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TORCH – A Cost Effective, Environmentally Resilient Optical Clock for Commercial Timing Applications

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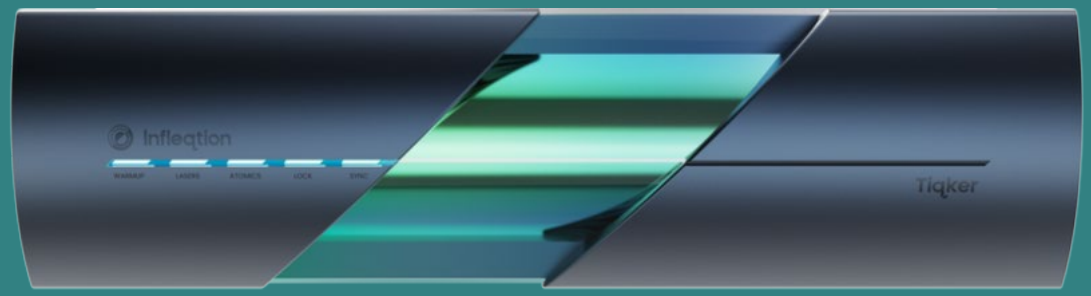
Commercially Available Optical Clocks

https://infleqtion.com/tiqker/



ADEV (1 s) < 3E-13
Flicker Floor < 0.9E-14
Er:fiber comb + Doubled 1556 nm cw laser

https://vectoratomic.com/

ADEV (1 s) < 4E-14
Flicker Floor < 1E-14
Er:fiber comb + Doubled 1064 nm cw laser

NEW

https://vescent.com/

ADEV (1 s) < 3E-13
Flicker Floor < 2E-14
Er:fiber comb + (direct) 1530 nm cw laser

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Challenges With Bringing Optical Clocks to Market

- Performance
  - Long term?
- Reliability
  - Laser maturity - Industrial or emerging source?
  - How exotic is the physics package?
- Supply Chain
  - Lasers, lasers, lasers
  - Physics packages?
- Cost
  - Complexity - # of lasers, control electronics for laser manipulation
  - Pathways to reduce cost at scale?

Long Term Performance Issues for Optical Clocks

- Temperature sensitivities – all subsystems are thermometers
  - Optical alignments
    - Beam walk off on photodetector appears the same as change in absorption.
  - Physics packages
    - Vapor pressure
    - Ideal gas law
- Changes in laser optical power can degrade long term performance
  - AC Stark shift for atomic clocks
- Lifetime
  - Lasers (if not Telcordia or Industrial)
  - Gas Cells (leaking/diffusion)

Optical Atomic Clock Opportunities and Challenges

	Warm Vapor			Ions			Neutral Lattice		Nuclear
Parameter	**I_2**	**Rb**	**C_2H_2**	**Sr+**	**Yb+**	**Ca+**	**Sr**	**Yb**	**^{229m}Th**
Short-term Performance (1 s ADEV)	<4E-14	<3E-13	<3E-13	<3E-15	<3E-15	<1E-15	<1E-16	<1E-16	<1E-18
Long-term Operation	> 7 mo.	?	> 8.5 mo.	wks	wks	wks	hrs – days	hrs – days	?
Complexity (# lasers)	1	1	1	4	5	5	6	5	5-8
Laser Wavelength (nm)	500-550	778	1530-1560	674, 420, 1033, 1092	436, 367, 935, 760, 467	729, 397, 866, 854, 423	698, 461, 689, 679, 707, 813	578, 399, 556, 649, 759	148, ?, ?
Laser Reliability	++	++	+++	+	+	+	+	+	- - -
Current Size (L)	30	30	30	200+	2000+	1000+	1000+	1000+	-
Commercial Cost	$$$	$$$	$	$$$$$ $$$$$	$$$$$$$ $$$$$$$	-	-	-	-
Available for purchase?	Y	Y	Y	Optical Only	Y	N	N	N	N

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Acetylene (C_2H_2) Optical Clock Kit Overview

100 MHz Clock Output

- An Optical Clock made with commercially available components has shown maser-like instability with significantly lower environmental sensitivity.
  - Long-term testing revealed current Stabilaser design has temperature sensitivities between 20-50 Hz/°C ($1\text{-}2.5\times10^{-13}$/°C).
- Based on this performance, Vescent has decided to integrate this system to improve long term performance, increase ruggedization, and reduce costs.

