High-accuracy Time and Frequency in VLBI

IVS Technical Operations Workshop

TOW 2025

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Peraton

CNS SYSTEMS
Communication Navigation Surveillance INC.

Agenda

Background – Richard 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 - Richard Hambly

- More on Troubleshooting and Performance monitoring
- Week rollover may mean retiring old GPS receivers
- GPS receiver 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

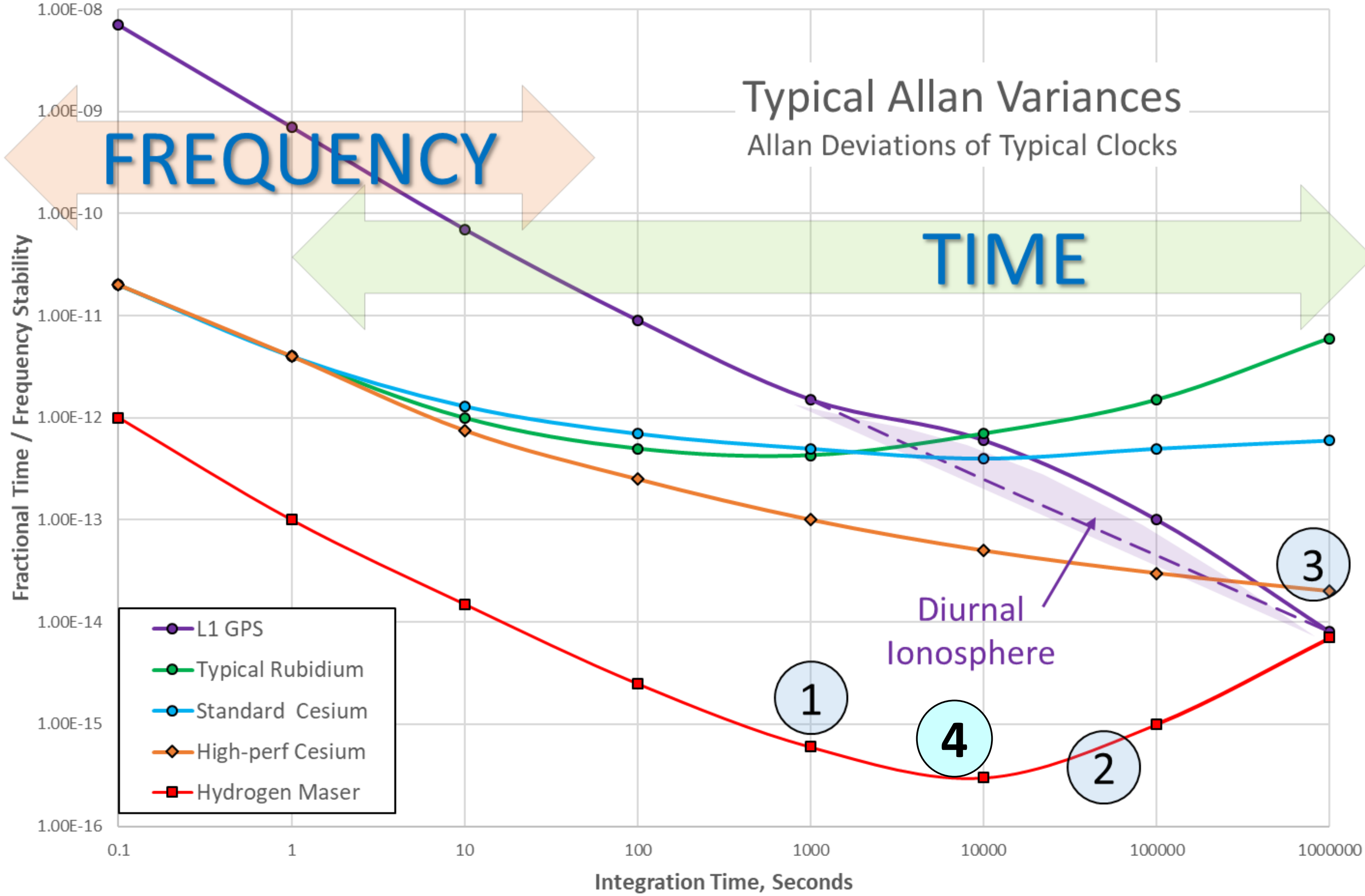
- Gears
- Electronic Counters
- Real Clocks

Long-Term

TIMING

seconds - years

Allan Variance – A graphical look at clock performance



What "Clock" Performance Does VLBI Need?

The Radio Astronomy and Geodesy VLBI community uses Hydrogen Masers at about 50 remote sites around the world.

To achieve ~10° signal coherence for ~1000 seconds at 10 GHz we need the two 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.

1

What “Clock” Performance Does VLBI Need?

In Geodetic applications, the station clocks are modeled at relative levels ~30 psec over a day:

- ≈ [30 * 10^{-12} / 86400 sec] ≈ 3.5 * 10^{-16} @ 1 day

2

- A hydrogen maser provides this level of performance.

What “Clock” Performance Does VLBI Need?

To correlate data acquired at 16 Mb/s, station timing at relative levels ~50 nsec or better was needed. VGOS acquires data at 8 Gb/s, so 125 psec is needed.

For 16 Mb/s, after a few days of inactivity, this requires: **3**

- ≈ $[50 * 10^{-9} / 10^{6}$ sec]
- H-maser -> ≈ $5 * 10^{-14}$ @ 10^{6} sec

For 8 Gb/s, after a day of inactivity, this requires: **4**

- ≈ $[125 * 10^{-12} / 86400$ sec] ≈ $1.5 * 10^{-15}$
- H-maser -> ≈ $2 * 10^{-16}$ @ 1 day

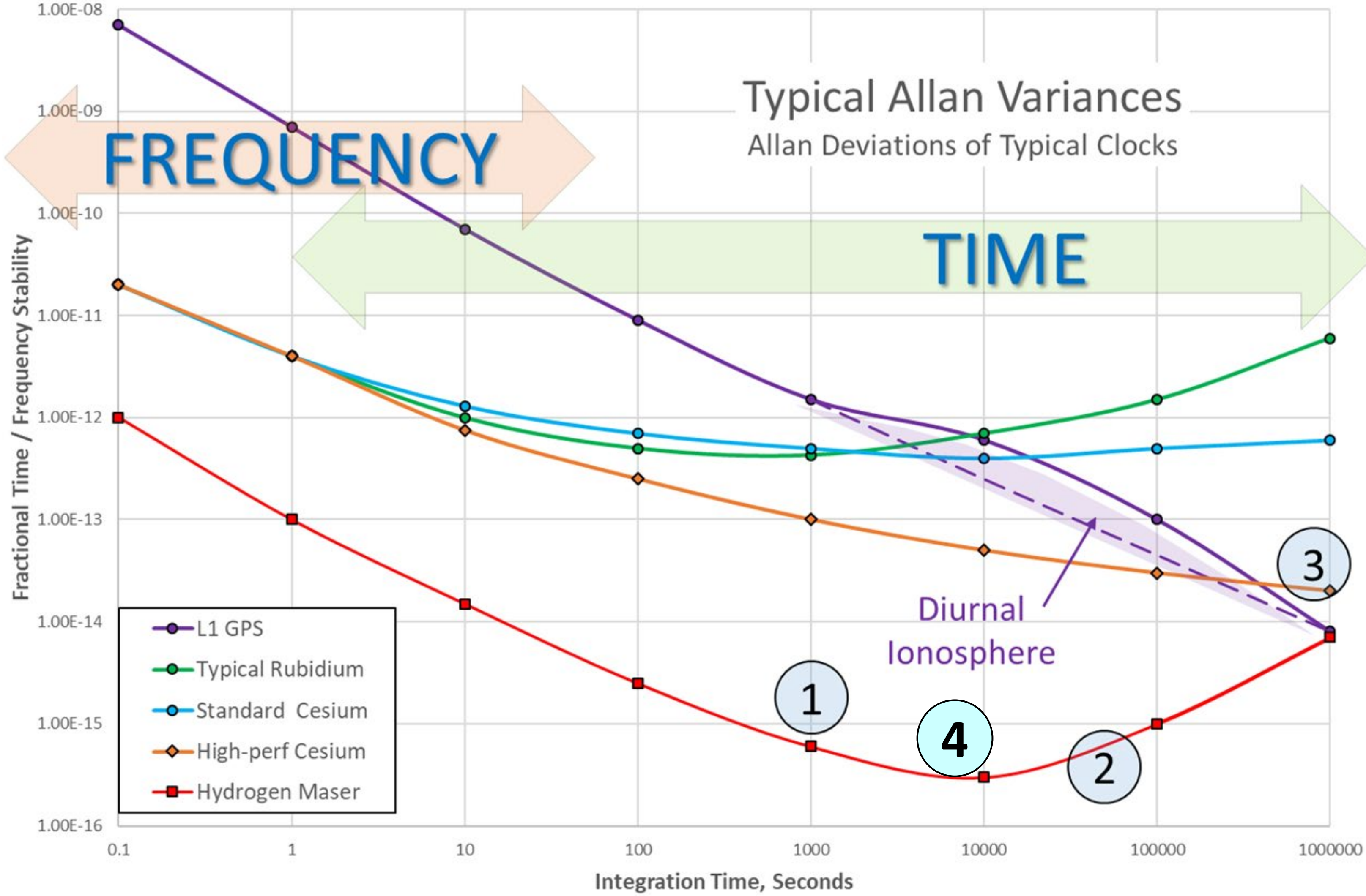
Since VLBI now defines UT1, VLBI needs to control [$UTC_{(USNO)}$ - $UTC_{(VLBI)}$] with an ***ACCURACY*** (traceable to USNO)

- ≈ 100 nsec to 1 μsec

To detect problems, VLBI should monitor the long-term behavior of the Hydrogen Masers (at least) every hour with ***PRECISION***

- ≈10 to 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:

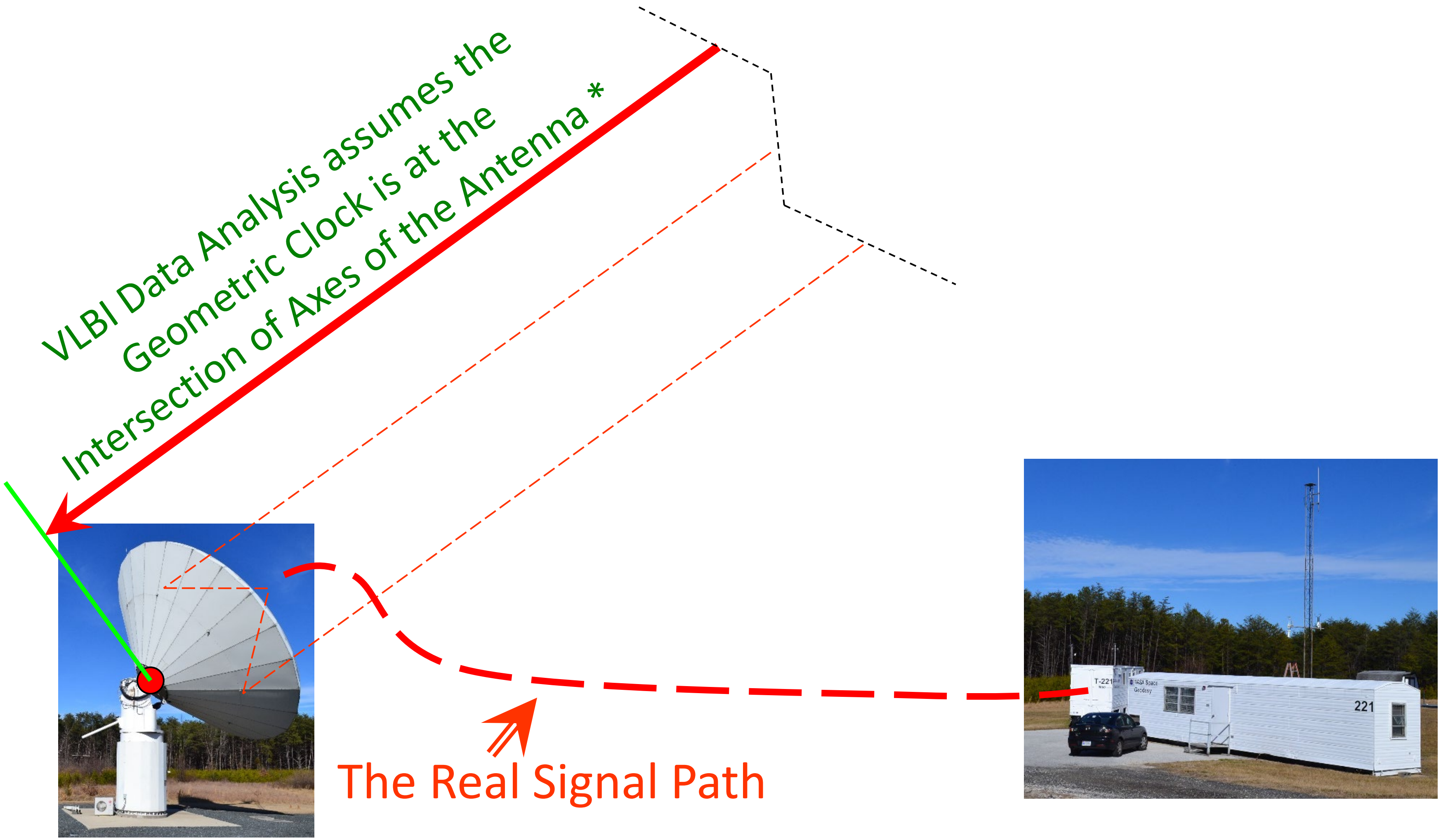
- Generating Sidereal Time to point antennas.
- Measuring UT1 (i.e., "Sundial Time") to see changes due to redistribution of mass in/on the earth over long periods of time (a.k.a. "The Reference Frame")
- Knowing the position of the earth with respect to the moon, planets and satellites.
- Making the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

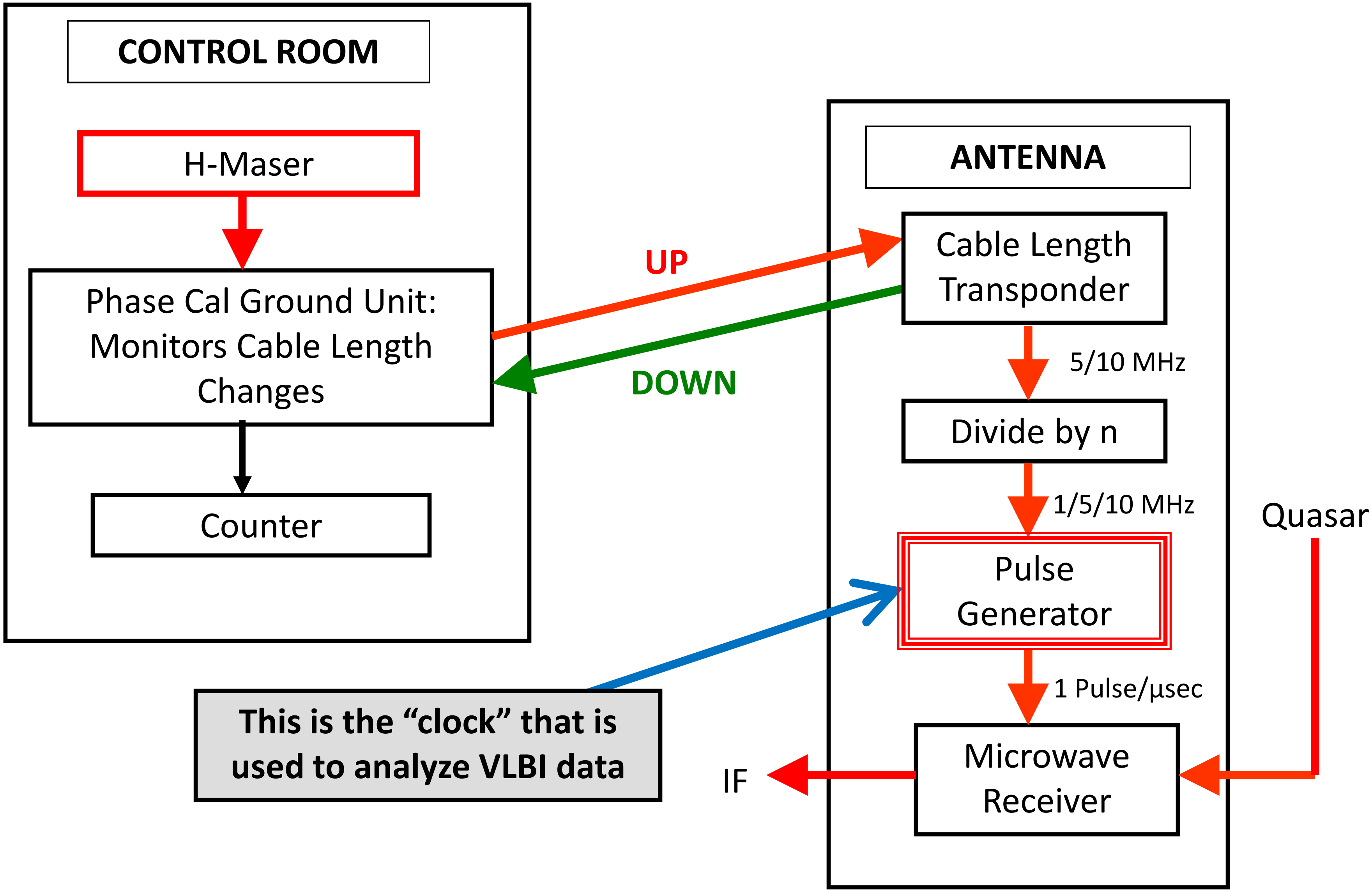
- Frequency Standard and Station Timing
- The lengths of all signal & clock cables
- The geometry of the feed/receiver to the antenna.
- Calibration of instrumental delays inside the receiver and backend.
- The care with which system changes are reported to the correlators and the data analysts.

VLBI's "REAL" Clocks (#1)

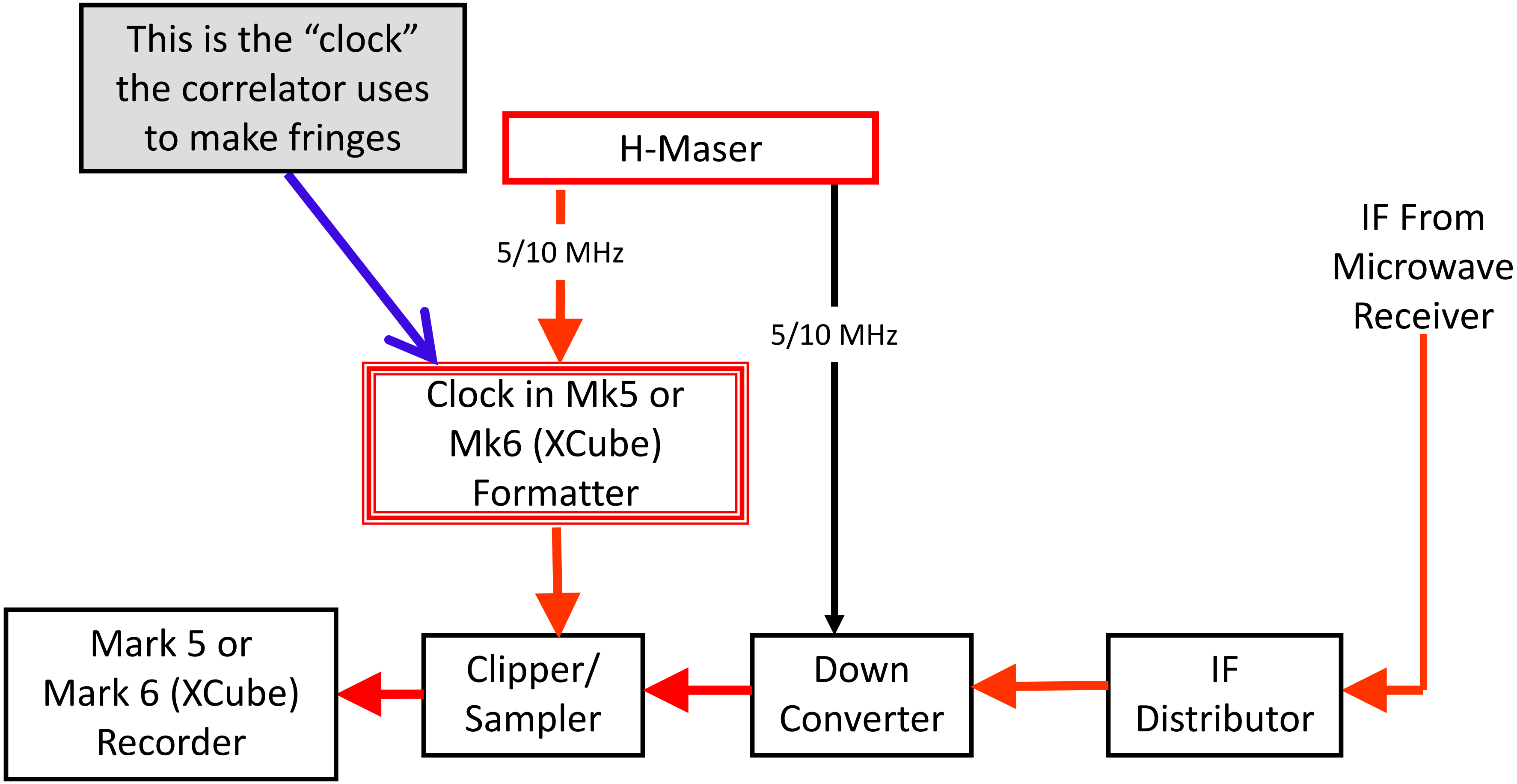


* Note -- If the axes don't intersect, then an "offset axis" model of the antenna is used

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 receiver but it’s hard to gain access to the internal clock.
  - Requires transferring ~1 MB/day of data from site
  - Requires 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 suffers from ionospheric error but dual frequency receivers are now available.

How we get less than 5 nsec 1-sigma timing

- Start with a good timing receiver, like the CNS Clock II with the Synergy SSR (u-blox M8) front end.
- Average the positioning data for 1 to 2 days to determine the station's coordinates. This should be good to <5 meters. If the site has been accurately surveyed, use these 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 are semi-automated in Tac32Plus & GPSTime.

