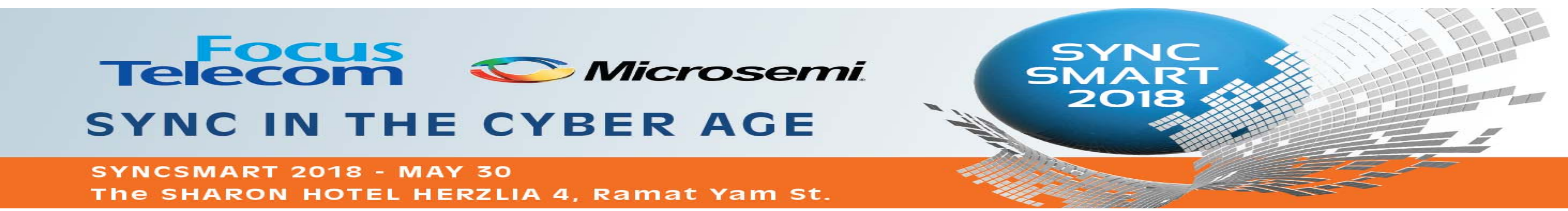
Jackson Labs Technologies, Inc.

Gregor Said Jackson, President

State of the Art GNSS Timing Applications

May 29th 2018

CONFIDENTIAL



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Jackson Labs Technologies, Inc.

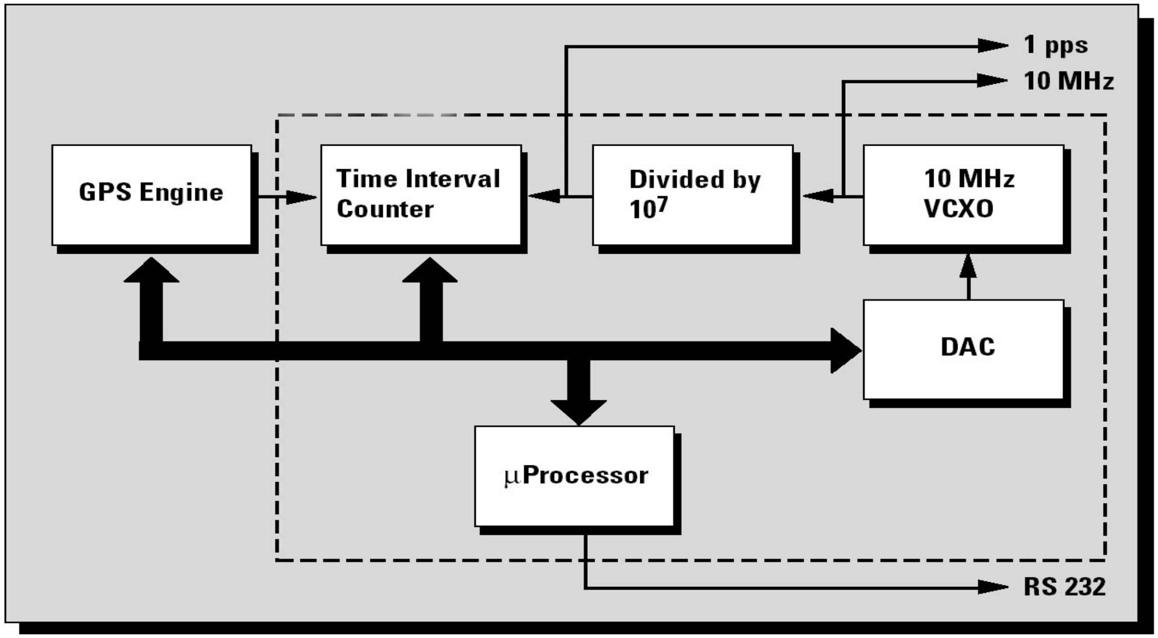
- Founded in 2003 in Silicon Valley, Factories in Nevada, California
- Microsemi Private-Labels many JLT products
- 38+ products for Commercial/Industrial/Military; 40,000+ fielded units
- Focus on embedded modules ranging from low-cost to ultra-high performance

GPSDO 101:
Explaining Behavior and Performance

- Often Asked Questions:
  1. What is your holdover drift after 1, 6, 12, x, y hours?
  2. Why is there a phase difference between units?
  3. What is the performance in motion versus stationary?
  4. How often do I have to connect to GPS to calibrate the unit?

GPSDO Block Diagram

- GNSS signals carry the NIST UTC master time-signal to the user. We decode this time signal, and generate a local version of it using a flywheel oscillator:



How Accurate are GNSS Today?

- GNSS UTC(USNO), UTC(SU) and UTC(E) versus UTC over one year:

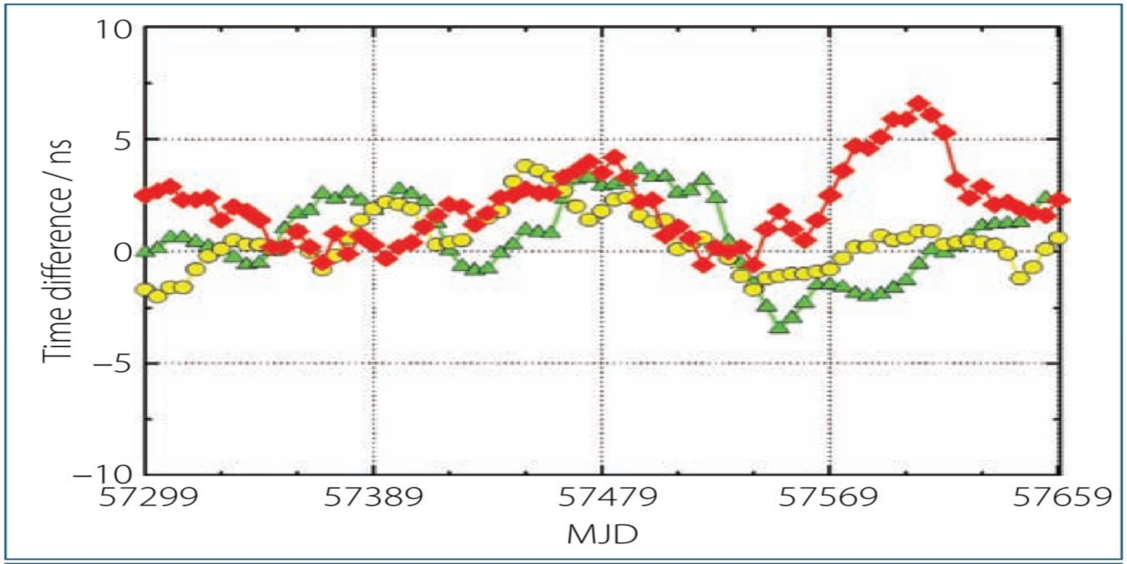
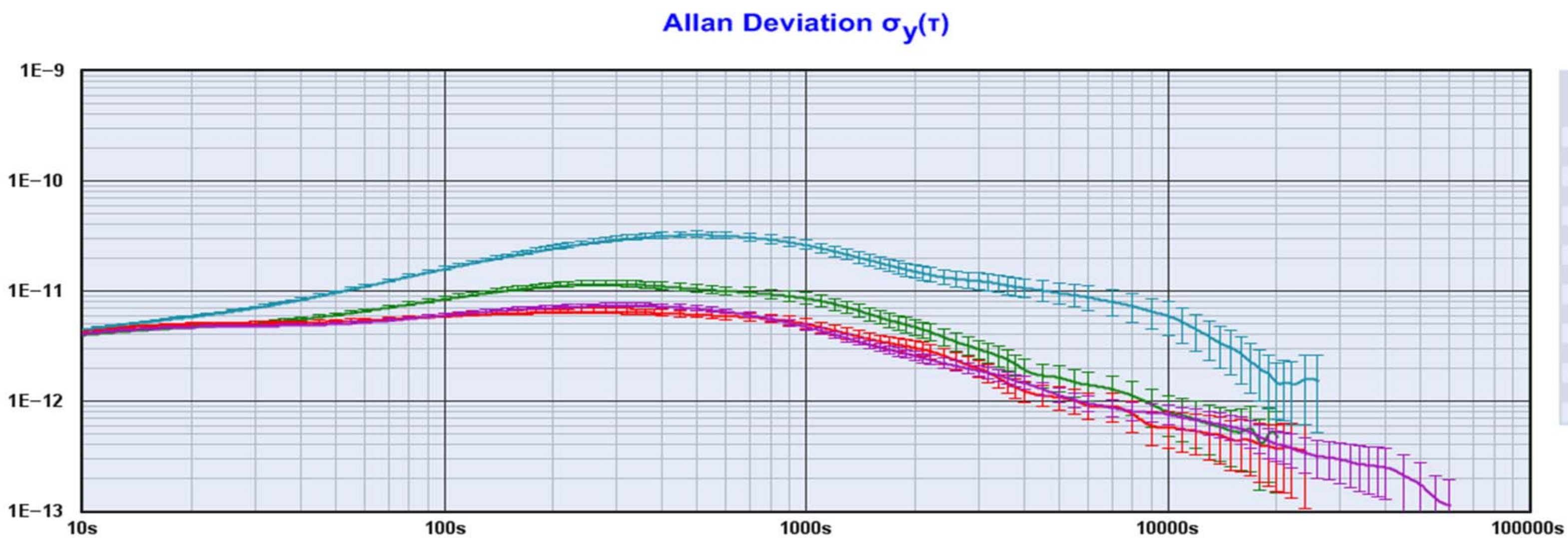


FIGURE 1 Reference time scales for GPS (yellow), GLONASS (red) and Galileo (green) in comparison with UTC during one year, ending at Modified Julian Day (MJD) 57659, September, 28 2016.

