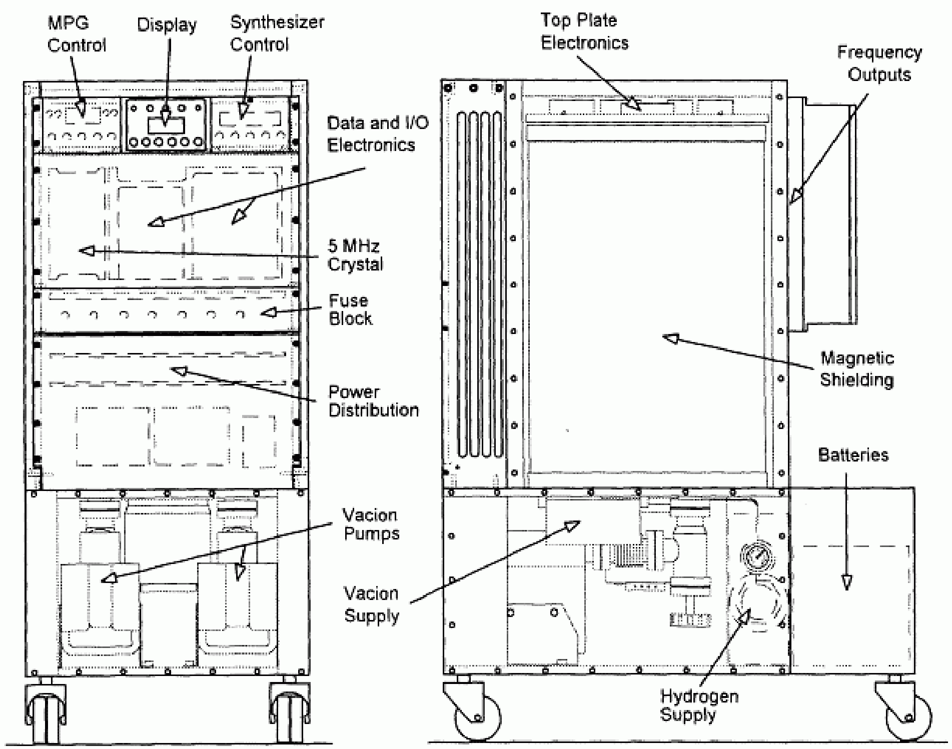
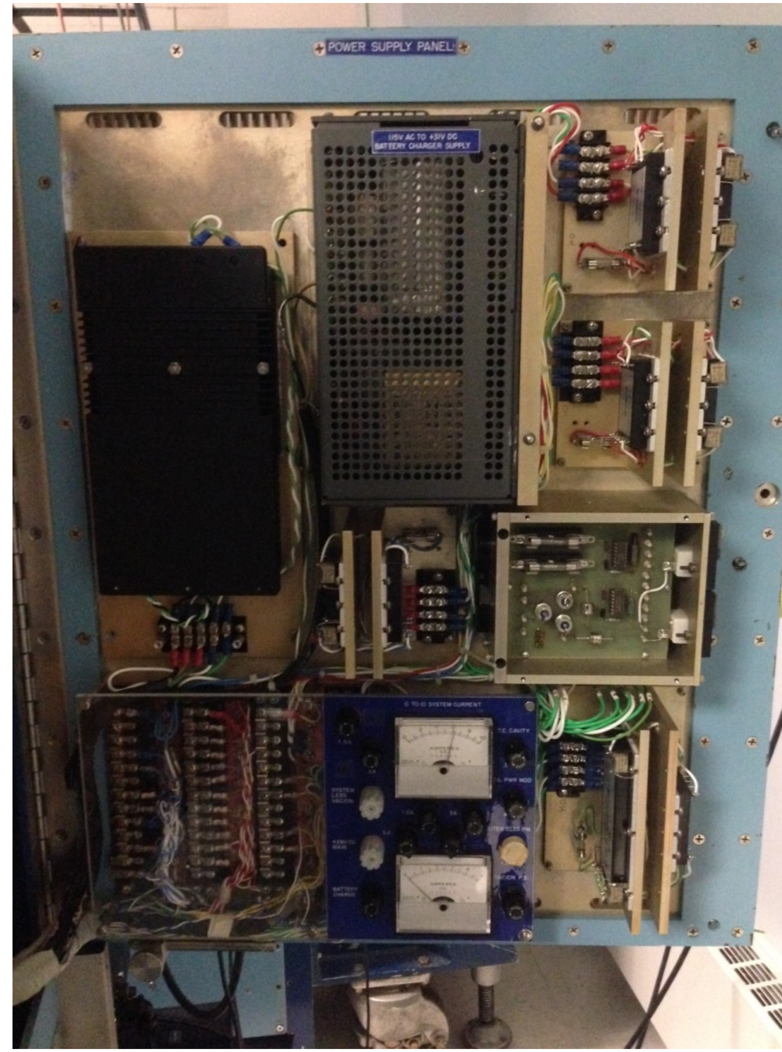


Figure 3. Hydrogen Maser, System Layout and Identification.