IVS Recommended Maser Timing Practices

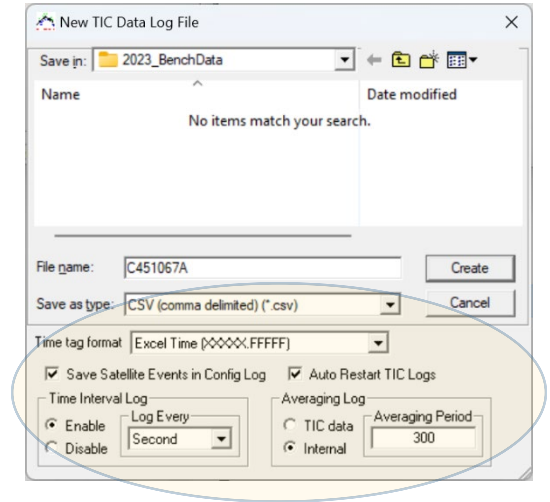
- IVS Memorandum 2014-001v01, 29 April 2014

  IVS Recommended Maser Timing Practices

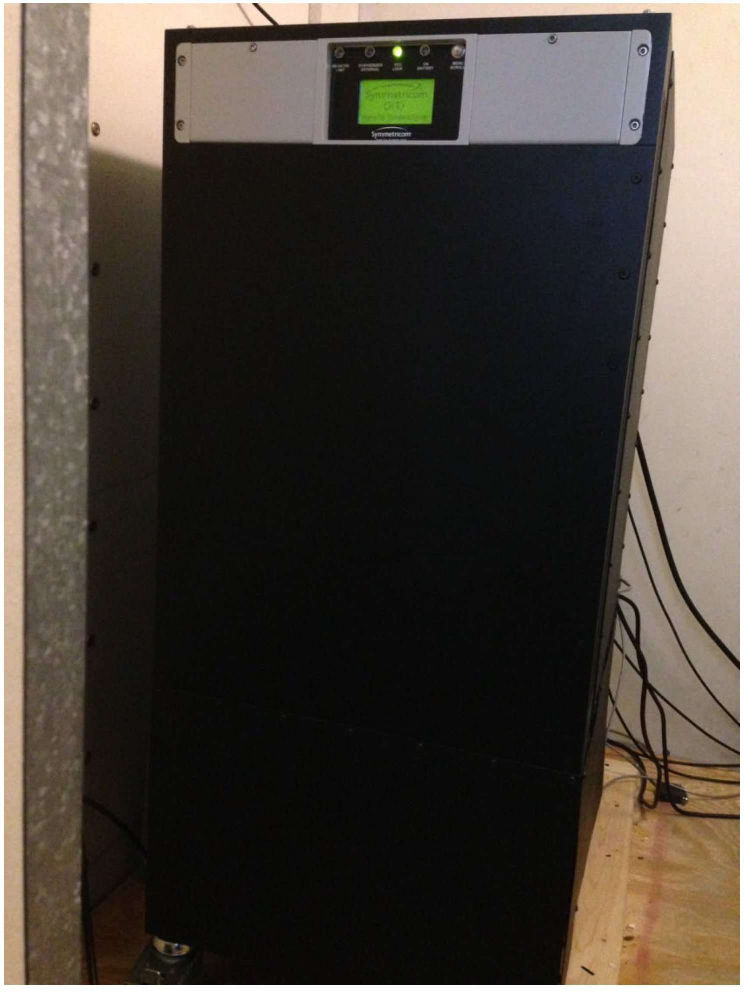
  Roberto Ambrosini, Tom Clark, Brian Corey, Ed Himwich
  https://ivscc.gsfc.nasa.gov/publications/memos/ivs-2014-001v01.pdf

- *Tac32Plus, Tac32Multi Time Interval Counter (TIC) Module*
  https://www.cnssys.com/documents/Tac32Plus.pdf

- When recording data with Tac32Plus or GPSTime, set up as shown here:



Hydrogen Masers



Physics Package

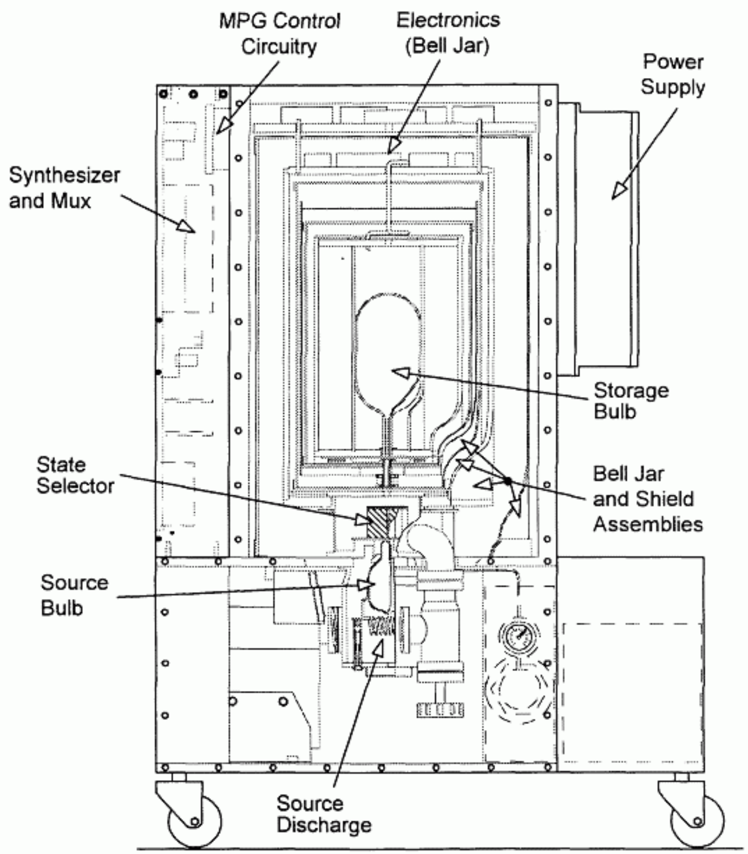


Figure 4. Hydrogen Maser, Physics Layout and Identification.

Credit: Microsemi MHM2010 Manual

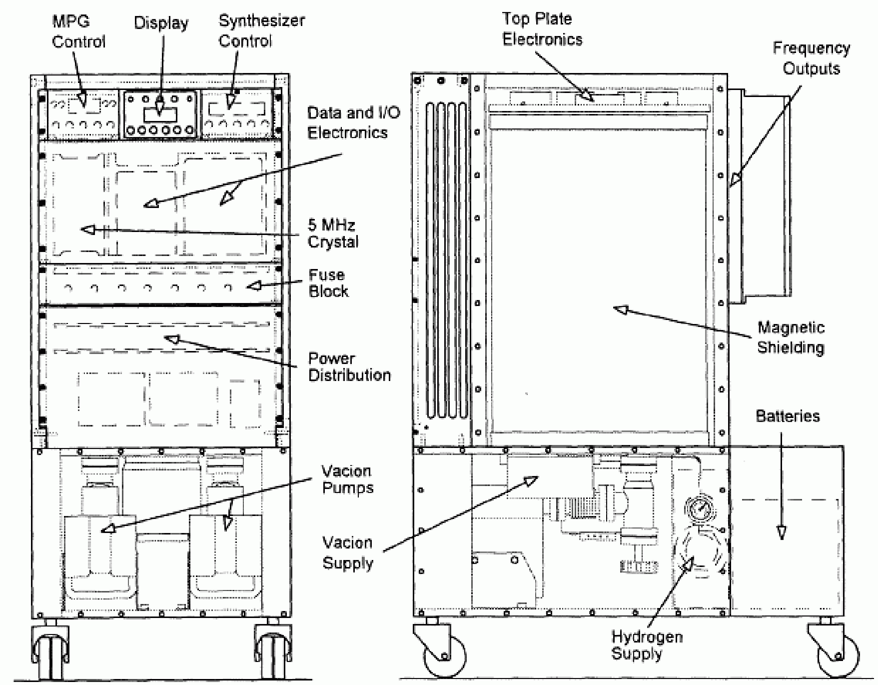


Figure 3. Hydrogen Maser, System Layout and Identification.

Credit: Microsemi MHM2010 Manual

MHM-2020 Maser

- **Maser outputs at NASA stations:**
  - 3x5MHz
  - 4x10MHz
  - 2x1PPS
  - 1PPS synchronization port
  - Telemetry data output
    - USB port (57600 Baud rate)
    - RS-232 port (9600 Baud rate)
    - Ethernet (for real time observation only)
- **Maser telemetry data will push to the NASA Monitor and Archive System for logging**

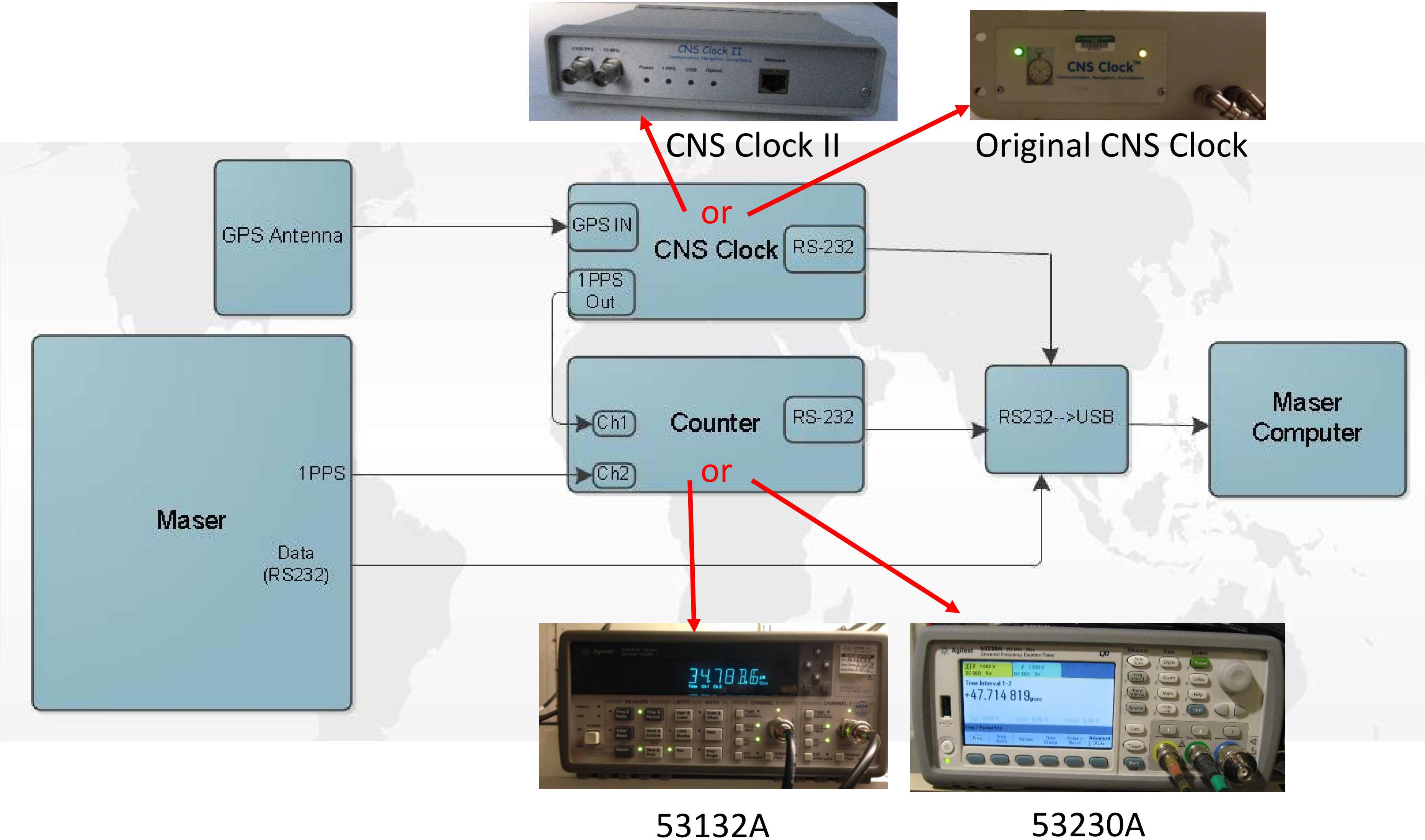
MICROCHIP

Microchip MHM-2020 SW: V1.2.2 | PN: 0 | SN: testbox

Telemetry

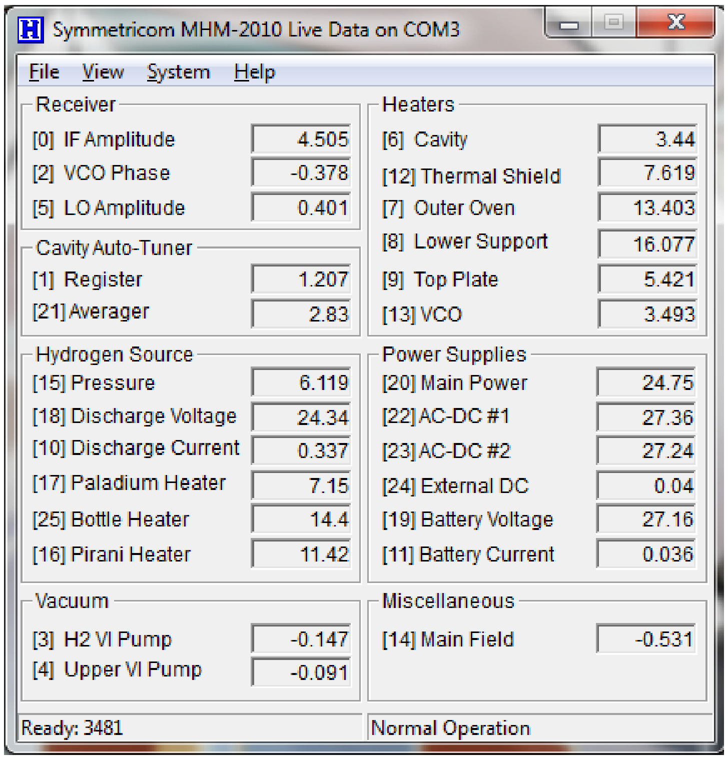
Channel	Channel Name	Value (Volts)
0	IF Amplitude	0.000
1	Cavity Register	0.000
2	VCO Control Voltage	0.000
3	VI Pump H2	0.000
4	VI Pump Upper	0.000
5	Local Oscillator	0.000
6	Cavity Heater	0.000
7	Outer Oven Heater	0.000
8	Lower Support Heater	0.000
9	Top Control Heater	0.000
10	Source Discharge Current	0.000
11	Battery Charge Current	0.000
12	Shield Heater	0.000
13	VCO Heater	0.000
14	Main Magnetic Field	0.000
15	Hydrogen Pressure	0.000
16	Pirani Gauge Heater	0.000
17	Palladium Heater	0.000
18	Source Discharge Voltage	0.000
19	Battery Voltage	0.000
20	Main Bus Voltage	0.000
21	Cavity Averager	0.000
22	Main AC-DC Out 1	0.000
23	Main AC-DC Out 2	0.000
24	External DC Input	0.000
25	Bottle Heater	0.000
26	IF Alarm	0.000
27	VCO Alarm	0.000
28	Register Limit Alarm	0.000
29	DC External Available	0.000
30	AC 1 & 2 Available	0.000
31	Battery In Use	0.000

Timing Configuration

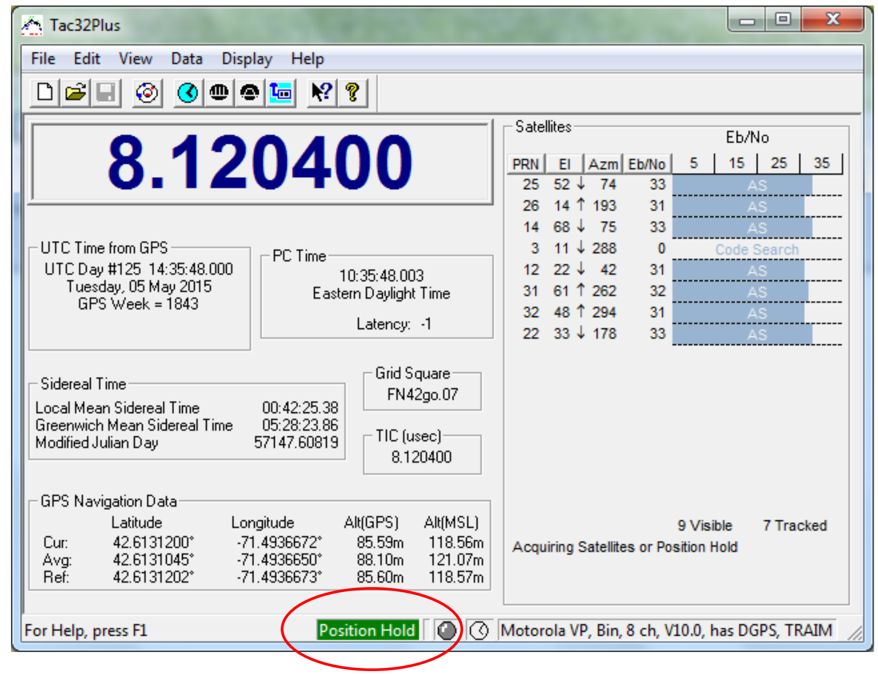


Data/Frequency Monitoring

Maser Data Monitoring

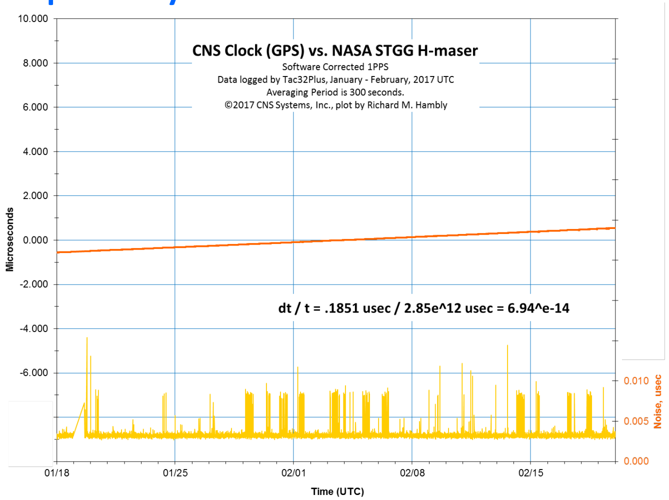


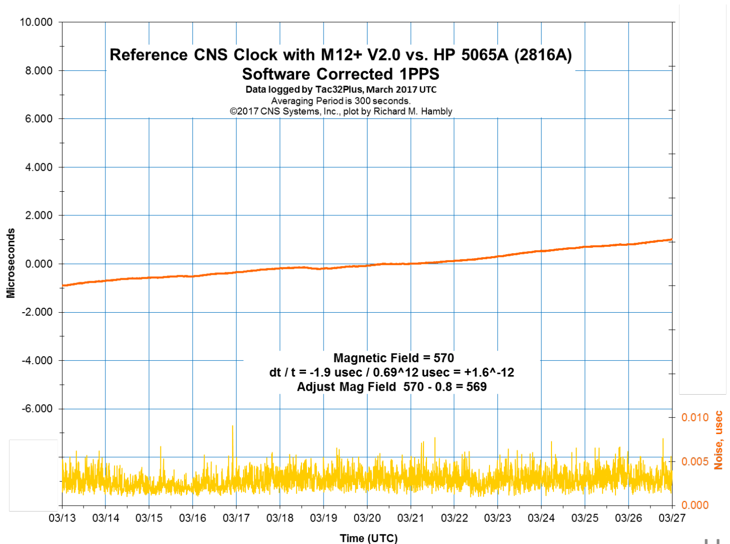
Frequency Data – Tac32Plus



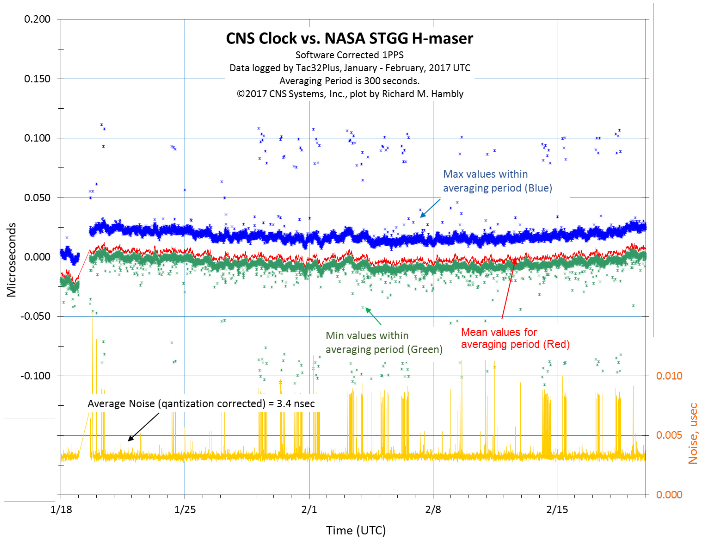
Data/Frequency Monitoring

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





A more detailed look at the data set shows an old GPS receiver with known data issues. This GPS receiver should be upgraded or replaced.



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

Troubleshooting/Routine Maintenance

- Power Outages
  - Temperature instabilities-heater currents
  - Loss of IF/VCO
  - Backup Batteries
- Adjust VCO
- Adjust Cavity Register
- Hydrogen tank supplied for 20 years of operation
- Vacion pumps are designed for over 20 years of operation before needing maintenance
- Frequency corrections are not needed because the auto-tuner is continuously on

More on Troubleshooting and Performance Monitoring

- NTP Time Performance.
- Westford Time or Frequency Problem?
- Need to replace old GPS receiver modules.

NTP Performance of Tac32Plus and CNS Clock II

```
Welcome to Ubuntu 20.04.4 LTS (GNU/Linux 4.9.312-125-OncoreGPS-0.4+ aarch64)

 * Documentation:  https://help.ubuntu.com
 * Management:     https://landscape.canonical.com
 * Support:        https://ubuntu.com/advantage
New release '22.04.2 LTS' available.
Run 'do-release-upgrade' to upgrade to it.

Last login: Sat Mar  4 21:30:55 2023 from fe80::e6a0:f0ce:b2ae:3def%eth0
            .-/+oossssoo+/-.
        `:+ssssssssssssssssss+:`           -----------
      -+ssssssssssssssssssyyssss+-         OS: Ubuntu 20.04.4 LTS aarch64
    .ossssssssssssssssssdMMMNysssso.       Host: Hardkernel ODROID-N2
   /ssssssssssshdmmNNmmyNMMMMhssssss/      Kernel: 4.9.312-125-OncoreGPS-0.4+
  +ssssssssshmydMMMMMMMNddddyssssssss+     Uptime: 33 days, 1 hour, 42 mins
 /sssssssshNMMMyhhyyyyhmNMMMNhssssssss/    Packages: 1348 (dpkg)
.ssssssssdMMMNhsssssssssshNMMMdssssssss.   Shell: bash 5.0.17
+sssshhhyNMMNyssssssssssssyNMMMysssssss+   Terminal: /dev/pts/0
ossyNMMMNyMMhsssssssssssssshmmmhssssssso   CPU: Hardkernel ODROID-N2 (6) @ 1.896GHz
ossyNMMMNyMMhsssssssssssssshmmmhssssssso   Memory: 287MiB / 3709MiB
+sssshhhyNMMNyssssssssssssyNMMMysssssss+
.ssssssssdMMMNhsssssssssshNMMMdssssssss.
 /sssssssshNMMMyhhyyyyhdNMMMNhssssssss/
  +sssssssssdmydMMMMMMMMddddyssssssss+
   /ssssssssssshdmNNNNmyNMMMMhssssss/
    .ossssssssssssssssssdMMMNysssso.
      -+sssssssssssssssssyyyssss+-
        `:+ssssssssssssssssss+:`
            .-/+oossssoo+/-.

NTP Performance Snapshot:  ntpq -pu
NTP Vizualization Stats:   ntpstats -h
NTP Configuration:         sudo nano /etc/ntpsec/ntp.conf
NTP Oncore Configuration:  sudo nano /etc/ntp.oncore0
rick@cnsntp:~$ ntpq -pu
```

a) CNS Clock, RS232 port directly connected to Linux NTP server

b) Tac32Plus server on Windows computer

c) CNS Clock II units, internal NTP servers in test bed.

d) CNS Clock II units, internal NTP servers on work bench.

e) External internet time references.

	remote	refid	st	t	when	poll	reach	delay	offset	jitter
a	oONCORE(0)	.GPS.	1	l	2	16	377	0ns	1.003us	233ns
b	x192.168.10.15	GPS.	1	u	14	64	377	1.0629ms	27.823ms	5.6897ms
c	+192.168.10.24	.GPS.	1	u	44	64	377	696.26us	-990.6us	16.696us
c	+192.168.10.26	.GPS.	1	u	3	64	377	689.15us	-995.7us	9.974us
c	+192.168.10.33	.GPS.	1	u	56	64	377	651.50us	-1.038ms	34.023us
d	+192.168.1.190	.GPS.	1	u	-	64	377	707.09us	-996.2us	14.606us
d	192.168.1.191	.STEP.	16	u	-	1024	0	0ns	0ns	477ns
e	-tick.usnogps.navy.mil	.IRIG.	1	u	32	64	377	118.29ms	-11.96ms	198.84us
e	-192.5.41.40	.IRIG.	1	u	38	64	377	96.159ms	8.5046ms	22.077ms
e	-time-a-wwv.nist.gov	.NIST.	1	u	120	64	372	37.565ms	1.2614ms	101.64us
e	-time-a-b.nist.gov	.NIST.	1	u	83	64	76	34.687ms	1.0697ms	213.61us

Westford Time or Frequency Problem?

