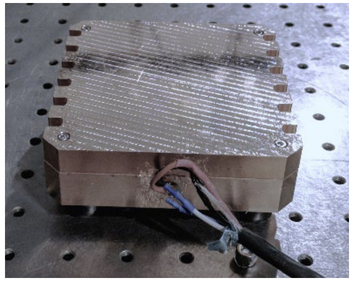
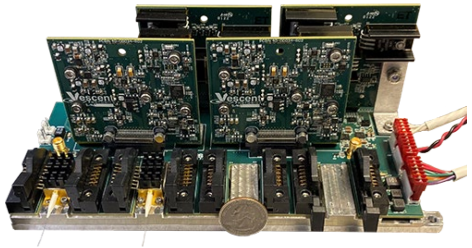
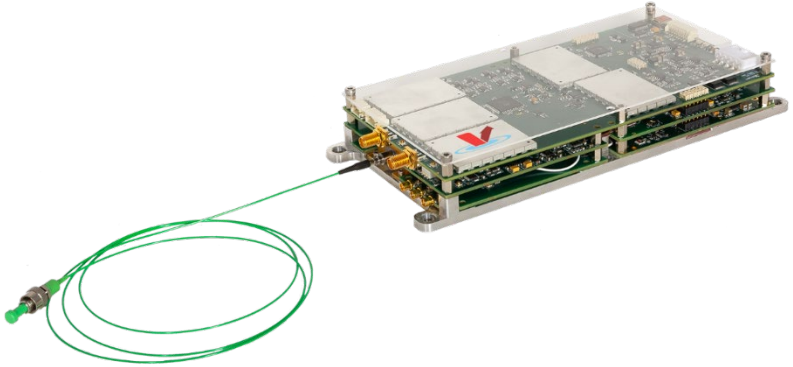
Compact, Ruggedized Frequency Combs for Real-world Optical Atomic Clocks

Henry Timmers, Bennett Sodergren, Andrew Attar, Star Fassler, Cole Smith, Jason Pinon, Kurt Vogel, **Kevin Knabe (kknabe@vescent.com)**

Motivation - Need for next-gen GPS

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- GPS can be jammed/spoofed with~$100 worth of RF equipment!
- The DoD is interested in better long-term clocks, as they need to check in less often with GPS (timing error = navigation error).

Truck Driver with GPS Jammer Accidentally Jams Newark Airport

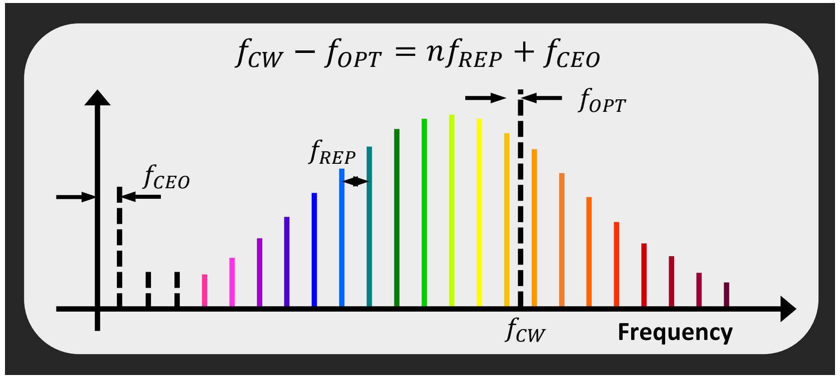
Jamming company-issued GPS in vehicles not just a bad career move

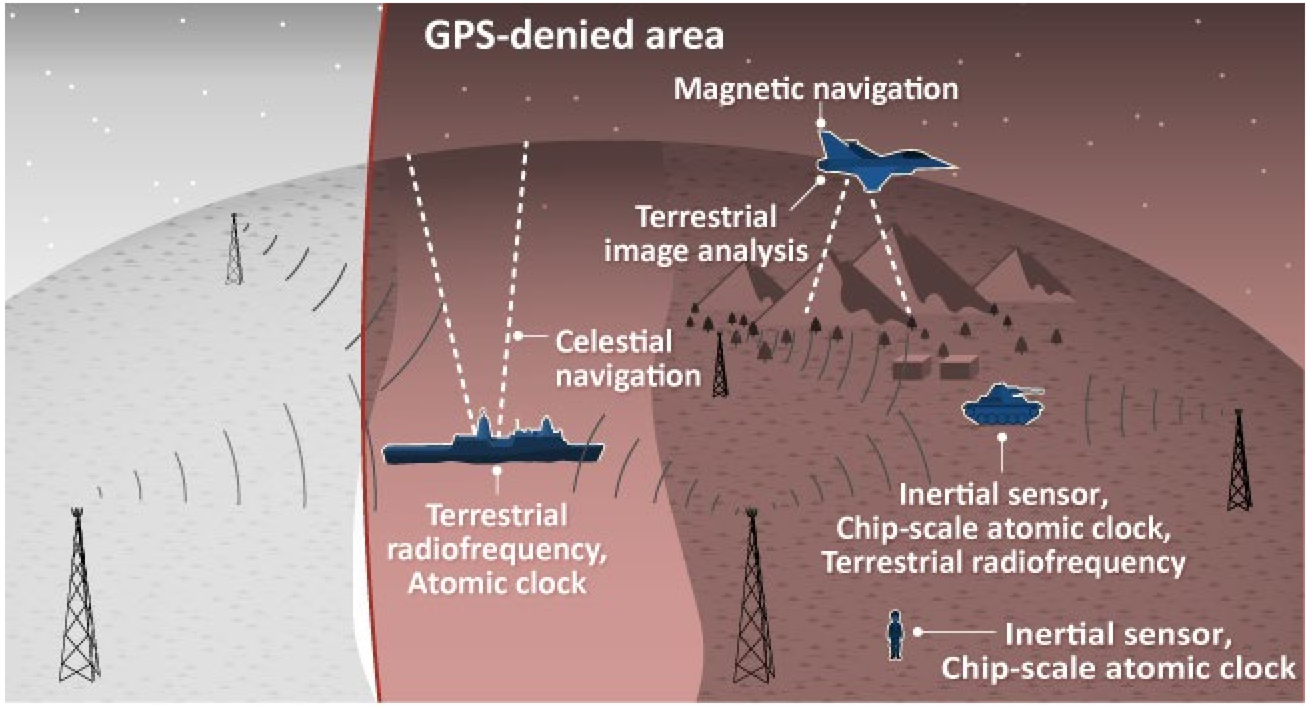
2013

Optical Atomic Clock Readout & Dissemination

- Next-generation GPS
- Assured PNT in GPS denied environments

Required Tools: Field deployable **frequency comb** locked to an **atomic-stabilized laser.**





