Rb Atomic Clocks for wireless mobile(5G) and Test & Measurement applications

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Clocks BU

Agenda

- Test & Measurement requirements and Oscillator options
  - Legacy and new options
- Reasons to consider Gas cell clocks
  - g-sensitivity, vibration/shock, drift performance data
- New Features/enhancements of Rb-CPT clocks
  - Drift, calibration, warm-up time, retrace, temperature sensitivity data

Traditional Oscillator Requirements for the T&M market

- Low profile height, small size
- Good phase noise & ADEV
- Low aging (enables long calibration cycle time)
- Low power consumption (enables battery-powered applications)
- Temperature Stability (for mobile applications)

- OCXO was the traditional choice due to low power, cost, size and STS.
- Lamp offered good stability, but too big.

	OCXO	Rb-Lamp
Cost	$	$$$
Power (W)	3 to 4	10 to 18
Volume (cm^3)	15 to 20	200 to 500
Warm-up time:		
-Time to $5x10^{-8}$ (min's.)	3	5
-Time to $1x10^{-10}$ (min's.)	n/a	12
1PPS calibration	No	Yes
Temperature range (˚C)	-40 to +85	-10 to +75
Stability:		
-TempCo ($x10^{-9}$)	±0.4	<0.6
-ADEV @1s ($x10^{-12}$)	5	10 to 30
-Aging/month ($x10^{-11}$)	83	5
-Retrace ($x10^{-10}$)	20	0.2

Telecom Oscillator Requirements for the T&M market

- Modern Telecom measurement requirements:
  - SyncE (G.826x) and IEEE1588v2 (PTP) Measurements require **Nanosecond** accuracy
    - Packet Delay Variation (PDV)
    - Time Error
    - Needs to be maintained w/o GNSS (±45ns to UTC): vendor requirement for stable environment test
  - Ethernet and IP one-way delay (OWD) network latency
    - Locate assymmetric network delays
  - Ability to emulate a PTP grand master (PRTC) base station-level accuracy
  - **Frequency accuracy** <1.5E-11 over 2 hours, 2.5E-11/day
    - Longer duration/variable temperature requirements:
      - Timing accuracy of 300ns (holdover) in 10,000s (~2.5hours)
      - Timing accuracy in variable temperature environment: 7us (holdover) in 24hours (0 to +60C range).
  - **1PPS input for GNSS receiver disciplining**, Time-of-Day information

Tighter timing requirements have necessitated high performance oscillators as a reference. Rb is one option to consider…

Oscillators options for T&M

- Rb-CPT clocks emerged 10 years ago as alternative to OCXO to meet more stringent timing requirements
  - Smaller size with minor compromise in performance, compared to lamp.
- Modern Rb-CPT has closed the Lamp performance gap.
  - Enabled by higher processing power and electronics miniaturization

	OCXO	Rb-Lamp	Rb-CPT	(Next-Gen) Rb-CPT
Cost	$	$$$	$$$	$$$
Power (W)	3 to 4	10 to 18	5	6.5
Volume (cm^3)	15 to 20	200 to 500	50	50
Warm-up time:				
-Time to $1x10^{-10}$ (min's.)	n/a	12	15	7
1PPS calibration	No	Yes	No	Yes
Temperature range (˚C)	-40 to +85	-10 to +75	-10 to +75	-40 to +75
Stability:				
-TempCo ($x10^{-9}$)	±0.4	<0.6	<0.1	<0.1
-ADEV @1s ($x10^{-12}$)	5	10 to 30	30	20
-Aging/month ($x10^{-11}$)	83	5	10	5
-Retrace ($x10^{-10}$)	20	0.2	0.5	0.5

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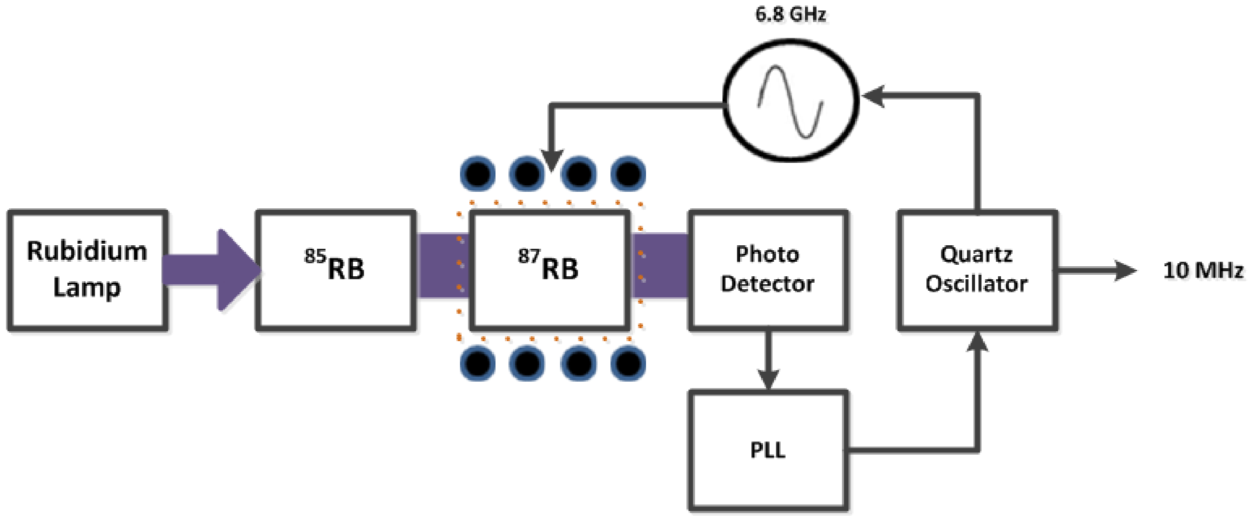
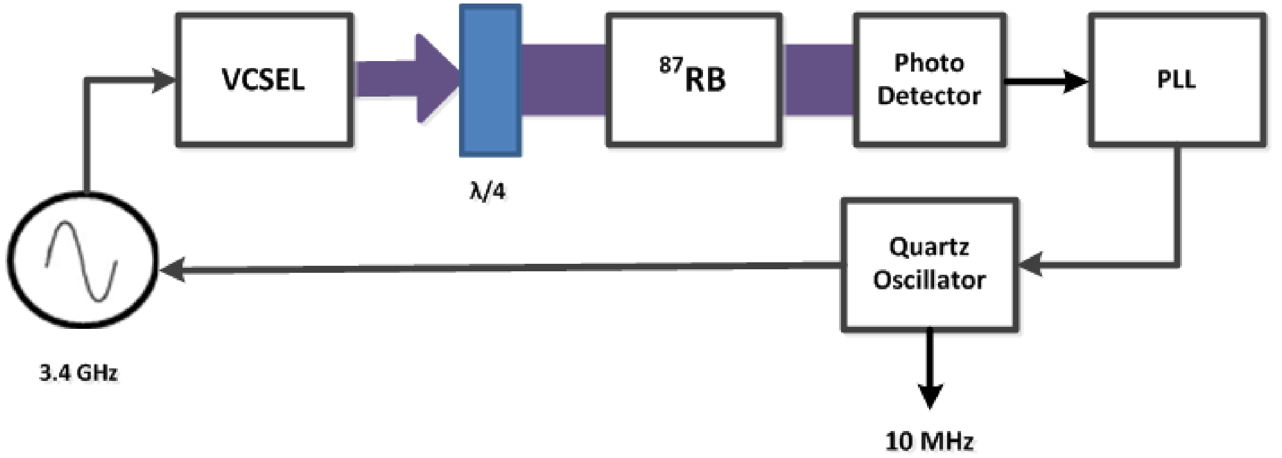
CPT Versus Lamp-based Clocks