First, we will look at good Westford data for reference.

Then we will look at data from Westford in 2023 and try to determine what was wrong.

The following slides are the output from a data analysis tool written in Python that automatically gathers up data from many Tac32Plus TIC "A" and "T" log files that may be on any network accessible computer and produces a PDF report file for analysis.

GNSS Test Bed Analysis

User Input

Data Directory containing the Tac32Plus or GPSTime data files

C:/Users/rick/Dropbox/Shared Folders/Westford Radio Telescope/TAC2025 [Browse]

Output Directory for the report file

C:/Users/rick/Documents/CNS Systems Inc/Organizations/NASA/Westford Telescope/Westford Data [Browse]

Enter the start time for the Average Data charts

02/27/2025

Enter the duration (days) for the Average Data charts.

60

Enter the Average Data sample size

300

<- This is needed to validate each data line

Enter the Time (noise) data start time.

02/28/2025

<- Note that the one hour block of data must be in a single data file

Enter the Magnetic Field Setting (optional).

<- This is for an HP5064A Rubidium Standard. If not needed, set blank or zero.

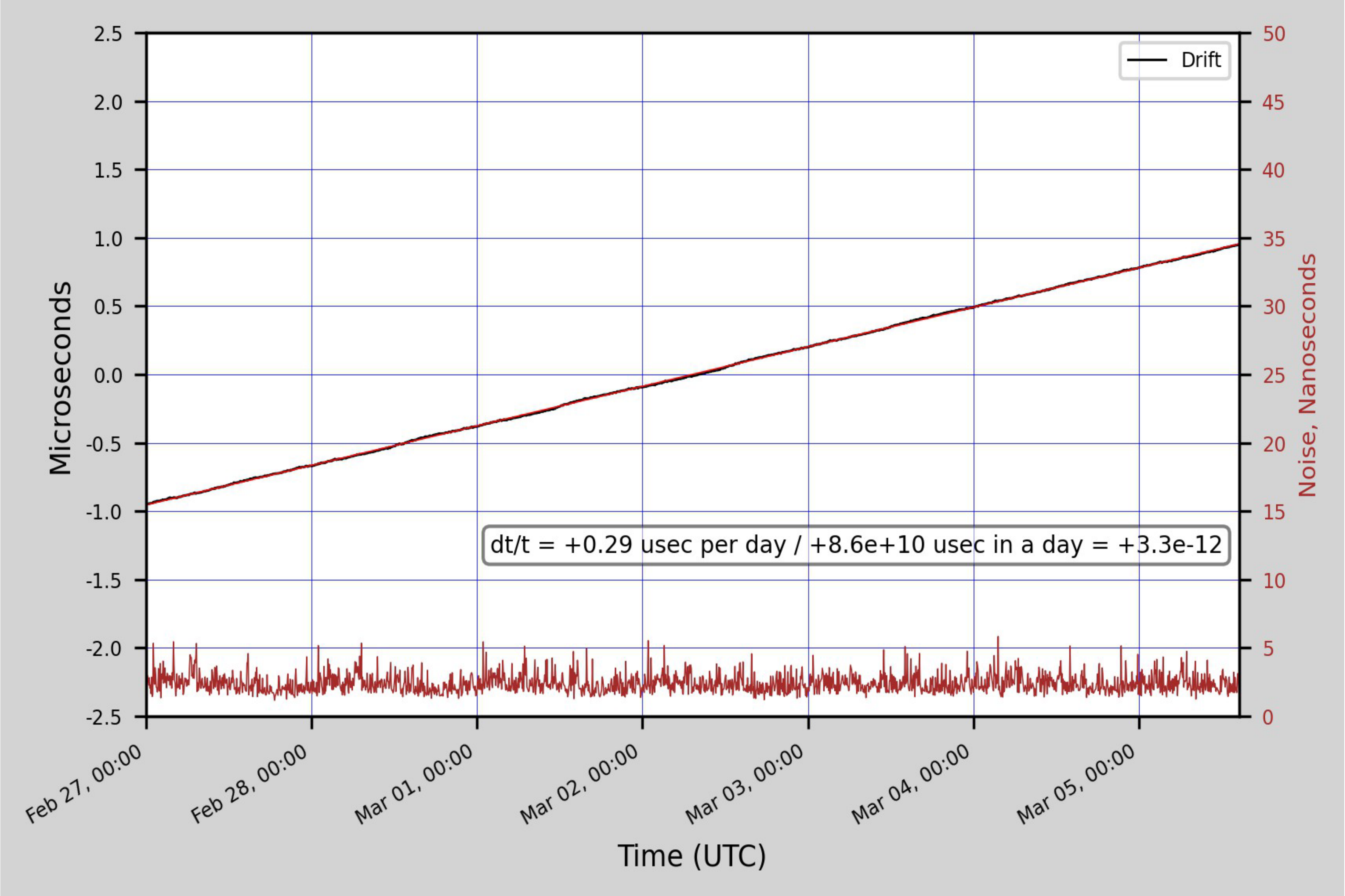
Data sets to include in the report

	Enter the Prefix for the data file series	Enter the Primary Header	Enter the Secondary Header Extension
✔	04WF	CNS Clock 404447 (SSR-M8F+ X) vs. NR4 Maser at Westford	Hardware corrected PPS with 8 nsec RxDelay
☐	07HY	CNS Clock 801038 (SSR-UT+ with LEA6Tf) vs. NR4 Maser at Westford	Software corrected PPS with 54 nsec RxDelay
☐			
☐			

[OK] [Cancel]

CNS Clock 404447 (SSR-M8F+ X) vs. NR4 Maser at Westford Drift Chart

Data logged by Tac32Plus. Analyzed by Python + Pandas on 05-Mar-2025, © 2025 CNS Systems, Inc.
Averaging period is 300 seconds, Hardware corrected PPS with 8 nsec RxDelay



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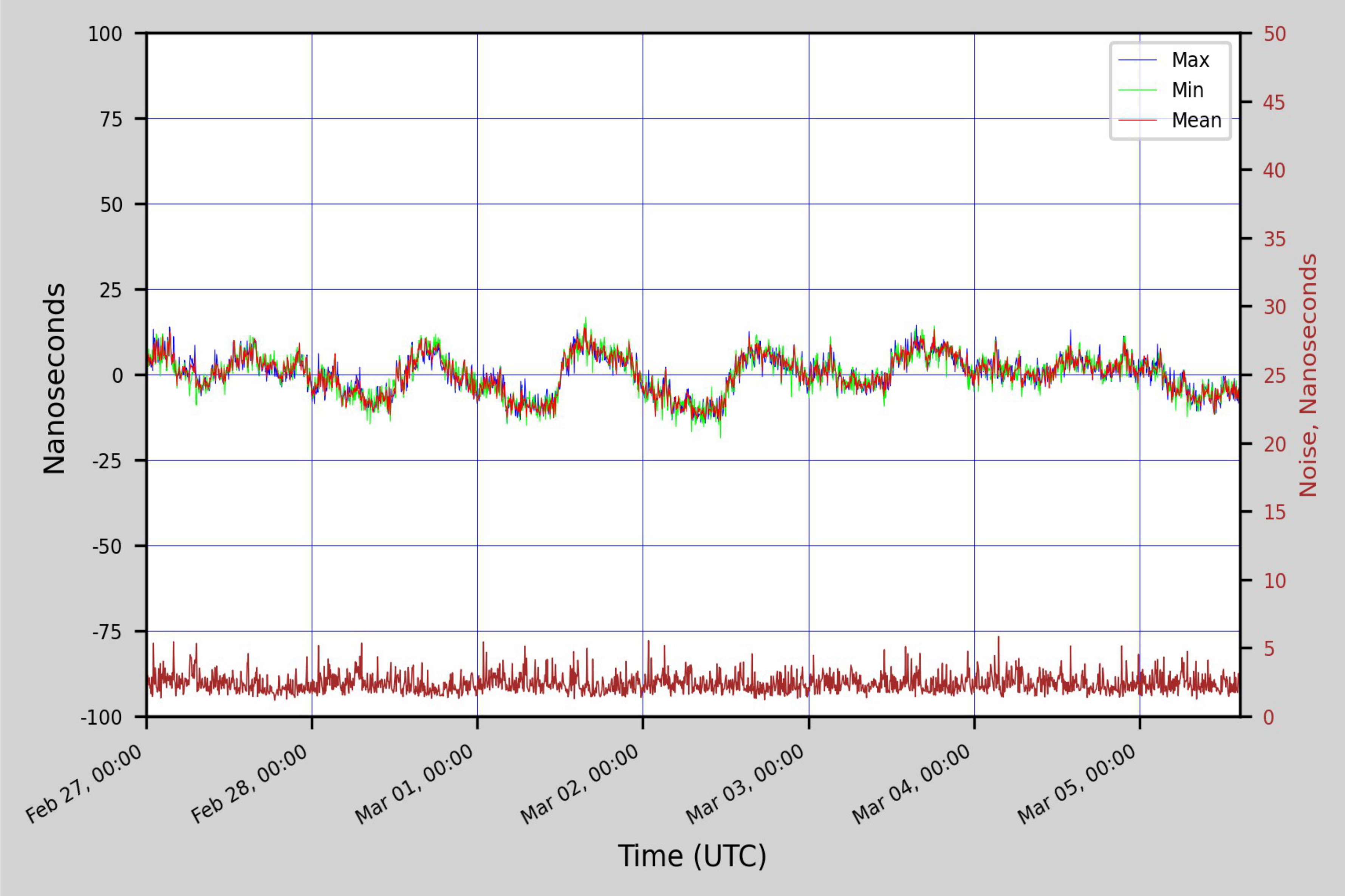
CNS Clock 404447 (SSR-M8F+ X) vs. NR4 Maser at Westford Average Data Chart

Data logged by Tac32Plus. Analyzed by Python + Pandas on 05-Mar-2025, © 2025 CNS Systems, Inc.
Averaging period is 300 seconds, Osc drift removed, Hardware corrected PPS with 8 nsec RxDelay



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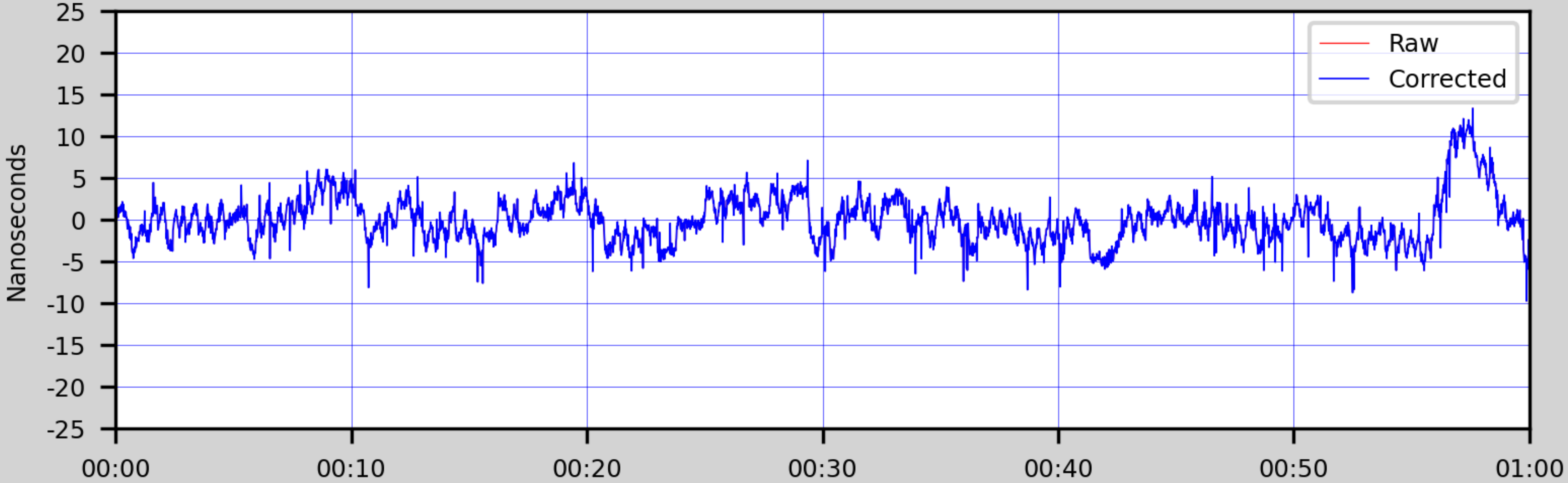
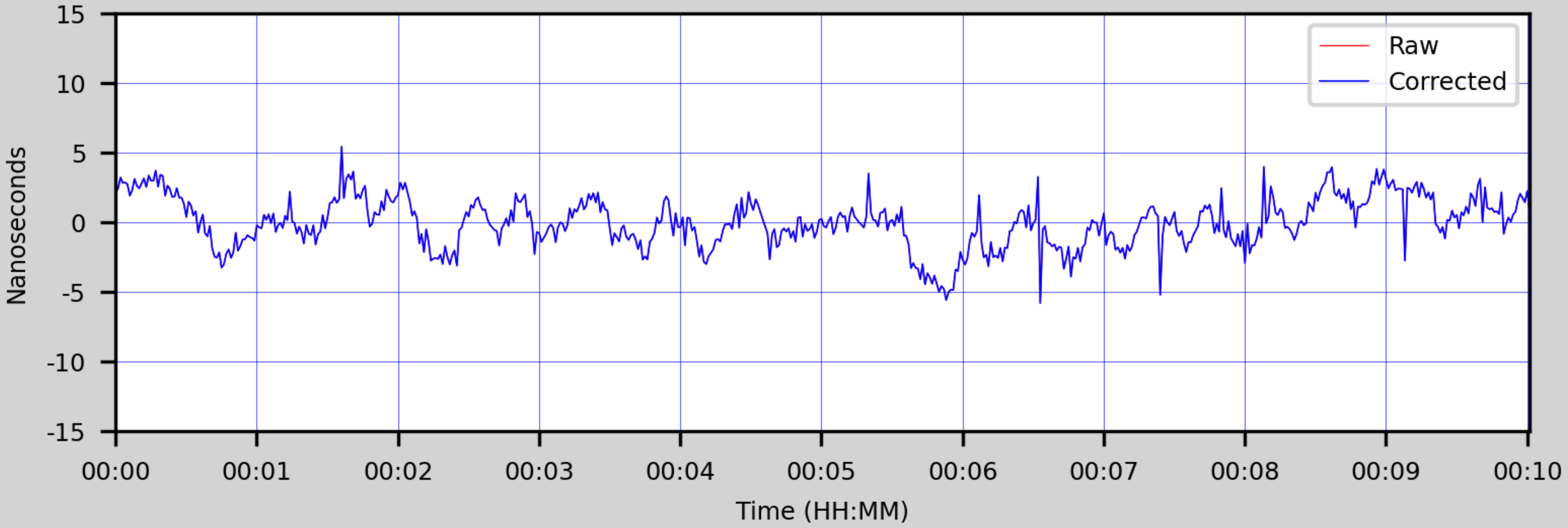
CNS Clock 404447 (SSR-M8F+ X) vs. NR4 Maser at Westford Noise Chart

Data logged by Tac32Plus. Analyzed by Python + Pandas on 05-Mar-2025, © 2025 CNS Systems, Inc.
Hardware corrected PPS with 8 nsec RxDelay





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Westford Time or Frequency Problem?

Now let us look at the Westford Data from February 2023

GNSS Test Bed Analysis

User Input

Data Directory containing the Tac32Plus or GPSTime data files

C:/Users/rick/Documents/CNS Systems Inc/Testbed_Reports/Westford Data/04WFFeb2023 [Browse]

Output Directory for the report file

C:/Users/rick/Documents/CNS Systems Inc/Testbed_Reports/Westford Data [Browse]

Enter the start time for the Average Data charts

2/1/2023 00:00:00

Enter the duration (days) for the Average Data charts.

28

Enter the Average Data sample size

300

<- This is needed to validate each data line

Enter the Time (noise) data start time.

2/21/2023 00:00:00

<- Note that the one hour block of data must be in a single data file

Enter the Magnetic Field Setting (optional).

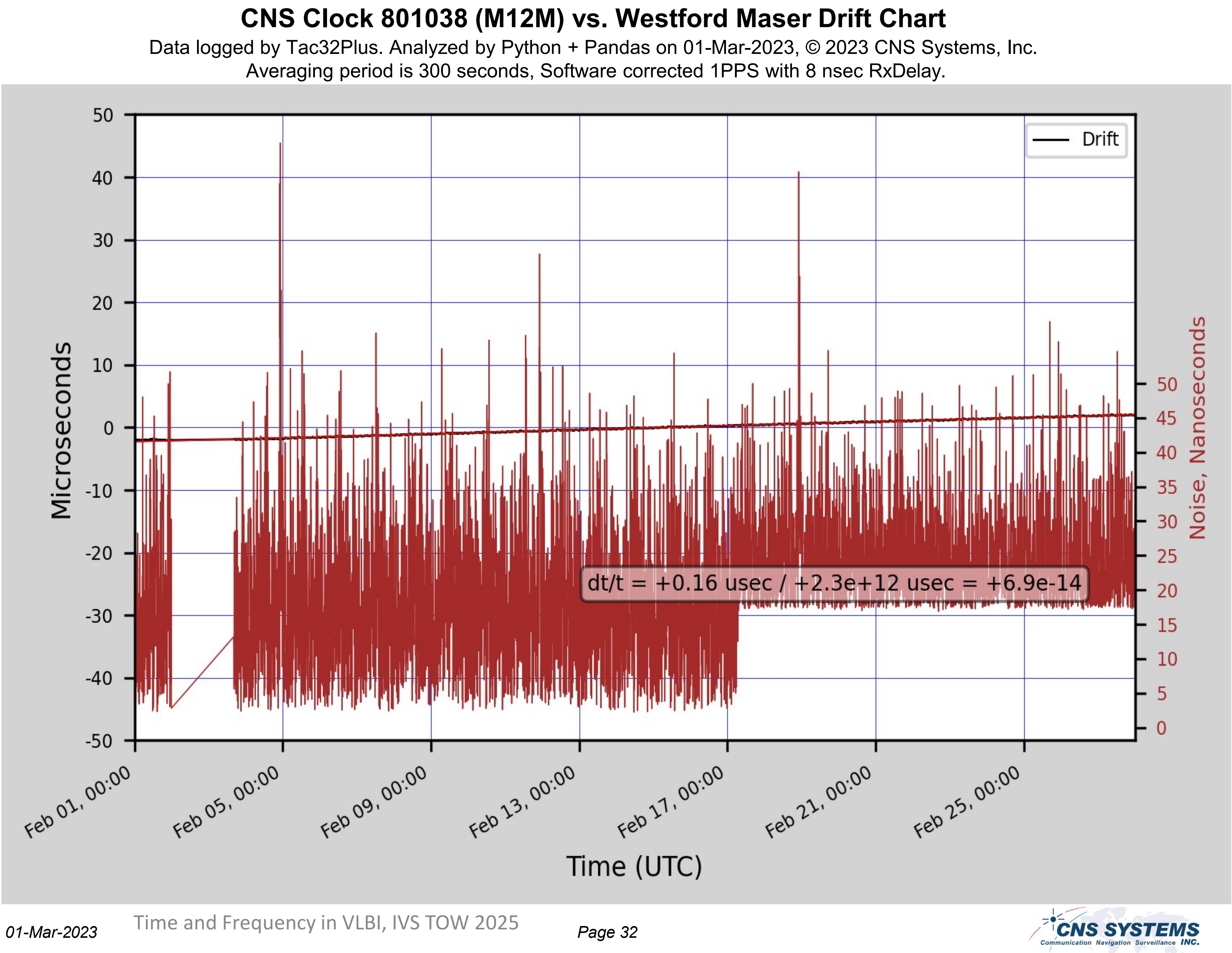
0

<- This is for an HP5064A Rubidium Standard. If not needed, set blank or zero.

Data sets to include in the report

	Enter the Prefix for the data file series	Enter the Primary Header	Enter the Secondary Header Extension
✔	04WF	CNS Clock 801038 (M12M) vs. Westford Maser	Software corrected 1PPS with 8 nsec RxDelay.

[OK] [Cancel]


CNS Clock 801038 (M12M) vs. Westford Maser Drift Chart
Data logged by Tac32Plus. Analyzed by Python + Pandas on 01-Mar-2023, © 2023 CNS Systems, Inc.
Averaging period is 300 seconds, Software corrected 1PPS with 8 nsec RxDelay.
Drift
Microseconds
Noise, Nanoseconds
dt/t = +0.16 usec / +2.3e+12 usec = +6.9e-14
Feb 01, 00:00
Feb 05, 00:00
Feb 09, 00:00
Feb 13, 00:00
Feb 17, 00:00
Feb 21, 00:00
Feb 25, 00:00
Time (UTC)
01-Mar-2023
Page 32
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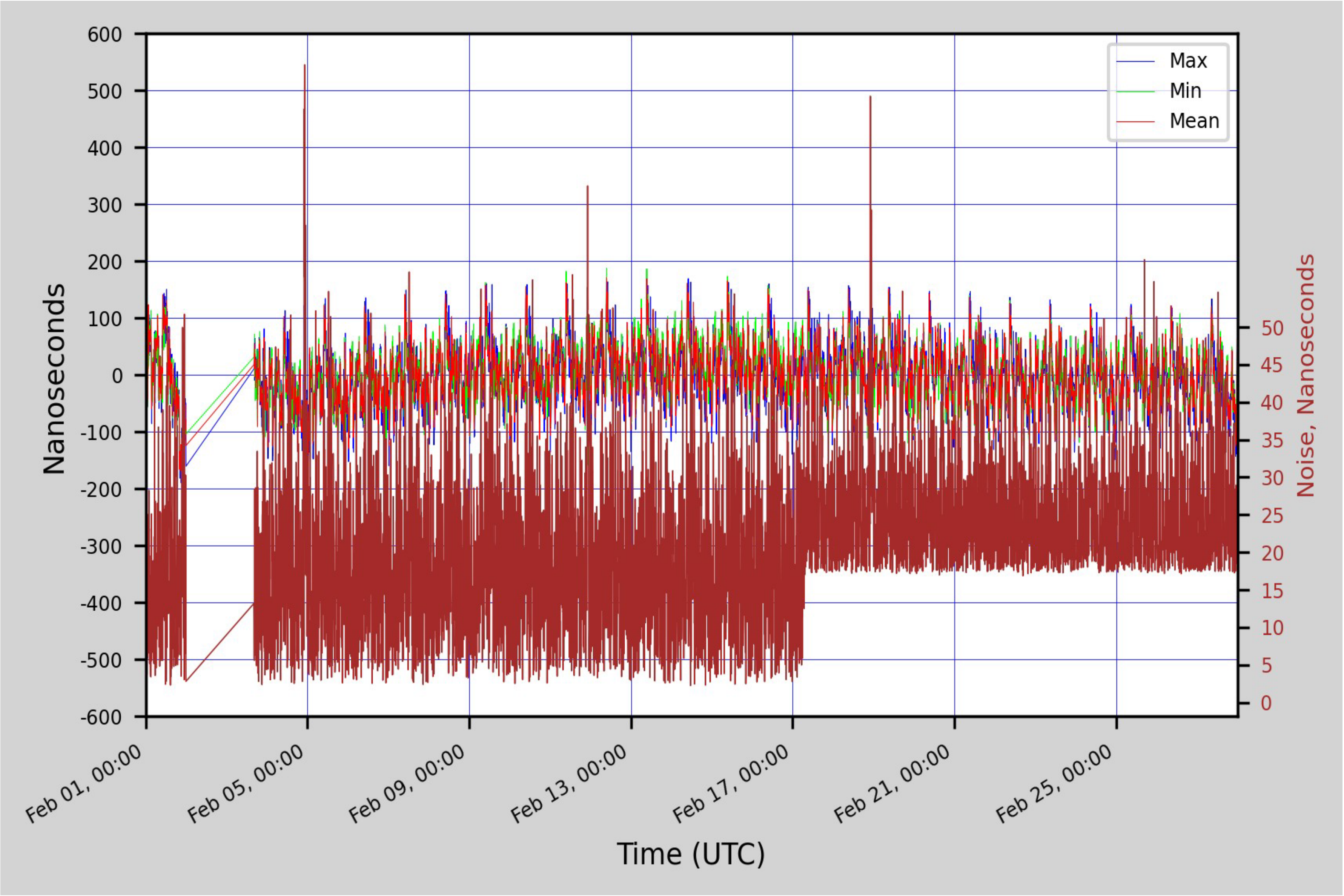
CNS Clock 801038 (M12M) vs. Westford Maser Average Data Chart

Data logged by Tac32Plus. Analyzed by Python + Pandas on 01-Mar-2023, © 2023 CNS Systems, Inc.
Averaging period is 300 seconds, Osc drift removed, Software corrected 1PPS with 8 nsec RxDelay.



