NIST's unique timekeeping duties as a National Metrology Institute

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NIST Time and Frequency Division
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CGSIC
September 17, 2024

NIST | NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

15 US Code §261:

UTC is "maintained through the General Conference of Weights and Measures and interpreted or modified for the US by the Secretary of Commerce in coordination with the Secretary of the Navy."

Agreement Responsibilities:

USNO:

- Uniquely responsible for providing time and frequency to the DoD.
- Provides the high-stability time scale performance required for demands of DoD applications.

USNO & NIST:

- Coordinate our programs.
- Each maintain the most accurate real-time realization of UTC possible (equivalence < 20 ns.)
- Act independently when necessary

NIST:

- Unique responsibility for realizing the SI units
- Develop frequency standards with high stability & absolute accuracy
- Provide time for civilian applications through measurement services

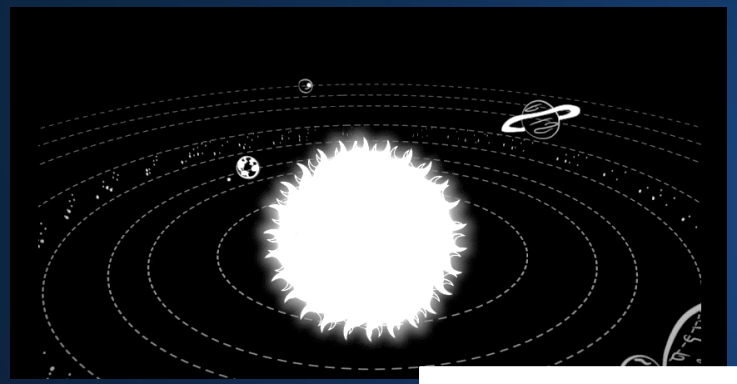
USNO

NIST

Realizing the SI Second

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

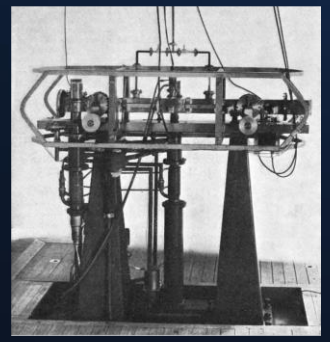
The SI Second



1967: The duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the ^{133}Cs atom

1956: The second is the fraction 1/31 556 925.9747 of the tropical year for 1900 ….