Simplified Lamp Based Rubidium Clock Model

Lamp Based Clock

- Lamp
- Microwave Resonator
- Characteristics
  - Higher Power
  - Higher Heat
  - Larger Size
  - Lower Reliability



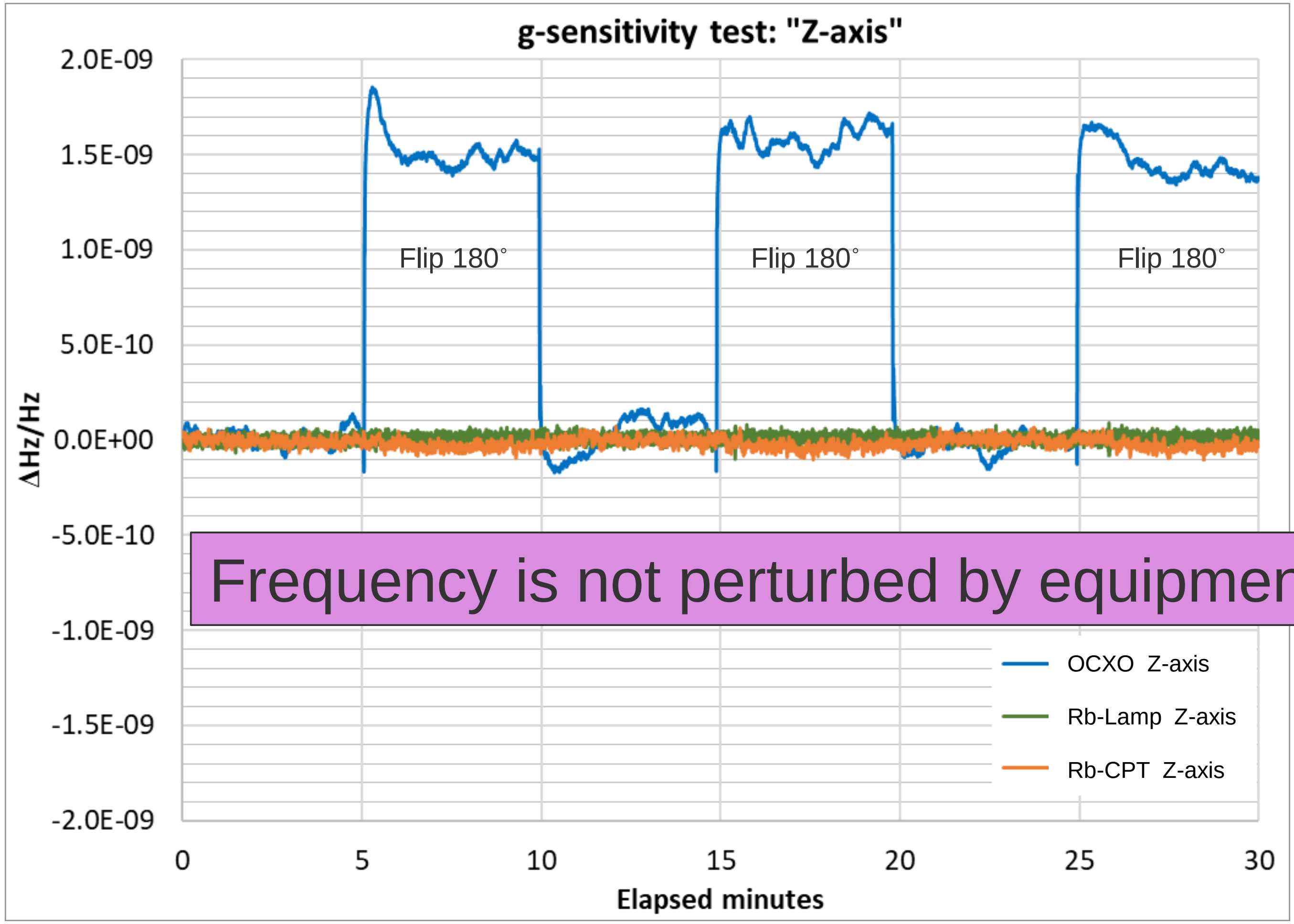
Simplified CPT Based Rubidium Clock Model

CPT Based Clock

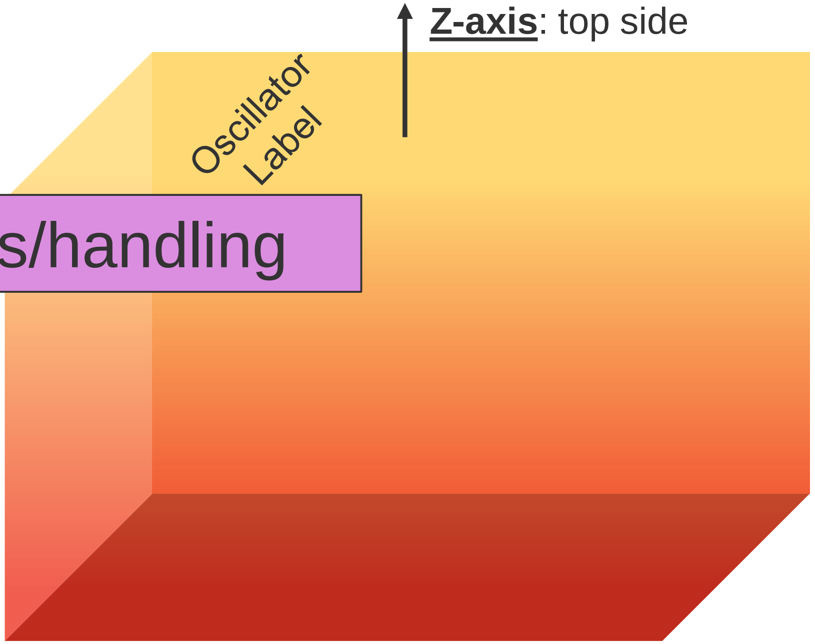
- Laser (no lamp)
- No Microwave Resonator
- Characteristics
  - Lower Power
  - Lower Heat
  - Smaller Size
  - Higher Reliability