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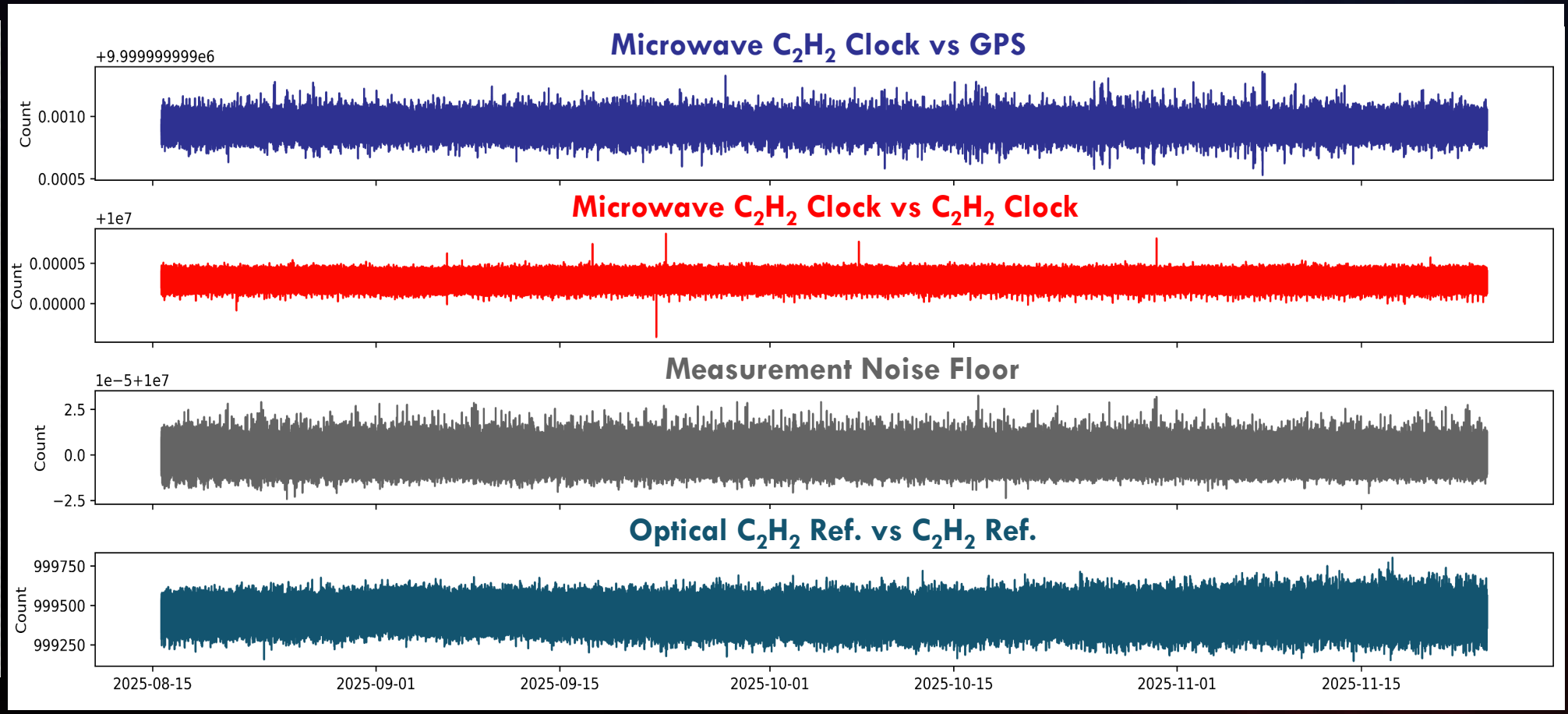
Long-term Acetylene Clock Measurement Setup

- Individual Acetylene Optical Clock Kit occupies 6U.
- All hardware mounted in ~20U rack.
  - Includes counter and temperature monitoring.