Source: GAO analysis of DOD information. | GAO-21-320SP

https://www.gao.gov/products/gao-21-320sp

Motivation – Next generation quantum sensors

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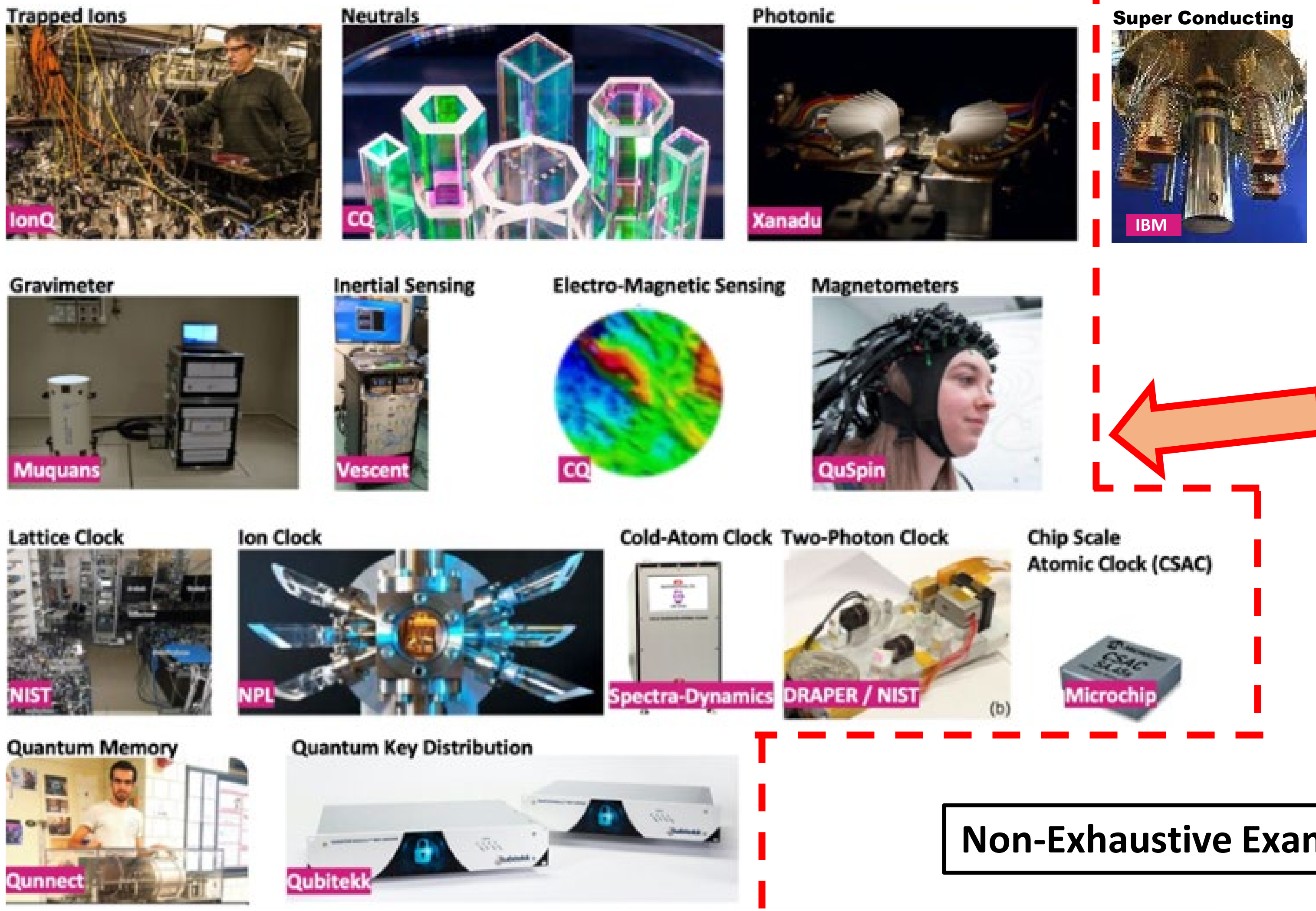
Quantum Computing

Quantum Sensing

Quantum Timing

Quantum Networking



Requires deployable lasers and precision control electronics

Non-Exhaustive Examples

Quantum-Enabling Laser Solutions

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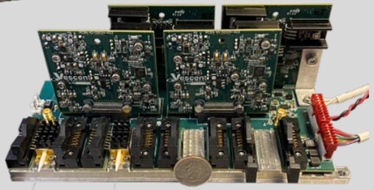
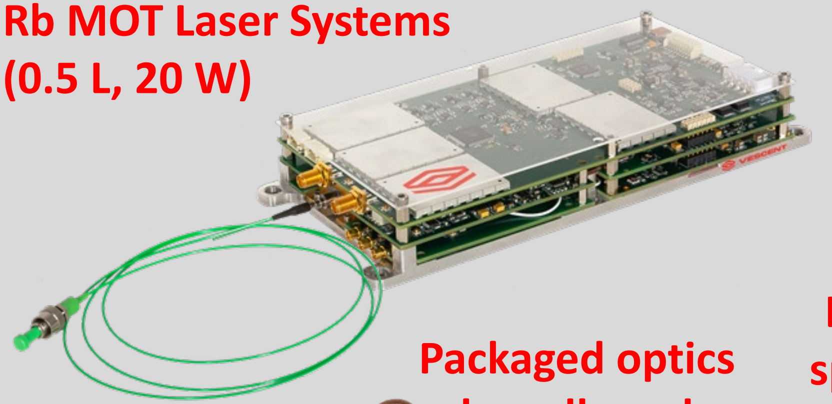
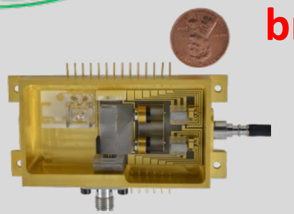


Optical Frequency Combs (4 L, 15 W)

Rb MOT Laser Systems (0.5 L, 20 W)

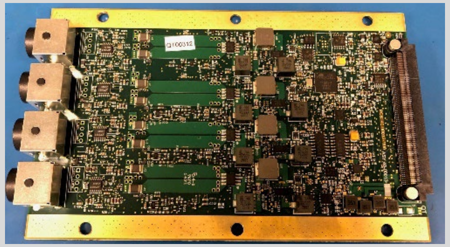


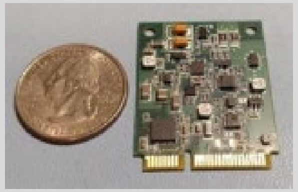
Low timing jitter oscillators



Packaged optics breadboard modules

Low-noise high-speed electronics





Low SWaP board level solutions

Deployable laser system are necessary to realize Quantum 2.0 outside of the lab!