Bauch, A. and Whibberley, P., "Reliable Time from GNSS Signals", *Inside GNSS*, March/April 2017, pp. 39-44, 2017

GNSS Comparisons

- GPS-3500 with either GPS or Glonass enabled
- Both stationary (Position Hold) and Mobile (3D) modes tested



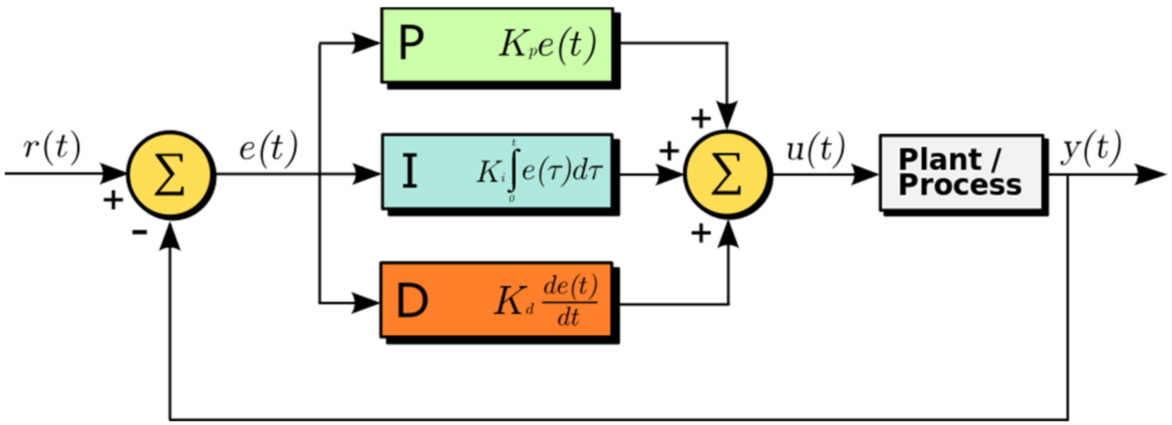
Tau	Sigma(Tau)
1s	1.76E−12
2s	2.25E−12
4s	2.91E−12
8s	3.84E−12
10s	4.15E−12
20s	4.76E−12
40s	4.96E−12
80s	5.71E−12
100s	6.11E−12
200s	7.21E−12
400s	7.36E−12
800s	5.60E−12
1000s	4.74E−12
2000s	2.58E−12
4000s	1.47E−12

Trace	Notes	Input Freq	Sample Interval	ADEV at 7s	Duration	Acquired	Instrument
LN-Rb short holdover tests (Unsaved)		10 MHz	0.100 s		44m 20s	26604 pts	Symmetricom 5115A/512XA
LN-Rb short holdover tests (Unsaved)		10 MHz	0.100 s		6d 0h 0m 0s	5184000 pts	Symmetricom 5115A/512XA
LN-Rb Filter GPS nav mode		10 MHz	0.100 s		22h 48m 0s	820798 pts	Symmetricom 5115A/512XA
LN-Rb Filter GPS tmode on		10 MHz	0.100 s		1d 2h 44m 19s	962591 pts	Symmetricom 5115A/512XA
LTE-Lite 24.567MHz - Eval Board		24.567 MHz	0.100 s		1h 59m 37s	71773 pts	Symmetricom 5115A/512XA
LN Rb Filter GPS tmode on - fast filters (Unsaved)		10 MHz	0.100 s		10m 40s	6400 pts	Symmetricom 5115A/512XA
LN Rb Filter GPS tmode on - fast filters		10 MHz	0.100 s		19h 33m 39s	704185 pts	Symmetricom 5115A/512XA
LN Rb Filter GLONASS tmode on (Unsaved)		10 MHz	0.100 s		2d 19h 11m 39s	2418985 pts	Symmetricom 5115A/512XA
LN Rb Filter GLONASS nav mode (Unsaved)		10 MHz	0.100 s		144 h	1105839 pts	Symmetricom 5115A/512XA

JLT GPSDO Control Theory

- Traditional model well understood, but:
  - Oscillators present non-stable, but deterministic plant process
  - During retrace oscillator requires continuous control voltage change for constant frequency
  - Reference r(t) created by GNSS receiver is unstable, noisy, and must be qualified and filtered

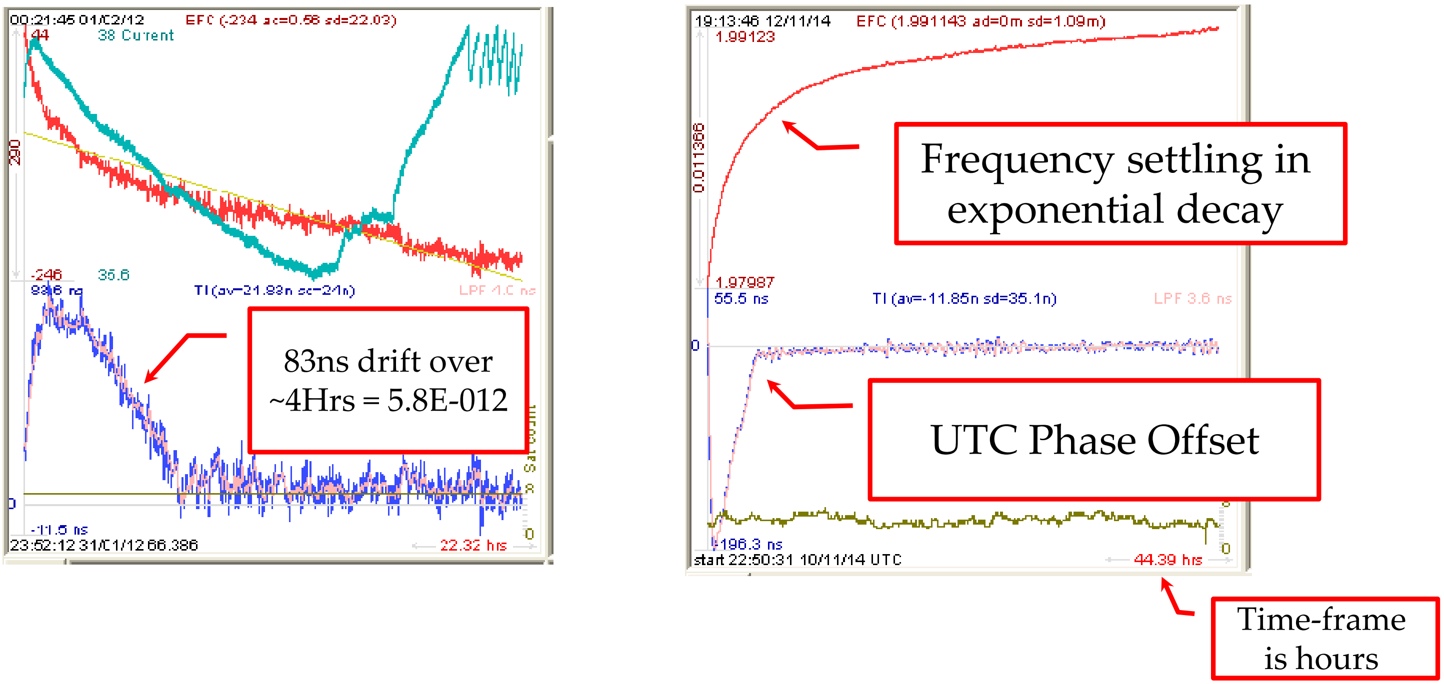
$$u(t) = K_{\mathrm{p}} e(t) + K_{\mathrm{i}} \int_0^t e(t')\,dt' + K_{\mathrm{d}} \frac{de(t)}{dt}$$



