## Harnessing the Power of Optical Frequency Combs: Moving Quantum Sensors Far from the Metrology Lab



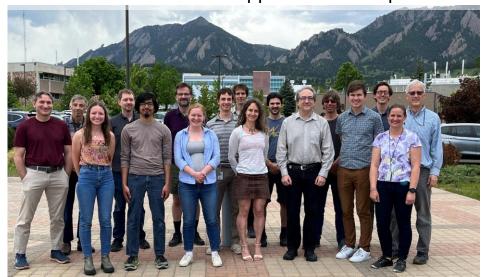
"Thus, the frontiers lie at the interdisciplinary intersection of physics, engineering, chemistry, materials science, and biology."

- Manipulating Quantum Systems: An Assessment of Atomic, Molecular, and Optical Physics in the United States, p. 25

### The data shown today represents the work of many hands...



The NIST Fiber Sources and Applications Group circa 2023



Women of Time Transfer 2019



Mauna Loa Observatory 2022



#### The Optical Time Transfer Project

(present)

NIST

Emily Caldwell, Allie Christensen, Ian Coddington, Fabrizio Giorgetta, Laura Sinclair, William Swann, and Theodora Triano OctoSig Consulting

Hugo Bergeron, Jean-Daniel Deschenes

(past)

Esther Baumann, Hugo Bergeron, Martha Bodine, Mick Cermak, Jennifer Ellis, Christopher Flood (CU Aerospace), Isaac Khader, Paritosh Manurkar, Nathan Newbury, Sarah Stevenson, Benjamin Stuhl (Space Dynamics Laboratory), and Saad Syed

In collaboration with

Vector Atomic, The Boulder Atomic Clock Optical Network (BACON) Collaboration











#### Passively Mode-Locked Laser

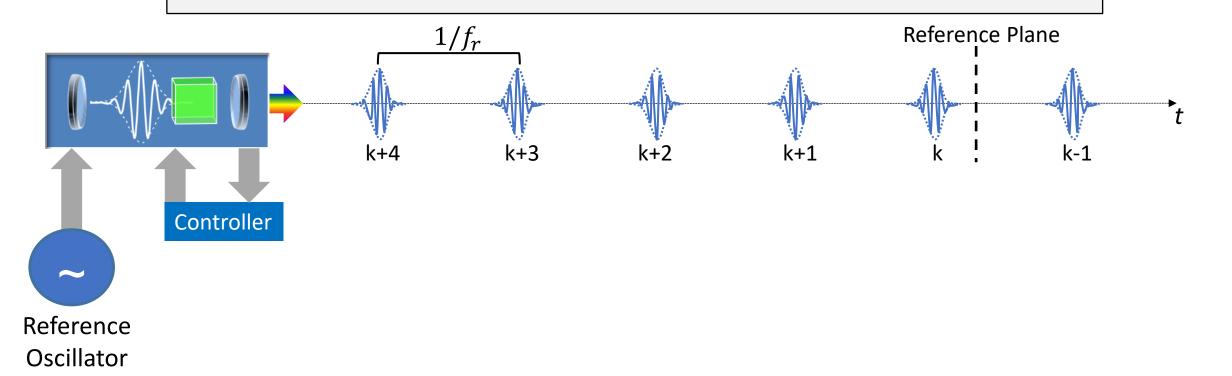
- Output time of laser pulses and phase relationship between pulses are variable
- And set by the dynamics of the laser cavity
- In the frequency domain, broad spectral bandwidth
- > A laser with short pulses with relatively low timing jitter





#### Fully Self-Referenced Optical Frequency Comb

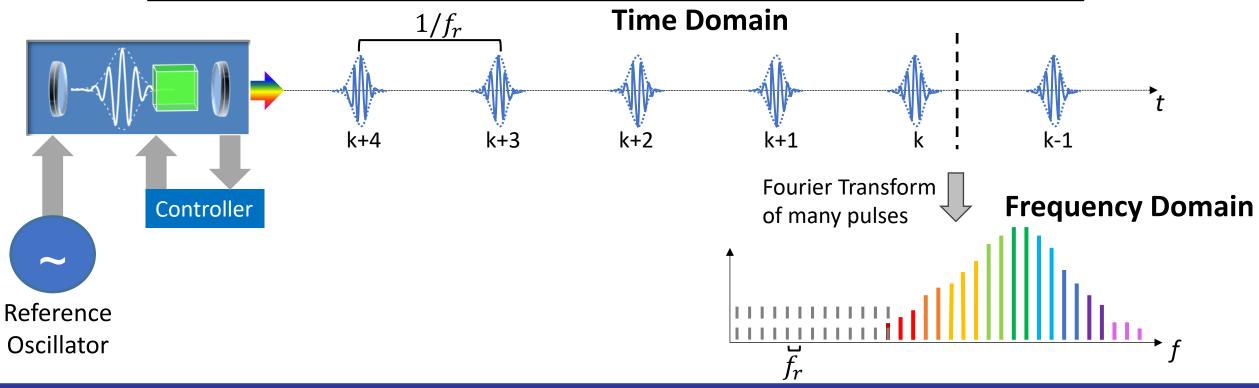
- Stabilize a passively mode-locked laser
- Output time of comb pulses and phase relationship between pulses are fixed
- And defined by the reference oscillator





#### Fully Self-Referenced Optical Frequency Comb

- Stabilize a passively mode-locked laser
- Output time of comb pulses and phase relationship between pulses are fixed
- And defined by the reference oscillator
- In the frequency domain, a "comb" of optical frequencies