g-sensitivity: 2g tip-over test

- ΔFrequency / g = $(f_{max} – f_{min})/2$



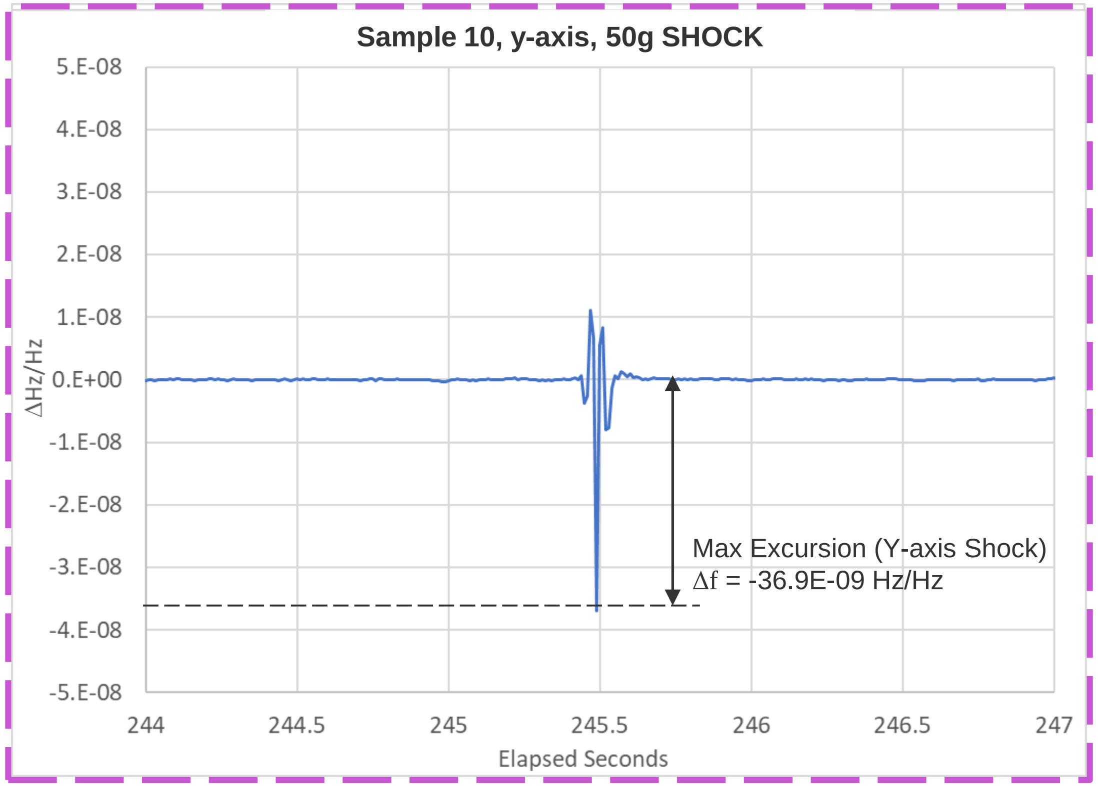
Device	Δfreq/g X-axis	Δfreq/g Y-axis	Δfreq/g Z-axis
OCXO	0.20ppb	0.75ppb	0.75ppb
Rb-CPT_1	<0.10ppb	<0.10ppb	<0.10ppb
Rb-Lamp_1	<0.10ppb	<0.10ppb	<0.10ppb



Frequency is not perturbed by equipment rotations/handling

Shock: Rb-CPT clock Freq. excursions

- Three Rb-CPT samples
  - 30g & 50g shock
    - Profile: 11mS, Half Sine
      - 6 shocks/axis (3 + / 3 -)
  - Y-axis is most sensitive (~10x)



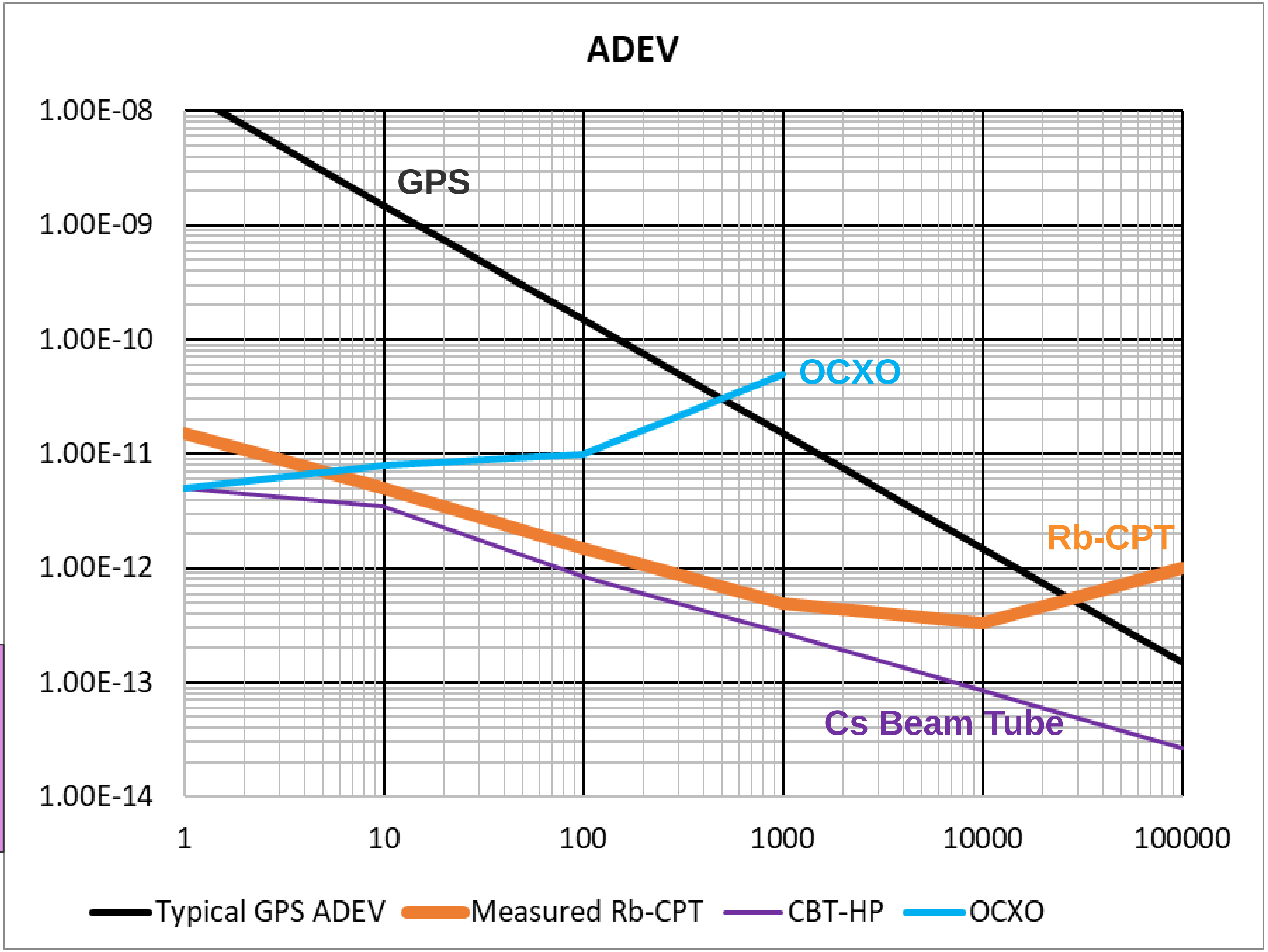
SN	Shock Level	Max excursion (ΔHz/Hz) X-axis	Max excursion (ΔHz/Hz) Y-axis	Max excursion (ΔHz/Hz) Z-axis
Sample 10	30g	1.68E-09	22.0E-09	1.35E-09
	50g	3.43E-09	**36.9E-09**	3.04E-09
Sample 18	30g	1.84E-09	17.5E-09	2.28E-09
	50g	2.28E-09	31.0E-09	3.37E-09
Sample 34	30g	1.61E-09	21.0E-09	1.85E-09
	50g	3.63E-09	34.9E-09	1.87E-09

Frequency comes back after momentary shock perturbation

ADEV of various frequency references

- Generally OCXO has superior short term stability
- Rb has better mid to long term stability
  - Enabling better holdover for durations > several hours
- PLL featuring Rb and GPS approaches performance of a CBT