Wikipedia

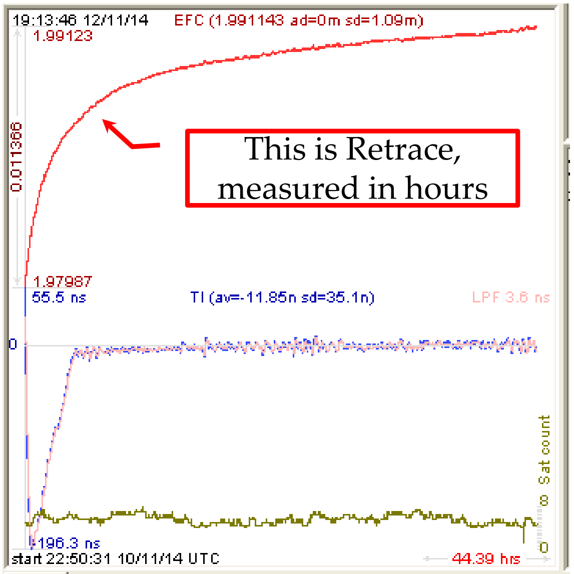
OSCILLATOR RETRACE

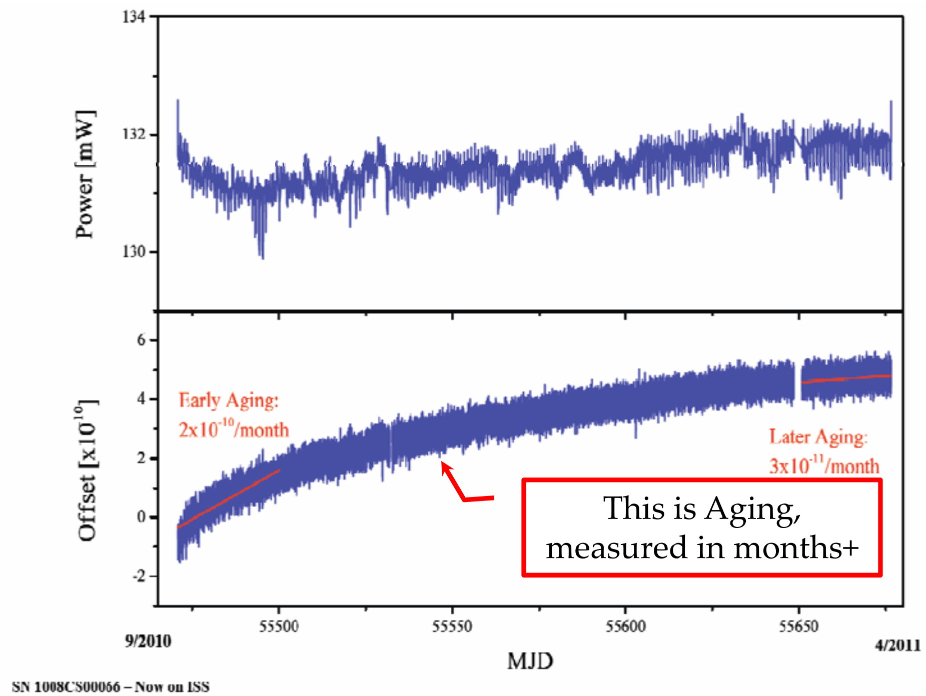
- Power-on: frequency changes in exponentially-decaying manner



OSCILLATOR RETRACE VERSUS AGING

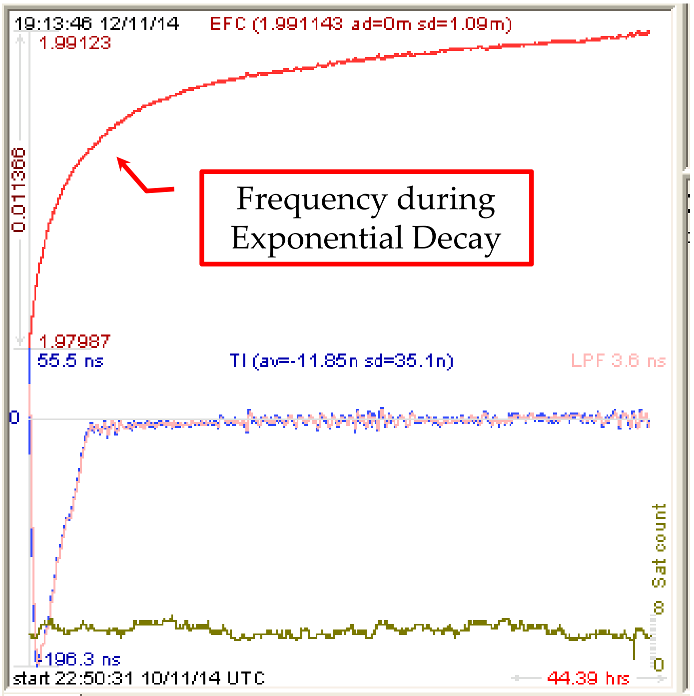
- Oscillator still following exponential decay curve after 200+ days
  - When is it considered “stabilized”? Depends on your definition of “stable”

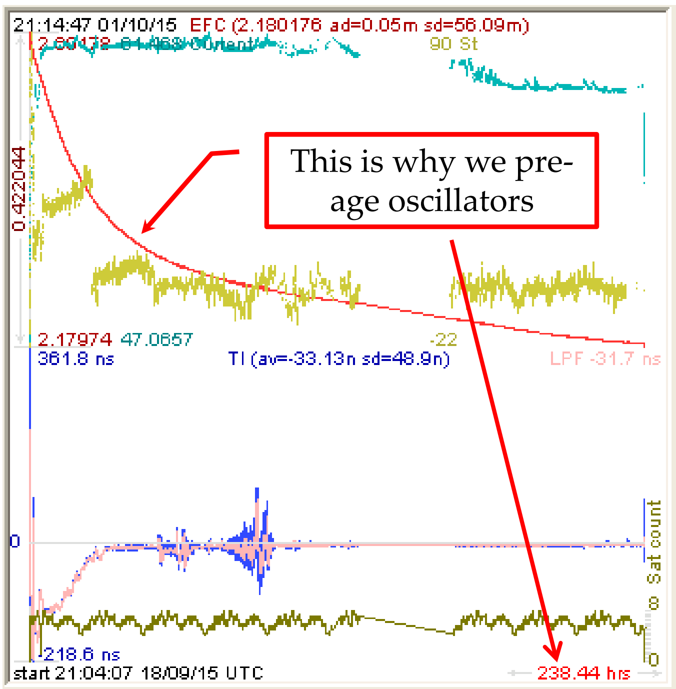




Phase Drift Over Time

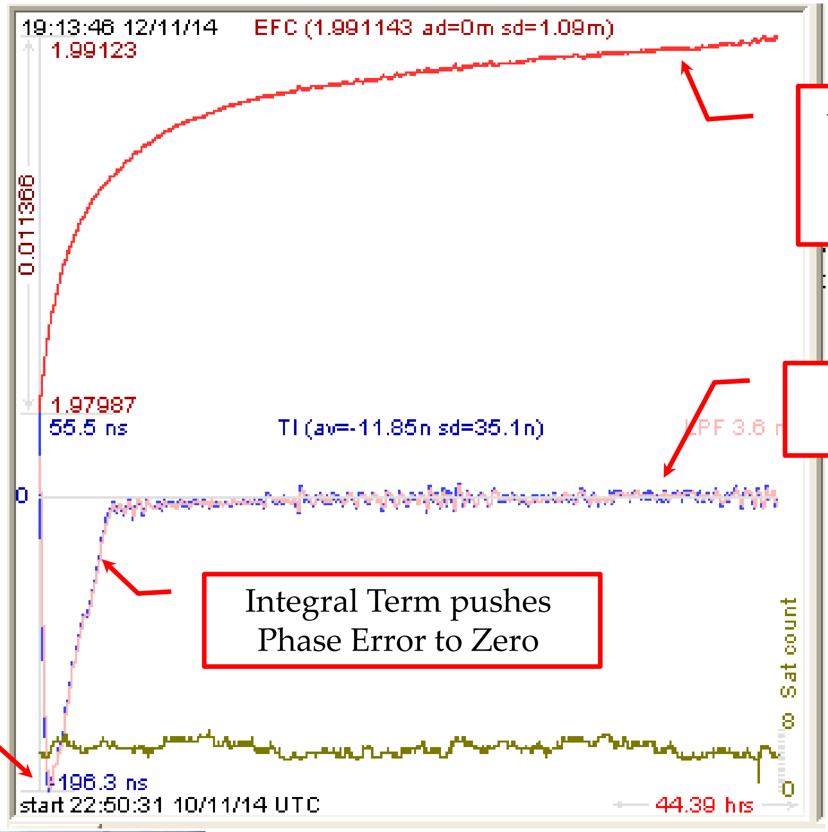
- Question: what is the phase drift over time? Answers:
  - depends on how long after power-on before going into holdover
  - Depends on environment after going into holdover





Integral Versus Proportional Steering

- Both are individually adjustable, but inter-related



Long-Term Accuracy guaranteed by software Aging- and Temperature Compensation

Both Terms maintain Frequency And Phase

Integral Term pushes Phase Error to Zero

Proportional Term pulls Frequency in quickly

Time Error Model

- Question: what is the phase drift over time?
  - Predicting Drift is non trivial, multi-variable dependency

$$E(t) = E_0 + \int_0^t y(t)dt + \varepsilon(t)$$

$$E(t) = E_0 + \left(y_0 t + \frac{1}{2}at^2\right) + \int_0^t y_e(t)dt + \tau\sigma(\tau) \qquad \textit{EQ 1}$$

Aging/retrace rate, this is not linear!

