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Commercial Atomic Oscillators versus Crystal Oscillators

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Clocks and Frequency references

Technology	Intrinsic Accuracy ($\Delta\text{Hz}/\text{Hz}$)	1S-ADEV ($\Delta\text{Hz}/\text{Hz}$)	ADEV floor ($\Delta\text{Hz}/\text{Hz}$)	Aging (/day) ($\Delta\text{Hz}/\text{Hz}$)	Power (W)	Cost
H-Maser	$\sim 10^{-11}$	$\sim 10^{-13}$	$\sim 10^{-15}$	10^{-15} to 10^{-16}	100	$\sim 150X$
Cs Beam	$\sim 10^{-13}$	$\sim 10^{-11}$	$\sim 10^{-14}$	~ 0	30	$\sim 20X$
Passive HM	$\sim 10^{-10}$	$\sim 10^{-12}$	$\sim 10^{-15}$	10^{-15}	100	$\sim 40X$
Rb-Lamp (Gas Cell)	$\sim 10^{-9}$	$\sim 10^{-11}$	$\sim 10^{-13}$	10^{-11} to 10^{-13}	10	$\sim X$
Rb-CPT	$\sim 10^{-9}$	$\sim 10^{-11}$	$\sim 10^{-13}$	10^{-11} to 10^{-13}	0.125 to ~ 6	$\sim X$
Hi-quality Qz	10^{-6} to 10^{-8}	$\sim 10^{-12}$	$\sim 10^{-12}$	10^{-9} to 10^{-11}	~ 5	$\sim 0.5X$



H- Masers 1955



CBT (5071A) - 1955



RbO
1958 – 1970s



Rb Gas Cell (XPRO)
1995



Rb Gas Cell (SA.22c / X72)
1997



SA.3Xm (MAC)
2008



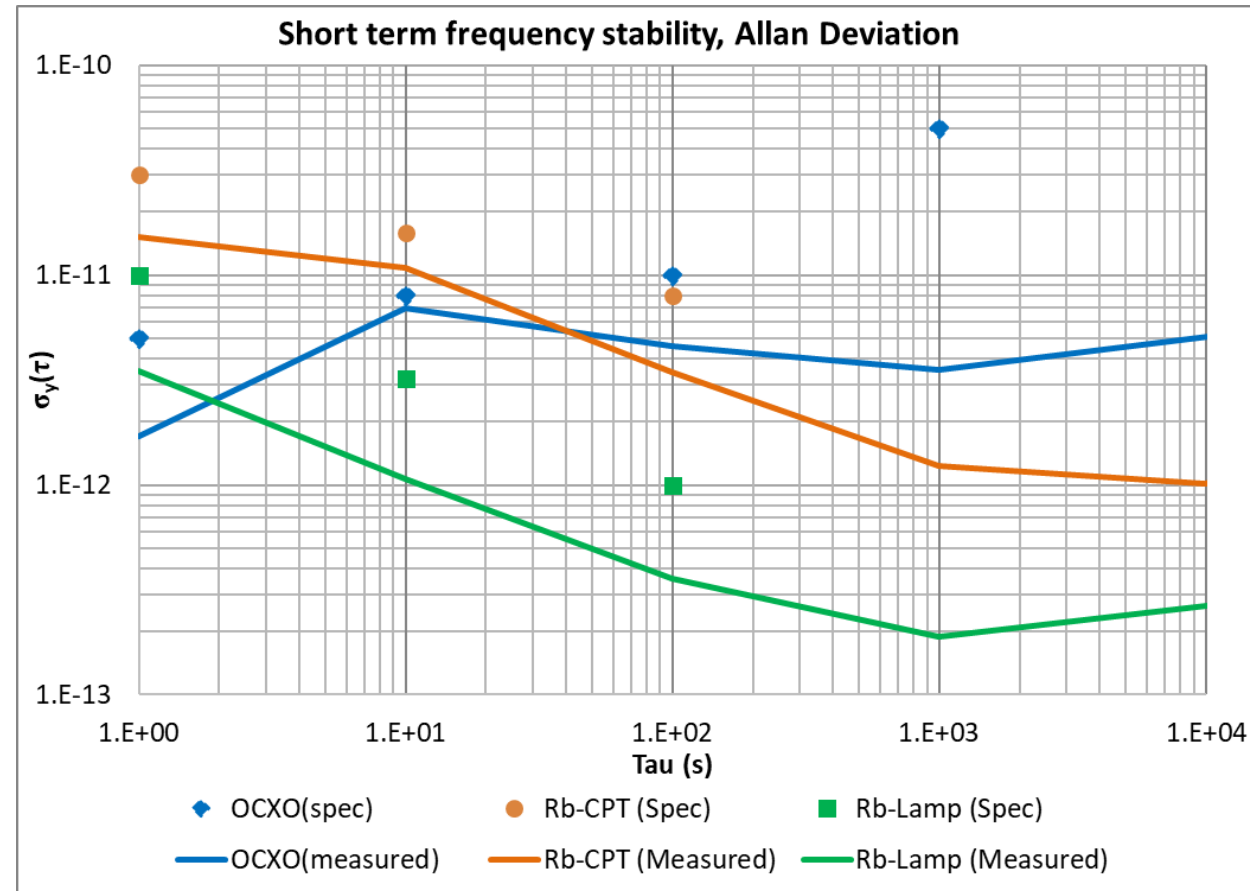
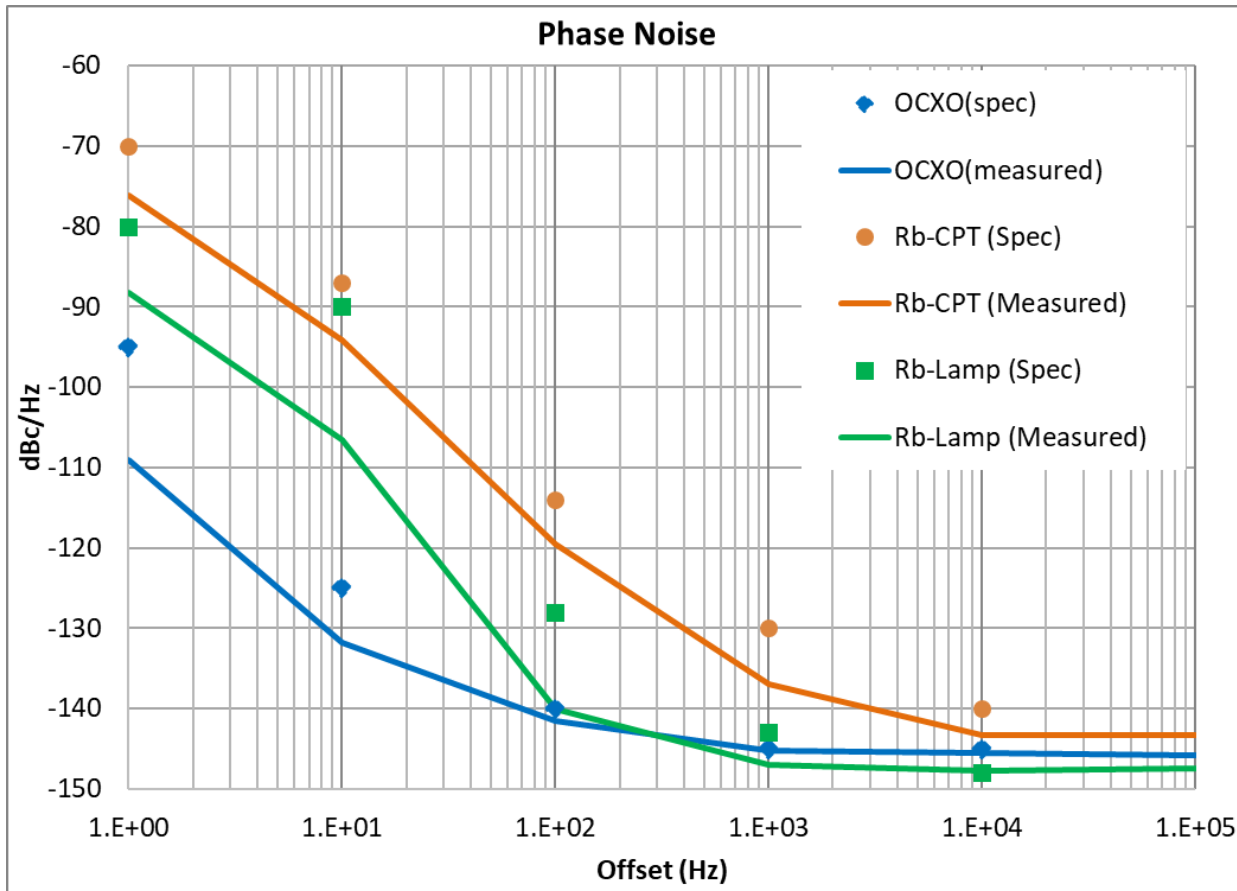
SA.45s (CSAC)
2011

Agenda

- **Oscillator stability in static environmental conditions**
 - ADEV, Phase Noise
 - Performance during Power-on
 - Frequency drift (Aging) & Time Error over 1 – 4 days
- **Oscillator stability in perturbed environmental conditions**
 - Effects of rapid temperature changes during 6hr missions
 - Effects of gravity
 - Effects of Magnetic Field
 - Effects of power disruption (retrace)

