Commercial Atomic Oscillators versus Crystal Oscillators

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Clocks and Frequency references

Technology	Intrinsic Accuracy (ΔHz/Hz)	1S-ADEV (ΔHz/Hz)	ADEV floor (ΔHz/Hz)	Aging (/day) (ΔHz/Hz)	Power (W)	Cost
H-Maser	$\sim10^{-11}$	$\sim10^{-13}$	$\sim10^{-15}$	10^{-15} to 10^{-16}	100	~ 150X
Cs Beam	$\sim10^{-13}$	$\sim10^{-11}$	$\sim10^{-14}$	~0	30	~ 20X
Passive HM	$\sim10^{-10}$	$\sim10^{-12}$	$\sim10^{-15}$	10^{-15}	100	~ 40X
Rb-Lamp (Gas Cell)	$\sim10^{-9}$	$\sim10^{-11}$	$\sim10^{-13}$	10^{-11} to 10^{-13}	10	~ X
Rb-CPT	$\sim10^{-9}$	$\sim10^{-11}$	$\sim10^{-13}$	10^{-11} to 10^{-13}	0.125 to ~6	~ X
Hi-quality Qz	10^{-6} to 10^{-8}	$\sim10^{-12}$	$\sim10^{-12}$	10^{-9} to 10^{-11}	~ 5	~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