Credit: Microsemi MHM2010 Manual



Maser Outputs

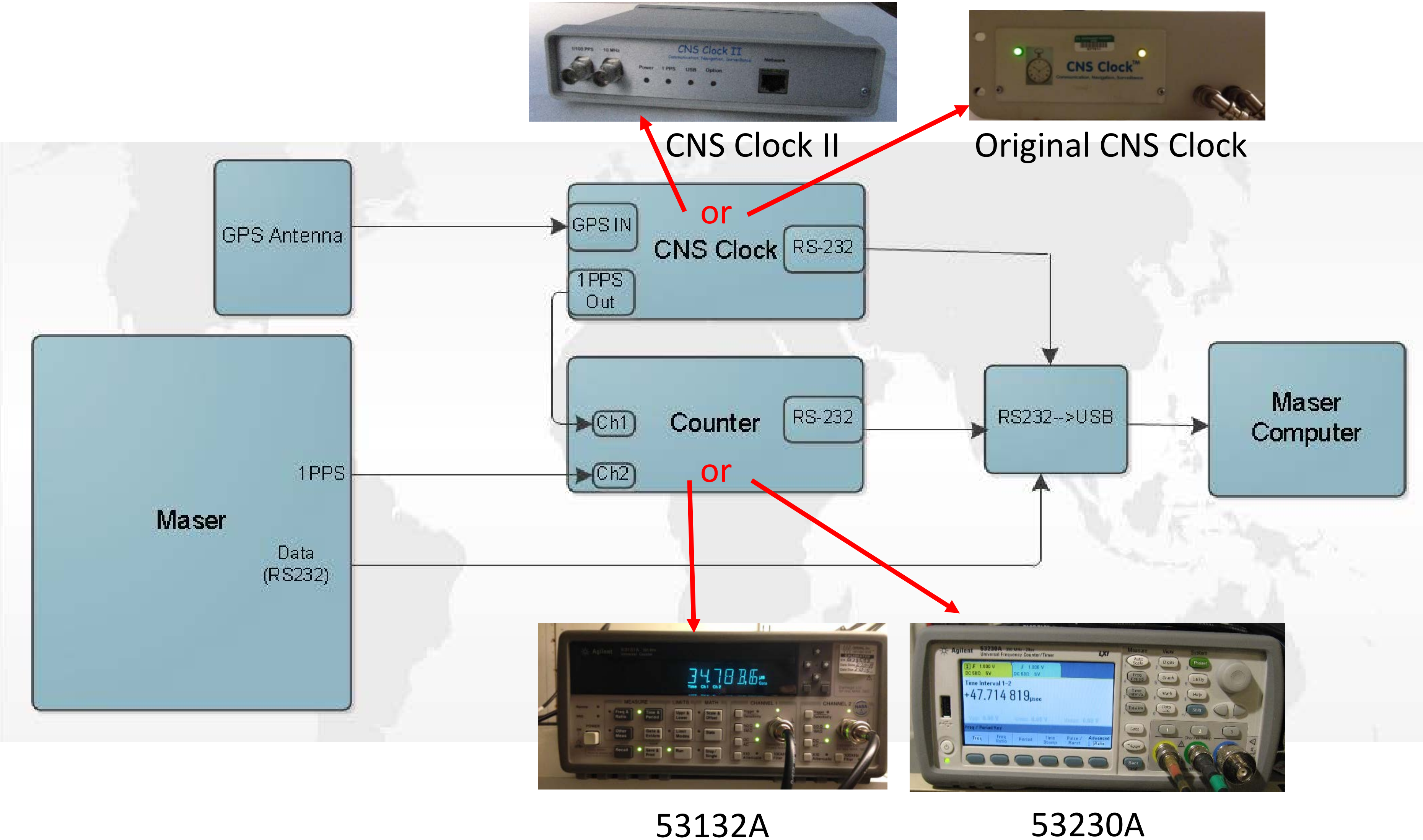
Sigma Tau MHM 2010

- 2 5MHz
- 2 10 MHz
- 2 1PPS
- Maser Data
- Sync Port

NR Maser

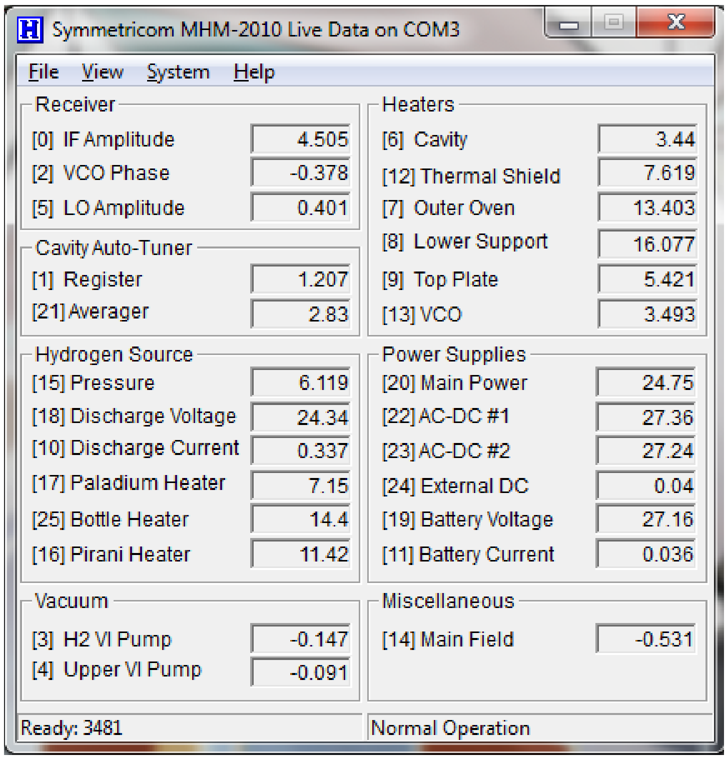
- 4 5MHz
- 2 1 PPS
- Maser Data

Timing Configuration

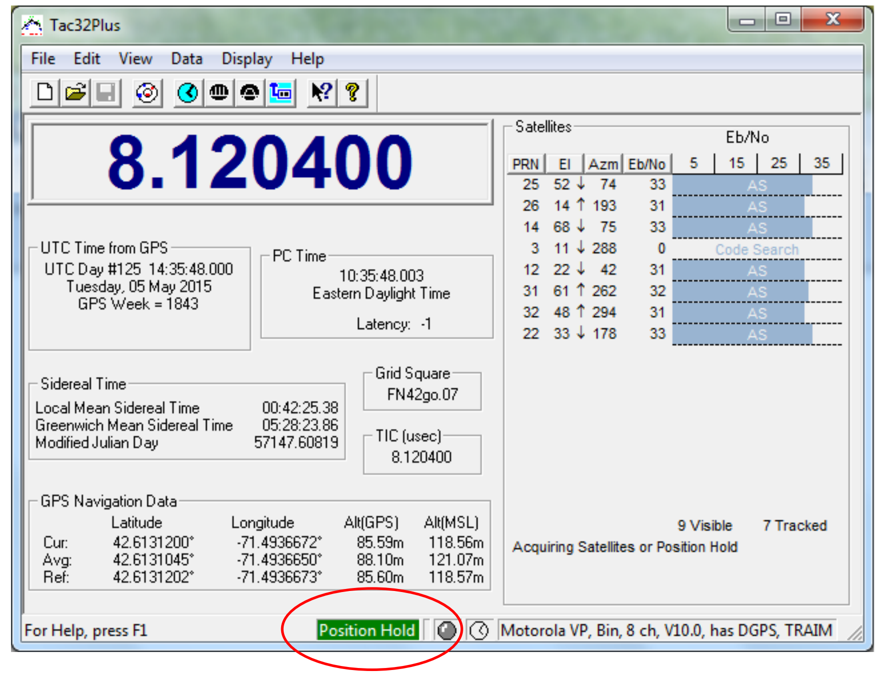


Data/Frequency Monitoring

Maser Data Monitoring

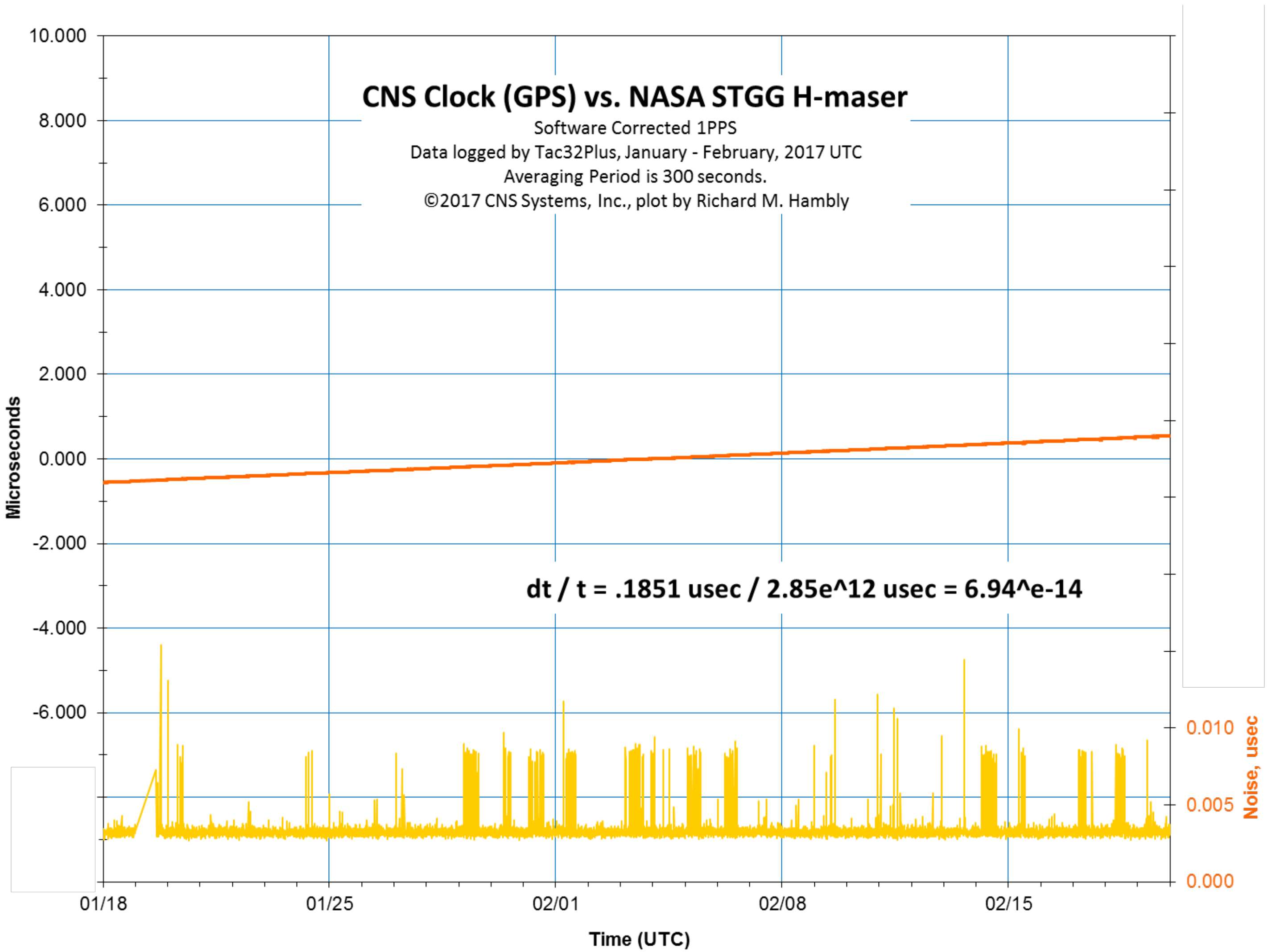


Frequency Data – Tac32Plus



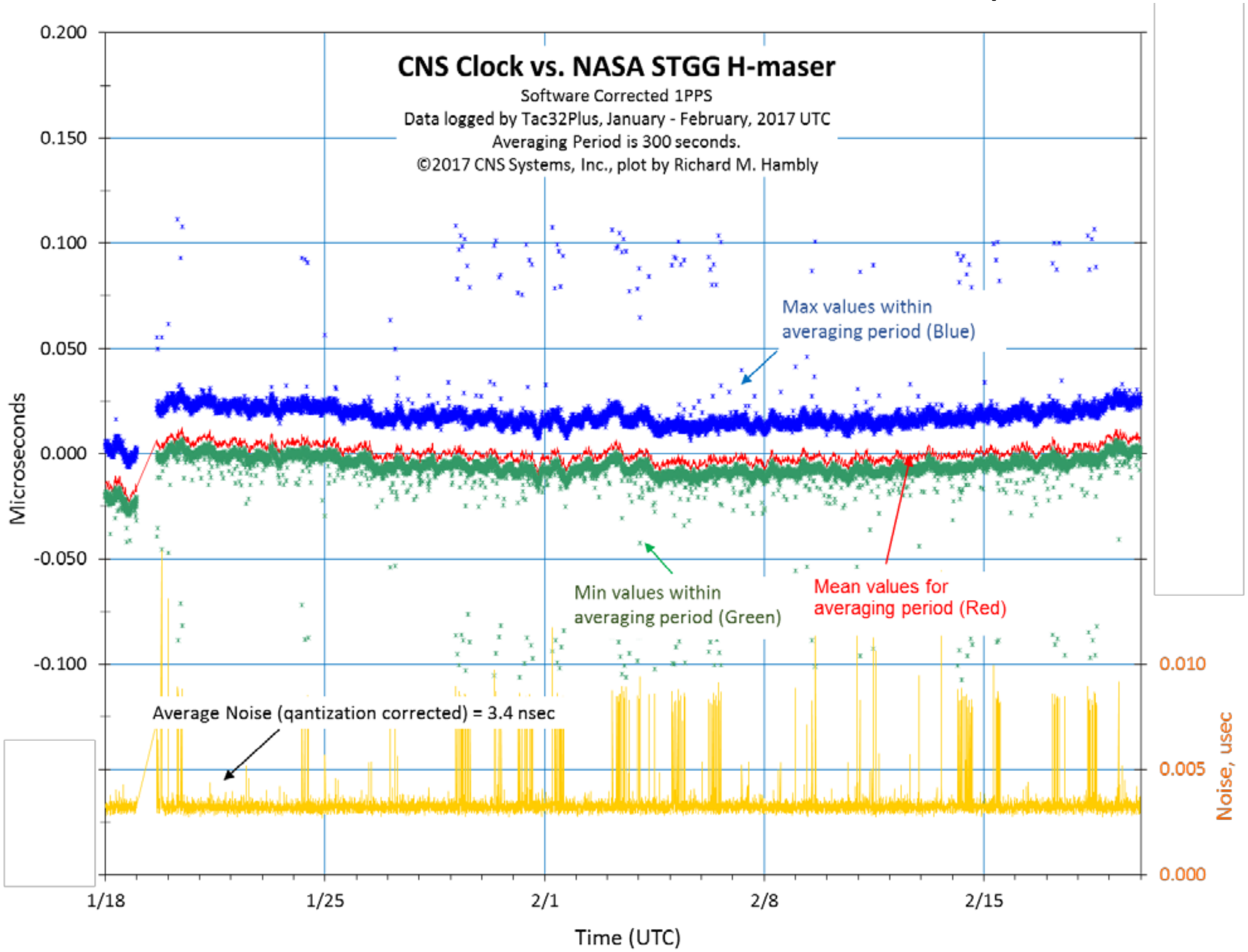
Data/Frequency Monitoring

This data set shows the H-maser frequency error of about $7*10^{-14}$



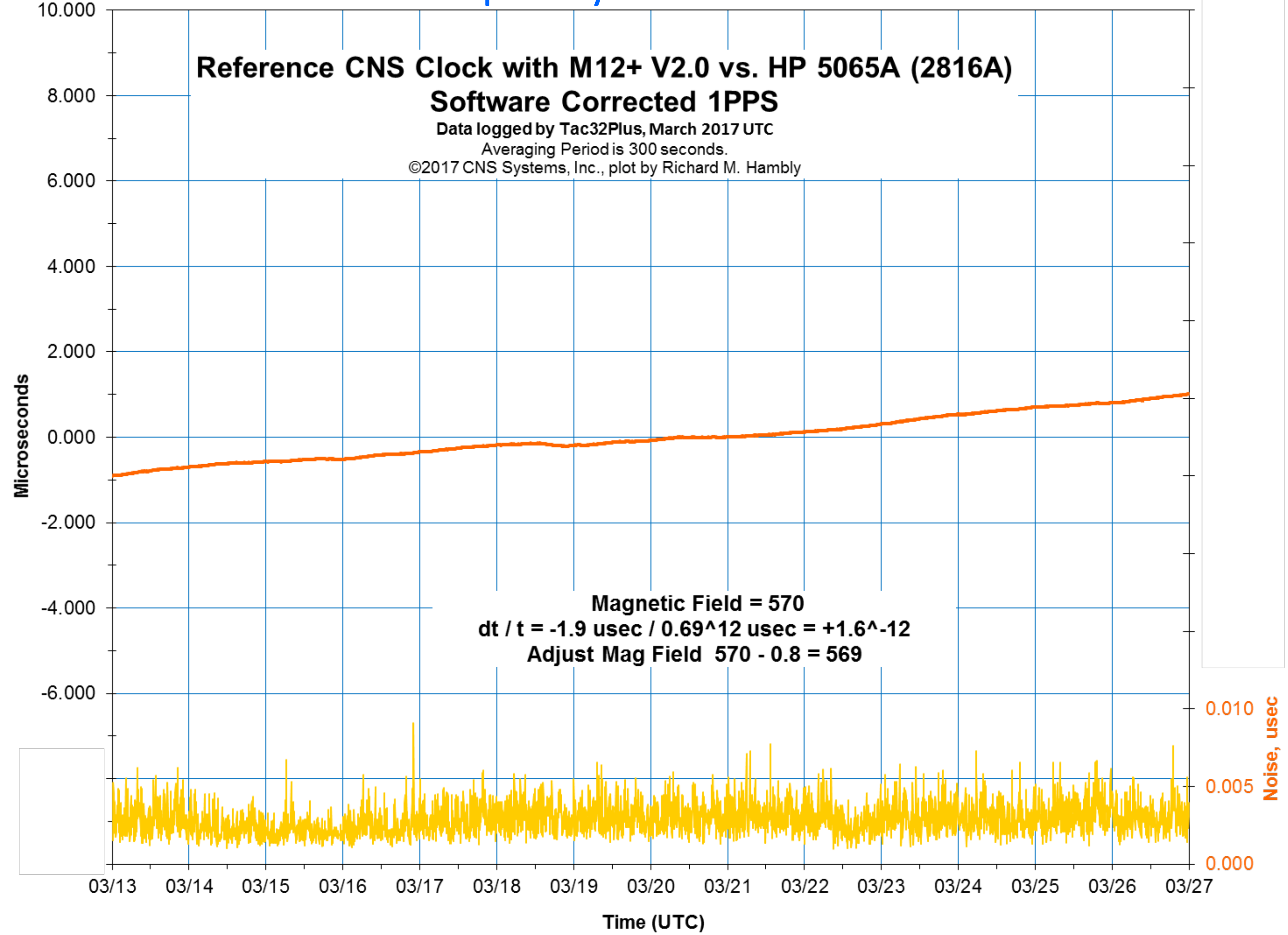
Data/Frequency Monitoring

