Time & Frequency Activities at NIST

Elizabeth Donley

NIST Time & Frequency Division

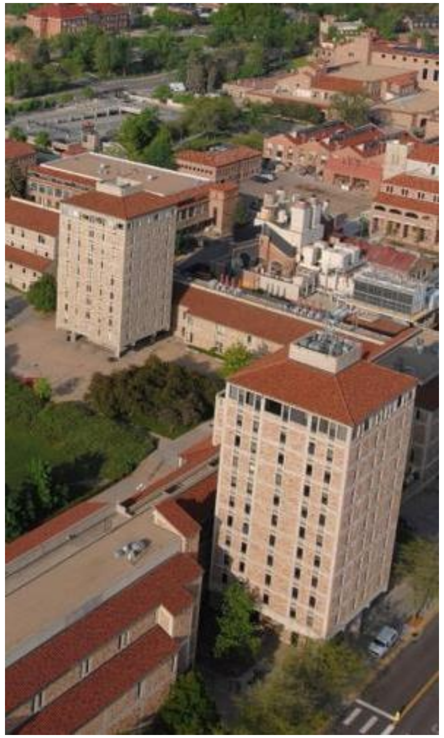
September 22, 2020

NIST

Time & Frequency Division

Applied Physics Division

JILA



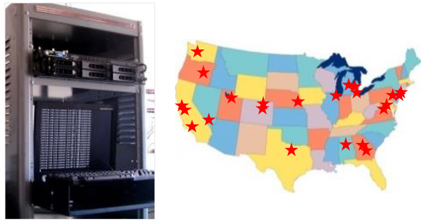
NIST Time and Frequency Division

Distribution

Primary Standards, NIST Time Scale

Research: Future Standards & Distribution

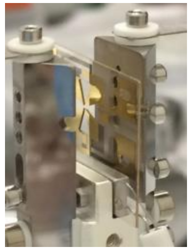

Radio Stations


Networks

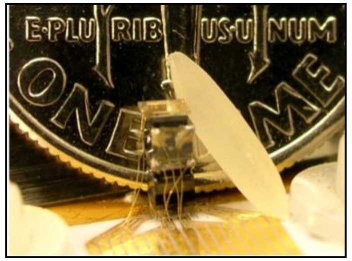

Satellites


Noise metrology


Hydrogen Maser & Measurement system


Optical clocks


Optical frequency synthesis

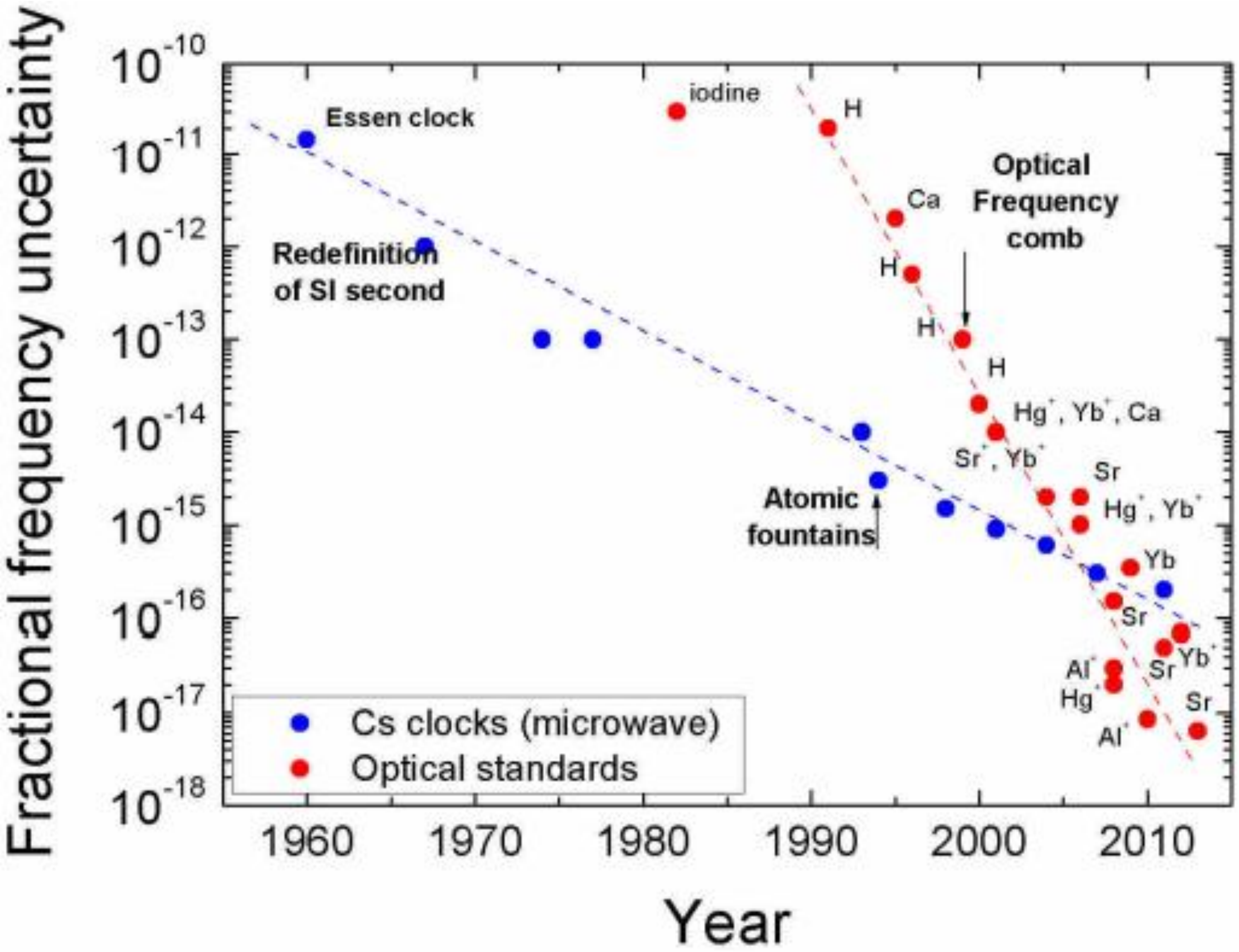

Chip-scale atomic devices

Talk with focus on two topics:

1. NIST’s optical clocks
2. New efforts to distribute timing over optical fiber networks

Optical Clocks

Progress in Atomic Clocks



Higher Q **optical** transitions

Optical frequency combs

New laser stabilization methods

Arias, Matsakis, Quinn, & Tavella: The 50th Anniversary of the Atomic Second, TUFFC **65** (2018)

Progress in Atomic Clocks

5 CCTF criteria to change the basis of the SI second to a new transition (2017):
≥ 3 optical clocks demonstrate uncertainties 100× better than Cs ($\Delta f/f \approx 10^{-18}$).
≥ 3 optical clocks in different labs are measured to be in agreement at $\Delta f/f \approx 10^{-18}$.
Optical standards are compared to ≥ 3 Cs fountains with uncertainty limited by the fountains.
≥ 5 measured optical frequency ratios agree at 5×10^{-18} and are measured twice by independent labs.
Optical clocks contribute regularly to TAI.