Enables longer duration between frequency re-calibration



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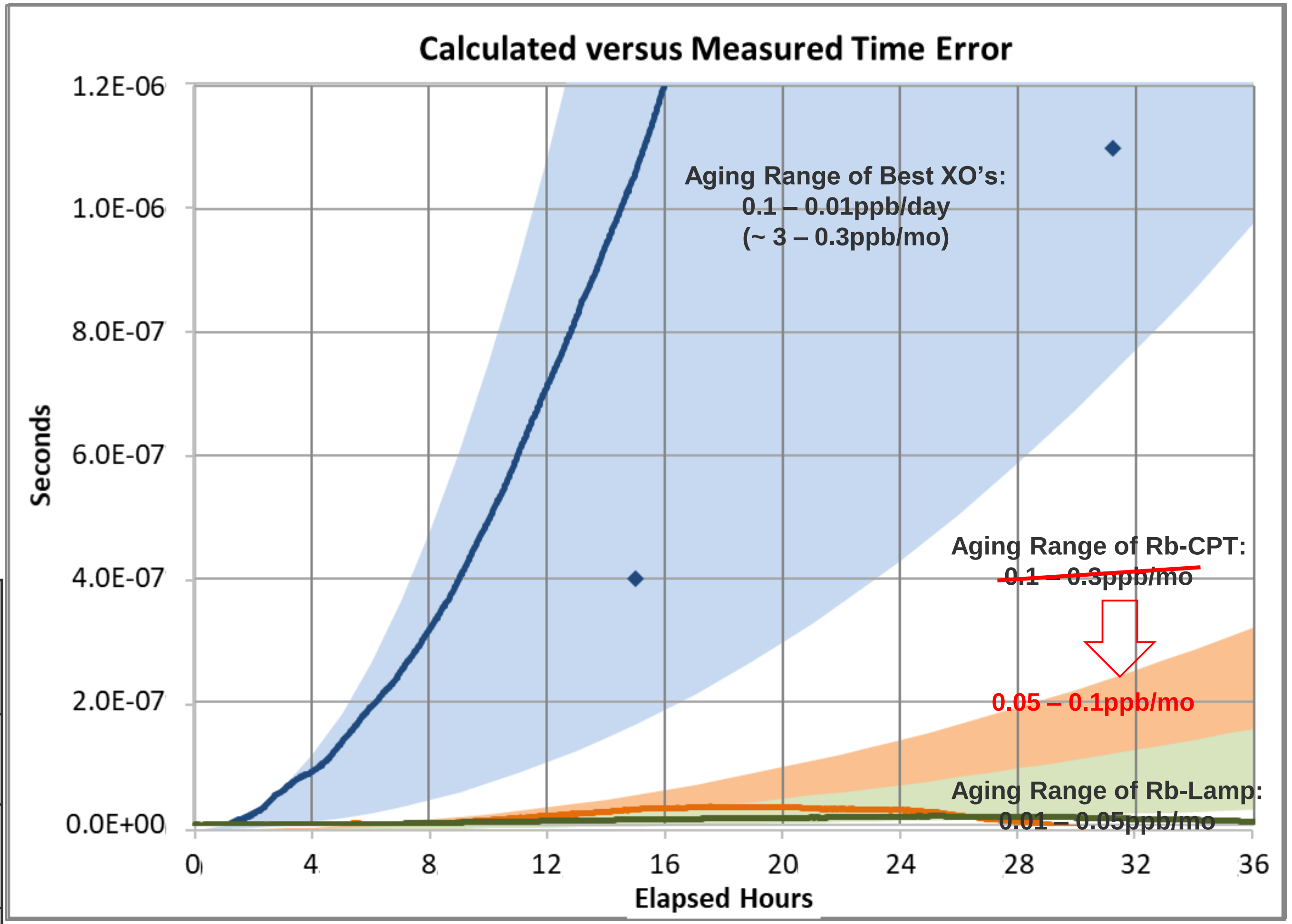
Aging, Time Error of various timing references

- Recent developments in Quartz have pushed performance toward Rb-CPT clocks
- Similarly, Next Gen Rb-CPT clocks have filled the performance gap between CPT and Lamp designs

Rb = Nanosecond Timing accuracy

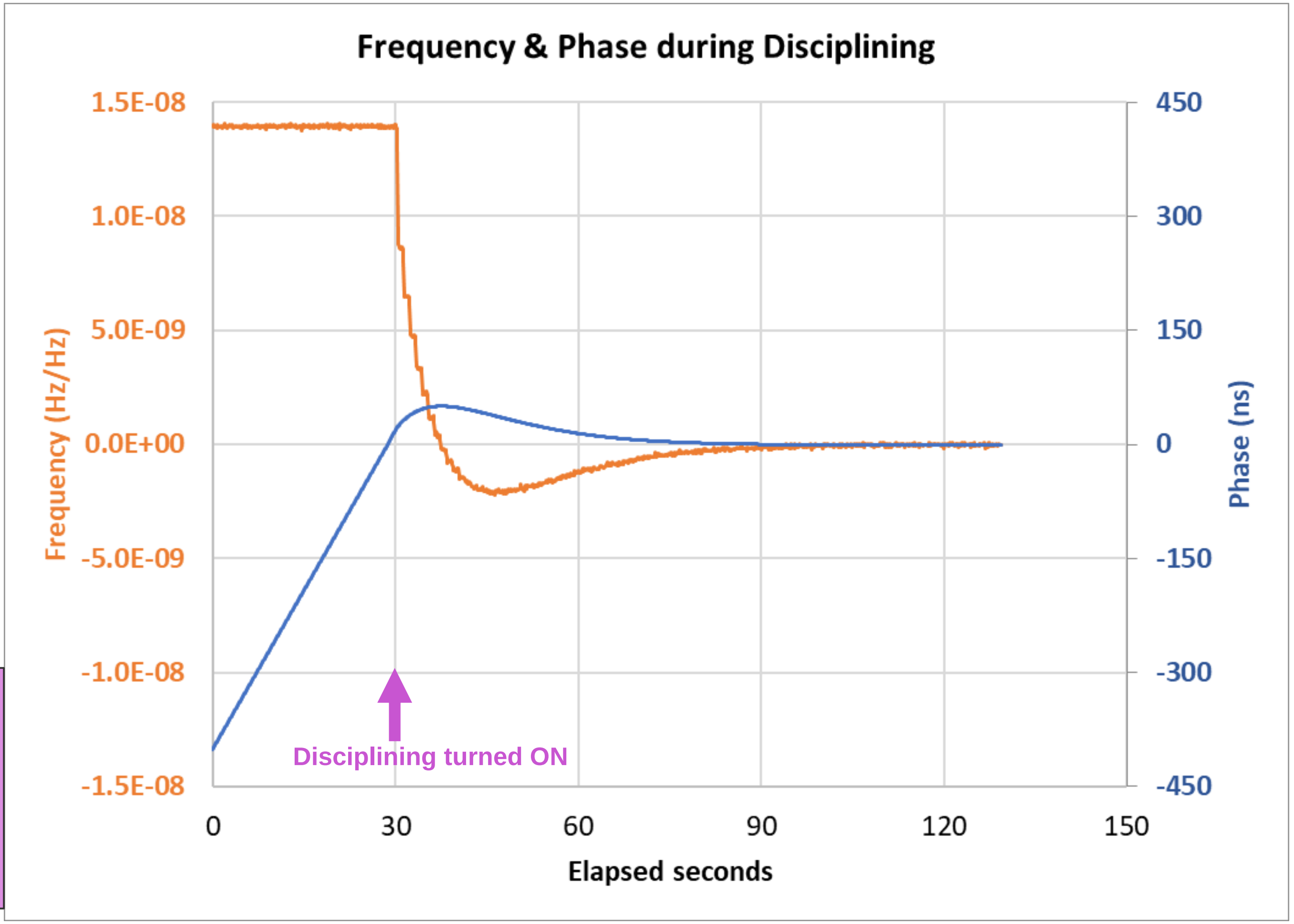
Device	**TE (ns) @ 8h**	**TE (ns) @ 16h**	**TE (ns) @ 24h**	**TE (ns) @ 36h**
OCXO	48 – 480	192 – 1,920	432 – 4,320	972 – 9,720
Rb-CPT (Nex-Gen)	8 – 16	32 – 64	72 – 144 ns	162 – 324
Rb-Lamp	1.6 – 8	6.4 – 32	14.4 – 72 ns	32.4 – 162