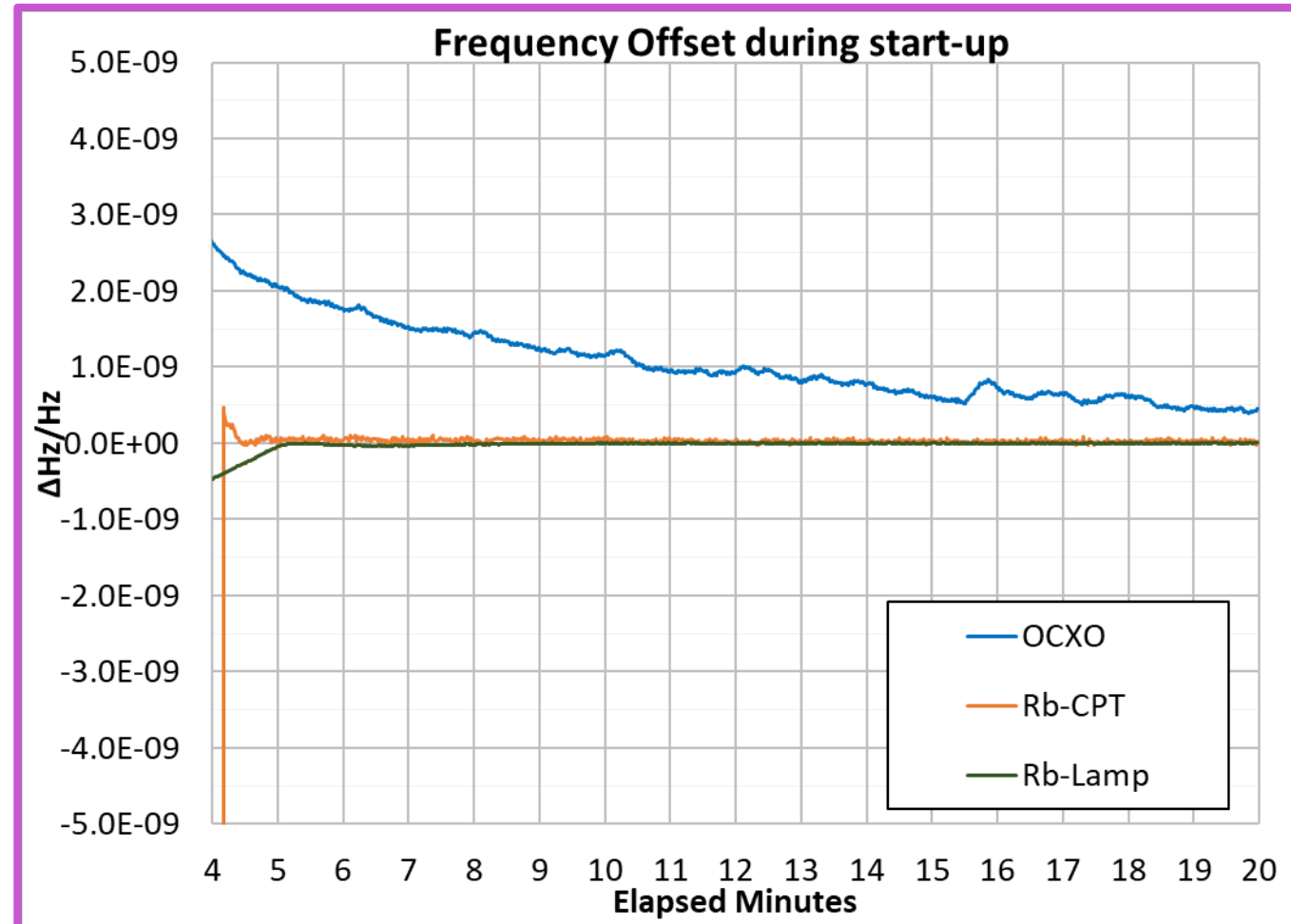
Short-term Stability of Commercial Oscillators

- Generally, OCXO's have superior phase noise and Short-term (<10s) frequency stability compared to Gas Cell/ CPT clocks



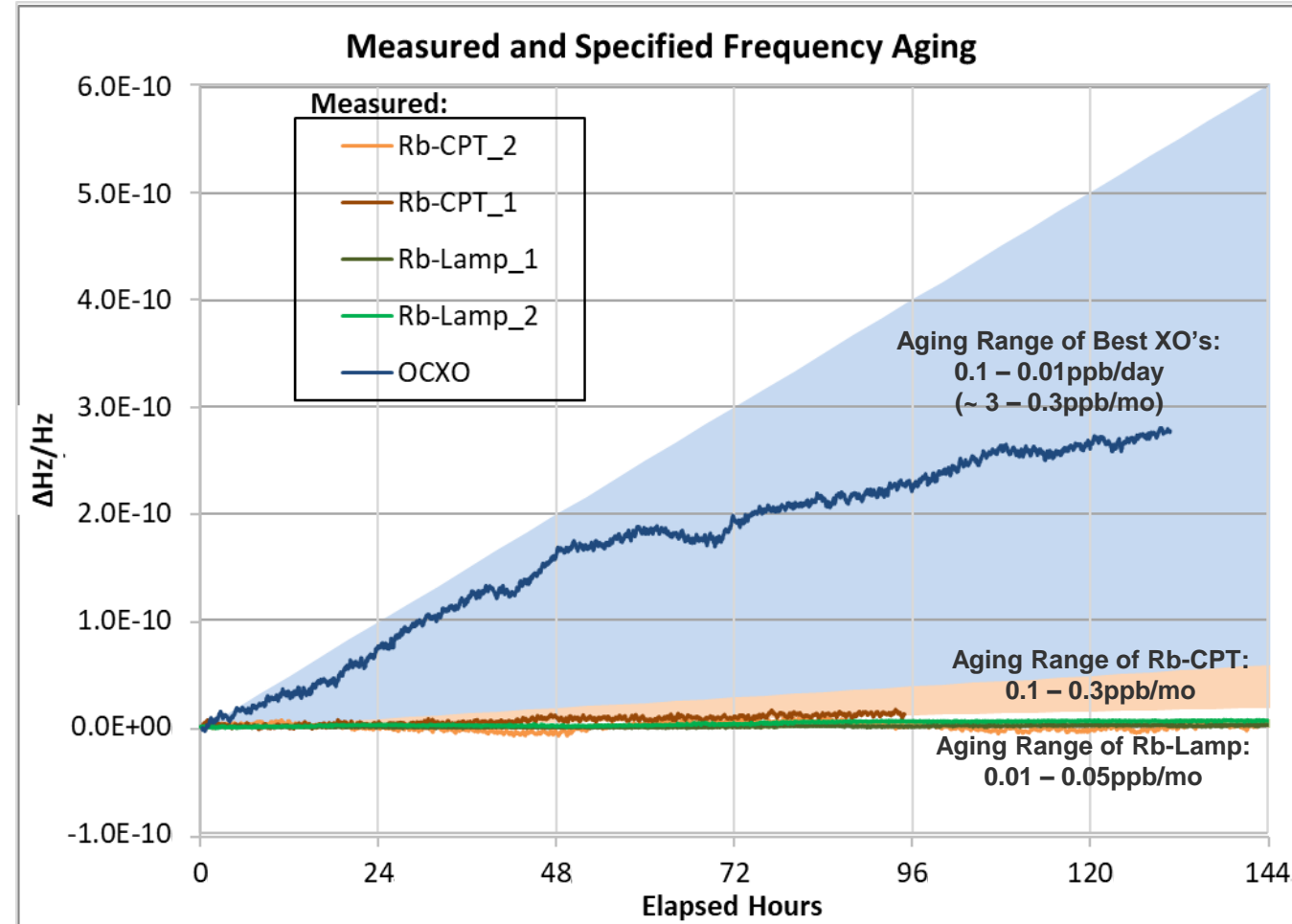
Output Frequency during Start-up

- Atomic Clocks take several minutes to acquire Lock before achieving specified stability performance
- Once Locked, accuracy $\sim 10^{-10}$



Long-term Frequency Stability: predicted versus measured

- Also known as “Aging”, this is how much the frequency will drift over one day, month, etc
- Unlike CBT, CPT & Lamp clocks will have some measurable drift.

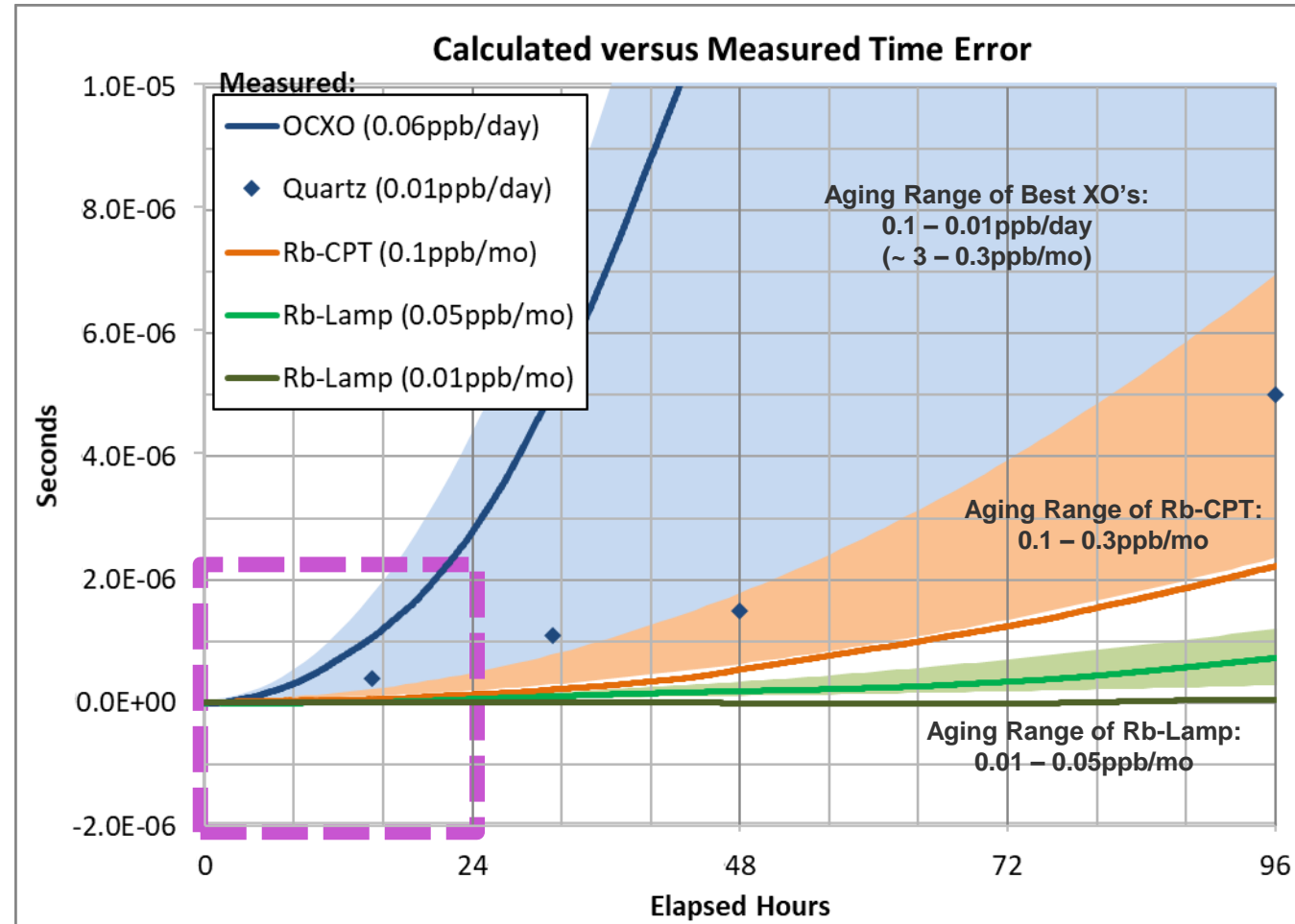


- Rb Oscillators offer a 15 - 160x improvement in *measured* frequency aging.
- Rb is a 3-30x improvement over best claimed aging XO spec (0.01ppb/day)