However, a more detailed look at the data set shows an old GPS receiver with known data issues. This GPS receiver should be replaced.



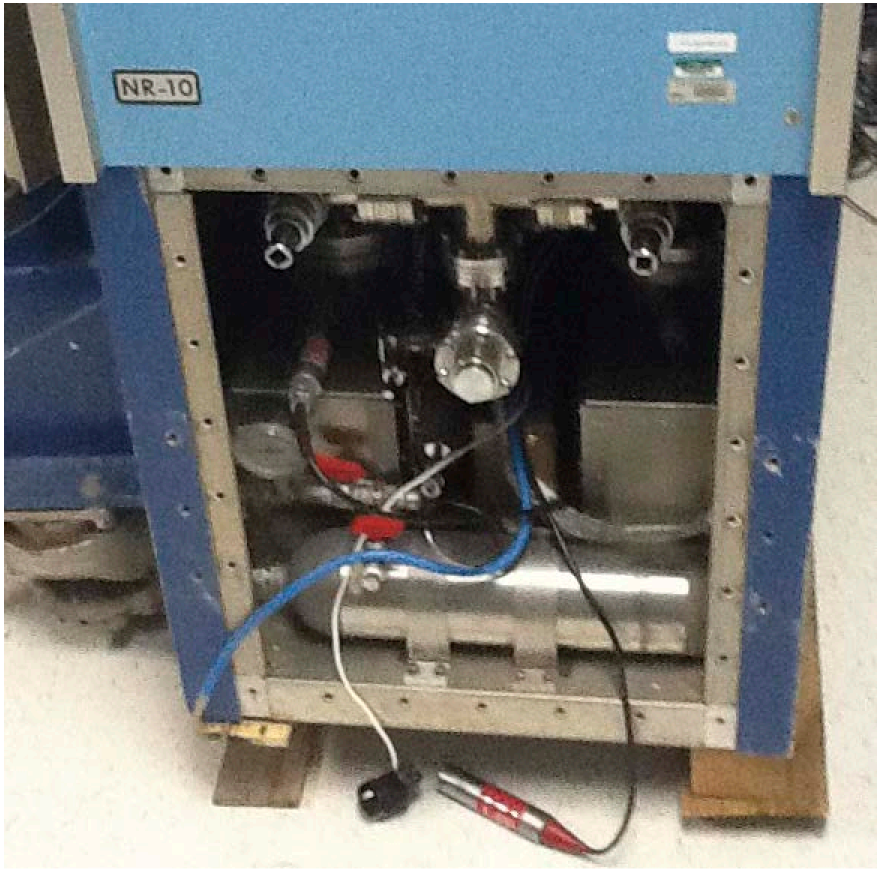
Data/Frequency Monitoring

For comparison, this data set shows the CNS HP5065 Rubidium frequency error of about $1.6*10^{-12}$



Troubleshooting/Routine Maintenance

- Hydrogen Pressure
- Microprocessor batteries
- Magnetics/Degaussing
- Vacion pumps
- Hydrogen gas
- Frequency corrections



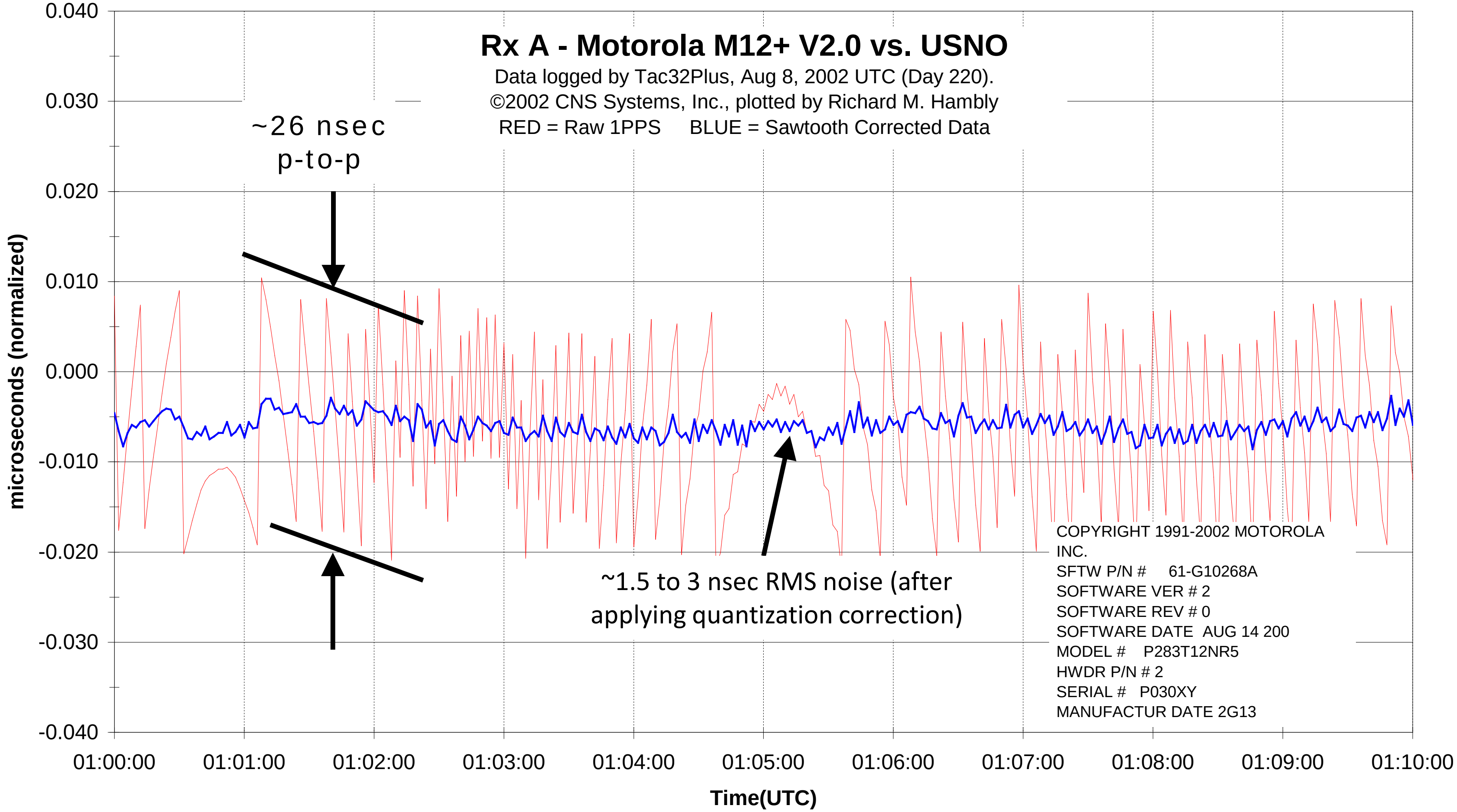
Troubleshooting/Routine Maintenance

- Power Outages
  - Temperature instabilities-heater currents
  - Loss of IF/VCO
  - Backup Batteries
- Microprocessor Failure
- Power Supplies
- Fuses