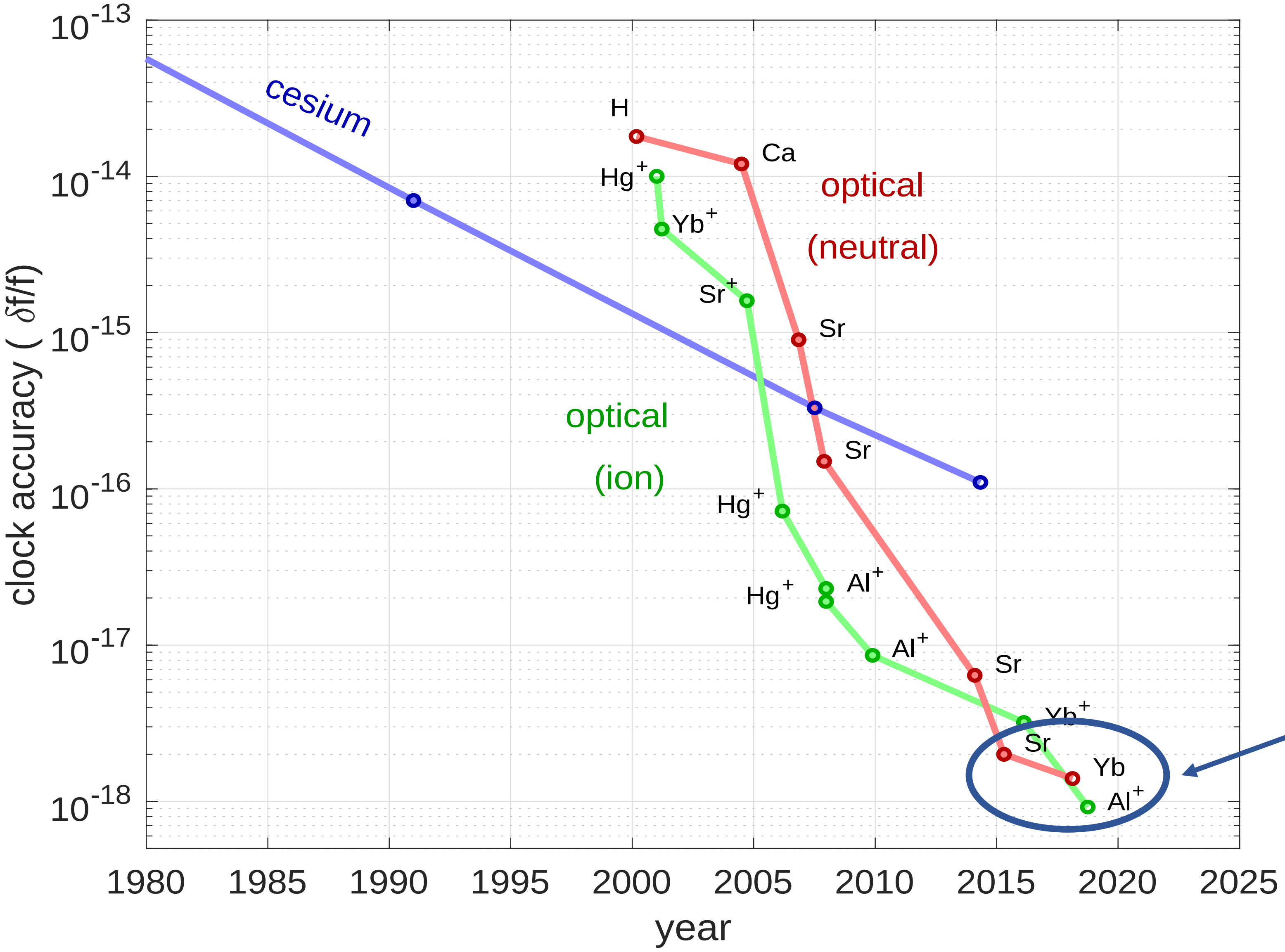
Higher Q **optical** transitions

Optical frequency combs

New laser stabilization methods

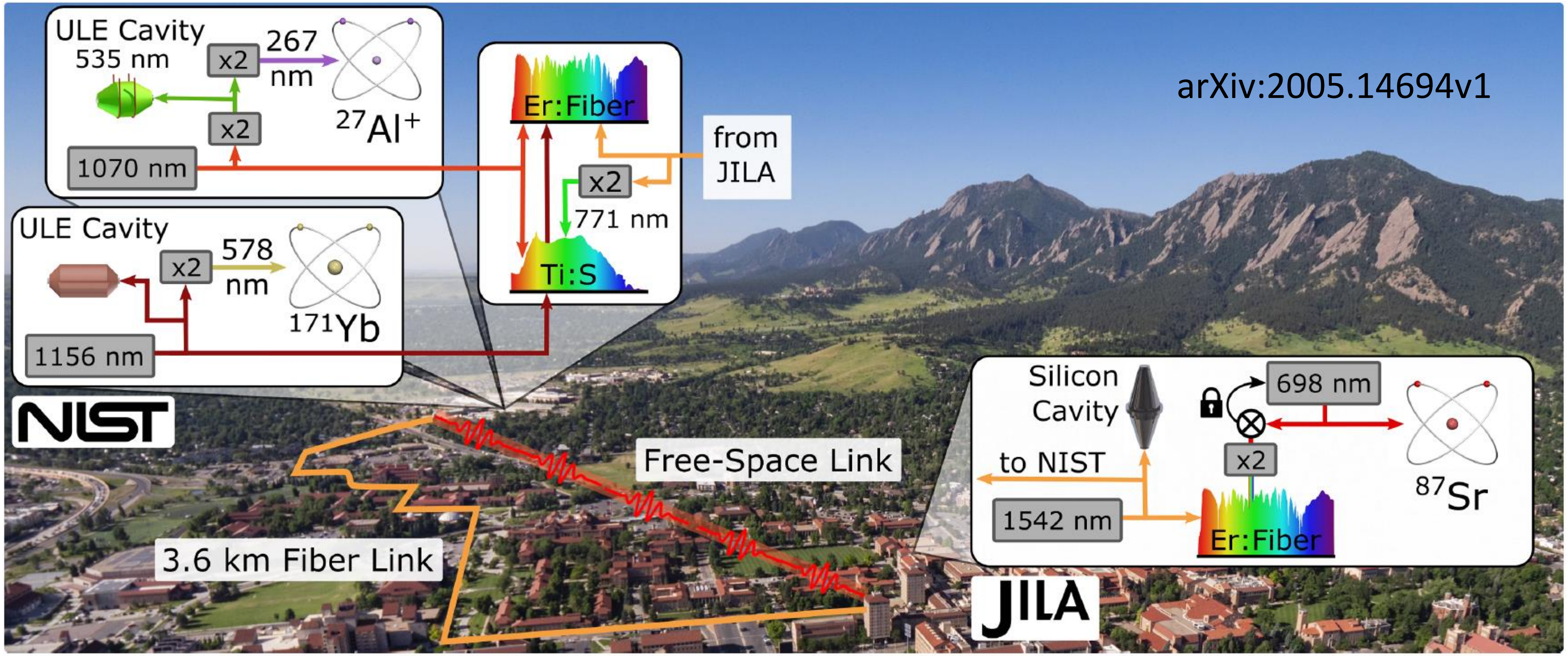
Arias, Matsakis, Quinn, & Tavella: The 50th Anniversary of the Atomic Second, TUFFC **65** (2018)

Historical accuracy of atomic clocks



Three of the world's best optical clocks are at NIST Boulder.

Boulder Optical Clock Network (BACON)

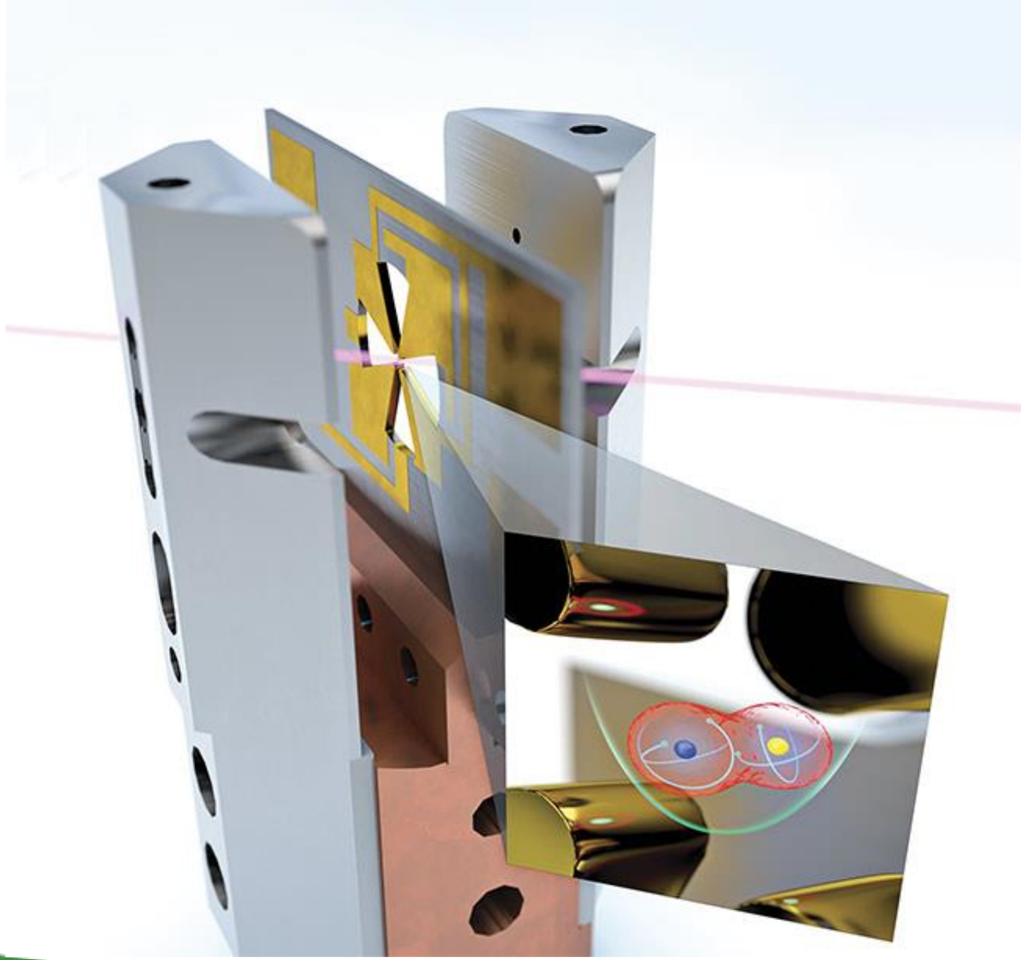


Sr clock: Nicholson, T., et al. *Systematic evaluation of an atomic clock at 2 × 10^{-18} total uncertainty. Nat Commun* **6,** (2015).