<u>Device</u>	<u>Measured Δfreq</u>	<u>Specification</u>
OCXO	<i>0.055ppb/day (1.650ppb/mo)</i>	0.06ppb/day
Rb-CPT_1	<i>0.105ppb/mo</i>	0.30ppb/mo
Rb-CPT_2	<i>0.010ppb/mo</i>	0.10ppb/mo
Rb-Lamp_1	<i>0.010ppb/mo</i>	0.05ppb/mo
Rb-Lamp_2	<i>0.026ppb/mo</i>	0.05ppb/mo

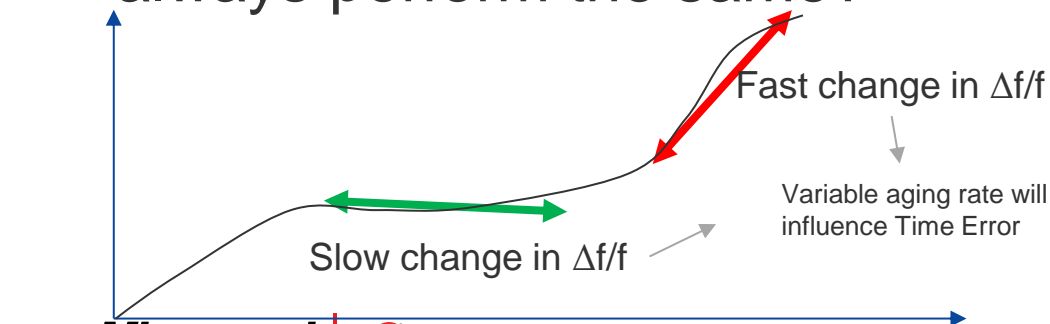
Time Error: predicted versus measured (4 days)

- A simple time error *estimation* is to use the aging rate, as reported in literature[1],[2].
 - Simplifies to $T.E. = \frac{1}{2} a t^2$
 - a: specified aging rate (frequency drift / time)
 - t: elapsed time
 - Assumptions: no environmental effects (temperature, vibe, etc), zero initial phase/freq offset
- A one-off time error measurement can be deceiving. Will the Oscillator always perform the same?



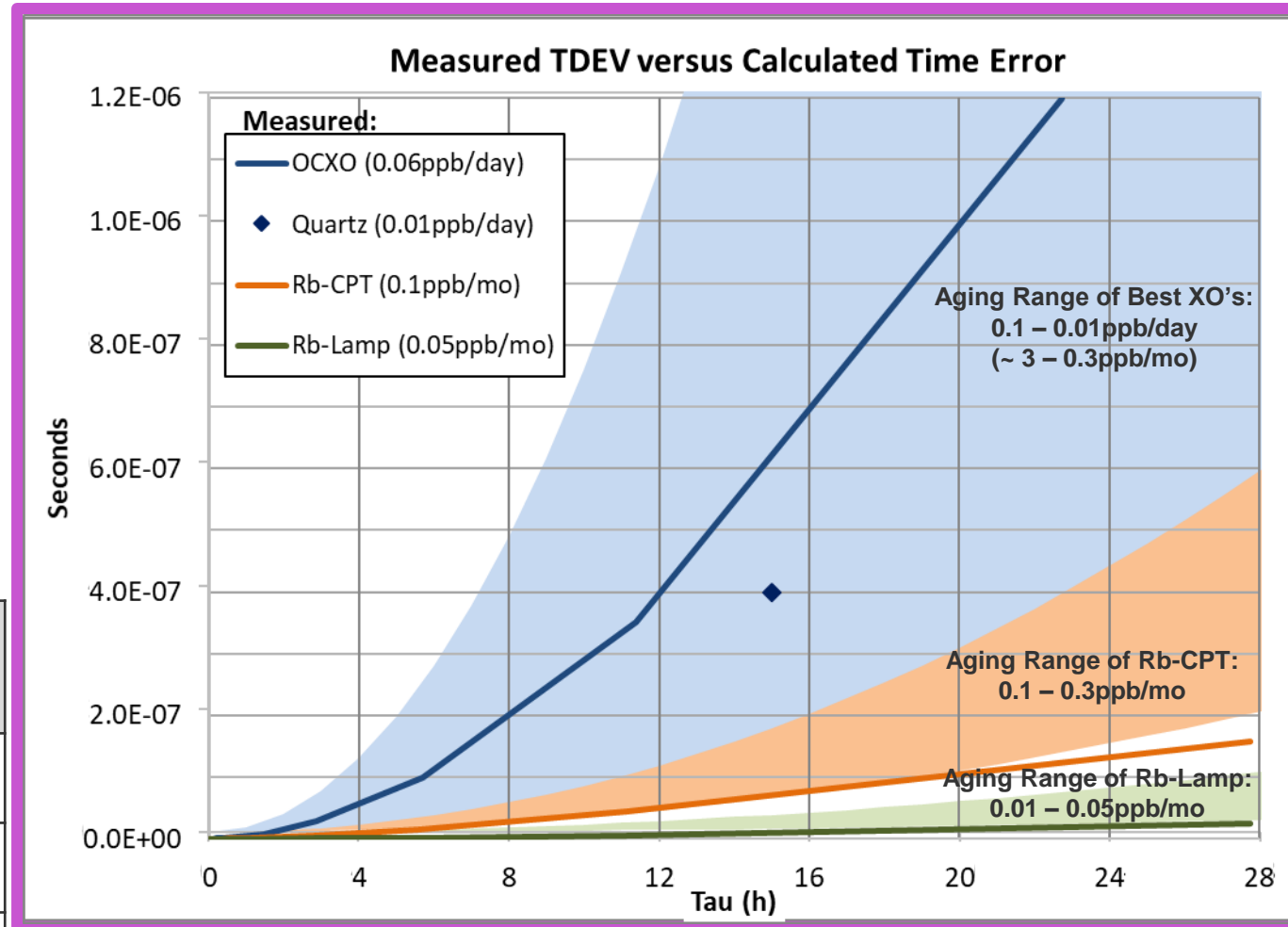
*Note: Data for "Quartz" device was reported on datasheet and has not been measured by the author.

1. John R. Vig, "Quartz Crystal Resonators and Oscillator for Frequency Control and Timing Applications, A Tutorial", FCS, 1996.
2. D.B.Sullivan, "Characterization of Clocks and Oscillators", NIST Technical Note 1337, 1990.



TDEV to predict 24h Time Error

- Using the long-term drift measurement data, we can take a statistical approach to Time Error (TDEV) over a shorter window.
 - TDEV: time stability of phase versus an observation interval (Tau) of a measured clock source.



*Note: Data for "Quartz" device was reported on datasheet and has not been measured by the author.

Device	TDEV @ 8h	TDEV @ 16h	TDEV @ 24h
OCXO	200ns	700ns	~1300ns
Rb-CPT_1	25ns	90ns	150ns
Rb-Lamp_1	10ns	15ns	20ns

