Introduction and Report from NIST

Bijunath R. Patla★
Time and Frequency Division – NIST, Boulder

CGSIC, 2020✦

★ brp1@nist.gov / / ✦ the year of the toilet paper shortage

Theme and scope of this year's program

- Timing in a challenging and expansive landscape
- Atomic clocks and fundamental science

Civil GPS Service Interface Committee

Timing Subcommittee

Chair: Dr. Bijunath Patla, National Institute of Standards and Technology (NIST)
Co-Chair: Dr. Lin Yi, NASA Jet Propulsion Laboratory (JPL)

21 September 2020

Timing Subcommittee

2:00 pm Central Daylight Time

2:00 **Introduction** *Dr. Bijunath Patla, National Institute of Standards and Technology (NIST)*

2:20 **USNO Laboratory Update** Mr. Stephen Mitchell, U.S. Naval Observatory (USNO)

2:40 **Algorithms and Features of the New GPS System Timescale** *Dr. Michael Coleman, Naval Research Laboratory (NRL)*

3:00 Report From the Jet Propulsion Laboratory (JPL)
Dr. Lin Yi, JPL, California Institute of Technology

3:20 **Break (Reconvene 3:40)**

Timing Subcommittee

3:40 Control Algorithm for Resilient Timing
Dr. Ilya Udovydchenkov, Lead Electrical Engineer, MITRE

4:00 NIST Network Time Services: Current Status and Future Plans *Prof.*
Dr. Judah Levine, NIST

4:20 Atomic Clocks for Fundamental Physics: Time for Discovery *Prof.*
Marianna Safronova, University of Delaware

4:40 GPS/Galileo Time Transfer with Absolutely Calibrated Receivers *Dr.*
Roberto Prieto, European Space Agency, ESTEC

5:00 Discussion

5:20 Session End


CGSIC 2021
September 20-21, 2021
Union Station Hotel
St Louis, Missouri

Report from NIST

National Institute of Standards and Technology
U.S. Department of Commerce

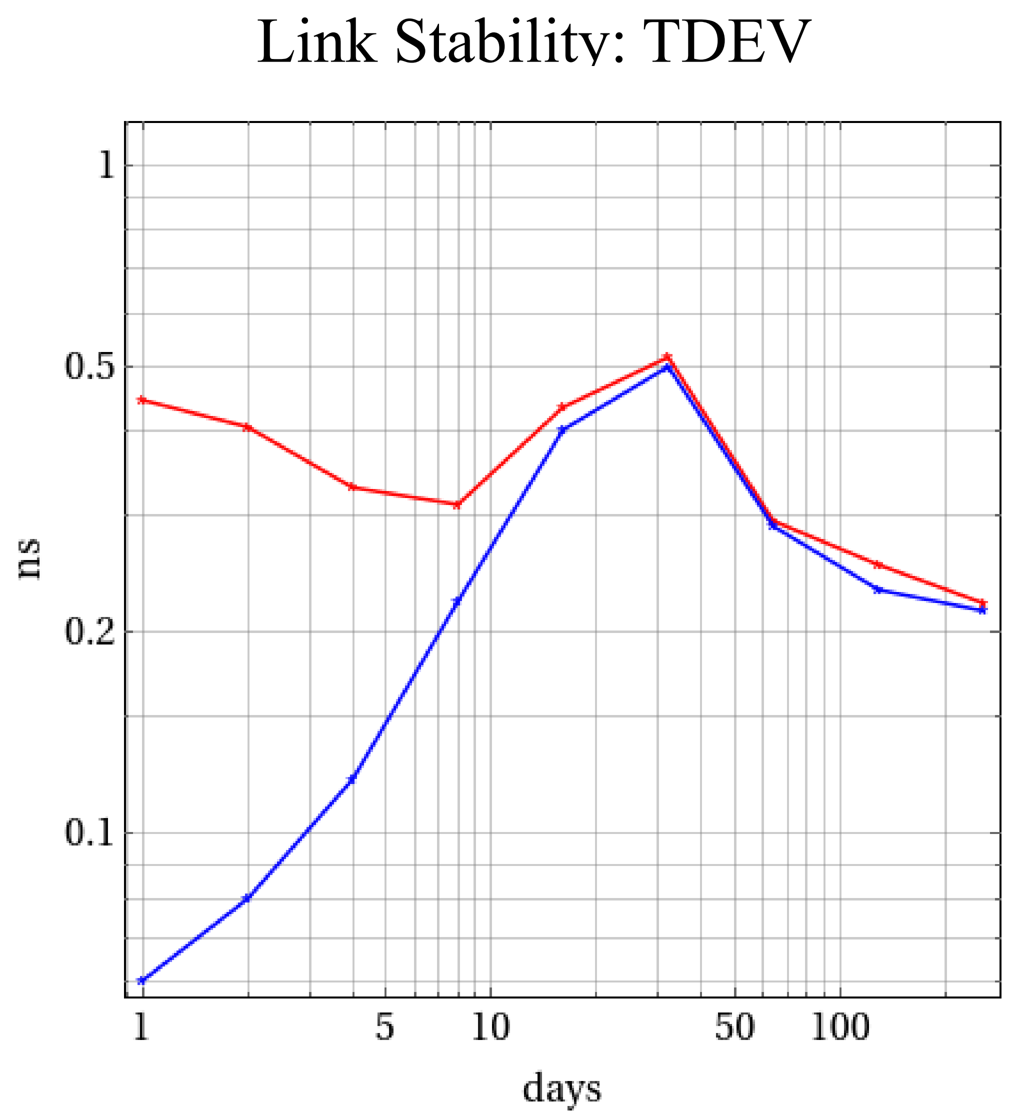
GPS/GNSS

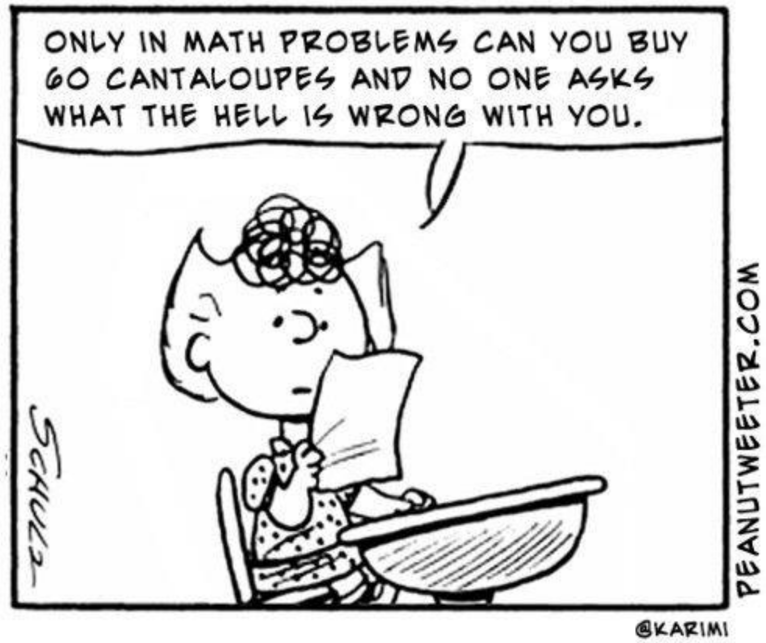
- Time transfer to BIPM
- Subscription-based NIST time service
- Calibrations

Scientific research and data analysis

- Analyze/study data from GNSS timing receivers
- Develop theoretical models for physics/geophysics and resilient timing applications
- Exploring the frontiers of fundamental physics using atomic clocks

Time Transfer with GPS (NIST-PTBB)