Computing

Timing

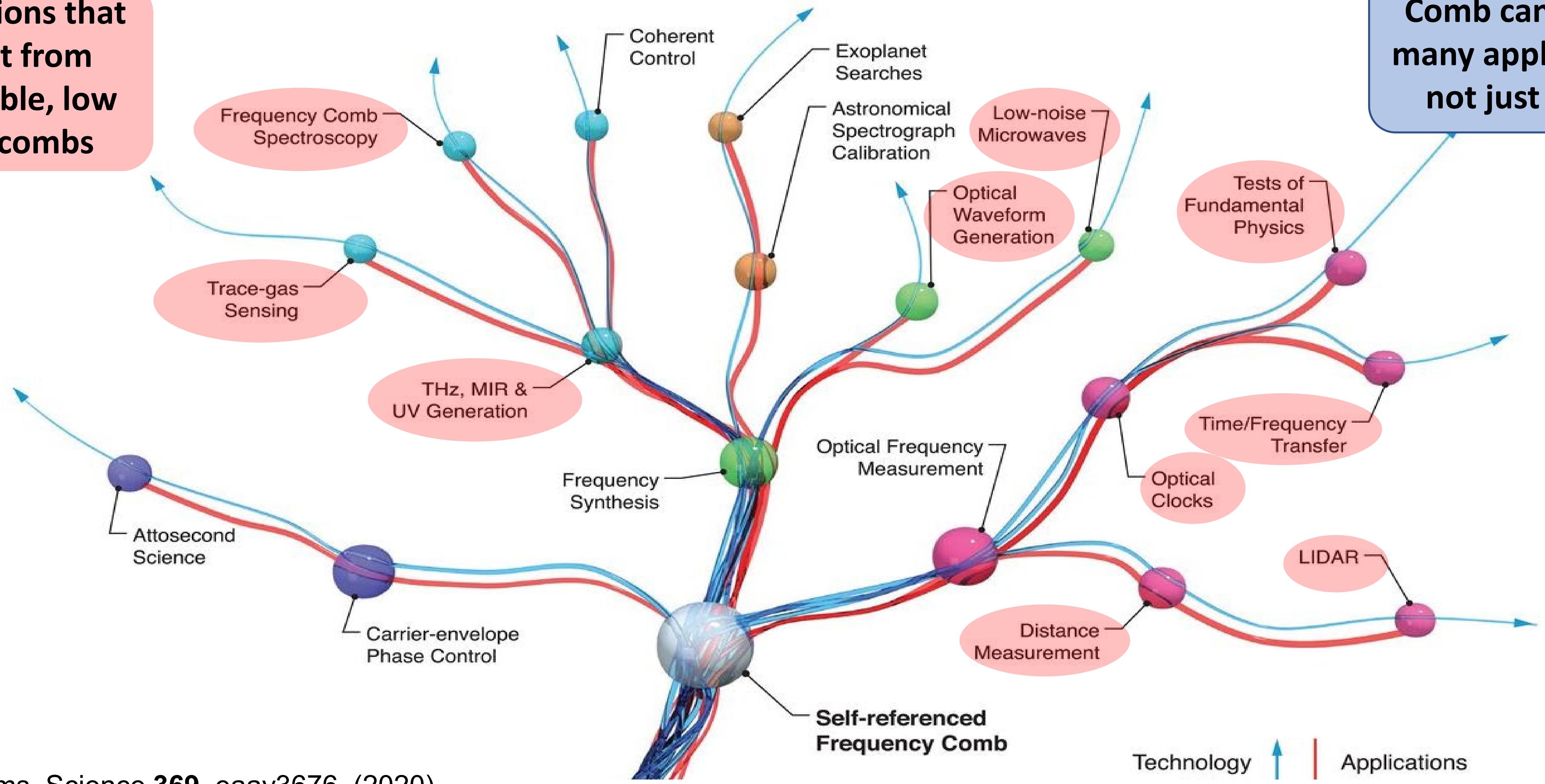
Sensing

Networking

Optical Frequency Combs –Applications

Applications that benefit from deployable, low SWaP combs

Comb can support many applications – not just timing!



S.A. Diddams, Science **369**, eaay3676, (2020).
https://doi.org/10.1126/science.aay3676

What are Optical Frequency Combs?

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S.A. Diddams, Science **369**, eaay3676, (2020).
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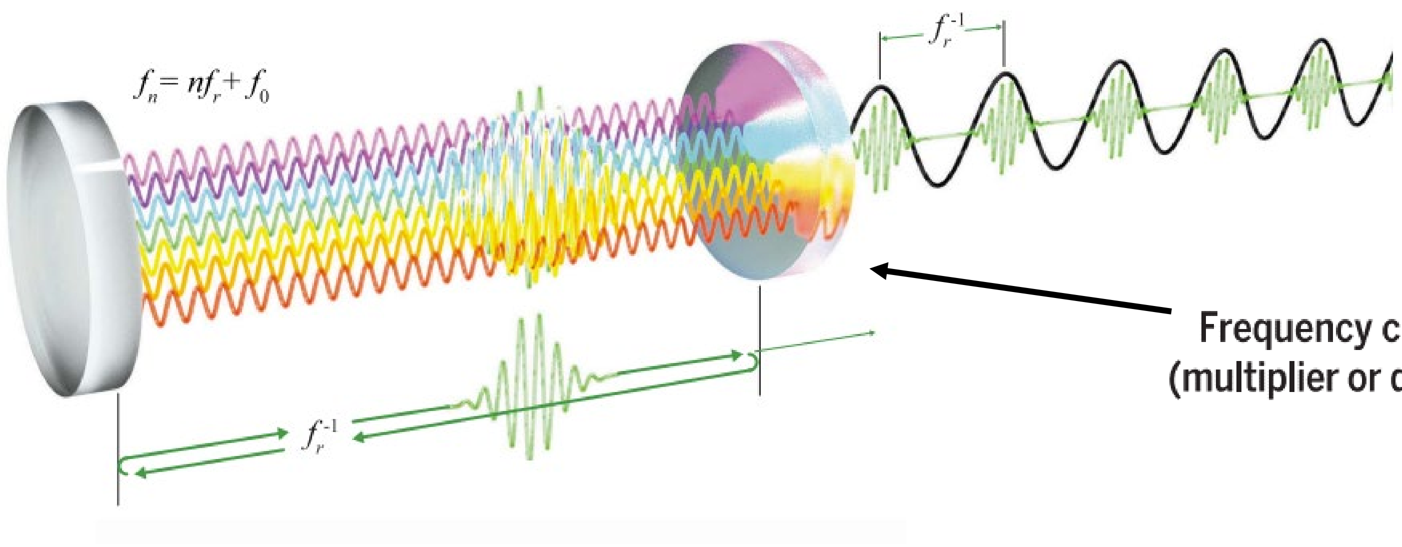
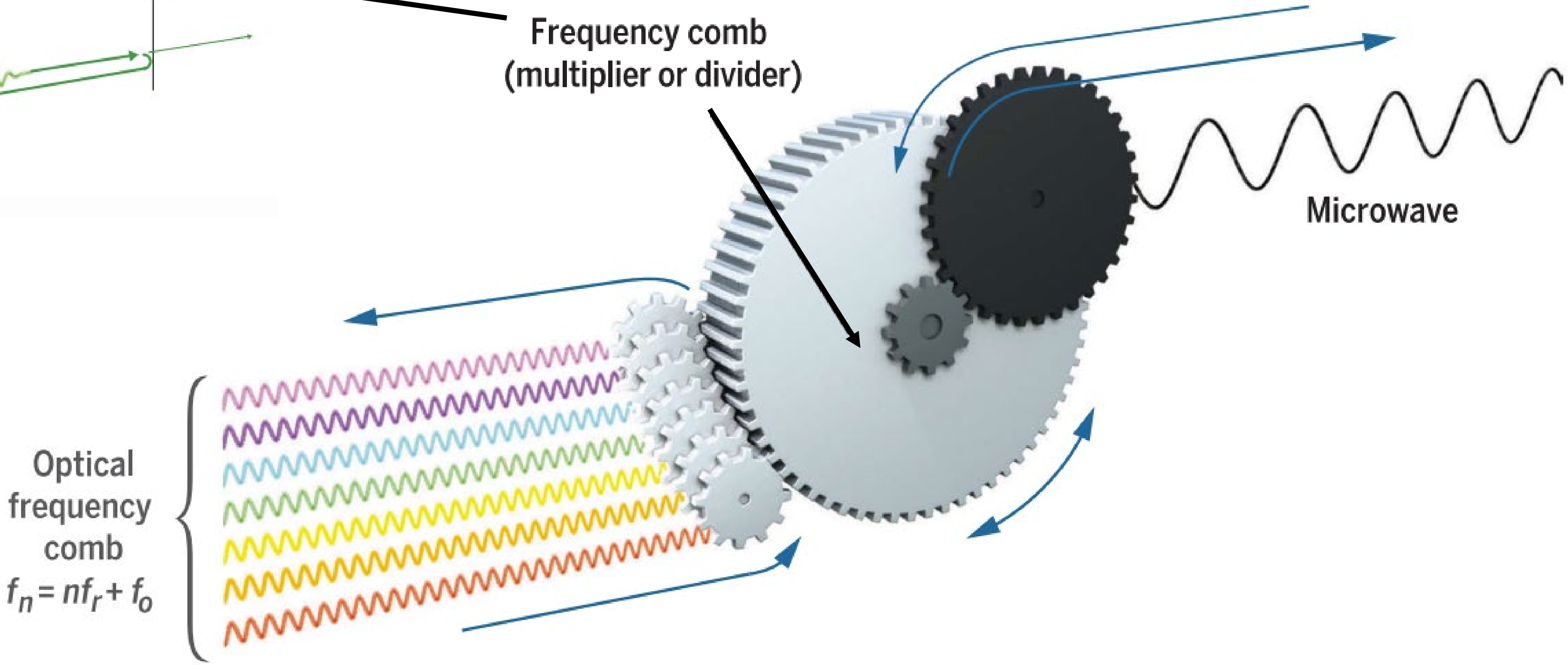
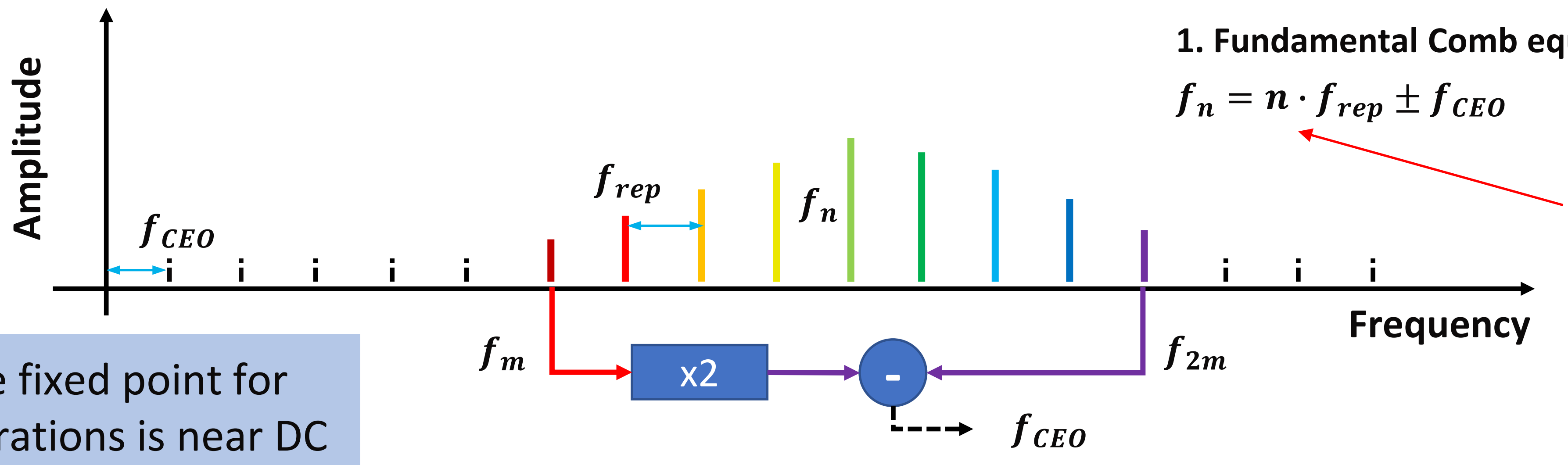