Long-term Acetylene Clock Measurement Timeseries



Phase-stable Operation (> 100 Days) Without Intervention – measurement is on-going.

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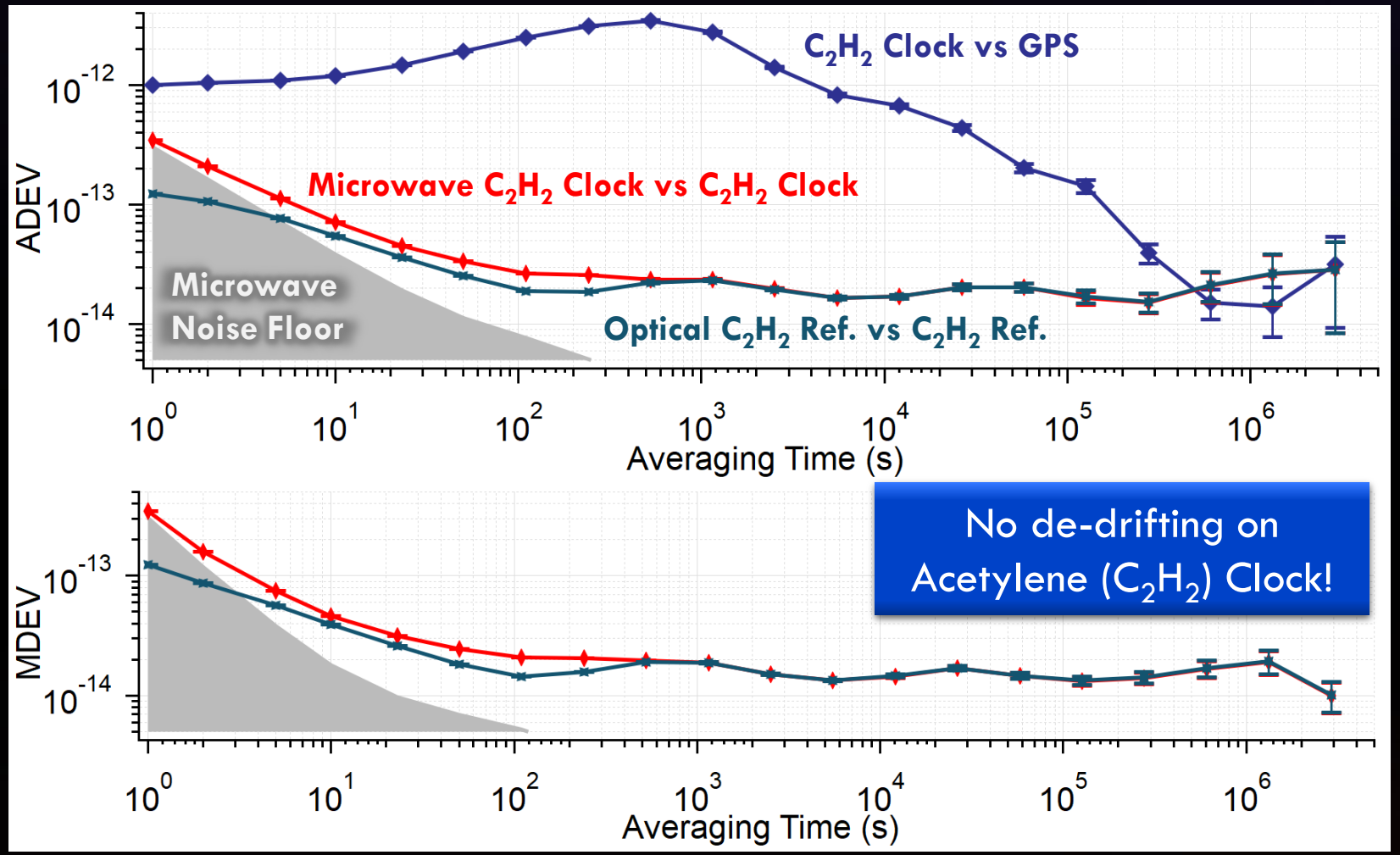
<3x10^{-14} ADEVs AT >3.5×10^{6} SECONDS



- Long-term performance of the Acetylene Optical Clock Kit has shown <4E-14 at timescales between 100 s and >1 month.
- No user intervention required for >240 days of phase-slip free operation.
- Additional measurements (DoD, DFM, NPL) are underway.