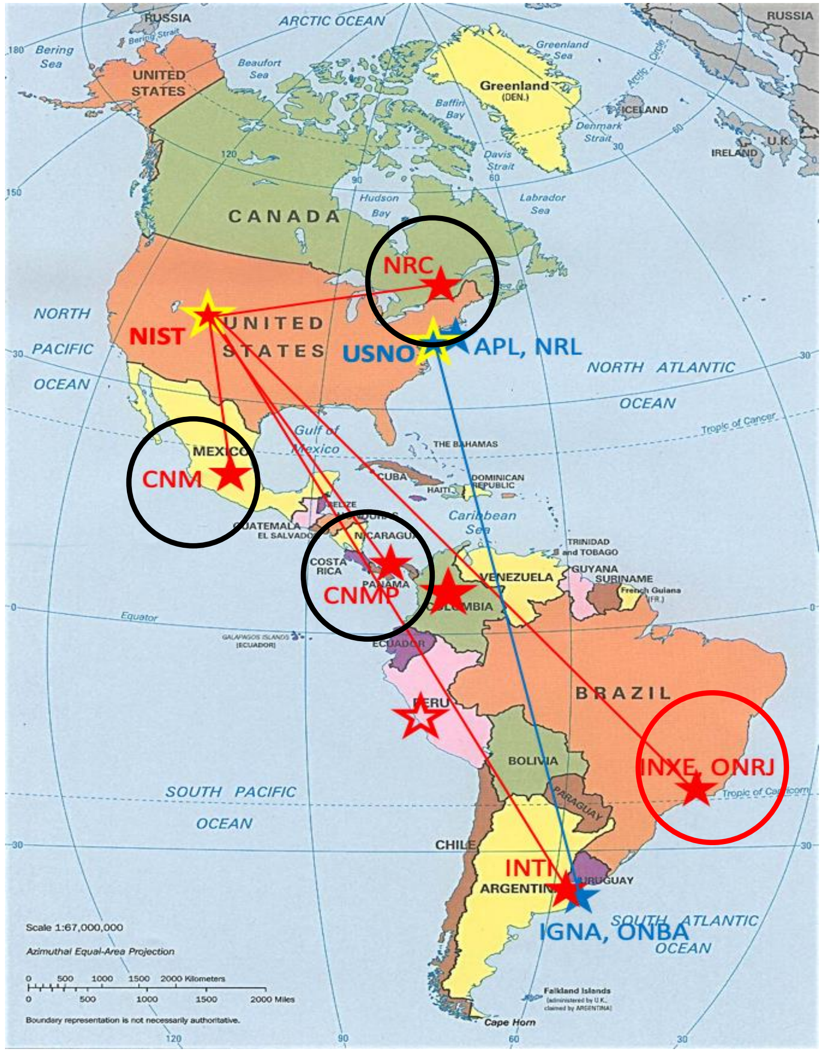


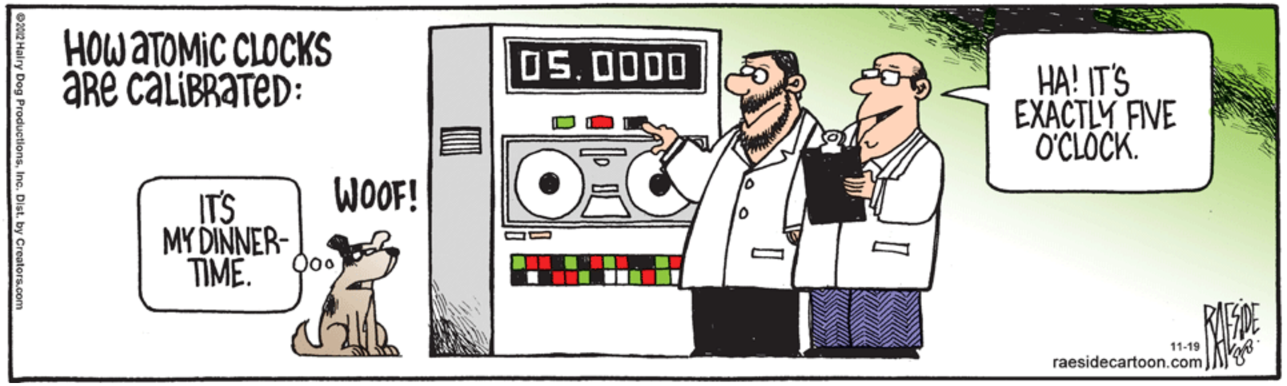
Because mathematicians care less about cantaloupes and more about averaging.

Two-way time transfer
(primary mode of time transfer to BIPM)

Ionosphere-free combination GPS

Calibrations: Group 2 (G2)





Scientists wearing lab coats is an exaggeration.

○ Completed

- ✦ NRC : Ottawa, Canada / Cal_Id:1019-2017
- ✦ CNM : Queretaro, Mexico / Cal_Id:1011-2017
- ✦ CNMP : Panama / Cal_Id: 1011-2017

○ Ongoing

INXE, ONRJ in Brazil

Subscription-based NIST Time Services

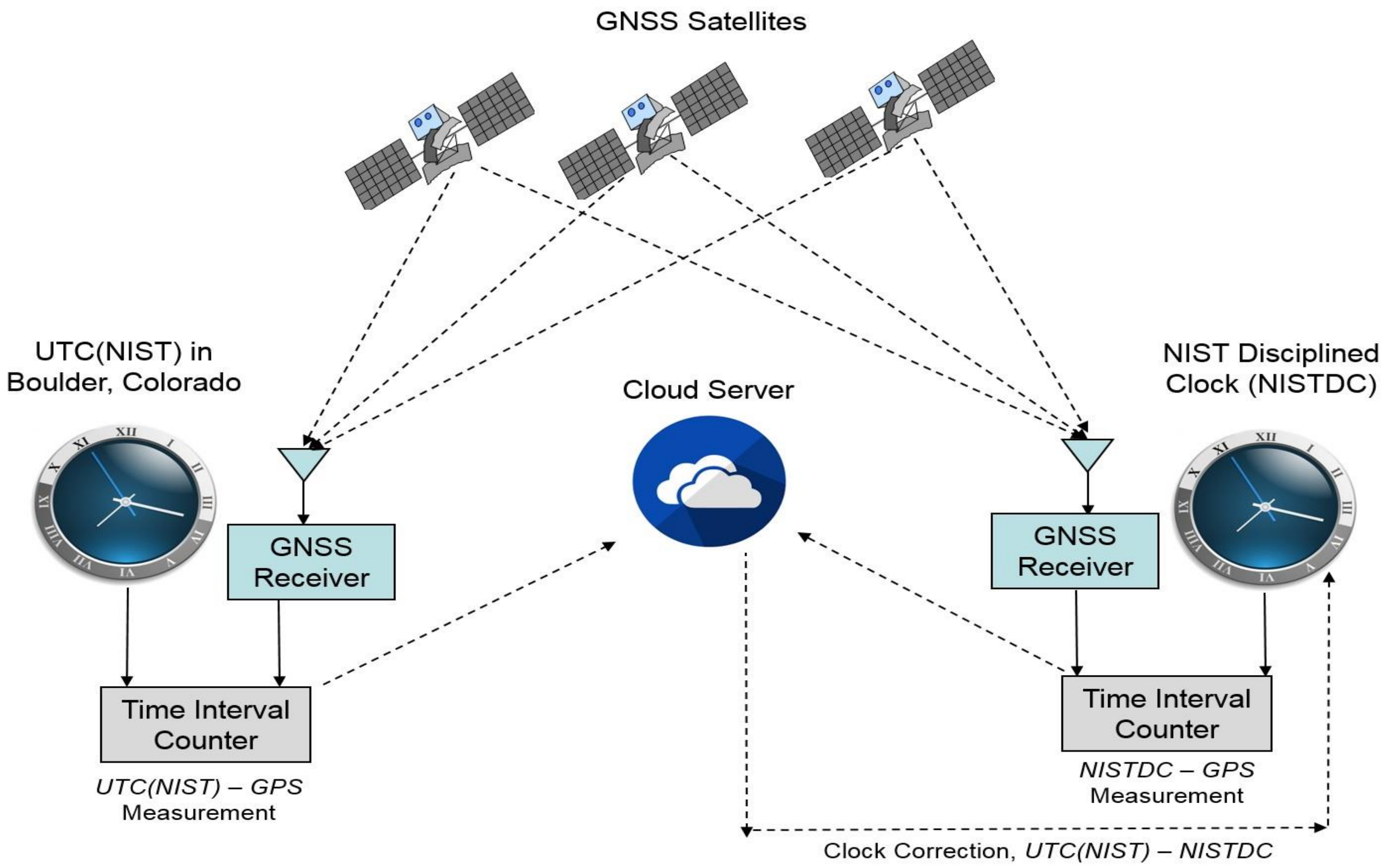
- ✓ NIST provides frequency and time references to paying customers through its Time Measurement and Analysis Service (TMAS), Frequency Measurement and Analysis Service (FMAS), and NIST Disciplined Clock service (NISTDC). All services are based on GPS common-view measurements.