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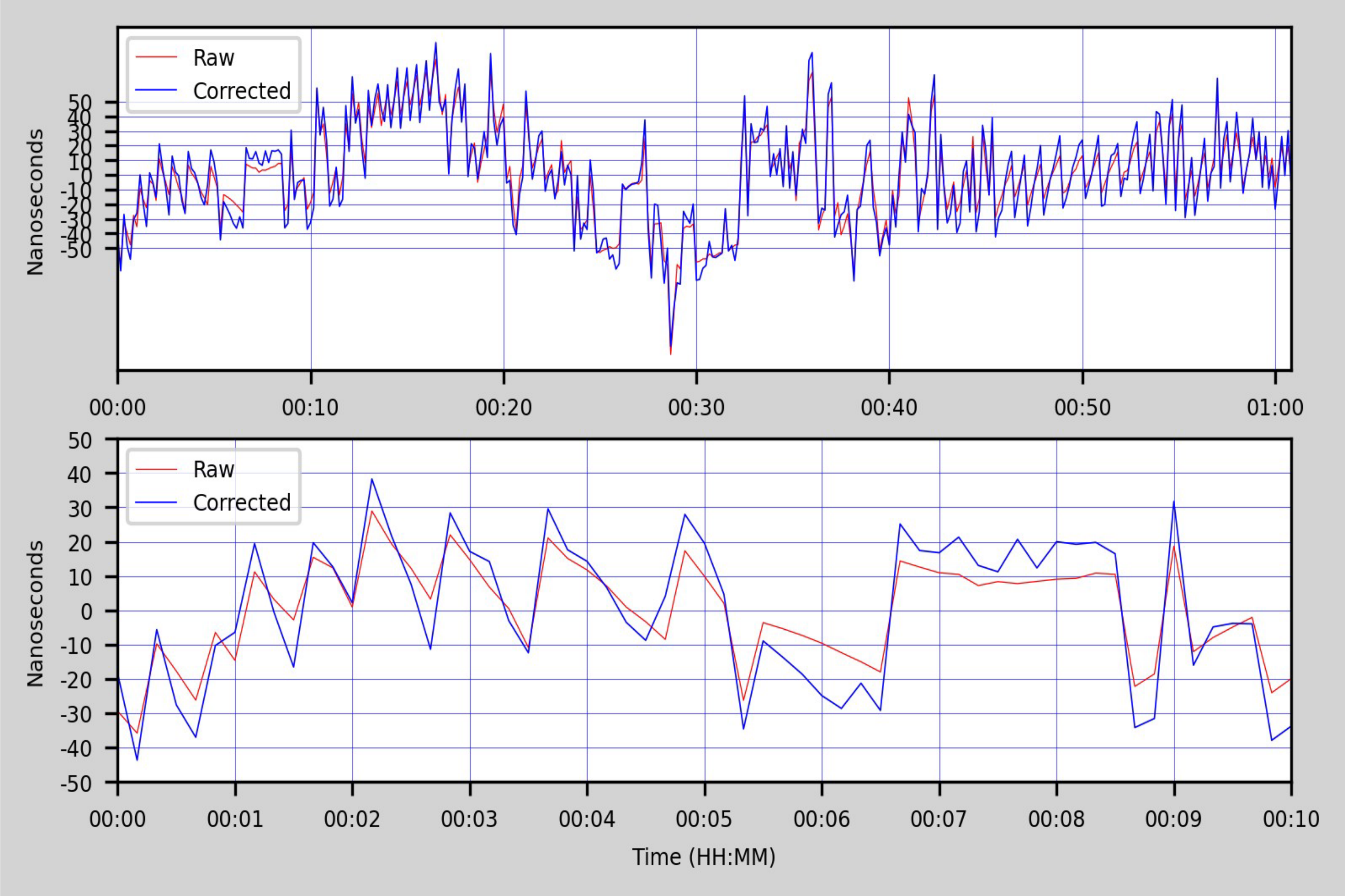
CNS Clock 801038 (M12M) vs. Westford Maser Noise Chart

Data logged by Tac32Plus. Analyzed by Python + Pandas on 01-Mar-2023, © 2023 CNS Systems, Inc.
Software corrected 1PPS with 8 nsec RxDelay.



CNS SYSTEMS INC. Communication Navigation Surveillance

Westford's old CNS Clock 801038 (M12M)

- The CNS Clock at Westford is part of a closed loop system designed to detect failures of the H-maser
- The CNS Clock at Westford is an original "TAC" design and has no internal PPS quantization correction or other features.
  - It was purchased in Feb-1999. It originally had a Motorola VP 8-channel GPS receiver.
  - It was upgraded in Aug-2017 with new front and rear panels and an M12M 12-channel GPS receiver module.
- To evaluate the Westford data, we need to understand the data produced by this old receiver.
- With the following understanding, it is likely that the GPS module in this CNS Clock is not working correctly. However, it also could be a problem with the Time Interval Counter.

GGAO has a Similar Problem

Let’s look at GGAO Data from March 2023

GNSS Test Bed Analysis

Data Directory containing the Tac32Plus or GPSTime data files

C:\Users\rick\Documents\CNS Systems Inc\Organizations\NASA\NASA TOW\2023\GGAO Data [Browse]

Output Directory for the report file

C:\Users\rick\Documents\CNS Systems Inc\Organizations\NASA\NASA TOW\2023\GGAO Data [Browse]

Enter the start time for the Average Data charts

03/21/2023 00:00:00

Enter the duration (days) for the Average Data charts.

7

Enter the Average Data sample size

300

<- This is needed to validate each data line

Enter the Time (noise) data start time.

03/28/2023 00:00:00

<- Note that the one hour block of data must be in a single data file

Enter the Magnetic Field Setting (optional).

0

<- This is for an HP5064A Rubidium Standard. If not needed, set blank or zero.

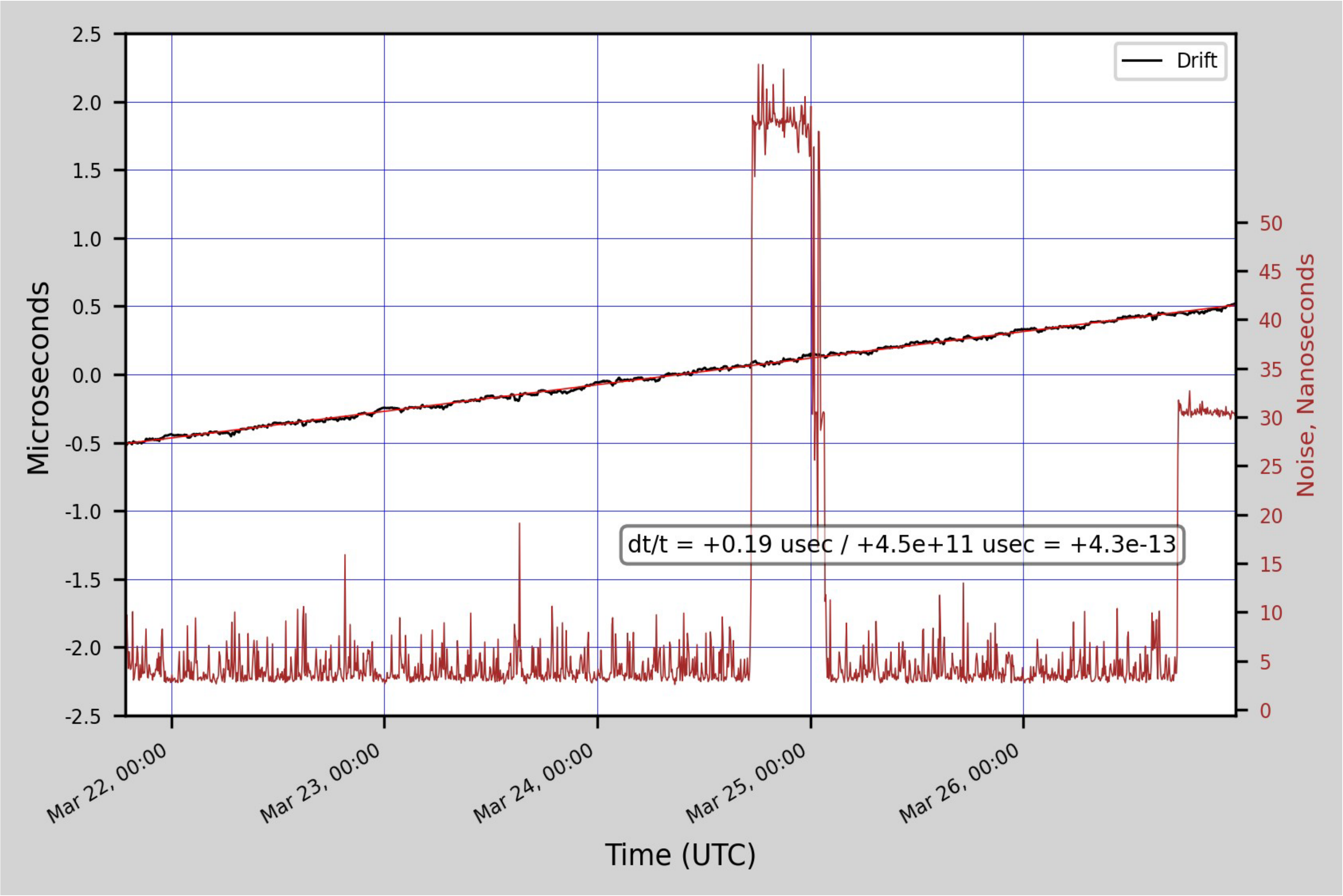
Data sets to include in the report

	Enter the Prefix for the data file series	Enter the Primary Header	Enter the Secondary Header Extension
✔	GS00	CNS Clock 801041 vs. Maser at GGAO,	Software corrected 1PPS with 8 nsec RxDelay.
☐			
☐			
☐			

[OK] [Cancel]

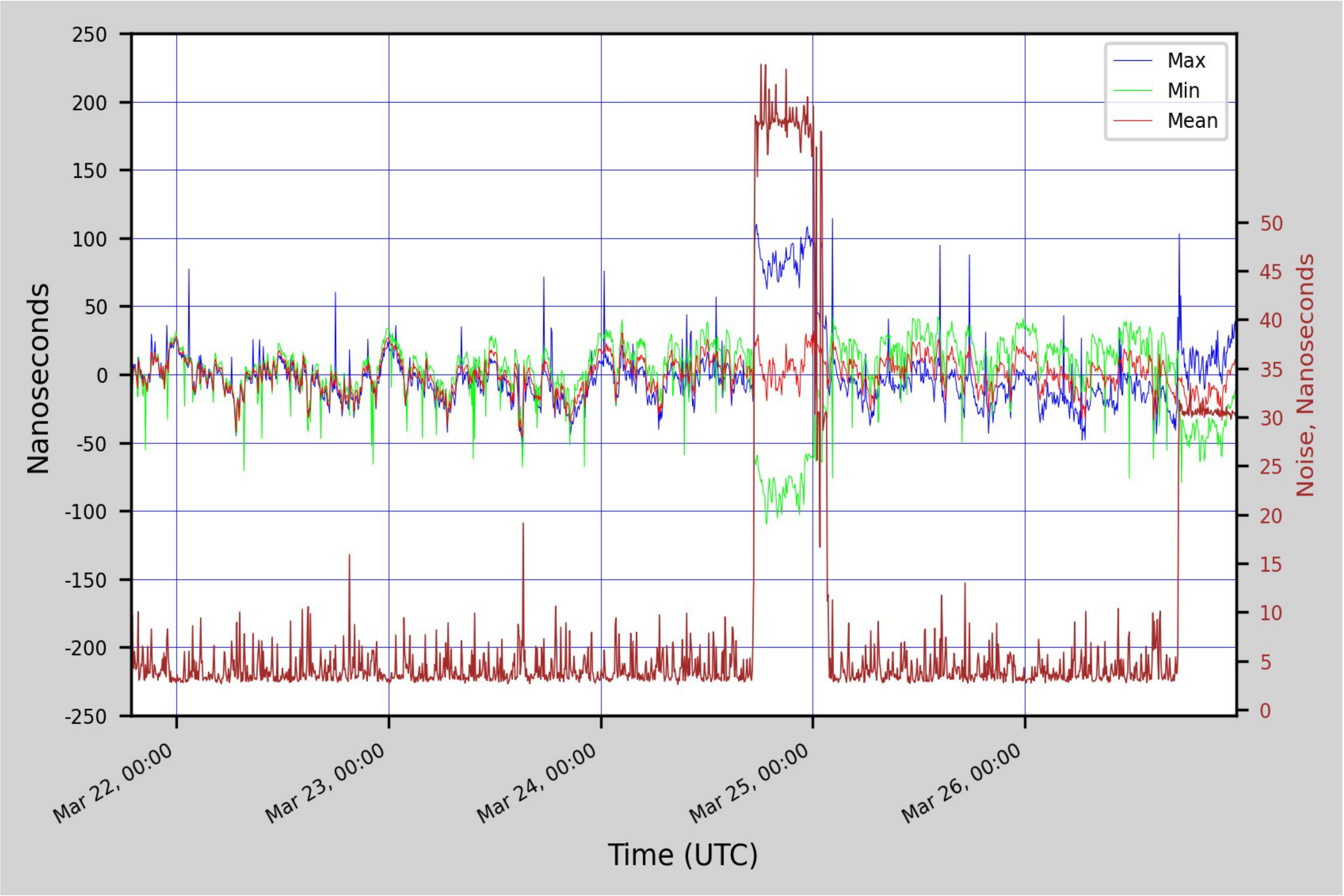
CNS Clock 801041 vs. Maser at GGAO, Drift Chart

Data logged by Tac32Plus. Analyzed by Python + Pandas on 05-Apr-2023, © 2023 CNS Systems, Inc.
Averaging period is 300 seconds, Software corrected 1PPS with 8 nsec RxDelay.



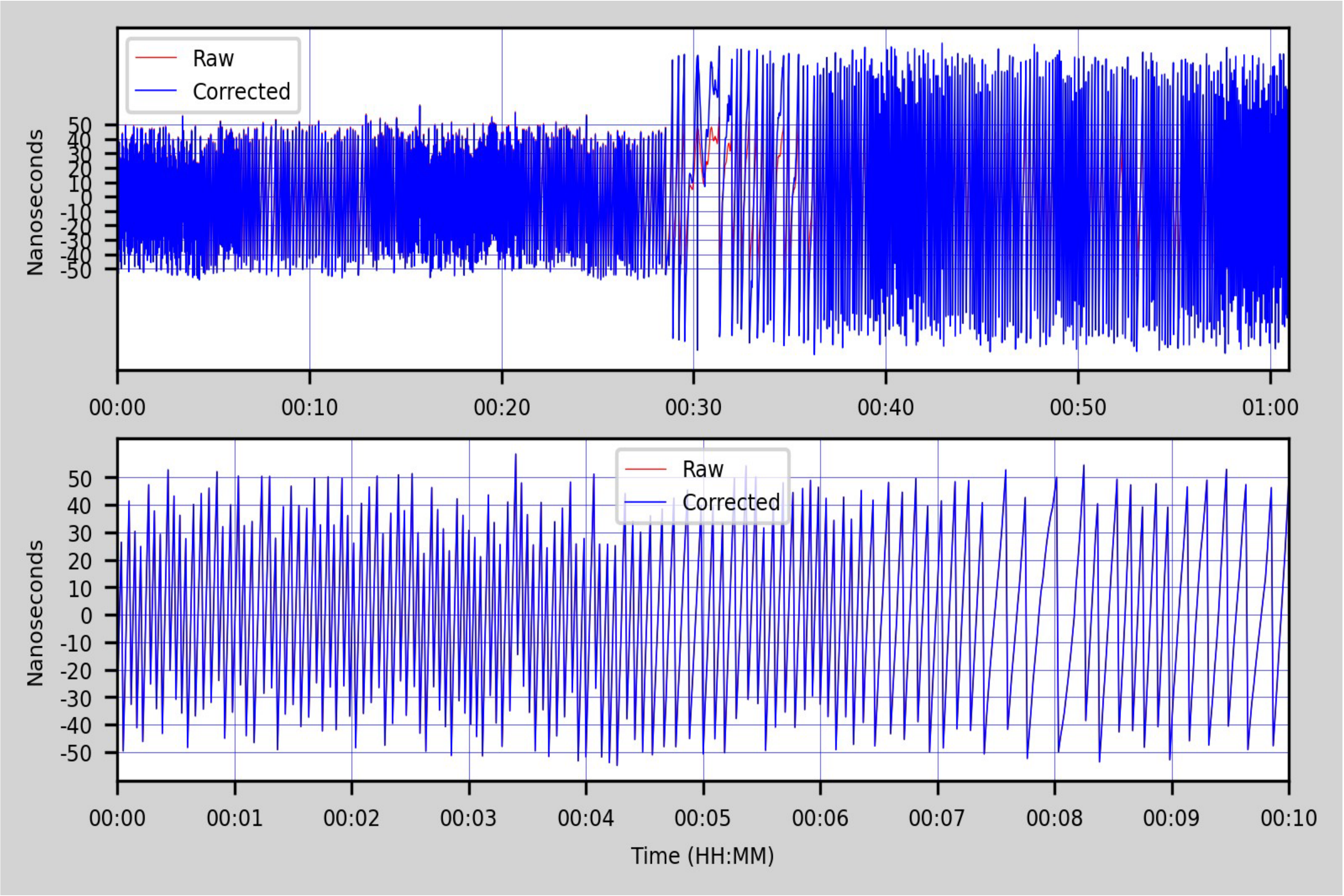
CNS Clock 801041 vs. Maser at GGAO, Average Data Chart

Data logged by Tac32Plus. Analyzed by Python + Pandas on 05-Apr-2023, © 2023 CNS Systems, Inc.
Averaging period is 300 seconds, Osc drift removed, Software corrected 1PPS with 8 nsec RxDelay.

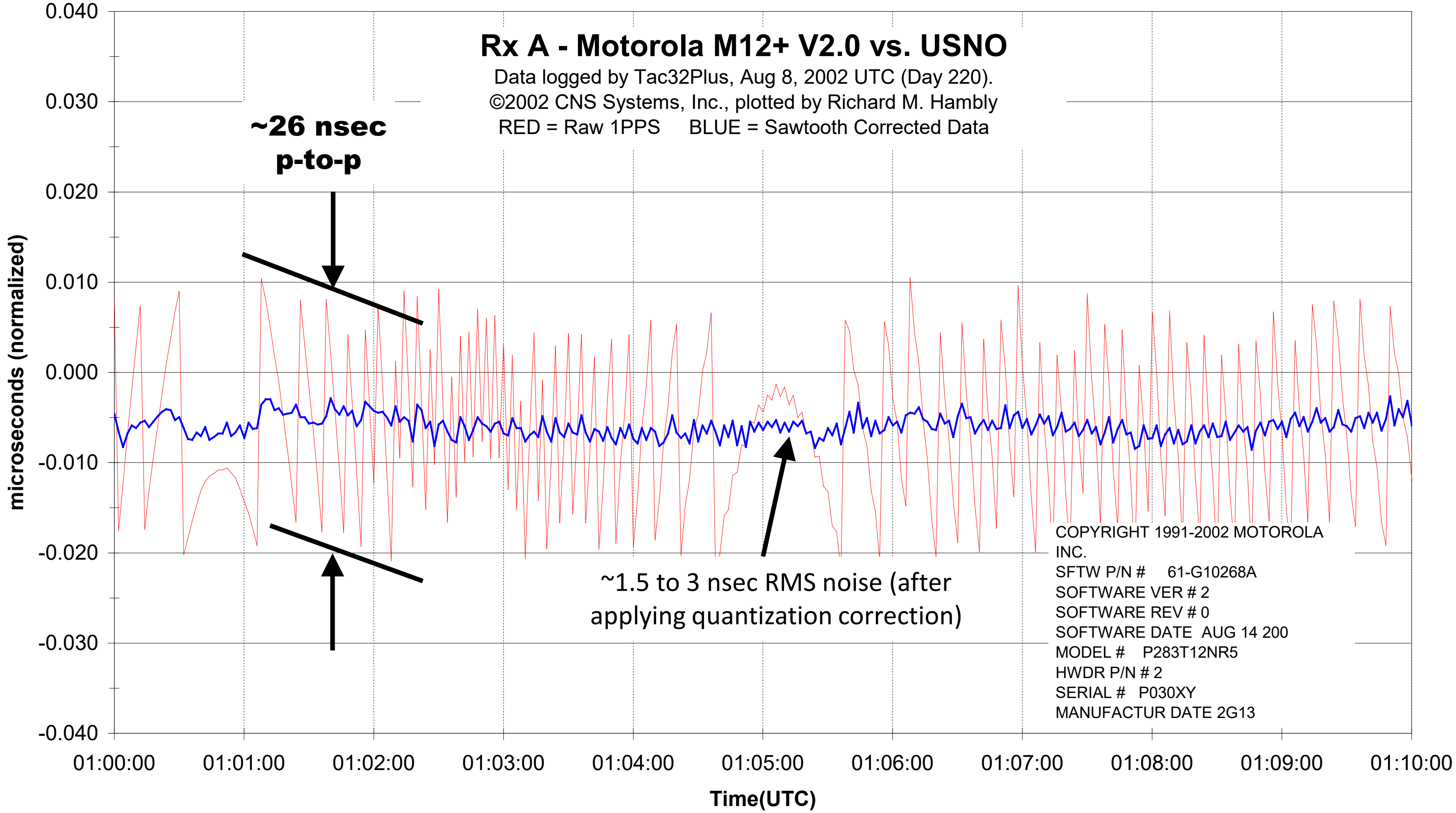


CNS Clock 801041 vs. Maser at GGAO, Noise Chart

Data logged by Tac32Plus. Analyzed by Python + Pandas on 05-Apr-2023, © 2023 CNS Systems, Inc.
Software corrected 1PPS with 8 nsec RxDelay.