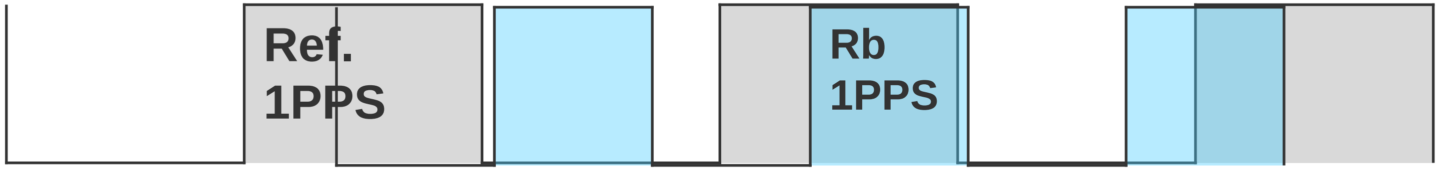
Calculated based upon zero initial freq/phase error. No environmental perturbations.

Calibration: Rb-CPT allows 1PPS disciplining

- Some oscillators allow an input 1PPS signal to correct the output frequency
  - If using a valid GPS, the clock can be steered to UTC (**Minutes**)
  - Generally there is a trade-off between size/cost with this added functionality
    - Embedded into a module or,
    - Included within modern CPT clocks



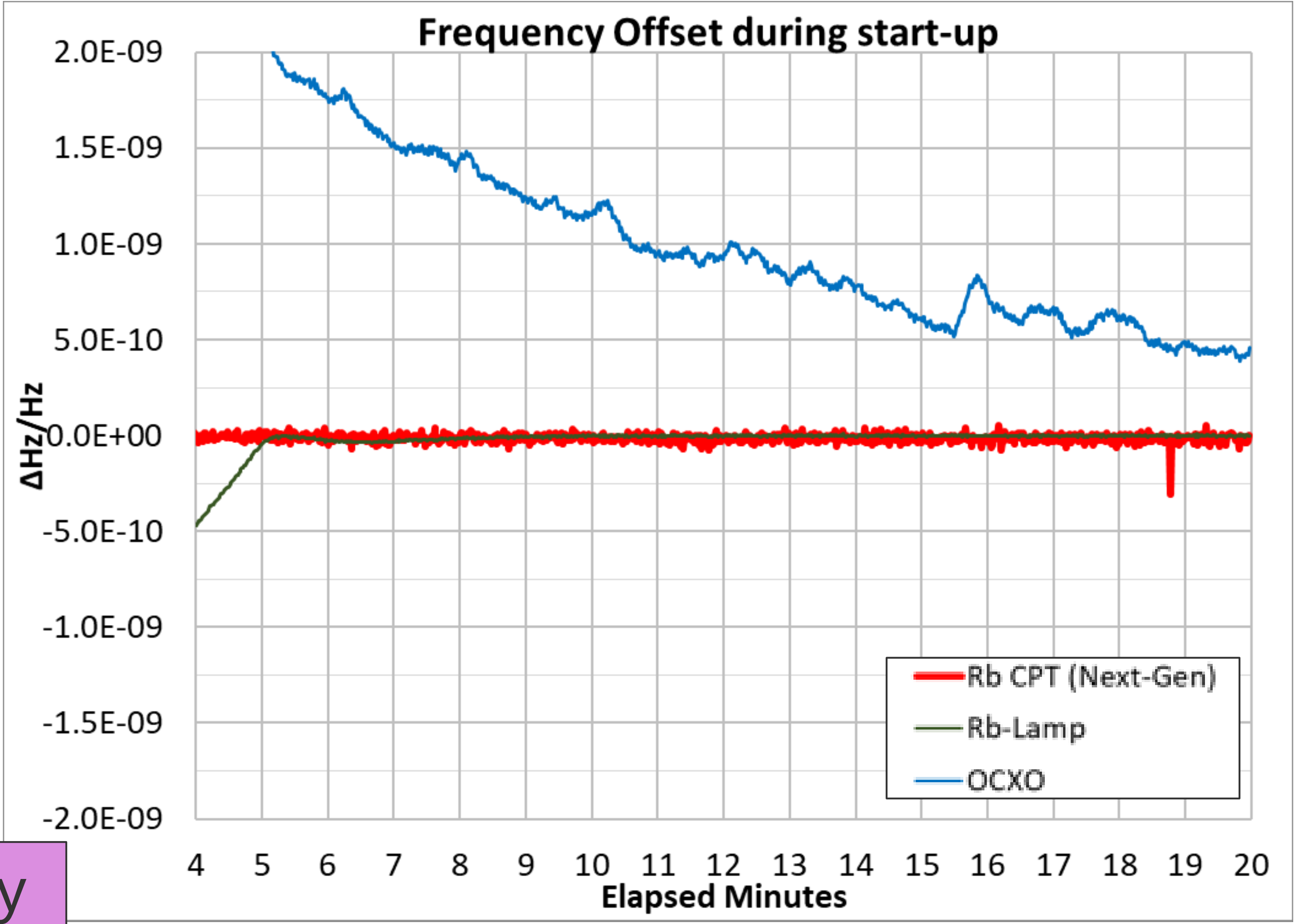
New PPS disciplining algorithms enable rapid frequency calibration
= More test-time