- ✓ UTC(NIST) is the reference for all of these services. The NISTDC can provide NIST time at customer sites to within 10 nanoseconds. NISTDC customers include the New York Stock Exchange and the NASDAQ stock exchange – as NIST time is the official reference for U. S. stock markets.

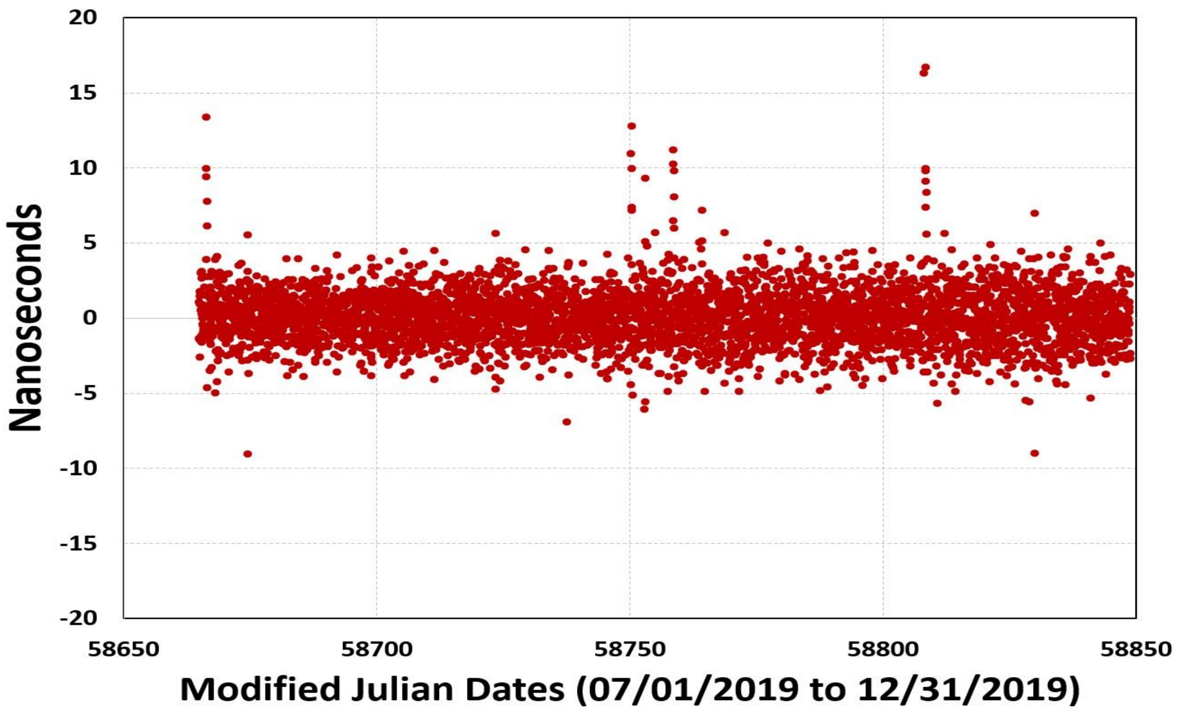
Customer sites for NIST common-view GPS services

- ✓ NIST common-view GPS systems are installed at 58 customer sites, located in 23 states and seven sites outside the U. S. Some sites receive NIST frequency only and not time.
- ✓ The red clocks on the map represent FMAS customers, the blue clocks represent TMAS customers, and the green clocks represent TMAS/NISTDC customers.

Schematic of NIST Disciplined Clock



Accuracy of NISTDC, at major US stock exchange, compared to UTC(NIST)

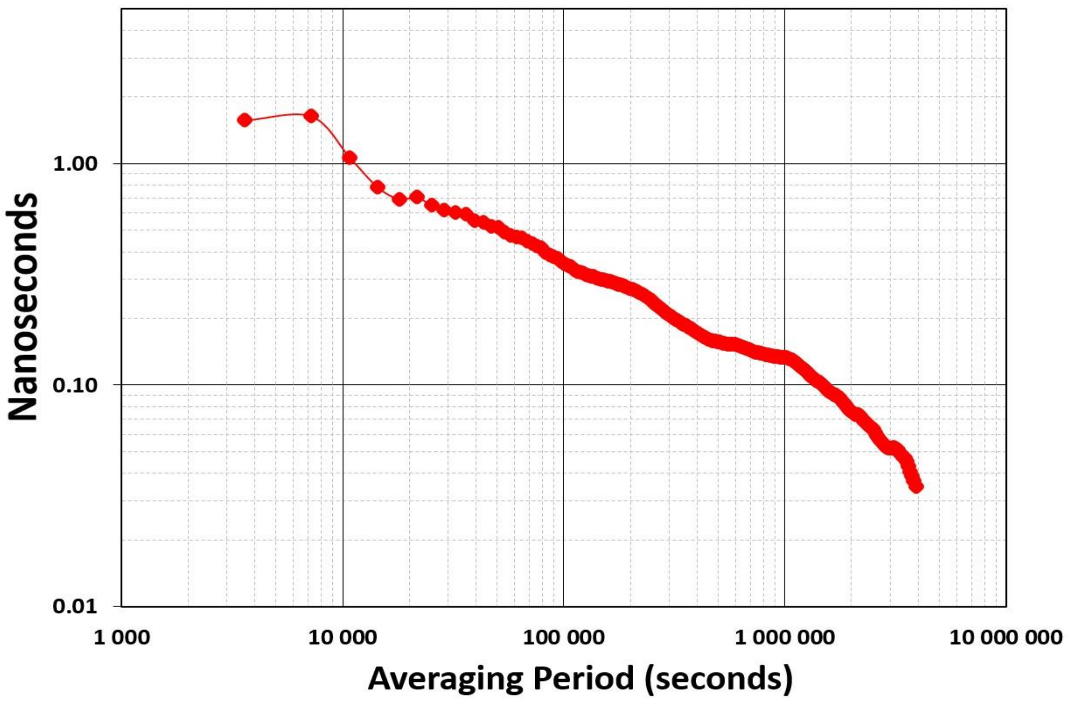


- ✓ A locked NISTDC seldom deviates by more than ±10 ns (±0.01 μs) from UTC(NIST).

- ✓ The peak-to-peak variation over the 6-month interval shown in the graph is ~25 ns, but most data points fall within ±5 ns and the average time offset is less than 0.1 ns, or essentially 0.