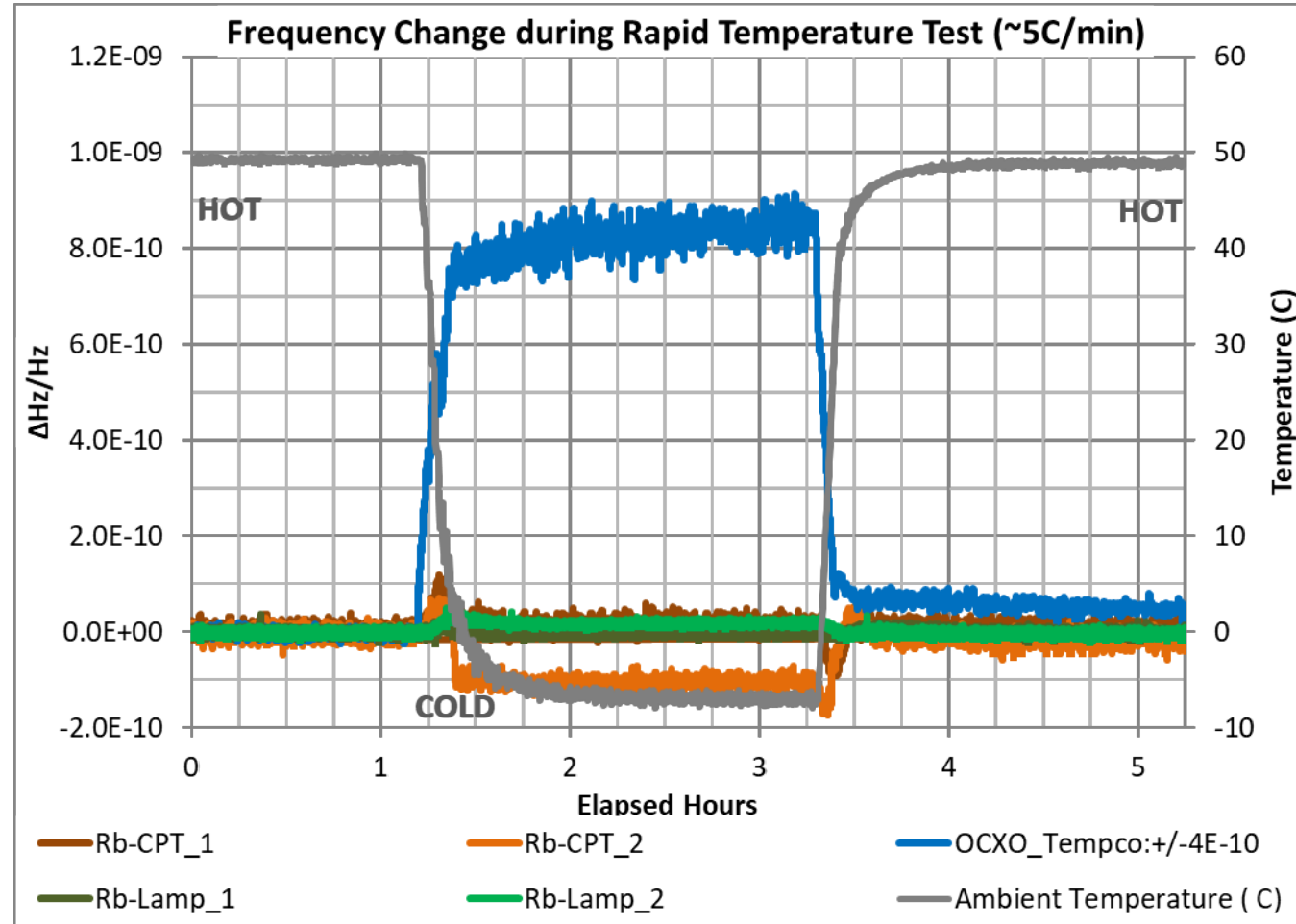
Agenda

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Rapid Temperature Test (Frequency Response)

Test scenario:

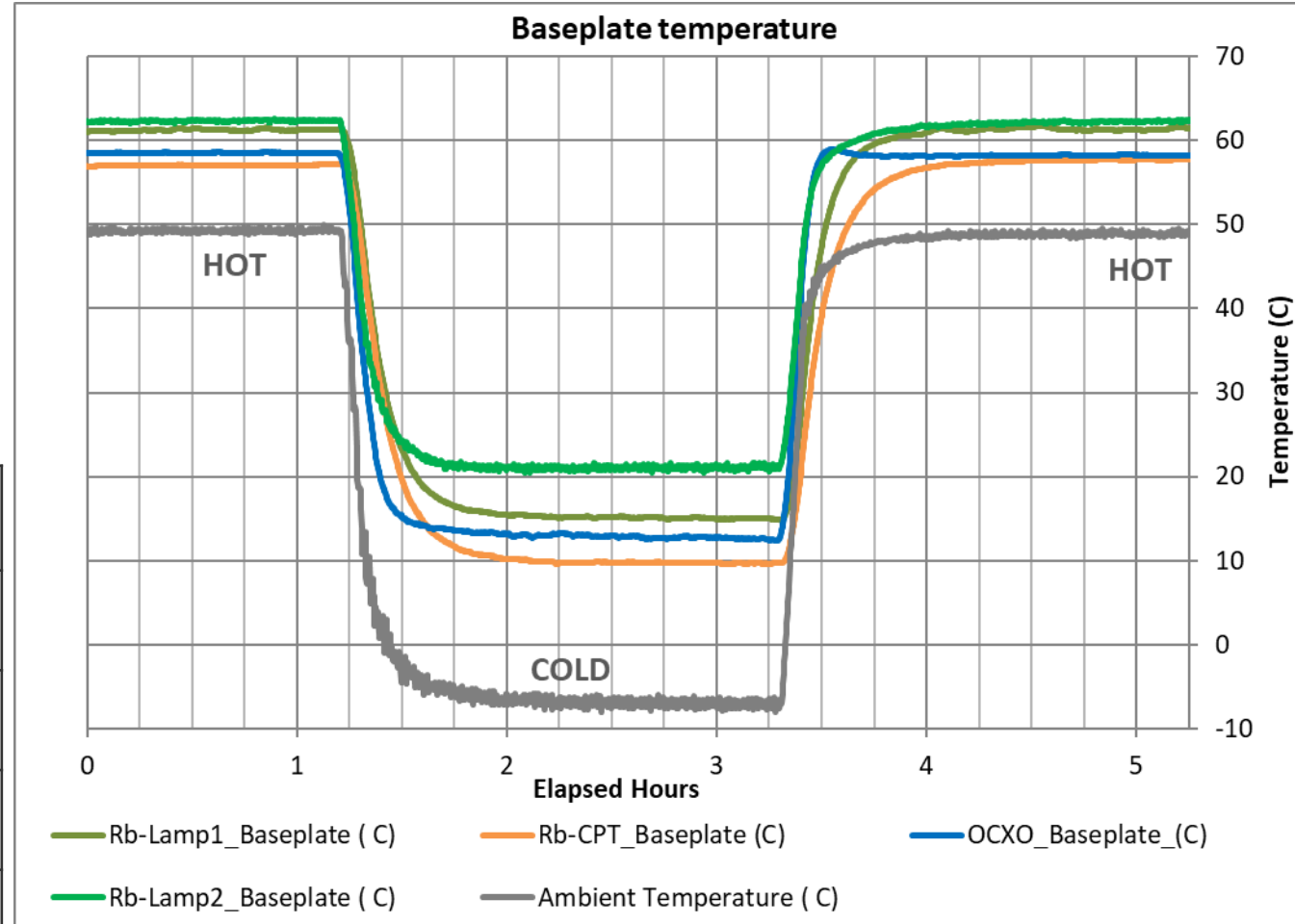
- Soak at a Hot temperature for 2 hours
- Rapidly cool 50 → -5 °C in 15 minutes
 - Soak for 2 hours
- Rapidly heat -5 → 50 °C in 15 minutes
 - Soak for 2 hours



The Rb Oscillators offer a >4x improvement in frequency stability

Rapid Temperature Test (Baseplate temperature)

- Why is the Rb-Lamp superior?
 - Thermal mass, more powerful heater for the lamp reduces its cold temperature exposure
 - 14W, 1.1lbs, heat sink, larger Gas Cell



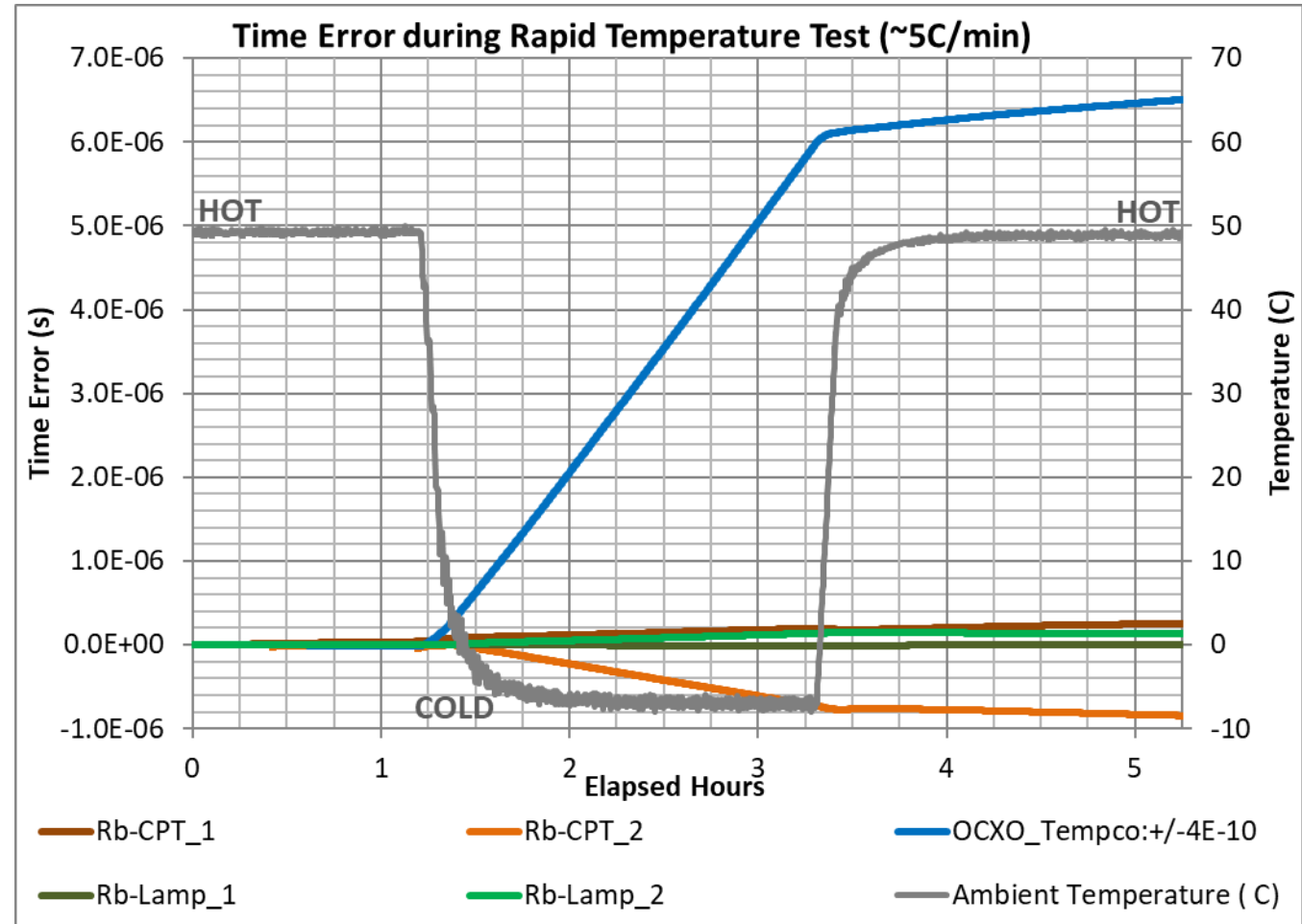
The Rb Oscillators offer a >4x improvement in frequency stability