K. Beloy, M. I. Bodine, T. Bothwell, S. M. Brewer, S. L. Bromley, J.-S. Chen, J.-D. Deschenes, S. A. Diddams, R. J. Fasano, T. M. Fortier, Y. S. Hassan, D. B. Hume, D. Kedar, C. J. Kennedy, I. Khader, A. Koepke, D. R. Leibrandt, H. Leopardi, A. D. Ludlow, W. F. McGrew, W. R. Milner, N. R. Newbury, D. Nicolodi, E. Oelker, T. E. Parker, J. M. Robinson, S. Romisch, S. A. Schaffer, J. A. Sherman, L. C. Sinclair, L. Sonderhouse, W. C. Swann, J. Yao, J. Ye, X. Zhang

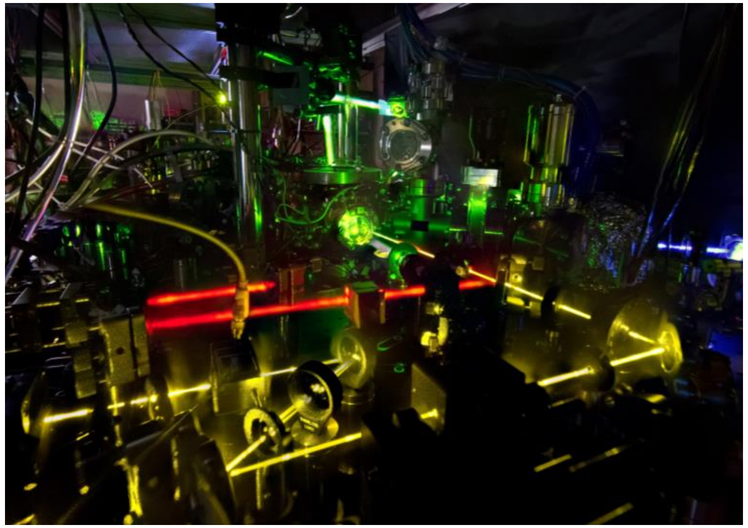
Al^+ quantum logic clock systematic uncertainty

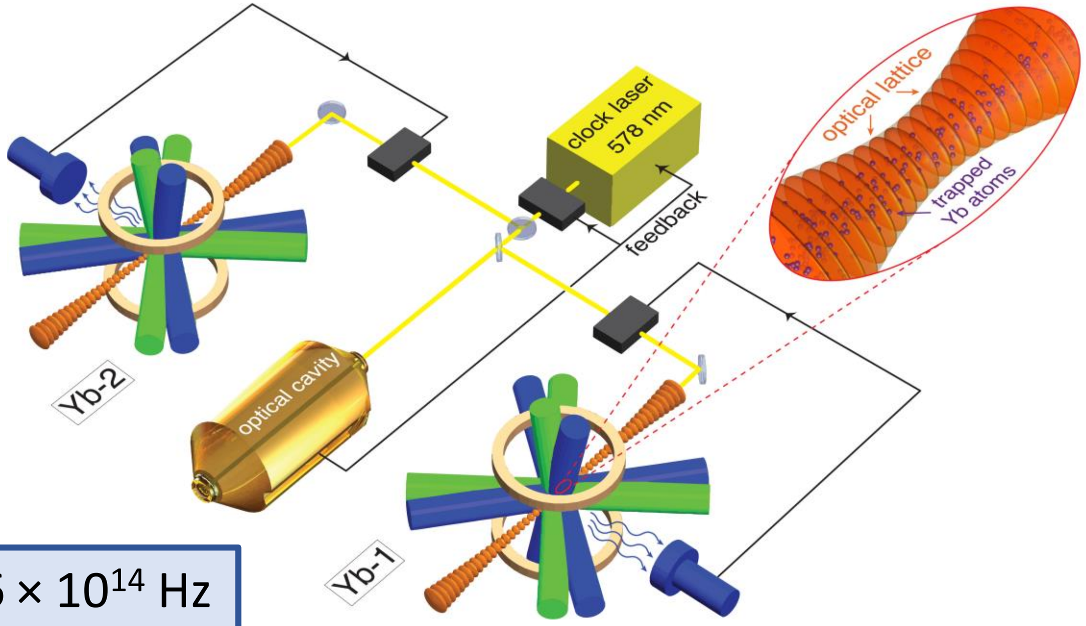
Brewer *et al.*, PRL **123** (2019)

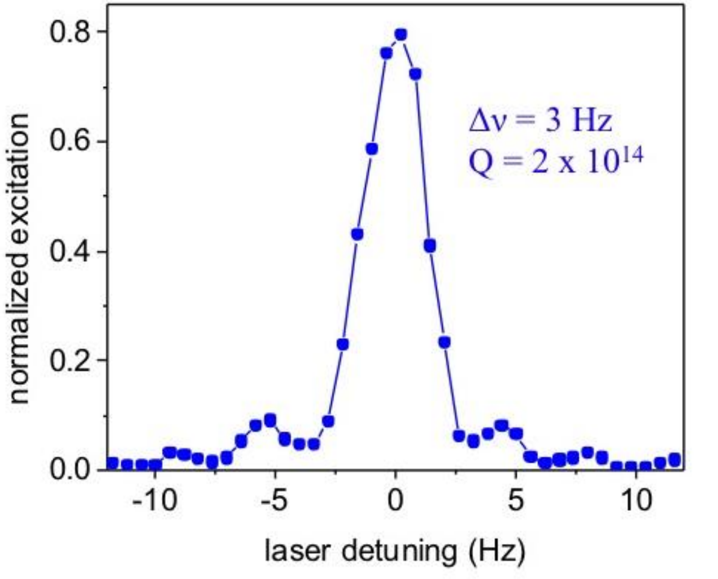


Effect	Wheel Trap (Mg^+/Al^+) shift | uncertainty [× 10^{-18}]	
Blackbody radiation	-3.05	0.43
Micromotion time dilation	-4.57	0.59
Secular motion time dilation	-1.73	0.29
Cooling light shift	0	0
Quadratic Zeeman shift	-924.16	0.37
Linear Doppler shift	0	0.22
Background gas collision	-0.06	0.24
Total	-932.77	0.94