An optical frequency comb is a discrete series of evenly-space, phase-coherent spectral components. Stabilization of only 2 key parameters enables high performance RF-to-optical multiplication or optical-to-RF division.

Optically-Referenced Frequency Comb



1. Fundamental Comb equation:

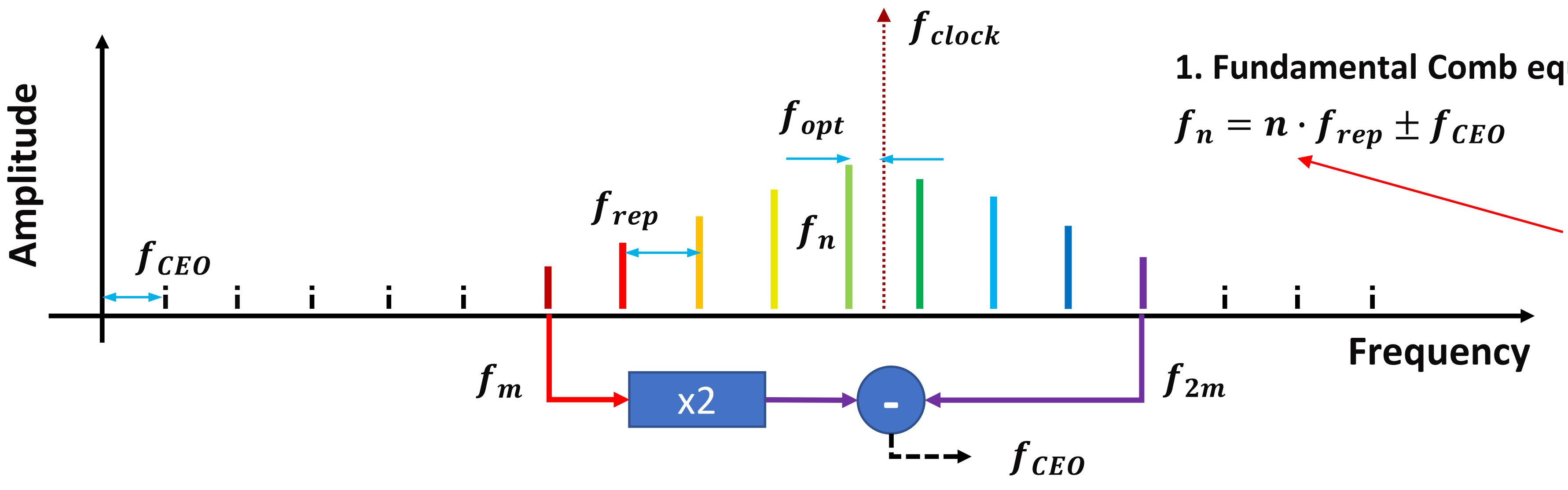
$$f_n = n \cdot f_{rep} \pm f_{CEO}$$

n is on the order of ~10^6

The fixed point for vibrations is near DC – so f_{CEO} is immune.

Optical Frequency Combs – A Review

Optically-Referenced Frequency Comb



1. Fundamental Comb equation:

$f_n = n \cdot f_{rep} \pm f_{CEO}$

n is on the order of ~10^6

2. Relationship between cw laser and comb: $f_{clock} = f_n \pm f_{opt}$

3. Clock read-out equation: $f_{rep} = \frac{(f_{clock} \mp f_{opt} \mp f_{CEO})}{n}$

System Instability: $\delta f_{rep} = \frac{\sqrt{|\delta f_{clock}|^2 + |\delta f_{opt}|^2 + |\delta f_{CEO}|^2}}{n} \approx \frac{\delta f_{clock}}{n}$

Fiber Frequency Combs

Rack-mount Laboratory Options

Modular Options

- Optical frequency combs has largely been confined to laboratories due to:
  - The physical size of the optics
  - Temperature sensitivities
  - Vibration sensitivities
- Modular options are being developed that address operation in real-world conditions.