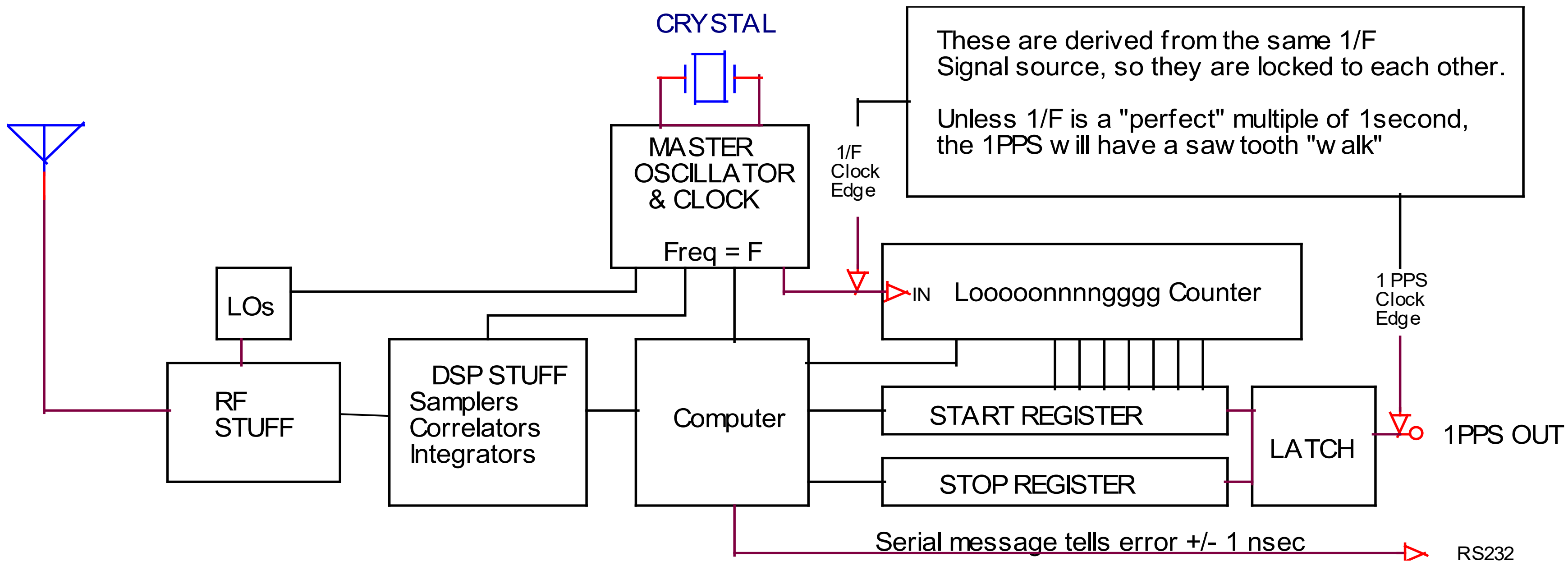
An Example of 1PPS Quantization Error Correction



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 quantization error ("sawtooth").
- "Absolute" Receiver Calibration
- New developments
  - The SSR-M8T GNSS receiver
  - Tac32Plus updates
  - CNS Clock II improvements (NTP, Oscillator, PPS)

What Causes the Quantization Error ?

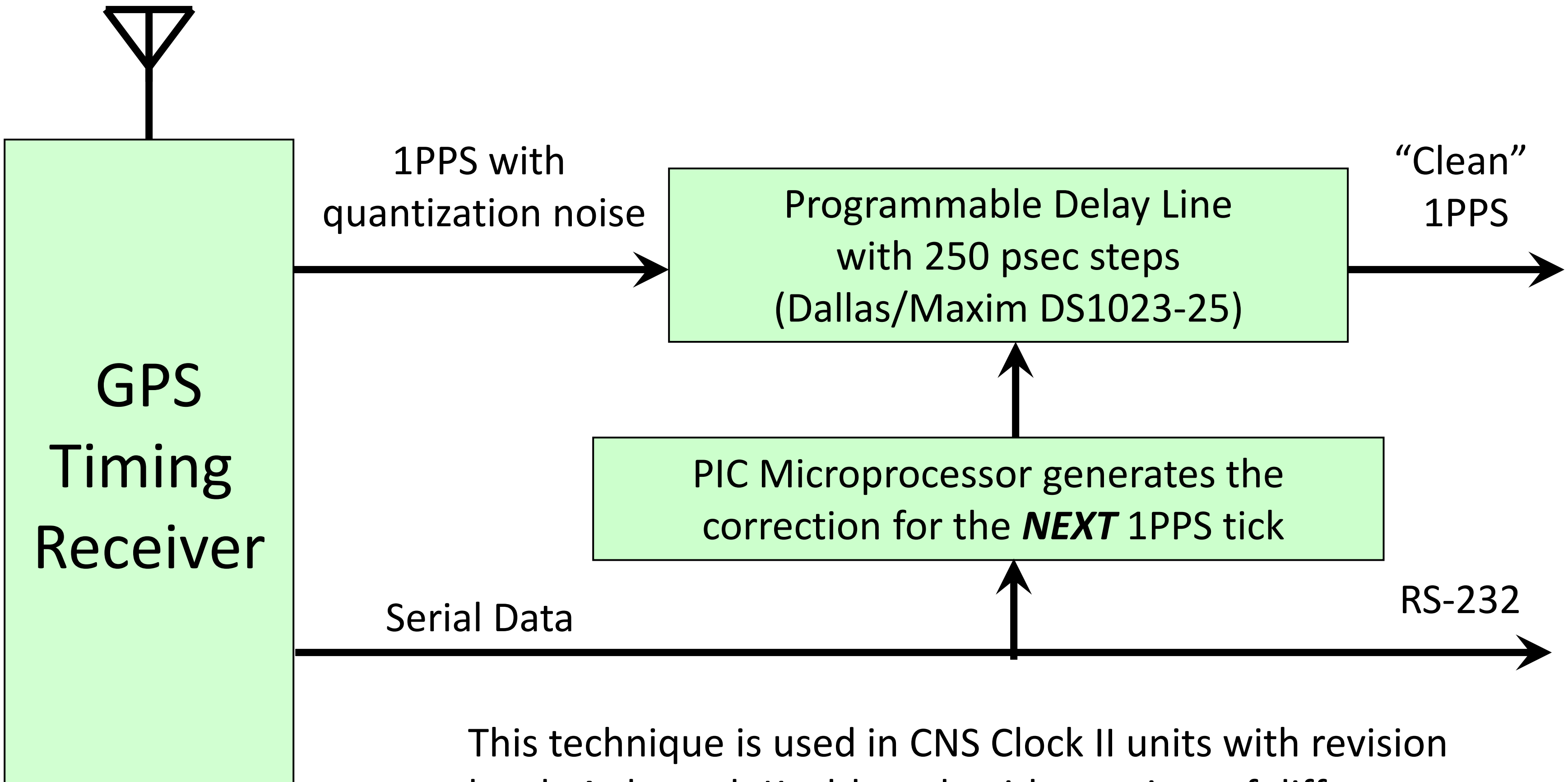


- For the older VP, UT+ Oncore, F=9.54 MHz, so the 1/F quantization error has a range of +/- 52 nsec (104 nsec peak-to-peak).
- The M12+ & M12M have F ≈ 40 MHz, so the quantization error has been reduced to +/- 12.5 nsec (25 nsec).
- SSR-M8T has F ≈ 30.72 * 2 = 61.44 MHz, so the quantization error has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

VLBI's Annoying Problem Caused by the Quantization Timing Error

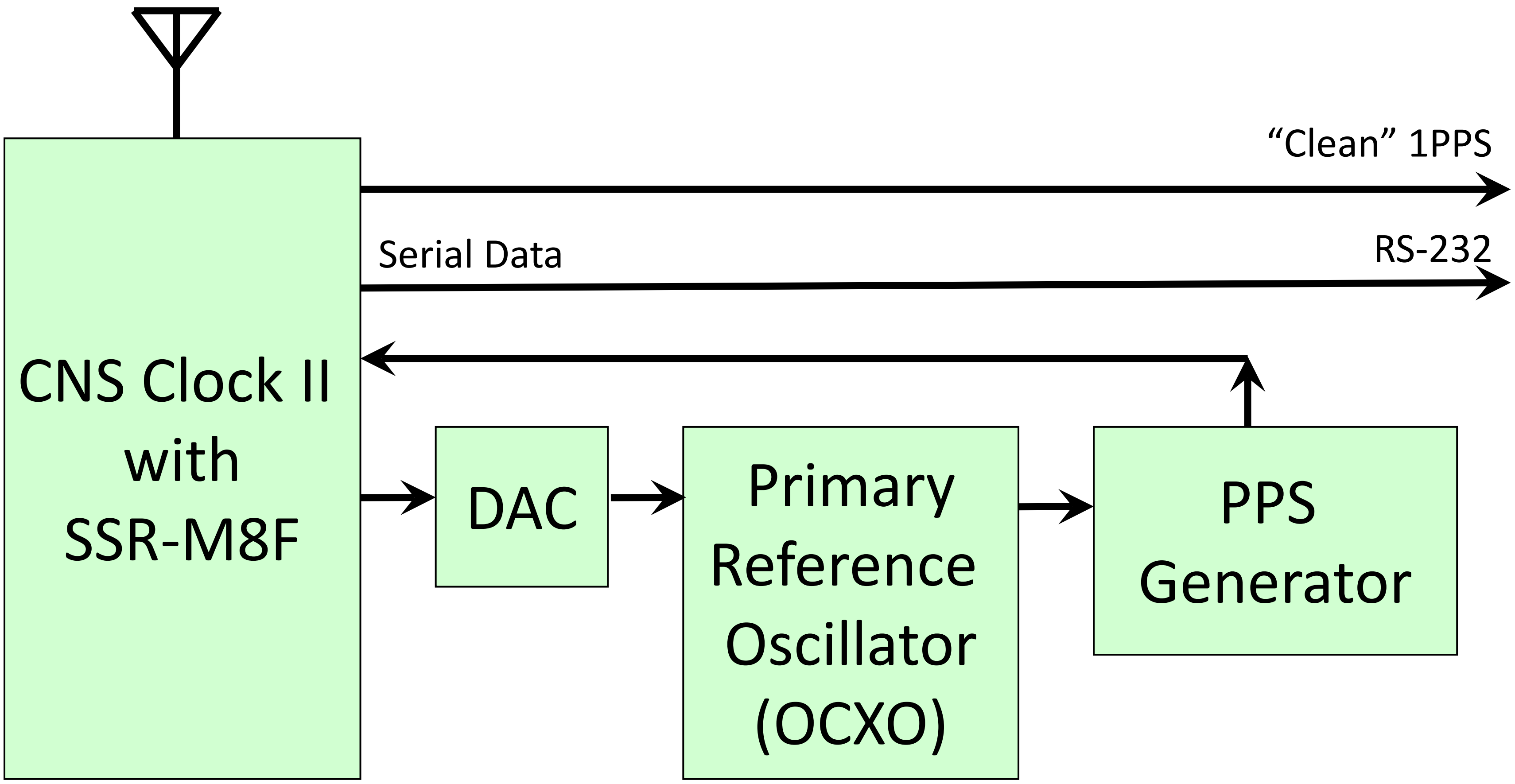
- When the formatter (Mark 5/6 sampler) needs to be reset, you have to feed it a 1PPS timing pulse to restart the internal VLBI clock. After it is started, it runs smoothly at a rate defined by the Maser's 5/10 MHz.
- The **AVERAGE** of the 1PPS pulses from the GPS receiver is "correct", but any single 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 achieved.
- Or you can use the 1PPS from a CNS Clock II which has the quantization error removed.

How can quantization noise be eliminated ?



This technique is used in CNS Clock II units with revision levels A through K, although with a variety of different delay line types and step values.

How else can quantization noise be eliminated ?



This technique is used in CNS Clock II units, beginning with revision L. Among other benefits, this provides holdover with synchronized date and time for better NTP and IRIG-B performance. The PPS stability is better than the delay line version.

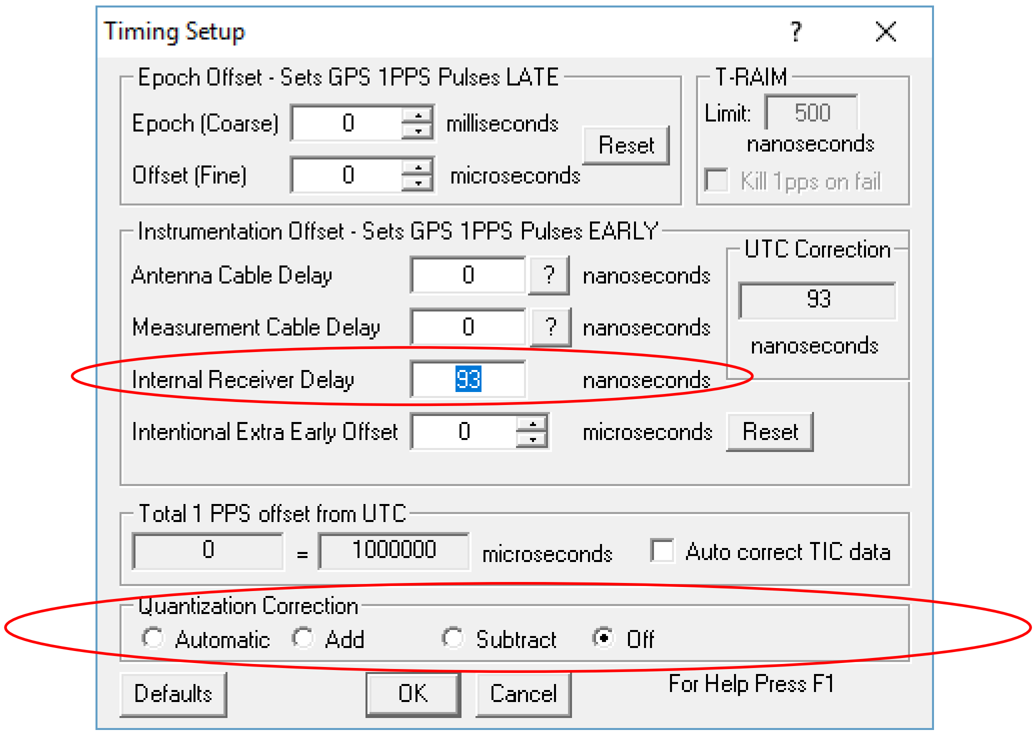
The CNS Clock continues to Evolve

1994 – 2004: the TAC

Available Since January 2005, now at Revision M

- Data available on RS-232, USB, Ethernet, RS-485 and solid-state relay ports.
- Ethernet NTP Server.
- TNC GPS Antenna Connector.
- Buffered 1 PPS outputs.
- GPS Steered OCXO
  10 (or 5) MHz output.
- High Performance PPS.
- IRIG-B
- Good holdover performance

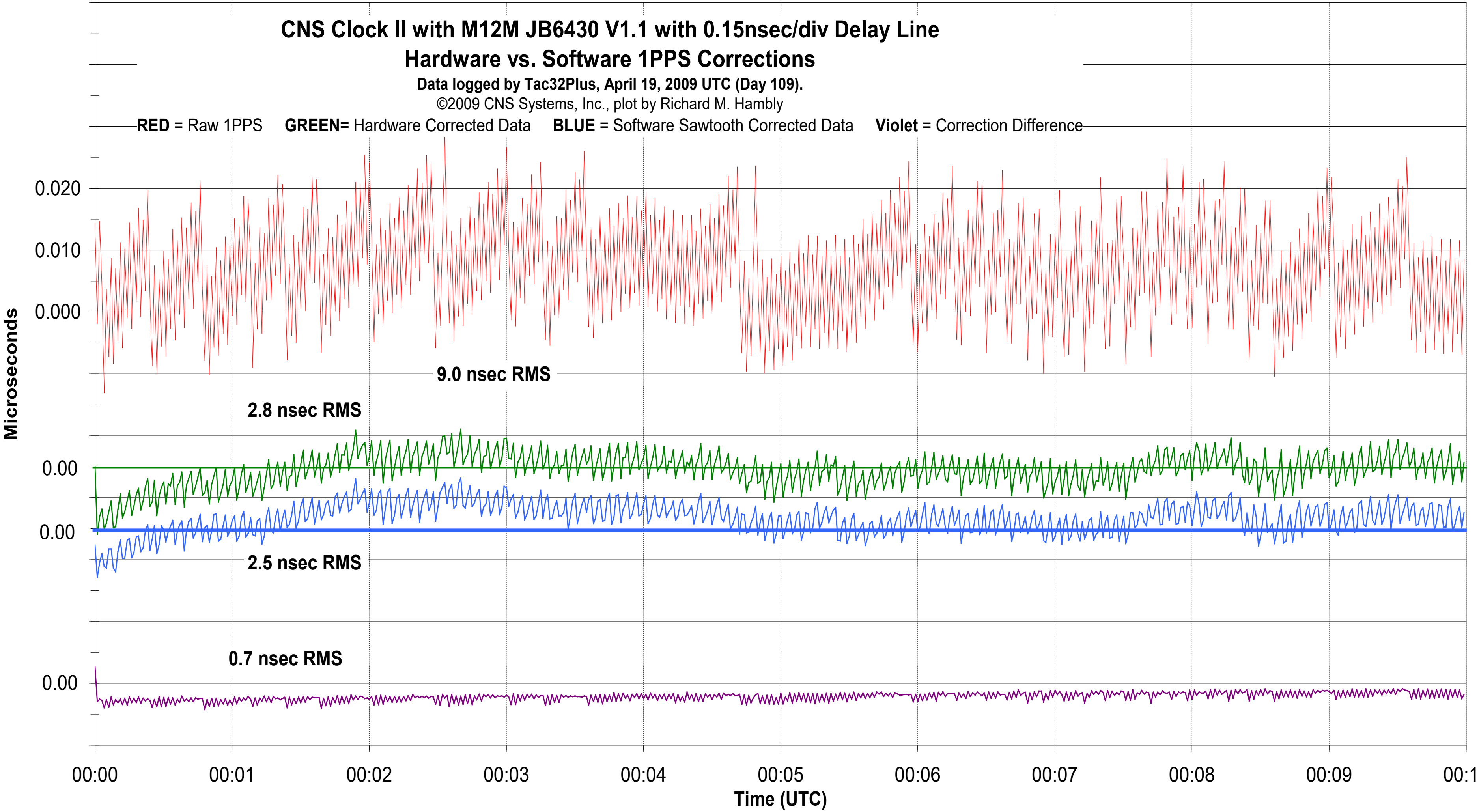
CNS Clock and CNS Clock II Setup Note



Revision	Serial Number Range		Internal Receiver Delay (nanoseconds)
CNS Clock (original)	801001	801455	8
CNS Clock II Rev A	n/a	n/a	
Rev B	404001	404028	53 (estimated)
Rev C	n/a	n/a	53 (estimated)
Rev D	404029	404055	53 (estimated)
Rev E	404056	404108	53 (estimated)
Rev F	404109	404159	53 (estimated)
Rev G	404160	404265	53 (estimated)
Rev H	404266	404138	53 (estimated)
Rev I	404319	404344	97 (estimated)
Rev J	404345	404371	97
Rev K	404372	404398	97
Rev L	404399	404425	48
Rev M	404426		48

- The current CNS Clock internal delay is set using the table in the latest instruction manual, available online. This offset is removed by setting the parameter in Tac32Plus or GPSTime.
- CNS Clock II units perform quantization correction in hardware so the software correction should be set to “Off”.

Does the hardware 1PPS correction work?

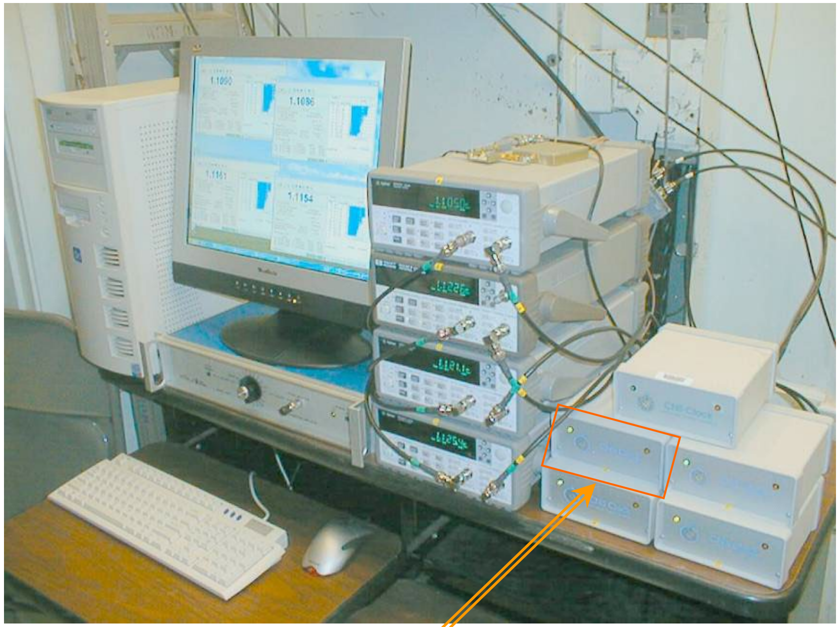


CNS Systems' Test Bed at USNO

Calibrating the UTC Offset (ACCURACY) of M12+ receivers with 2.0 Firmware.

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 in 2002.

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.

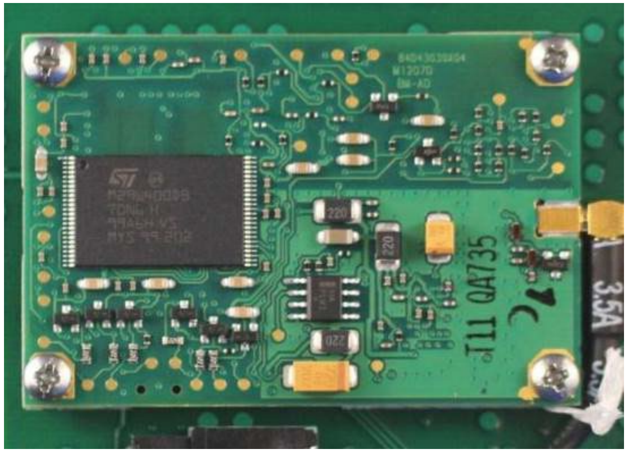
This is the "Gold Standard" "A" receiver that we used for subsequent calibrations.

Trying to keep up with New Technology!