Yb Lattice Clock







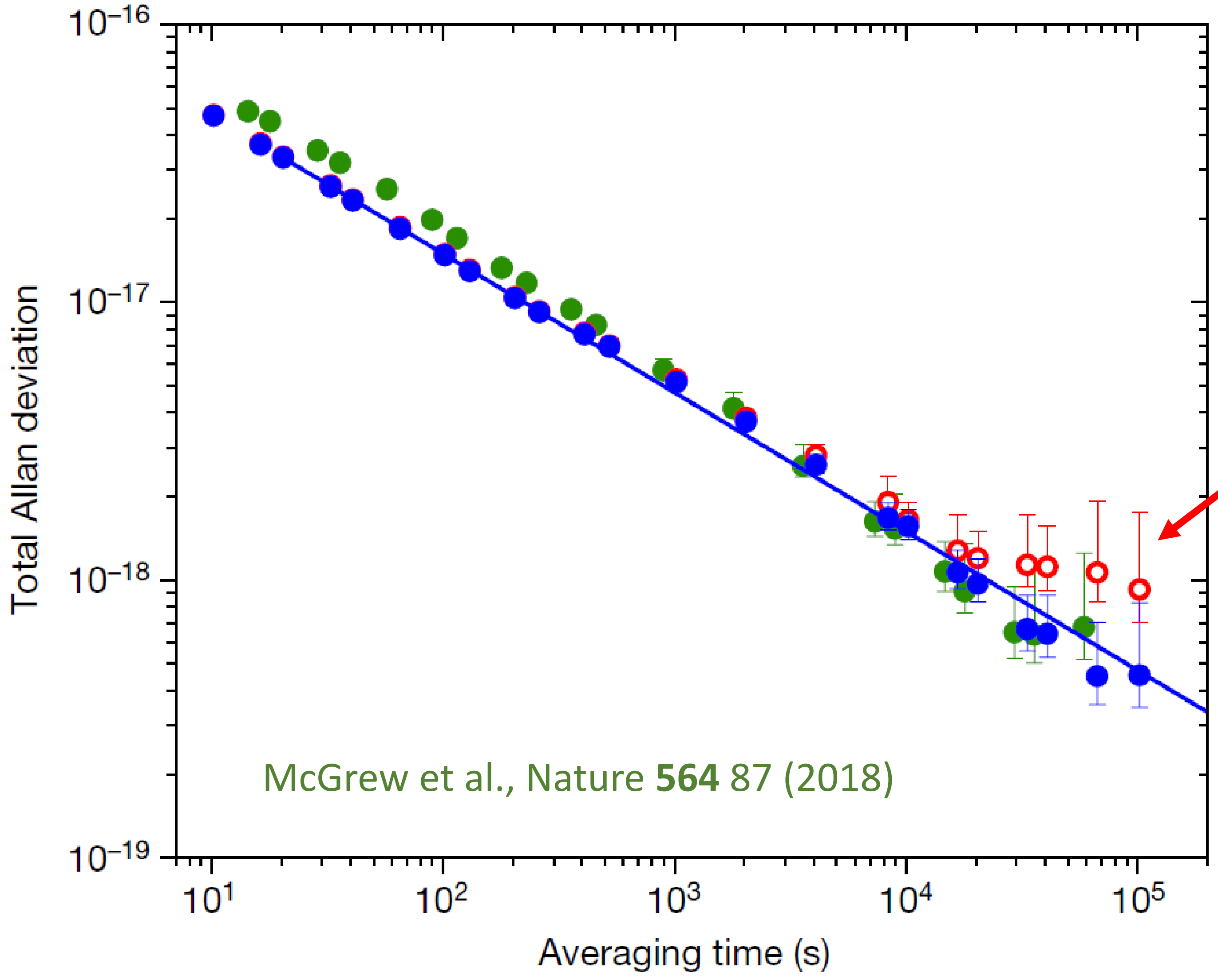
ν = 5.182958365908636 × 10^{14} Hz

$\Delta\nu$ = 3 Hz

Q = 2 × 10^{14}, SNR = 50

1/(Q×SNR) = 10^{-16} !!!