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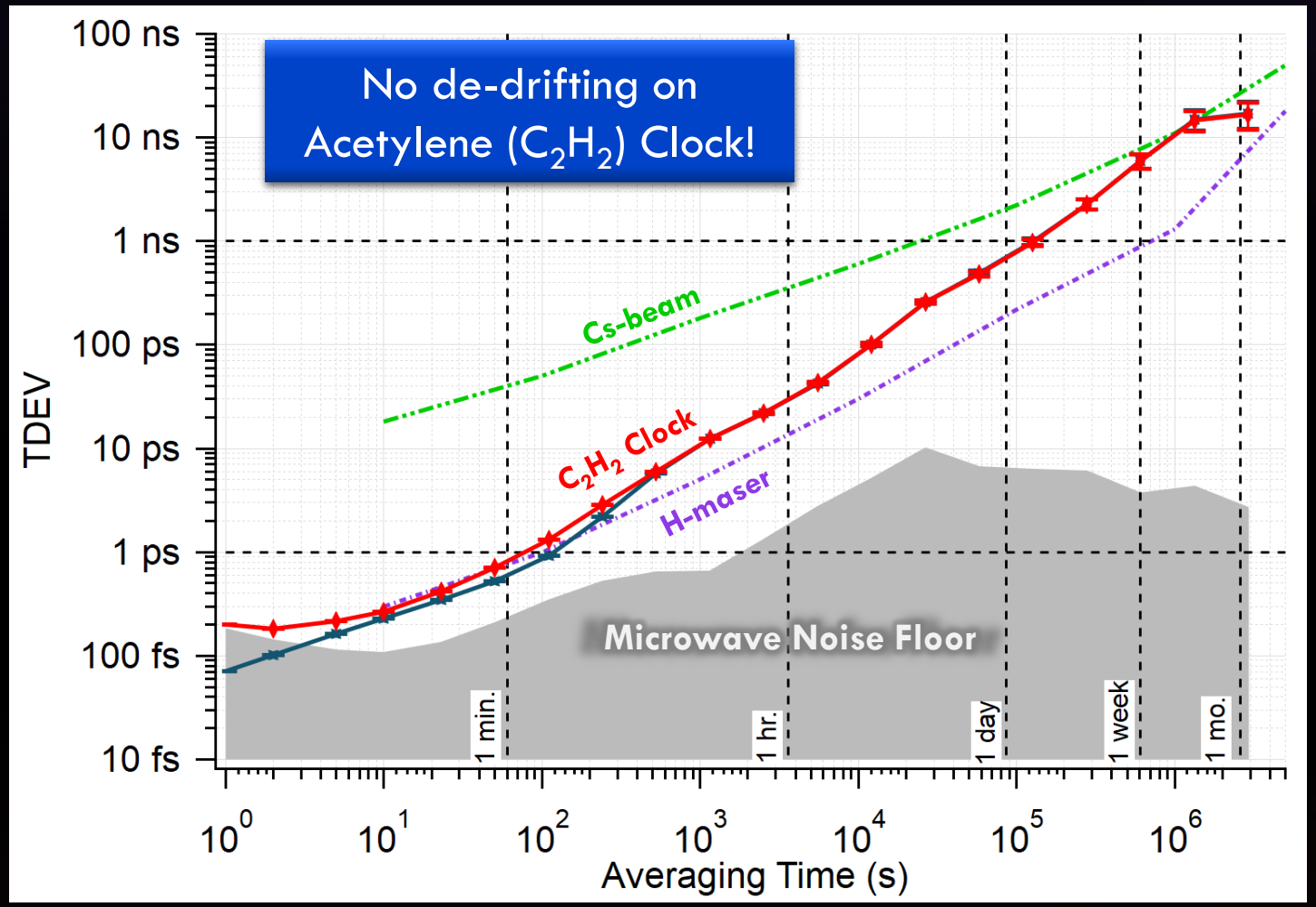
Timing Deviation / Holdover



- TDEVs competitive with masers at short timescales and Cs-beam for holdover.
  - Sub-ps TDEV > 1 min.
  - Sub-ns TDEV > 1 day.
  - TDEV <20 ns @ 1 month.