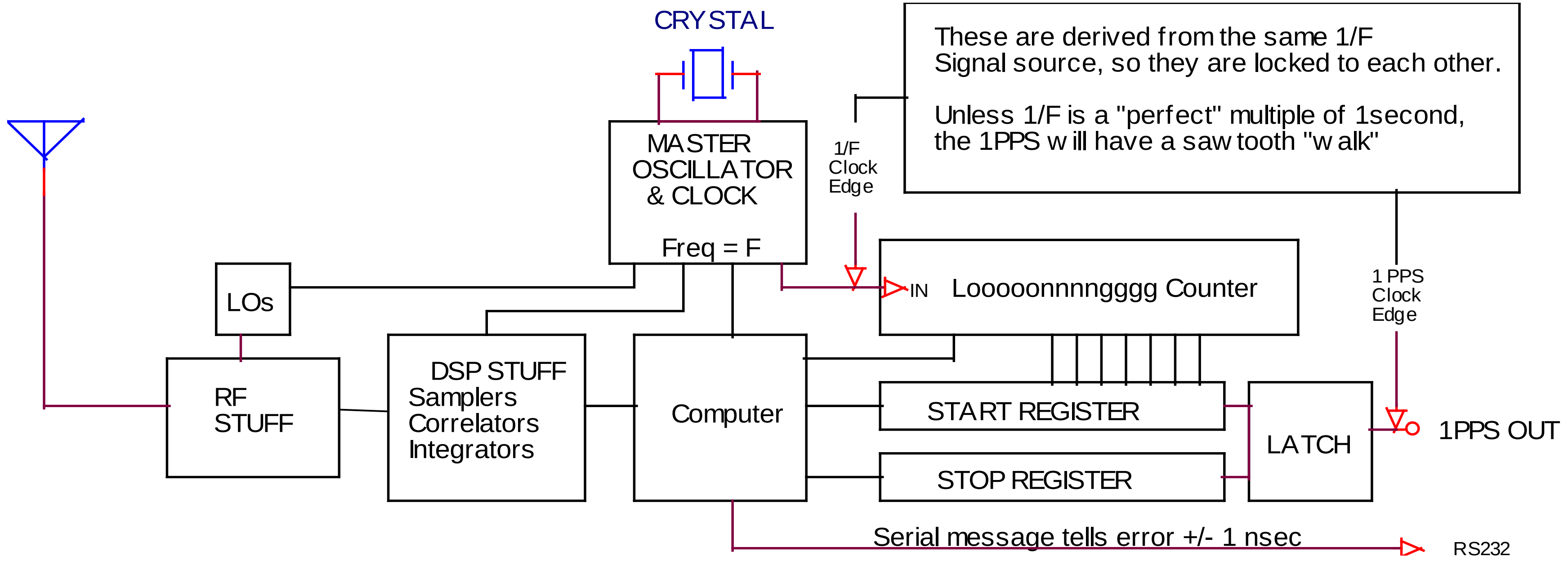
Now let's discuss . . .

- Week rollover may mean retiring old GPS receivers (Motorola VP, UT+, etc.)
  - "We have legacy equipment using the Oncore VP. We have found that the VP receivers have a cutoff date after which the date reverts back 1024 weeks." The compile date of v10.0 was 24-Sep-1999 => rollover is 10-May-2019.
- GPS receiver's quantization error ("sawtooth").
- "Absolute" Receiver Calibration
- New developments
  - The SSR-M8T GNSS receiver
  - Tac32Plus updates
  - CNS Clock II improvements (NTP, Oscillator, PPS)

An Example of 1PPS Quantization Error Correction



What Causes the Quantization Error ?

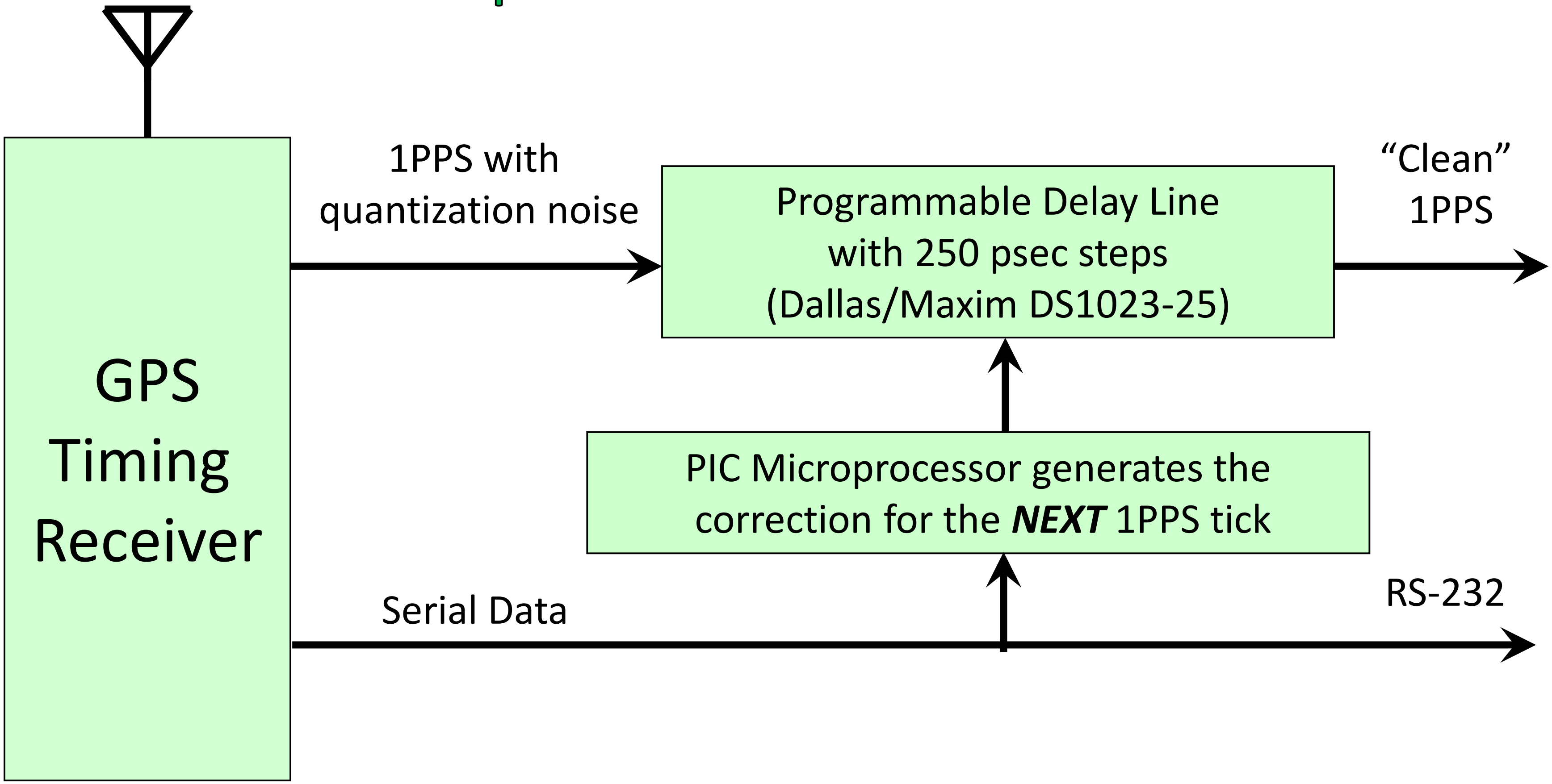


- For the older VP, UT+ Oncore, F=9.54 MHz, so the 1/F quantization error has a range of +/- 52 nsec (104 nsec peak-to-peak).
- The M12+ & M12M have F ≈ 40 MHz, so the quantization error has been reduced to +/- 12.5 nsec (25 nsec).
- SSR-M8T has F ≈ 30.72 * 2 = 61.44 MHz, so the quantization error has been reduced to +/- 8 nsec (16 nsec).

VLBI's Annoying Problem Caused by the Quantization Timing Error

- When the formatter (Mark 5/6 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 ±52, ±13, or ±8 nsec because of the quantization error.
- 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 CNS Clock II which has the quantization error removed.

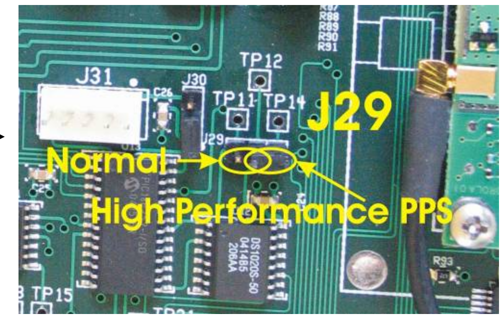
How can the quantization noise be eliminated ?



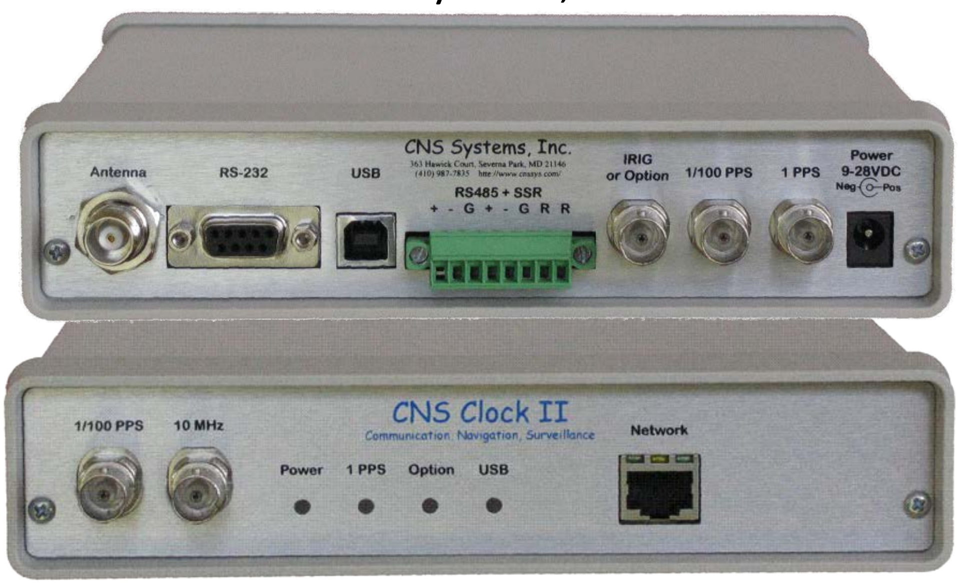
The Future is here now! The CNS Clock II