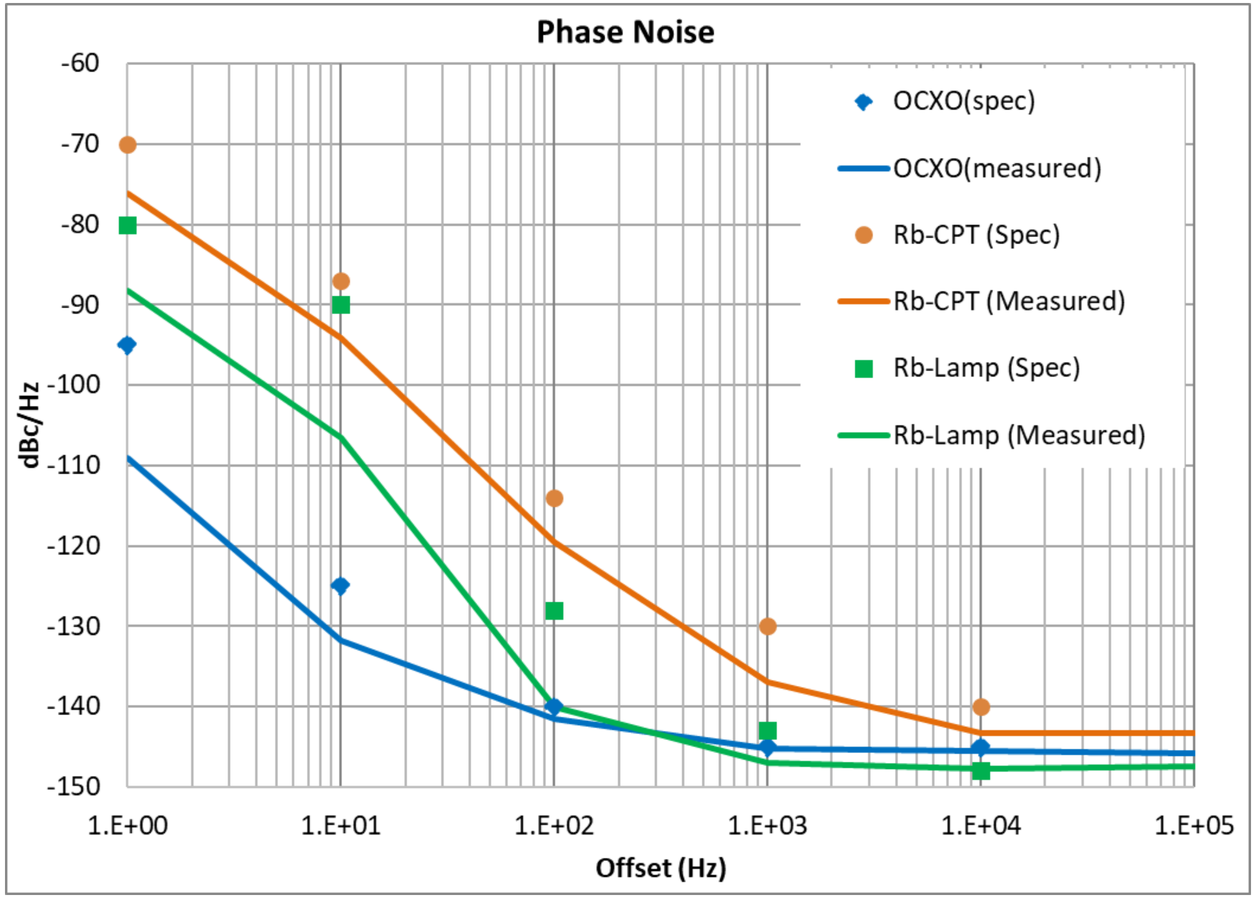
SA.45s (CSAC)
2011

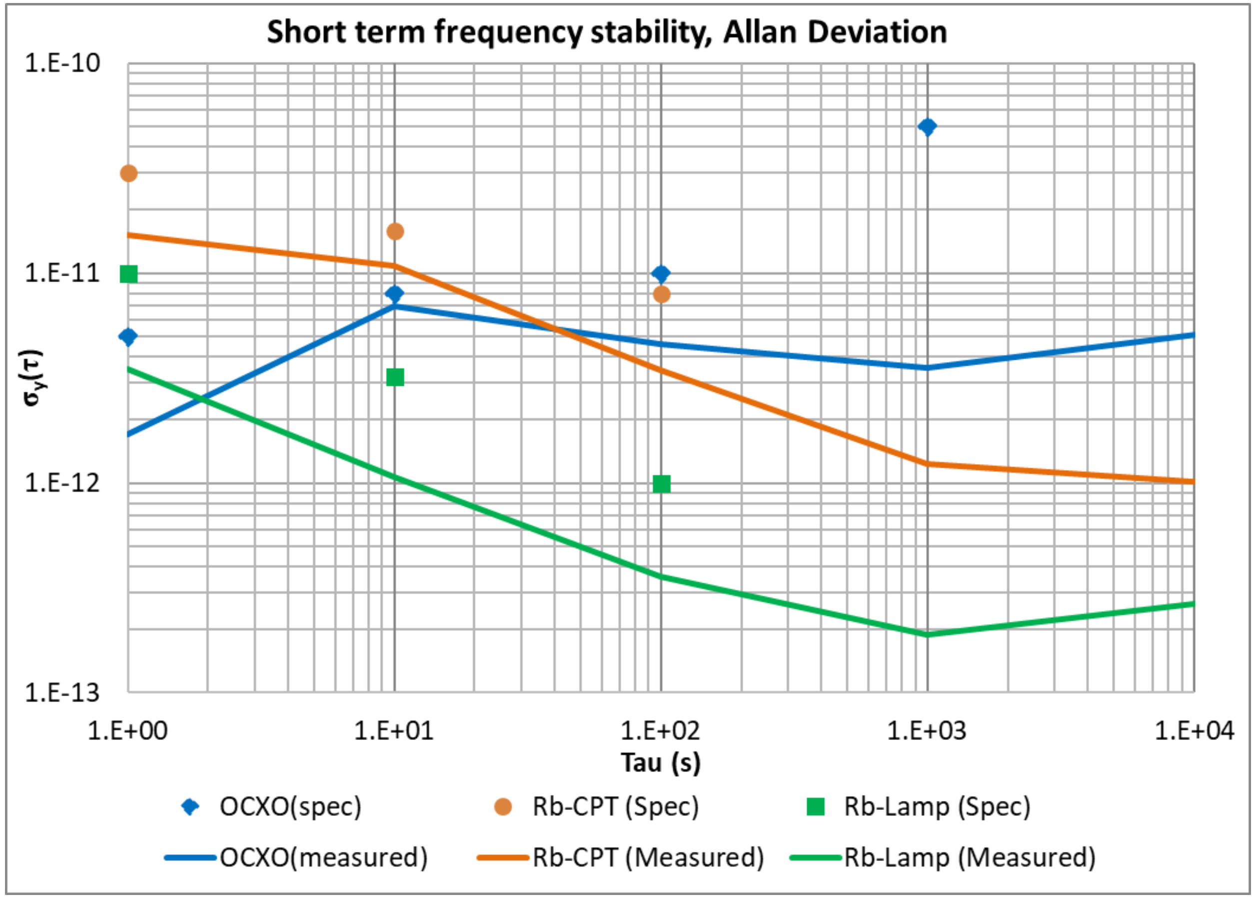
Agenda

- **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

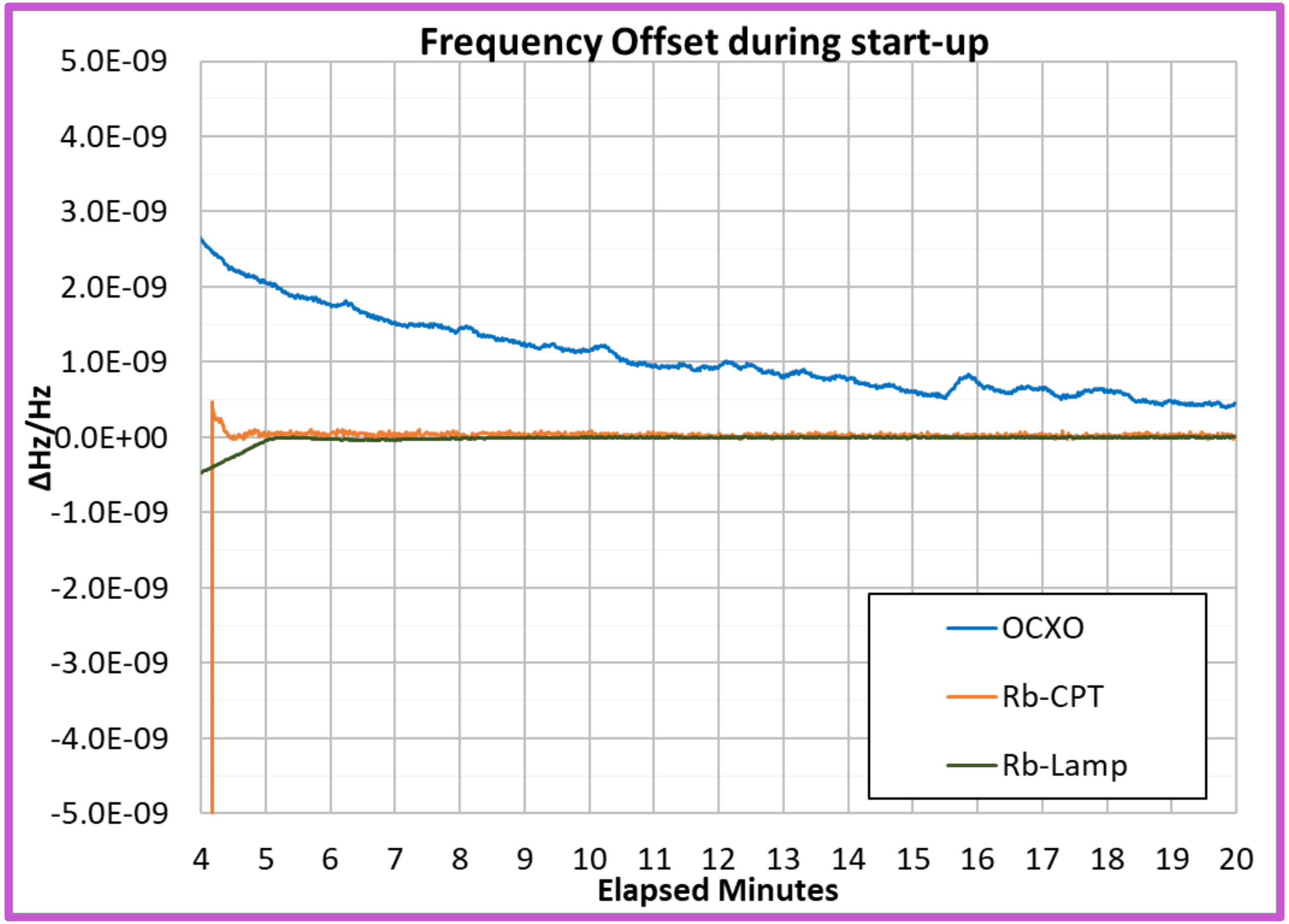
- Generally, OCXO's have superior phase noise and Short-term (<10s) frequency stability compared to Gas Cell/ CPT clocks





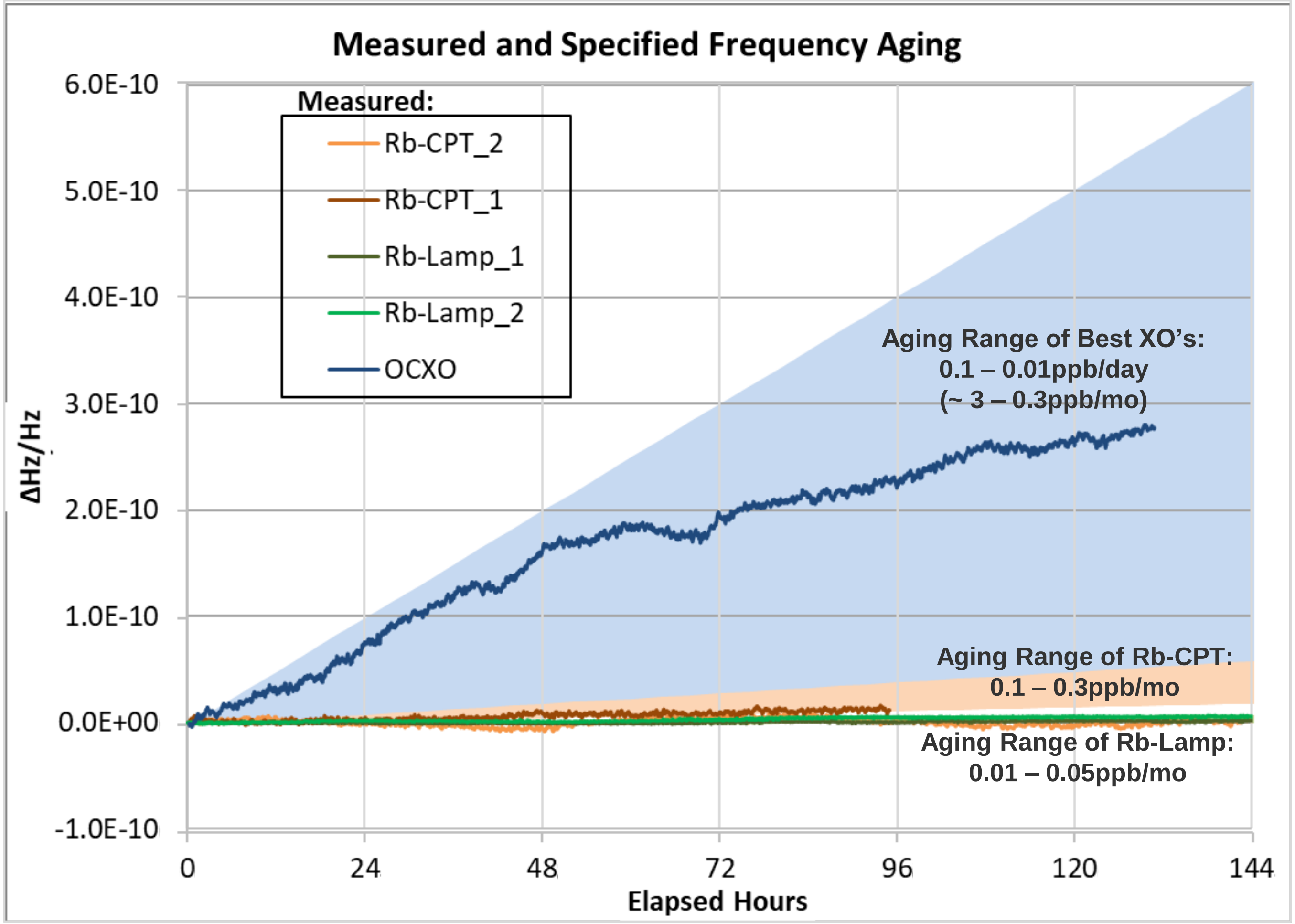
Output Frequency during Start-up

- Atomic Clocks take several minutes to acquire Lock before achieving specified stability performance
- Once Locked, accuracy ~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.