Oscillator noise

Temperature, tilt, shock, crystal jumps

where

E(t): Time error accumulation at time "t" after initial synchronization

E_0: Initial time error at t = 0

y(t): Fractional frequency of the clock at time t, approximated as

$y(t) = y_0 + at + y_e(t)$

y_0: Fractional frequency offset at t = 0

a: Clock aging rate

$y_e(t)$: Fractional frequency offset due to environmental effects (i.e., temperature)

$\varepsilon(t)$: Random fractional frequency fluctuations

$\varepsilon(t) = \tau\sigma(\tau)$

$\sigma(\tau)$: Allan deviation at sampling rate (τ)

For applications where holdover is important, it is likely that the clock has been disciplined and synchronized to a superior timing reference such as GPS. In this case, we assume that initial phase and frequency offset from the reference is zero ($E_0 = y_0 = 0$). This zero offset can be observed in the measured results shown later in this white paper.

Microsemi Time Error Model Appnote

LONG TERM CSAC RETRACE TESTING

- 20 units tested since January 2014, last stored for 2 years
  - Frequency Accuracy (retrace) after 5, 30, 60 minutes after power-on
  - Large performance spread, overall very good aging performance

Worst Unit: 0.9ppb

Test Date	Unit	Datecode	Test no.	Cs Lock Time (m:ss)	5 min retrace	30 min retrace	1 hr retrace	laser current (mA)	heater power (mW)
2/7/2018	1	1211	2	01:20	2.51E-11	1.75E-11	-3.11E-11	0.64	9.6
	2	1305	2	01:35	4.86E-10	4.19E-10	3.14E-10	0.8	8.25
	3	1207	3	01:20	-5.30E-10	4.77E-10	8.69E-10	0.64	11.8
	4	1301	3	01:25	-4.57E-11	1.08E-10	1.03E-10	0.76	9.48
	5	1301	4	01:35	5.25E-11	1.28E-10	1.47E-10	0.65	8.44
	6	1301	4	01:35	8.73E-11	9.06E-11	1.46E-10	0.65	10.3
	7	1212	5	01:40	6.42E-11	3.00E-11	3.50E-11	0.66	9.3
	8	1301	5	01:35	1.00E-11	1.92E-11	6.50E-11	0.74	8.85
	9	1301	6	02:00	1.04E-11	2.75E-11	3.61E-11	0.88	8.36
	10	1207	6	01:30	3.15E-10	2.97E-10	2.85E-10	0.68	9.05
	11	1301	7	01:45	1.07E-10	1.27E-10	1.28E-10	0.79	9.52
	12	1301	7	01:35	1.10E-10	9.61E-11	1.19E-10	0.74	9.79
	13	1301	8	02:15	3.90E-10	3.90E-10	3.09E-10	0.86	9.86
	14	1301	8	01:30	-3.69E-10	-3.23E-10	-3.21E-10	0.74	15.03
	15	1301	9	02:15	-1.24E-10	-9.04E-11	-1.17E-10	0.82	10.12
	16	1301	10	01:30	2.35E-11	4.67E-11	6.57E-11	0.89	7.86
	17	1301	10	01:50	-2.29E-10	-1.18E-10	-1.62E-11	0.75	10.6
	18	1301	11	01:40	1.35E-10	1.16E-10	1.03E-10	0.75	9.22
	19	1212	11	01:30	7.43E-11	9.20E-11	1.12E-10	0.81	11.12
	20	1301	12	01:40	-8.08E-12	-4.33E-12	-1.58E-11	0.74	8.54

Best Unit: 0.016ppb

To Discipline or Not?

- Drift examples with and without initial GPS Disciplining
  - CSAC worst-case sample unit #3 compared

Freq. Accuracy	Without GPS	With 5 min. GPS disciplining:
• 5 minutes:	-5.30E-10	0.0E-00
• 30 minutes:	4.77E-10	10.07E-10
• 60 minutes:	8.69E-10	13.99E-10

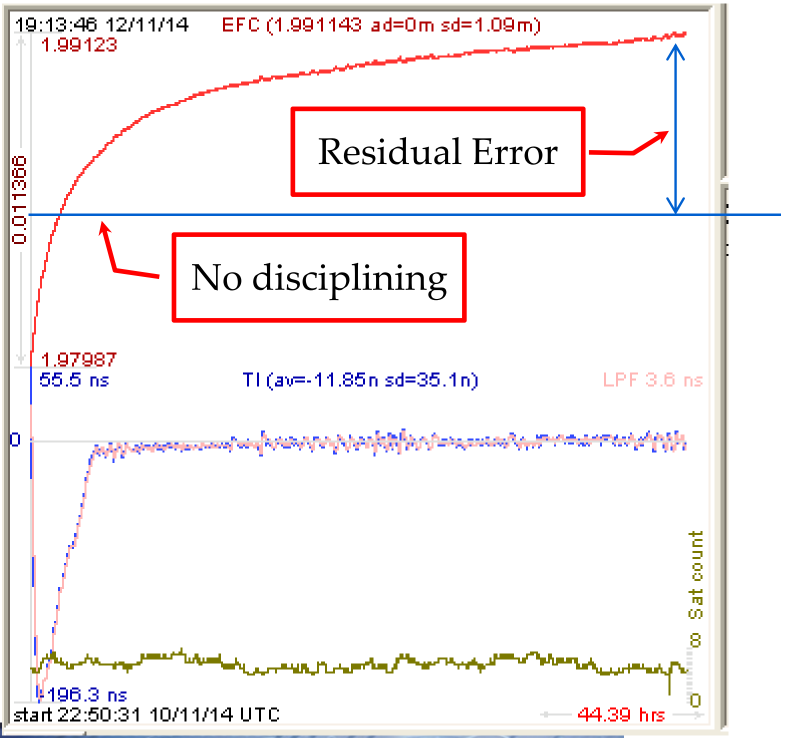
Estimated Phase Drift (due to frequency error only) :

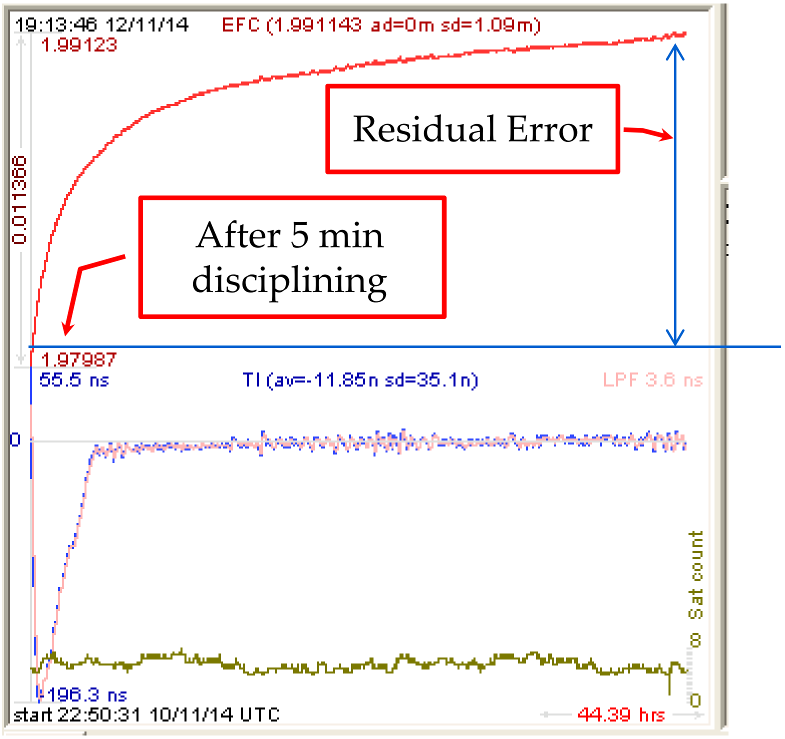
	Only Synchronized to UTC	Synchronized and Syntonized (disciplined)
• 5 minutes:	0.0ns	0.0ns
• 30 minutes:	40ns	755ns
• 60 minutes:	1.2us	2.2us

Disciplining Actually Causes larger Error due to Retrace!

TO DISCIPLINE OR NOT CON'TD

- Special use-case with 3 to 10 min. disciplining time
  - Must always discipline since no a-priori knowledge of oscillator behavior available





How About Thermal Sensitivity?