1950 1960 1970

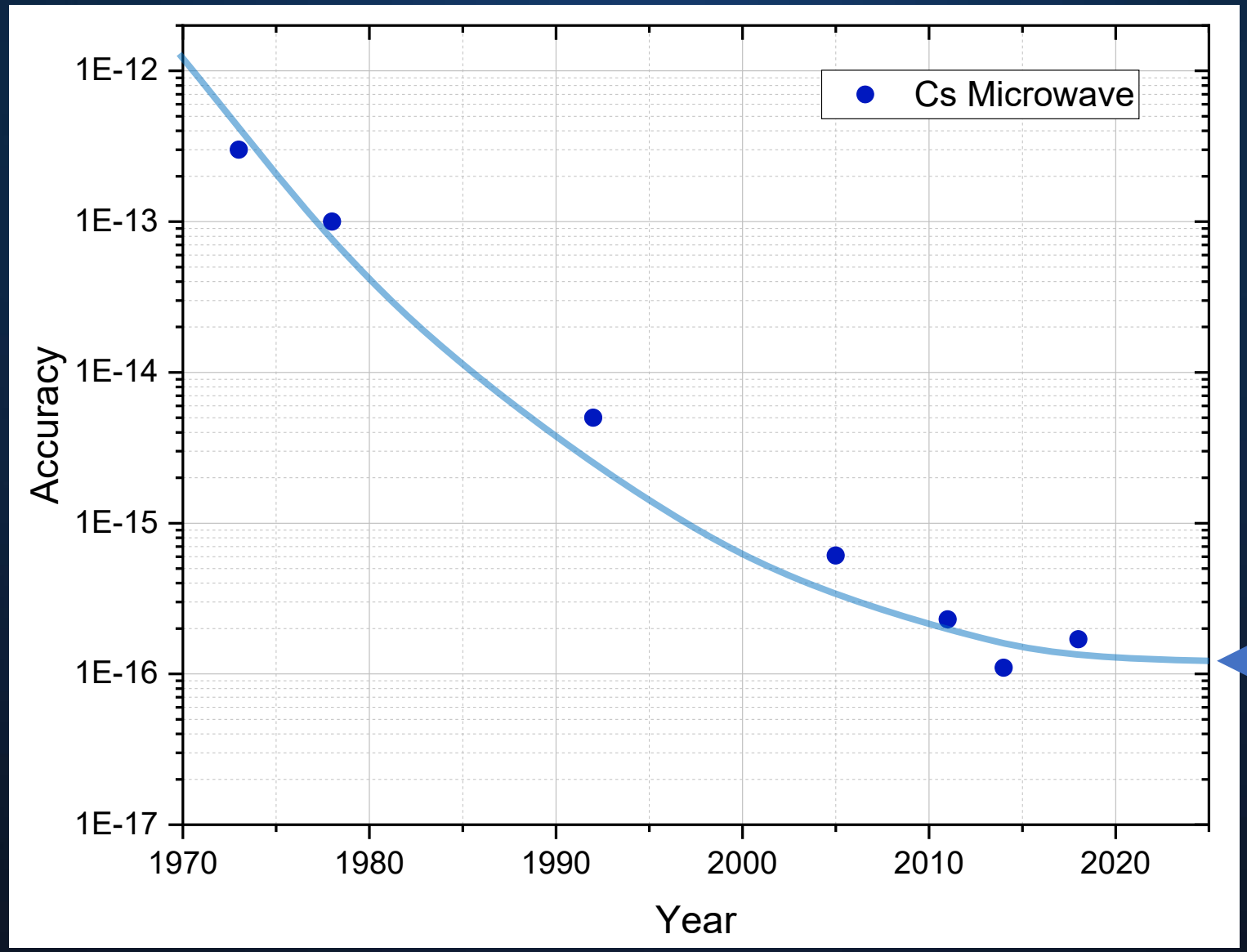


AN ATOMIC STANDARD OF FREQUENCY AND TIME INTERVAL

L. Essen
J. V. L. Parry

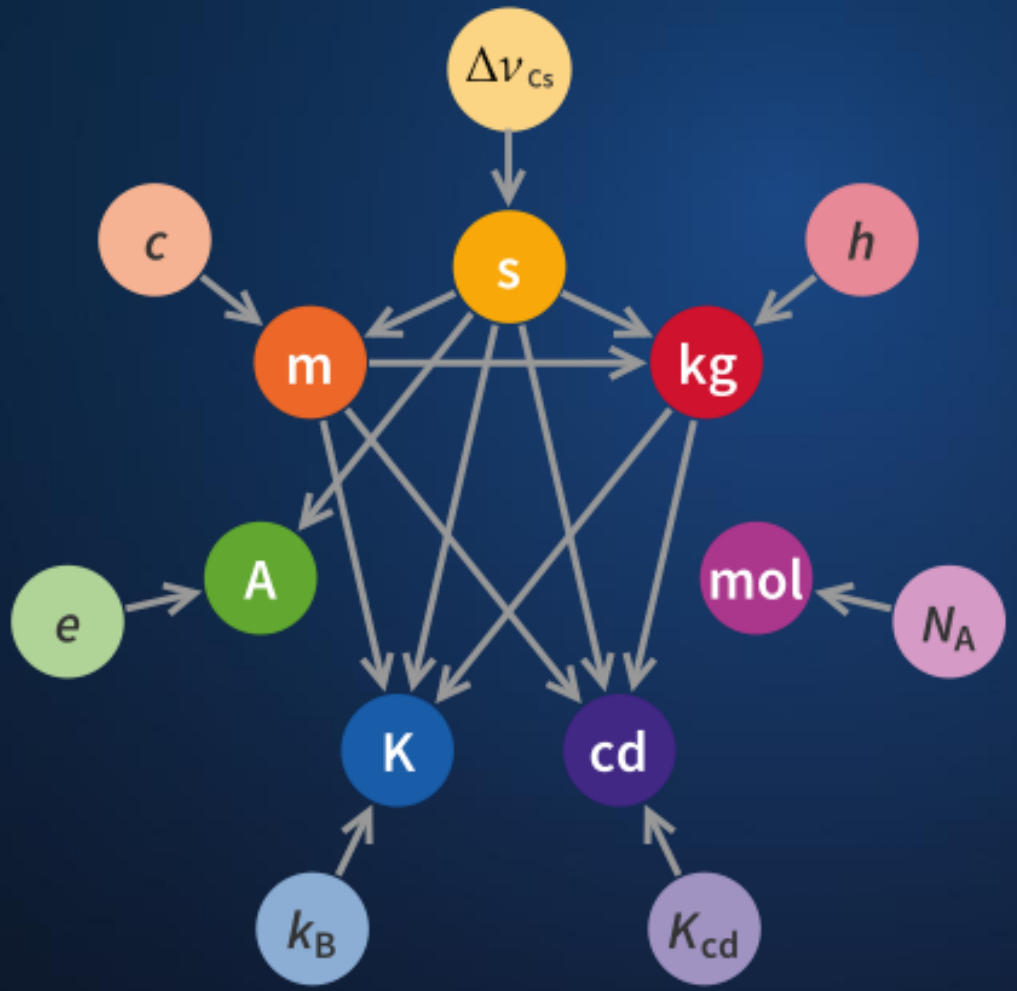
No. 4476 August 13, 1955 NATURE

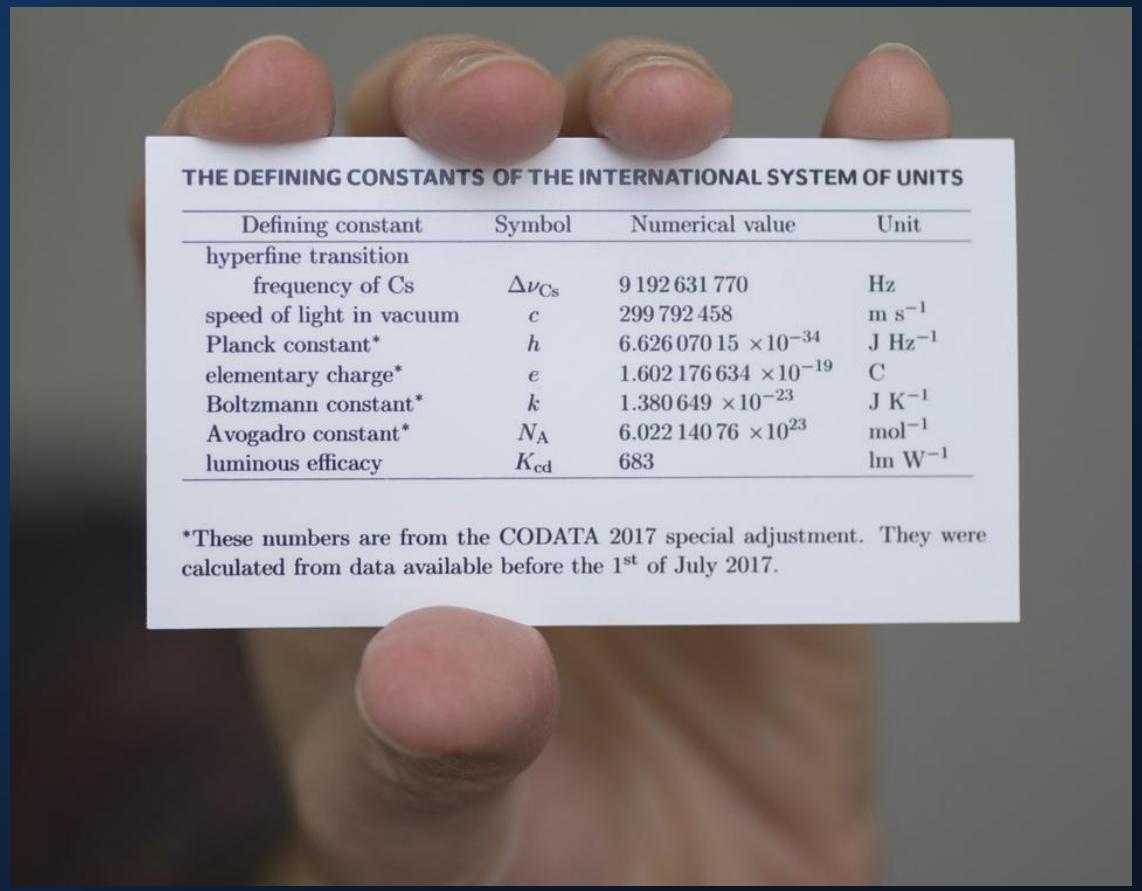
Accuracy of atomic frequency standards



10,000× lower relative uncertainty than next best SI unit (the meter)