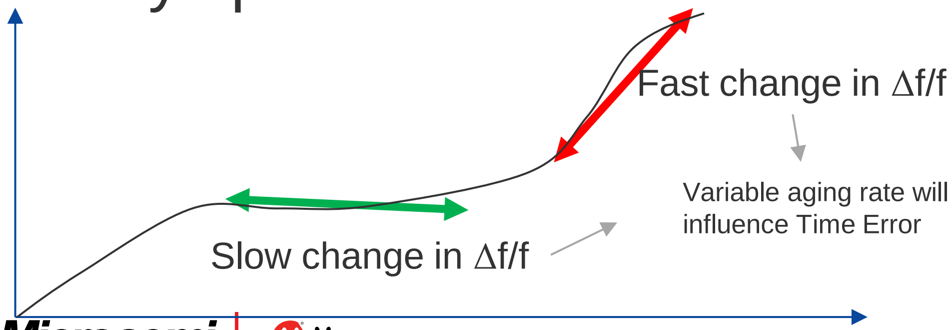


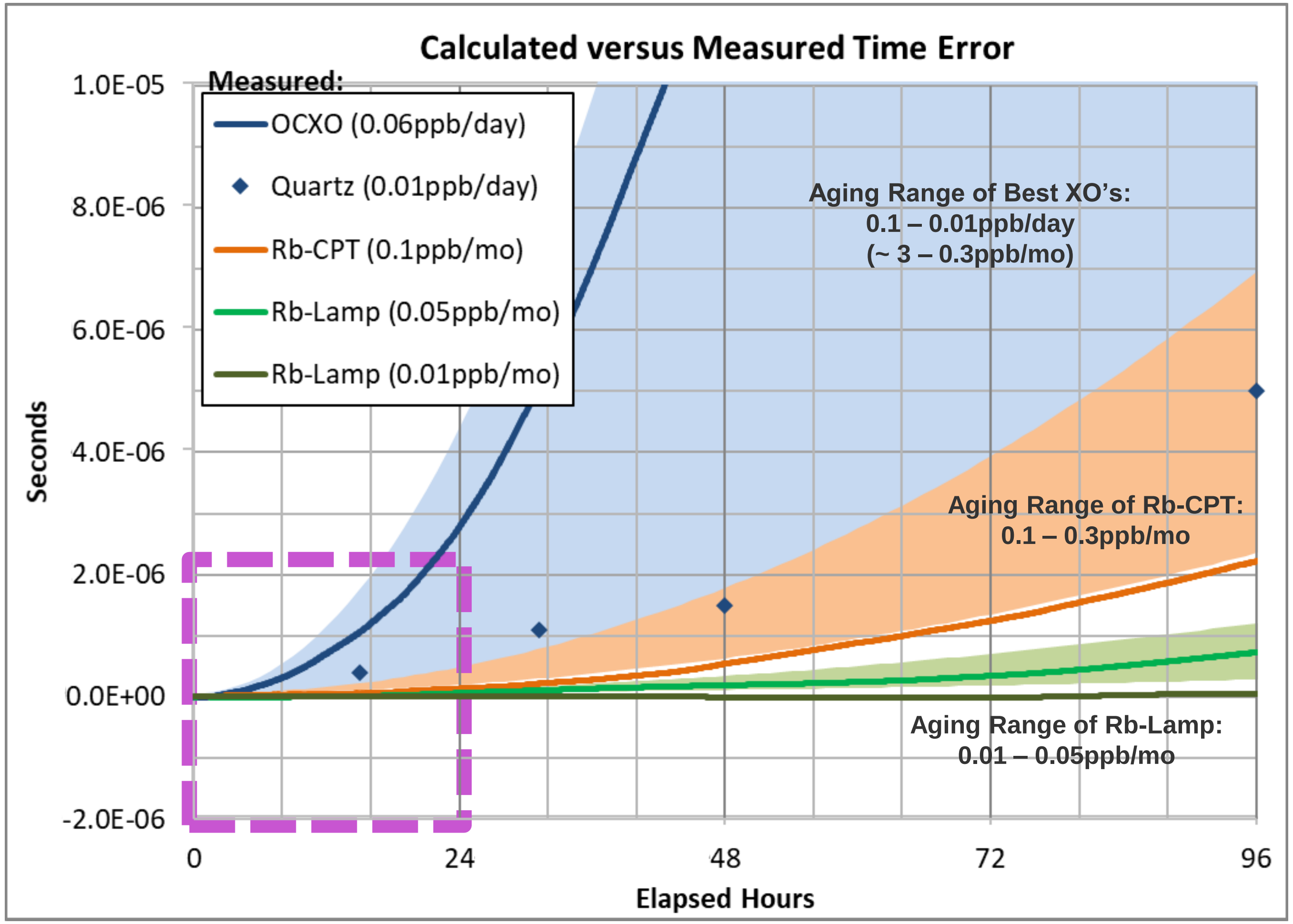
Device	Measured Δfreq	Specification
OCXO	***0.055ppb/day (1.650ppb/mo)***	0.06ppb/day
Rb-CPT_1	***0.105ppb/mo***	*0.30ppb/mo*
Rb-CPT_2	***0.010ppb/mo***	*0.10ppb/mo*
Rb-Lamp_1	***0.010ppb/mo***	*0.05ppb/mo*
Rb-Lamp_2	***0.026ppb/mo***	*0.05ppb/mo*

- 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)

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?





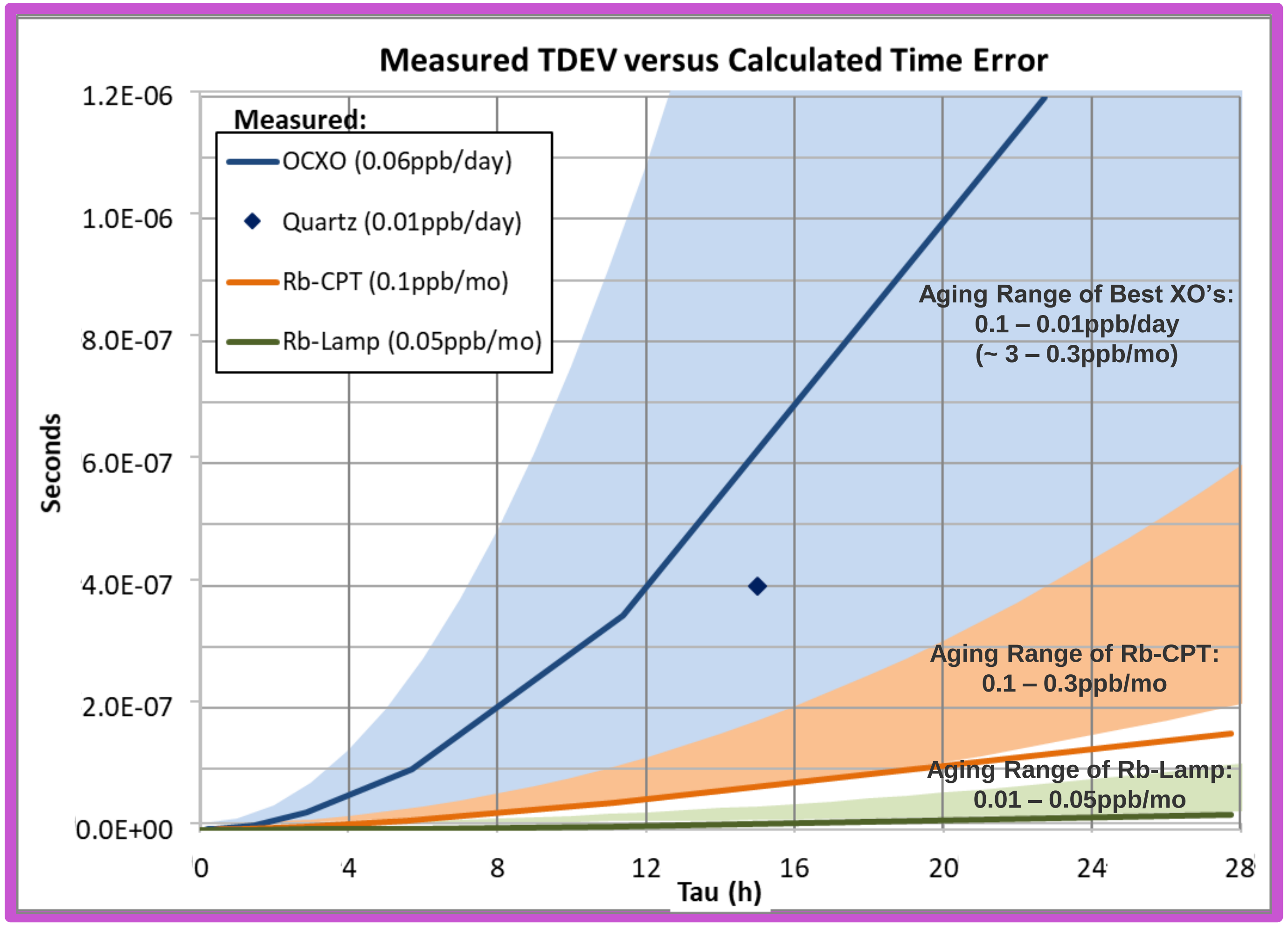
*Note: Data for "Quartz" device was reported on datasheet and has not been measured by the author.

1. John R. Vig, "Quartz Crystal Resonators and Oscillator for Frequency Control and Timing Applicatons, 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.