- CSAC Specification is +/- 5E-010 from -10C to +70C
  - Let's assume a linear temperature to frequency relationship (it's not)

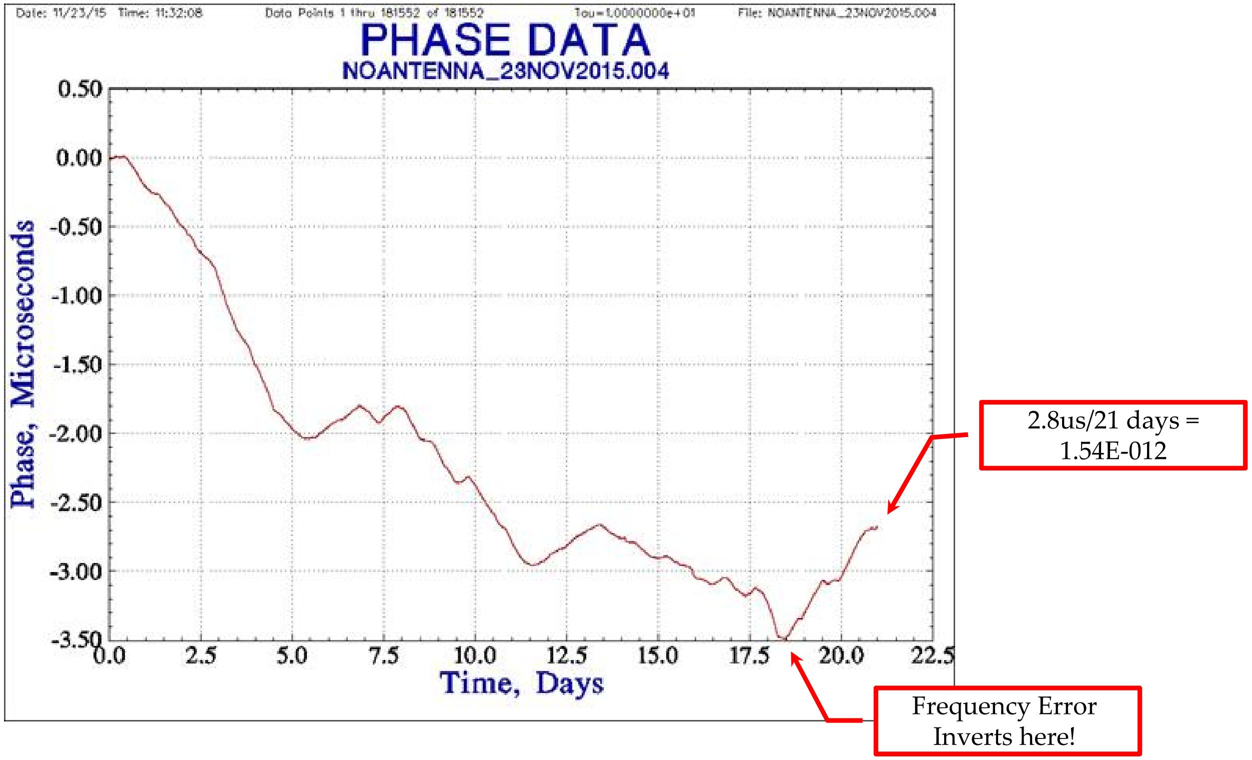
- Using Time Error Model, no retrace, no initial error, and assuming +/-10C change after going into holdover:
  - +/- 0.5ppb / (80C) * +/- 10C = +/-1.25E-010 frequency error, then:

    +/-0.125ppb * 60 minutes * 60 seconds = +/- 450ns Drift

Small Temperature Change has large impact on Drift Performance

DRIFT PERFORMANCE

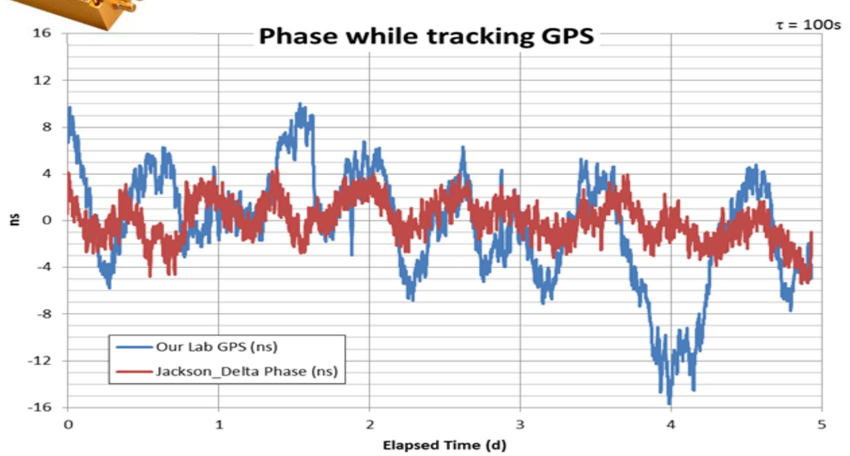
- GPS-3500, Steady-State operation, laboratory conditions
  - After 5+ days with GNSS disciplining



STATE OF THE ART RUBIDIUM

- LN Rubidium GNSDO with latest-gen Concurrent GNSS receiver
  - Costs is 1/10 of traditional solutions
  - Comparable performance to Microsemi XLI SAASM-disciplined 5071A Cesium Vapor Standard
  - Selectable UTC source (GPS, Glonass, Galileo, BeiDou, QZSS, or up to 3 concurrent)

GPS-3500: 10ns peak to peak:



GPS-3500 (LN Rubidium Ultimate – Magenta trace) measured versus Microsemi House Maser.

5071A: 12ns peak to peak:

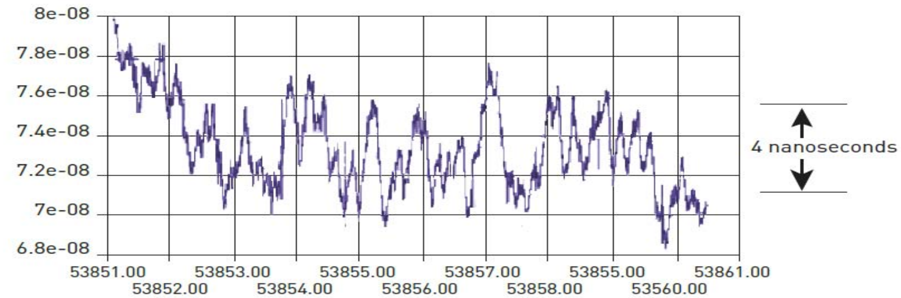
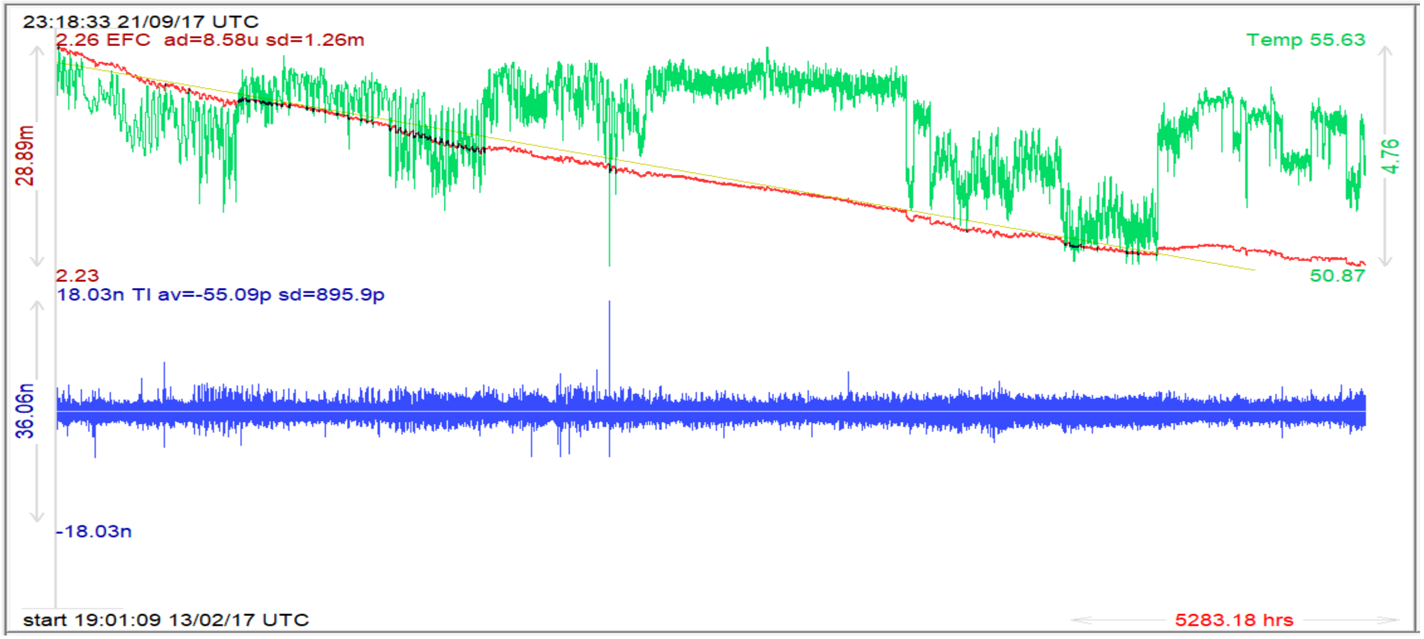


Figure 2. USNO tests of the XLi SAASM Disciplined 5071A Cesium Oscillator option show a clock variation of less than 4 nanoseconds root mean square over the 10 days test period.