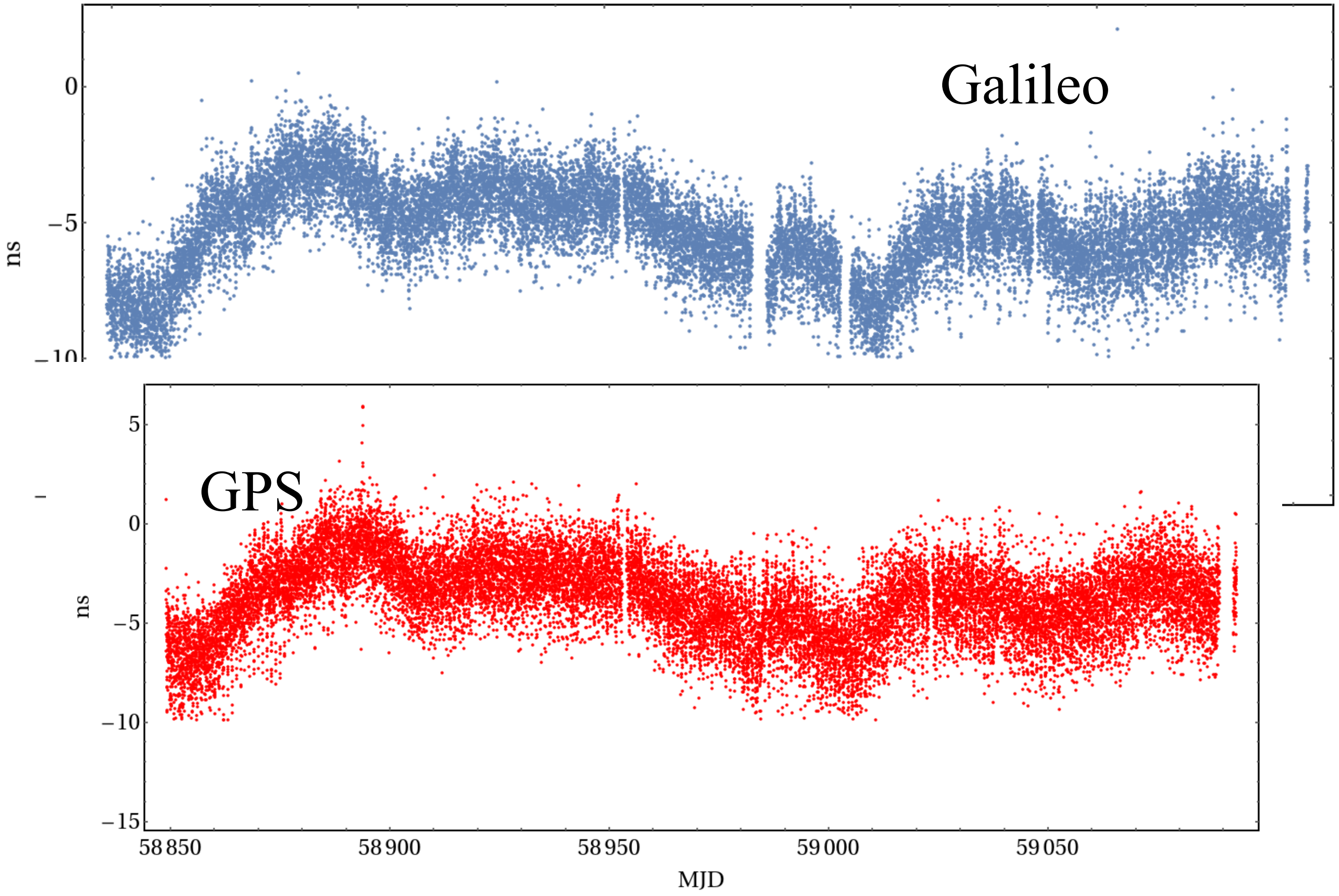
- ✓ The reported time differences between the NISTDC and UTC(NIST) may actually be larger due to uncertainties in the common-view method. These uncertainties (*k* = 2, or 2σ) typically range from ~10 ns (0.01 μs) in the best case to ~50 ns (0.05 μs) in the worst case. These uncertainties are estimated and reported to stock market clients.

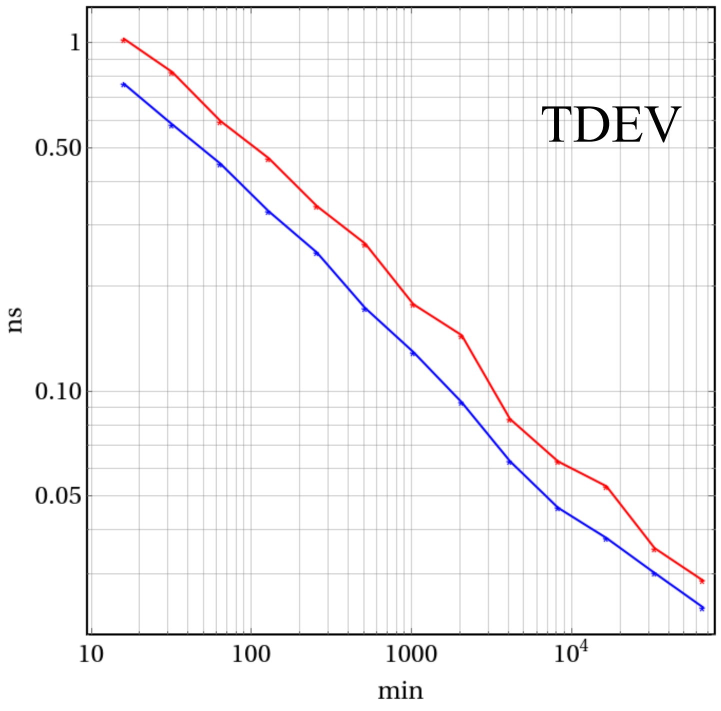
Time deviation (stability) of NISTDC



- ✓ The graph shows the time deviation (stability) of a NISTDC for averaging periods ranging from one hour to about one month.
- ✓ After averaging for one hour, the stability is about 1.5 ns, dropping below 0.4 ns after one day and below 0.2 ns after one week.
- ✓ This high level of stability is possible because the time differences between UTC(NIST) and the NISTDC are always compensated for by the common-view corrections.

Galileo versus GPS (NIST-PTBB)





[RINEX to CGGTTS conversion, see for example, Defraigne,P and Petit, G. *Metrologia 2015 52 G1*]

Galileo versus GPS (NIST-PTBB)

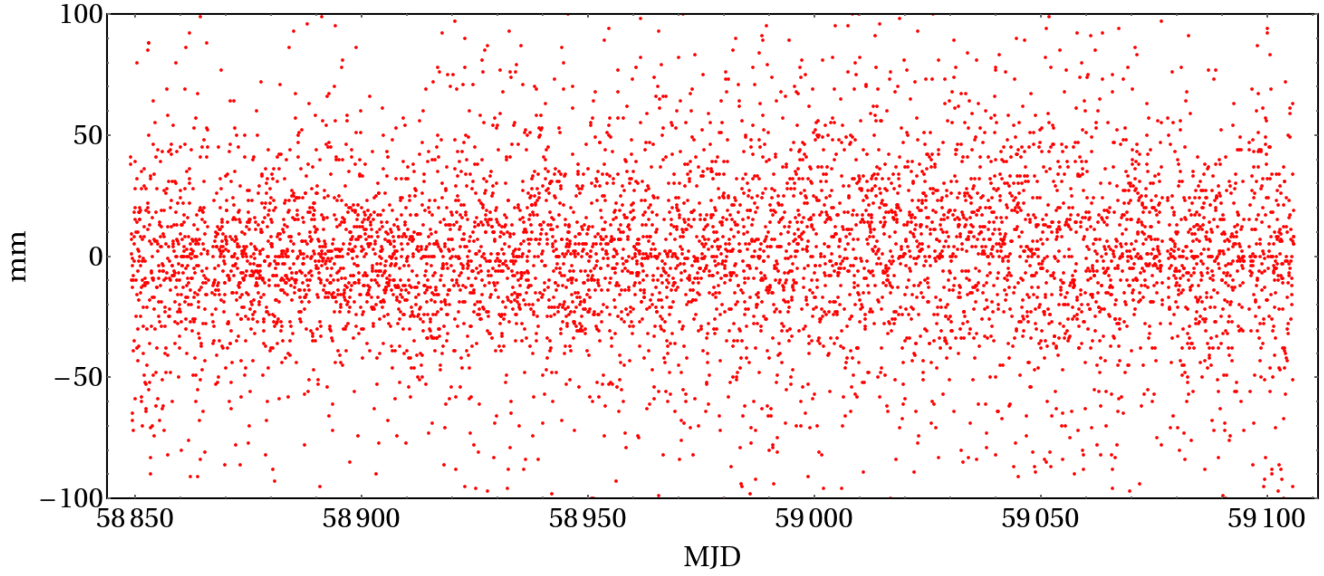
- Identical and calibrated receivers at NIST and PTB
- Using GPS P1, P2, Galileo E1, E5