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



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  - ADEV, Phase Noise
  - Performance during Power-on
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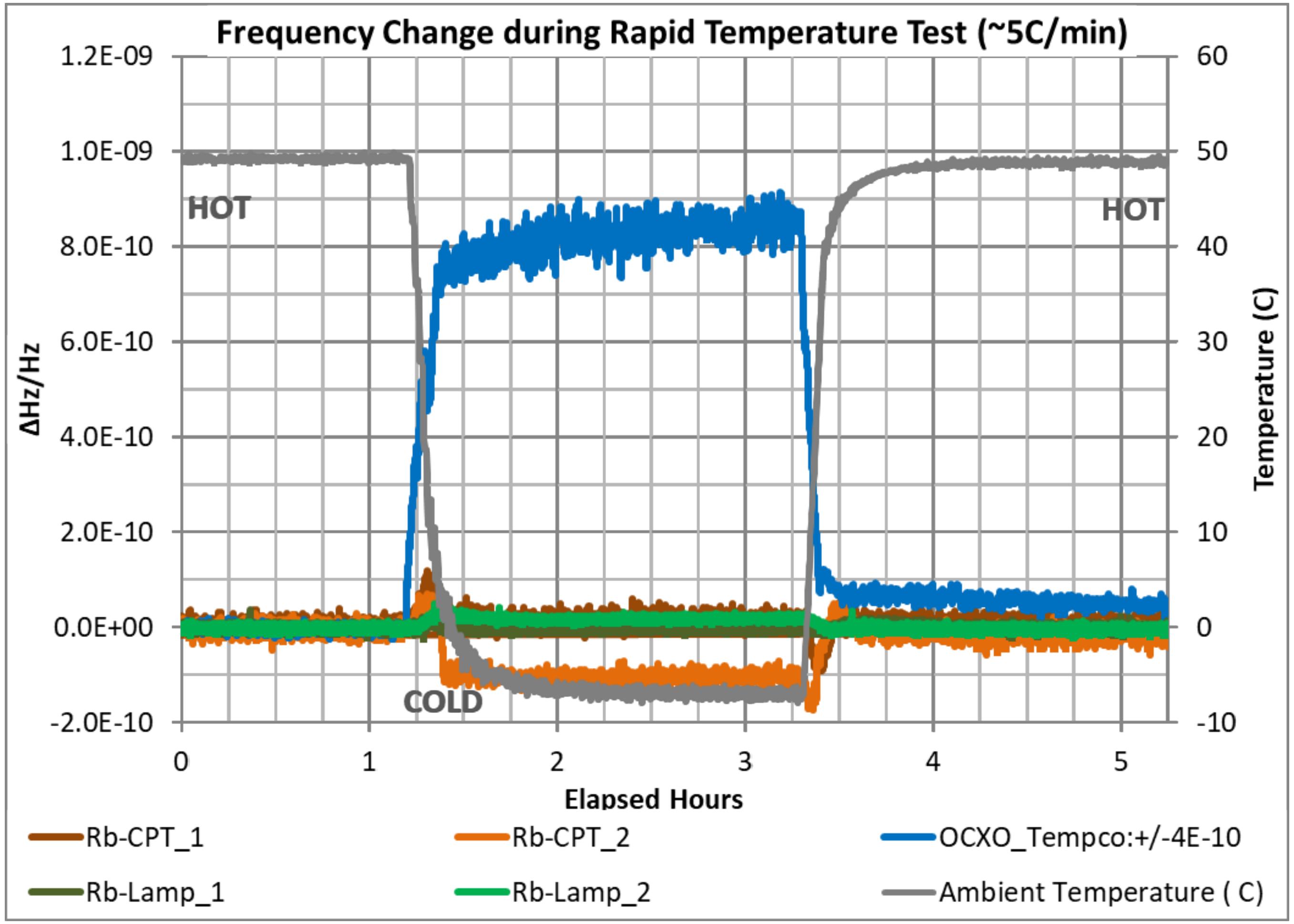
  - Effects of rapid temperature changes during 6hr missions
  - Effects of gravity
  - Effects of Magnetic Field
  - Effects of power disruption (retrace)

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

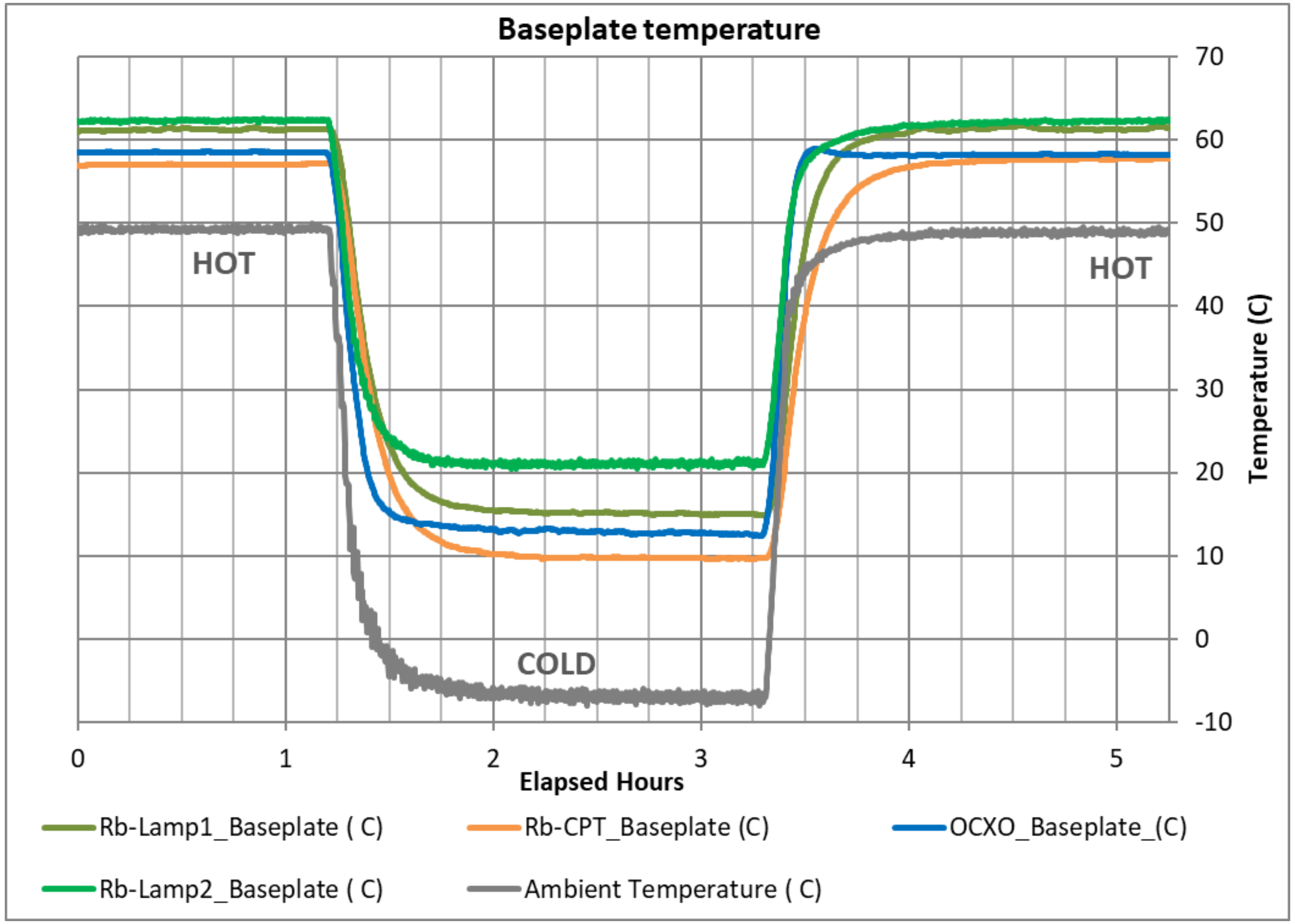
Device	Measured Δfreq. (max)	Specification	Specification Range
OCXO	***0.85ppb***	±0.40ppb	0 to +70˚C
Rb-CPT_1	***0.12ppb***	0.07ppb	-10 to +70˚C
Rb-CPT_2	***0.18ppb***	0.07ppb	-10 to +70˚C
Rb-Lamp_1	***0.05ppb***	0.60ppb	-25 to +70˚C
Rb-Lamp_2	***0.03ppb***	0.60ppb	-25 to +70˚C



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



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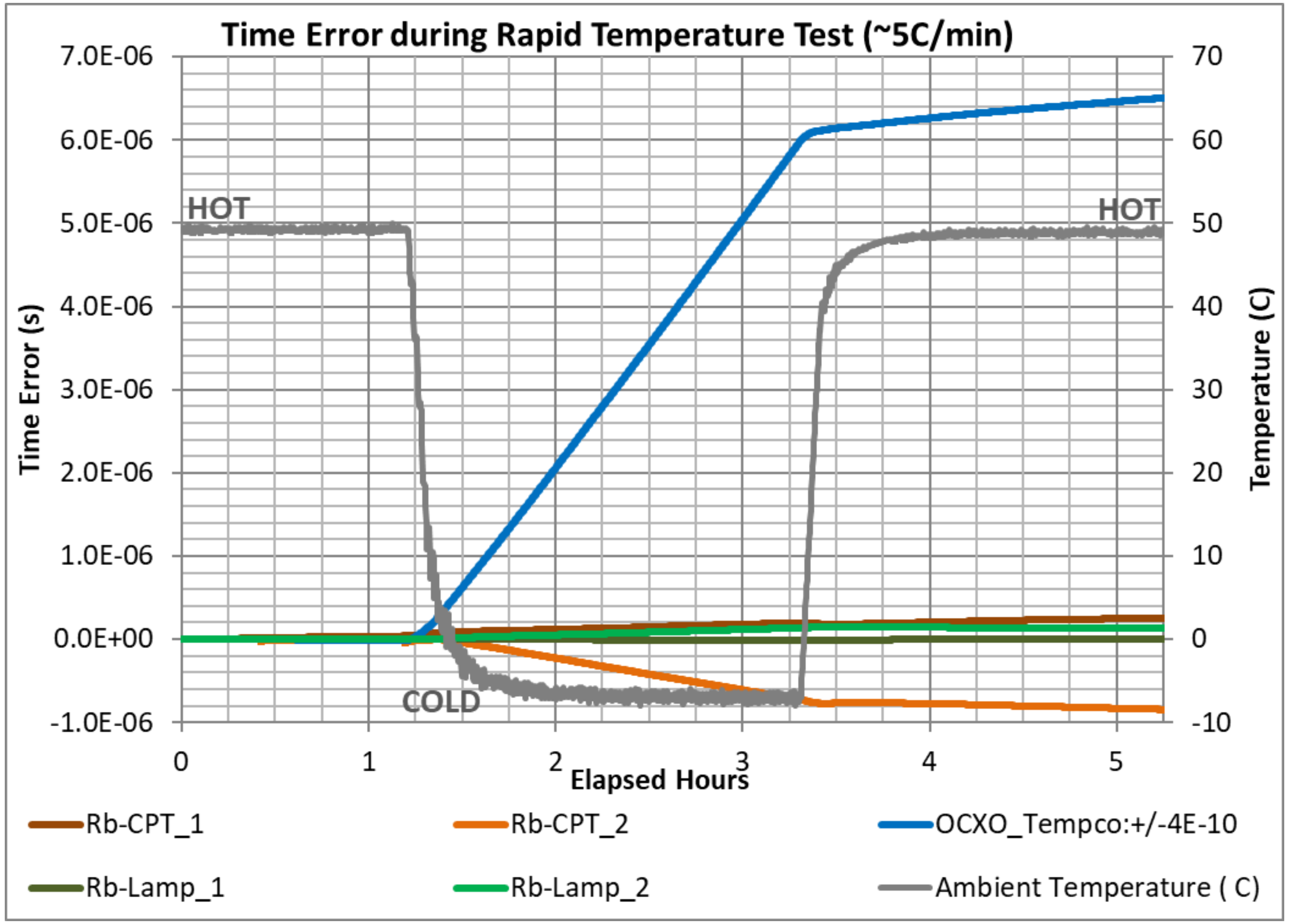
Rapid Temperature Test (*Phase Response)