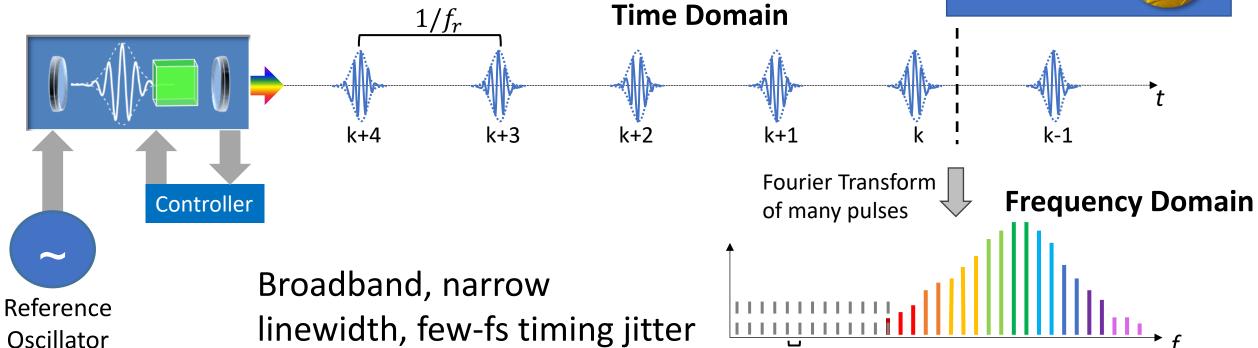


### Fully Self-Referenced Optical Frequency Comb

- Stabilize a passively mode-locked laser
- Output time of comb pulses and phase relationship between pulses are fixed
- And defined by the reference oscillator
- In the frequency domain, a "comb" of optical frequencies
- An ultra-precise fixed ruler for time and frequency

Nobel Prize 2005 T. Hänsch J. Hall





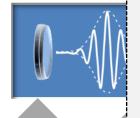


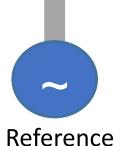
#### Fully Self-Referenced Optical Frequency Comb

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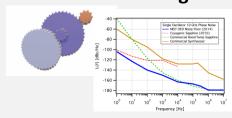




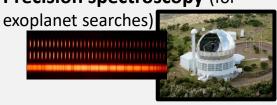
Oscillator

#### "Conventional" Combs Enable

#### **Precision microwave generation**



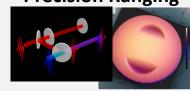
Precision spectroscopy (for



#### **Optical clock networks**



#### **Precision Ranging**



#### **Precision molecular spectroscopy**

(for greenhouse gases)



Advanced communications Fundamental scientific tests And much more...



### Sidebar:

### Fiber optical frequency combs have become fieldable instruments



#### **Laboratory Instruments**

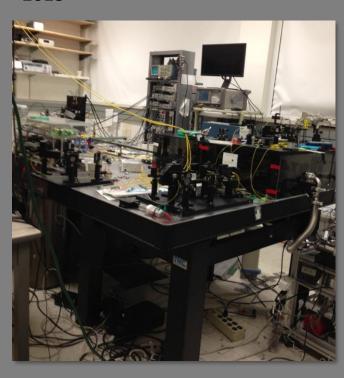


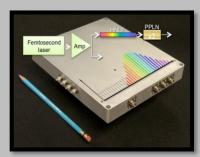
#### Fieldable Instruments



### <u>Compact Commercially-Available</u> <u>Fieldable Instruments</u>

Fiber Sources and Applications Lab, NIST 2013







L.C. Sinclair et al, Rev. Sci. Instr., 86 (2015)

Unheated van 2019



Mauna Loa Observatory 2022



Photo of commercial dual comb electro-optics package and two comb controllers in NIST lab 2023

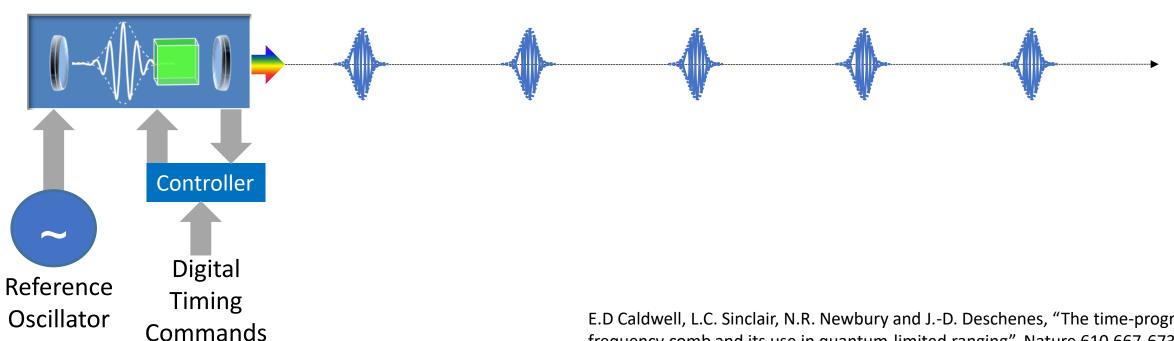


### Expanding the Toolbox: The Time Programmable Frequency Comb



#### The Time Programmable Frequency Comb

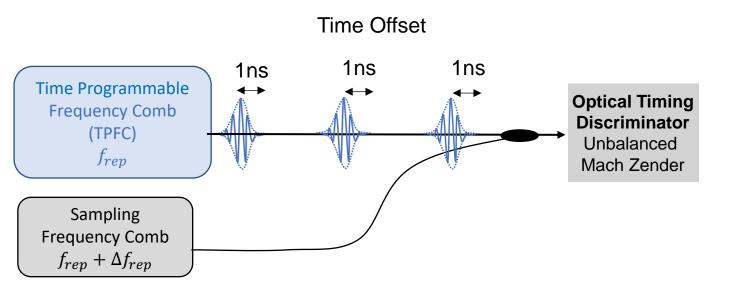
- Combine a self-referenced comb with modern digital control
- Output time of comb pulses and phase relationship between pulses can be adjusted to an arbitrary user-defined value with attosecond-level accuracy
- Values are still defined by the reference oscillator
- A numerically controlled optical oscillator

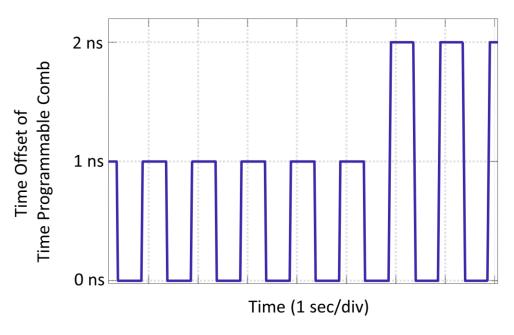


E.D Caldwell, L.C. Sinclair, N.R. Newbury and J.-D. Deschenes, "The time-programmable frequency comb and its use in quantum-limited ranging", Nature 610 667-673 (2022)