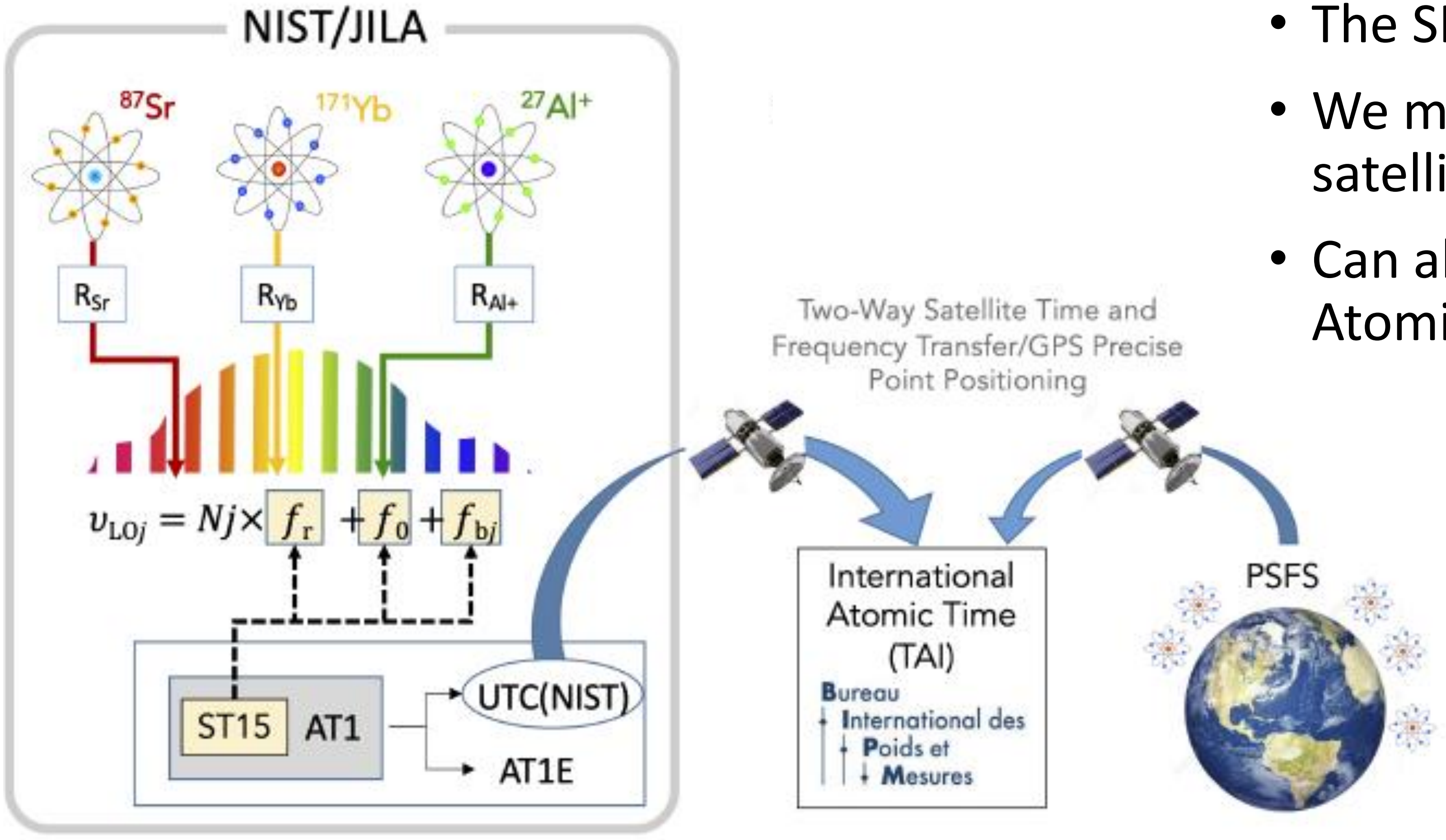
Yb Frequency Instability



Red data uncorrected for blackbody shift

Two Yb clocks stable and in agreement @ 7 x 10^{-19}

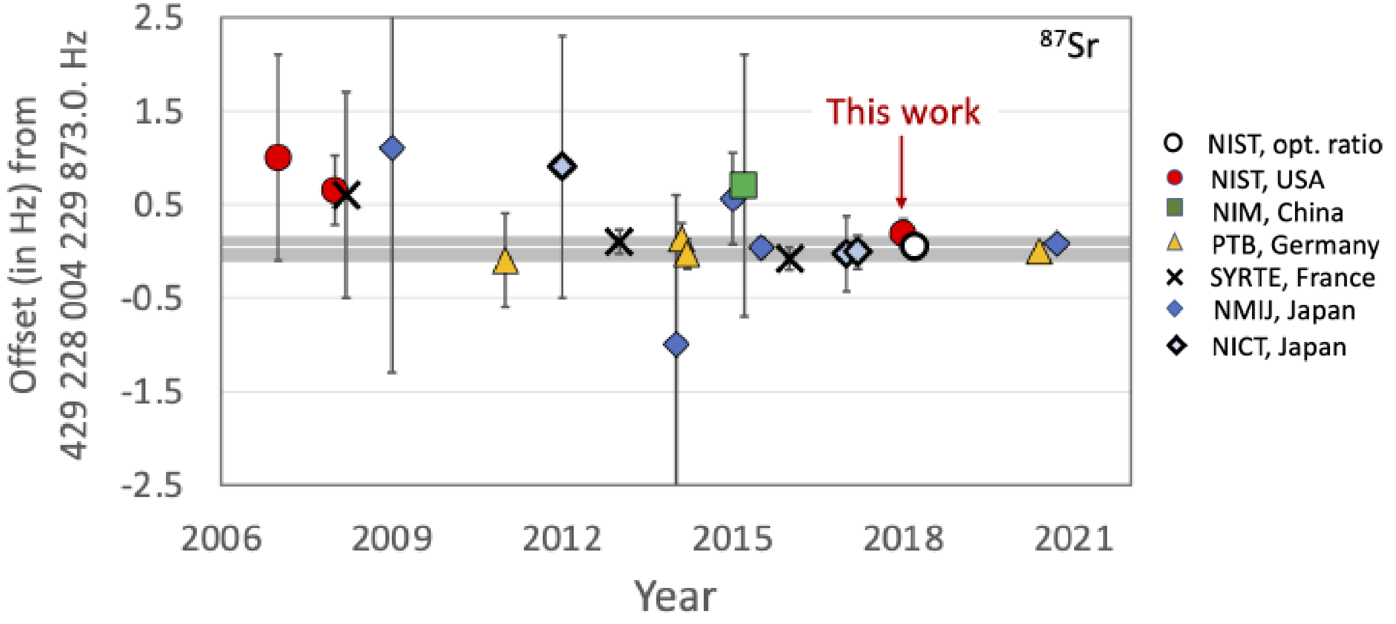
Absolute Frequency Measurements

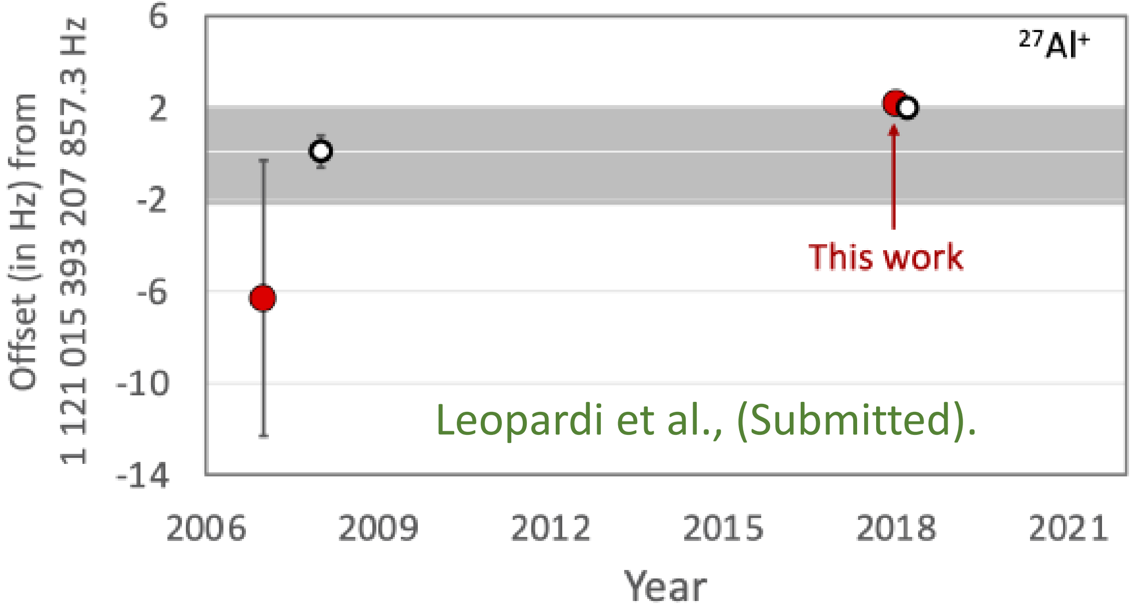


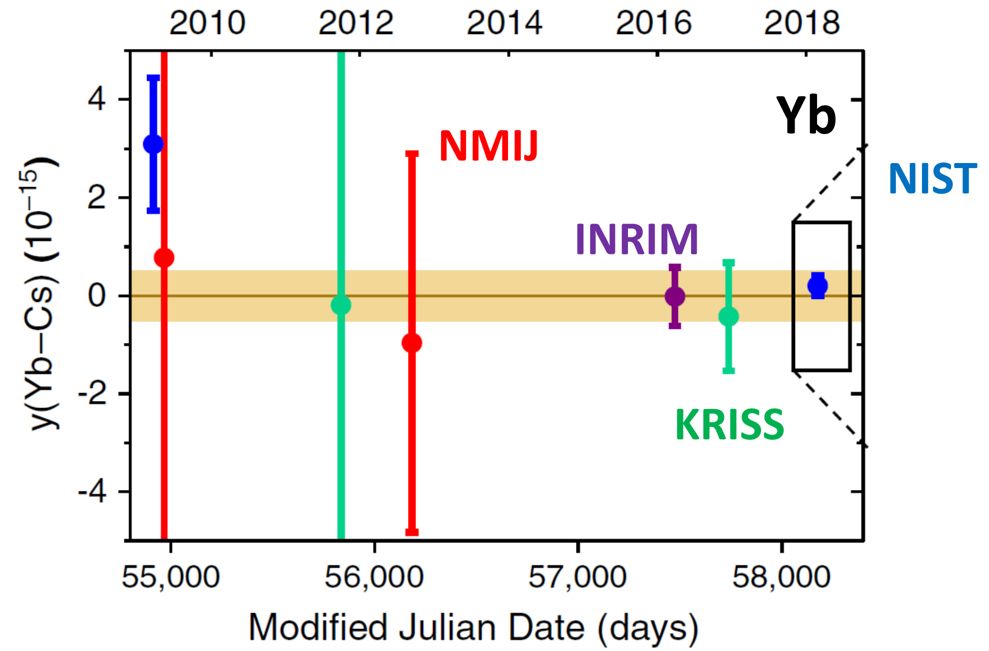
- The SI second is defined by cesium.
- We measure optical frequencies by satellite time transfer to the BIPM.
- Can also contribute to International Atomic Time with these comparisons.

Leopardi et al., Measurement of the $^{27}Al^+$ and ^{87}Sr absolute optical Frequencies, (Submitted).

Absolute Optical Frequency Measurements





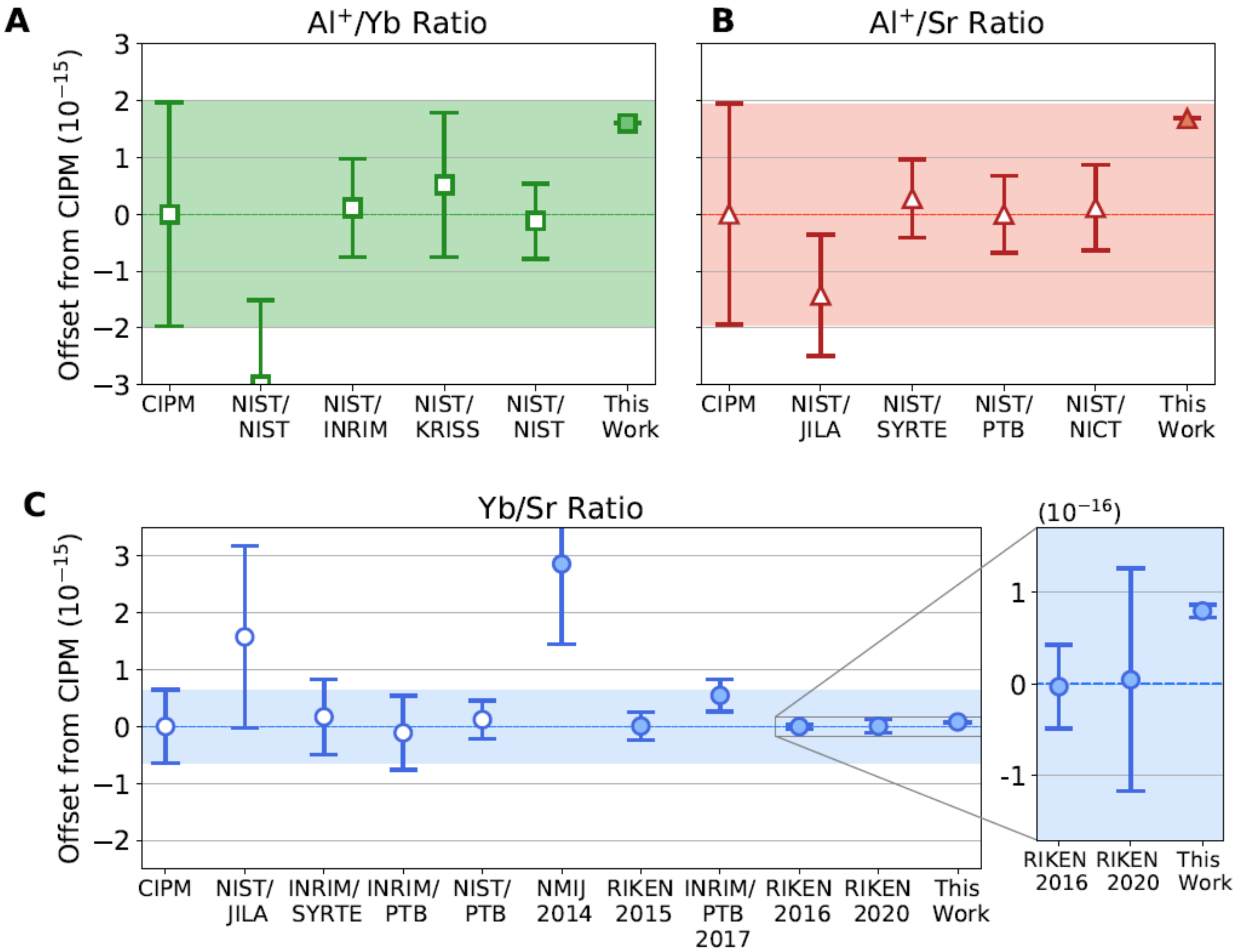


McGrew et al., Optica **6**, 2019:

Measurement uncertainties limited at the 2-3 × 10^{-15} level by the Cs uncertainty (and time transfer)

Optical Frequency Ratio Measurements

Not limited by Cs statistical uncertainty



ArXiv:2005.14694v1

$$\delta_{Al/Yb} = 6 \times 10^{-18}$$
$$\delta_{Al/Sr} = 8 \times 10^{-18}$$
$$\delta_{Yb/Sr} = 7 \times 10^{-18}$$

30 × lower uncertainties than measurements referenced to Cs.