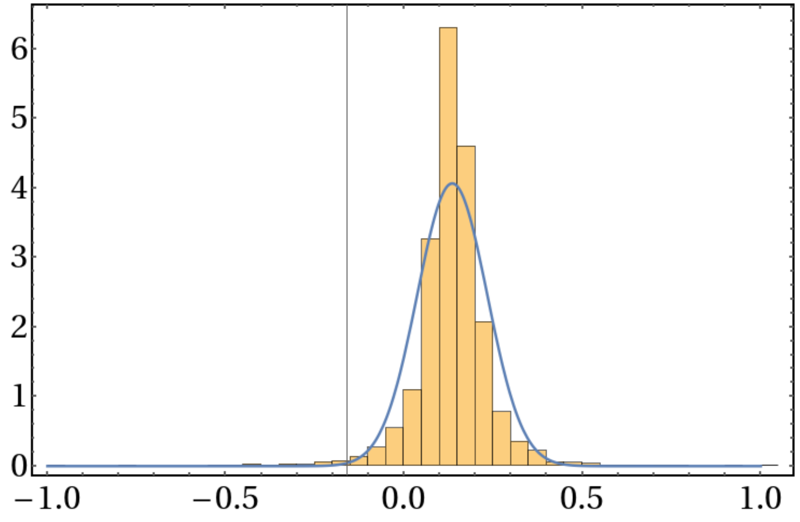
- Results
  - ✓ Constellations have comparable performance
  - ✓ Difference in accuracy and stability are statistically insignificant
  - ✓ With noise characteristics resembling white PM

	GPS	Galileo
$\sigma_y(\tau)$	$\mu = -0.93$	$\mu = -0.91$
Mod $\sigma_y(\tau)$	$\mu = -1.46$	$\mu = -1.43$

Studying Earth tide models

x coordinate in ECEF (GNSS antenna)

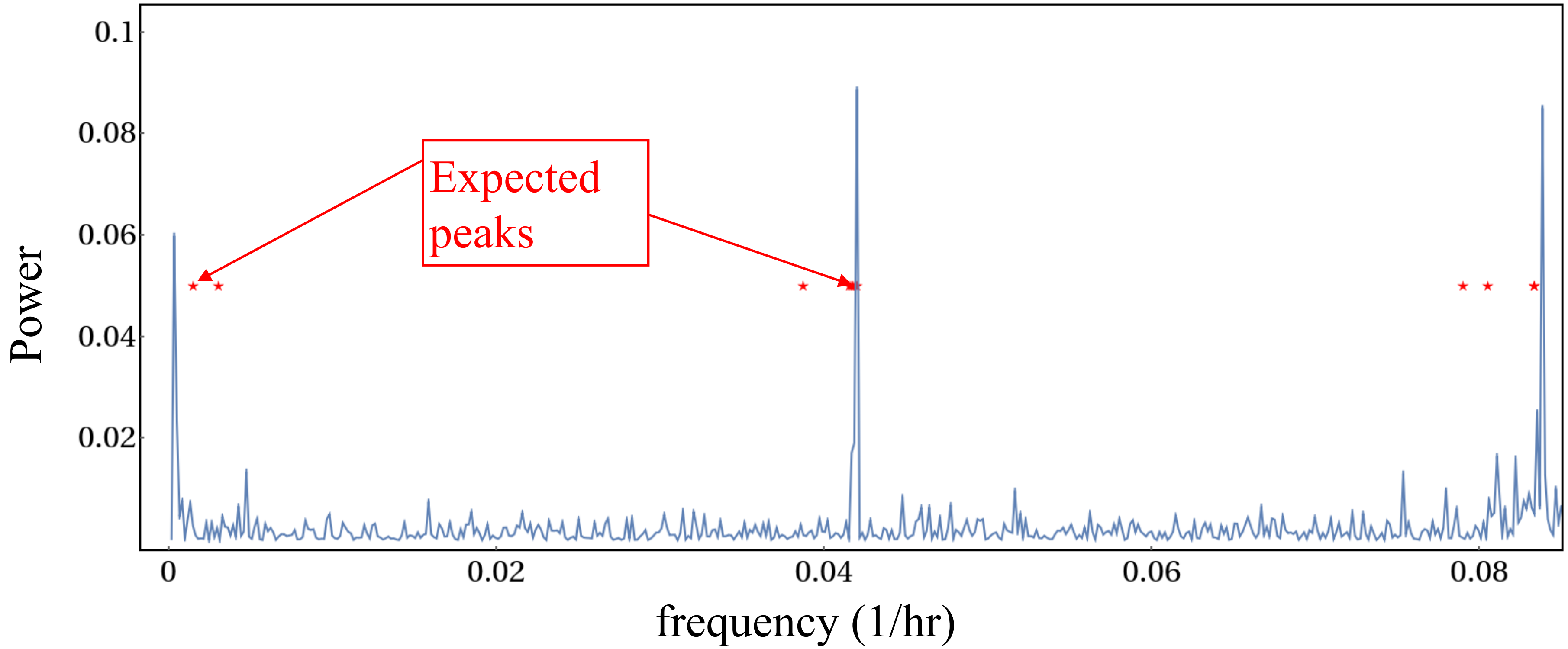




Precise point positioning using GPS code and carrier phase

[Zumberge, J et al., *Geophys. Res., 102(B3), 5005-5017,* 1997]

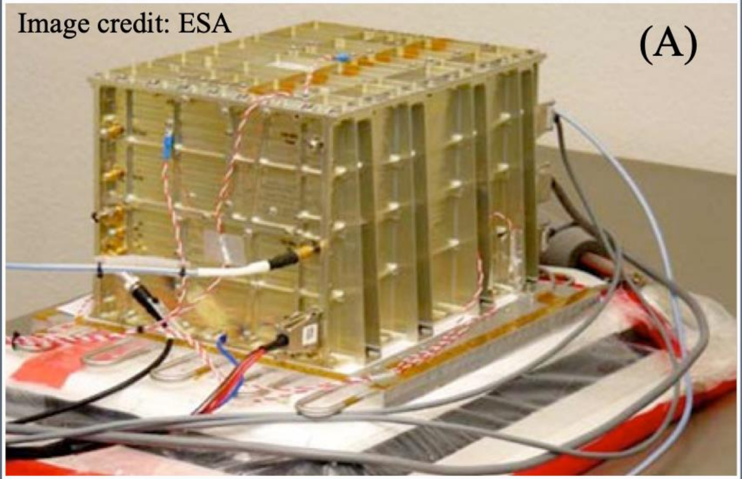
Studying Earth tide models



Spectral decomposition with some of the known peaks identified

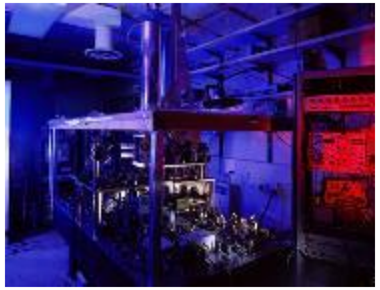
Atomic Clock Ensemble in Space (ACES)

✦Time and frequency transfer studies (stability: $10^{-13}/\sqrt{\tau}, \tau$ →integration time, accuracy ~ 10^{-16})
✦ Tests of general relativity (gravitational redshift)
✦ Scheduled launch to ISS in mid 2021 on SpaceX-23



Carrier frequency: 13.5 GHz (up),14.7 GHz (down)
PN-code modulation: 100 Mcps
Reference signal 100 MHz, UTC (k) , 1pps
4 channel; dual frequency

The rise of the planet of the clocks



The SI Second is really important!