Frequency Comb Performance

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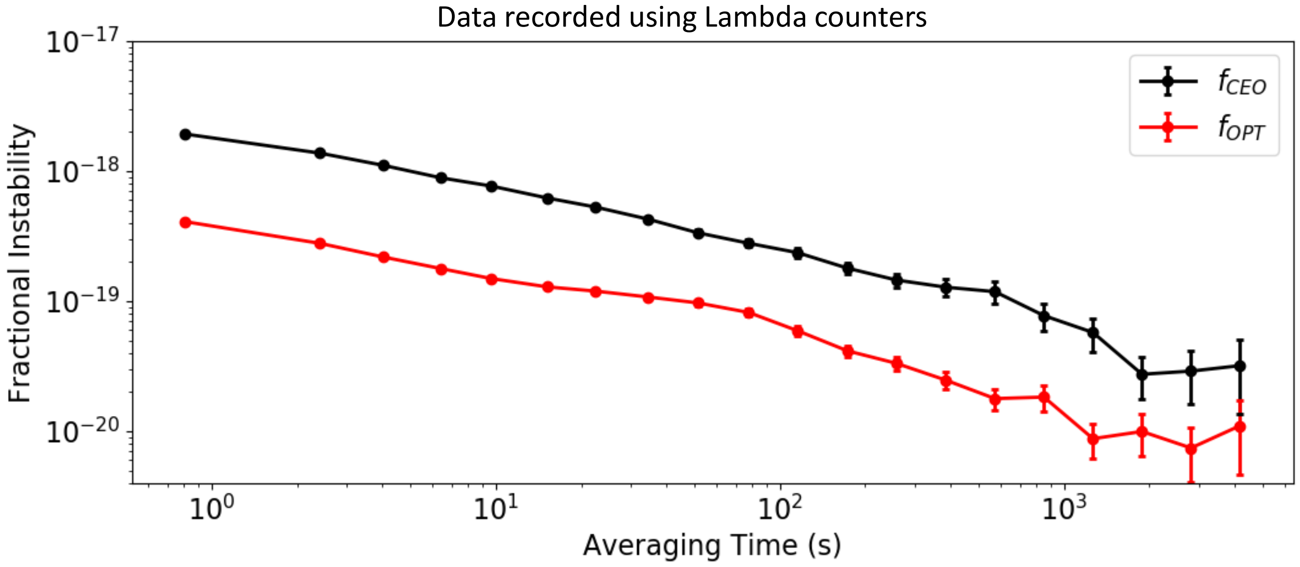
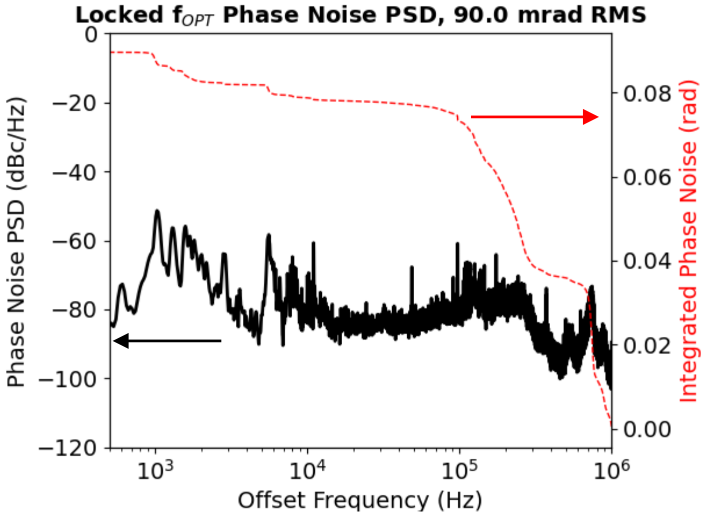
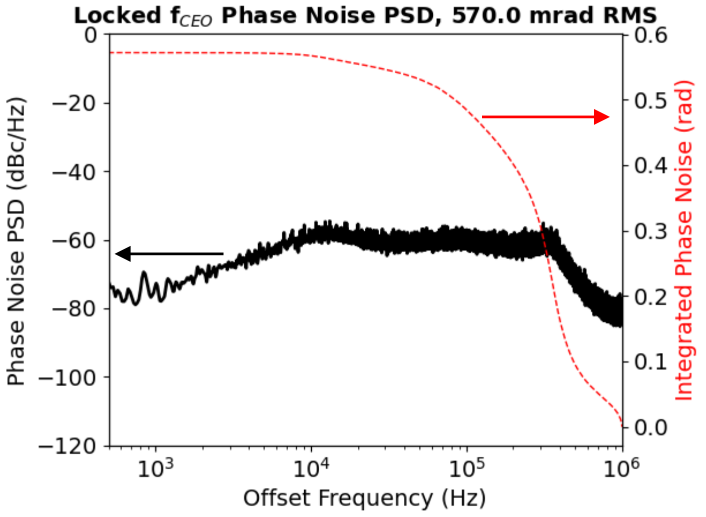
- In-loop instabilities show contribution to optical frequency reference noise.
- Next-generation Optical Atomic Clocks require comb performance below $1 \times 10^{-14}/\sqrt{\tau}$
- Applications such as Time and Frequency Transfer, Low Phase Noise Microwave Generation, and Dual Comb Spectroscopy have low phase noise requirements.



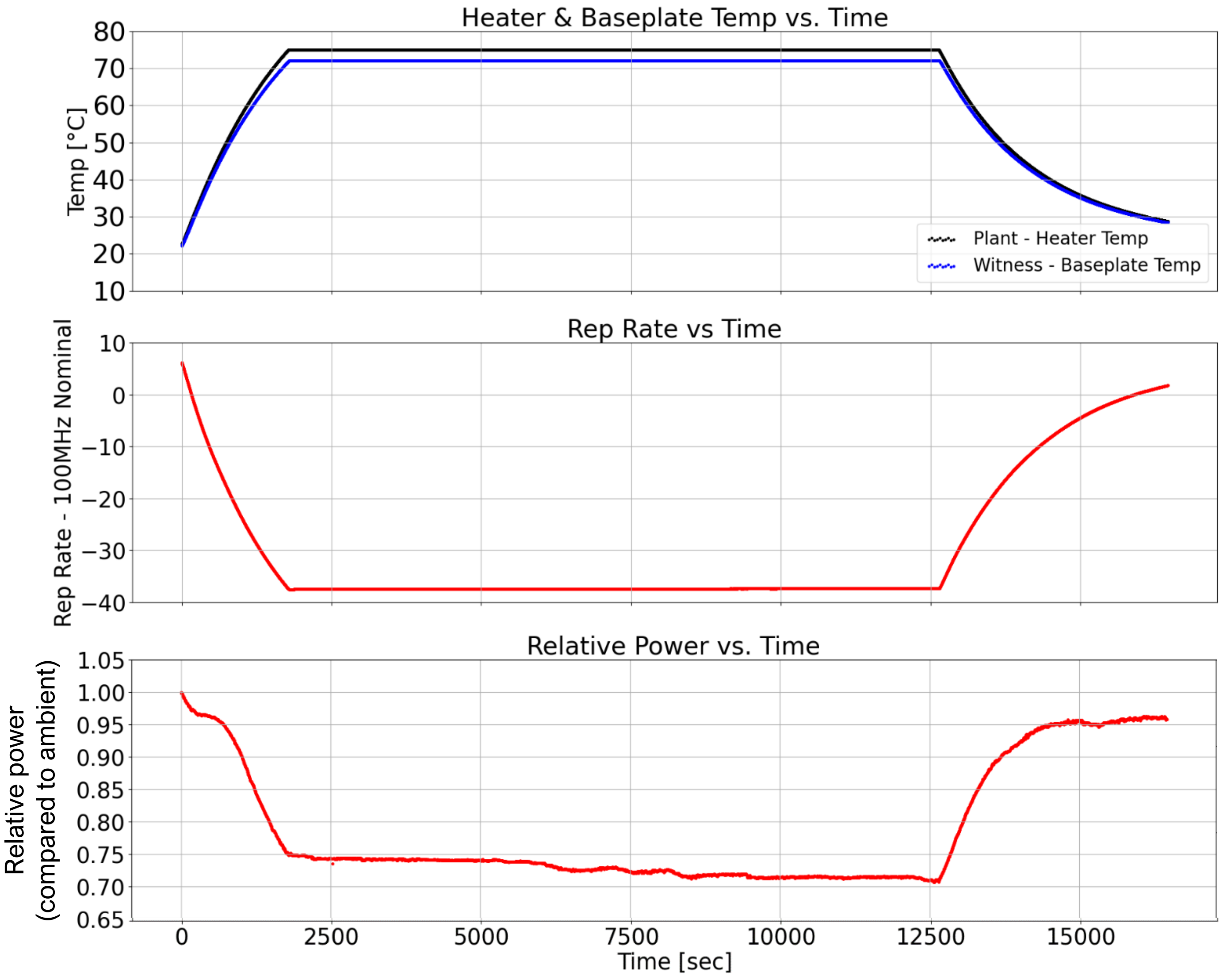




Work on this slide was funded under AFRL SBIR contract FA864921P0956.