Warm-up performance

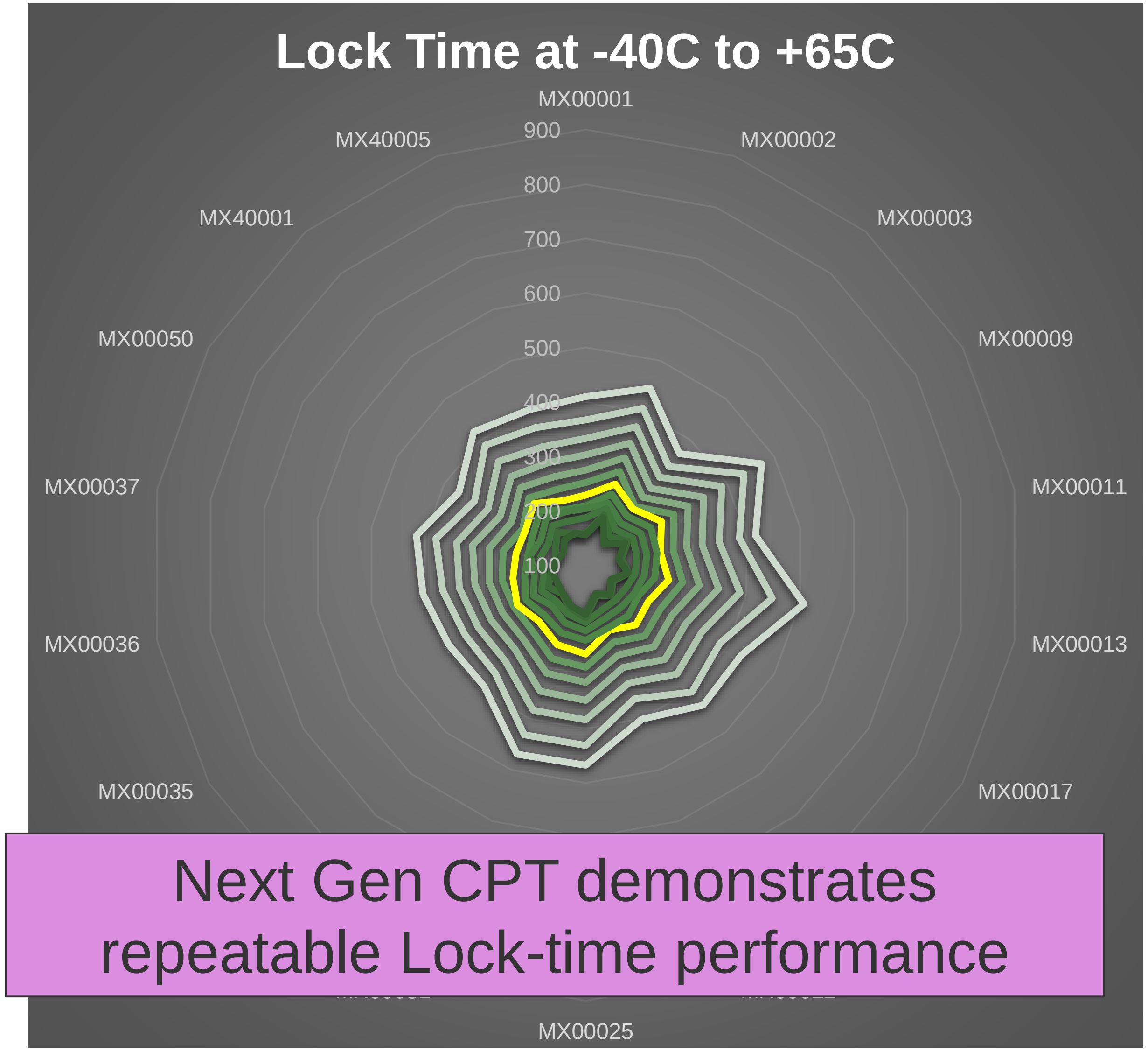
- Rb clocks sweep their TCXO during Lock-acquisition.
  - User must wait until Lock is complete
- OCXO has the nice feature of having $<5x10^{-8}$ accuracy within a few minutes of power-on.
- Now, Next Gen Rb-CPT clocks:
  - $\sim 5x10^{-8}$ accuracy immediately after power-on
  - $\pm 5x10^{-11}$ accuracy within several minutes of power-on
  - Consistent Lock times

Next Gen CPT has a usable frequency immediately after power-on



It takes several days for OCXO's to reach the aging rates cited previously.

Warm-up (a closer look at the Rb-CPT clock)



Next Gen CPT demonstrates repeatable Lock-time performance

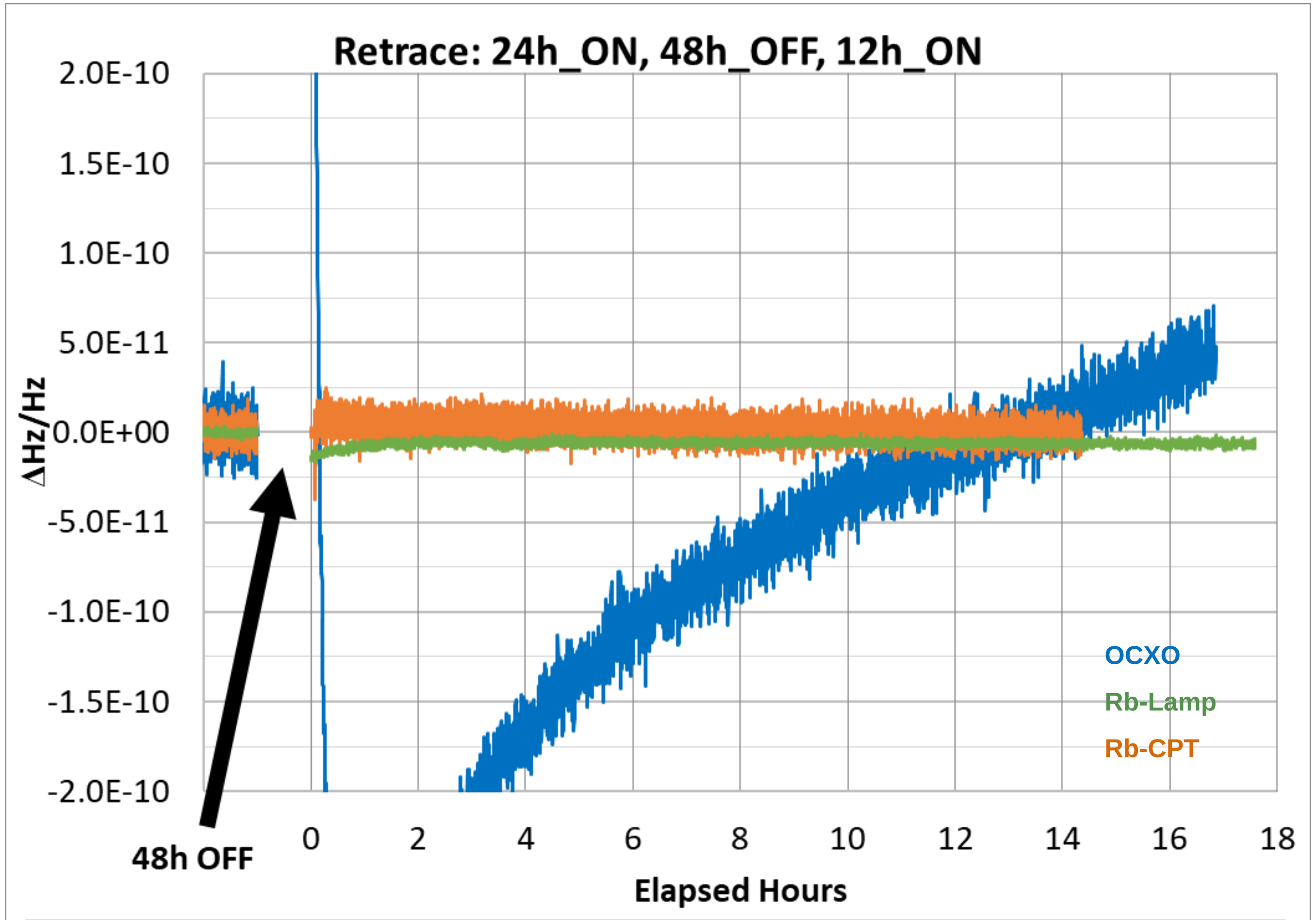
180 trials at 12 ambient temperature settings: All Lock within specification (< 6minutes from -10 to +65C)

Temperature	Attempts
-40 C	180
-30 C	180
-20 C	180
-10 C	180
0 C	180
+10 C	180
+20 C	180
+30 C	180
+40 C	180
+50 C	180
+60 C	180
+65 C	180

Retrace test

- 24h ON
  - (measure f_1)
- 48h OFF
- 12h ON
  - (measure f_2)
- Compute $\Delta f = f_2 - f_1$
- Important for power-down app's

Device	**Retrace 1h**	**Retrace 2h**	**Retrace 4h**	**Retrace 8h**	**Retrace 12h**	**Retrace Spec.**
OCXO	0.40ppb	0.30ppb	0.20ppb	0.10ppb	0.10ppb	±2.00ppb
Rb-CPT	0.03ppb	0.03ppb	0.02ppb	0.02ppb	0.02ppb	±0.05ppb
Rb-Lamp	0.02ppb	0.01ppb	0.01ppb	0.01ppb	0.01ppb	±0.03ppb