<u>Device</u>	<u>Measured Δfreq. (max)</u>	<u>Specification</u>	<u>Specification Range</u>
OCXO	0.85ppb	±0.40ppb	0 to +70°C
Rb-CPT_1	0.12ppb	0.07ppb	-10 to +70°C
Rb-CPT_2	0.18ppb	0.07ppb	-10 to +70°C
Rb-Lamp_1	0.05ppb	0.60ppb	-25 to +70°C
Rb-Lamp_2	0.03ppb	0.60ppb	-25 to +70°C

Rapid Temperature Test (*Phase Response)

Test scenario:

- Soak at a Hot temperature for 2 hours
- Rapidly cool 50 → -5 °C in 15 minutes
 - Soak for 2 hours
- Rapidly heat -5 → 50 °C in 15 minutes
 - Soak for 2 hours



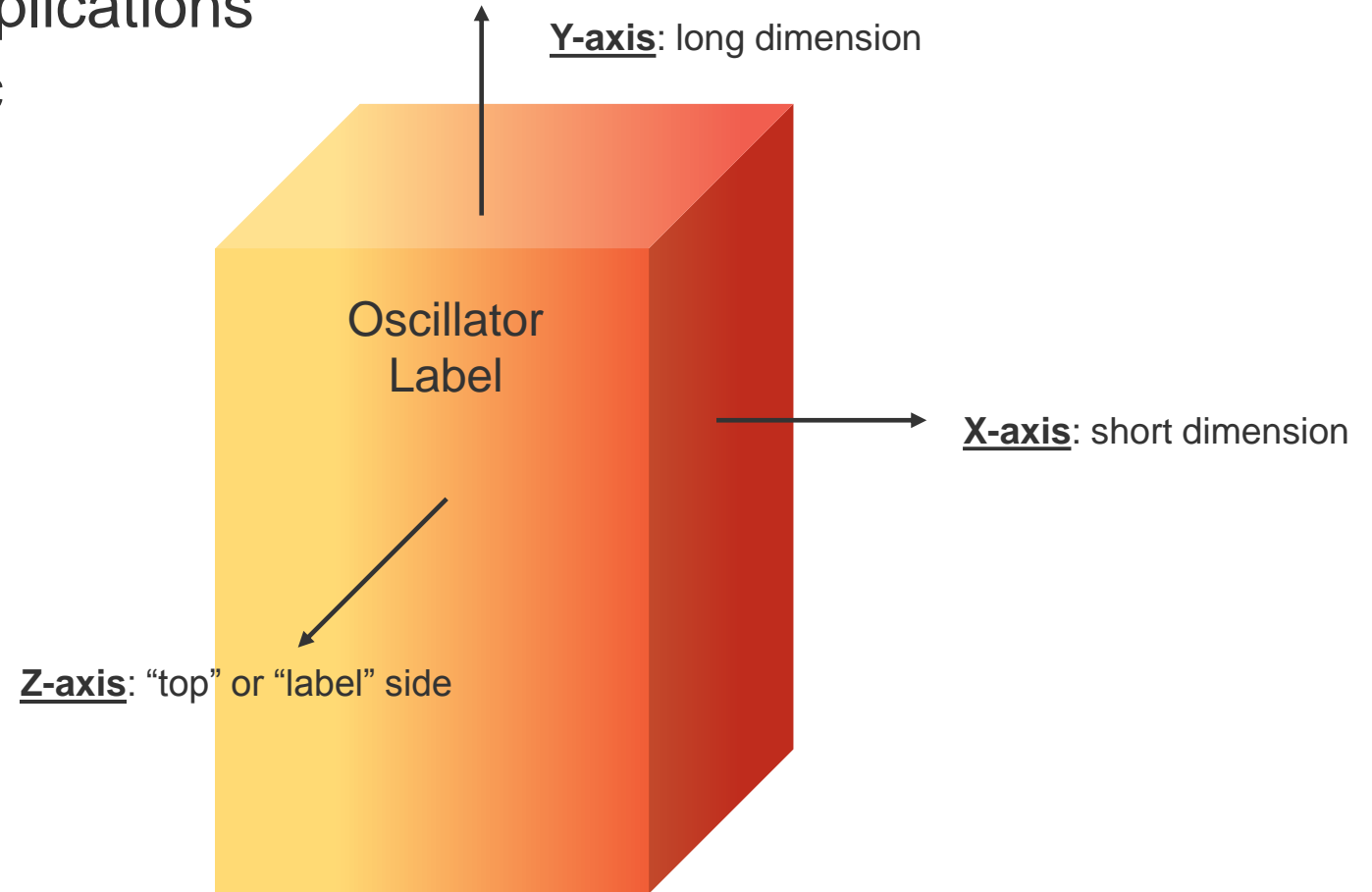
*The terms “phase” and “time error” are used interchangeably, in this instance

The Rb Oscillators offer a >8x improvement in phase stability

<u>Device</u>	<u>Measured Δphase (max)</u>	<u>Specification</u>
OCXO	6.50μs	n/a
Rb-CPT_1	0.30μs	n/a
Rb-CPT_2	0.80μs	n/a
Rb-Lamp_1	0.05μs	n/a
Rb-Lamp_2	0.10μs	n/a

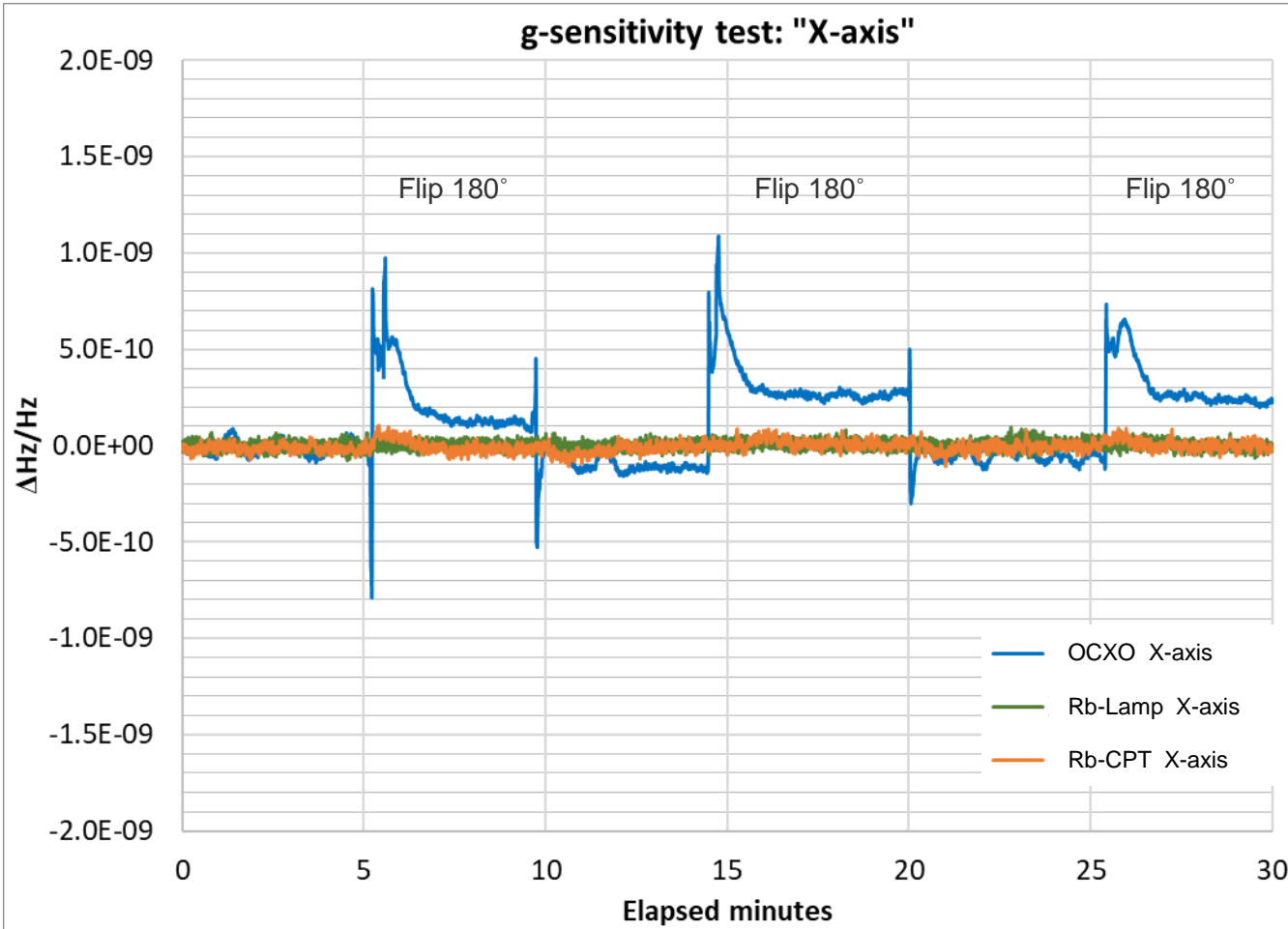
2g tip-over test

- Flip the oscillator 180°, all three axes. Record frequency change.
- Important for mobile equipment applications
- Simulates “roll” of aircraft, ship, etc