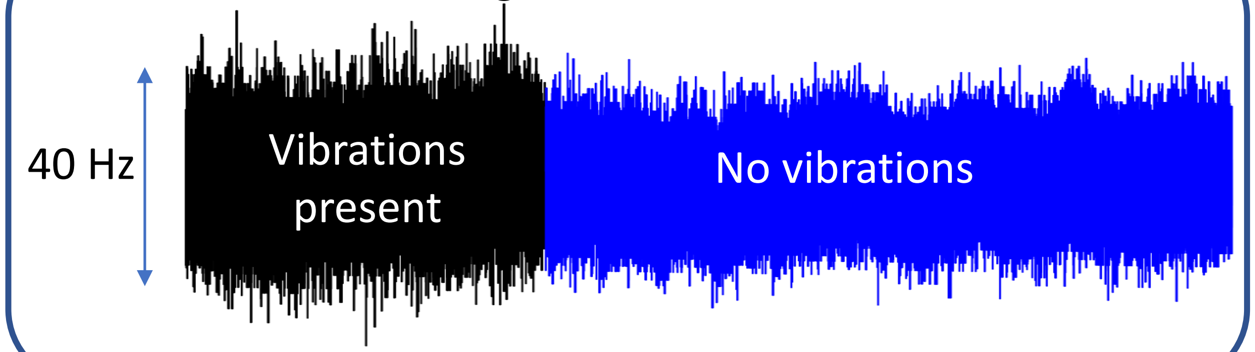
Field Deployment: Temperature Testing

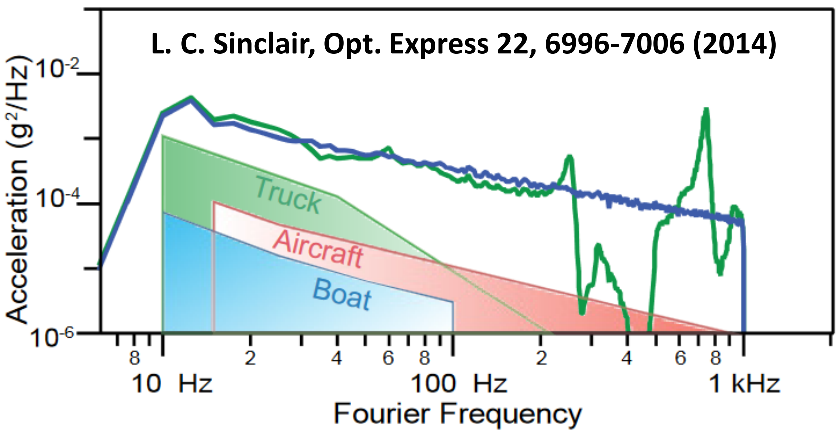
- Low Size, Weight, and Power (SWaP) combs are being developed to operate over wide temperature ranges.
  - Free-running oscillator tested from +25 to +75 °C. Mode-locking maintained over entire range!
  - Oscillator needs to be temperature stabilized for high performance operation; shrinking system size will be key to reducing power consumption.



Work on this slide was funded under ONR BAA contract N0001422C1045.

Field Testing: Vibration Testing

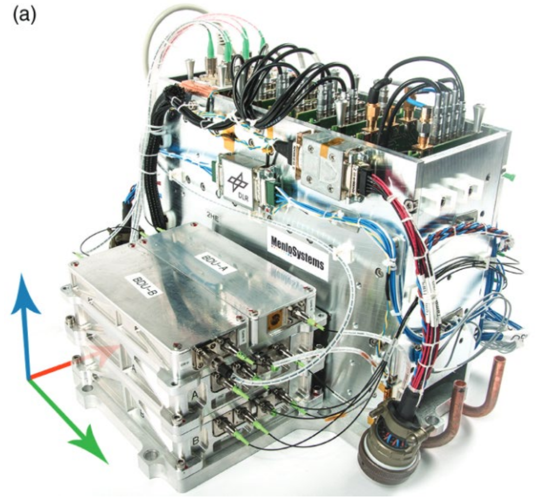




Testing with similar integrated vibration profiles >>0.5 g_{RMS} (blue trace).

Menlo has tested miniaturized combs for deployment on sounding rockets.

B. J. Pröbster, et.al., JOSAB 38, 932-939 (2021)



Only a few companies are working on making combs that can operate in extreme environments. Development is on-going.

Work on this slide was funded under ONR BAA contract N0001422C1045.

Optical Clockwork Overview

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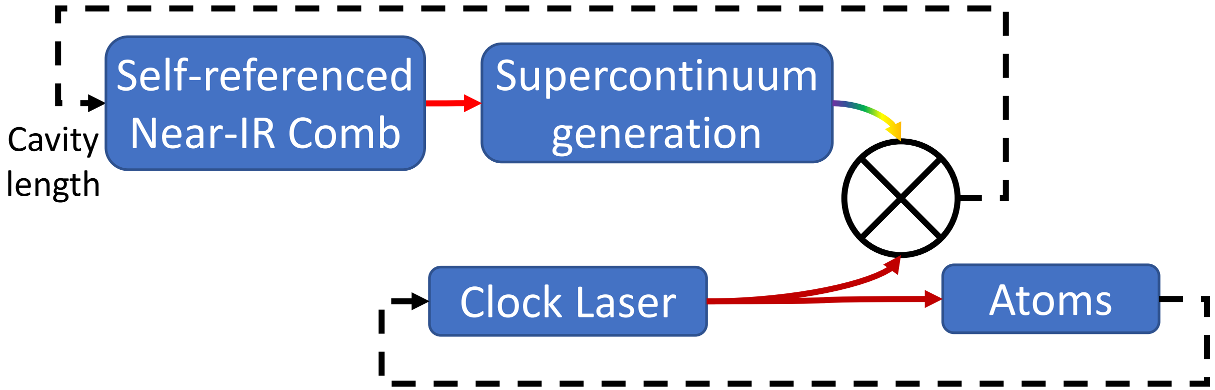
- Simplest optical clock implementation utilizes an (ultra)narrow linewidth (UNL) laser stabilized to an atomic resonance and uses the optical frequency comb as the RF read out.
  - The inherent noise of the cw laser can degrade optical clock operation through the Dick effect.
  - In most deployable, high-performance optical clock systems, laser linewidths below 100 Hz are necessary – there are few COTS solutions.



- Current technique to narrow cw lasers utilizes ULE reference cavities – expensive, prone to vibration, and require ultrahigh vacuum.
- The availability of (ultra)narrow linewidths at the correct wavelengths can be experimentally limiting (and definitely not field-ready).

Stable Lasers reference laser system

Menlo

Commercially-available cavity options are large, expensive, and prone to vibration.

Ultranarrow Linewidth (UNL) Laser Preliminary Results

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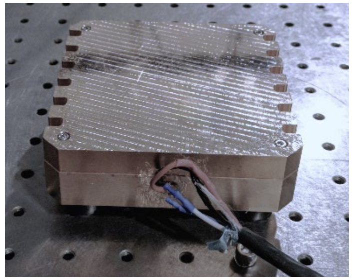
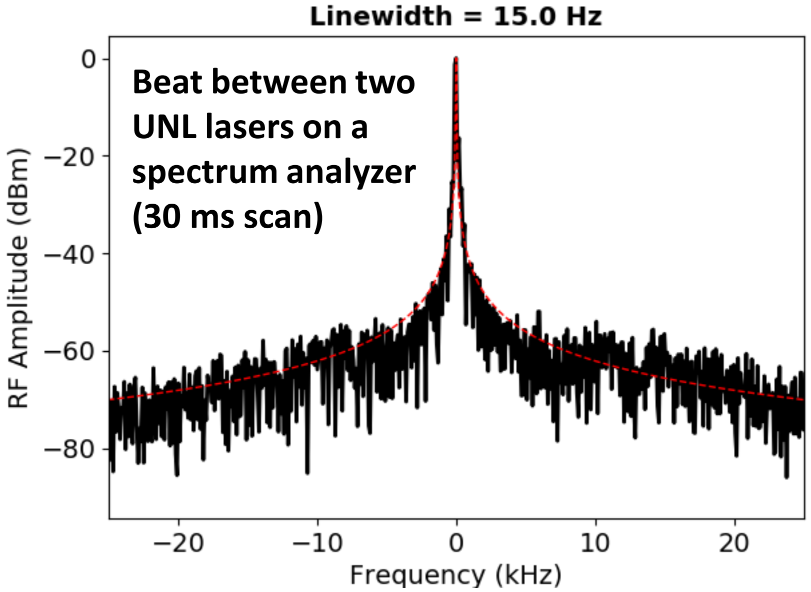
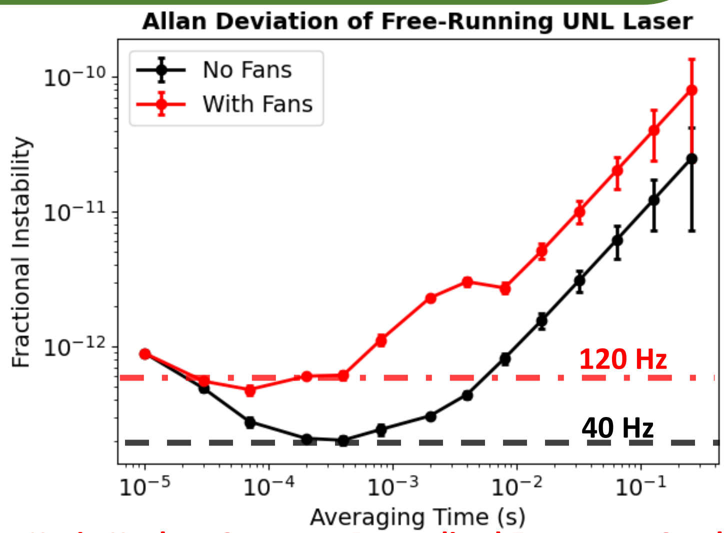
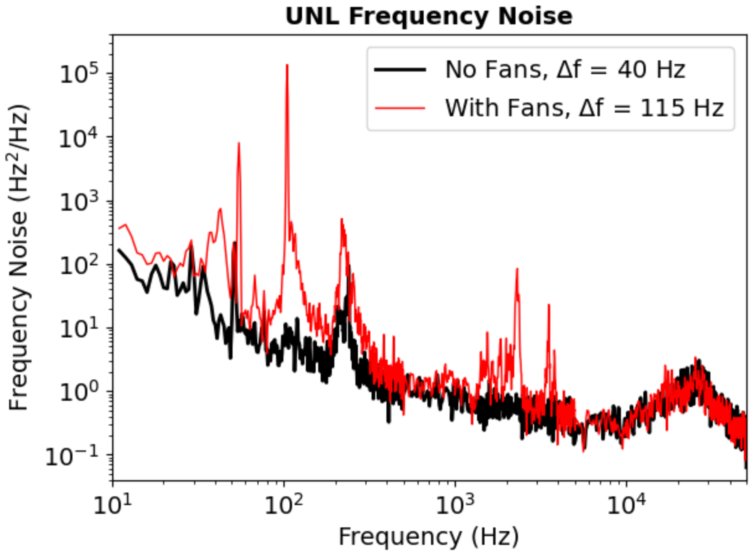
- The first prototype has been constructed in a 2U-rack enclosure (10 L volume).
- The optics module is <0.5 L; a rugged modular option is targeted at <2 L.