Symmetricom, "Time and Frequency System Unites GPS Accuracy with Cesium Stability", *Application Brief*, December 2012, pp. 3, 2012

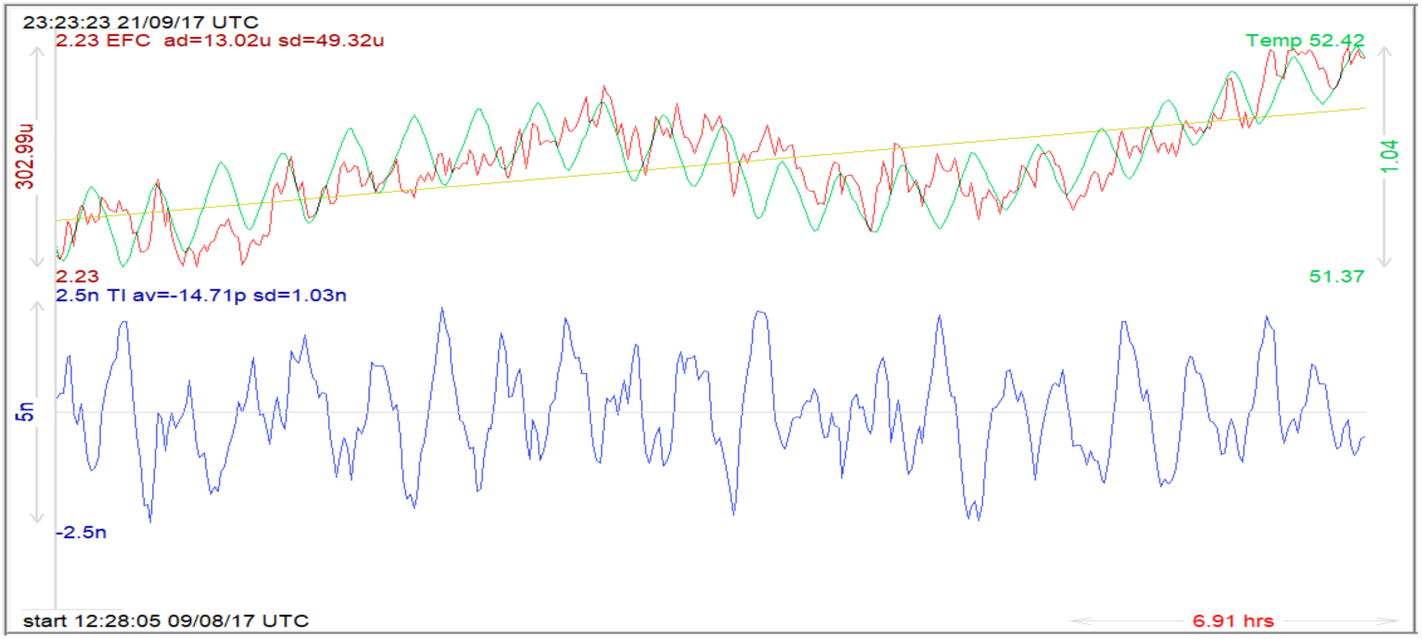
LONG TERM GPS LOCK

- 7 months of GPS locked performance: 0.055ns average, 0.9ns SD
- Thermal changes present most error



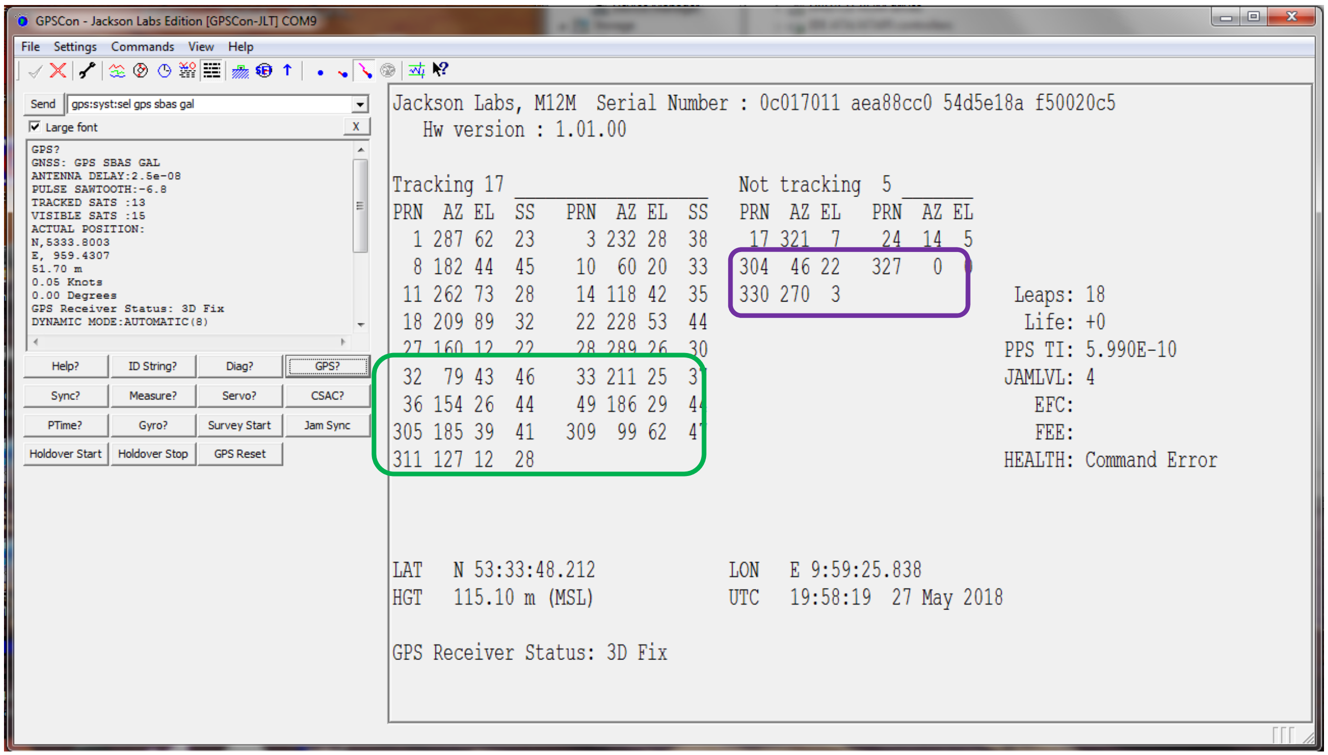
GPS TRACKING

- Short-term thermal effects (Air Conditioning) clearly visible
- Short-term phase error bounded by +/-2.5ns window



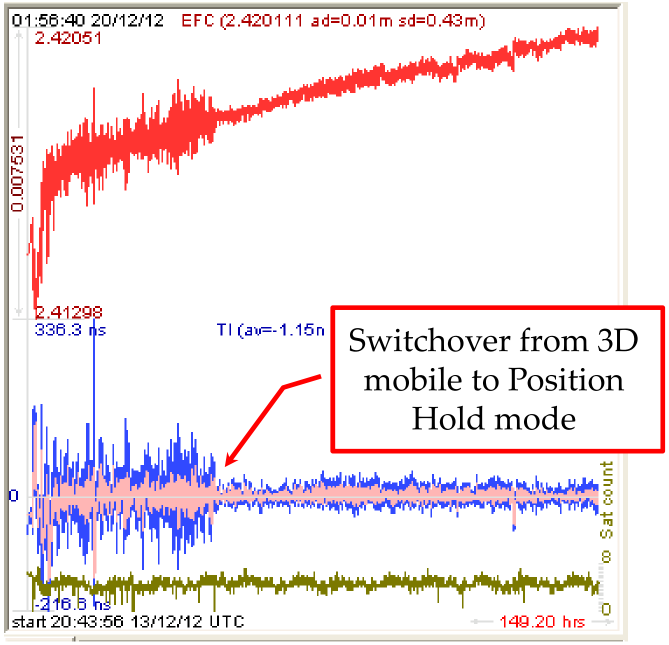
GNSS RECOMMENDATIONS

- Enable Galileo (PRN 300+), and SBAS (PRN 33+)
  - Adds 3 – 7 sats, tracked just like GPS sats



3D Mobile Versus Stationary Operation

- Auto-Survey, Position-Hold mode versus Mobile
  - Position-Hold mode can crucially improve performance in certain conditions
  - Can be used effectively with Auto Survey periods of as short as three minutes
  - Timing Performance improved by ~SQR(Num-Sats)



WEEK 1023 ROLLOVER RECOMMENDATIONS

- Background:
  - Trimble products have started rolling-over week 1023 prematurely
  - Many Trimble products are affected, Trimble does not offer a firmware fix
  - Some products producing incorrect date on February 2016 and July 2017
  - A number of first-responder, financial transaction handling, and other applications were rendered non-operational, some for several weeks until the root-cause could be identified
  - Preview of the major issues that can be expected in April 2019 GPS week rollover

Officials patch York County 911 paging glitch, but questions linger

Jason Addy, 505-5437/@JasonAddyYD Published 4:15 p.m. ET Aug. 9, 2017 | Updated 3:05 p.m. ET Aug. 10, 2017

York County spokesman Mark Walters talks about the recent problems with the county's 911 paging system.