### Nanosecond Agility with Attosecond Accuracy



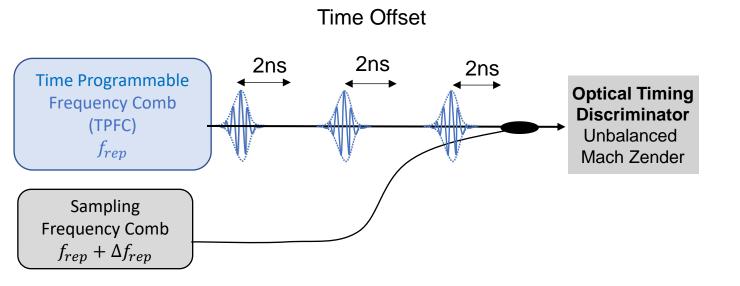


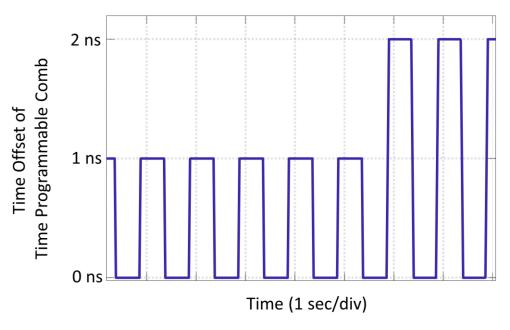


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## Nanosecond Agility with Attosecond Accuracy



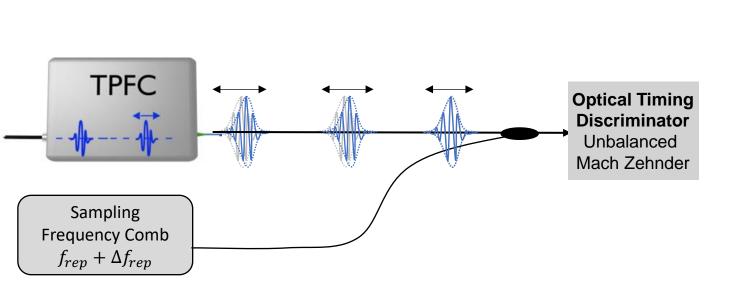


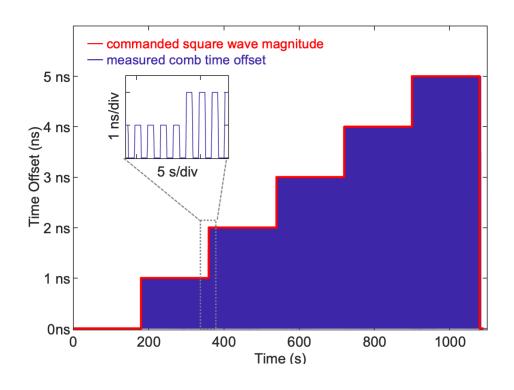


Caldwell, E. D., Sinclair, L. C., Newbury, N. R. & Deschenes, J.-D. The time-programmable frequency comb and its use in quantum-limited ranging. *Nature* **610**, 667–673 (2022).

## Nanosecond Agility with Attosecond Accuracy







#### **Time Offset Error Statistics:**

mean = 0.66 attoseconds

 $\pm$  standard error =  $\pm$  1.73 attoseconds

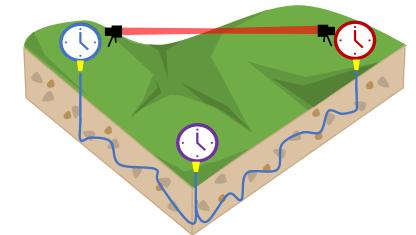
Caldwell, E. D., Sinclair, L. C., Newbury, N. R. & Deschenes, J.-D. The time-programmable frequency comb and its use in quantum-limited ranging. *Nature* **610**, 667–673 (2022).

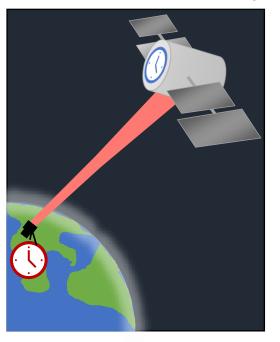
### Optical Time Transfer Enables Optical Timing Networks

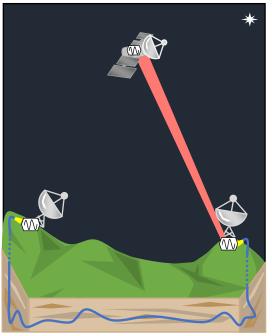


# Optical clocks (quantum sensors) need to be networked for

- ➤ Time/frequency dissemination (e.g. redefinition of the second in 2030)
- > Fundamental physics measurements
  - relativity tests
  - dark matter searches
  - > searches for variations in the fundamental constants
  - gravitational wave sensing
  - > etc...
- Distributed coherent sensing (e.g. VLBI)
- ➤ High precision navigation
- Support of quantum networks