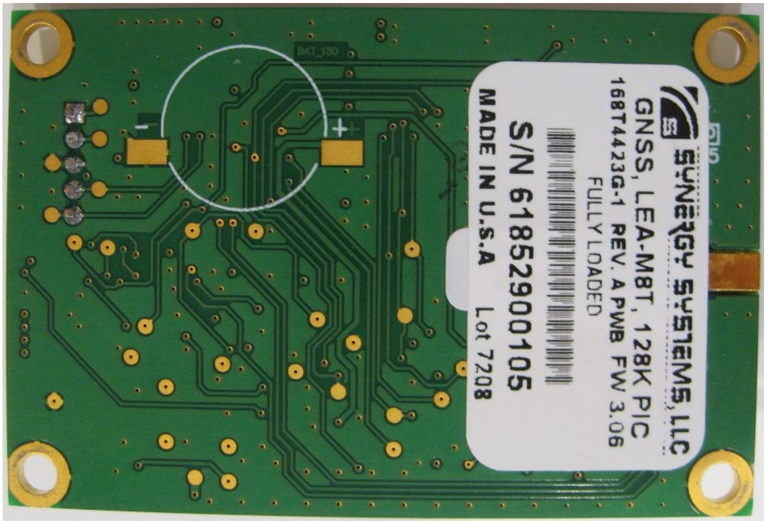
- Motorola quit the GPS business in 2005. The M12 design was licensed to iLotus in Singapore. The current variant is the M12M.
- Anticipating the need for an M12 replacement, Synergy Systems LLC and CNS Systems, Inc. developed the SSR series of receivers. These are form, fit, and function replacements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

Comparing an M12+, M-12M & SSR GPS Receiver

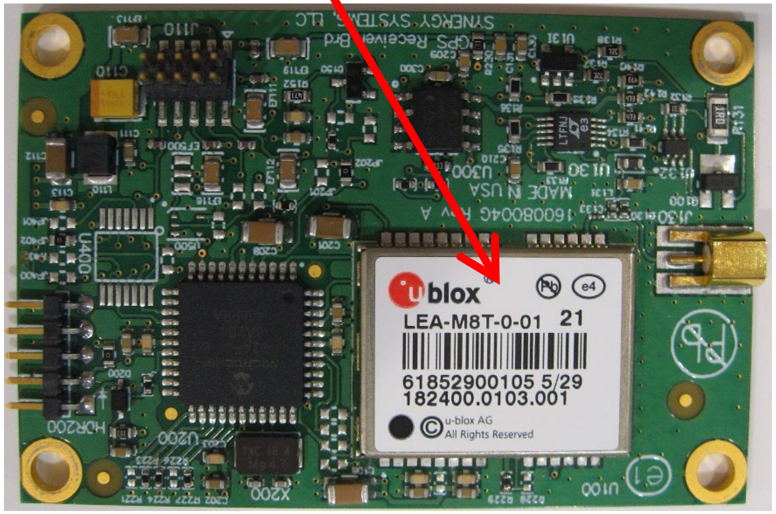
An iLotus M-12M receiver.
The M12+ looks the same



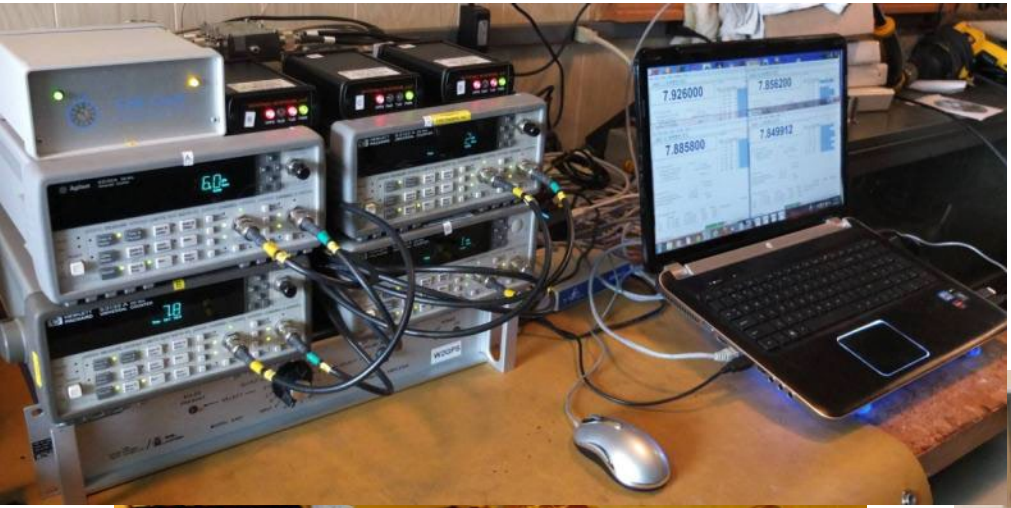
The Synergy SSR-M8T Receiver



The u-blox LEA-M8T module



A Four Receiver Test @ GGAO

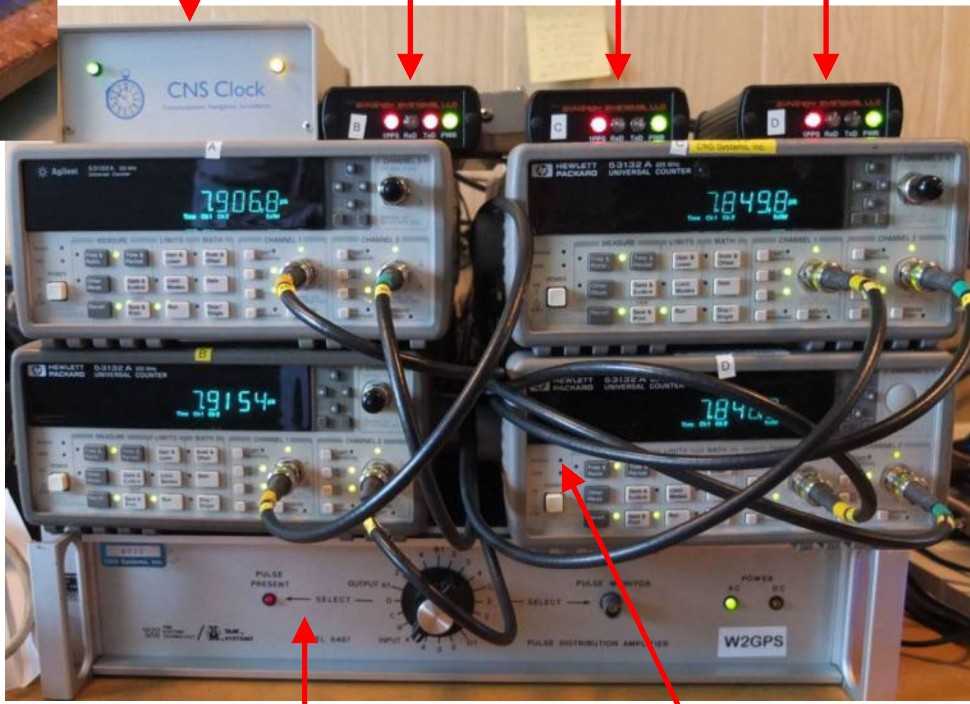


"Gold" Motorola M12+

iLotus M12-M

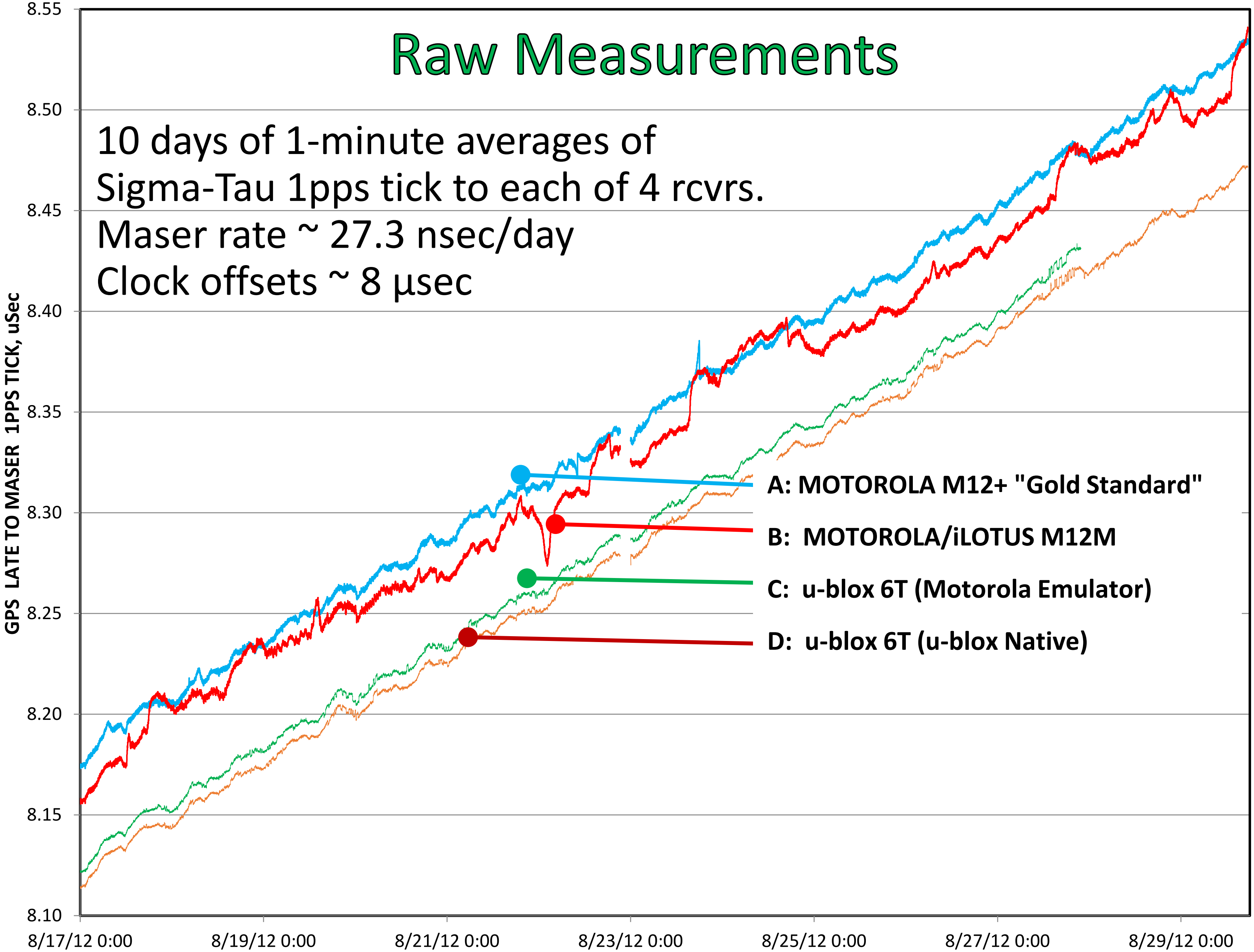
Synergy u-blox Moto Emul .

LEA-6Ts u-blox Native Cmds

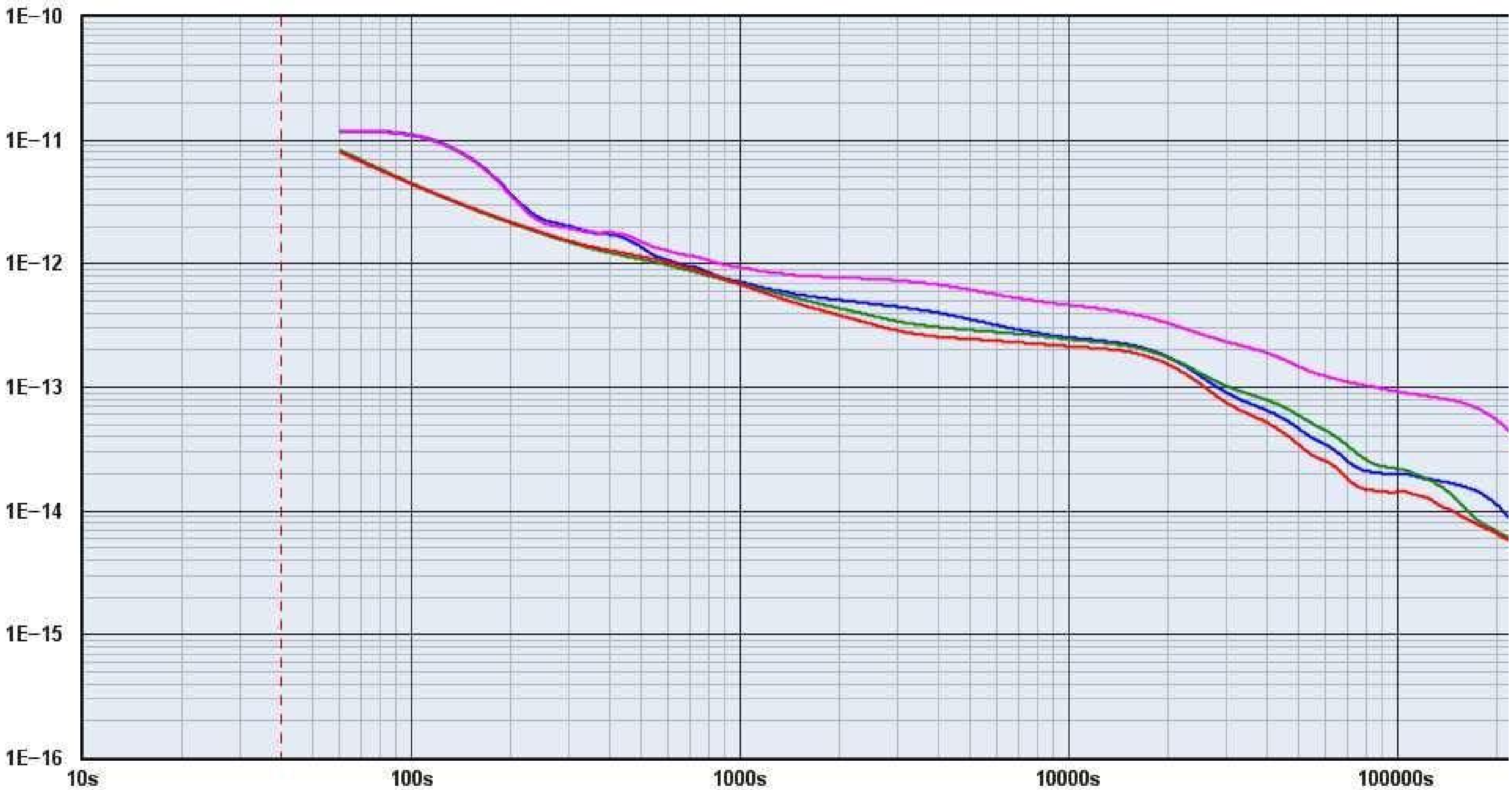


Maser 1PPS Distributor

Four HP53132 Counters

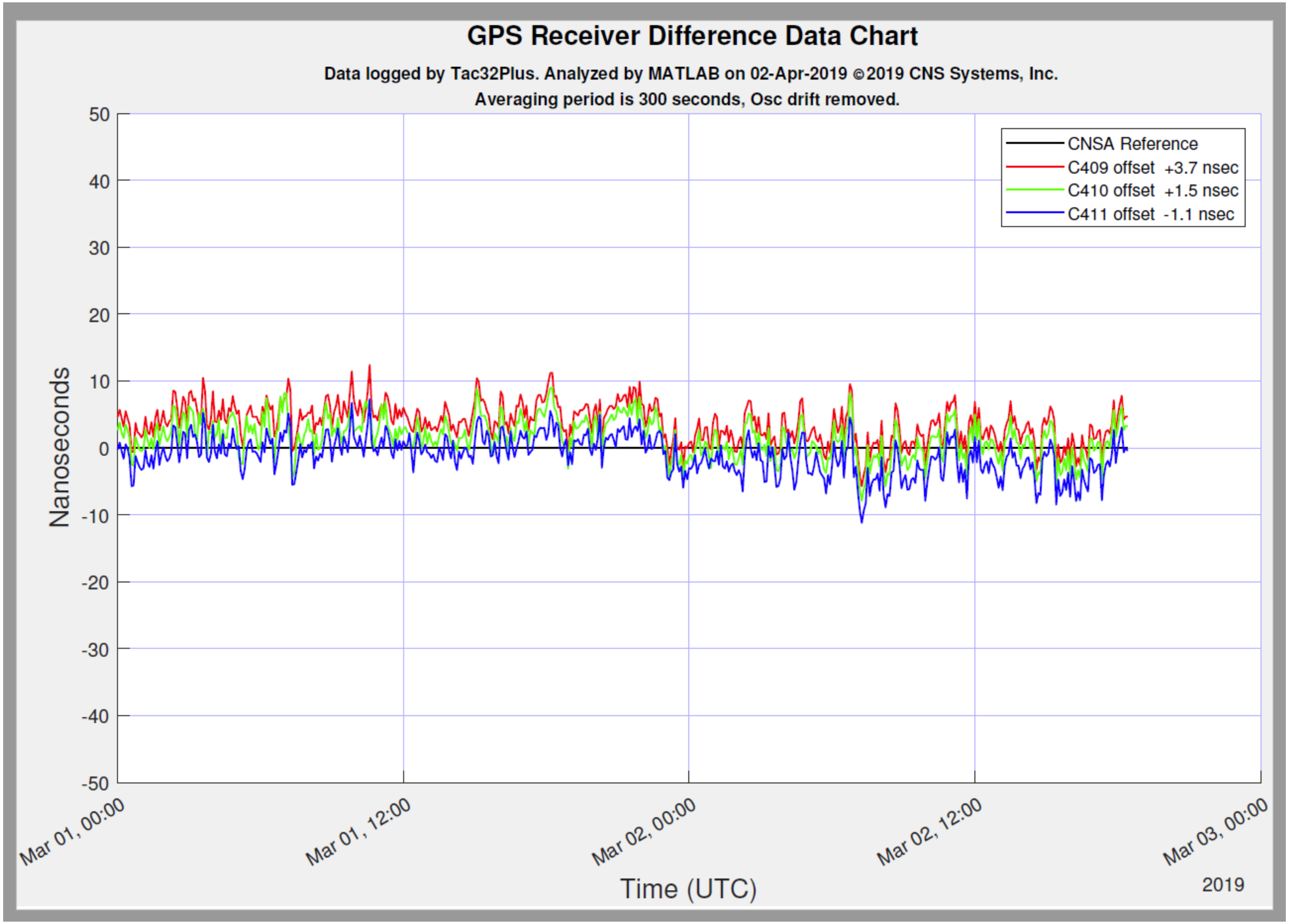

Raw Measurements
10 days of 1-minute averages of
Sigma-Tau 1pps tick to each of 4 rcvrs.
Maser rate ~ 27.3 nsec/day
Clock offsets ~ 8 µsec
A: MOTOROLA M12+ "Gold Standard"
B: MOTOROLA/iLOTUS M12M
C: u-blox 6T (Motorola Emulator)
D: u-blox 6T (u-blox Native)
GPS LATE TO MASER 1PPS TICK, uSec
8.55
8.50
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 Test with CNS Clock II rev L Receivers



Conclusions

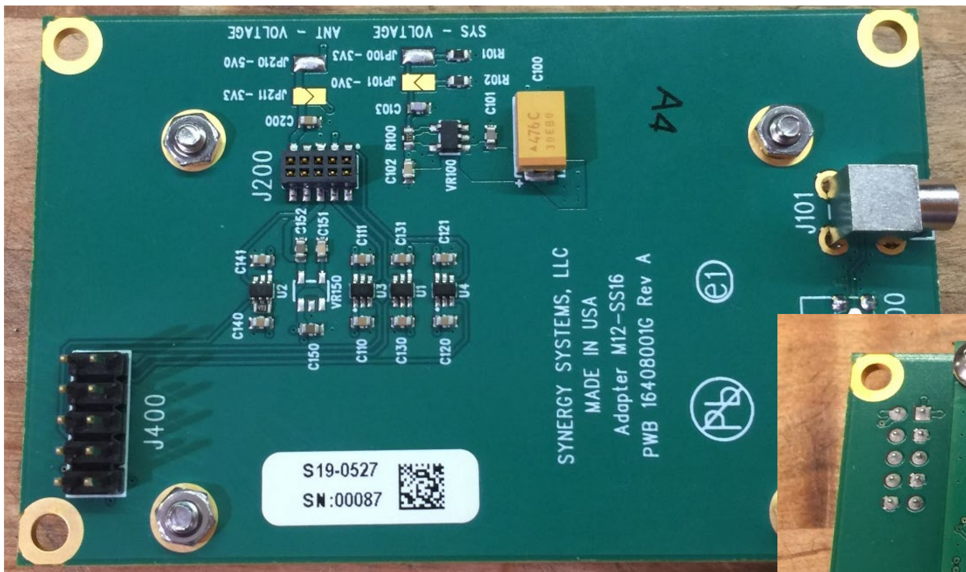
1. Small, low-cost GPS receivers can provide timing needed for VLBI anywhere in the world. This is not a new statement; it's been true since the 1990's! See www.cnssys.com under the "Publications" tab for "Timing for VLBI" notes from the IVS TOWs for more details.

2. Existing designs based on Motorola/iLotus M12s should have no problem in making the change to u-blox by using the Synergy SSR-M8T/M8F receivers.

3. The Synergy SSR receiver with the uBlox LEA-M8T/M8F (GNSS) is a superior product. **In fact, the u-blox we tested were a factor ~5 BETTER than the M12's** in all tests. When used in the CNS Clock II with its quantization correction circuit, the UTC offset is set based on a chart in the latest manual. Just plug that value into Tac32Plus or GPSTime and all is good.

Obsolescence Issues – GPS Receivers

Motorola UT+ receivers, used in some original CNS Clocks have failed due to the week rollover event. These now provide the wrong date and time.



A receiver upgrade kit is available for original TAC and CNS Clock units.

Replaces old Motorola VP and UT+ with new SSR-M8T (u-blox) receivers.

Obsolescence Issues – Time Interval Counters

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 1104 as an alternative.

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

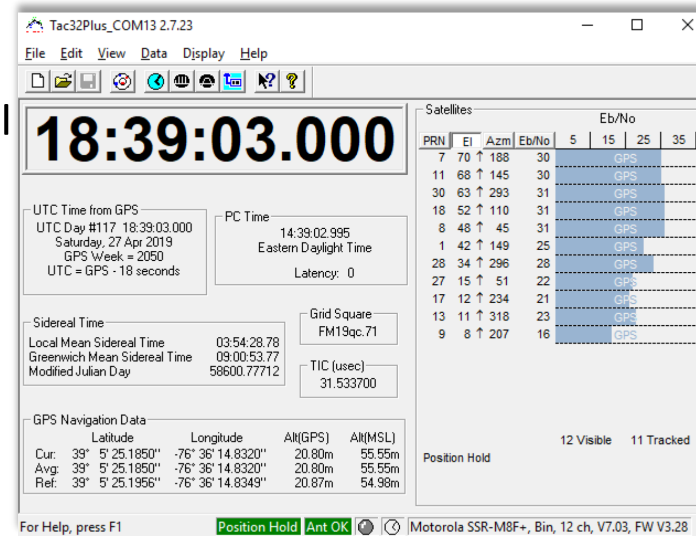
Tac32Plus & GPSTime Support Time Interval Counters via Ethernet.