The Second in the SI





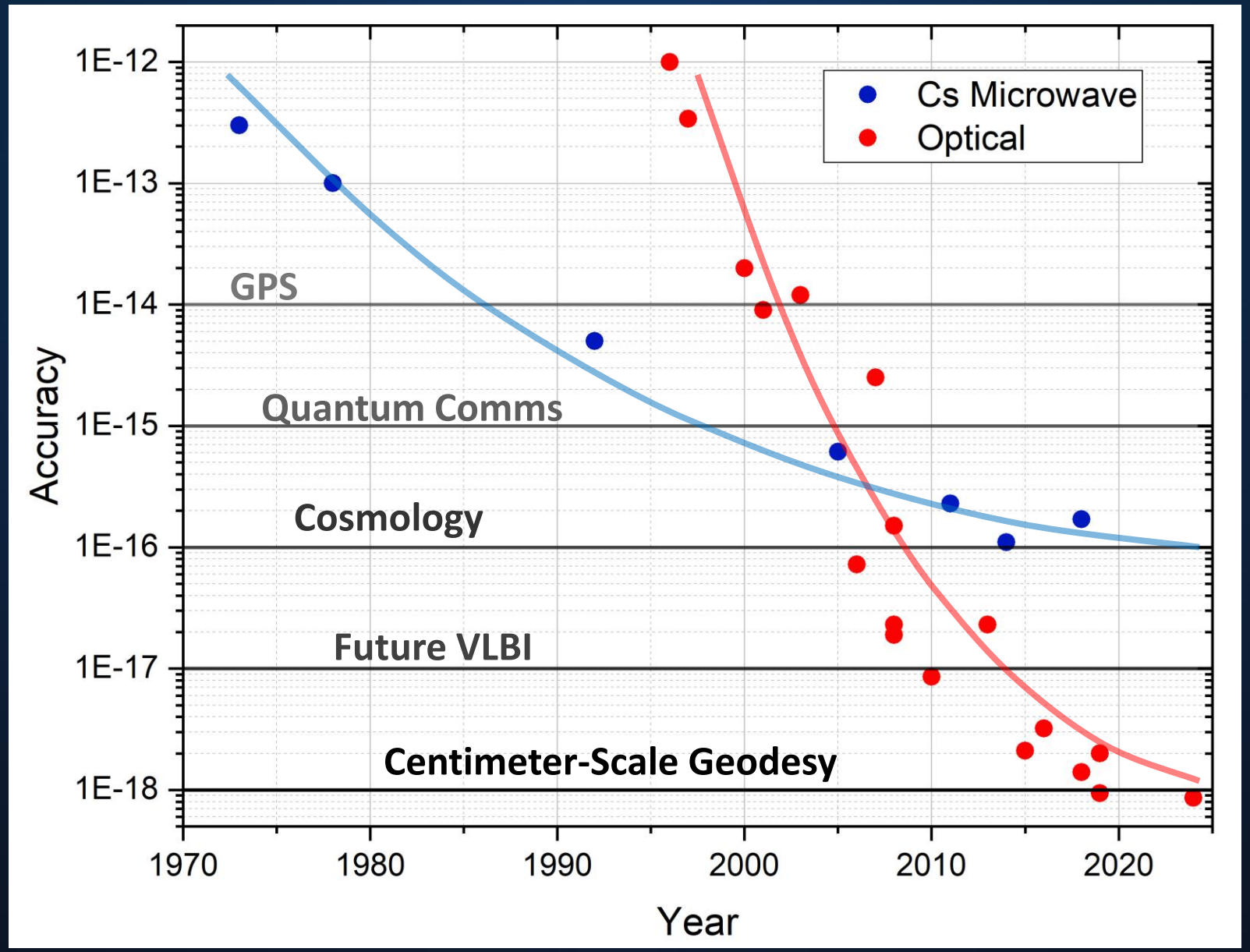
THE DEFINING CONSTANTS OF THE INTERNATIONAL SYSTEM OF UNITS

Defining constant	Symbol	Numerical value	Unit
hyperfine transition frequency of Cs	$\Delta\nu_{Cs}$	9 192 631 770	Hz
speed of light in vacuum	c	299 792 458	m s^{-1}
Planck constant*	h	$6.626\,070\,15 \times 10^{-34}$	J Hz^{-1}
elementary charge*	e	$1.602\,176\,634 \times 10^{-19}$	C
Boltzmann constant*	k	$1.380\,649 \times 10^{-23}$	J K^{-1}
Avogadro constant*	N_A	$6.022\,140\,76 \times 10^{23}$	mol^{-1}
luminous efficacy	K_{cd}	683	lm W^{-1}

*These numbers are from the CODATA 2017 special adjustment. They were calculated from data available before the 1st of July 2017.

The SI Second underpins most dimensional metrology

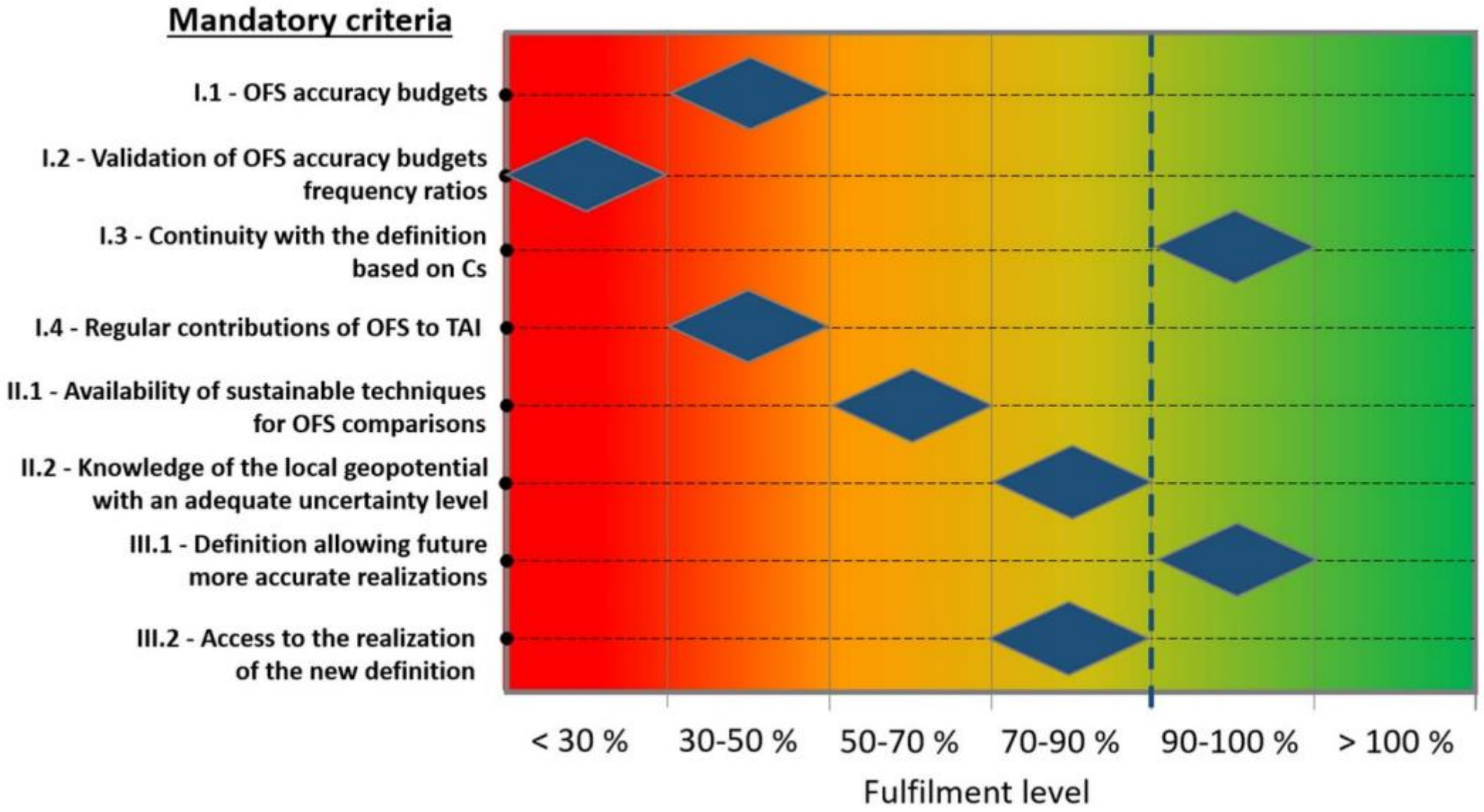
Accuracy of atomic frequency standards



Limit to the SI “Hz” as defined in terms of Cesium-133

Criteria & Conditions to Change the Definition

Dimarcq et al. “Roadmap towards the redefinition of the second,” *Metrologia* 61, 2024



Time Realization

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

Atomic Time Scales

NATIONAL BUREAU OF STANDARDS REPORT

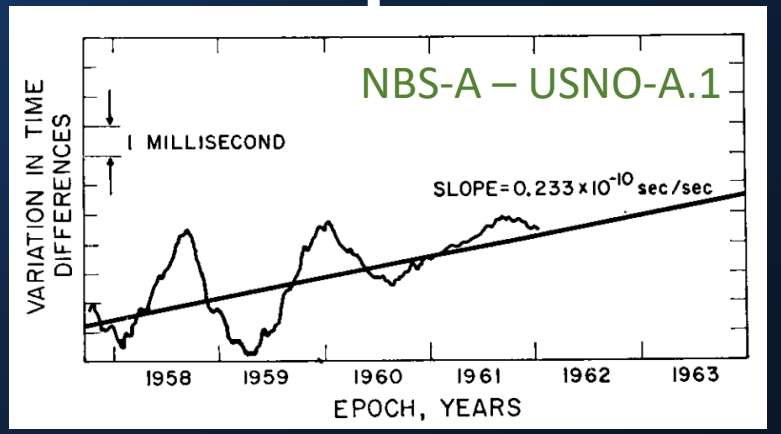
NBS PROJECT 8400-12-84104 | October 5, 1959 | NBS REPORT 6075

*AN EVALUATION OF A CESIUM BEAM FREQUENCY STANDARD

R. C. Mockler, R. E. Beehler, and J. A. Barnes

1955 1960 1965

January 1, 1958: NBS and USNO Atomic Time Scales made coincident



Proc. IEEE 51, 1963:

It would have taken 100 years before the relative errors would be as large as the best measurements of astronomical time.