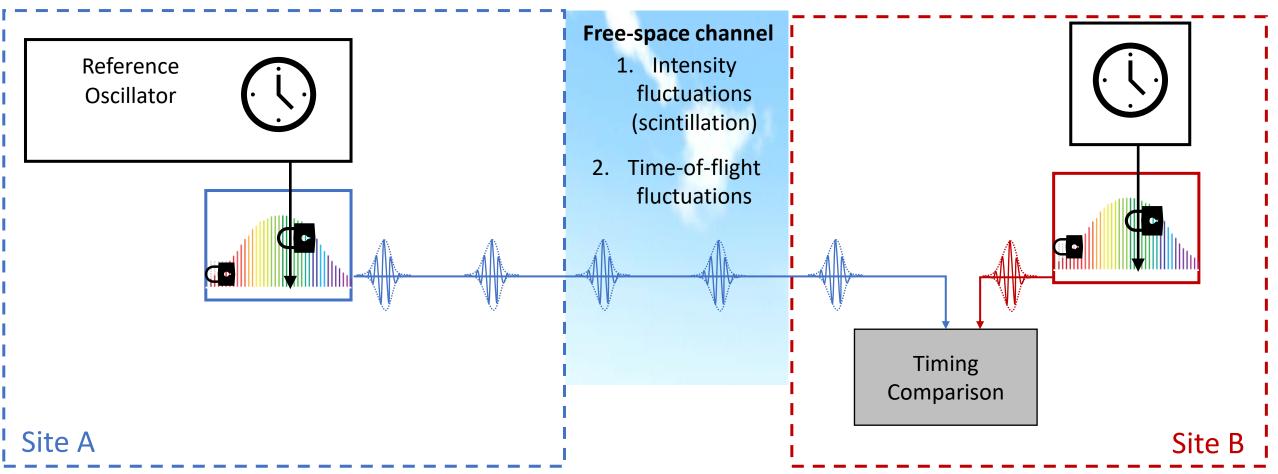






## Free-space Time Transfer Challenges

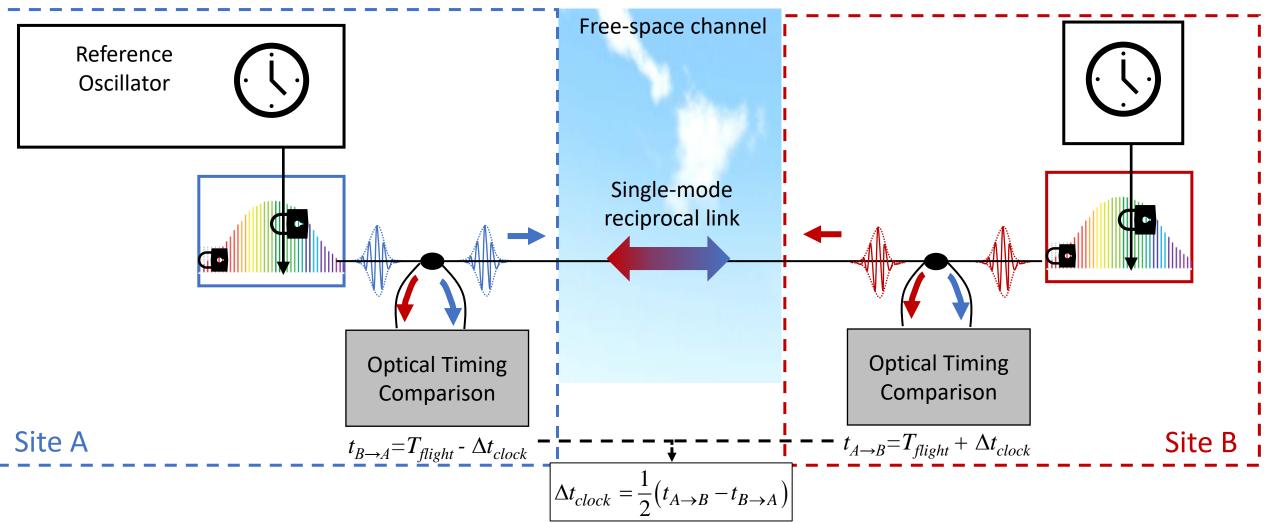




- Intensity noise: "ride over" by pulse-to-pulse coherence
- Time-of-flight fluctuations: degrades one-way pulse timing signals

### Two-way time transfer removes time-of-flight noise





Two-way timing measurements cancels common time-of-flight noise Requires Reciprocal Single Mode Link

# Many successful demonstrations of comb-based time transfer over past years...

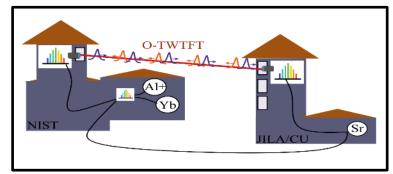


# Sub-femtosecond clock synchronization



Giorgetta et al., Nature Photonics (2013); Deschenes *et al.* Phys. Rev X (2016); Sinclair et al, Phys. Rev. Lett. (2018); Bergero. *et al. Optica* **3**, 441 (2016).

## State-of-the-art atomic optical clock network



Boulder Atomic Clock Optical Network Collaboration *et al. Nature* **591**, 564–569 (2021).

### Off a flying Quadcopter



Bergeron, H. *et al. Nature Communications* **10**, 1819 (2019). Sinclair, L. C. *et al. Phys. Rev. A* **99**, 023844 (2019).

## 113 km free-space path



Shen et al. Nature 610, 661-666 (2022).

#### 3 Node Network (28 km)

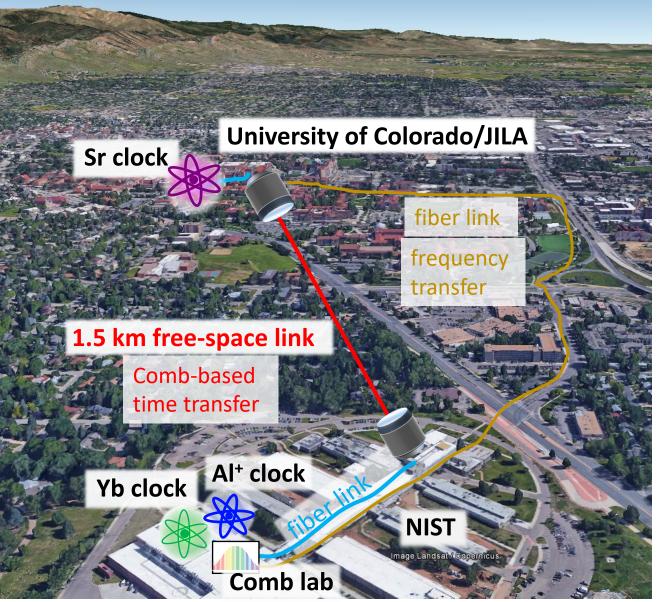


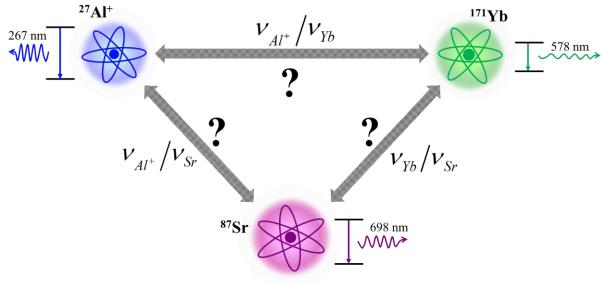
Bodine, M. I. et al. APL Photonics 5 (2020).