Buy Photo

(Photo: The York Dispatch)

f 10 CONNECT | TWEET | in LINKEDIN | COMMENT | EMAIL | MORE

For more than 10 days, outdated software caused a disconnect between York County 911 dispatchers and emergency responders, but normal order was — mostly — restored Wednesday, Aug. 9, with the installation of new equipment.

About an hour after the equipment updates took effect, dozens of first responders showed up at the county's 911 center in Springettsbury Township to voice concerns — some long-standing, some brought about by the glitch — over emergency communications systems in the area.

A handful of fire chiefs urged county officials to implement a countywide backup system to avoid another prolonged breakdown in communication between responders

TOP VIDEOS

VIDEO: York County Sheriff's K9 Program Fundraiser
1:46

VIDEO: Red Lion wins homecoming football game 31-14 over York High

http://www.yorkdispatch.com/story/news/2017/08/09/york-county-911-paging-glitch-fixed-wednesday/553677001/

A.10.30 Report Packet 0x8F-AB Primary Timing Packet

This automatic output packet provides time information once per second if enabled with packet 0x8E-A5. GPS week number, GPS time-of-week (TOW), UTC integer offset, time flags, date and time-of-day (TOD) information is provided. This packet can be requested with packet 0x8E-AB. This packet will begin transmission within 20 ms after the PPS pulse to which it refers.

Data Fields:

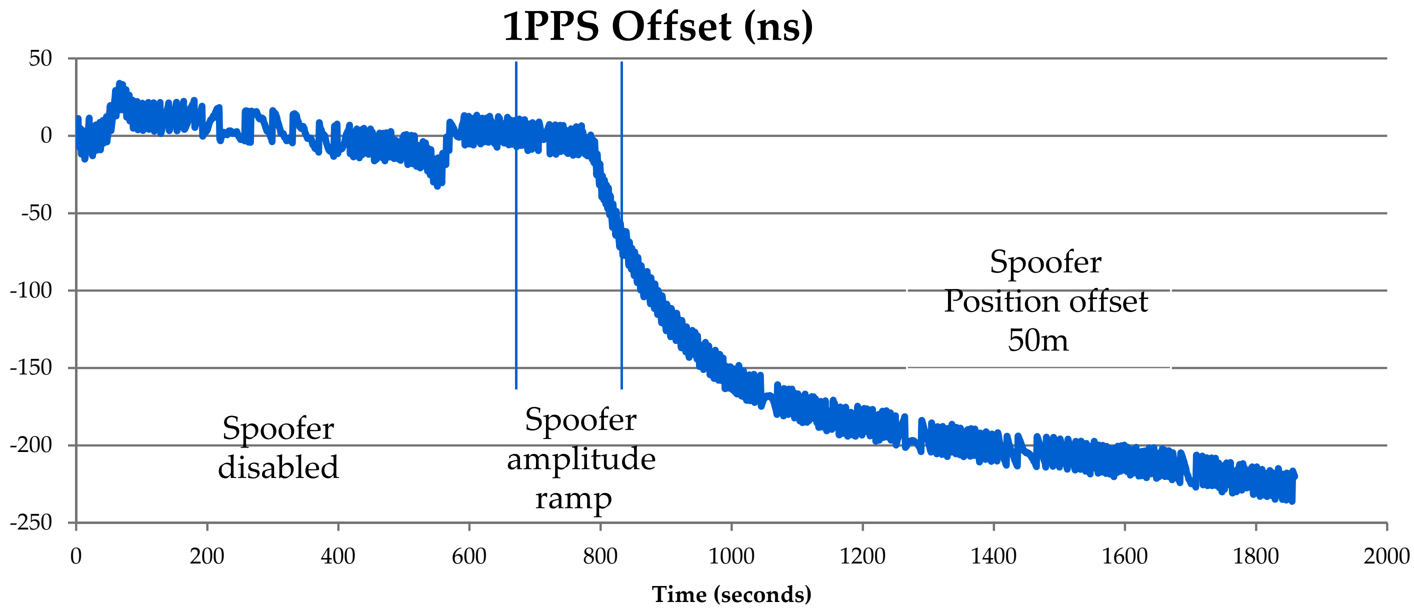
Time of Week: This field represents the number of seconds since Sunday at 00:00:00 GPS time for the current GPS week. Time of week is often abbreviated as TOW.

Week Number: This field represents the current GPS week number. GPS week number 0 started on January 6, 1980. Unfortunately, the GPS system has allotted only 10-bits of information to carry the GPS week number and therefore it rolls-over to 0 in just 1024 weeks (19.6 years,) and there is no mechanism built into GPS to tell the user to which 1024 week epoch the week number refers. The first week number roll-over will occur as August 21, 1999 (GPS) transitions to August 22, 1999 (GPS). The ThunderBolt adjusts for this week rollover by adding 1024 to any week number reported by GPS which is less that week number 936 which began on December 14, 1997. With this technique, the ThunderBolt will provide an accurate translation of GPS week number and TOW to time and date until July 30, 2017.

UTC Offset: This field represents the current integer leap second offset between GPS and UTC according to the relationship: Time (UTC) = Time (GPS) - UTC Offset. The UTC offset information is reported to ThunderBolt by the GPS system and can take up to 12.5 minutes to obtain. Before the ThunderBolt has received UTC information from the GPS system, it is only capable of representing time in the GPS time scale, and the UTC offset will be shown as 0.

SPOOFING SIMULATION

- Spoofing Simulation: JLT M12M (u-blox M8T), Position-Hold Mode
  - Spoofer power ramp-rate: 1 min. to +40dB relative to Live Sky
  - Spoofer position pseudorange error offset 50 meters relative to victim ant.
  - Spoofer has no added Phase or Frequency error versus UTC



M12M Position Spoofing

- Position Offset by 50 meters
- Motorola M12M (3D Mobile) with 12dB/minute Signal Ramp, 5 min.