- 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

Device	Measured Δphase (max)	Specification
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

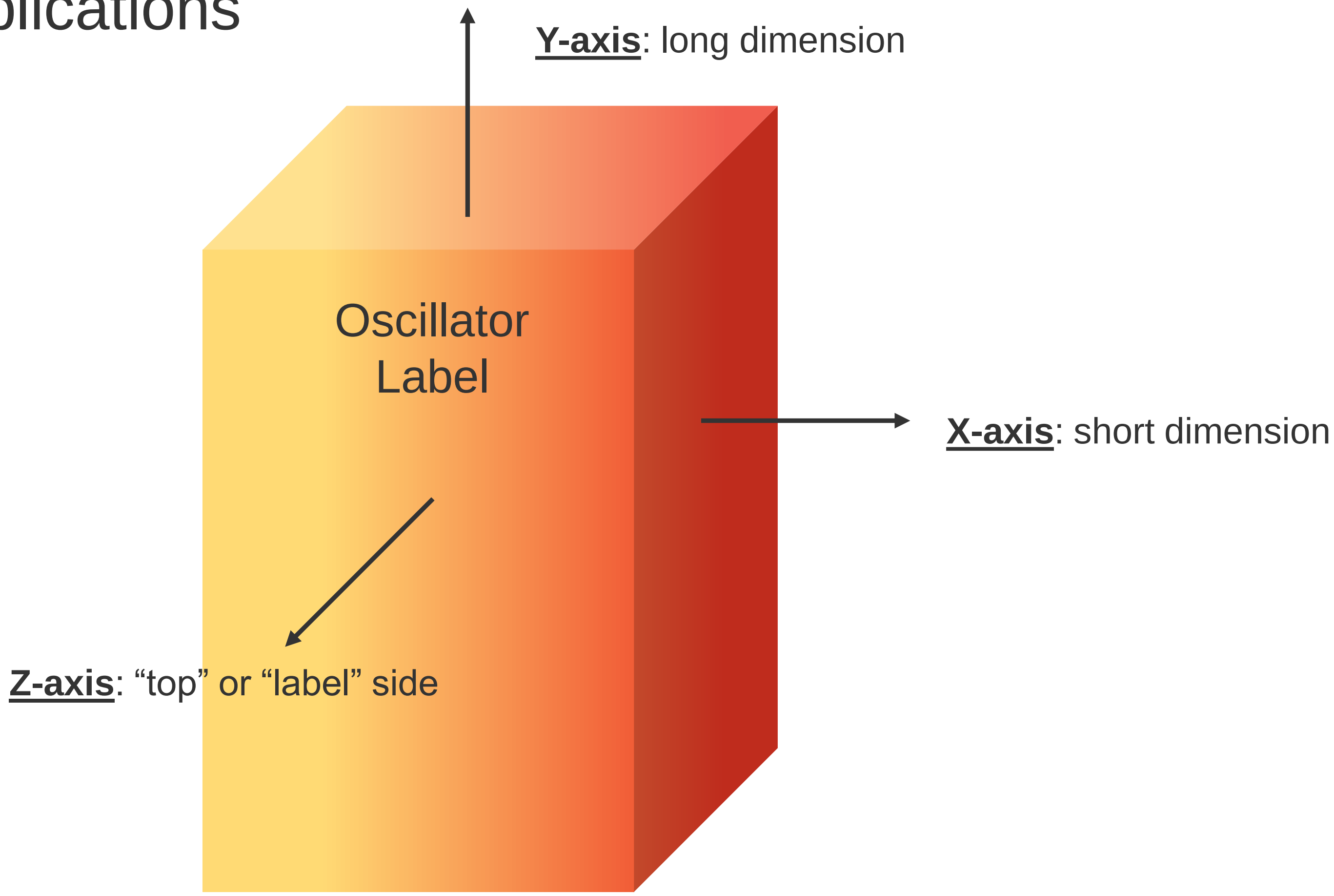


*The terms “phase” and “time error” are used interchangeably, in this instance

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

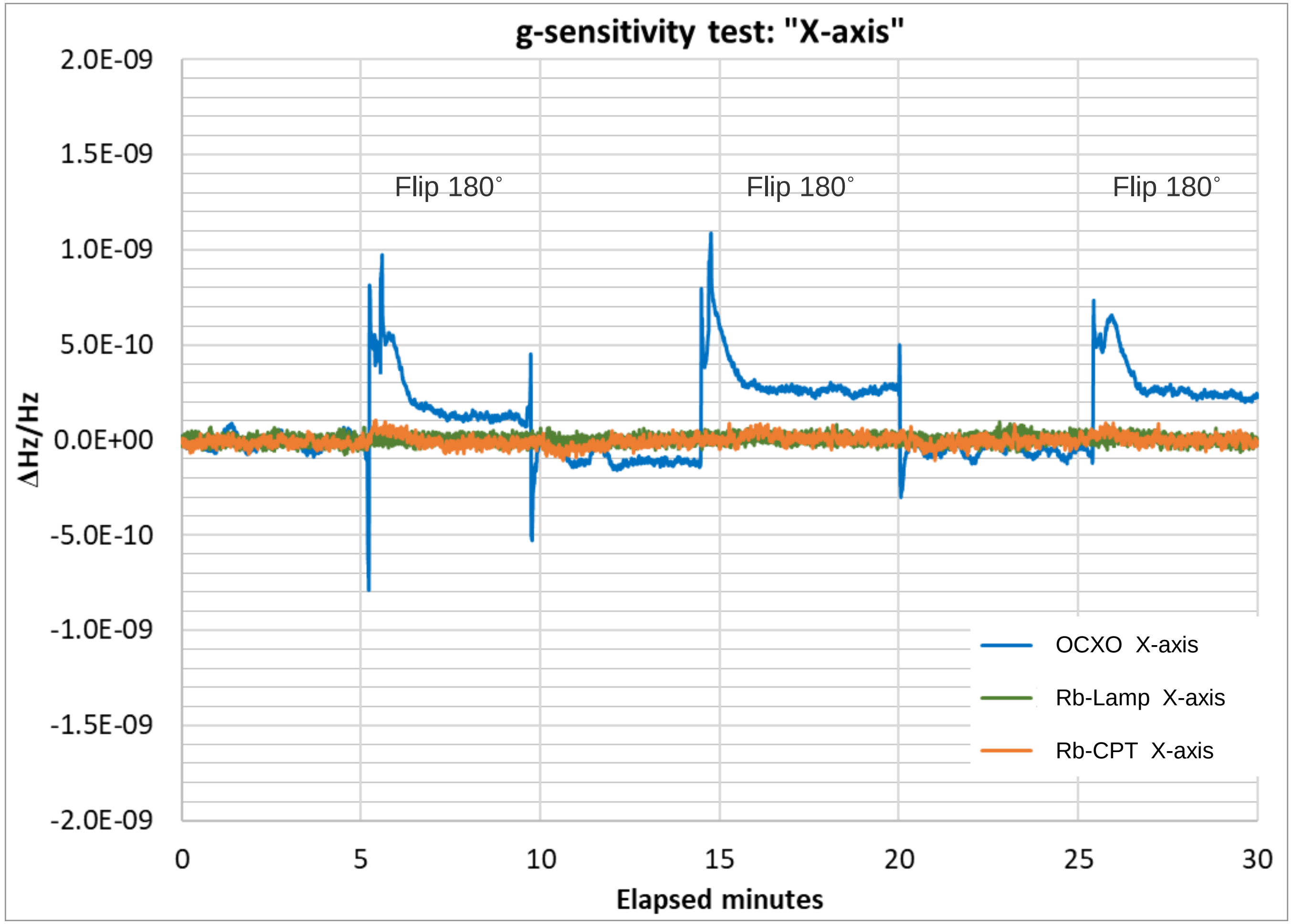
2g tip-over test

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

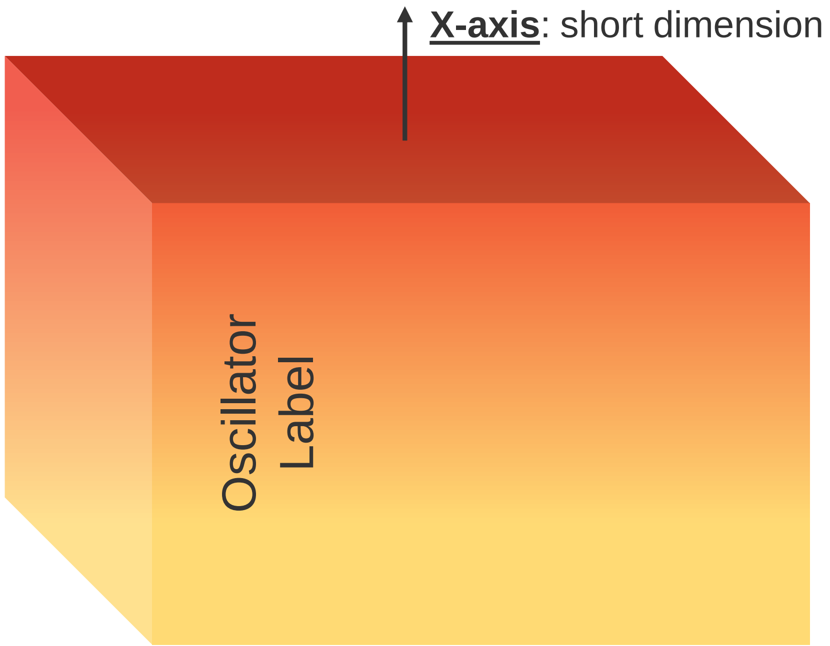


2g tip-over test: X-axis