Cs-beam and H-maser models taken from NIST at:
https://www.nist.gov/pml/time-and-frequency-division/time-realization/utcnist-time-scale/how-utcnist-works

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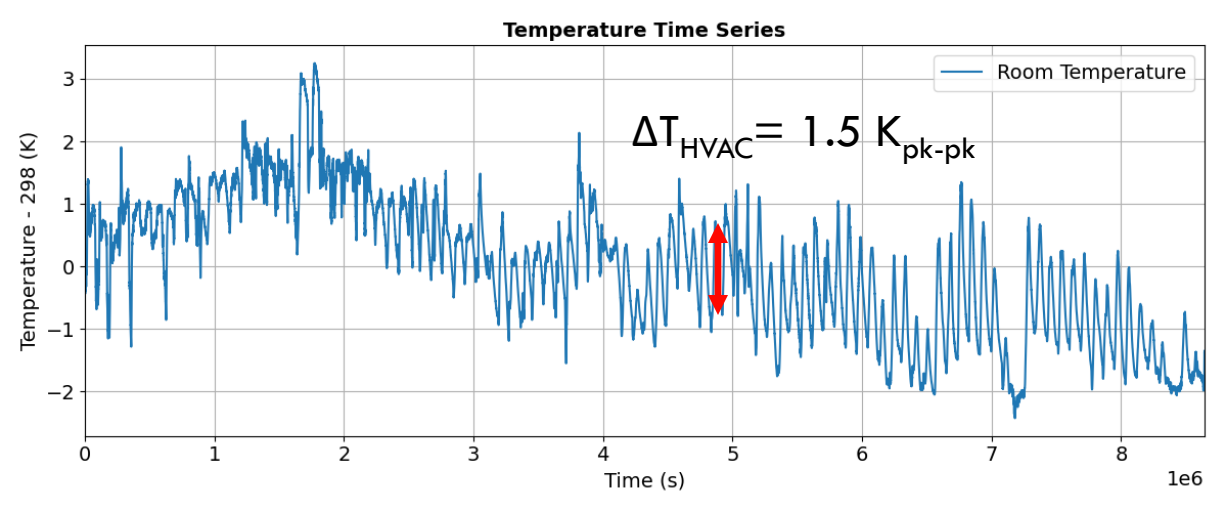
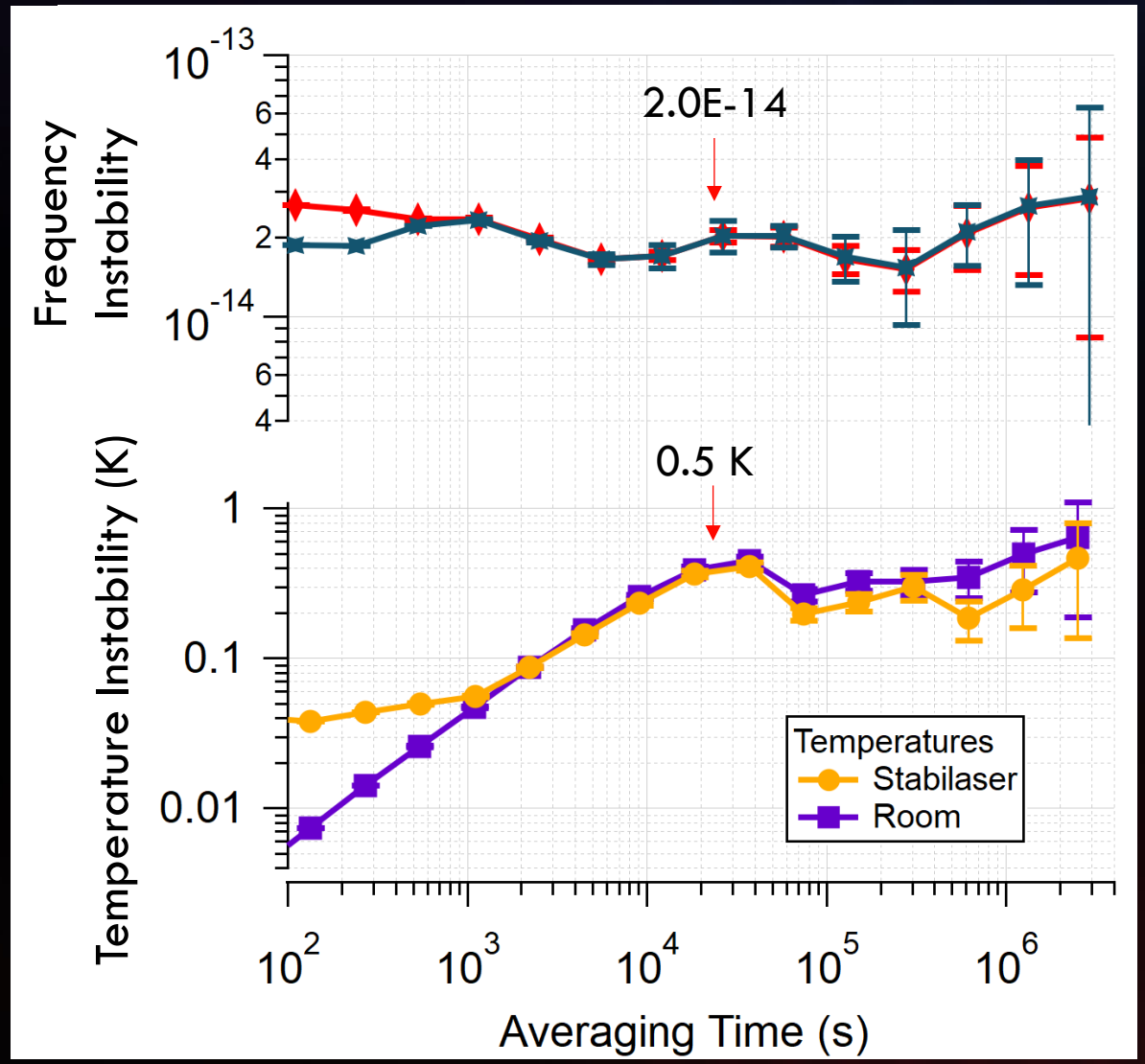
Operation in a (real world) changing temp environment