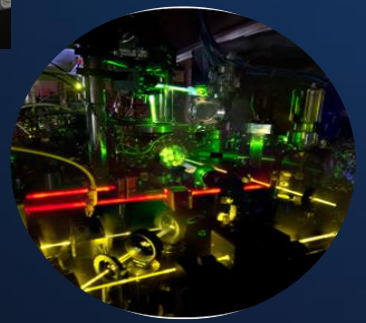
Frequency Evaluations
(up to monthly)

International Time &
Frequency Coordination

Primary & Secondary
Frequency Standards

NIST-F4

NIST-F3
Hoth, PTTI
(2023)



Yb1: McGrew,
Optica (2019)

The UTC(NIST) Time Scale

Daily Clock Data

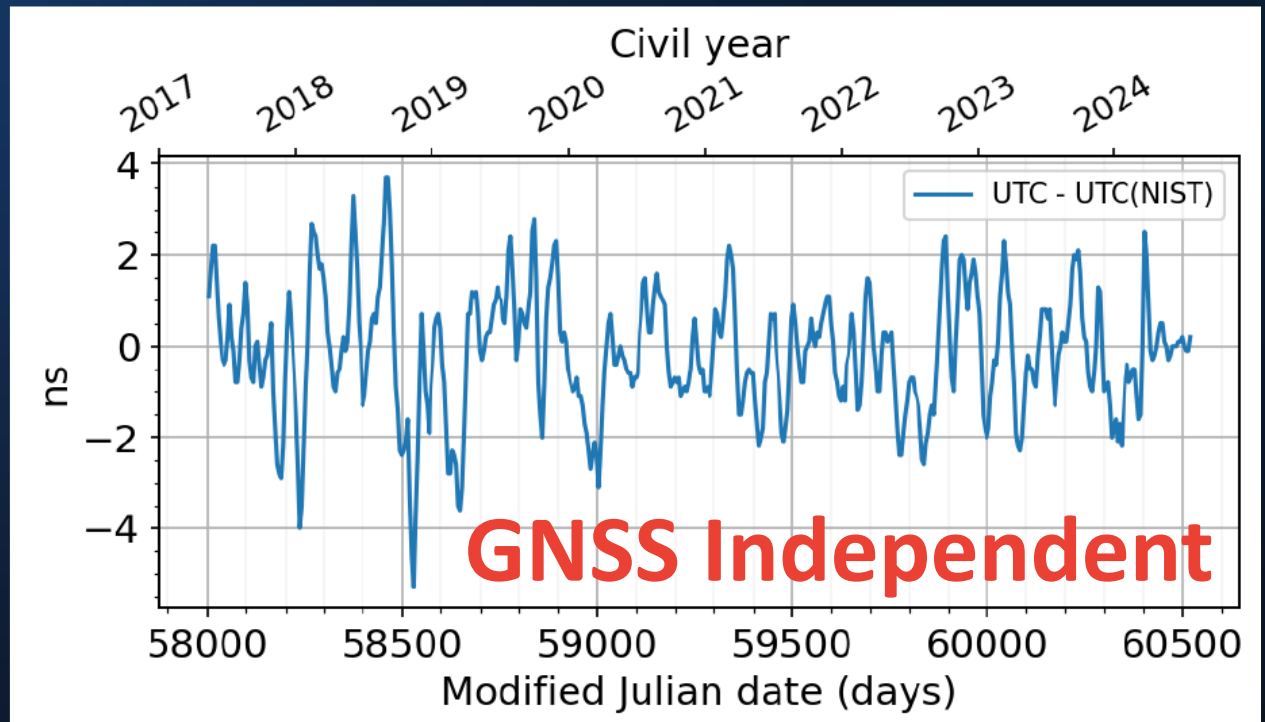
BIPM

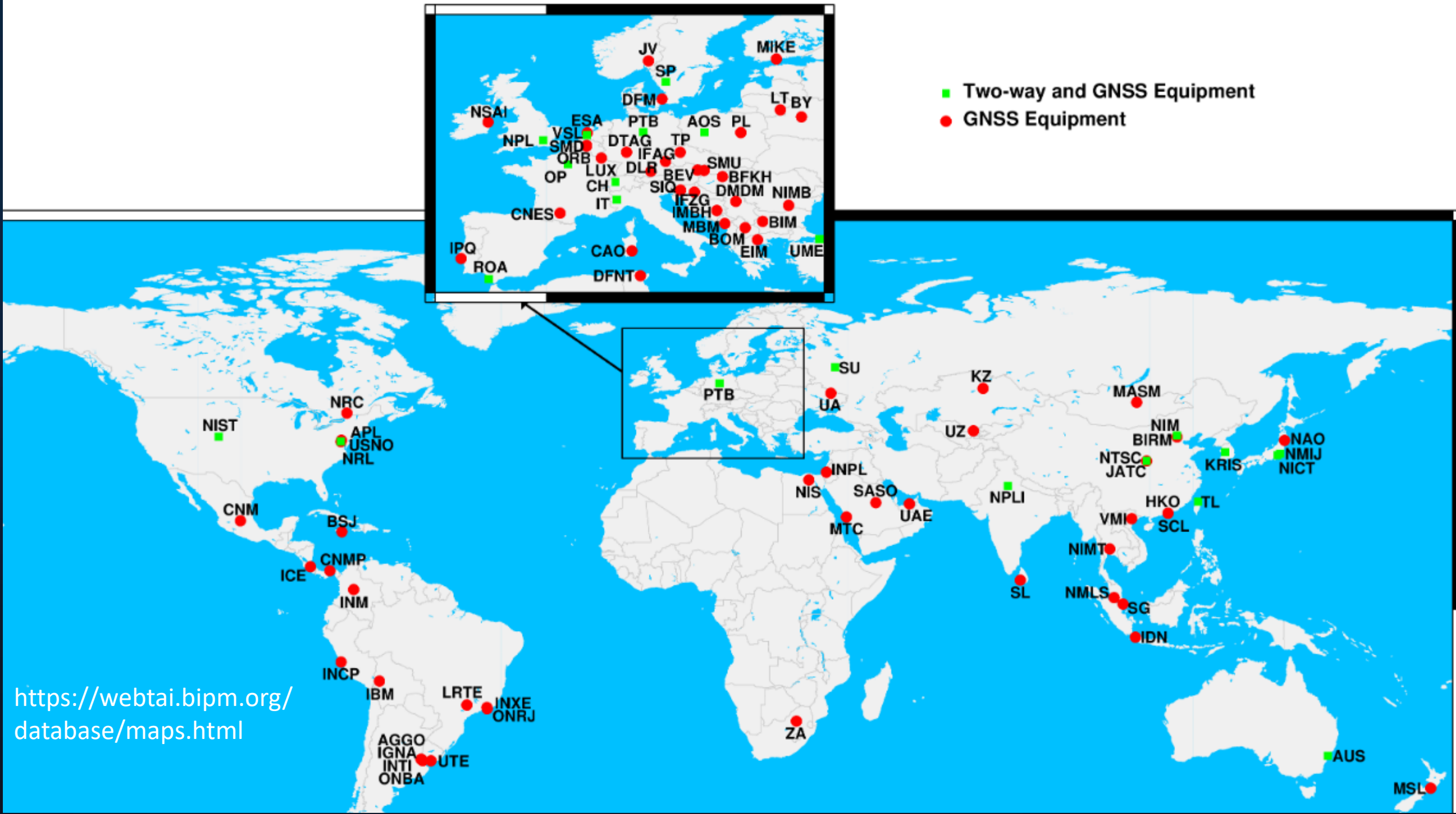
1e-15 freq. steers

Primary & secondary frequency standards

Clock Ensemble

Clock Difference Data
(weekly in UTCr, monthly in Circular-T)





https://webtai.bipm.org/database/maps.html

Time Distribution

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

The NIST Internet Time Service

$\sigma_x(\tau) = 10\ ms$

120 Billion daily NTP responses

Provides sync for between 500M and 1B computers daily.