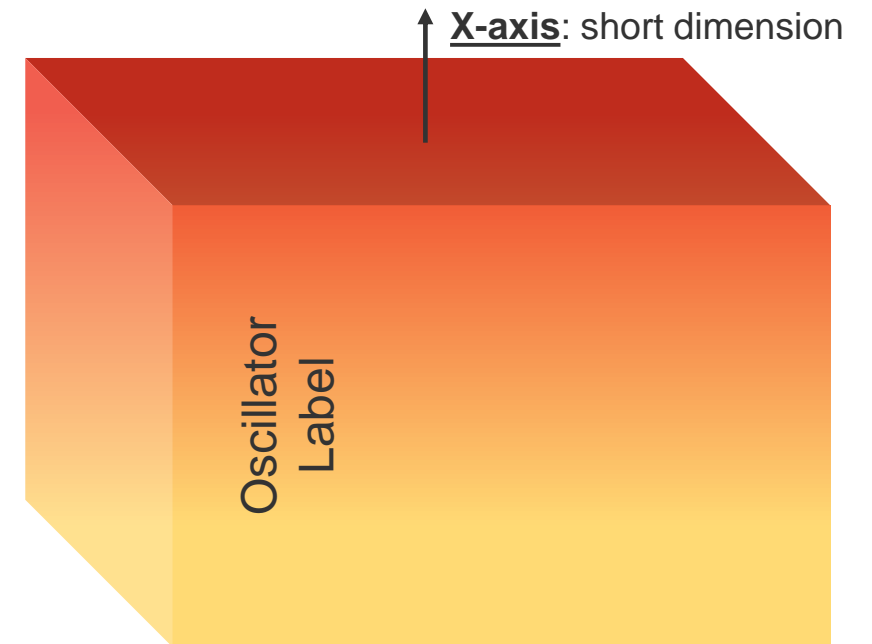


2g tip-over test: X-axis

- $\Delta\text{Frequency} / g = (f_{\text{max}} - f_{\text{min}})/2$

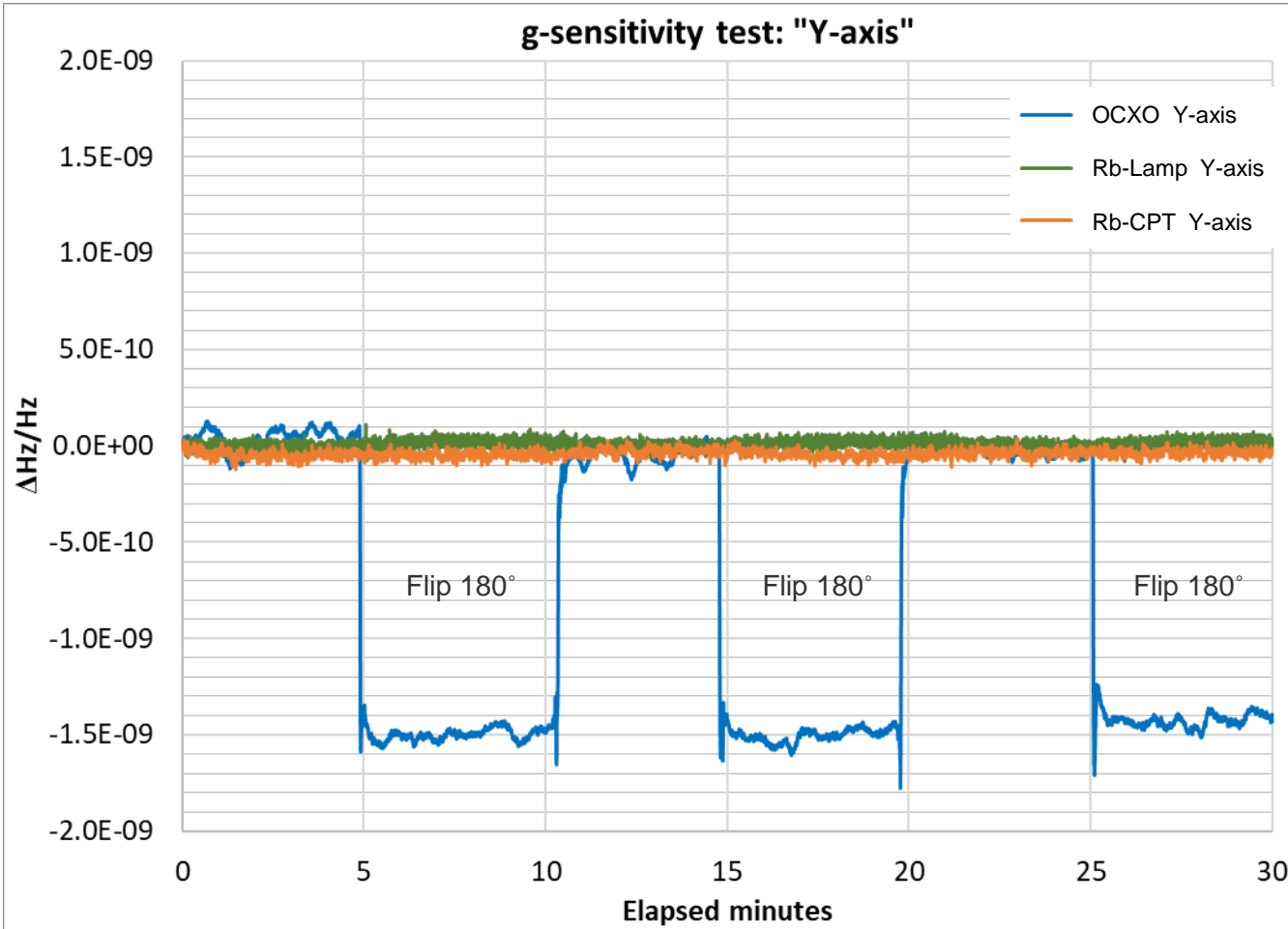


Device	$\frac{\Delta\text{freq}}{g}$ X-axis	$\frac{\Delta\text{freq}}{g}$ Y-axis	$\frac{\Delta\text{freq}}{g}$ Z-axis
OCXO	0.20ppb		
Rb-CPT_1	<0.10ppb		
Rb-Lamp_1	<0.10ppb		