- Additional independent measurements of Stabilaser in a stable temp environment (fluctuations <0.1 K) show opportunities to average down into the 10^{-15}'s.
- Vescent has performed multiple long-term measurements with different Acetylene Optical Clocks showing similar performance.



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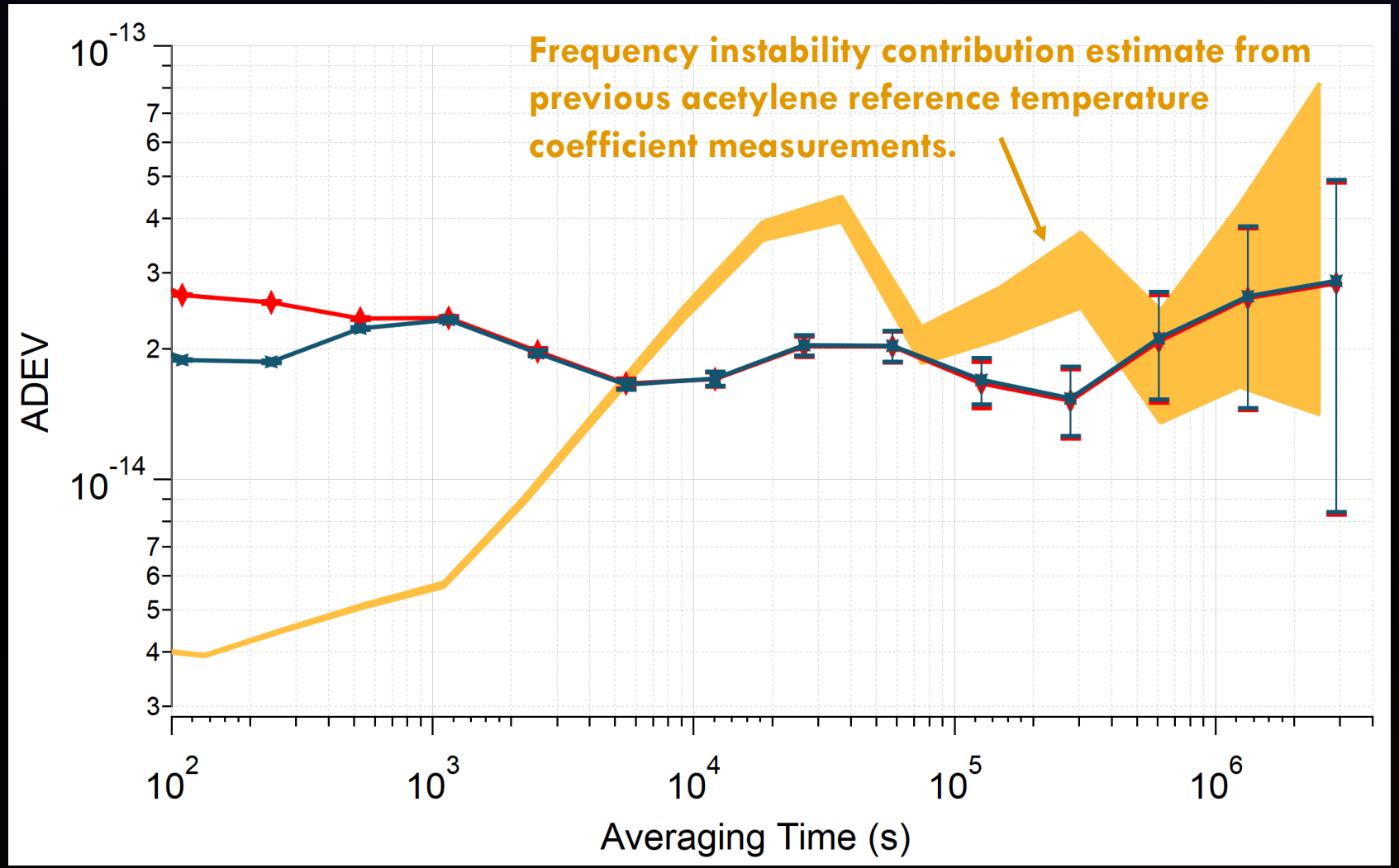

- Temperature is driving long-term performance.
- Mechano-optical alignments exhibit temperature sensitivities.
- Modeling of cell temperature effects on long-term stability indicate cell temperature control is necessary.
- Electronics noise levels and temperature sensitivities are being investigated.