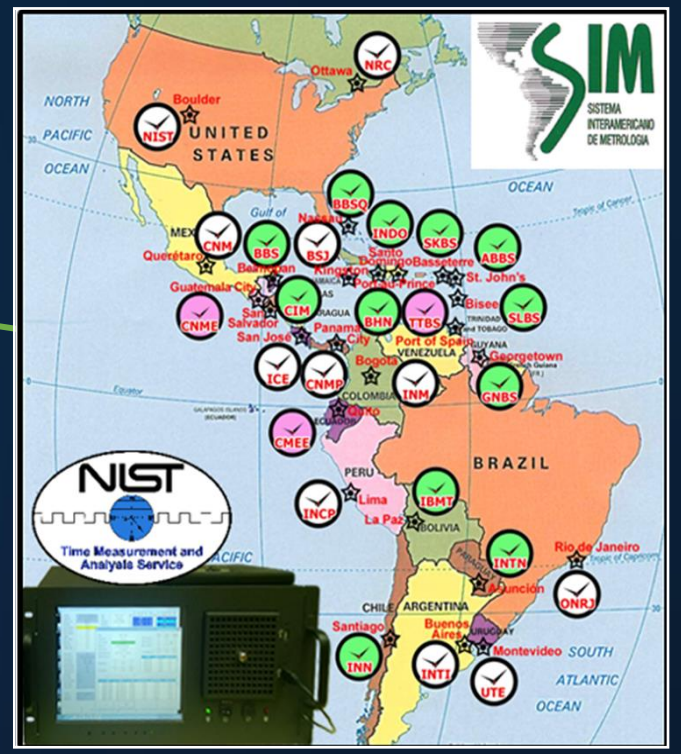
UTC(NIST)

Standard Radio Broadcasts

$\sigma_x(\tau) = 1\ ms$ *(WWV/WWVH)*

$\sigma_x(\tau) = 100\ \mu s$ *(WWVB)*

100 Million daily customers?



Remote Calibration Services (GPS Common View)

$\sigma_x(\tau) = 10\ ns$

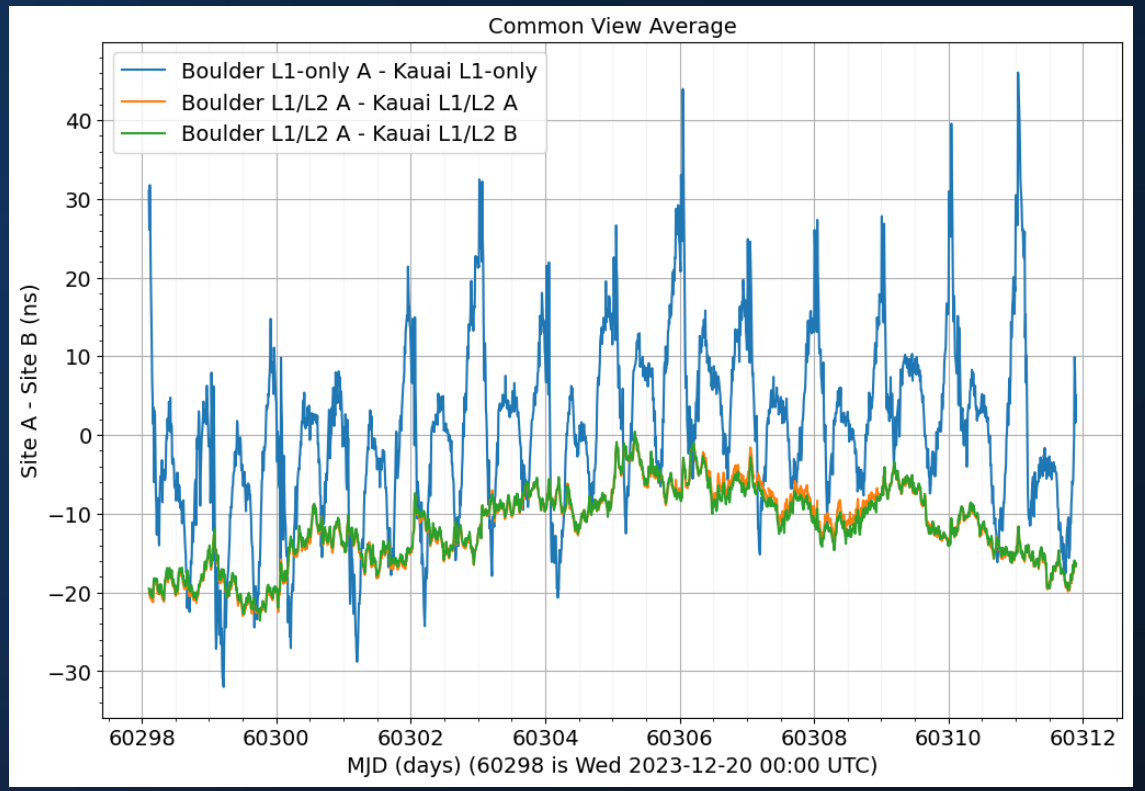
~60 customers

Time Measurement Analysis Service (TMAS)
GPS Common View

We build and calibrate the hardware and ship it to customers.

After a simple installation, the customer receives a steam of data with time differences between their local clock and UTC(NIST).

Recent upgrade to low-cost dual-frequency GPS Receiver reduces errors from ionosphere and coordinate errors



Very long baseline >5000 km (WWVH)
TDEV at 1 day ~1.6 ns

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U.S. DEPARTMENT OF COMMERCE

Contact: Andrew.Novick@nist.gov

GNSS Independent Timing Efforts

EO 13905 directs NIST to:

"…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."