- Integrated linewidths are < 50 Hz.
- ADEVs are below 5×10^{-13} at 1 ms
- Frequency noise < 10 Hz^2/Hz above 100 Hz offset
- Techniques to reduce linear drift (~kHz/s) and sensitivity to vibrations are being investigated.





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Optical Clockwork Overview

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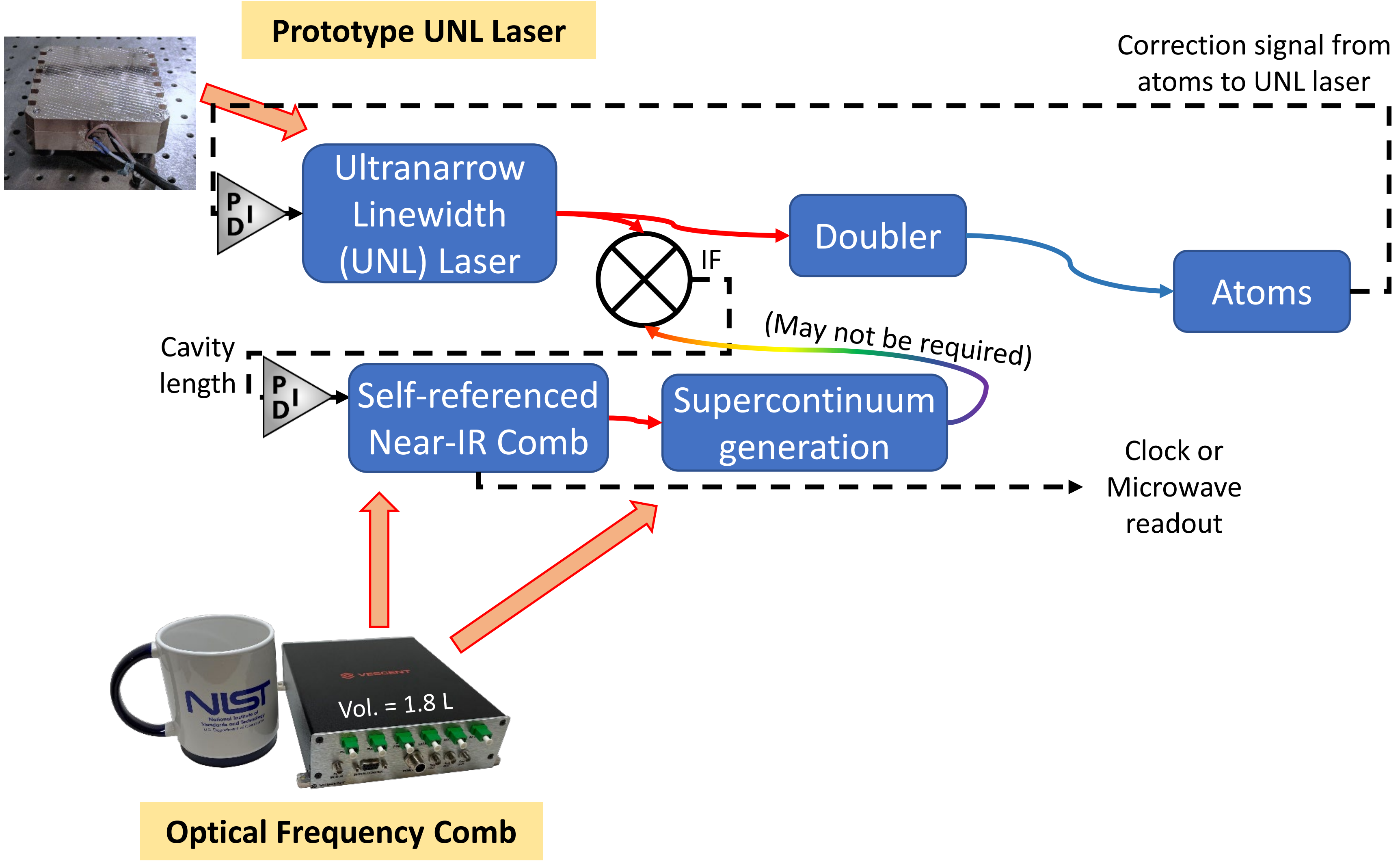
- Vescent has prototyped a UNL laser based on SBS generation in fiber.
  - This removes the need for expensive optical components and ultrahigh vacuum.

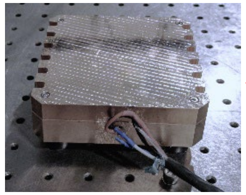


Loh, W., et. al, "Ultra-narrow linewidth Brillouin laser with nanokelvin temperature self-referencing." Optica **6**, 152-159 (2019).
Loh, W., et. al, "Operation of an optical atomic clock with a Brillouin laser subsystem." *Nature* **588**, 244–249 (2020).