1994 – 2004: the TAC

1PPS Sawtooth Correction Option

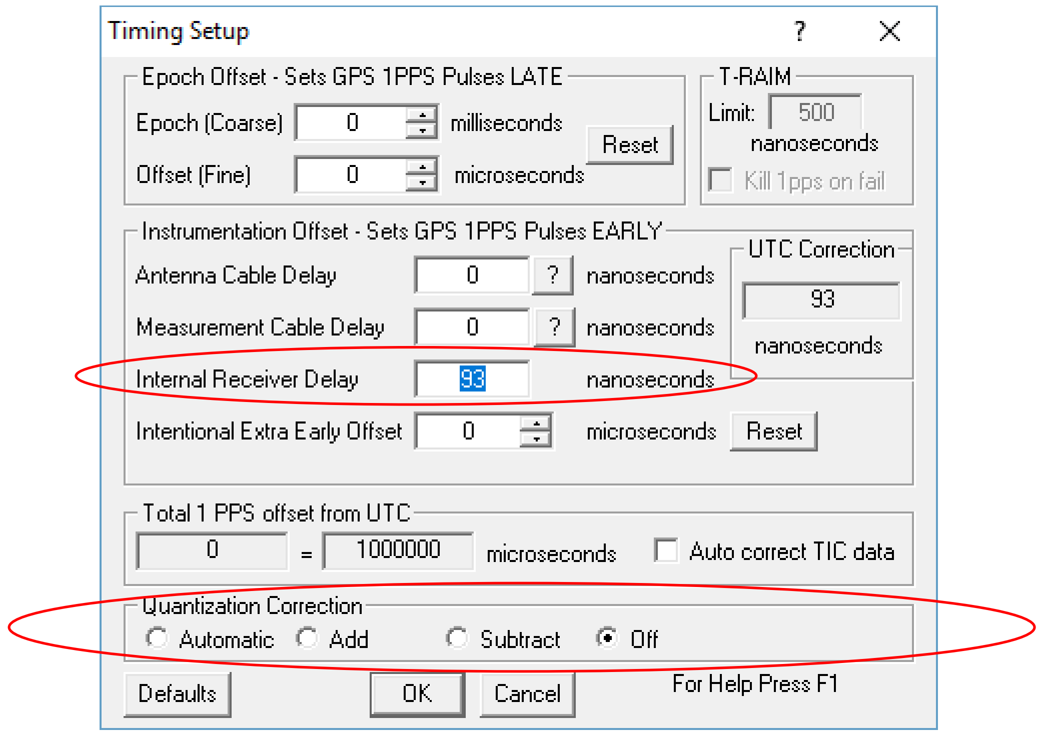


Available Since January 2005, now at Revision K



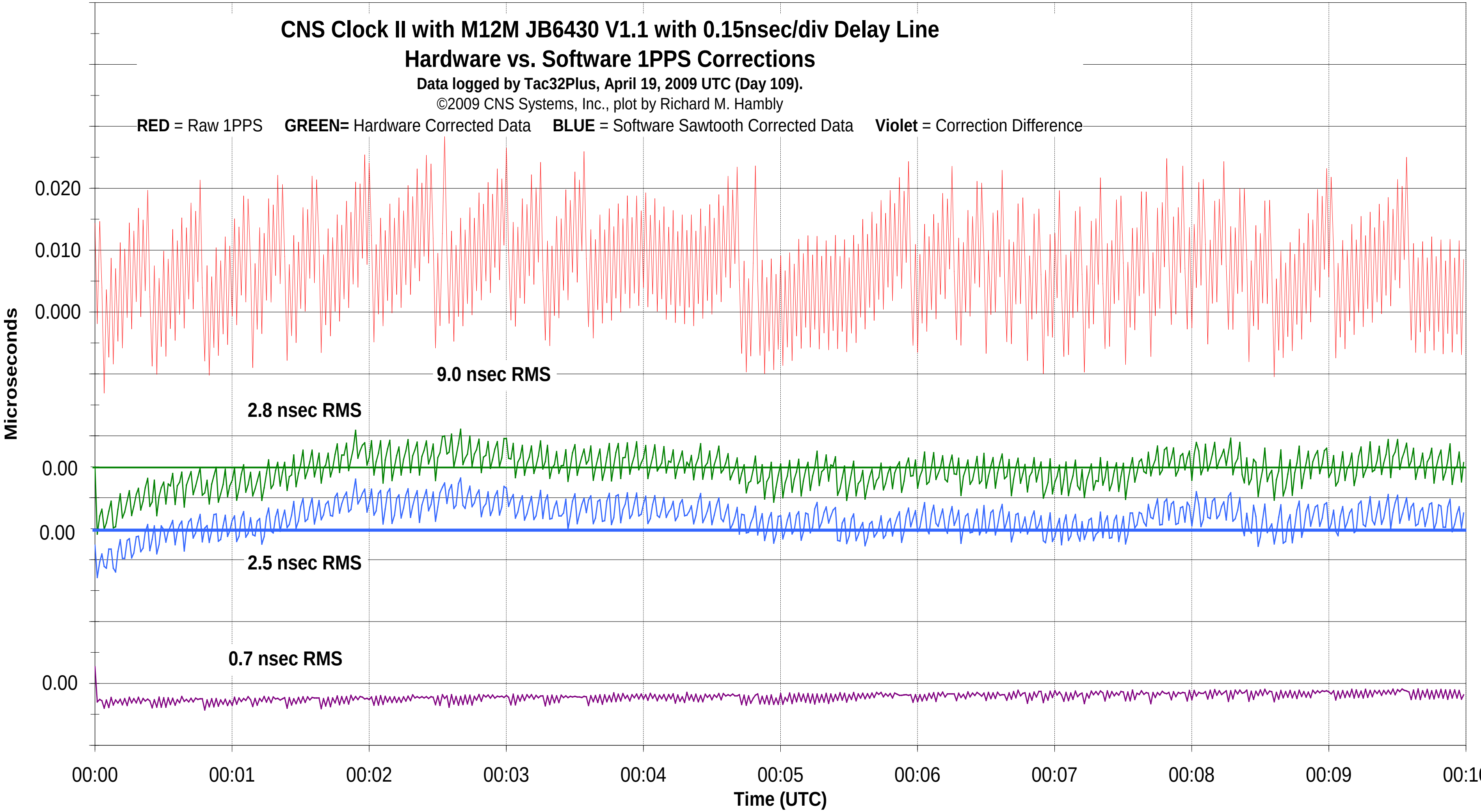
- Data available on RS-232, USB, Ethernet, RS-485 and solid state relay ports.
- Ethernet NTP Server for your LAN.
- TNC GPS Antenna Connector.
- Buffered 1 PPS outputs.
- GPS Steered OCXO 10 (or 5) MHz output.
- High Performance PPS.
- Options: IRIG-B, PPS from steered oscillator, etc.

CNS Clock II Setup Note



- The current CNS Clock II with the SSR-6T receiver and delay line has a 93 nsec internal delay. This is removed by setting the parameter in Tac32Plus. Other versions of the CNS Clock and CNS Clock II will have different delays.
- Because the quantization correction is performed in hardware, the software correction should be set to Off.

Does the hardware 1PPS correction work?

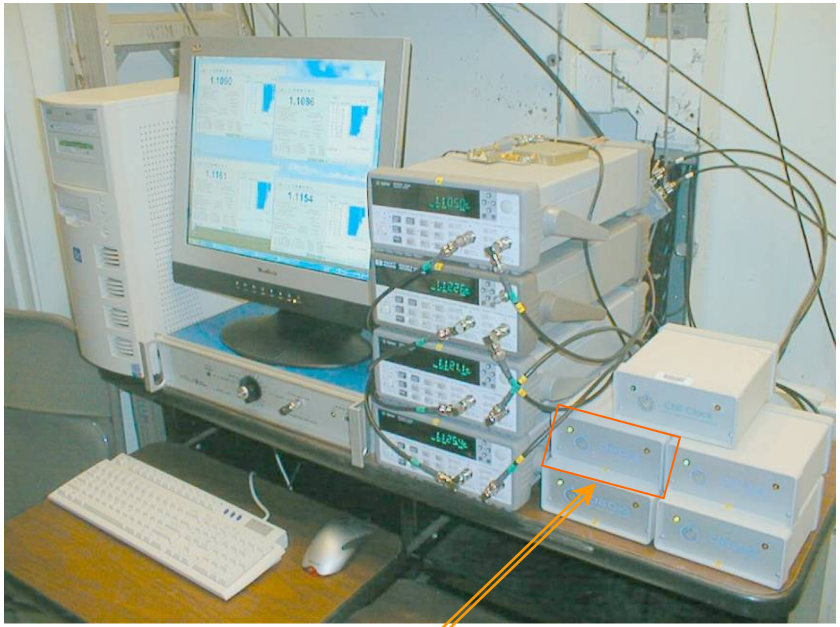


CNS Systems' Test Bed at USNO

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

We 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 CNS to calibrate the new M12+ receiver.

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.

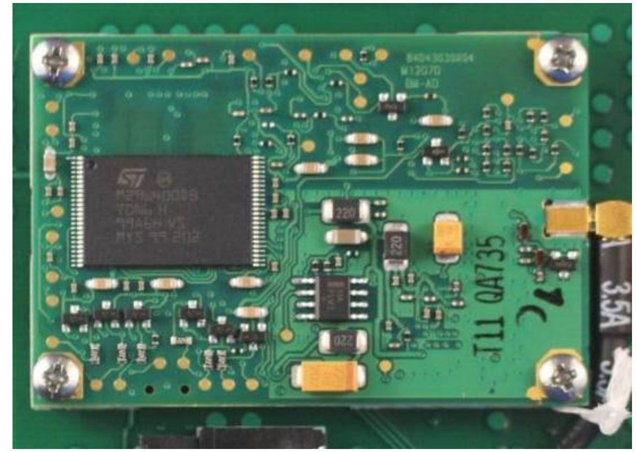
This is the "Gold Standard" "A" receiver that we used for subsequent calibrations.

Trying to keep up with New Technology!

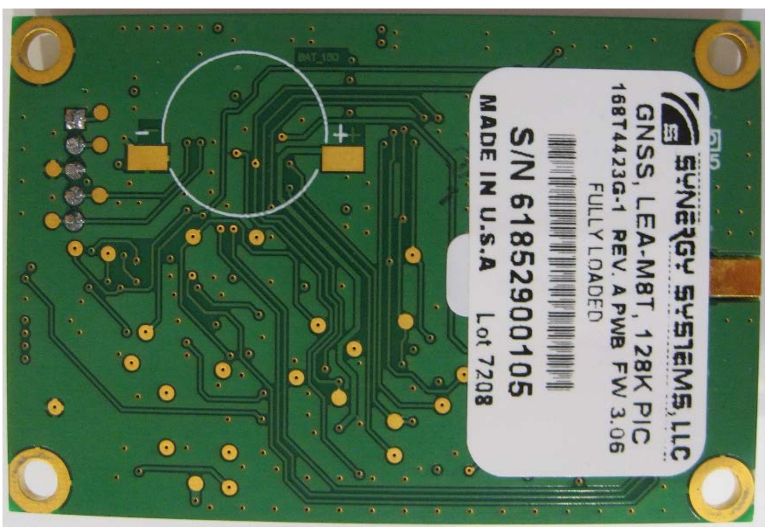
- Motorola quit the GPS business in 2005. The M12 design was licensed to iLotus in Singapore. The current variant is the M12M.
- Anticipating the need for an M12 replacement, Synergy Systems developed the SSR series of receivers. These are an M12 form, fit, and function replacements for the M12 using uBlox LEA-6T and M8T GPS engine modules.
- The latest version of this new receiver has improved hardware, firmware and the uBlox M8T GNSS module that supports multiple satellite systems. This is standard in the latest CNS Clock II product.
- CNS now has an upgrade kit for the original TAC and CNS Clock units that replace the obsolete Motorola VP and UT+ receivers with the latest SSR-M8T+ board.