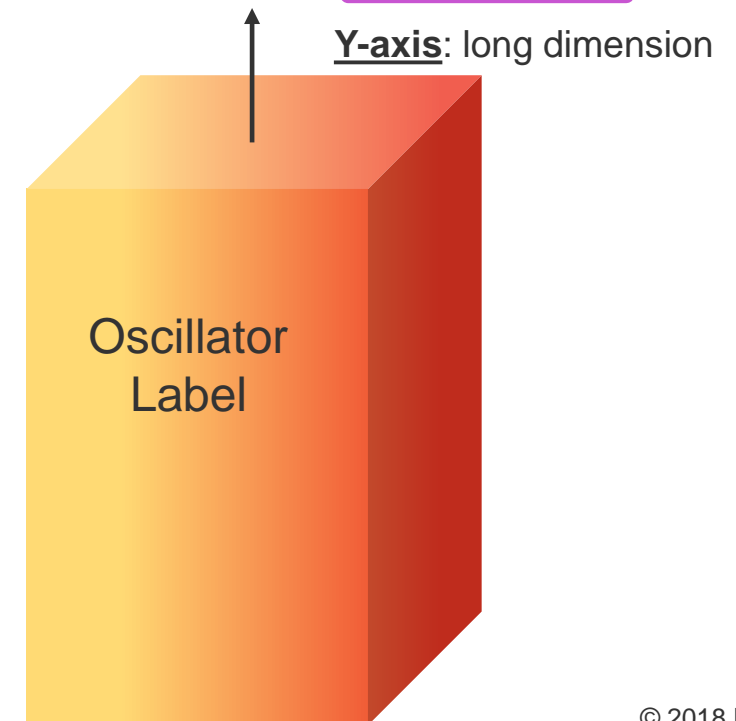


2g tip-over test: Y-axis

- $$\Delta \text{Frequency} / g = (f_{\text{max}} - f_{\text{min}}) / 2$$

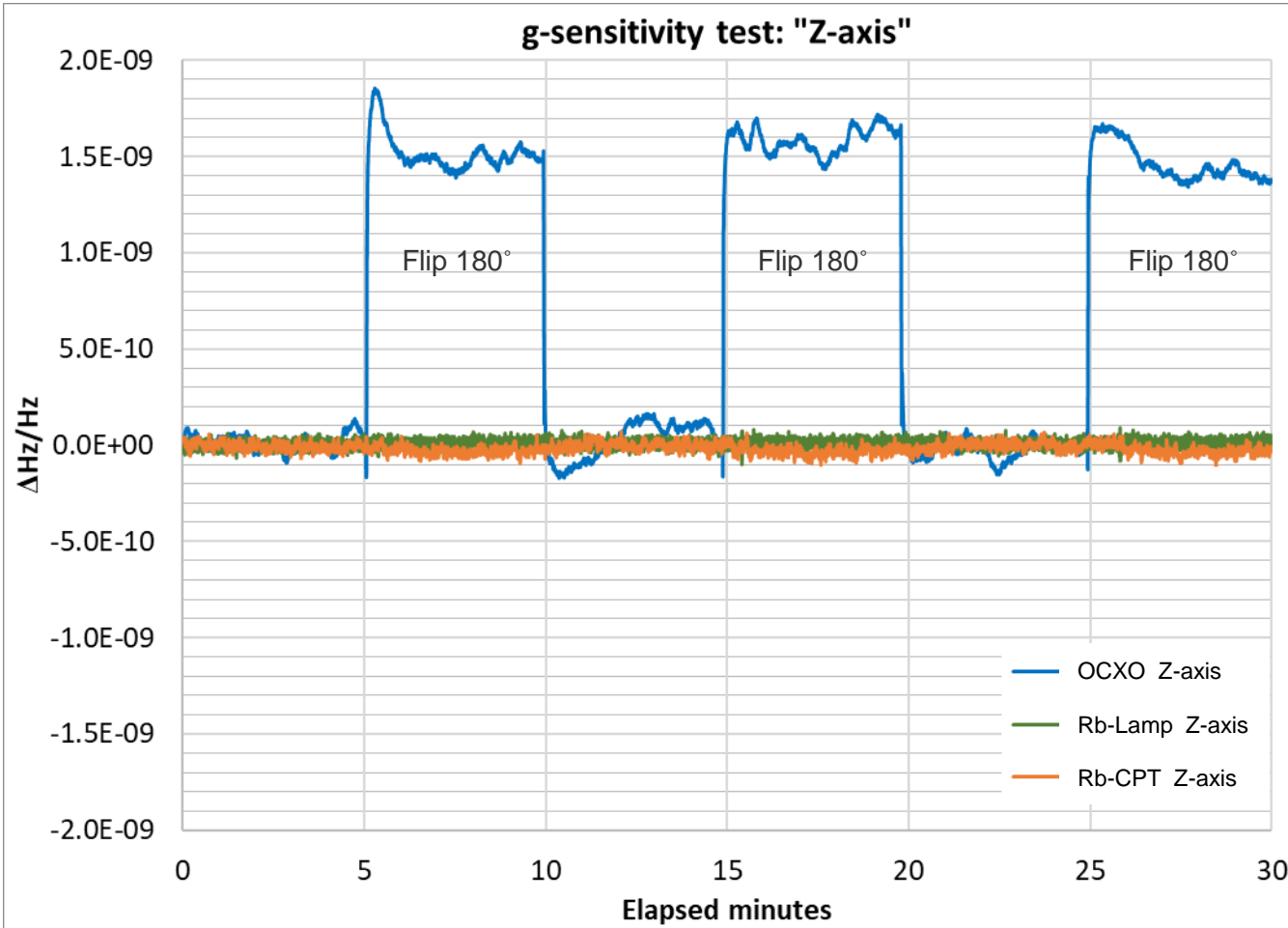


Device	$\frac{\Delta \text{freq}}{g}$ X-axis	$\frac{\Delta \text{freq}}{g}$ Y-axis	$\frac{\Delta \text{freq}}{g}$ Z-axis
OCXO	0.20ppb	0.75ppb	
Rb-CPT_1	<0.10ppb	<0.10ppb	
Rb-Lamp_1	<0.10ppb	<0.10ppb	

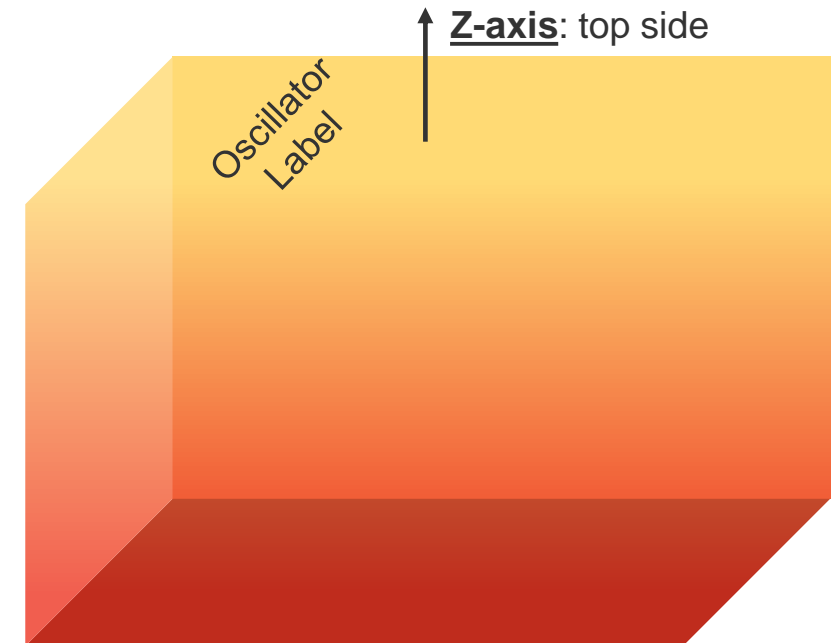


2g tip-over test: Z-axis

■ $\Delta\text{Frequency} / g = (f_{\text{max}} - f_{\text{min}}) / 2$

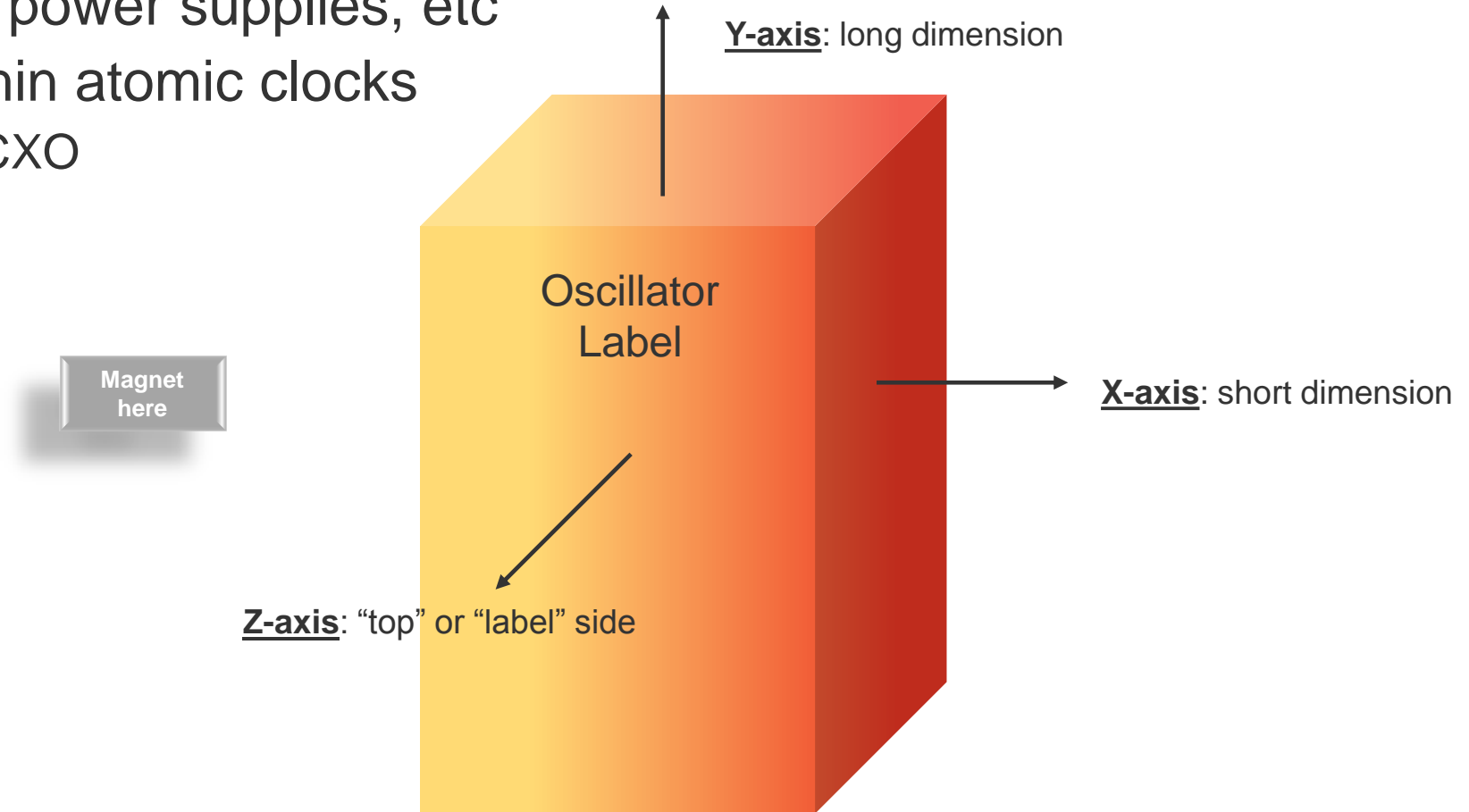


Device	$\frac{\Delta\text{freq}}{g}$ X-axis	$\frac{\Delta\text{freq}}{g}$ Y-axis	$\frac{\Delta\text{freq}}{g}$ Z-axis
OCXO	0.20ppb	0.75ppb	0.75ppb
Rb-CPT_1	<0.10ppb	<0.10ppb	<0.10ppb
Rb-Lamp_1	<0.10ppb	<0.10ppb	<0.10ppb