Most accurately realized SI unit ($<1 \times 10^{-15}$)

Other units depend on time (length, ampere, candela)

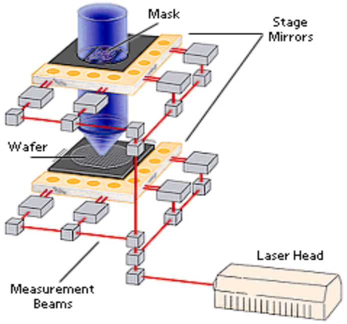
Two more? (kilogram, mole)

Precision metrology and fundamental science

Tests of fundamental physics

Improved timing for high energy physics/astronomy

Searches for new physics



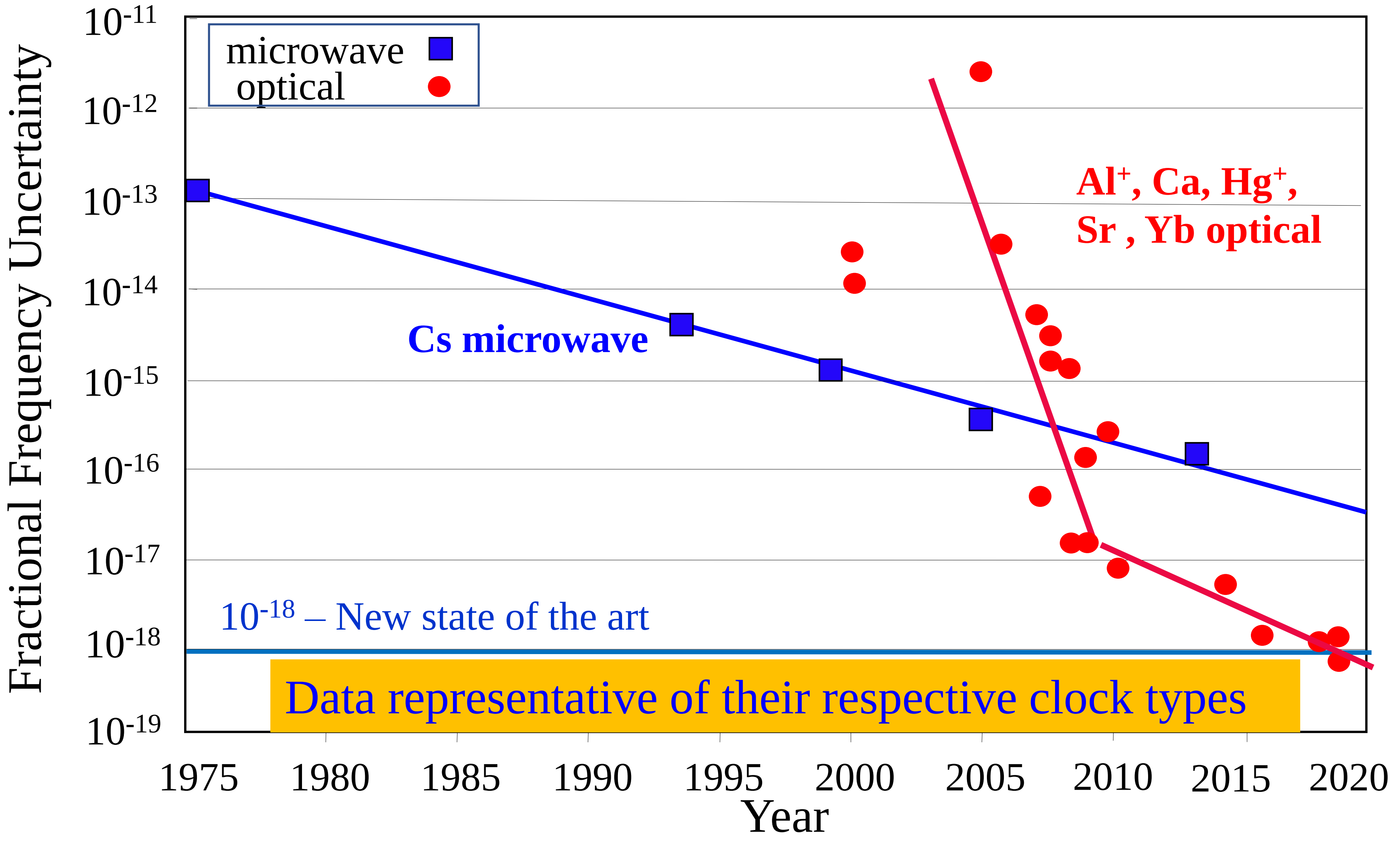
Advanced clocks will support advanced applications

Enhanced timing capabilities: femtoseconds vs. picoseconds

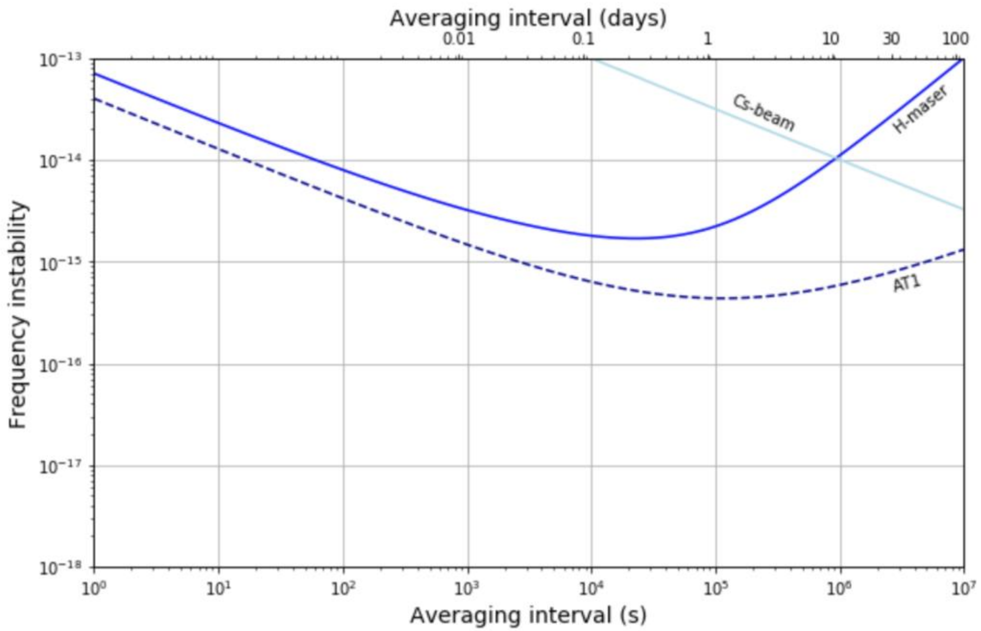
Navigation (ultra GPS) systems

Sensors, a new type of geodesy?

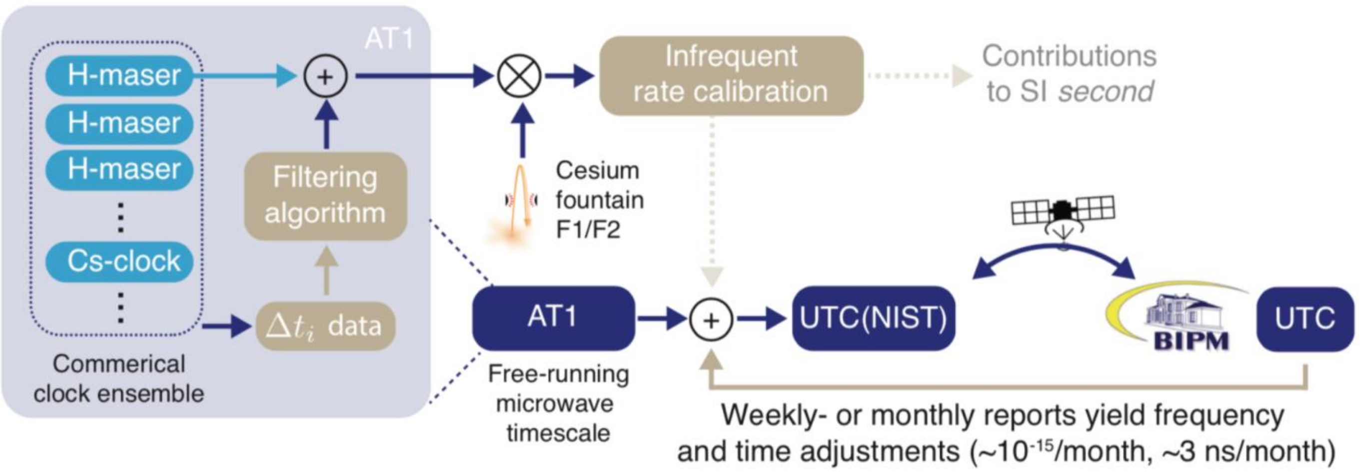
Evolution of Atomic Clocks: Microwave to Optical