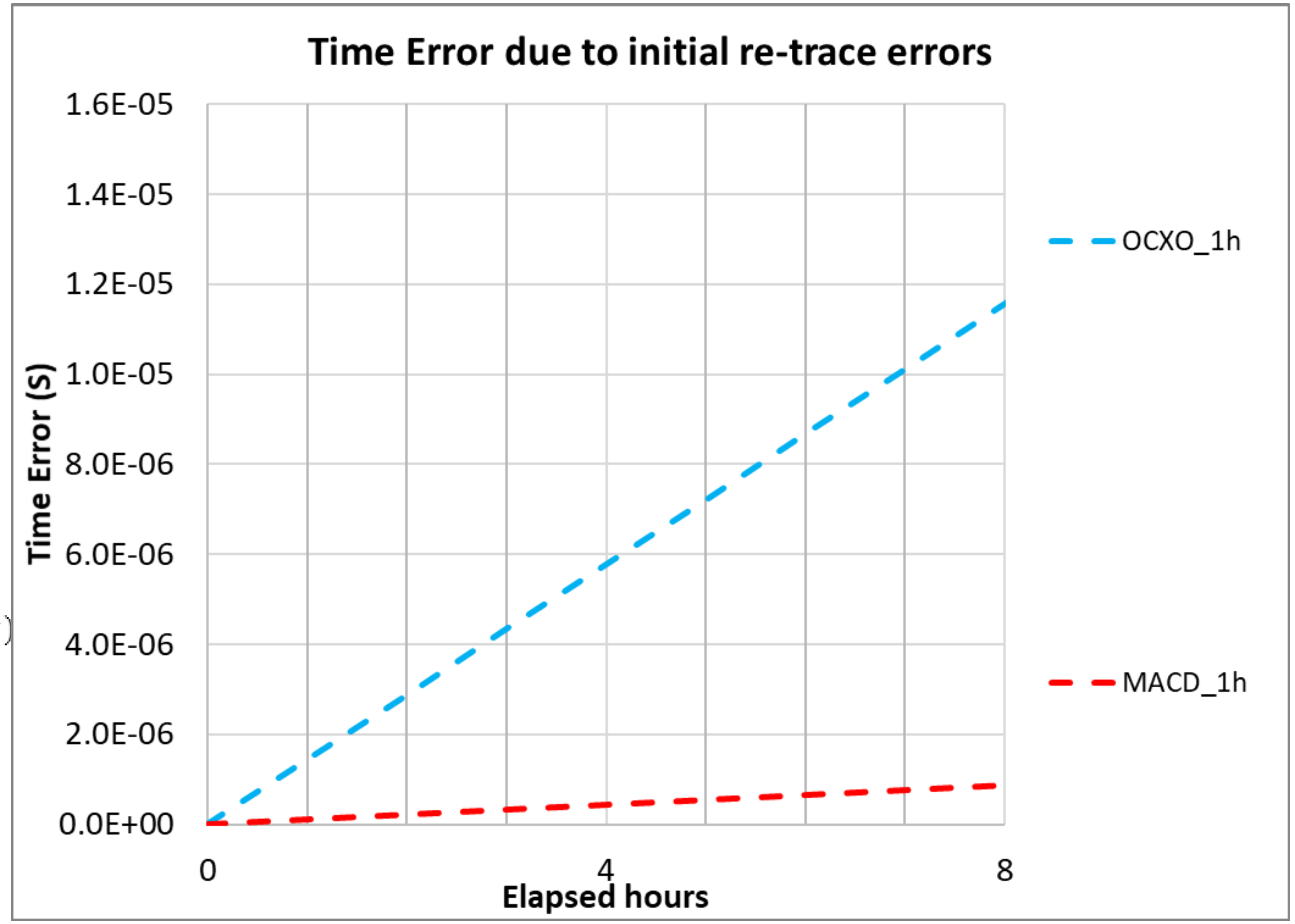
Fast re-trace enables equipment to quickly achieve accuracy after power-cycle

The consequences of poor re-trace: Growing Time Error

- Test set repeatability is effected by re-trace
- Time error of measurements taken 8 hours apart:
  - OCXO @ 8h = 3, 6 , 12 us, depending on initial retrace offset
  - Rb @ 8h **< 1 us**, for all retrace offsets

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

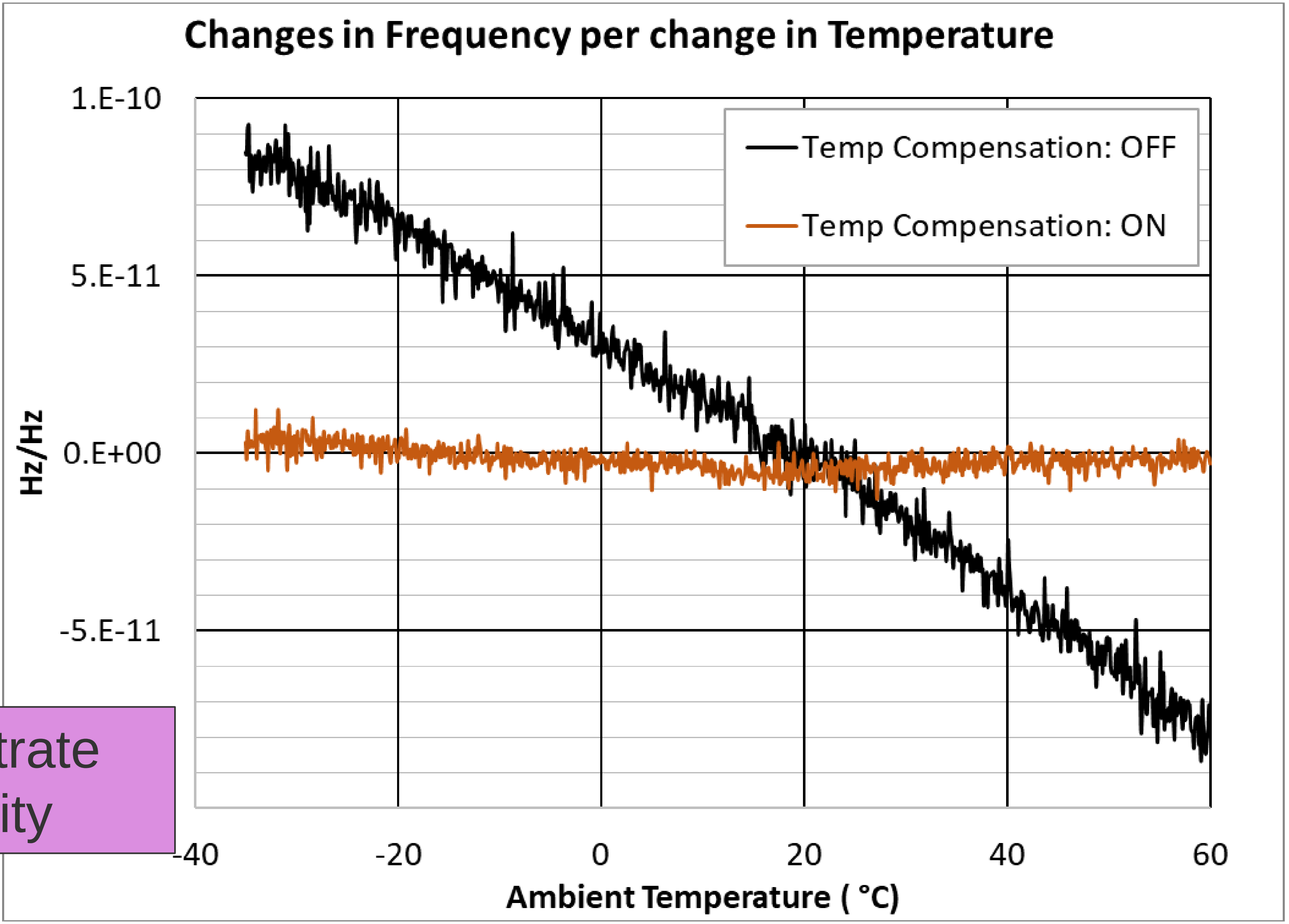
Device	Retrace 1h	Retrace 4h	Retrace 12h
OCXO	0.40ppb	0.20ppb	0.10ppb
Rb-CPT	0.03ppb	0.02ppb	0.02ppb