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

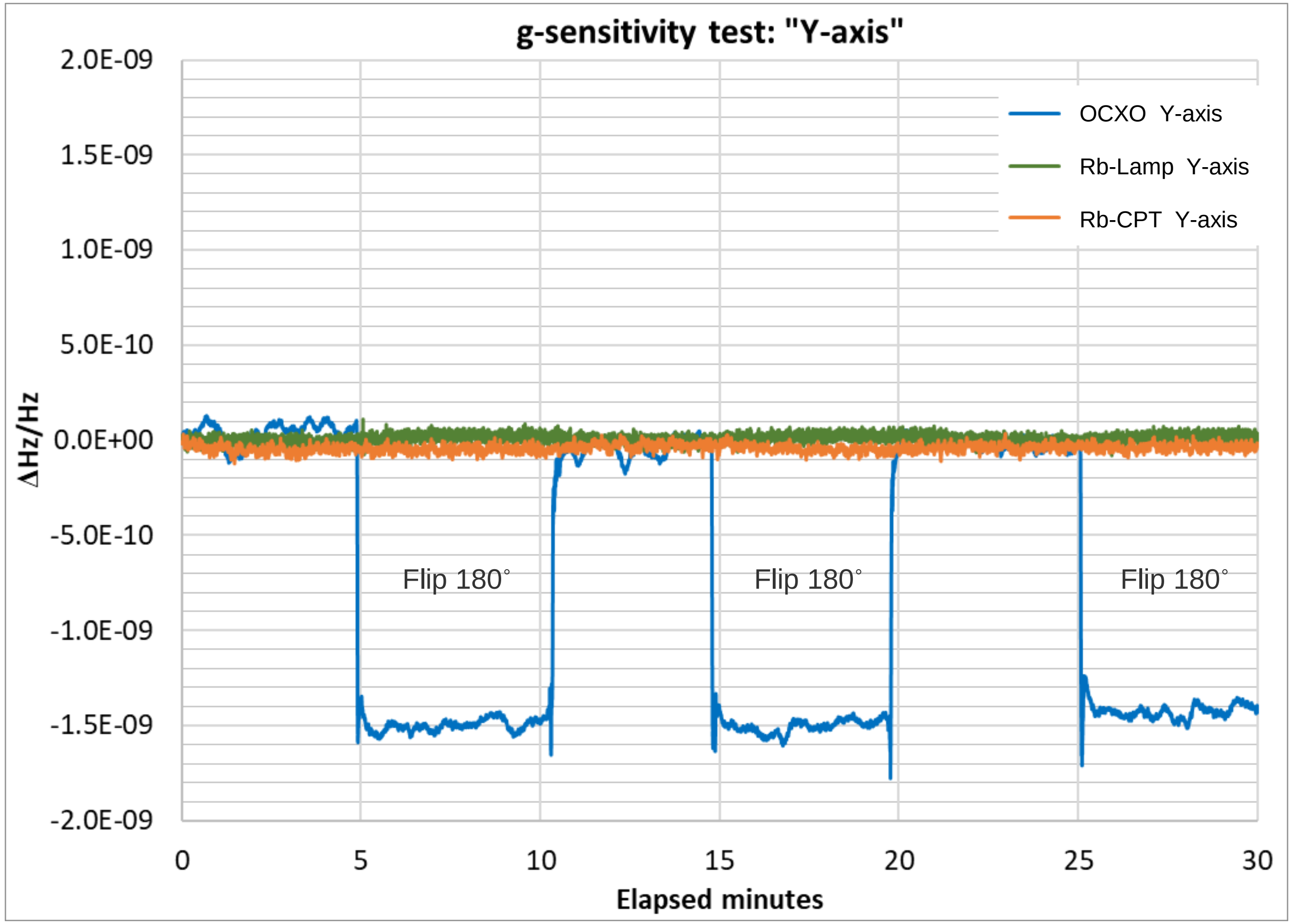


Device	Δfreq/g X-axis	Δfreq/g Y-axis	Δfreq/g Z-axis
OCXO	0.20ppb		
Rb-CPT_1	<0.10ppb		
Rb-Lamp_1	<0.10ppb		



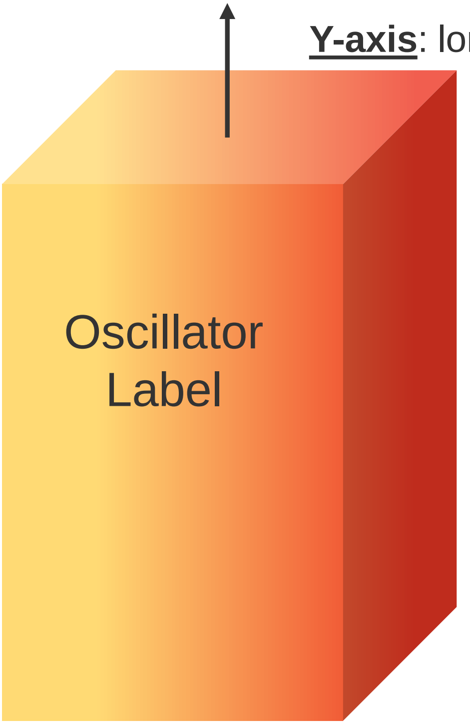
2g tip-over test: Y-axis

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



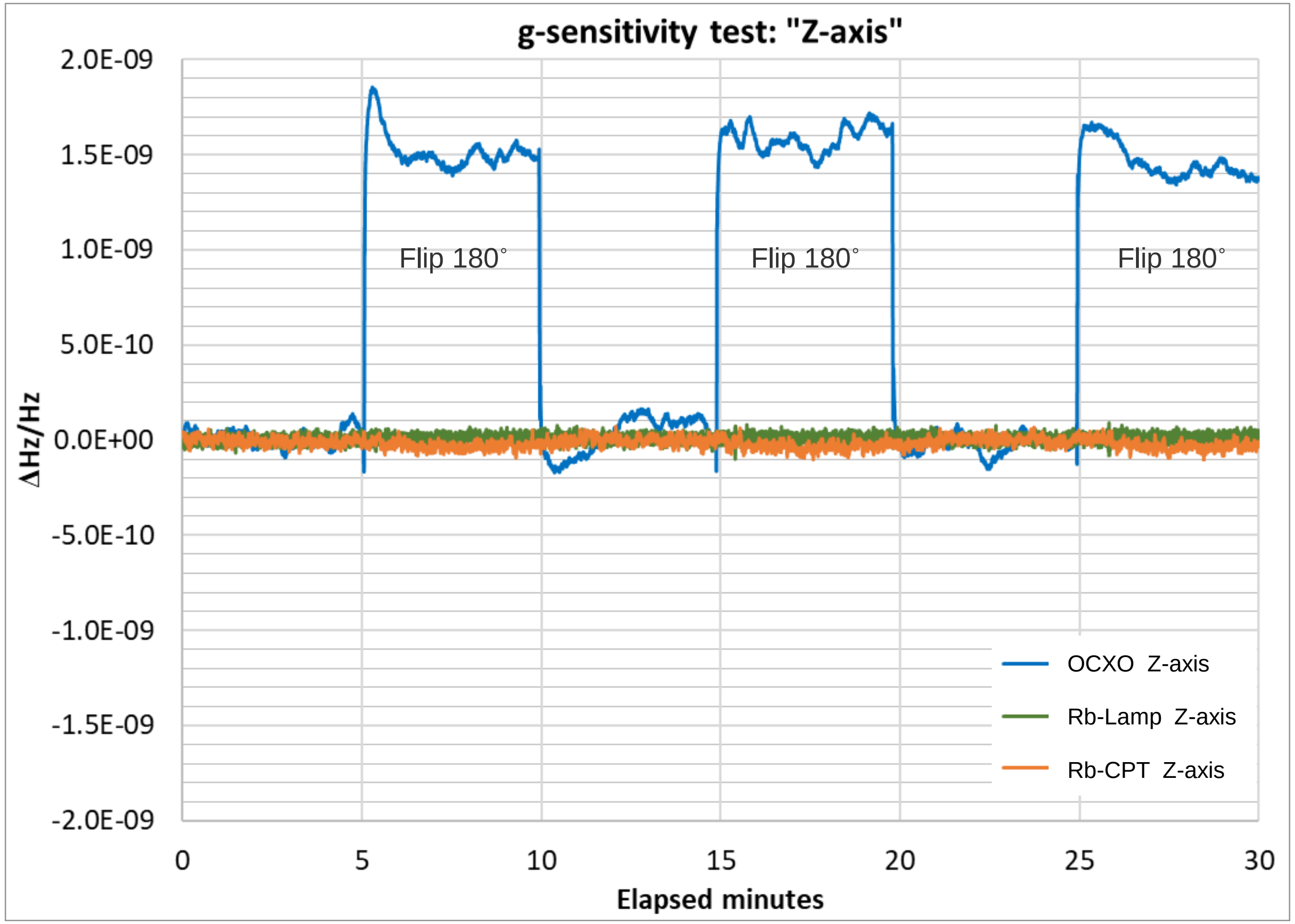
Device	**Δfreq/g X-axis**	**Δfreq/g Y-axis**	**Δfreq/g Z-axis**
OCXO	0.20ppb	0.75ppb	
Rb-CPT_1	<0.10ppb	<0.10ppb	
Rb-Lamp_1	<0.10ppb	<0.10ppb	