NIST Timescale: Incorporating an optical standard



- AT1 timescale: mainly H masers
- Ensemble frac. freq. stability ~E-15 over few weeks
- Over this duration, accumulated time error ~ few ns
- Steered out using freq. corrections



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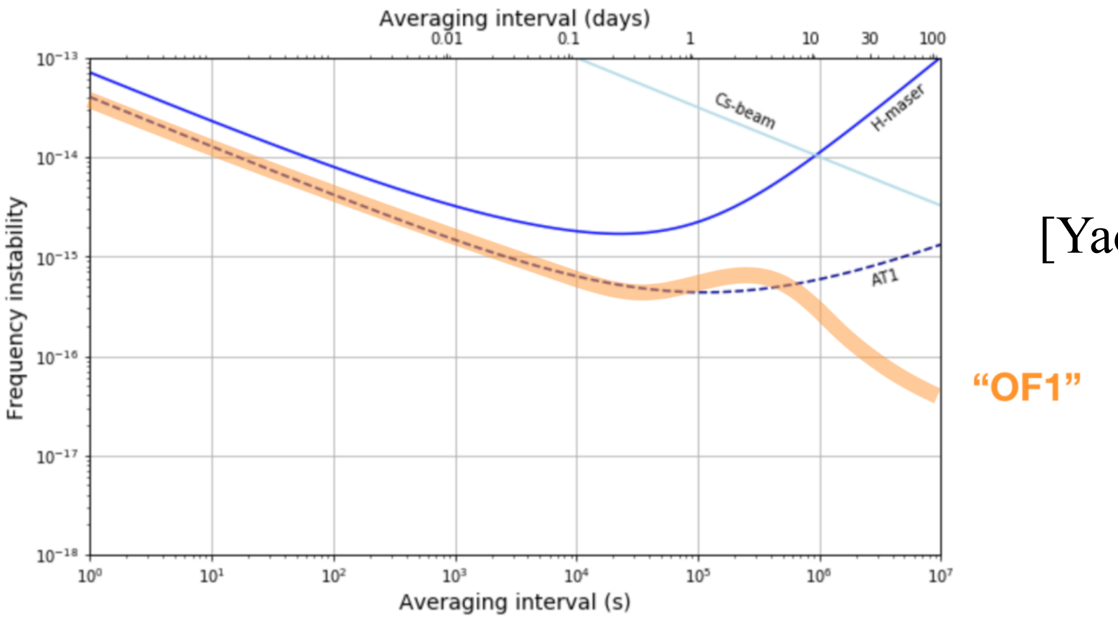
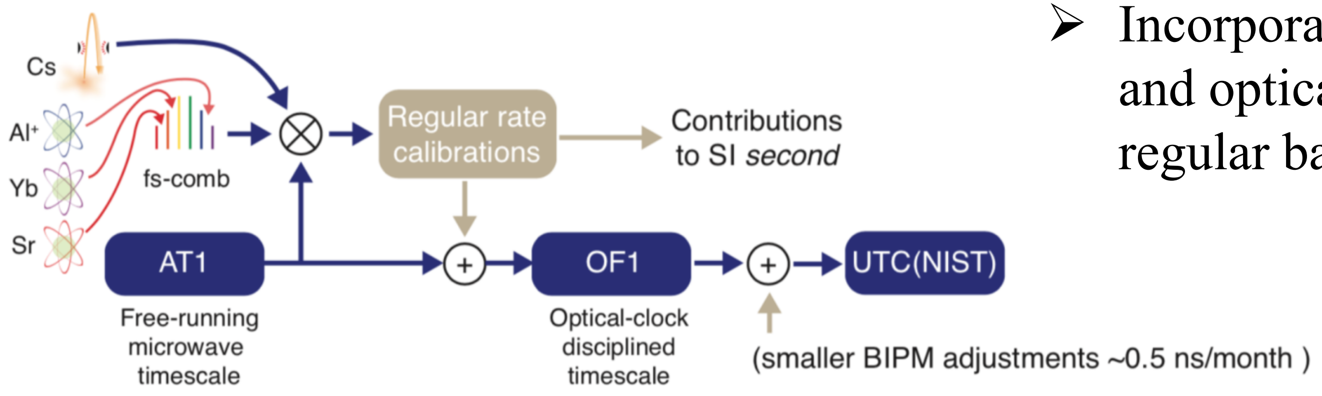


[Yao et al. *Phys. Rev. Applied* 12, 044069 (2019)]



Goals for next generation Timescale:

- Semi-autonomous operation of optical frequency references and optical comb measurement system
- Incorporating a combination of microwave and optical freq. standards on a more regular basis

Acknowledgement

Neil Ashby
Elizabeth Donley
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Judah Levine
Mike Lombardi
Chris Oates
Tom Parker
Joshua Savory
Jeff Sherman
Victor Zhang

More information regarding:

NIST time services
Mike Lombardi (michael.lombardi@nist.gov)

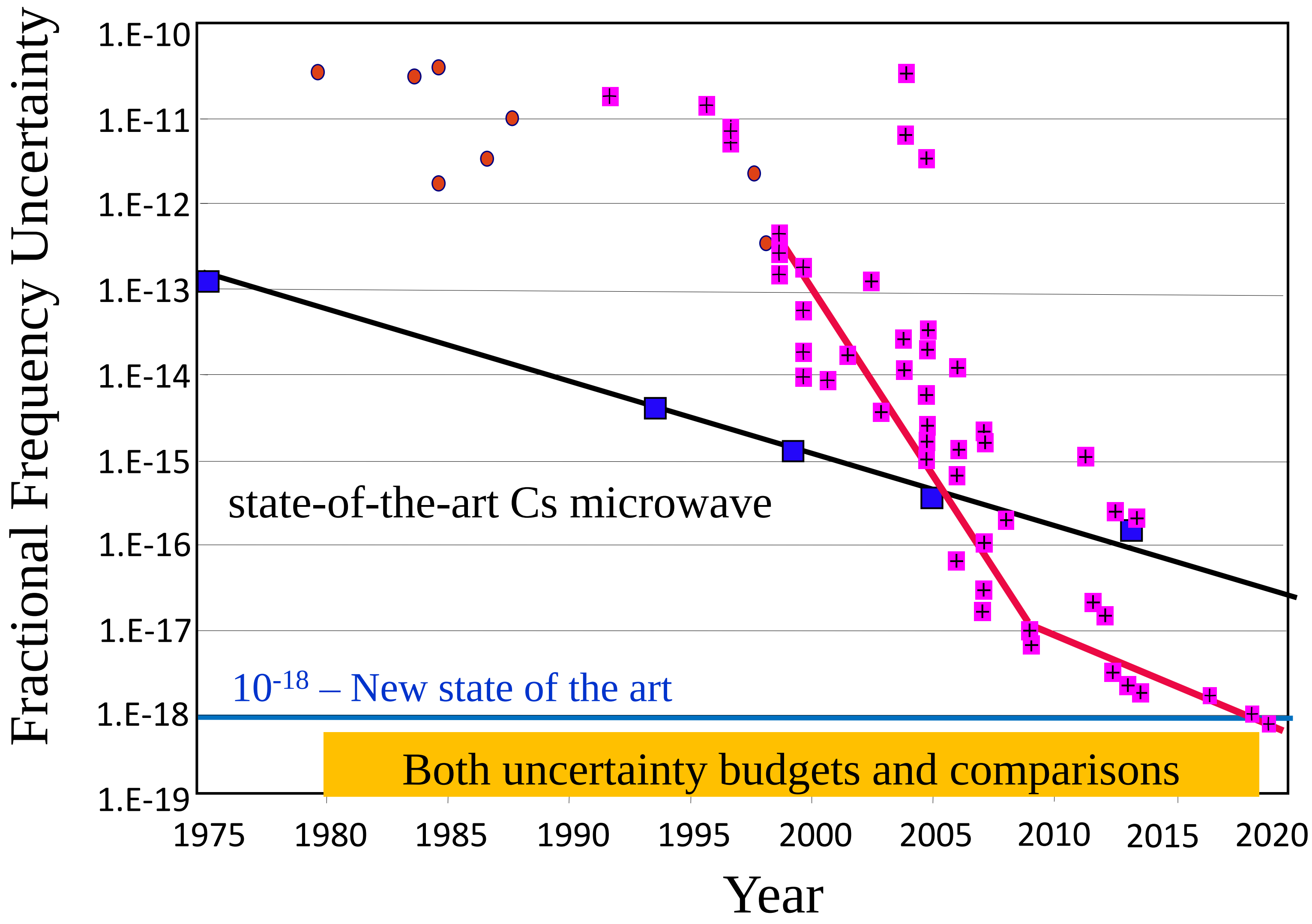
Optical frequency standards
Chris Oates (chris.oates@nist.gov)