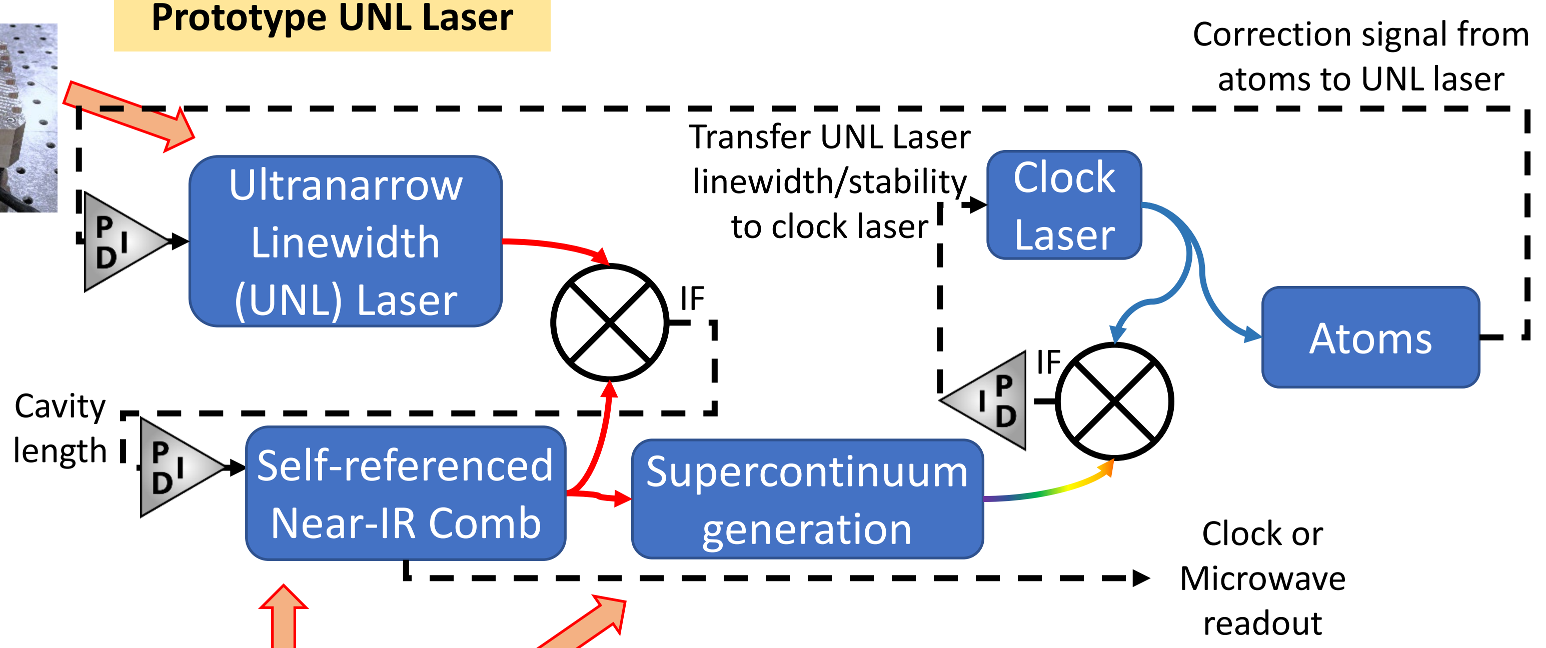
Optical Clockwork Overview

VESCENT

- Vescent has prototyped a UNL laser based on SBS generation in fiber.
  - This removes the need for expensive optical components and ultrahigh vacuum.
- The frequency comb can also act as a stability-transfer cavity. This alleviates laser requirements at challenging wavelengths.
  - Comb is phase-locked to UNL Laser.
  - Clock laser is locked to comb.
  - Comb steers clock laser to interrogate atoms; correction signal fed back to UNL Laser.



Prototype UNL Laser



Optical Frequency Comb

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Application: Ultralow phase noise microwave generation

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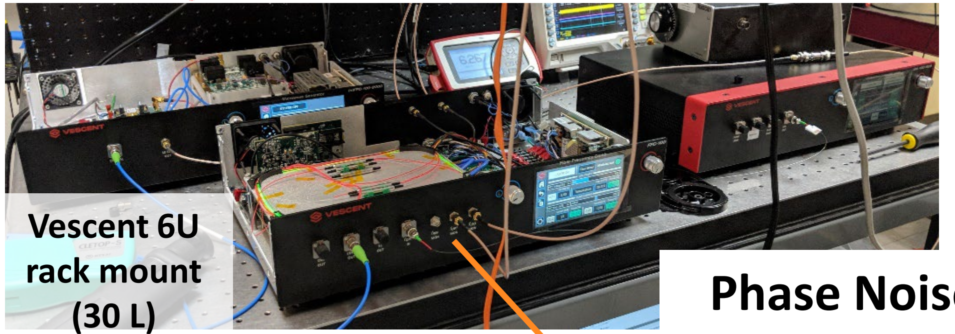
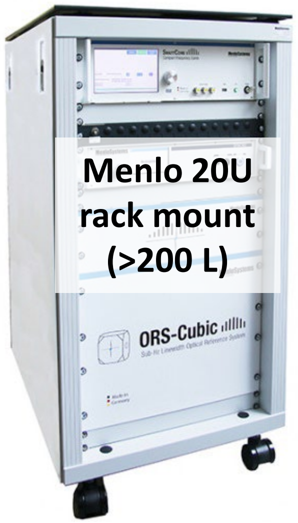
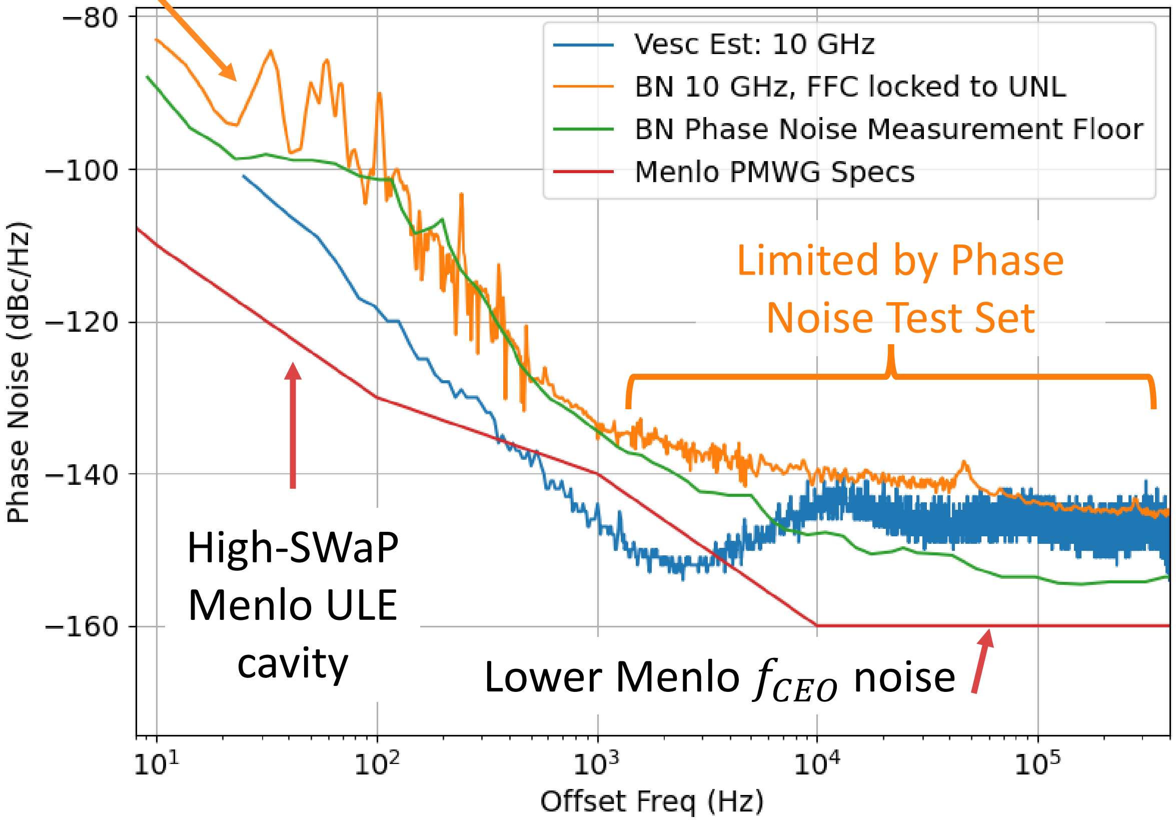




Phase Noise of 10 GHz carrier



- Vescent has constructed a 6U prototype brassboard (30 L) capable of generating ultralow phase noise microwaves @ 10 GHz
  - The system has been built modularly and can be shrunk
- We are currently limited by the phase noise test set noise floor below 1 kHz offset frequency.
- Additional performance improvements at both low and high offset frequencies are under investigation.

Work on this slide was funded under AFRL SBIR contract FA864921P0956.

Questions?

Scott Davis
CEO

Kurt Vogel
VP of Technology

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