Magnetic Field Sensitivity test

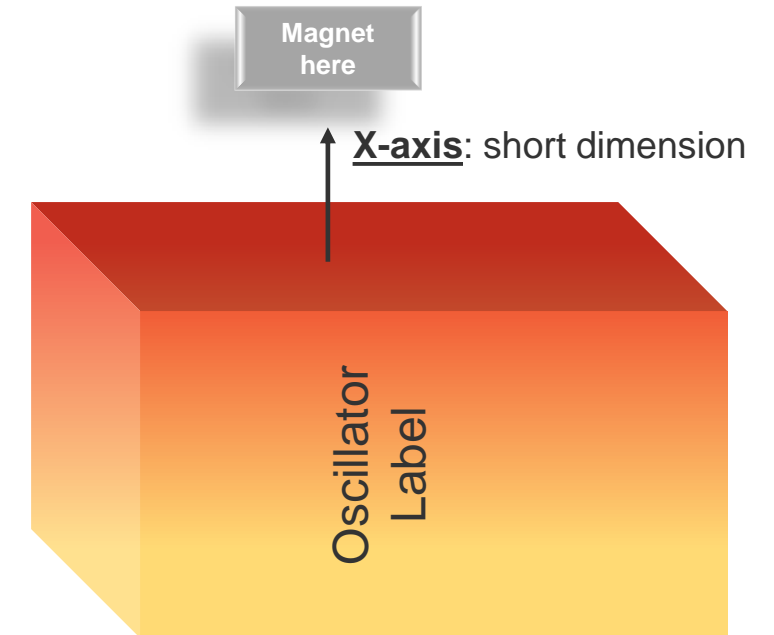
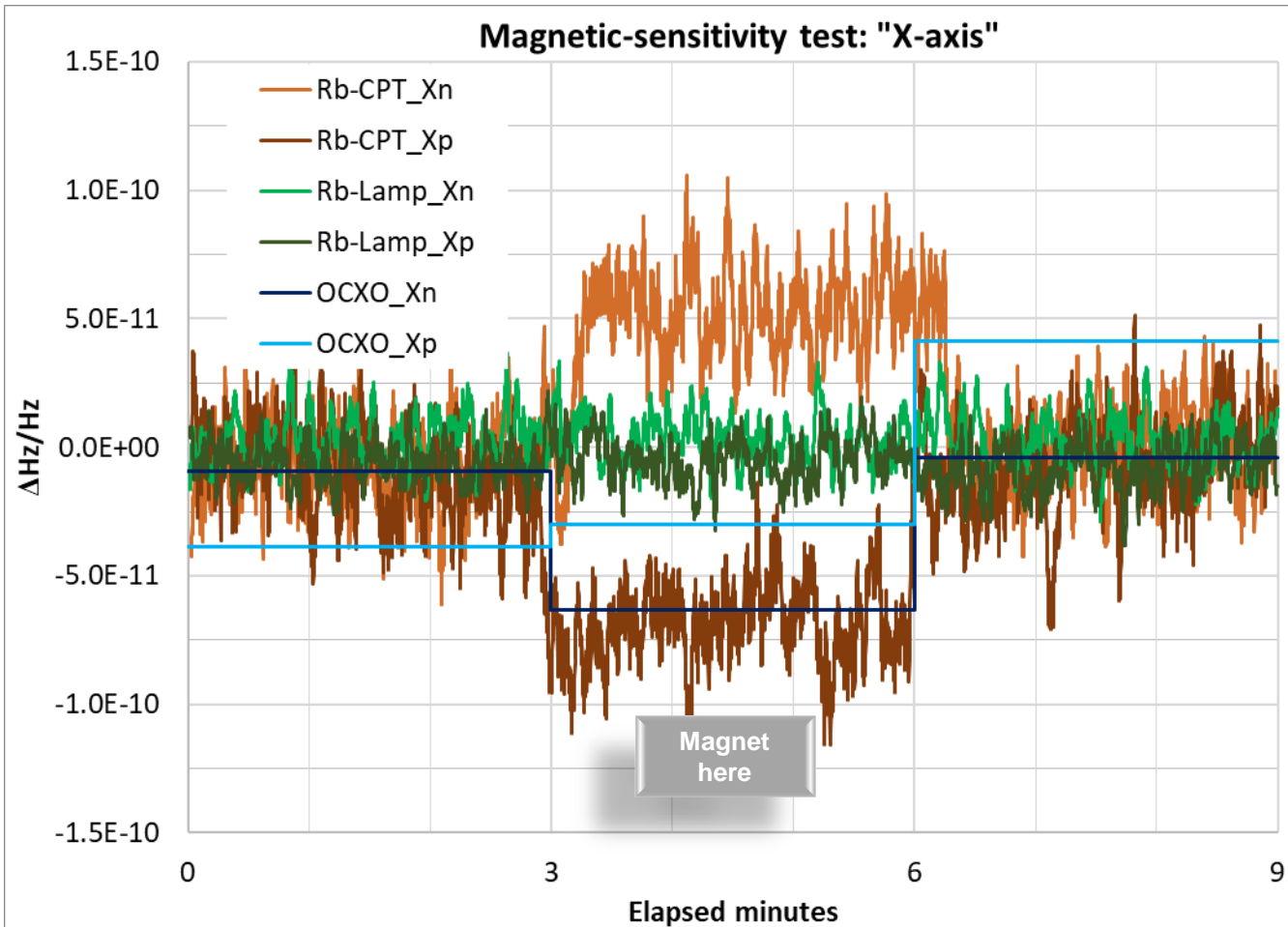
- Subject each axis to ± 2 Gauss. Record frequency change.
- Important for designing in power supplies, etc
- Magnetic field is used within atomic clocks
 - Not expected to influence OCXO



Magnetic Field Sensitivity test: X-axis

- $\Delta\text{Frequency} / \text{Gauss} = (f_{\text{max}} - f_{\text{min}}) / 2$
 - MAC is most susceptible

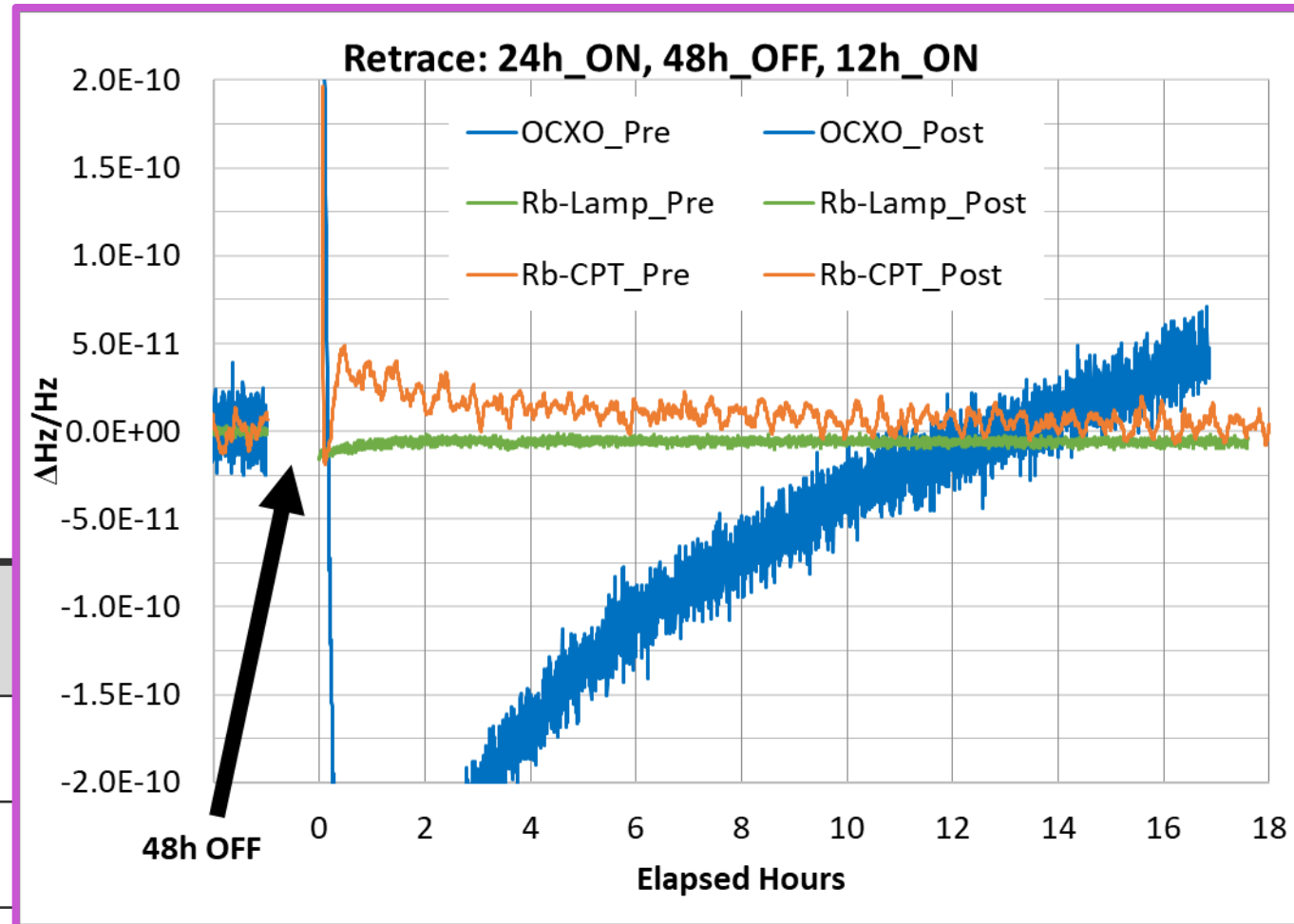
Device	$\Delta\text{freq}/\text{Gauss}$ X-axis	$\Delta\text{freq}/\text{Gauss}$ Y-axis	$\Delta\text{freq}/\text{Gauss}$ Z-axis
OCXO	-	-	-
Rb-CPT_1	5.75×10^{-11}	1.3×10^{-11}	1.8×10^{-11}
Rb-Lamp_1	$< 1 \times 10^{-11}$	$< 1 \times 10^{-11}$	$< 1 \times 10^{-11}$



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	± 2.00 ppb
MAC	0.05ppb	0.03ppb	0.02ppb	0.02ppb	0.02ppb	± 0.05 ppb
XPRO	0.02ppb	0.01ppb	0.01ppb	0.01ppb	0.01ppb	± 0.03 ppb



Rb Oscillators achieve fast retrace

Summary: CPT, Gas Cell and Quartz Clocks

Technology	24h Holdover (static)	Extreme Temp Stability (-5 to 50°C, 5C/min)	g-sensitivity ($\Delta\text{Hz}/\text{Hz}/g$)	Magnetic sensitivity ($\Delta\text{Hz}/\text{Hz}/\text{Gauss}$)	Re-trace ($\Delta\text{Hz}/\text{Hz}$)	Intrinsic Accuracy ($\Delta\text{Hz}/\text{Hz}$)	1S-ADEV ($\Delta\text{Hz}/\text{Hz}$)	ADEV floor ($\Delta\text{Hz}/\text{Hz}$)	Aging (/day) ($\Delta\text{Hz}/\text{Hz}$)	Power (W)	Cost
Rb-Lamp	< 0.1 μs	$\sim 10^{-11}$	$\sim 10^{-11}$	$\sim 10^{-12}$	$\sim 10^{-11}$	$\sim 10^{-9}$	$\sim 10^{-11}$	$\sim 10^{-13}$	10^{-11} to 10^{-13}	10	$\sim X$
Rb-CPT	0.2 to 0.5 μs	$\sim 10^{-10}$	$\sim 10^{-11}$	$\sim 10^{-11}$	$\sim 10^{-11}$	$\sim 10^{-9}$	$\sim 10^{-11}$	$\sim 10^{-13}$	10^{-11} to 10^{-13}	0.125 to 6	$\sim X$
Hi-quality Qz	0.5 to 2 μs	$< 10^{-9}$	$\sim 10^{-9}$	-	$\sim 10^{-10}$	10^{-6} to 10^{-8}	$\sim 10^{-12}$	$\sim 10^{-12}$	10^{-9} to 10^{-11}	~ 5	$\sim 0.5X$

Rb Oscillators offer excellent timing stability and a resistance to environmental effects:

- Resist Extreme temperature changes
- Low g-sensitivity
- Rapid frequency retrace after Lock



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