Revisiting the CCTF Criteria from 2017

5 CCTF criteria to change the basis of the SI second to a new transition (2017):
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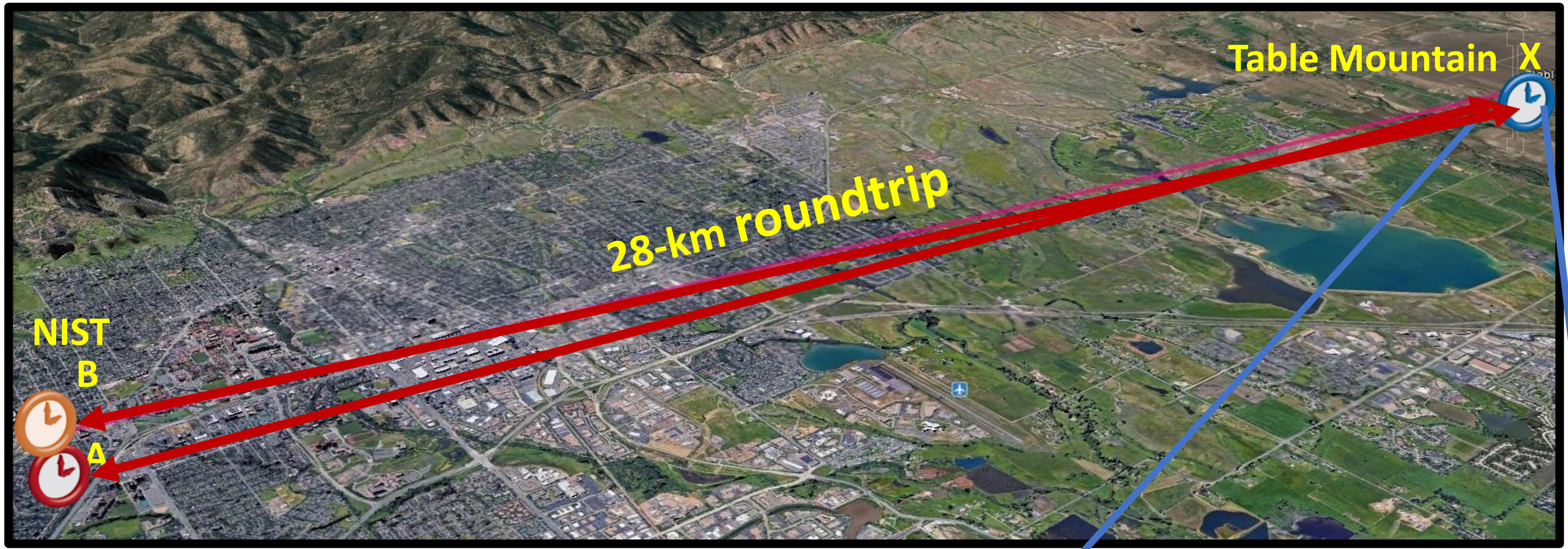
≥ 5 measured optical frequency ratios agree at 5×10^{-18} and are measured twice by independent labs.
Optical clocks contribute regularly to TAI.

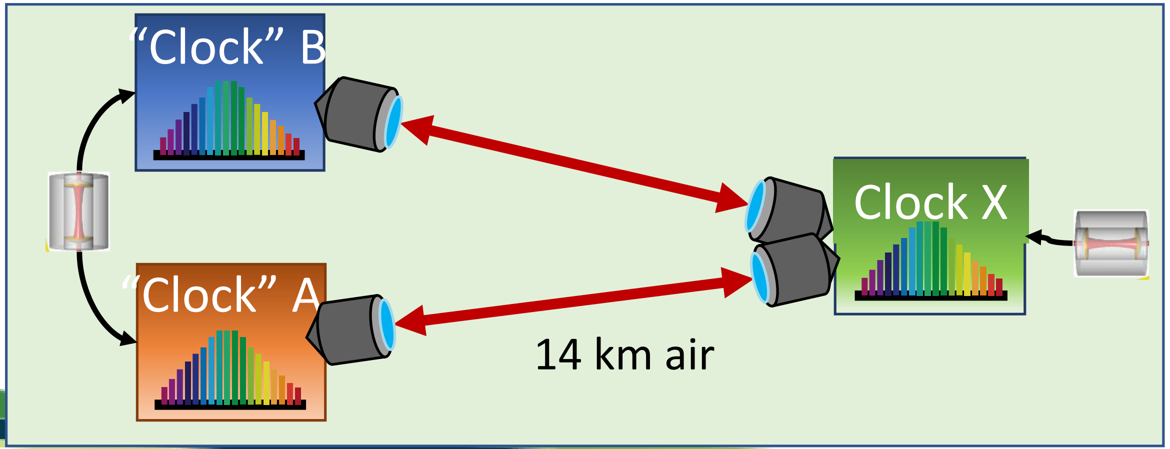
None of the criteria are solidly demonstrated but most are close

There may be new criteria added after the 2020/2021 CCTF meetings

How do we transfer time at the needed levels of uncertainty to take advantage of a redefinition?

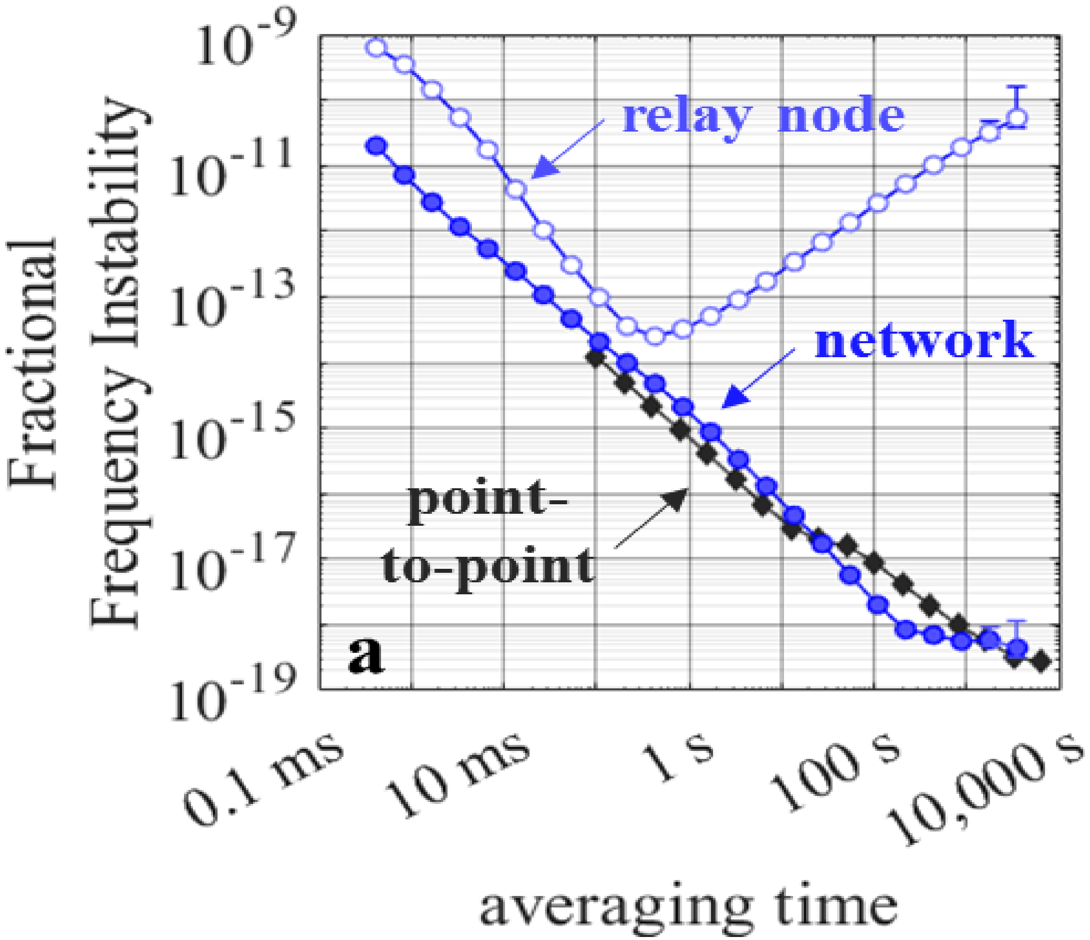
3-node Network across ~28 km of turbulent air





M. I. Bodine et al., *Optical time-frequency transfer across a free-space, three-node network*, APL Photonics 5 (2020)

Frequency Transfer @ 10^{-18} over 28 km



- Robust fieldable transceiver
- 10^{-18} at 1000s

Time & Frequency Distribution Over Optical Fiber

Executive Order 13905

Federal Register
Vol. 85, No. 32
Tuesday, February 18, 2020

Presidential Documents

Title 3—
The President

Executive Order 13905 of February 12, 2020

Strengthening National Resilience Through Responsible Use of Positioning, Navigation, and Timing Services

Section 4i: *Within 180 days of the date of this order, the Secretary of Commerce shall make available a GNSS-independent source of UTC, to support the needs of critical infrastructure owners and operators, for the public and private sectors to access.*

New Service!