- ✓ Time-frequency transfer in msec between distant sites
- ✓ Frequency transfer to better than one part in 10<sup>19</sup>
- ✓ Time synchronization to femtoseconds
- Operation despite turbulence & motion (up to 50 mph)

### Is it possible to compare atomic optical clocks with 18-digit accuracy?

Boulder Atomic Clock Optical Network (BACON) Collaboration



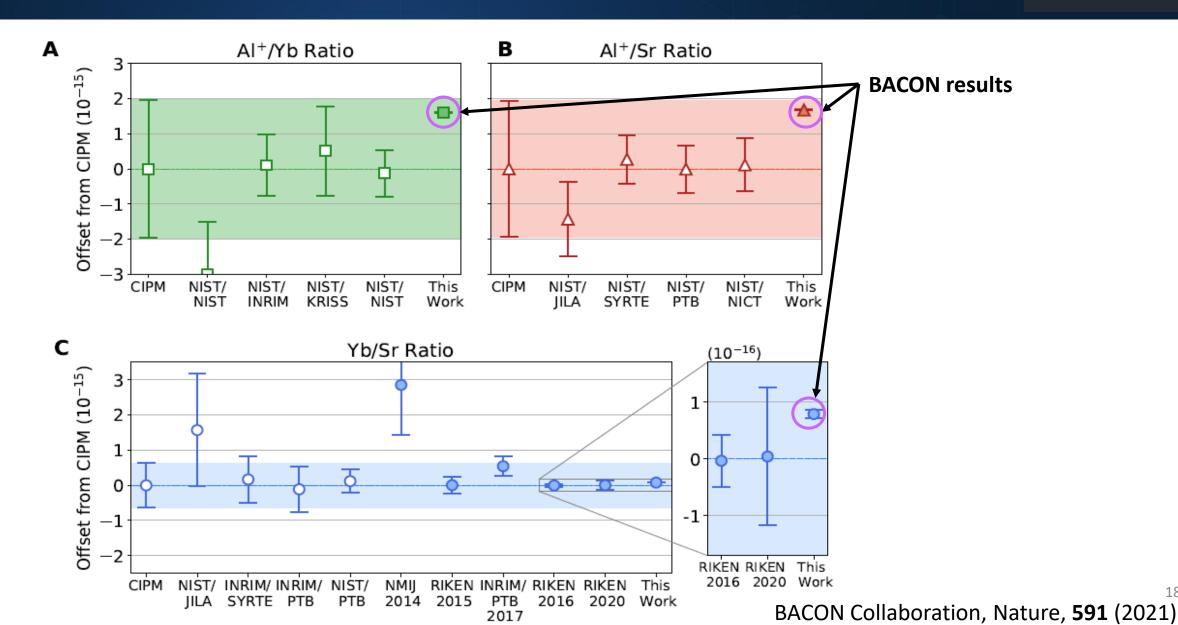


Boulder Atomic Clock Optical Network (BACON) Collaboration\*

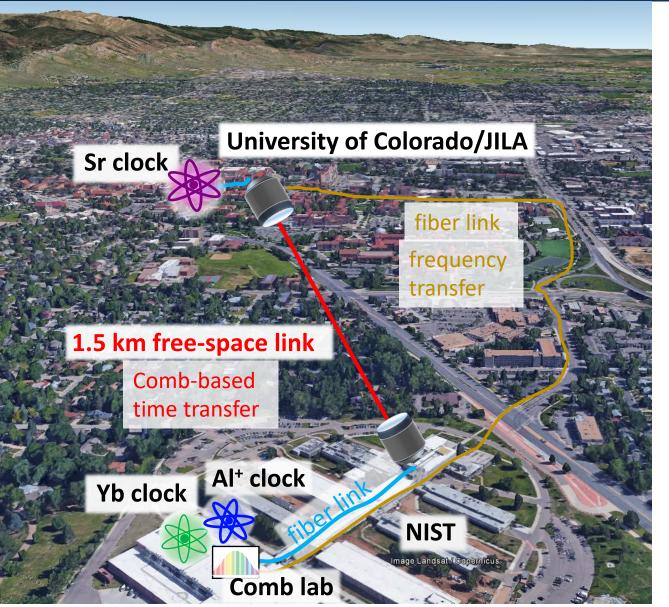
Kyle Beloy<sup>1</sup>, Martha I. Bodine<sup>1</sup>, Tobias Bothwell<sup>2</sup>, Samuel M. Brewer<sup>1,5</sup>, Sarah L. Bromley<sup>2,6</sup>, Jwo-Sy Chen<sup>1,3,7</sup>, Jean-Daniel Deschênes<sup>4</sup>, Scott A. Diddams<sup>1,3</sup>, Robert J. Fasano<sup>1,3</sup>, Tara M. Fortier<sup>1,2,1</sup>, Youssef S. Hassan<sup>1,3</sup>, David B. Hume<sup>1,2,1</sup>, Dhruv Kedar<sup>2</sup>, Colin J. Kennedy<sup>1,2,2,1</sup>, Isaac Khader<sup>1</sup>, Amanda Koepke<sup>1,2,1</sup>, David R. Leibrandt<sup>1,3</sup>, Holly Leopardi<sup>1,3,8,2,1</sup>, Andrew D. Ludlow<sup>1</sup>, William F. McGrew<sup>1,3</sup>, William R. Milner<sup>2</sup>, Nathan R. Newbury<sup>1</sup>, Daniele Nicolodi<sup>1,3</sup>, Eric Oelker<sup>1,2</sup>, Thomas E. Parker<sup>1</sup>, John M. Robinson<sup>2</sup>, Stefania Romisch<sup>1,9</sup>, Stefan A. Schäffer<sup>1,10</sup>, Jeffrey A. Sherman<sup>1</sup>, Laura C. Sinclair<sup>1,2,1</sup>, Lindsay Sonderhouse<sup>2</sup>, William C. Swann<sup>1</sup>, Jian Yao<sup>1</sup>, Jun Ye<sup>1,2,3</sup> & Xiaogang Zhang<sup>1,3,2,2</sup>