NATIONAL ARCHIVES

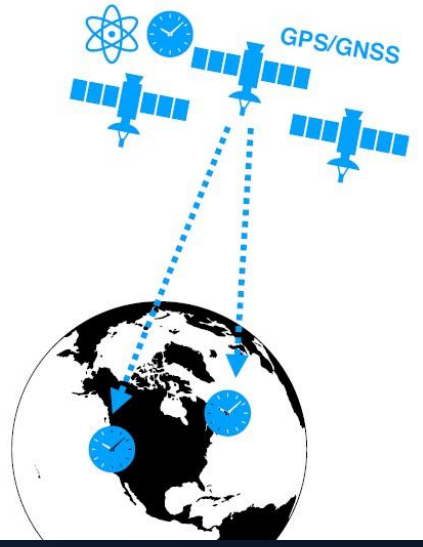
FEDERAL REGISTER

The Daily Journal of the United States Government

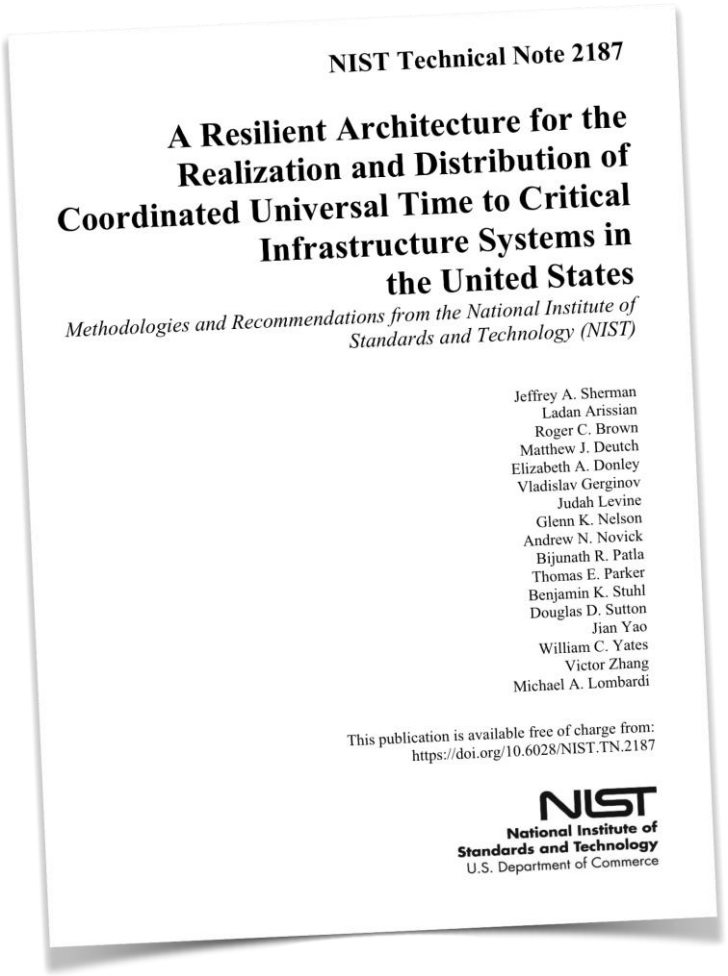
Presidential Document

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

A Presidential Document by the Executive Office of the President on 02/18/2020



Timing for Critical Infrastructure



NIST Technical Note 2187

A Resilient Architecture for the Realization and Distribution of Coordinated Universal Time to Critical Infrastructure Systems in the United States

Methodologies and Recommendations from the National Institute of Standards and Technology (NIST)

Jeffrey A. Sherman
Ladan Arissian
Roger C. Brown
Matthew J. Deutch
Elizabeth A. Donley
Vladislav Gerginov
Judah Levine
Glenn K. Nelson
Andrew N. Novick
Bijunath R. Patla
Thomas E. Parker
Benjamin K. Stuhl
Douglas D. Sutton
Jian Yao
William C. Yates
Victor Zhang
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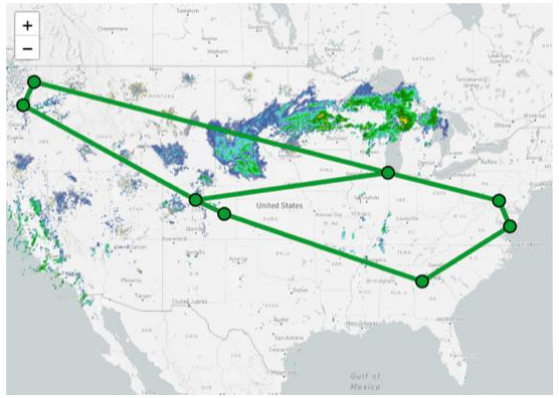
This publication is available free of charge from:
https://doi.org/10.6028/NIST.TN.2187

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



Time over Fiber (Conceptual Illustration)

$\sigma_x(\tau) = 50\ ns$

2 customers so far, 3 connections to Boulder & Gaithersburg

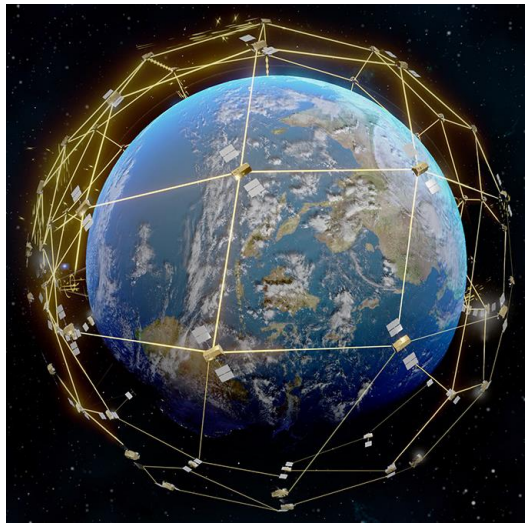
Judah.Levine@nist.gov

Two-Way Satellite Time and Frequency Transfer

$\sigma_x(\tau) = 2\ ns$

Two customers in testing

Jeff.Sherman@nist.gov



Real-Time Monitoring of Commercial PNT Services

Bring us your service and we will test it!

Two-Way Satellite Time & Frequency Transfer (TWSTFT)

… sub nanosecond stability for averaging times less than a minute

… still the best method to compare clocks over continental distances

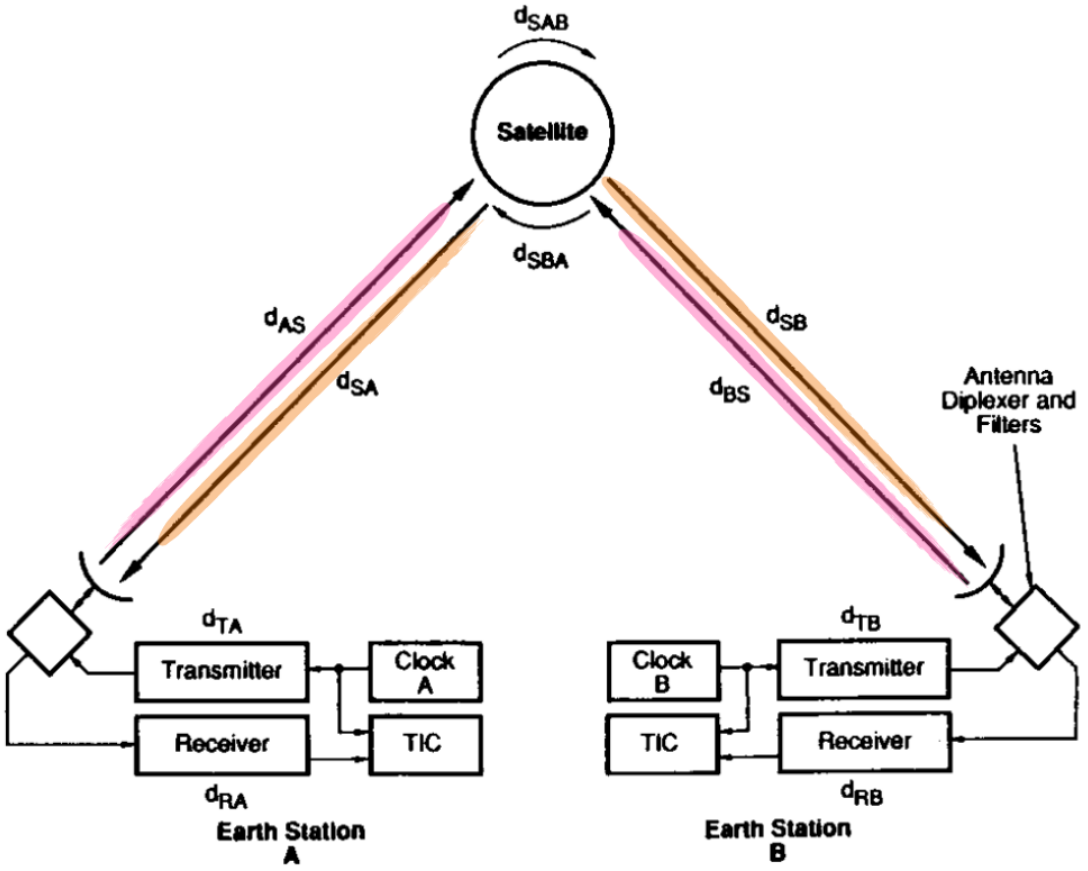
… exploits a high degree of path symmetry – very small asymmetries from ionosphere or other effects