Y-axis: long dimension

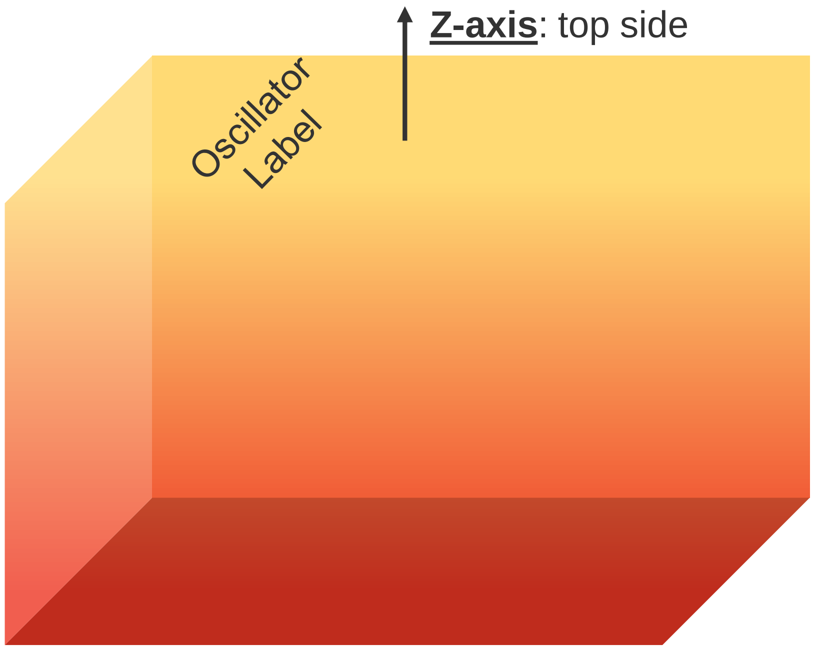


2g tip-over test: Z-axis

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

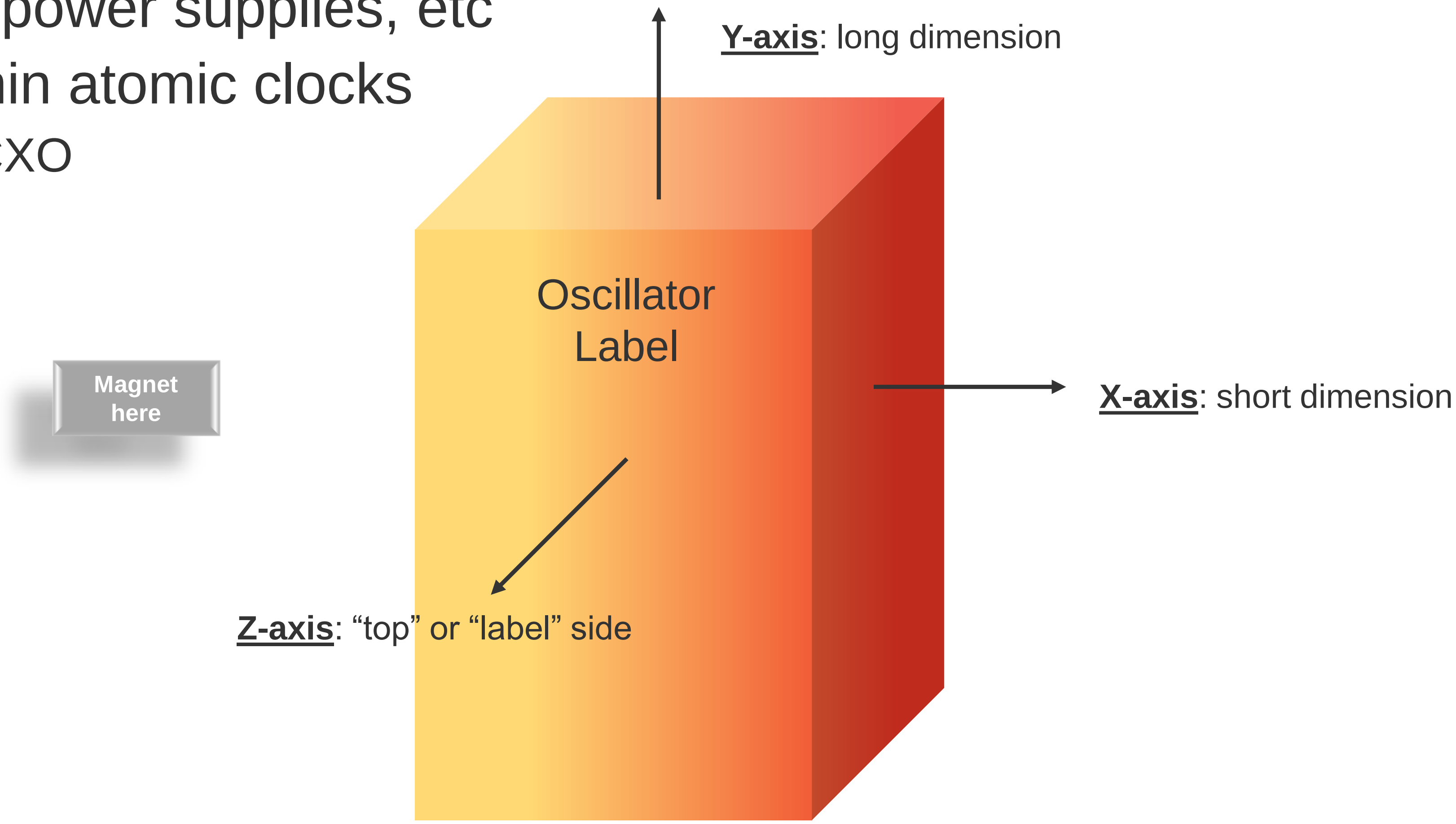


Device	**Δfreq/g X-axis**	**Δfreq/g Y-axis**	**Δfreq/g Z-axis**
OCXO	0.20ppb	0.75ppb	0.75ppb
Rb-CPT_1	<0.10ppb	<0.10ppb	<0.10ppb
Rb-Lamp_1	<0.10ppb	<0.10ppb	<0.10ppb