BACON Collaboration, Nature, **591** (2021)

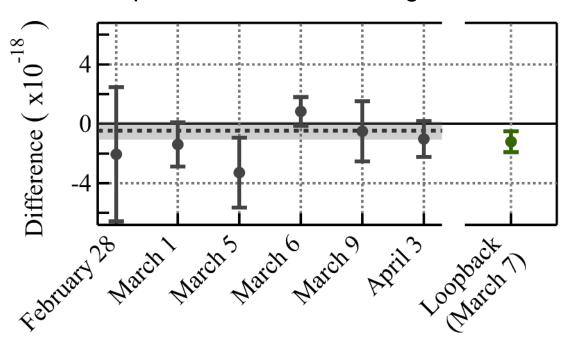
### Is it possible to compare atomic optical clocks with 18-digit accuracy? YES!



# Is it possible to compare atomic optical clocks with 18-digit accuracy? The comparison over the air is limited by the clocks and not the time transfer



Comparison with conventional measurements via fiber-optic link show 6x10<sup>-19</sup> agreement

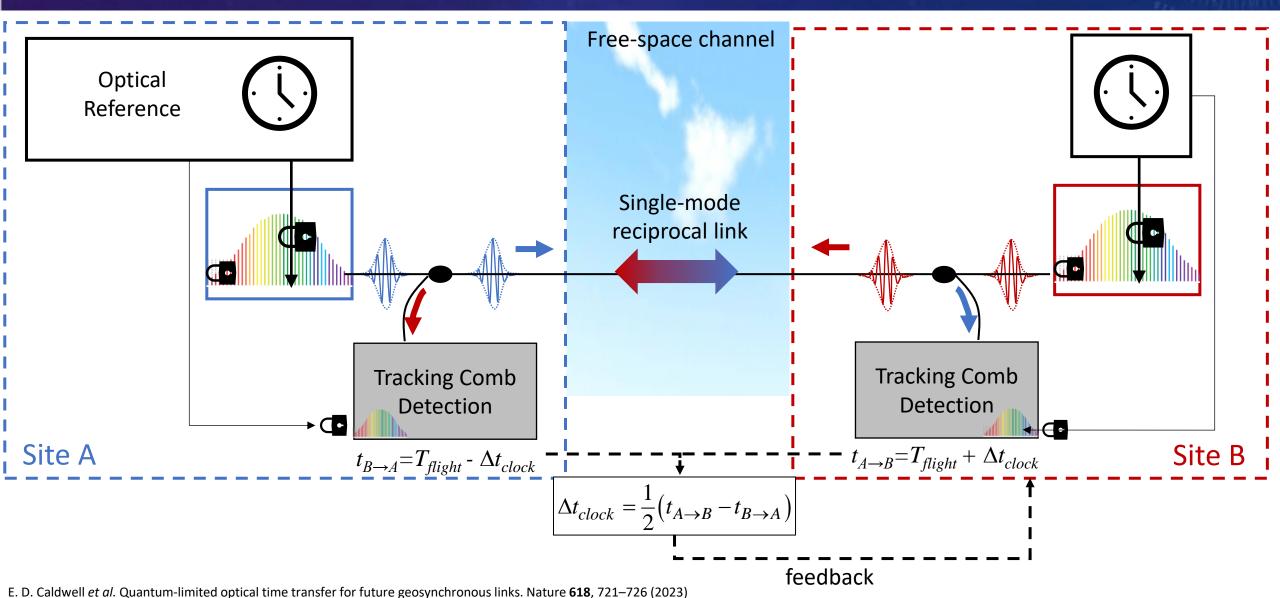


Uncertainty from transfer is an order of magnitude below uncertainty of optical clocks themselves!

Bodine et al., Phys. Rev. Research, **2** (2020) BACON Collaboration, Nature, **591** (2021)

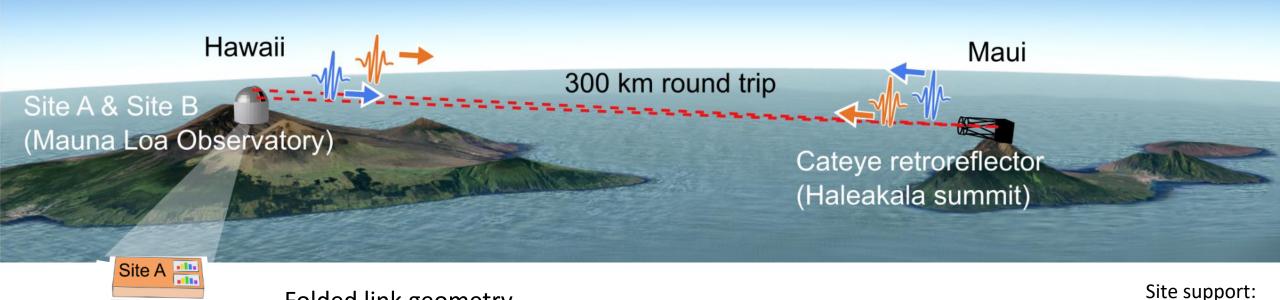
# Two-Way Optical Time Transfer at the Quantum Limit Using Time Programmable Frequency Combs





# Optical Time Transfer at the Quantum Limit Over 300 km of Turbulent Air





Truth by direct "shorted" comparison at Mauna Loa Observatory

E. D. Caldwell et al. Quantum-limited optical time transfer for future geosynchronous links. Nature 618, 721–726 (2023)

Site B

Folded link geometry

Link loss ~90 dB!