TIME AND FREQUENCY

Time over Fiber Special Test

SKU 78100S
Availability:

Add to Cart for Price Quote

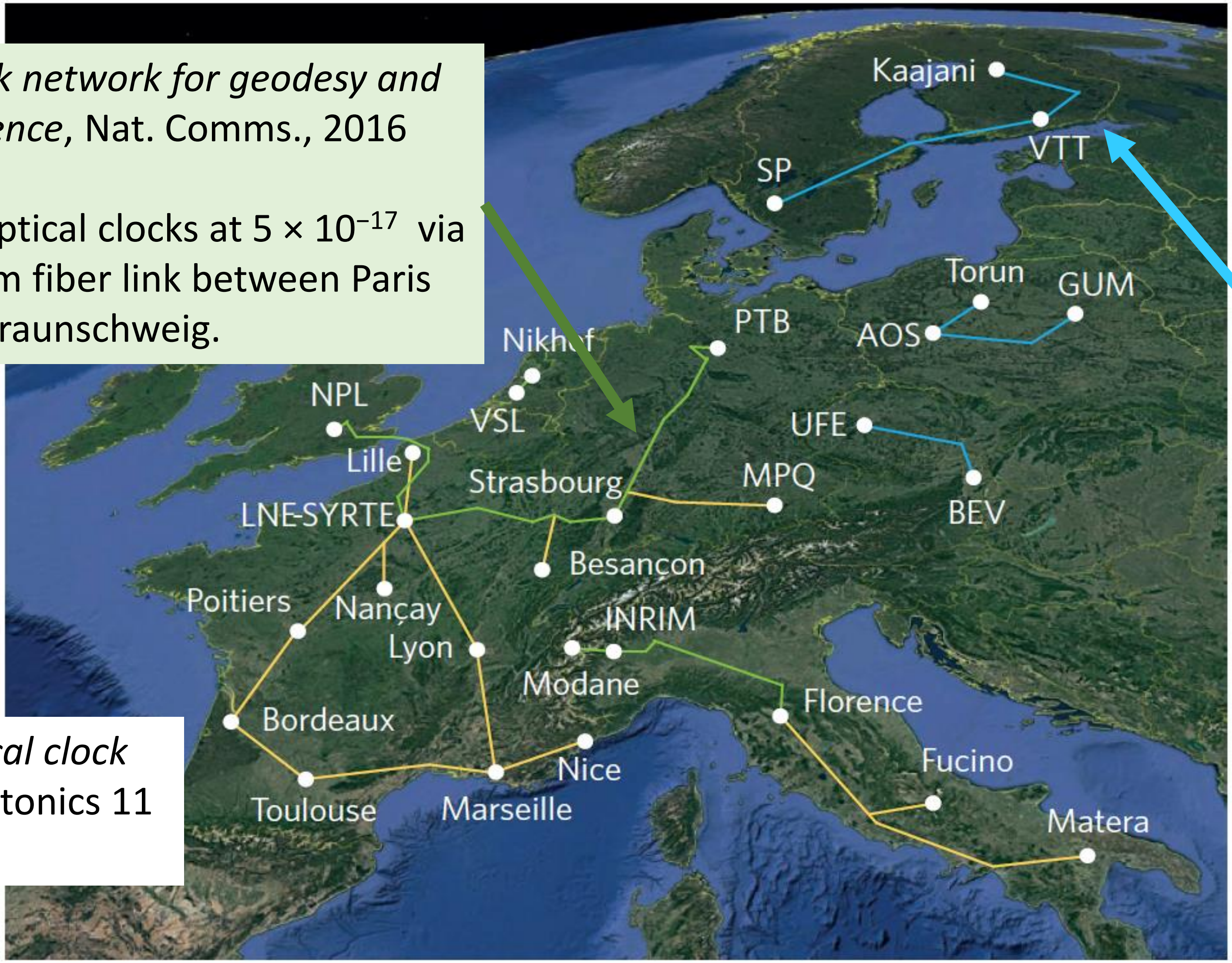
Primary NIST Technical Contact:
Name: Judah Levine
Phone: (303) 497-3903
Email: Email NIST Technical Contact

Provide a signal traceable to UTC(NIST) from NIST Gaithersburg through a third-party optical fiber to a customer's outside user facility.

- Customers subscribe to the service at cost.
- Initial goal : 1 μs in a remote location – eventual improvement to < 100 ns
- The types of hardware and signals are not constrained, leaving flexibility to subscribers.

Lisdat et al., *A clock network for geodesy and fundamental science*, Nat. Comms., 2016

Agreement of 2 Sr optical clocks at 5×10^{-17} via a 1,415 km telecom fiber link between Paris and Braunschweig.



Dierikx et al., *White Rabbit PTP on long-distance fiber links*, IEEE Trans UFFC, 2016

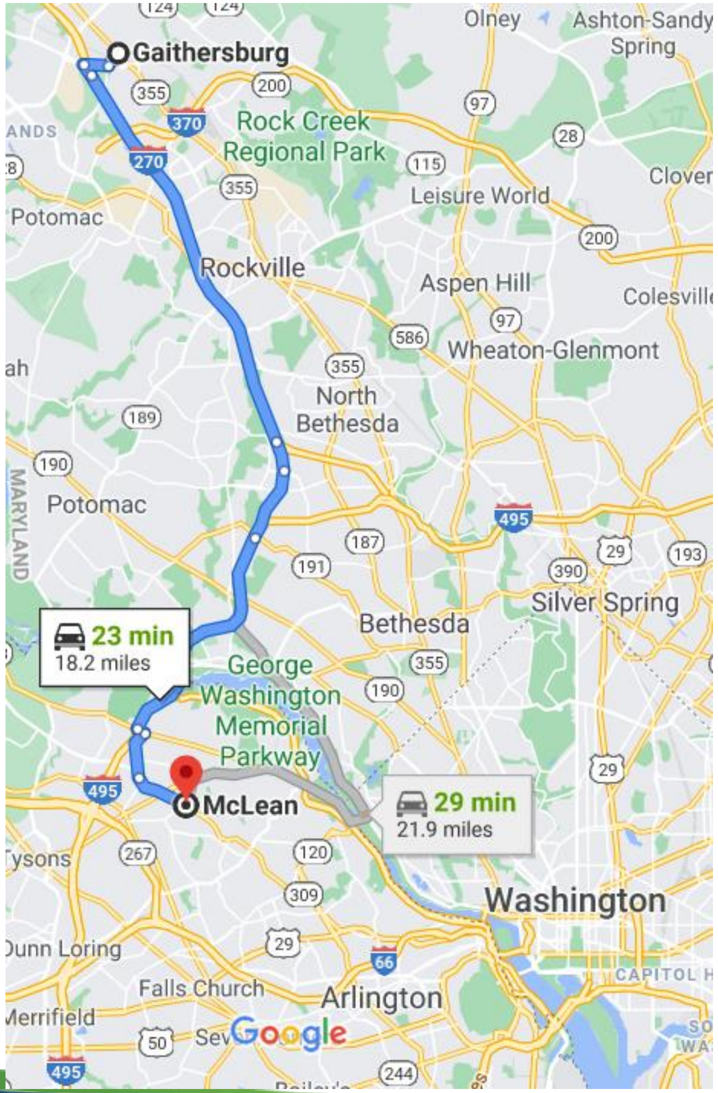
950-km White Rabbit link between Espoo and Kajaani, Finland. The time transfer compared against GPS.

±2 ns agreement over 3 months of measurements.