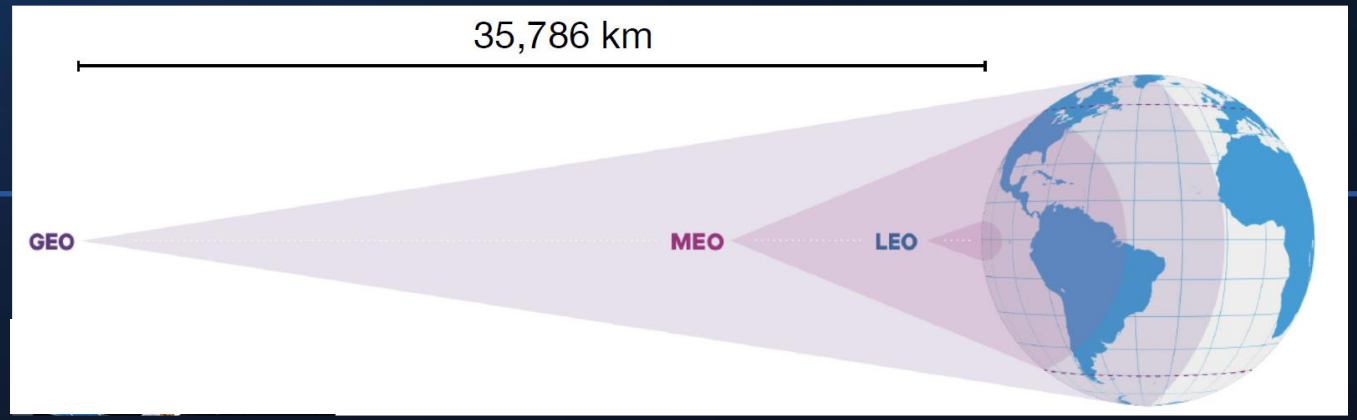
… satellites are in geostationary orbit – hard to jam or spoof

43rd Annual Symposium on Frequency Control - 1989

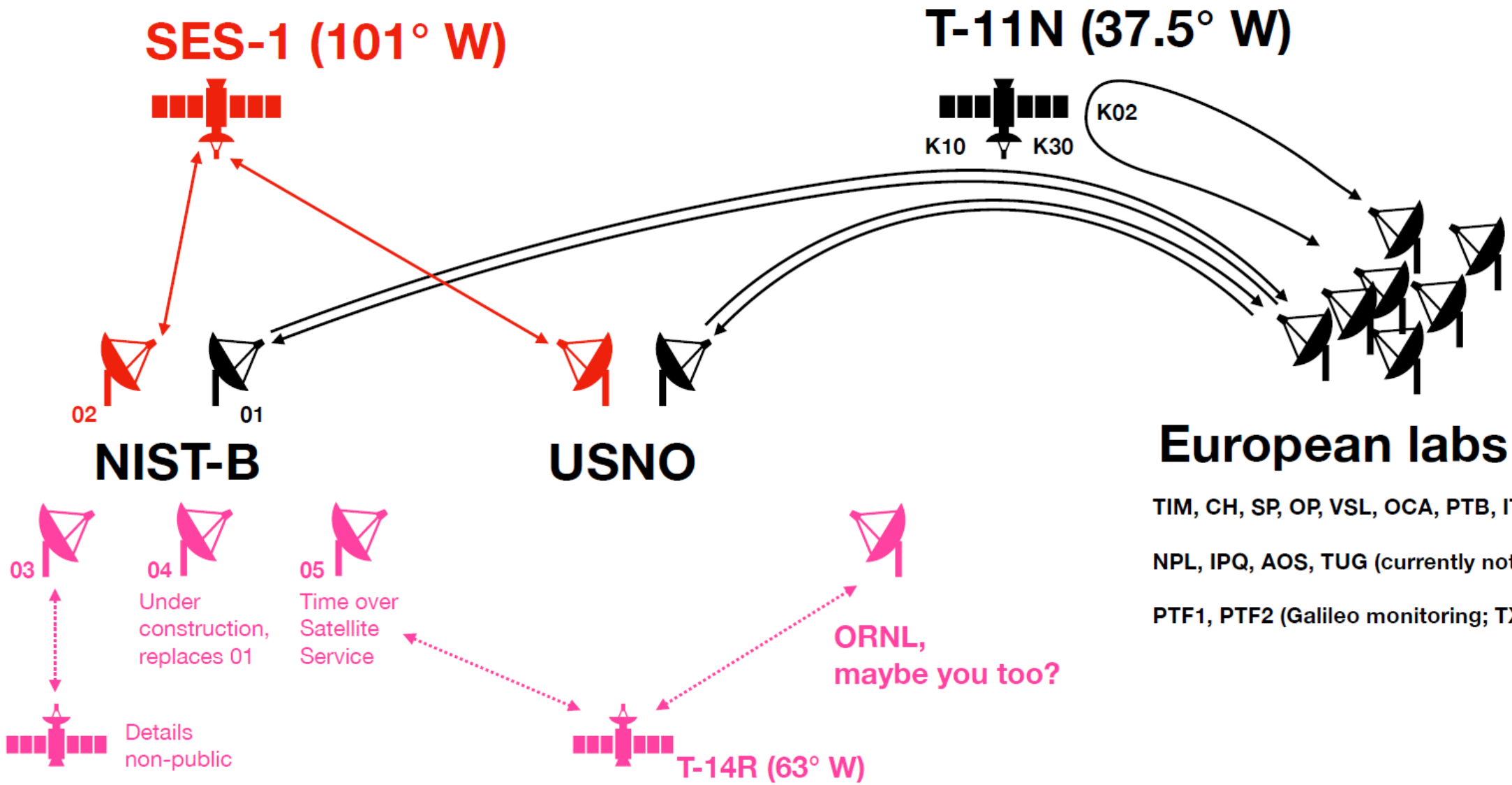
FUNDAMENTALS OF TWO-WAY TIME TRANSFERS BY SATELLITE*

D. W. Hanson
Time and Frequency Division
National Institute of Standards and Technology
325 Broadway
Boulder, Colorado 80303