OCXO @ 8h = 3, 6 , 12 us, depending on initial retrace offset
Rb @ 8h < 1 us, for all retrace offsets

Temperature Sensitivity

- Extra processing power in modern Rb allows for compensation of temperature effects
- TempCo can be improved ~10x
  - Δf < ±1E-11, for this unit
  - (-35 to +60C)
- Compensation is performed at the factory
  - Invisible to end-user

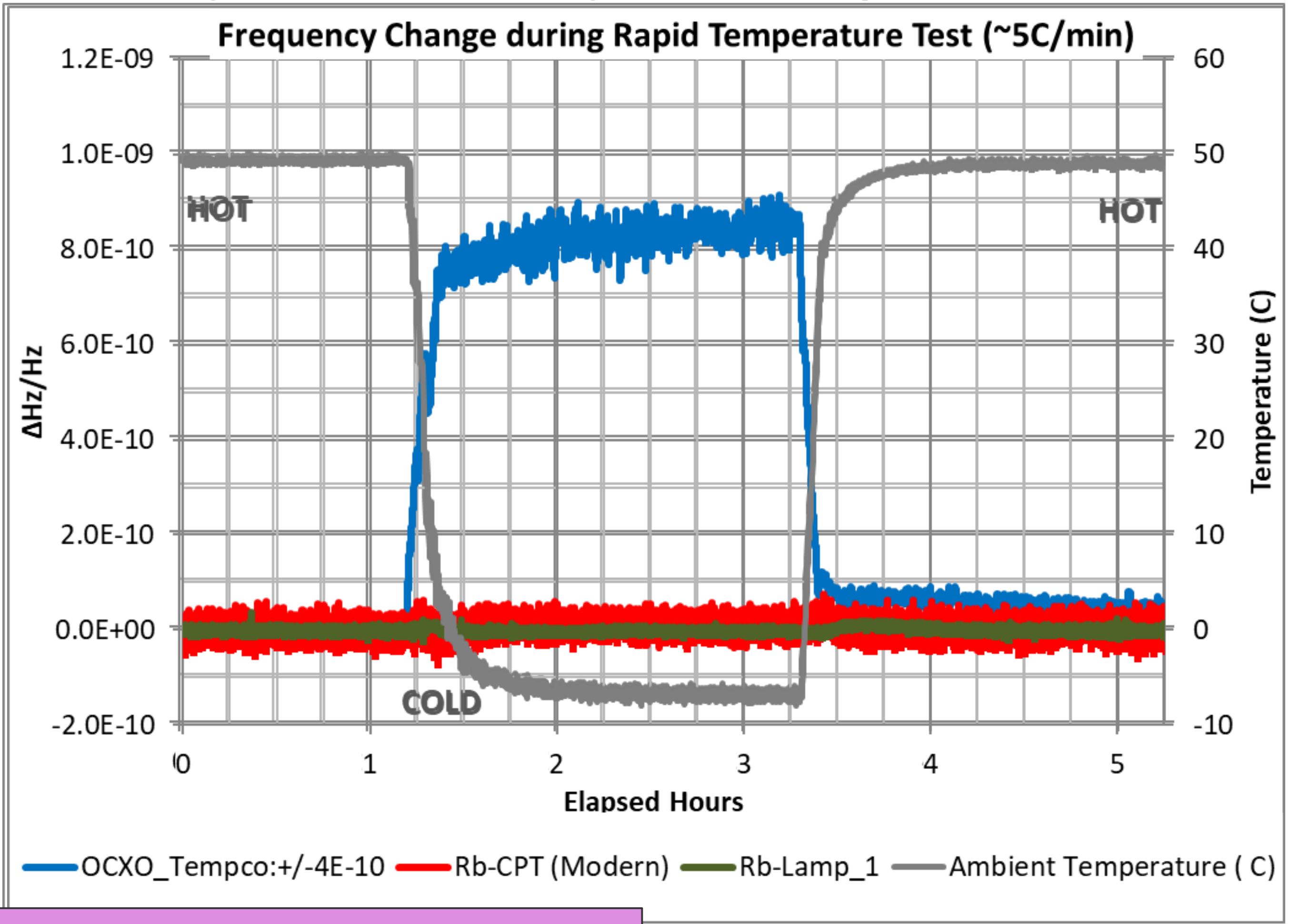


Next Gen CPT clocks demonstrate excellent Temperature Stability

Temperature Sensitivity: Extreme case

- Atomic clocks are especially good at resisting drastic changes in temperature
  - This test:
    - Rapidly cool 50 → -5 ˚C in 15 minutes
      - Soak for 2 hours
    - Rapidly heat -5 → 50 ˚C in 15 minutes
      - Soak for 2 hours

Device	Measured Δfreq. (max)	Specification	Specification Range
OCXO	***0.85ppb***	±0.40ppb	0 to +70˚C
Rb-CPT (Next-Gen)	***0.18ppb***	TBD	-40 to +75˚C
Rb-Lamp	***0.05ppb***	0.60ppb	-25 to +70˚C



Rb demonstrates ability to resist drastic temperature changes

What about Chip Scale Atomic Clocks?

- Chip Scale Atomic Clock
  - Low Noise versions too
- Advantages:
  - Power/Size
  - milliWatts
- Dis-Advantages:
  - Temp. Range
  - Aging
  - Price Point

	OCXO	Rb-Lamp	Rb-CPT	(Next-Gen) Rb-CPT	Chip Scale Atomic Clock
Cost	$	$$$	$$$	$$$	**$$$$**
Power (W)	3 to 4	10 to 18	5	6.5	**0.12**
Volume (cm^3)	15 to 20	200 to 500	50	50	**17**
Warm-up time:					
-Time to $5x10^{-8}$ (min's.)	3	5	15	7	4
-Time to $1x10^{-10}$ (min's.)	n/a	12	15	7	3
1PPS calibration	No	Yes	No	Yes	Yes
Temperature range (˚C)	-40 to +85	-10 to +75	-10 to +75	-40 to +75	-10 to +70
Stability:					
-TempCo ($x10^{-9}$)	±0.8	<0.6	<0.1	<0.1	±0.5
-ADEV @1s ($x10^{-12}$)	5	10 to 30	30	20	30
-Aging/month ($x10^{-11}$)	83	5	10	5	**90**
-Retrace ($x10^{-10}$)	20	0.2	0.5	0.5	5

Conclusions

- Electronics miniaturization and increased processing power has enabled improvements to temperature, stability and additional features
- Modern Rb-CPT clocks have leveraged these improvements to enable superior performance in mobile T&M applications
  - **FASTER CALIBRATIONS**: 1PPS Disciplining, warm-up time
  - **LONGER TIME BETWEEN RE-CALIBRATIONS**: mid / long-term stability, re-trace
  - **SUITABLE FOR HAND-HELD'S**: g-sensitivity, vibe
  - **SUITABLE FOR OUTDOOR USE**: excellent temperature stability
- Superior holdover stability enables more time with an accurate frequency / timing reference, enabling longer test-equipment run-time.