University of

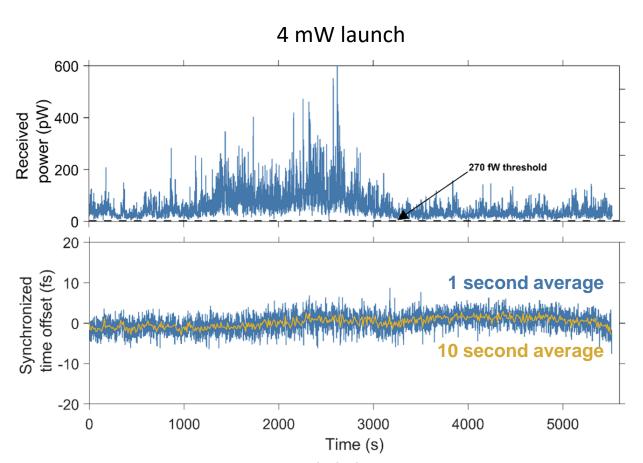
Hawaii and

NOAA 👺

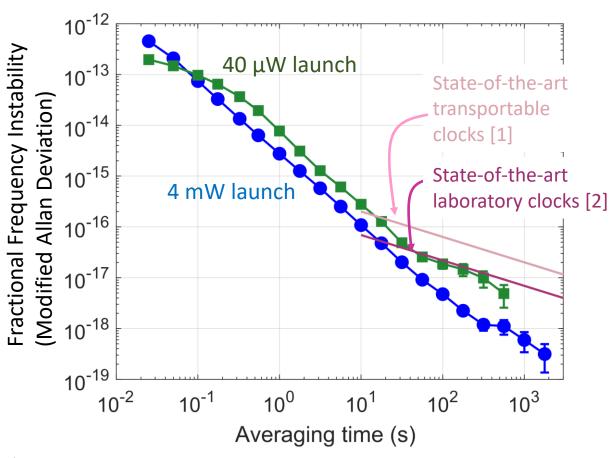
# Optical Time Transfer at the Quantum Limit Over 300 km of Turbulent Air



- Sub-femtosecond synchronization
- Shot-noise limited SNR
  - 270 fW threshold (~1/100 photons per pulse)



Time Transfer with Time Programmable Frequency Combs will support state-of-the-art optical clocks



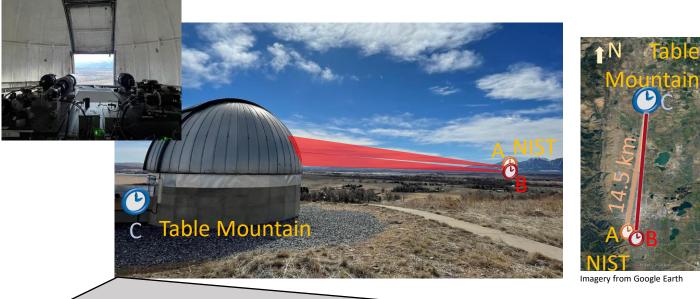
E. D. Caldwell et al. Quantum-limited optical time transfer for future geosynchronous links. Nature 618, 721–726 (2023)

<sup>[1]</sup> Takamoto, M. et al. Test of general relativity by a pair of transportable optical lattice clocks. Nature Photonics 1–5 (2020).

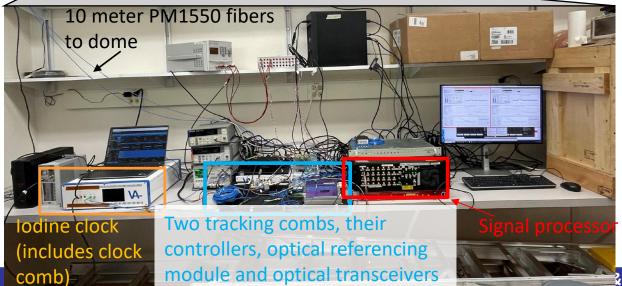
<sup>[2]</sup> Boulder Atomic Clock Optical Network (BACON) Collaboration et al. Frequency ratio measurements at 18-digit accuracy using an optical clock network. Nature 591, 564–569 (2021).