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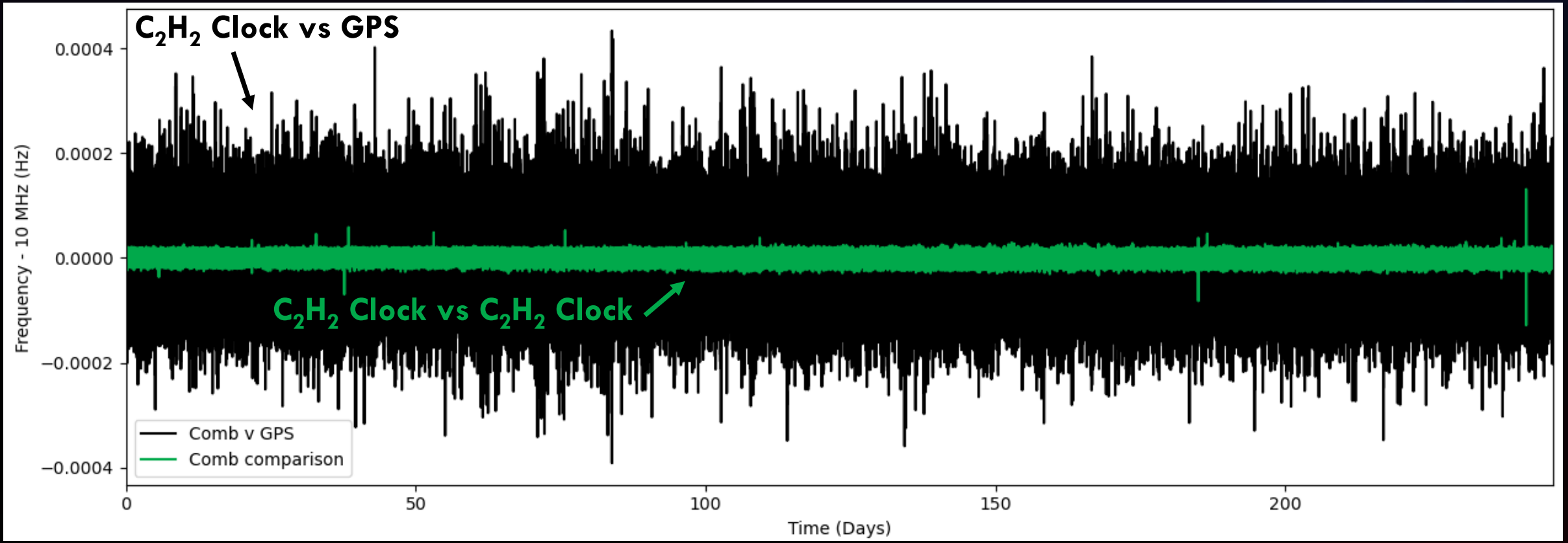
Continued Long-term Testing (>245 days)



Continuous, 100% up-time operation of 2 Acetylene Optical Clocks.

Temperature sensitivity issues causing long-term performance degradation will be addressed in commercialized product.

MIRIDIAN$_1$™ CLOCK Preliminary Specifications

- Integration of all subsystems into a single enclosure.
- Gen. 0 Prototype under development now (anticipated completion in February 2026).
  - Product release slated for Q4 2026.

Parameter	Value
RF/Timing Outputs	• 5 MHz • 10 MHz • 100 MHz • 1 PPS
Optical Outputs (optional)	• 1530 nm (cw) • Comb EDFA monitor 1525-1595 nm (pulsed)
Operational Temperature Range (to meet performance specs)	15-35 °C

Parameter	Value
Frequency Stability @ 1 s @ 1,000 s @ 100,000 s @ 1,000,000 s	 2×10^{-13} 2×10^{-14} 1×10^{-14} 1×10^{-14}
100 MHz Phase Noise @ 1 Hz offset	-80 dBc/Hz

Parameter	Value
Size	3U Rack enclosure 19 x 22 x 5.2 in^3 / 48.3 x 55.9 x 13.2 cm^3
Weight	14 kg
Power	100 W (max)
Line Voltage	100 – 230 V_{ac} @ 50-60 Hz

Summary

- Acetylene Optical Clock Kit (based on commercial components)
  - Minor initial user setup.
  - No user intervention for long-term phase-slip-free operation > 8.5 months.
  - ADEVs:
    - <4E-14 from 100 s to >3,000,000 s (measurement on-going).
  - TDEVs:
    - <1 ps up to 100 s
    - <1 ns @ > 1 day
    - <20 ns @ 1 month
  - Temperature Coefficient < 1E-13/°C.

Next Steps

- MIRIDIAN$_1$ (integrated optical clock)
  - Integrating system offering maser-like short-term performance and Cs-beam-like holdover.
  - Prototype development underway.
    - Pathways to improved long-term performance under investigation including spectrometer redesign and subcomponent temperature coefficient measurements.
  - Targeting $100,000 USD ASP for full product release in Q1 2027.

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