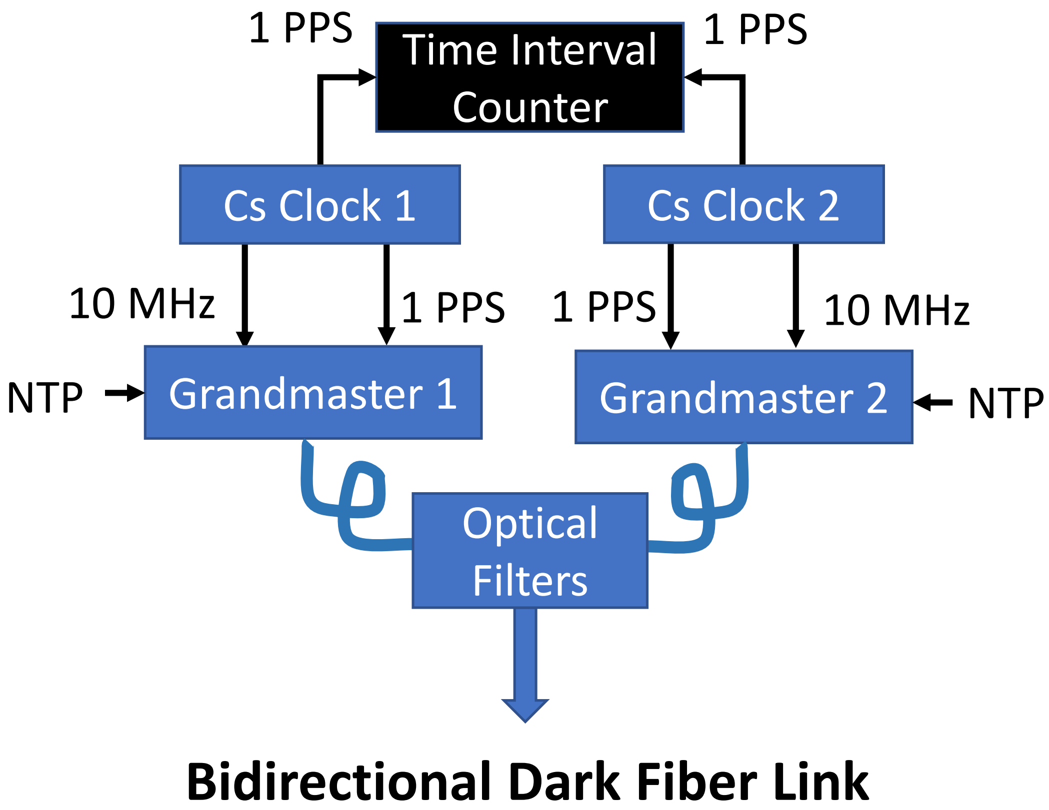
Fritz Riehle, *Optical clock networks,* Nat. Photonics 11 (2017)

Our new Time Over Fiber Service is not a research project.
It is an effort to build time and frequency distribution infrastructure.

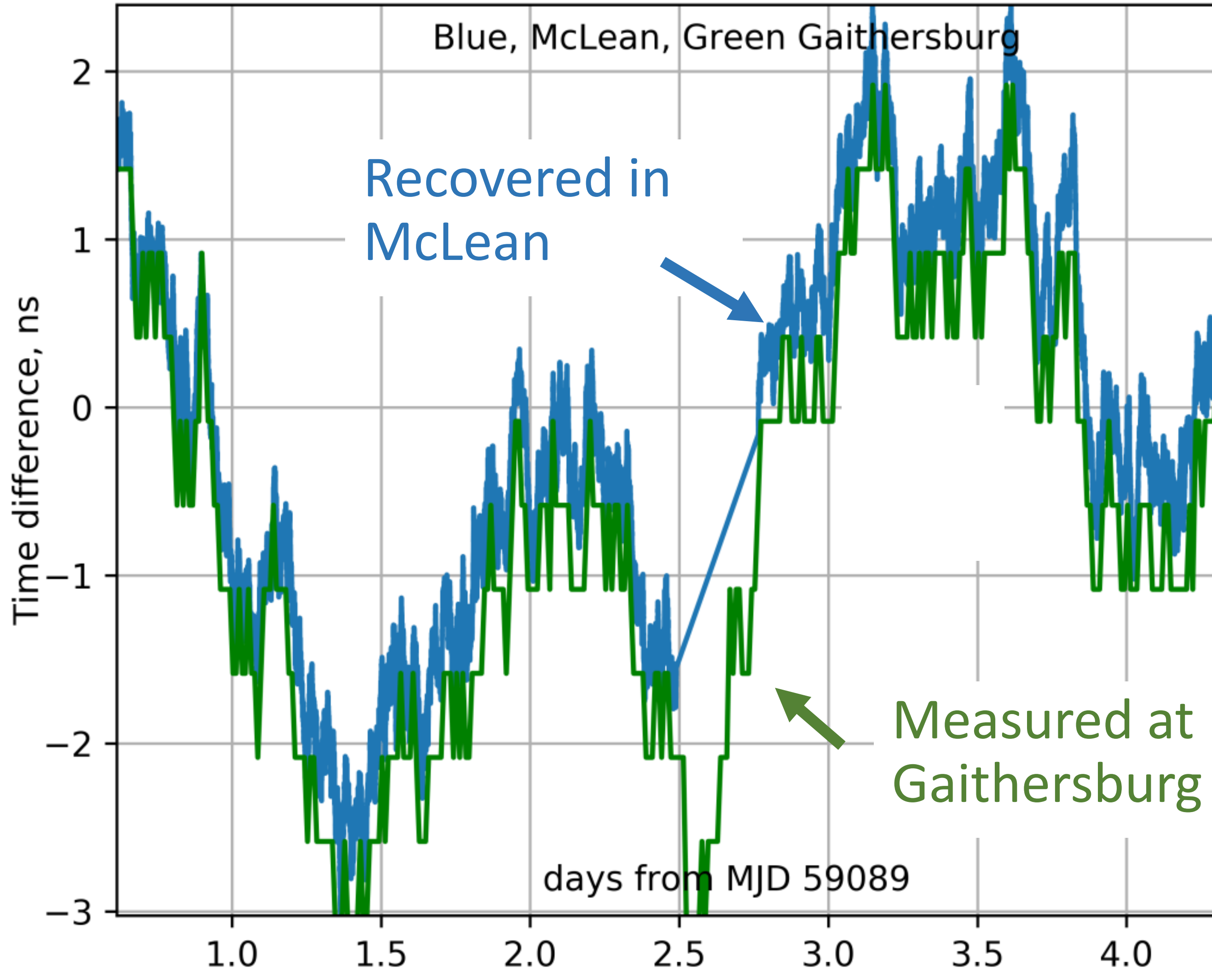
White Rabbit Link to McLean, VA



Judah Levine & Jonathan Hardis, NIST, Monty Johnson, OPNT

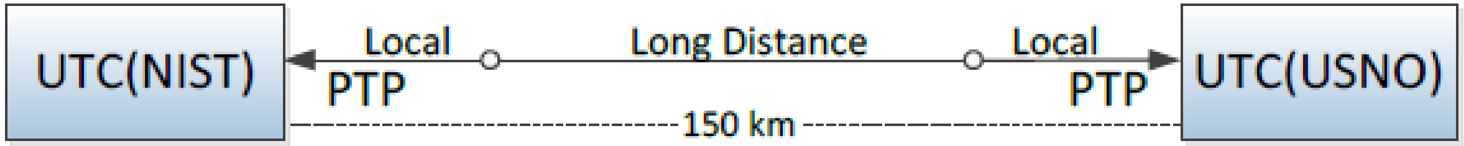


Time Difference Measurements



- Comparison between time differences measured in Gaithersburg and recovered in McLean
- Preliminary results suggest that the goal of ±100 ns uncertainty has been realized.
- Will have to be further tested and validated.

Time transfer over commercial optical fiber



UTC(NIST) in Boulder

AMC, in Colorado Springs

Weiss et al., *Precision time transfer using IEEE 1588 over OTN through a commercial optical telecommunications network*, Proc. IEEE Intl. Symp. on Prec. Clock Sync. (2016)

2-way timing signals sent over commercial fiber between end points synched to < 10 ns.

- Observed 10's of microseconds of time transfer error, but stable to < 100 ns between link resets.
- If network time delays can be calibrated, sub - 100 ns accuracy might be realized between equipment resets.

In an operational network, changes in the delays upon resetting a link would need to be addressed – possibly by comparing multiple sources for fault detection and recovery.

Review and Conclusions:

- The world's NMIs (including NIST) have made steady progress toward meeting the criteria to redefine the second based on an optical transition.

- We need to develop ways to distribute precision timing optically
  - Through fiber to augment and provide holdover for disruptions to the GNSS.
  - Through free space and fiber for time and frequency transfer commensurate with optical clock performance.

Thank you!

NIST

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Applied Physics Division

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