Comparing an M12+, M-12M & uBlox LEA-6/M8

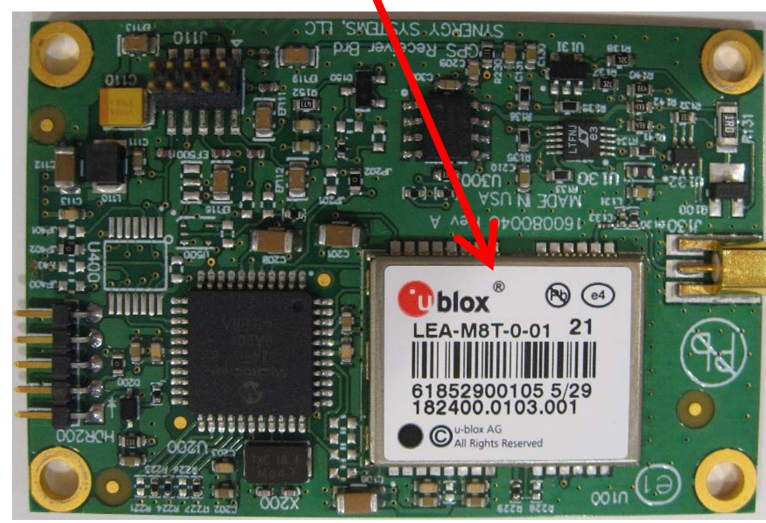
An iLotus M-12M module.
The M12+ looks the same



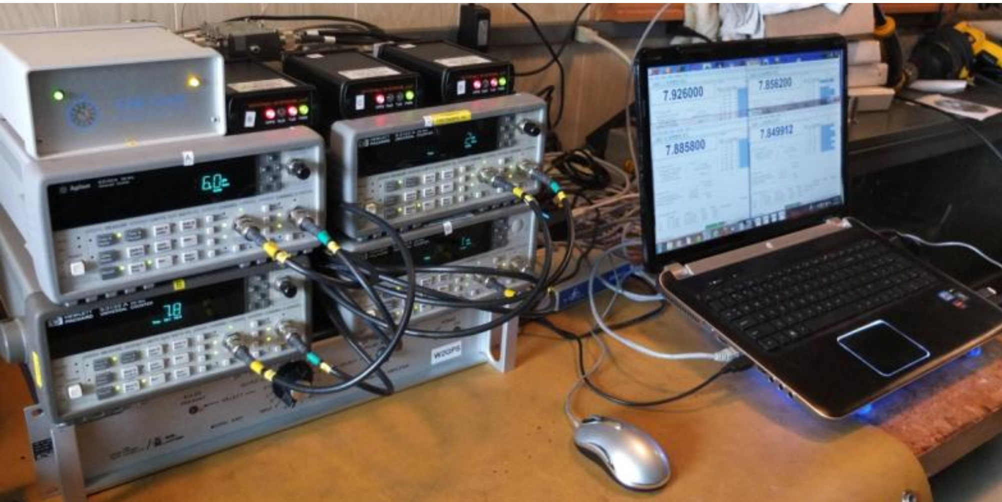
The Synergy SSR-M8T Receiver

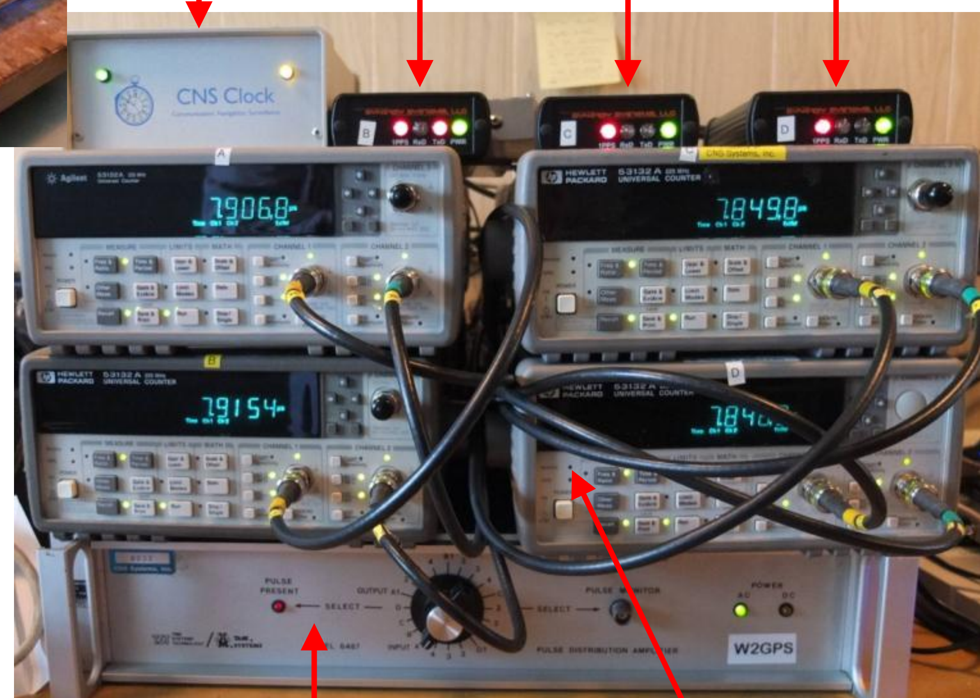


The uBlox LEA6T module



A Four Receiver test @ GGAO





“Gold” Motorola M12+

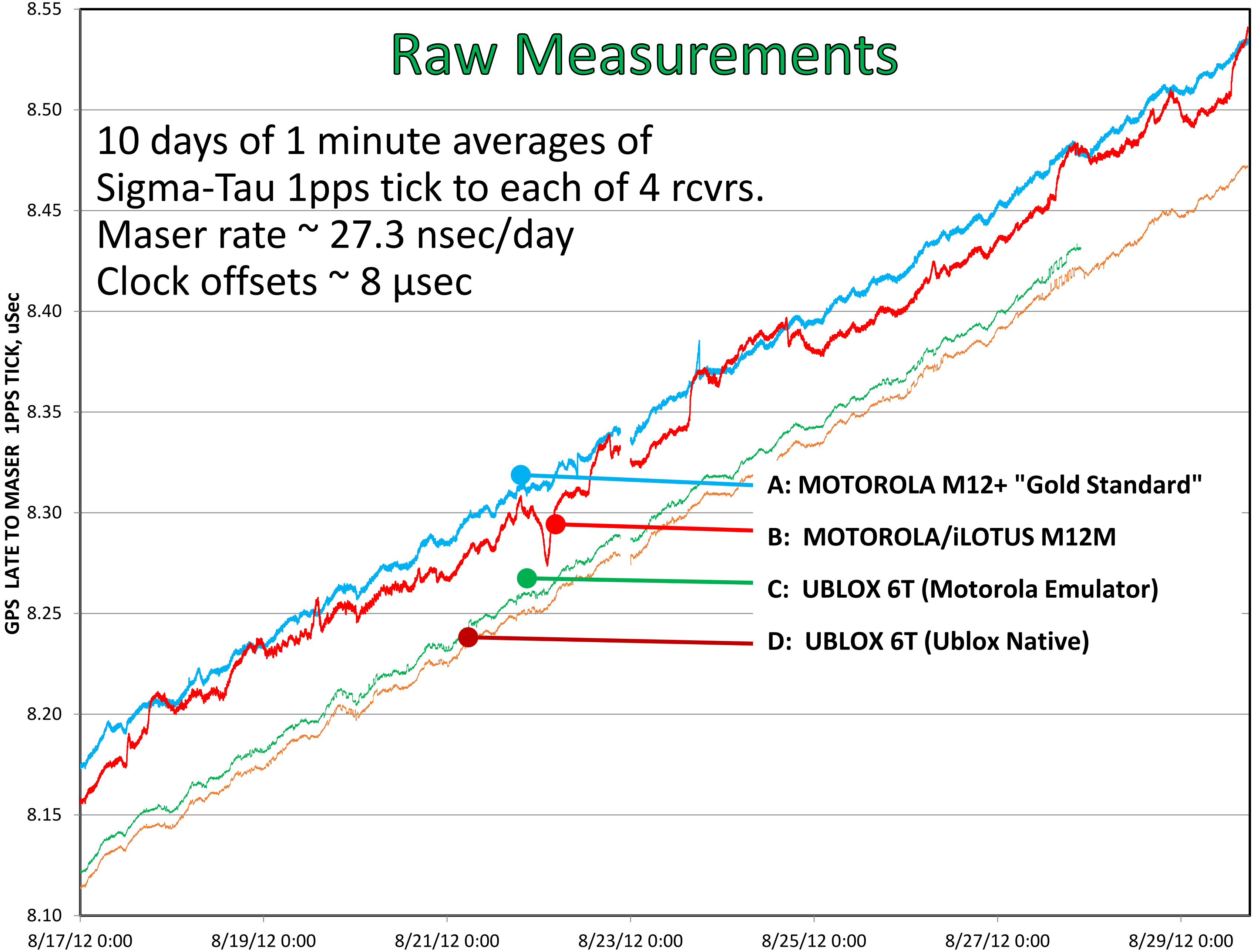
iLotus M12-M

Synergy uBlox Moto Emul .