NIST timescale
Jeff Sherman (jeff.sherman@nist.gov)

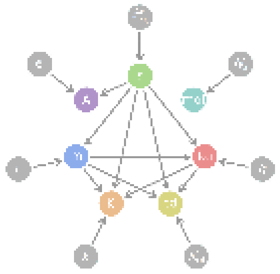
Two-way time transfer
Victor Zhang (victor.zhang@nist.gov)

Backup slides…..

Evolution of Atomic Clocks: Microwave to Optical



Evolution of Atomic Clocks: Microwave to Optical



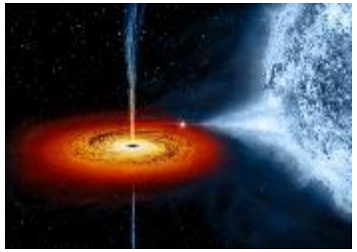
1) Redefining our basic physical units

Looking to redefine the SI second on an optical transition within the next decade

2) Probing new physics

Testing constancy of fundamental constants

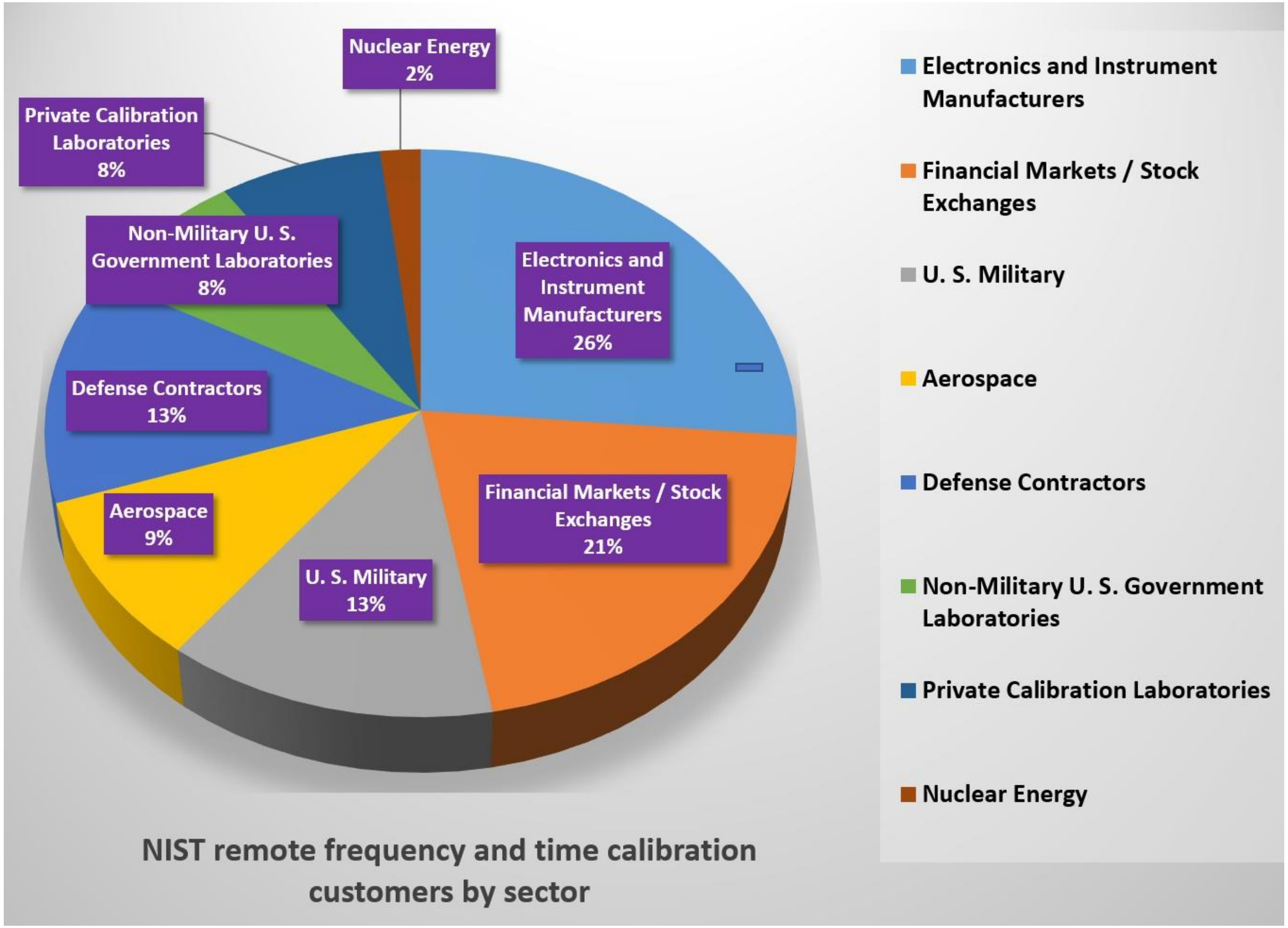
Searching for dark matter



3) Clocks, Einstein, and space

General Relativity – clock frequencies change 10^{-18} for 1 cm altitude change on earth!

Clocks will need to go to space!



Nuclear Energy
2%
Private Calibration
Laboratories
8%
Non-Military U. S.
Government Laboratories
8%
Electronics and
Instrument
Manufacturers
26%
Defense Contractors
13%
Financial Markets / Stock
Exchanges
21%
Aerospace
9%
U. S. Military
13%
Electronics and Instrument Manufacturers
Financial Markets / Stock Exchanges
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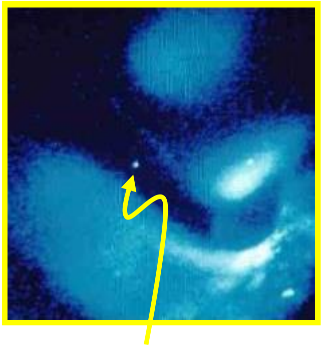
Non-Military U. S. Government Laboratories
Private Calibration Laboratories
Nuclear Energy
NIST remote frequency and time calibration customers by sector

Harmonic traps suppress motional effects, enable long interaction times

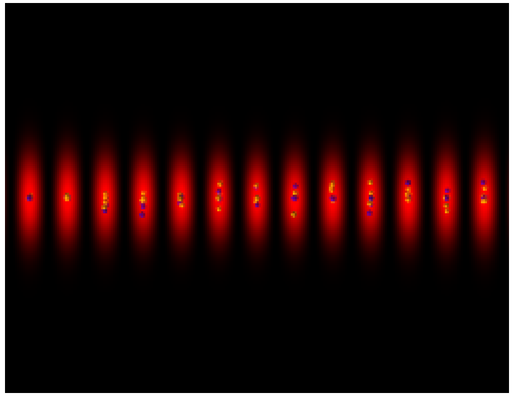
Trapped ions: Al^+, Hg^+, Yb^+, Sr^+, Ca^+



Exc. immunity to environmental effects

Limited S/N ratio – typically one clock ion

Neutral atoms: Sr, Yb, Hg, Ca



Need to use tailored optical lattices in 1, 2, or 3D

(Prof. H. Katori, U of Tokyo)

Good immunity to environmental effects

Potential for very high S/N (N > 10,000)

Dozens of trapped-atom optical clocks worldwide