CNS Clock II

HP/Agilent 53132A Serial Port

Agilent 53230A Ethernet

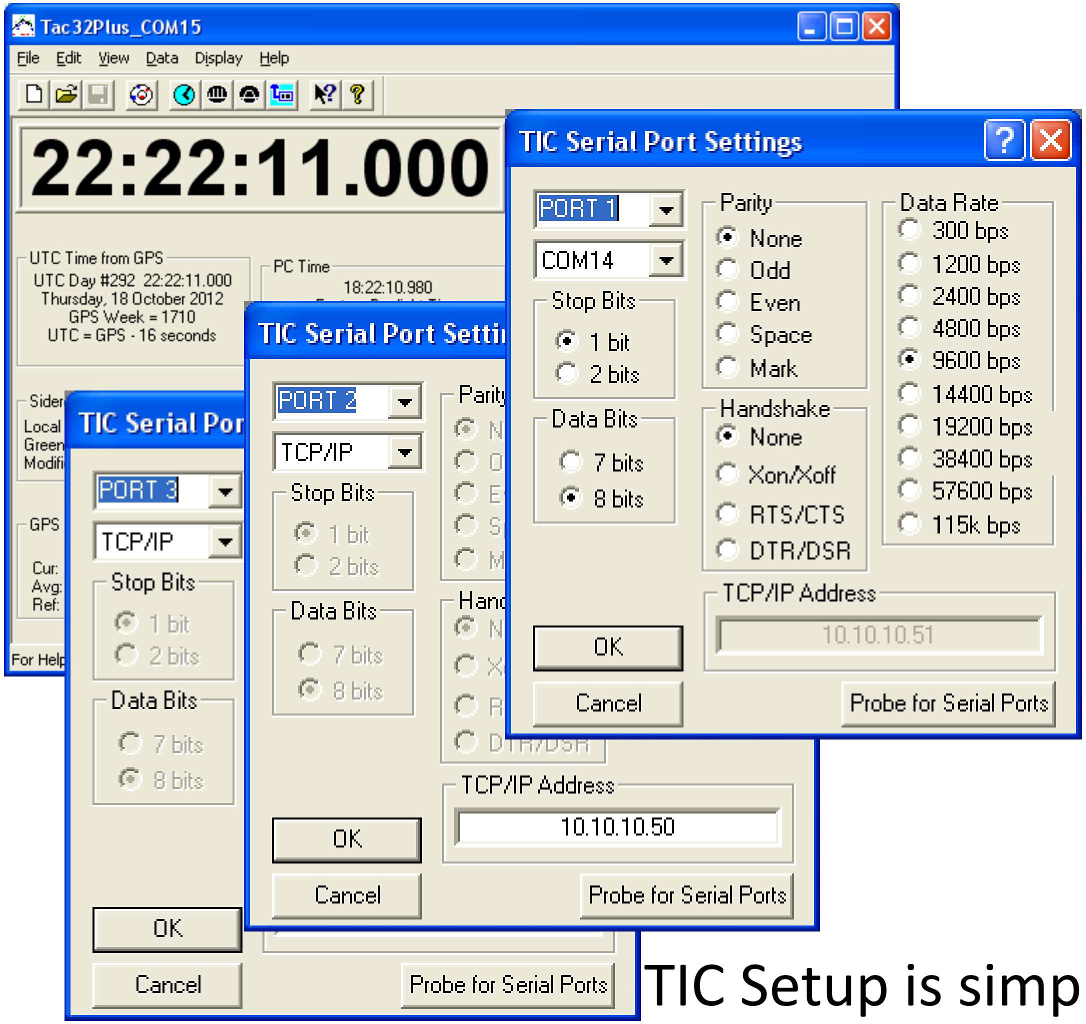
Berkeley Nucleonics Model 1104 Ethernet



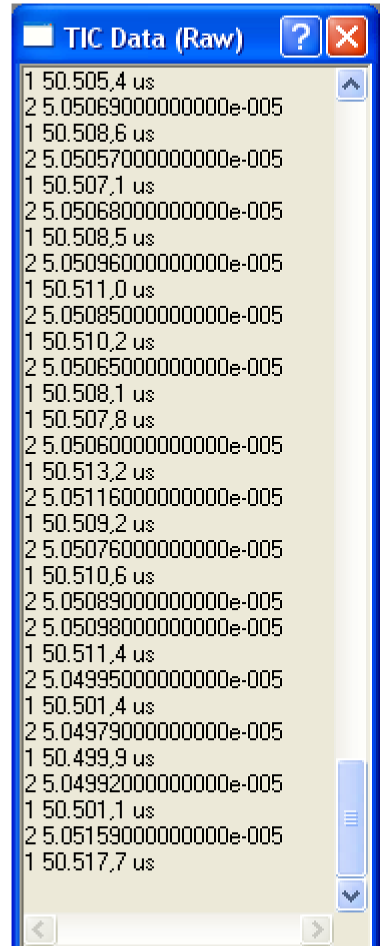
Tac32Plus

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

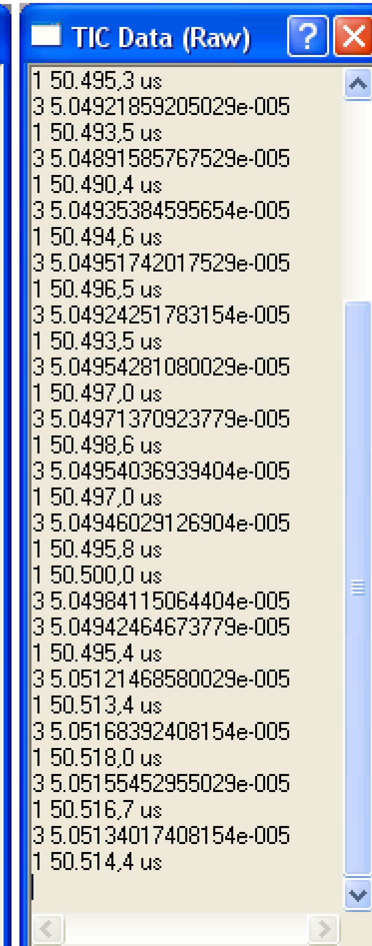
Tac32Plus & GPS Support Time Interval Counters via Ethernet.



TIC Setup is simple and familiar



53132A vs. BN1105



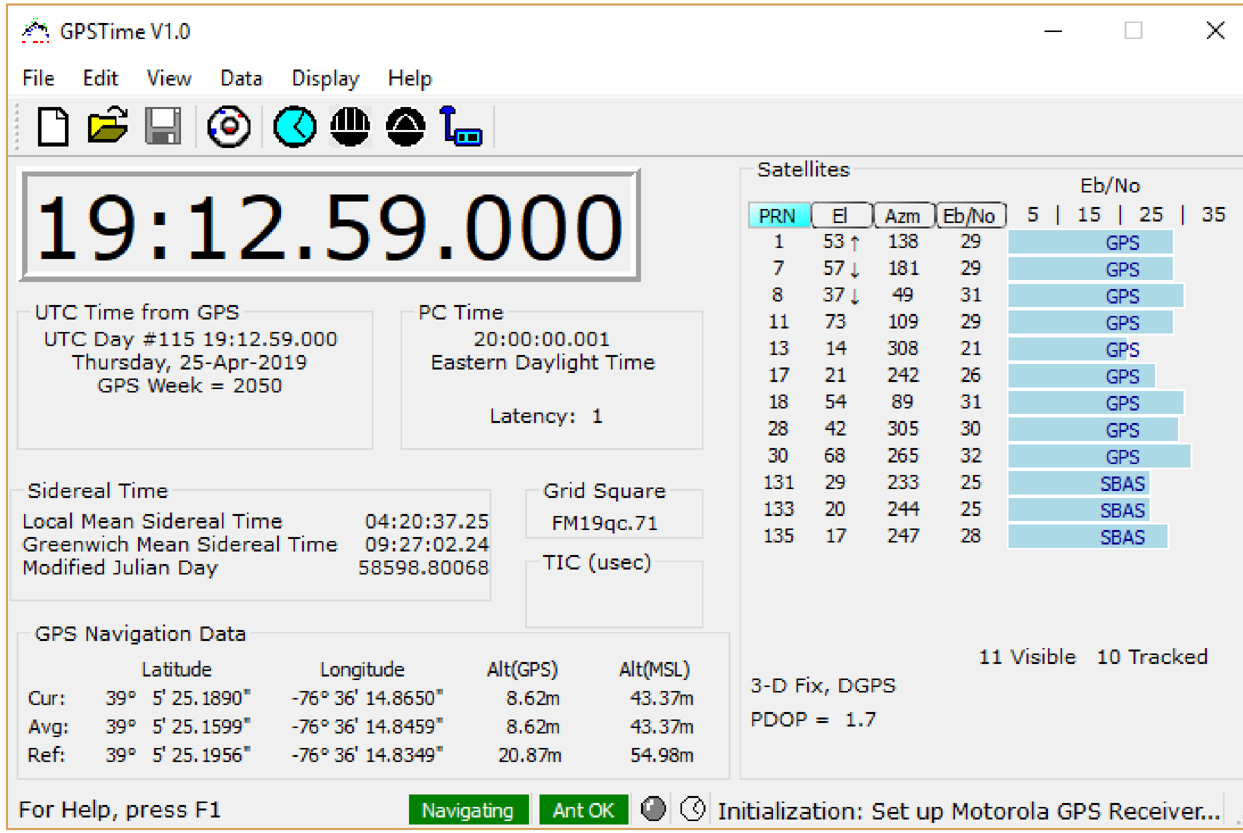
53132A vs. 53230A

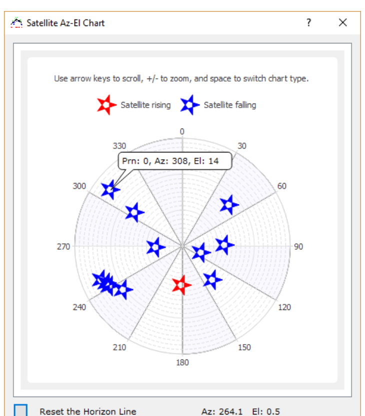
Tac32Plus Upgrades (2019 -> 2023)
Version 2.7.24 -> 2.7.32

- Correct the identification of GPS module firmware version numbers.
- Implement support for the new @@SP "Second PPS Rate" command and response.
- When using the @@Sc manual command, include the Satellite Selection inthe GPS Mode Selection window.
- When in UBX binary mode, correct the mode settings and transitions between Navigation, Position Hold (0D) and Survey.
- Correct the calculations used to resolve the automatic sawtooth correction add vs. subtract determination.
- Improve the decoding of @@Bn and @@En messages.
- Revise the decoding of special emulation modes for the SSR series receivers and add a new mode.
- Revise the detection of receiver types to so the special emulation modes of the SSR series receivers are correctly detected.
- Enable some supported features in the GPS Receiver Mode Selections window for the CNS Clock II and other SSR receivers in Motorola Binary mode. This includes Satellite Activation and Application Type.
- Enable and implement self-survey in u-blox UBX mode.
- Change the file extension of GPS receiver PVT logs from "txt" to "csv" and correct the column header for the PVT log files.
- Correct the encoding of baud rates for the UBX pass-through mode.
- Provide support for short PPS on CNS Clock II, rev L and newer, starting with serial number 404409.
- See https://www.cnssys.com/Tac32Plus/Tac32Plus.php

Future Enhancements - GPSTime Software

- Multi-Platform executables, especially Linux.





Future Enhancements:

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.

Contact Richard Hambly: rick@cnssys.com

Questions ?

Appendix

- IVS Recommended Maser Timing Practices
- Typical data comparing four CNS Clock units against a single HP5065A rubidium standard to show good data and relative performance.

IVS Recommended Maser Timing Practices

IVS Memorandum 2014-001v01

29 April 2014

"IVS Recommended Maser Timing Practices"

Roberto Ambrosini, Tom Clark, Brian Corey, Ed Himwich

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.

GNSS Test Bed Analysis

User Input

Data Directory containing the Tac32Plus or GPSTime data files

C:/Tac32PlusData/2023_CNS_Lab [Browse]

Output Directory for the report file

C:/Users/rick/Documents/CNS Systems Inc/Testbed_Reports/Testbed in Python [Browse]

Enter the start time for the Average Data charts

2/21/2023 00:00:00

Enter the duration (days) for the Average Data charts.

7

Enter the Average Data sample size

300

<- This is needed to validate each data line

Enter the Time (noise) data start time.

2/27/2023 00:00:00

<- Note that the one hour block of data must be in a single data file

Enter the Magnetic Field Setting (optional).

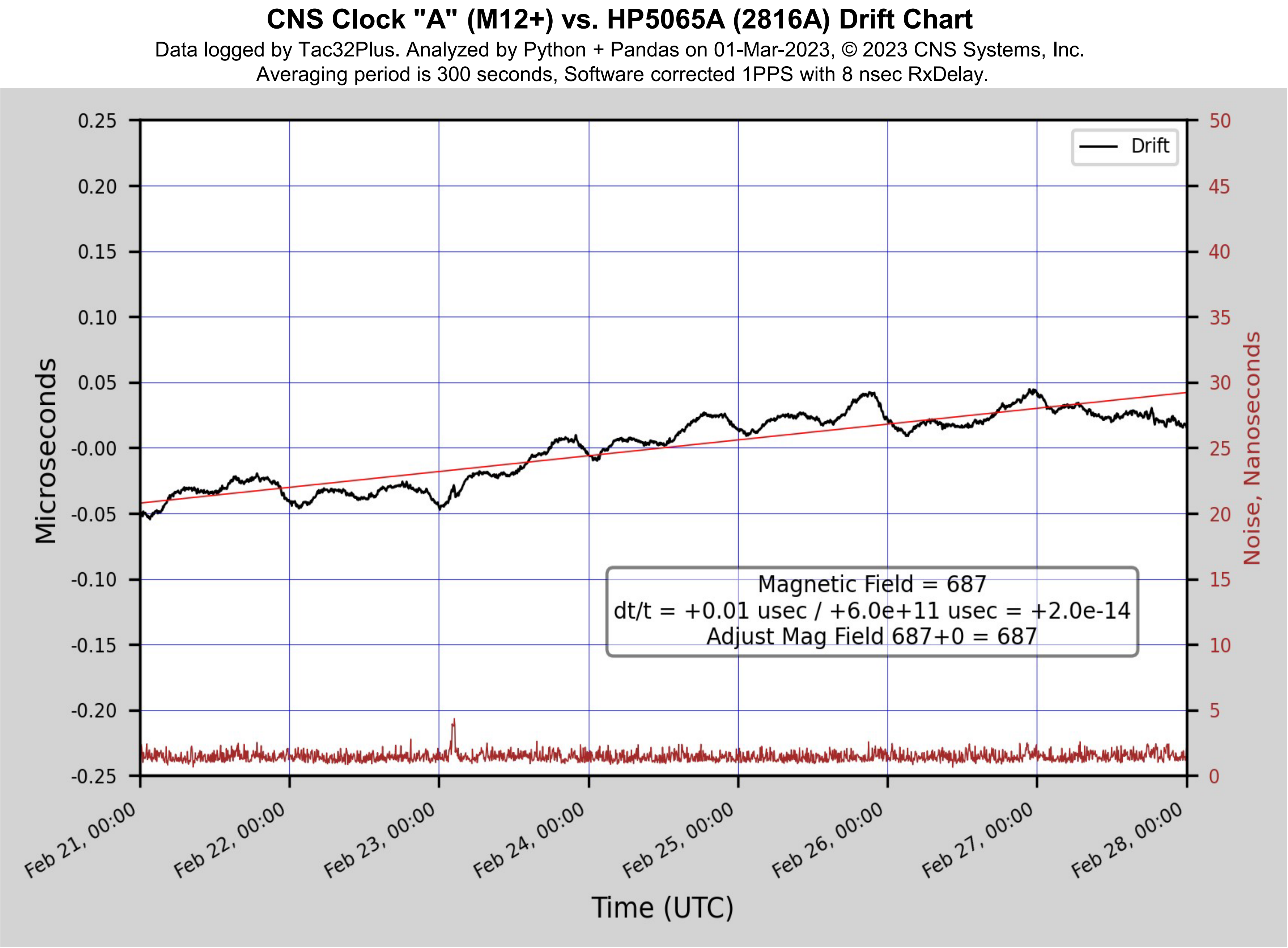
687

<- This is for an HP5064A Rubidium Standard. If not needed, set blank or zero.

Data sets to include in the report

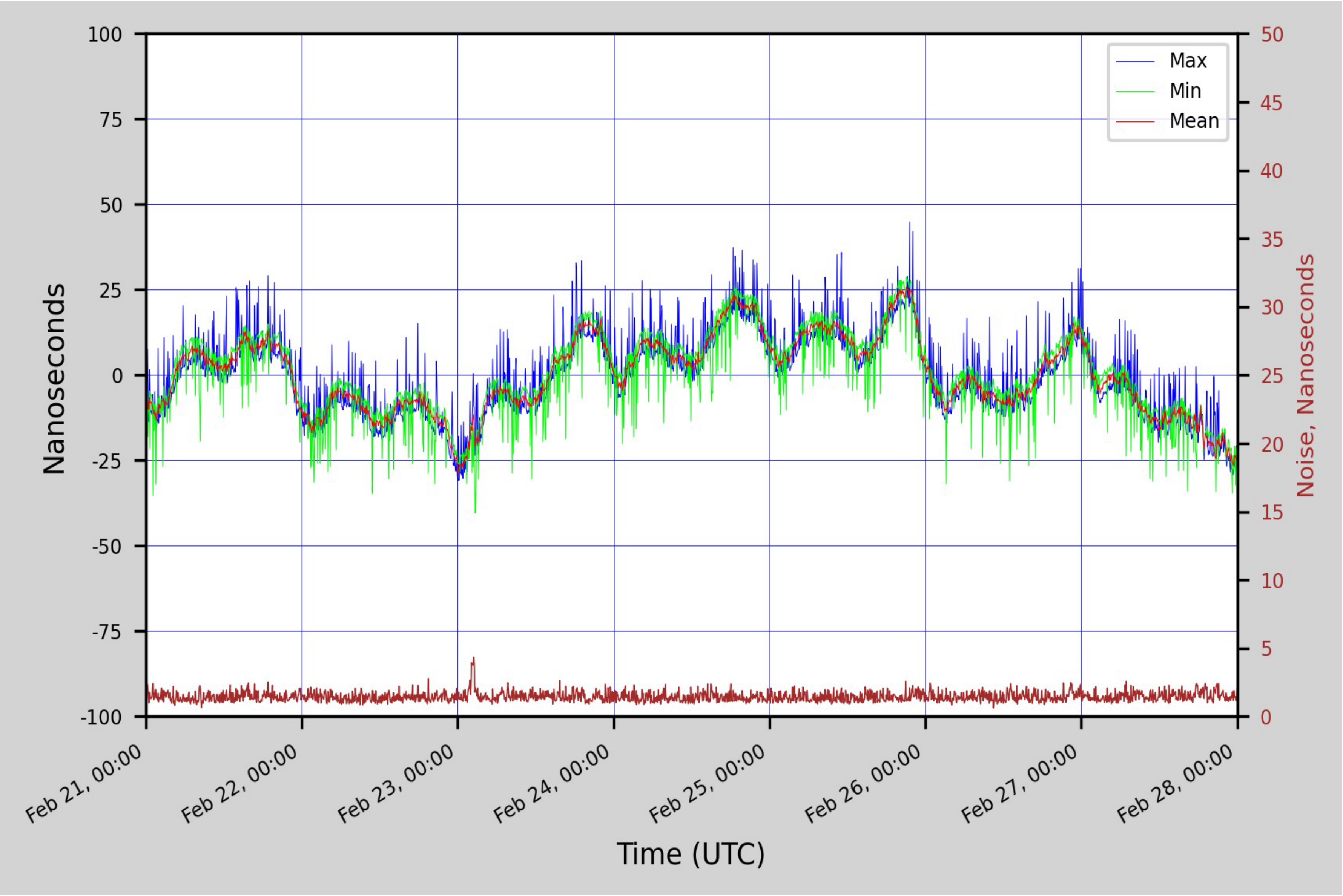
	Enter the Prefix for the data file series	Enter the Primary Header	Enter the Secondary Header Extension
✔	CNSA	CNS Clock "A" (M12+) vs. HP5065A (2816A)	Software corrected 1PPS with 8 nsec RxDelay.
✔	C449	CNS Clock II 404449 (SSR-M8F+) vs. HP5065A (2816A)	Hardware corrected PPS with 48 nsec RxDelay.
✔	C450	CNS Clock II 404450 (SSR-M8F+) vs. HP5065A (2816A)	Hardware corrected PPS with 48 nsec RxDelay.
✔	C451	CNS Clock II 404451 (SSR-M8F+) vs. HP5065A (2816A)	Hardware corrected PPS with 48 nsec RxDelay.

[OK] [Cancel]


CNS Clock "A" (M12+) vs. HP5065A (2816A) Drift Chart
Data logged by Tac32Plus. Analyzed by Python + Pandas on 01-Mar-2023, © 2023 CNS Systems, Inc.
Averaging period is 300 seconds, Software corrected 1PPS with 8 nsec RxDelay.
Drift
Microseconds
Noise, Nanoseconds
Magnetic Field = 687
dt/t = +0.01 usec / +6.0e+11 usec = +2.0e-14
Adjust Mag Field 687+0 = 687
Time (UTC)
0.25
0.20
0.15
0.10
0.05
-0.00
-0.05
-0.10
-0.15
-0.20
-0.25
50
45
40
35
30
25
20
15
10
5
0
Feb 21, 00:00
Feb 22, 00:00
Feb 23, 00:00
Feb 24, 00:00
Feb 25, 00:00
Feb 26, 00:00
Feb 27, 00:00
Feb 28, 00:00

CNS Clock "A" (M12+) vs. HP5065A (2816A) Average Data Chart

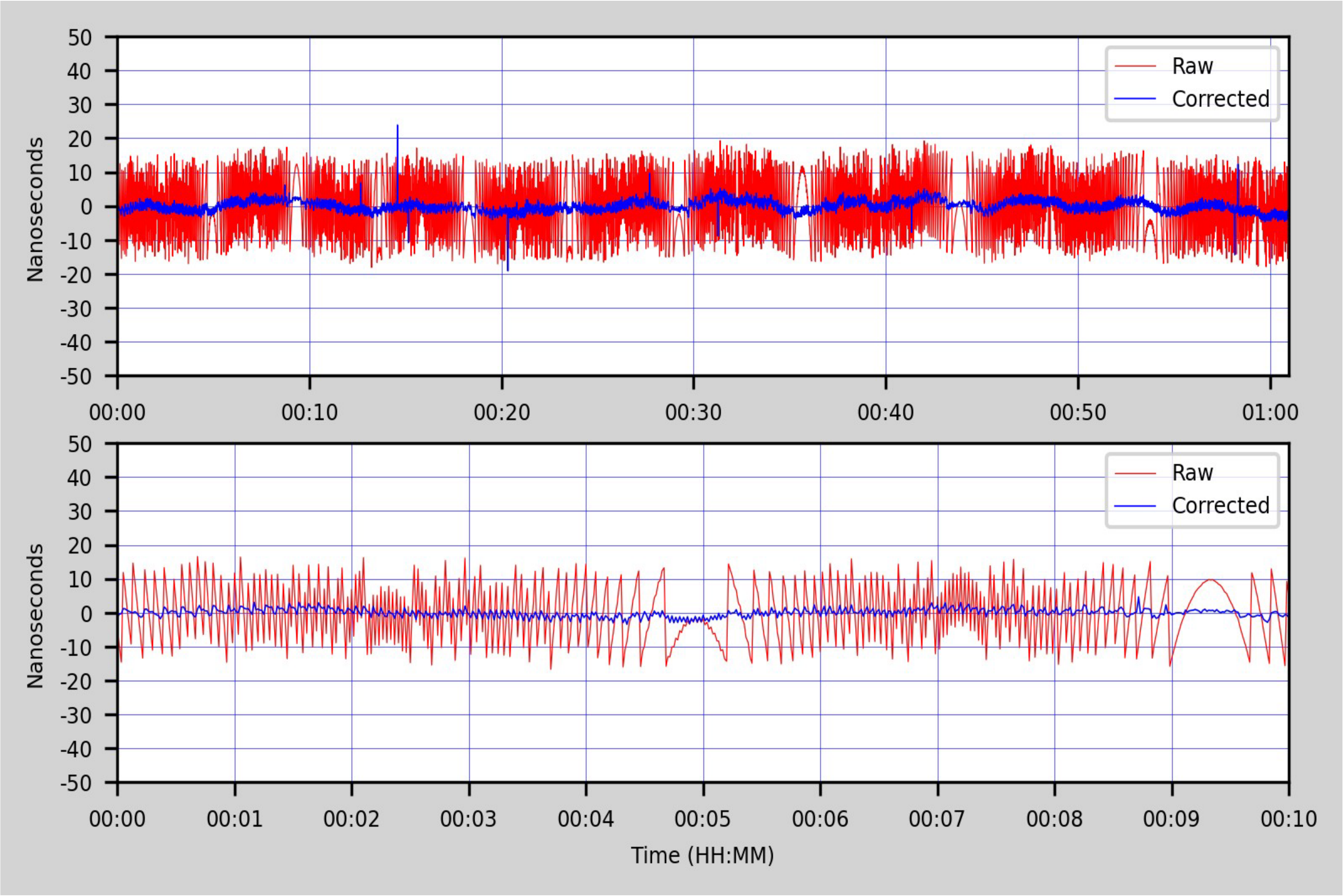
Data logged by Tac32Plus. Analyzed by Python + Pandas on 01-Mar-2023, © 2023 CNS Systems, Inc.
Averaging period is 300 seconds, Osc drift removed, Software corrected 1PPS with 8 nsec RxDelay.