LEA-6Ts uBlox Native Cmds

Maser 1PPS Distributor

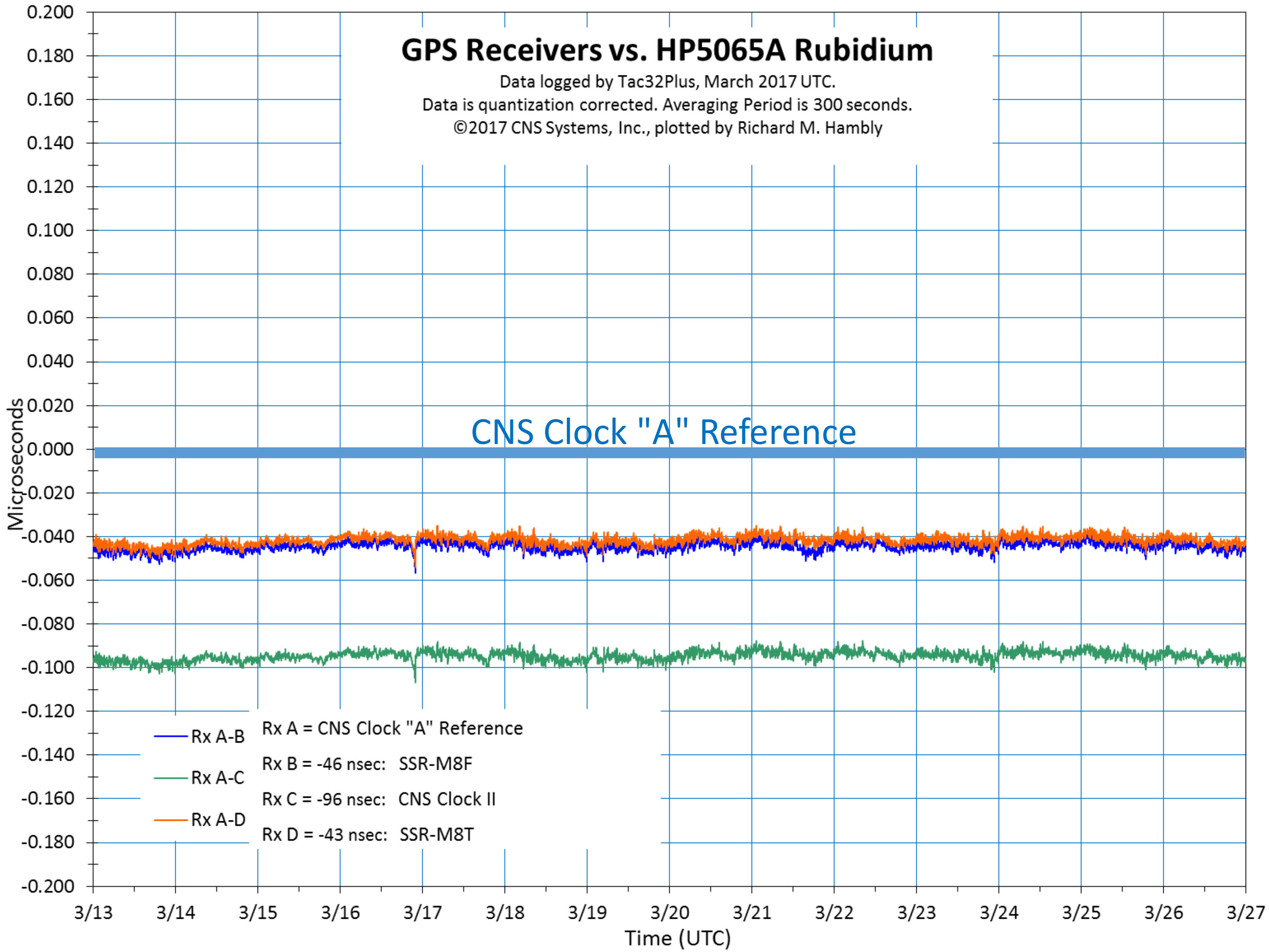
Four HP53132 Counters


Raw Measurements
10 days of 1 minute averages of
Sigma-Tau 1pps tick to each of 4 rcvrs.
Maser rate ~ 27.3 nsec/day
Clock offsets ~ 8 µsec
A: MOTOROLA M12+ "Gold Standard"
B: MOTOROLA/iLOTUS M12M
C: UBLOX 6T (Motorola Emulator)
D: UBLOX 6T (Ublox Native)
GPS LATE TO MASER 1PPS TICK, uSec
8.55
8.50
8.45
8.40
8.35
8.30
8.25
8.20
8.15
8.10
8/17/12 0:00
8/19/12 0:00
8/21/12 0:00
8/23/12 0:00
8/25/12 0:00
8/27/12 0:00
8/29/12 0:00

Modified Allan Deviation

Trace	Notes	Filename	Pathname	Input Freq	Sample Interval	MDEV at 40s
GGAA_A (Unsaved)	Motorola "Gold" M12+			60 Hz	60 s	
GGAA_A (Unsaved)	iLotus M12M			60 Hz	60 s	
GGAA_A (Unsaved)	uBlox 6T, Motorola Emulator			60 Hz	60 s	
GGAA_A (Unsaved)	uBlox 6T, uBlox native			60 Hz	60 s	

A New Four Receiver test @ CNS



Conclusions

1. Small, low cost GPS receivers can provide timing needed for VLBI anywhere in the world. This is not a new statement, it's been true since the 1990's! See www.cnssys.com under the "Publications" tab for "Timing for VLBI" notes from the IVS TOWs for more details.

2. Existing designs based on Motorola/iLotus M12s should have no problem in making the change to uBlox by using the Synergy SSR-M8T receivers.

3. The Synergy SSR receiver with either the uBlox LEA-6T (GPS only) or LEA-M8T (GNSS) is a superior product. **In fact, the uBlox we tested were a factor ~5 BETTER than the M12's** in all tests except for a UTC bias ~43 nsec. When used in the CNS Clock II with its quantization correction delay line, the UTC offset is -96 nsec. Just plug that into Tac32Plus and all is good.

Obsolescence Issues

Receiver upgrade kit is available for original TAC and CNS Clock units. This will replace 8-channel Motorola VP and UT+ receivers with new iLotus M12M receivers.

Obsolescence Issues

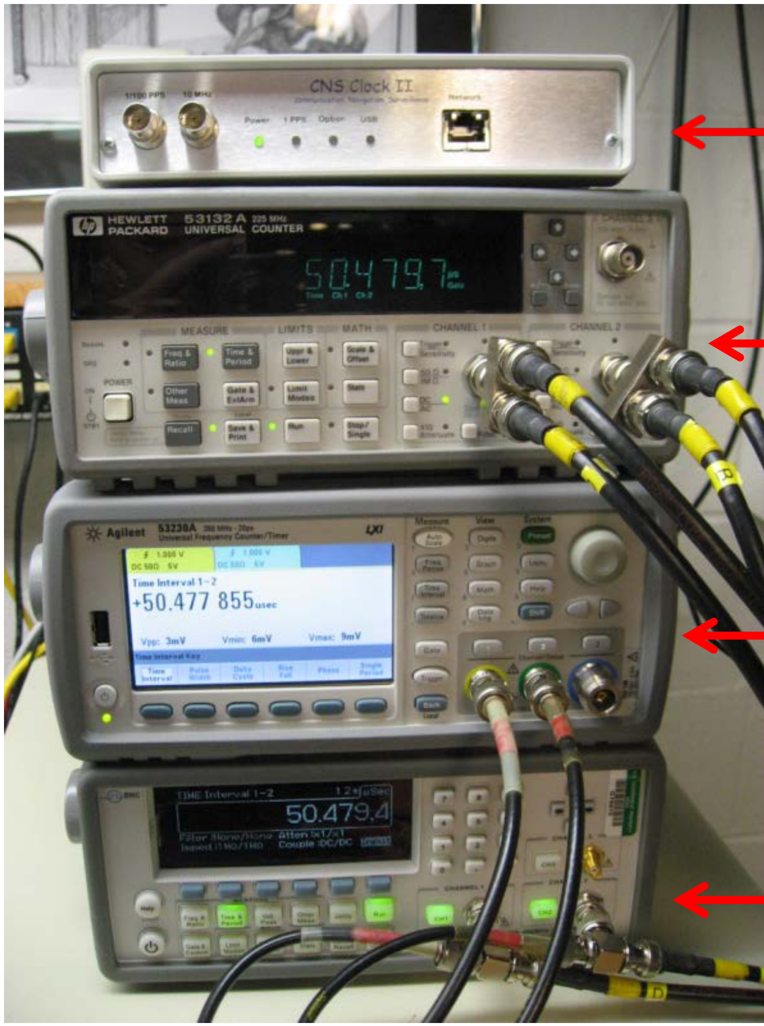
Agilent announced "End-of-Life" for the 53131 and 53132 counters that have been the standard VLBI Time Interval Counter. These use a simple RS232 printer port interface. Tac32Plus was built around this capability.

Agilent is recommending the 53230A as their suggested replacement for the 131/132. This is the counter that CNS is now using.

Berkeley Nucleonics offers their model Model 1104 as an alternative.

Both these counters use Ethernet ports for control and data. This allows Tac32Plus to implement setup commands and collect data. This will simplify station operation and interface wiring.

Tac32Plus v2.7.22 Supports Time Interval Counters via Ethernet.