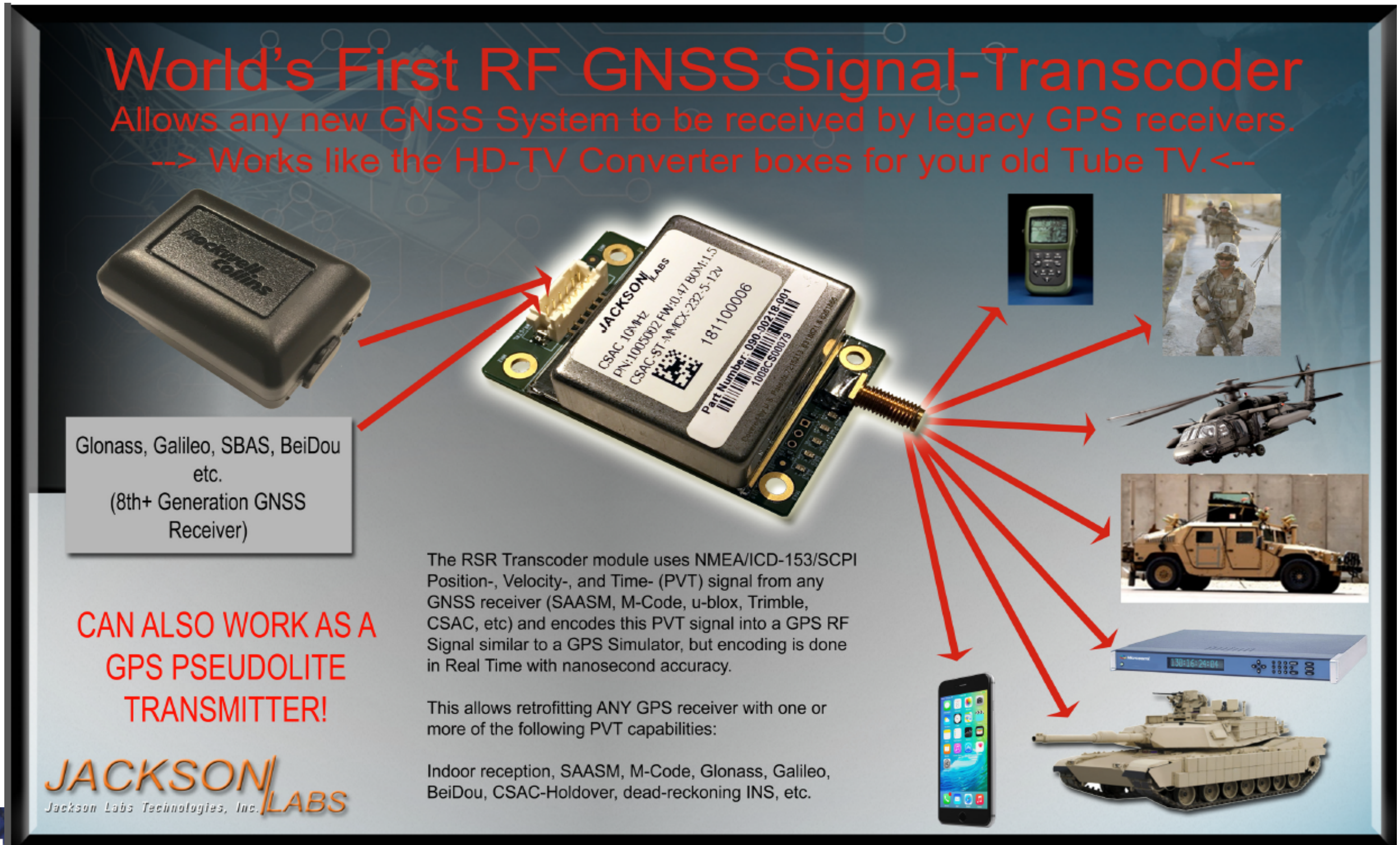
m12-300s-spoof-final.mp4

uBlox M8T Position Spoofing

- Position Offset by 50 meters
- u-blox M8T (3D Mobile) with 12dB/minute Signal Level Ramp, 5 min.

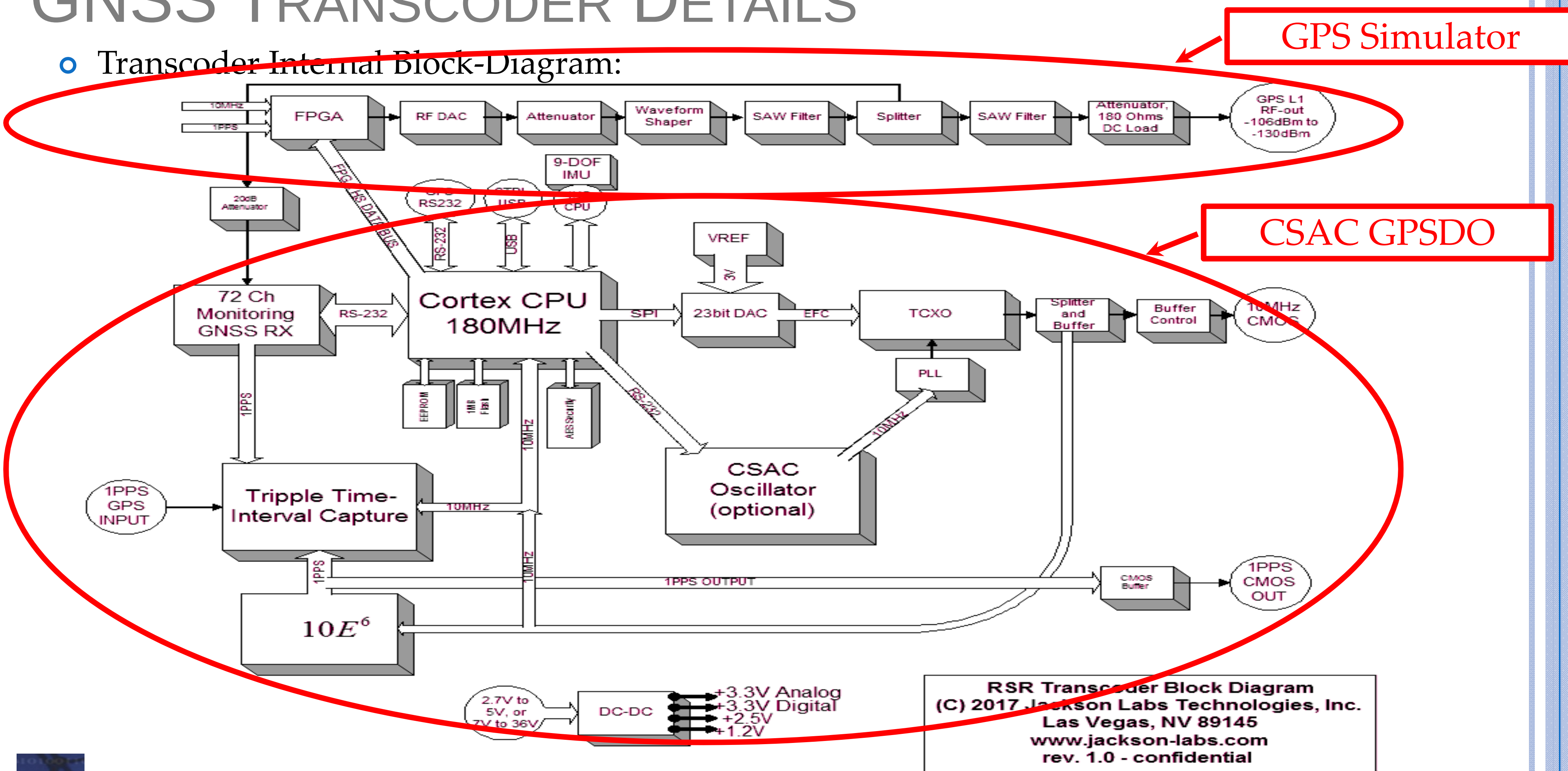
ublox8-300s-spoof-final.mp4

702.233.1334 p | 702.233.1073 f | www.jackson-labs.com


World's First RF GNSS Signal-Transcoder
Allows any new GNSS System to be received by legacy GPS receivers.
--> Works like the HD-TV Converter boxes for your old Tube TV.<--
Rockwell Collins
Glonass, Galileo, SBAS, BeiDou etc.
(8th+ Generation GNSS Receiver)
CAN ALSO WORK AS A GPS PSEUDOLITE TRANSMITTER!
The RSR Transcoder module uses NMEA/ICD-153/SCPI Position-, Velocity-, and Time- (PVT) signal from any GNSS receiver (SAASM, M-Code, u-blox, Trimble, CSAC, etc) and encodes this PVT signal into a GPS RF Signal similar to a GPS Simulator, but encoding is done in Real Time with nanosecond accuracy.
This allows retrofitting ANY GPS receiver with one or more of the following PVT capabilities:
Indoor reception, SAASM, M-Code, Glonass, Galileo, BeiDou, CSAC-Holdover, dead-reckoning INS, etc.
JACKSON LABS
Jackson Labs Technologies, Inc.

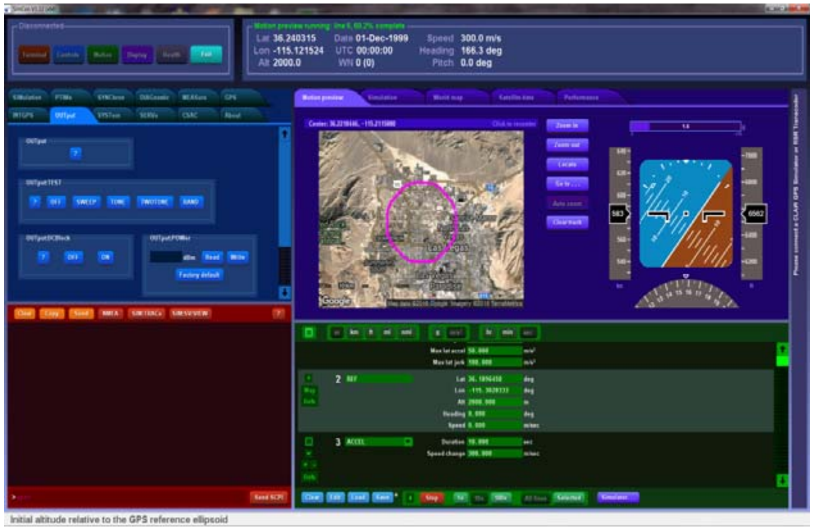
GNSS Transcoder Details

- Transcoder Internal Block-Diagram:



NEW PRODUCTS FOR 2018

- Micro-JLT GNSS™: low-cost, high volume GNSDO
- FireFly and CSAC update with concurrent GNSS capability (Q4)
- Transcoder series with comprehensive SAASM target-receiver support
- New DROR-IIA variant with 1PPS timing sync and enhanced locking
- CSAC products will get a software face-lift for faster initial phase lock
- SimCon GPS Simulator Windows Application Full release



Focus Telecom
TIMING / SYNCH. & TELECOM SOLUTIONS

Microsemi

Focus Telecom Microsemi

SYNC SMART 2018

SYNC IN THE CYBER AGE

SYNCSMART 2018 - MAY 30
The SHARON HOTEL HERZLIA 4, Ramat Yam St.