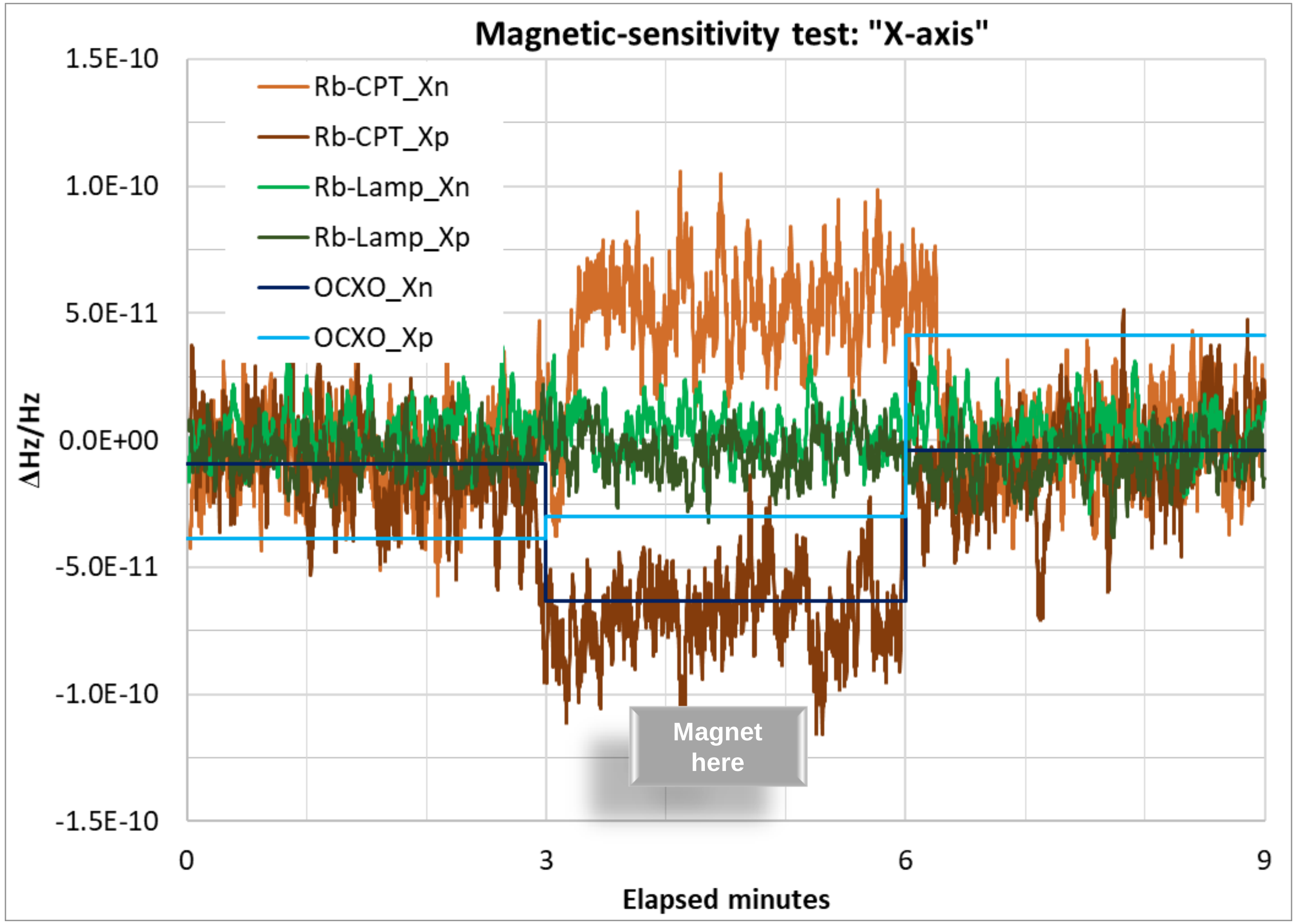
Magnetic Field Sensitivity test

- 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

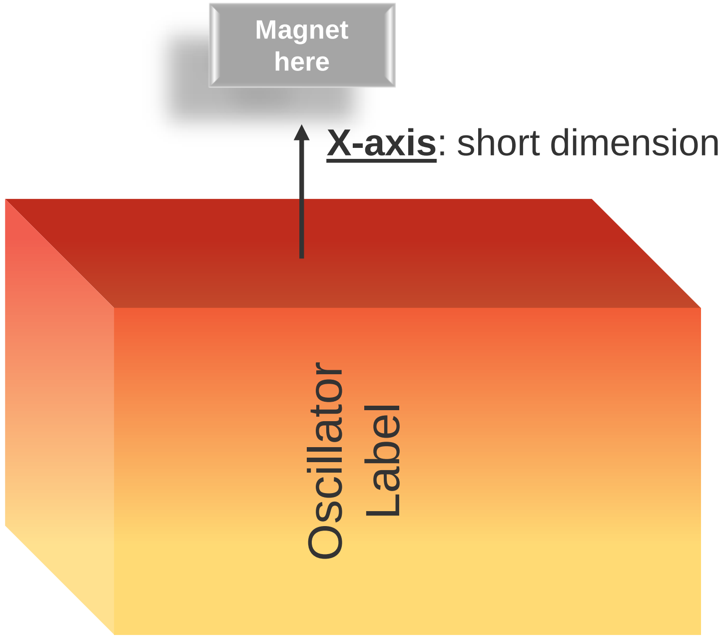


Magnetic Field Sensitivity test: X-axis

- ΔFrequency / Gauss = $(f_{max} - f_{min})/2$
  - MAC is most susceptible



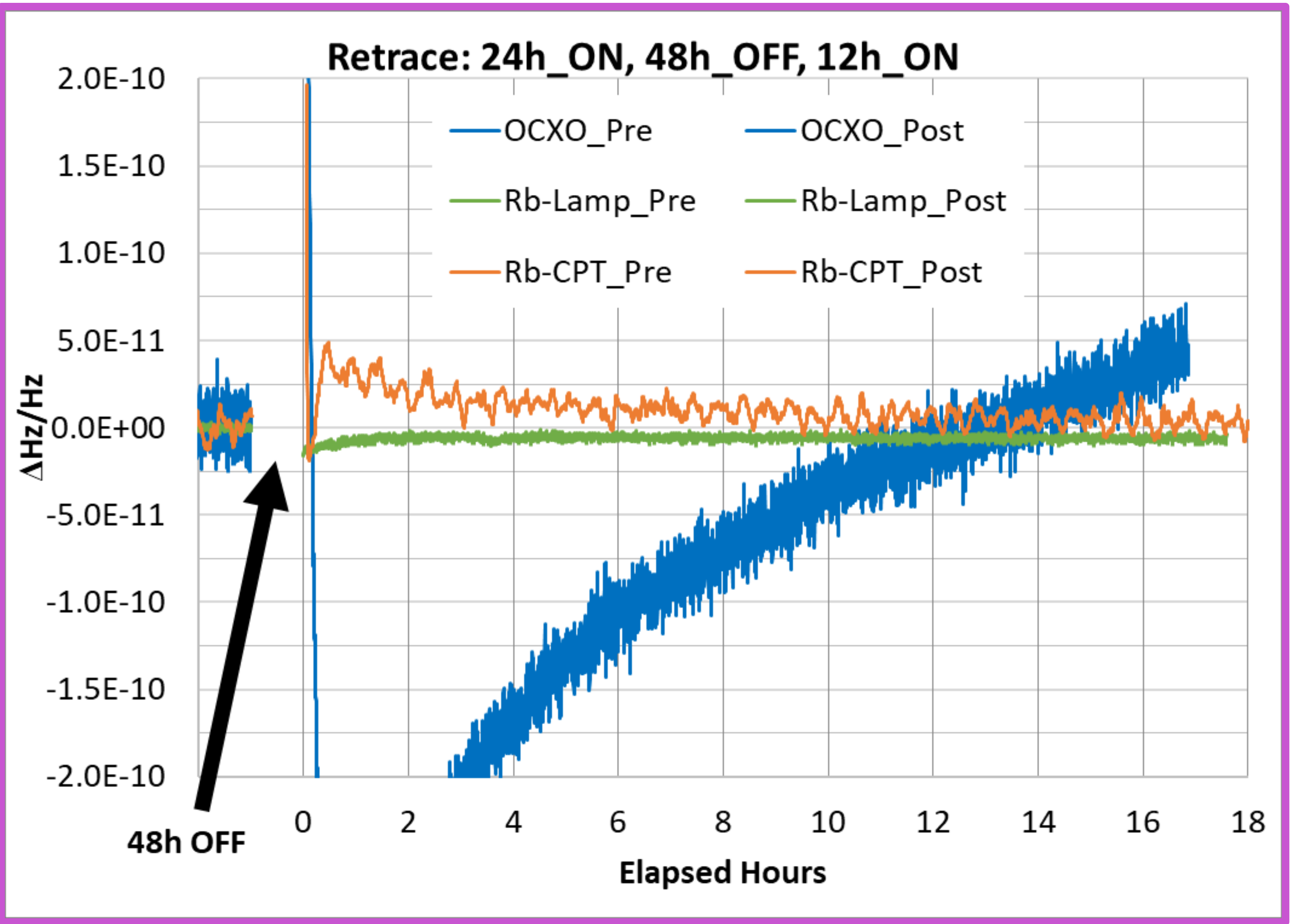
Device	Δfreq/Gauss X-axis	Δfreq/Gauss Y-axis	Δfreq/Gauss Z-axis
OCXO	-	-	-
Rb-CPT_1	5.75×10^{-11}	1.3×10^{-11}	1.8×10^{-11}
Rb-Lamp_1	$< 1 \times 10^{-11}$	$< 1 \times 10^{-11}$	$< 1 \times 10^{-11}$



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



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 (ΔHz/Hz /g)	Magnetic sensitivity (ΔHz/Hz /Gauss)	Re-trace (ΔHz/Hz)	Intrinsic Accuracy (ΔHz/Hz)	1S-ADEV (ΔHz/Hz)	ADEV floor (ΔHz/Hz)	Aging (/day) (ΔHz/Hz)	Power (W)	Cost
Rb-Lamp	< 0.1µs	~10^{-11}	~10^{-11}	~10^{-12}	~10^{-11}	~10^{-9}	~10^{-11}	~10^{-13}	10^{-11} to 10^{-13}	10	~ X
Rb-CPT	0.2 to 0.5 µs	~10^{-10}	~10^{-11}	~10^{-11}	~10^{-11}	~10^{-9}	~10^{-11}	~10^{-13}	10^{-11} to 10^{-13}	0.125 to 6	~ X
Hi-quality Qz	0.5 to 2 µs	<10^{-9}	~10^{-9}	-	~10^{-10}	10^{-6} to 10^{-8}	~10^{-12}	~10^{-12}	10^{-9} to 10^{-11}	~ 5	~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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