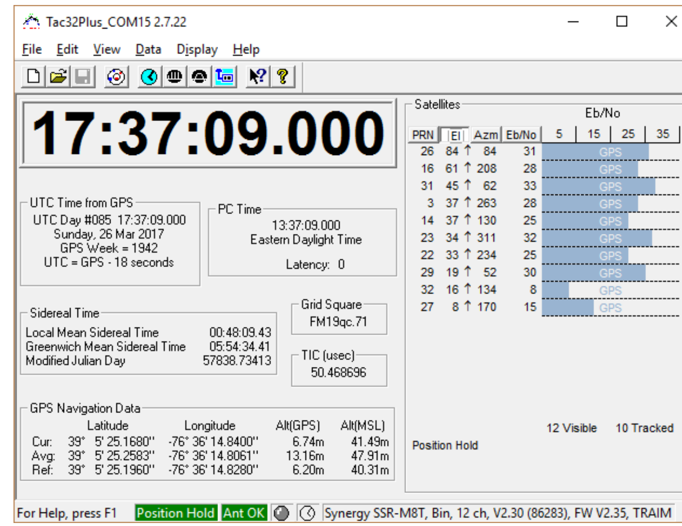


CNS Clock II

HP/Agilent 53132A Serial Port

Agilent 53230A Ethernet

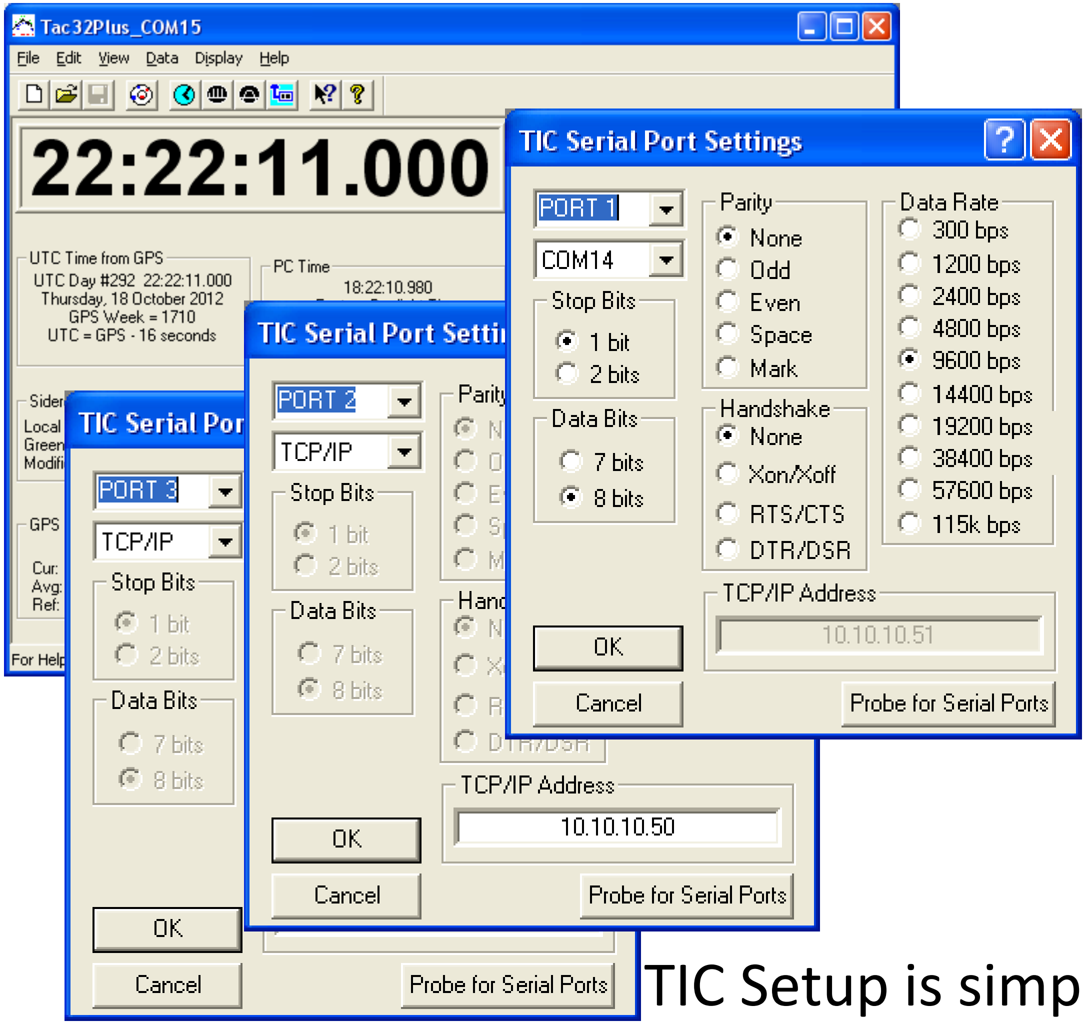
Berkeley Nucleonics Model 1104 Ethernet



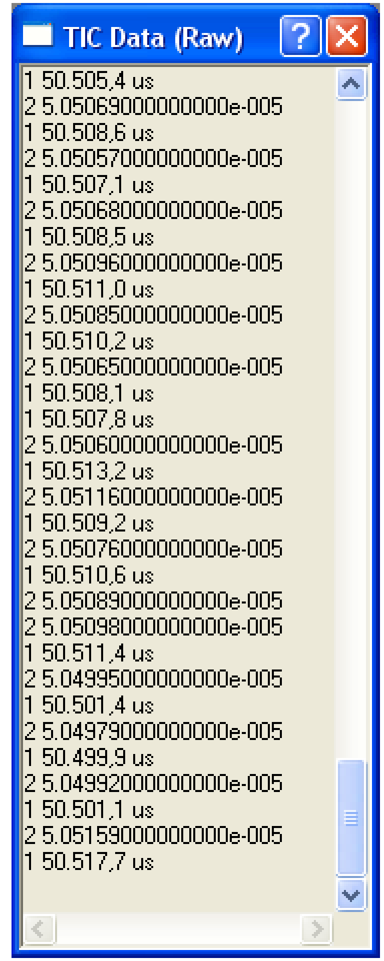
Tac32Plus V2.7.22

Note: GPS time vs. HP5065A Rubidium CNS Systems' time standard

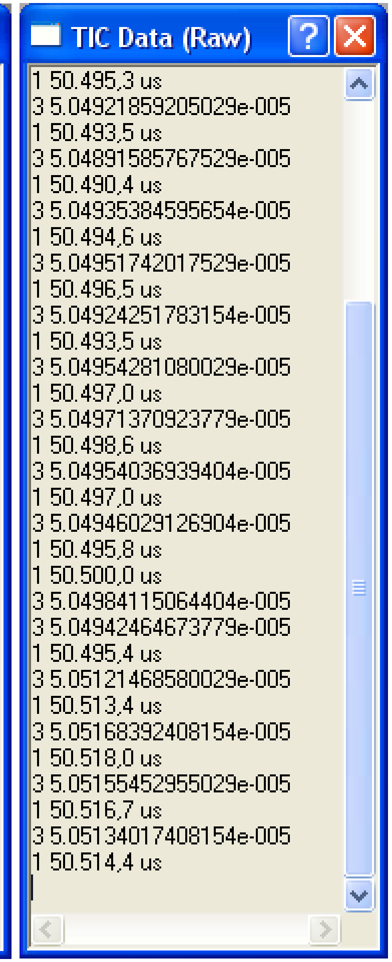
Tac32Plus v2.7.22 Supports Time Interval Counters via Ethernet.



TIC Setup is simple and familiar



53132A vs. BN1105



53132A vs. 53230A

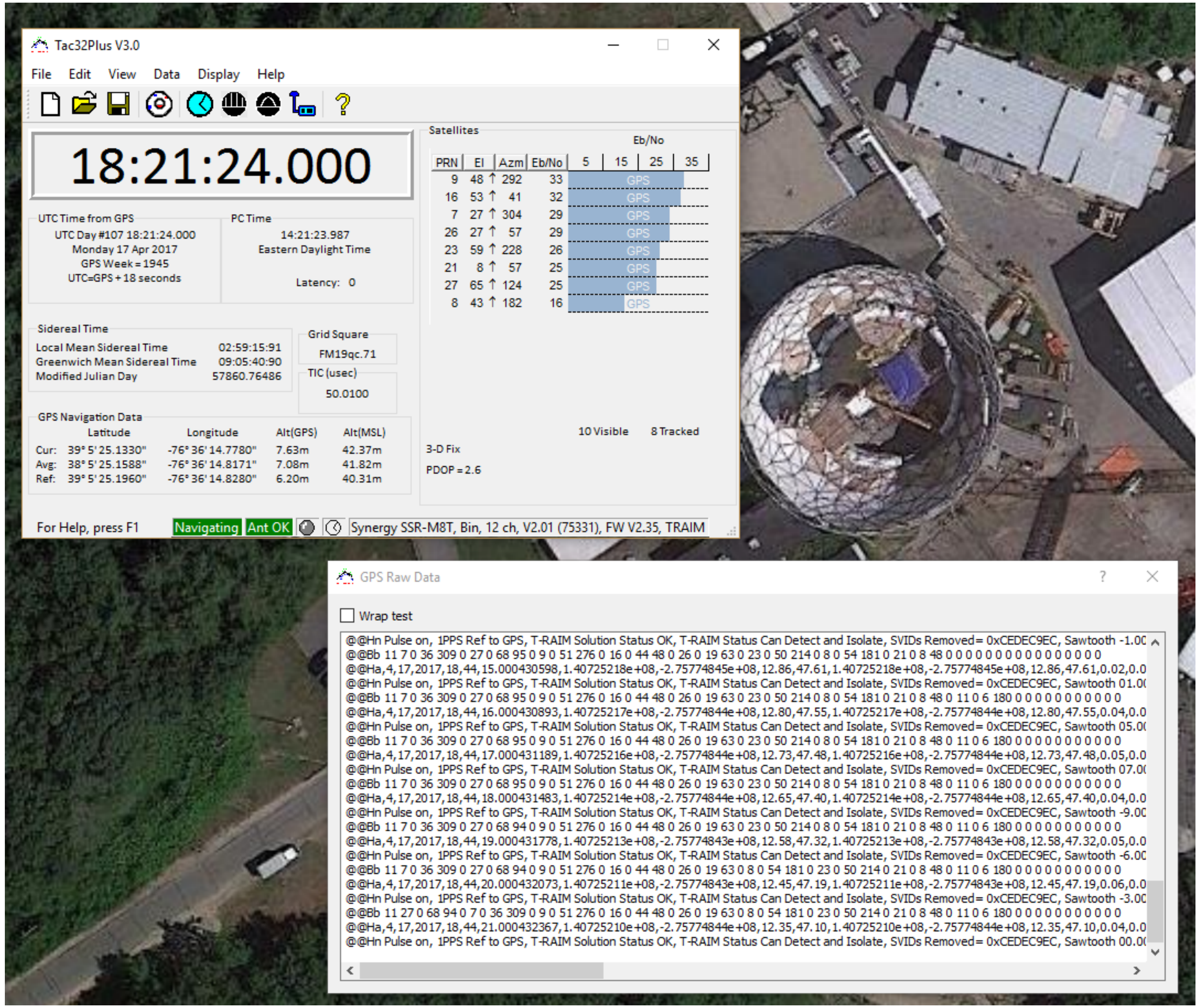
Tac32Plus Upgrades (2016 -> 2017) Version 2.7.20 -> 2.7.22

- Support for the TAPR TICC time interval counter.
- Add satellite constellation selection for SSR receivers: GPS, GLONASS, Galileo, Beidou, QZSS and/or SBAS (WAAS, etc.).
- Implement the Leap Indicator (LI) sub-field in the first word of the NTP protocol message.
- Enable dynamic mode settings for SSR (uBlox) receivers. Auto select based on navigation vs. position hold and self-survey.
- Improve restart after receiver power interruption.
- Improve startup after initial Tac32Plus installation.
- Improved the firmware upload capability for the SSR Plus series receivers.
- Many minor changes and bug fixes.
- See www.cnssys.com/Tac32Plus/Tac32Plus.php.

Future Enhancements:

Tac32Plus:

- Connect to CNS Clock II via TCP/IP.
- Multi-Platform executables, especially Linux. Open source?



Future Enhancements:

Tac32Plus:

- Connect to CNS Clock II via TCP/IP.
- Multi-Platform executables, especially Linux. Open source?

CNS Clock II:

- TCP/IP or UDP/IP data interface.
- Internal Web page setup.
- Expanded IRIG capabilities.
- Firmware updates using Ethernet.

Other enhancements based on user feedback.

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