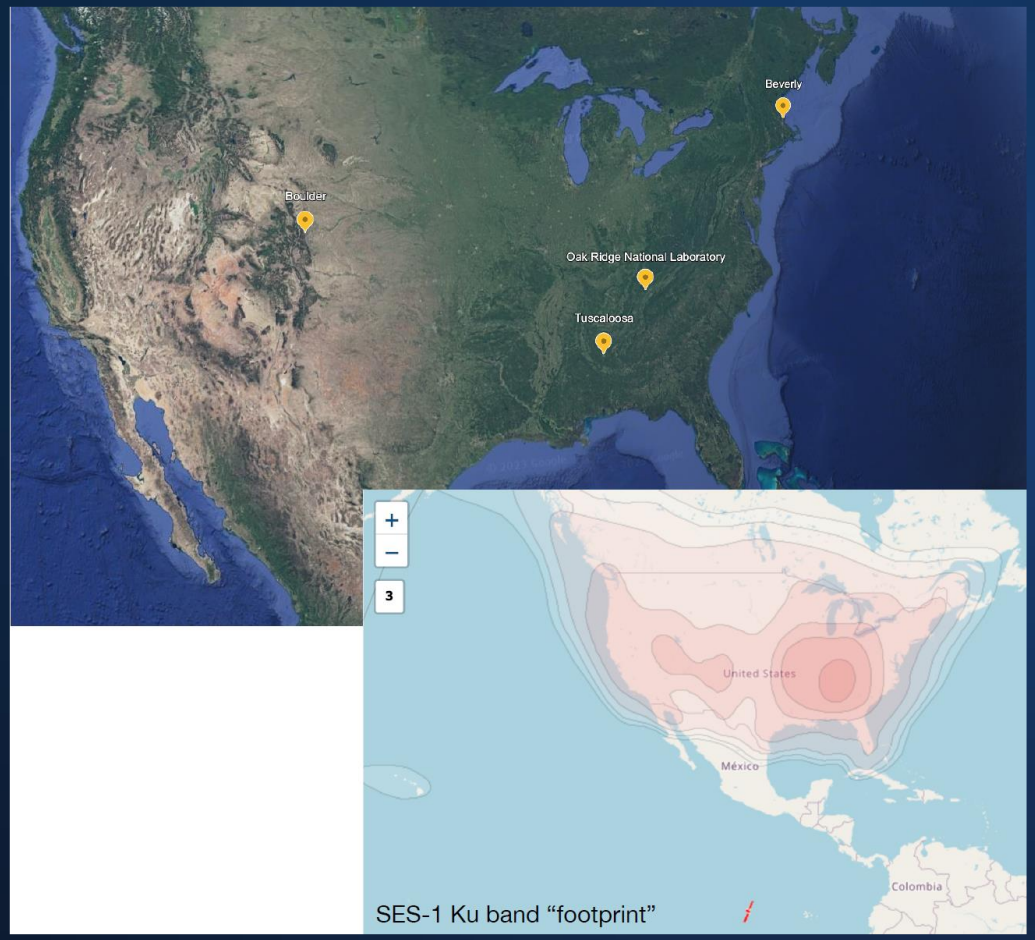


Existing TW satellite links at NIST-Boulder



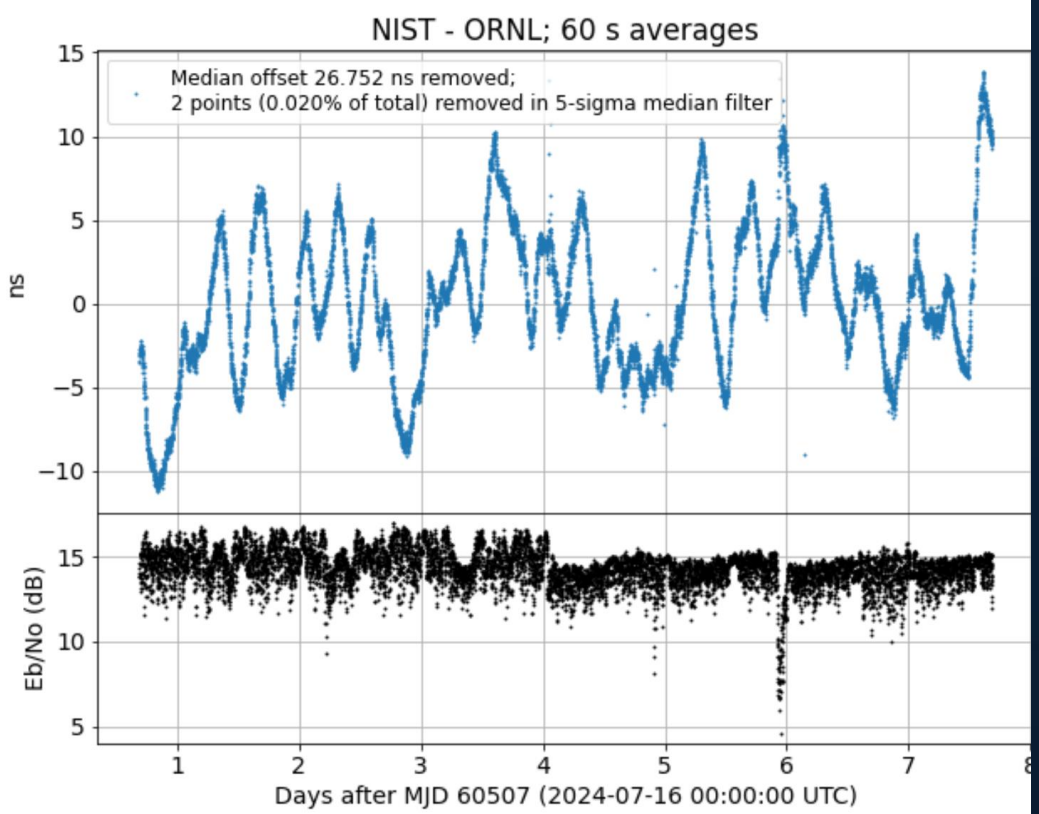
Contact: Jeff.Sherman@nist.gov

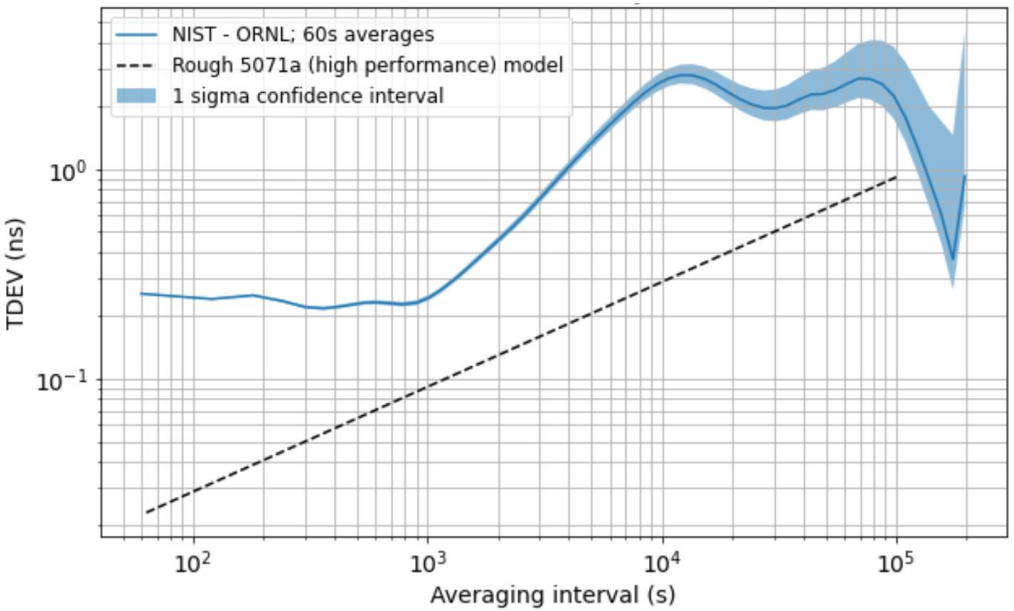
TWSTFT Test Network



Five participating stations:

- NIST (Boulder, CO)
- Oak Ridge National Lab (near Knoxville, TN)
- Microchip (Boulder, CO Beverly, MA Tuscaloosa, AL)





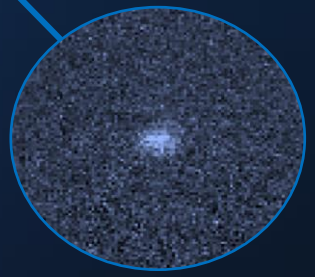
Timekeeping R&D

Chip-Scale Atomic Clocks & Sensors – Smaller, lower power

Lunar Timing Standards – Lending expertise in relativity and time scales

Photo: NASA

Optical Lattice Clocks – Record Frequency Stability



Single-ion Sr+ Clock – Optical Timekeeping in a liter-scale system

Thank you!

Boulder Time Realization and Distribution Group

Special thanks to Jeff Sherman, Judah Levine, Bijunath Patla, Andrew Novick, and Vladi Gerginov

WWVH, Kauai, HI

Jonathan Hardis (Gaithersburg)

WWV/WWVB, Ft. Collins, CO