### 3-node All-Optical Iodine Clock Network: Continuous Comparison for 26+ Hours



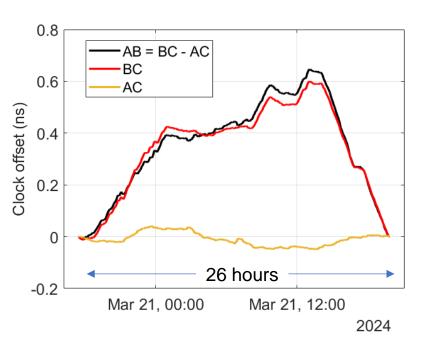






### Preliminary!

#### **Detrended clock offsets**

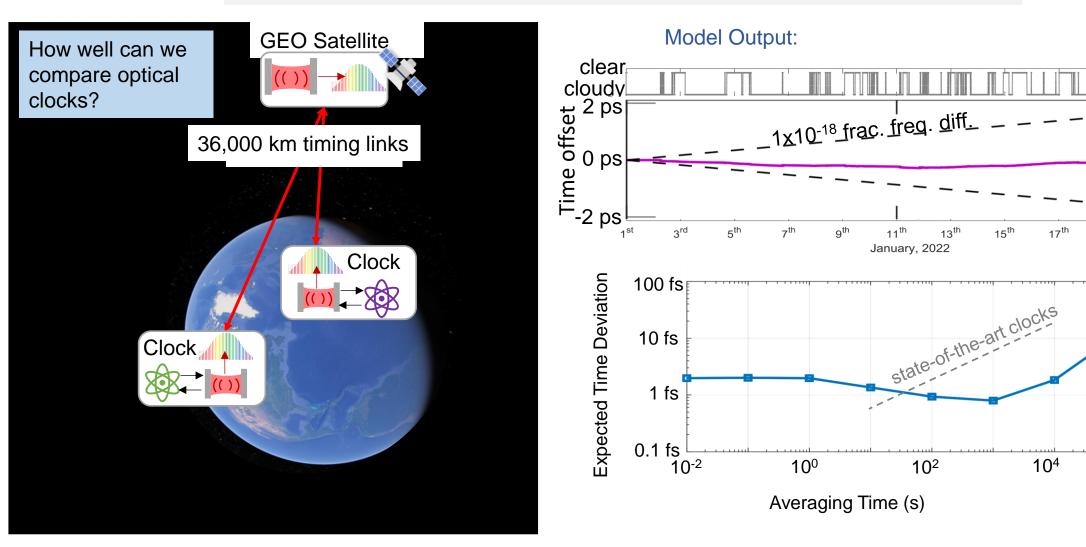


Detrended clock offset  $\leq$  700 ps over 26 hours

# Looking to the Future: What Could We Do With a Ground-to-GEO Link?



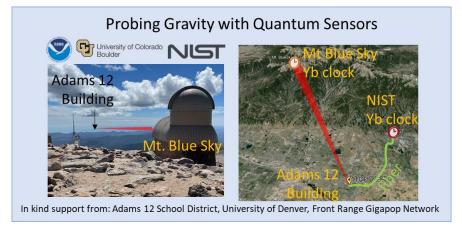
### Assuming a Lack of a State-of-the-Art Optical Clock in Space

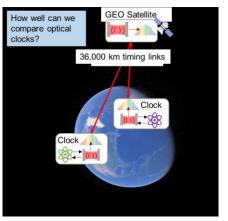


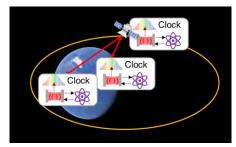
# Looking to the Future: Fundamental Physics Tests and More

National Institute of Standards and Technology

☐ Fundamental Physics Tests



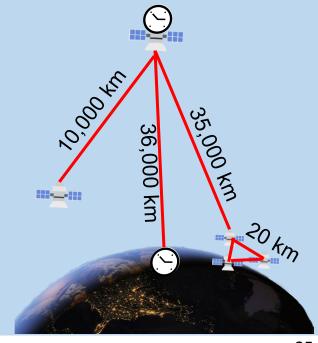




- ☐ Short term: Terrestrial networks using the exquisite precision of atomic optical clocks
- ☐ Medium term: Longer spans using ground-to-satellite links, good-enough oscillators onboard satellites and state-of-the-art ground clocks
- ☐ Long term: State-of-the-art atomic optical clocks in space
- ☐ Ratio measurements in support of the 2030 redefinition of the second
  - Same network architectures as many fundamental physics tests
- □ Support of quantum networks: Can optical time transfer (and ranging) help "build nearly perfect large-scale quantum machines out of a collection of imperfect parts"\*

Ultimate goal of ground-tosatellite links for fundamental physics tests (and other applications) will require

- Low-SWaP
- Long Link Distances
- Handling of high speeds and accelerations



### Beyond Clock Networks: Open-path dual comb spectroscopy (DCS) is an important new tool for greenhouse gas monitoring



### High resolution, perfect frequency accuracy

Negligible Instrument lineshape

#### **Broadband**

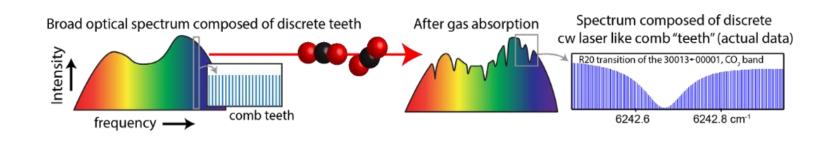
- Multi species
- Low interference
- Temperature measurements

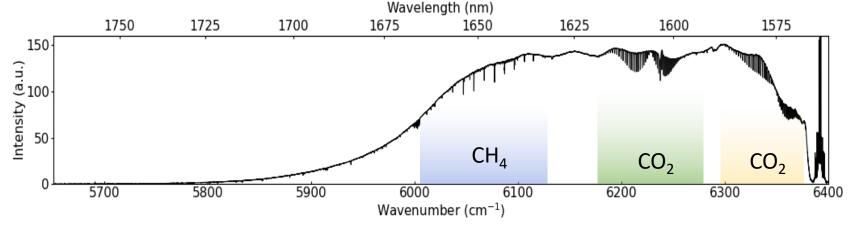
#### **Fast**

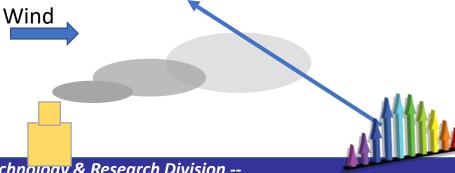
High immunity to turbulence

### High brightness single mode beam and simple detection scheme

Long open paths





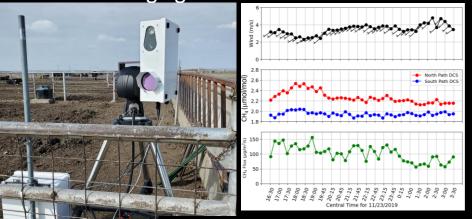


### Beyond Clock Networks:

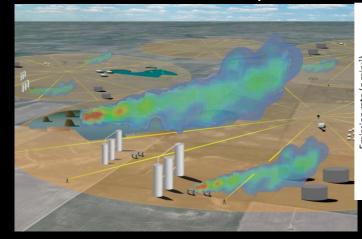
Measurement, Reporting and Verification (MRV) of greenhouse gases and air pollutants with frequency combs

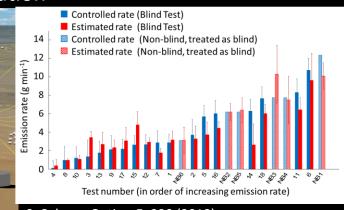
National Institute of Standards and Technology

Understanding agricultural emissions



Oil field leak location and quantification





S. Coburn, Optica. **5**, 320 (2018).

G. Mead, GRL, 51, e2023GL105973 (2024)



D. Herman et al., Science Advances 7(14), (2021).



### Thanks for listening. Questions?