CNS SYSTEMS
Communication Navigation Surveillance INC.

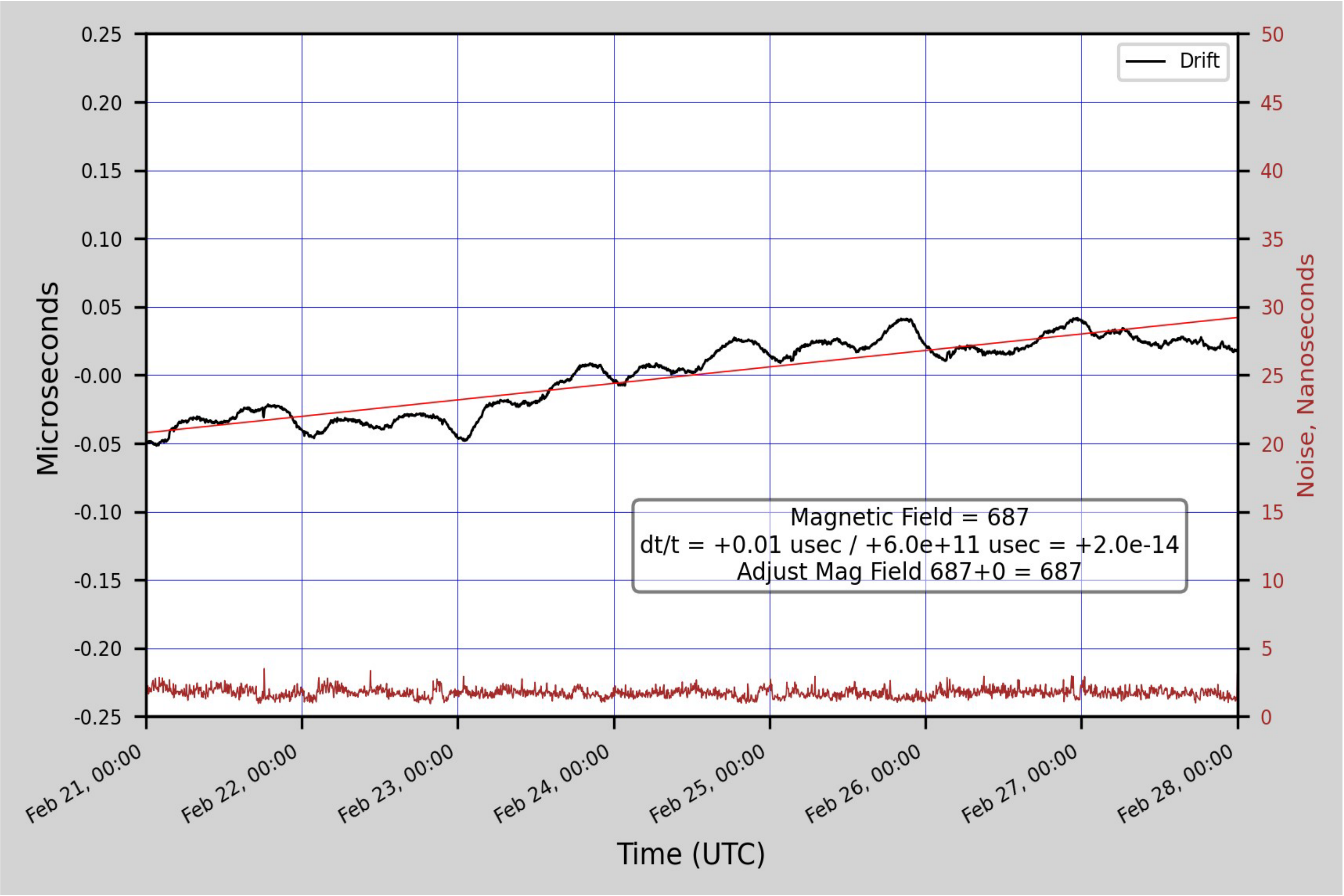
CNS Clock "A" (M12+) vs. HP5065A (2816A) Noise Chart

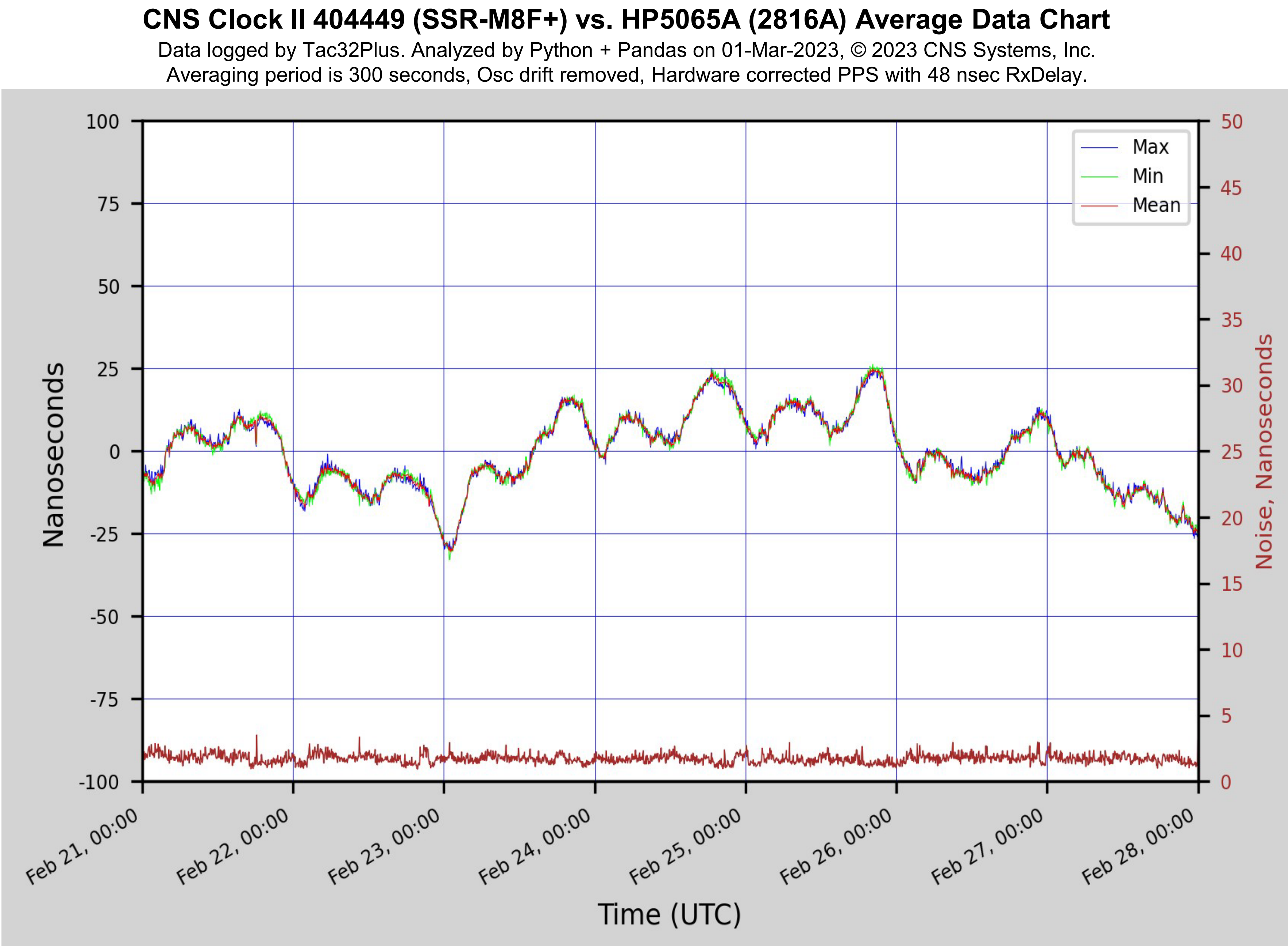
Data logged by Tac32Plus. Analyzed by Python + Pandas on 01-Mar-2023, © 2023 CNS Systems, Inc.
Software corrected 1PPS with 8 nsec RxDelay.



CNS Clock II 404449 (SSR-M8F+) vs. HP5065A (2816A) Drift Chart

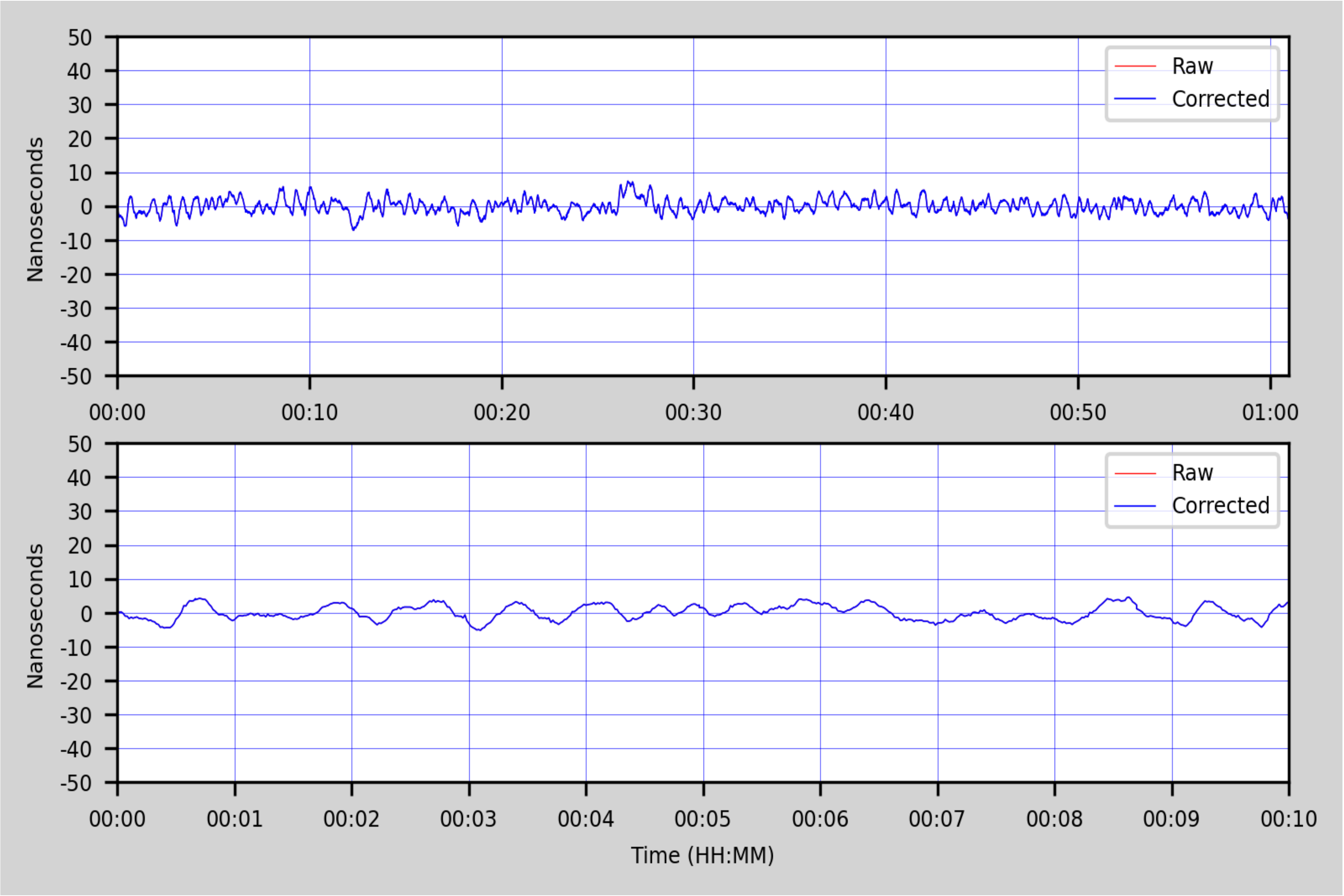
Data logged by Tac32Plus. Analyzed by Python + Pandas on 01-Mar-2023, © 2023 CNS Systems, Inc.
Averaging period is 300 seconds, Hardware corrected PPS with 48 nsec RxDelay.




CNS Clock II 404449 (SSR-M8F+) vs. HP5065A (2816A) Average Data Chart
Data logged by Tac32Plus. Analyzed by Python + Pandas on 01-Mar-2023, © 2023 CNS Systems, Inc.
Averaging period is 300 seconds, Osc drift removed, Hardware corrected PPS with 48 nsec RxDelay.
Max
Min
Mean
Nanoseconds
Noise, Nanoseconds
100
75
50
25
0
-25
-50
-75
-100
50
45
40
35
30
25
20
15
10
5
0
Feb 21, 00:00
Feb 22, 00:00
Feb 23, 00:00
Feb 24, 00:00
Feb 25, 00:00
Feb 26, 00:00
Feb 27, 00:00
Feb 28, 00:00
Time (UTC)

CNS Clock II 404449 (SSR-M8F+) vs. HP5065A (2816A) Noise Chart

Data logged by Tac32Plus. Analyzed by Python + Pandas on 01-Mar-2023, © 2023 CNS Systems, Inc.
Hardware corrected PPS with 48 nsec RxDelay.



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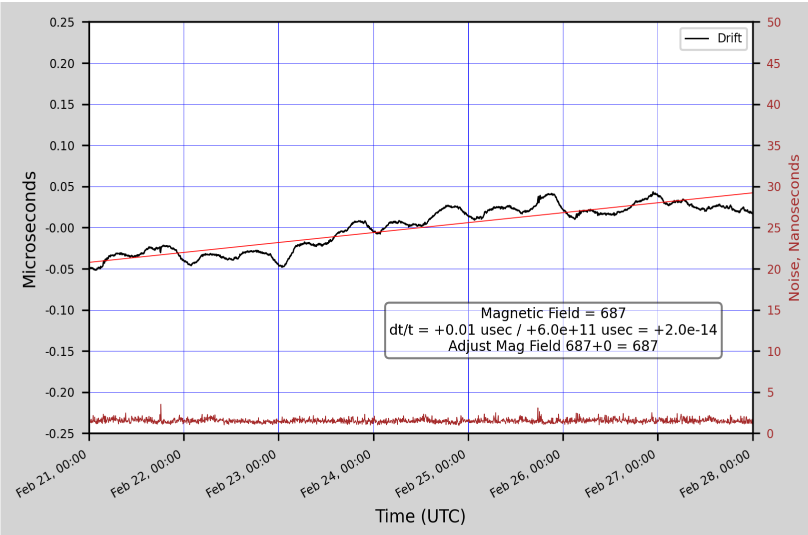
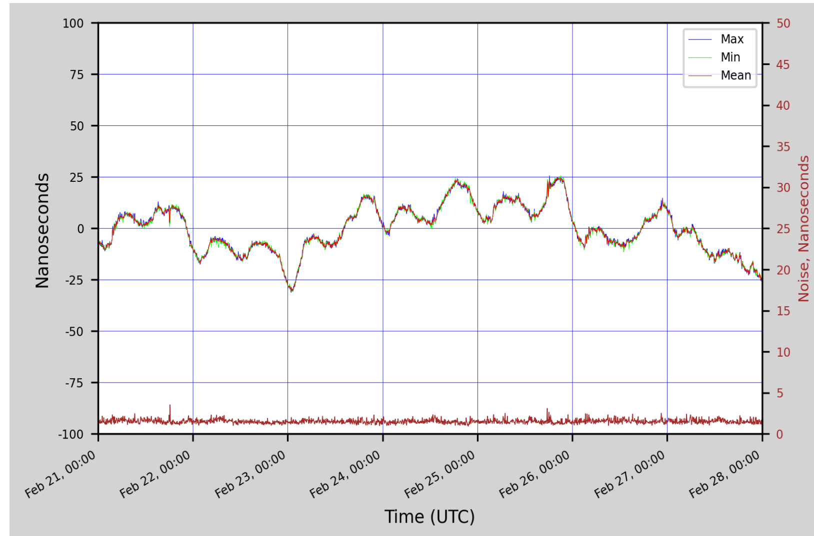
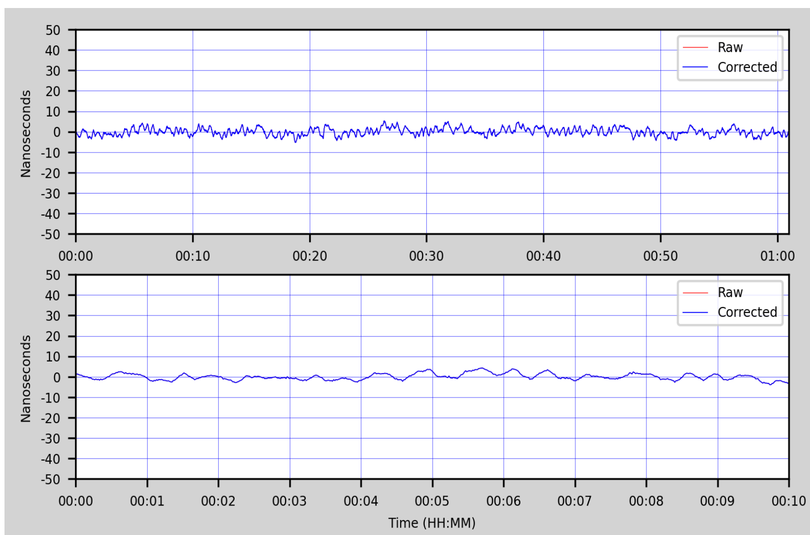
CNS Clock II 404450 (SSR-M8F+) vs. HP5065A (2816A) Drift Charts

Data logged by Tac32Plus. Analyzed by Python + Pandas on 01-Mar-2023, © 2023 CNS Systems, Inc.
Averaging period is 300 seconds, Hardware corrected PPS with 48 nsec RxDelay.



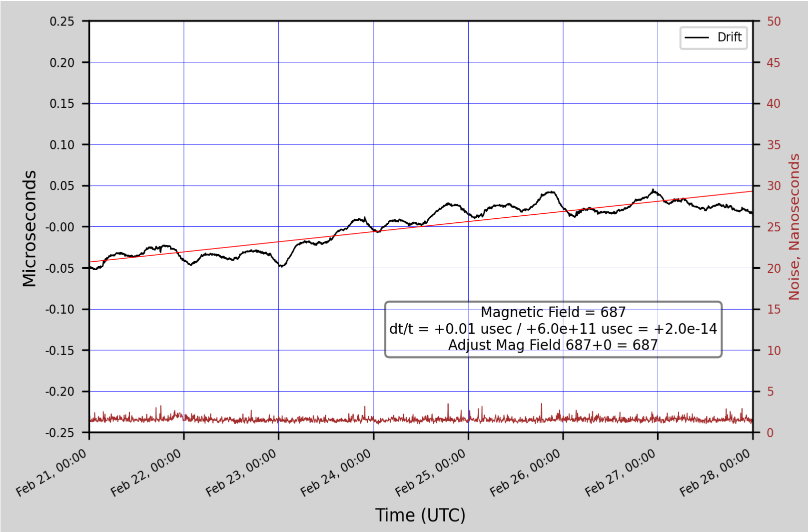


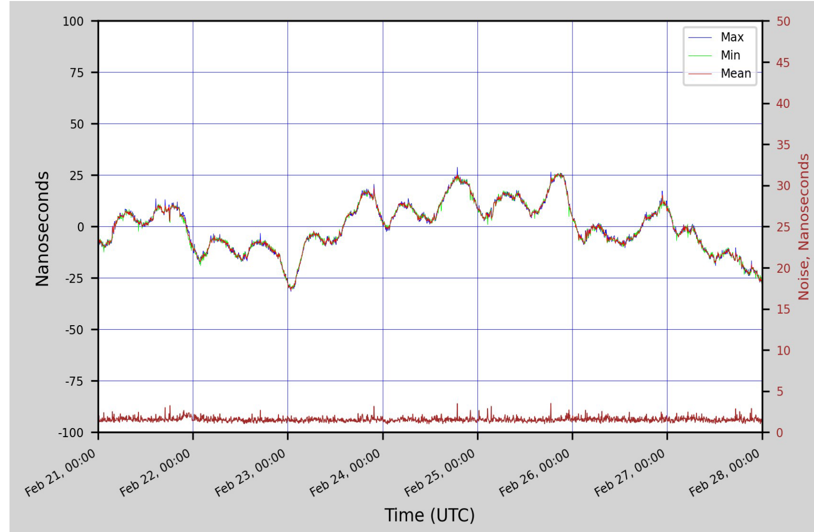


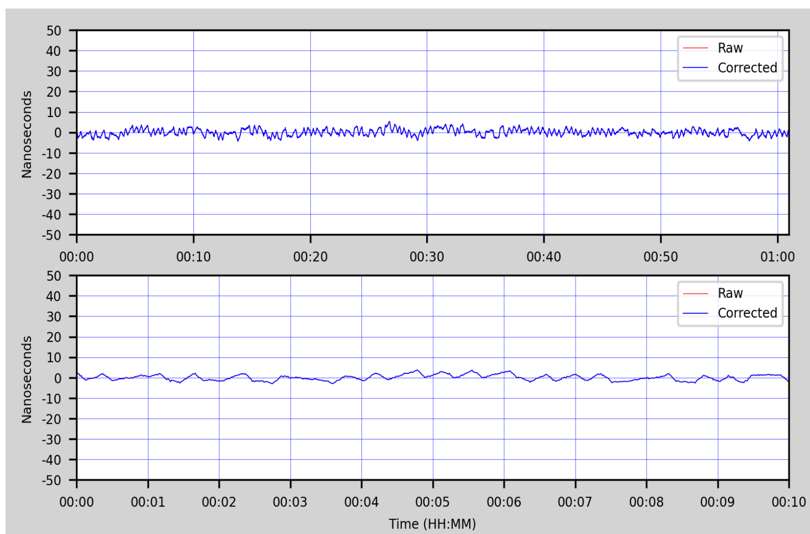
CNS Clock II 404451 (SSR-M8F+) vs. HP5065A (2816A) Drift Charts

Data logged by Tac32Plus. Analyzed by Python + Pandas on 01-Mar-2023, © 2023 CNS Systems, Inc.

Averaging period is 300 seconds, Hardware corrected PPS with 48 nsec RxDelay.







GPS Receiver Comparison Data Charts

Data logged by Tac32Plus. Analyzed by Python + Pandas on 01-Mar-2023, © 2023 CNS Systems, Inc.

Averaging period is 300 seconds, Osc drift removed.