GNSS-independent time: sources and activities at NIST

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(image attribution: unknown, https://i.imgur.com/v4xbEz7.jpg)

Importance of GPS/GNSS alternatives for timing

Virtually all industries requiring **≤ 1 μs** inaccuracy rely on distributed GPS/GNSS receivers to some extent.

Communication

Power grid/utilities

Transportation

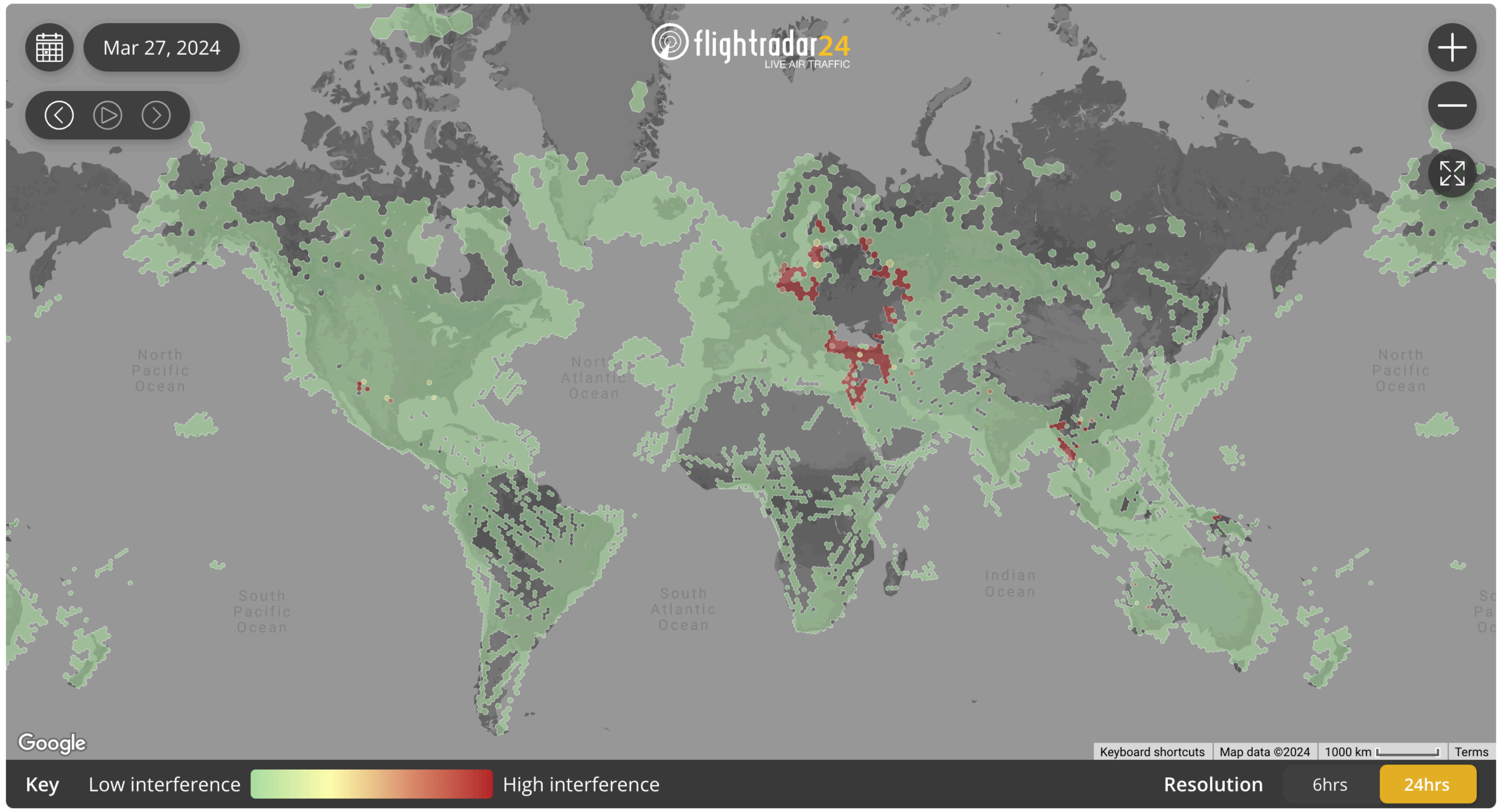
Finance

Agriculture / forecasting
Distributed sensing

GPS/GNSS signals are:

- weak at Earth's surface, jammable,
- spoof-able,
- vulnerable to space weather
- vulnerable to malfunction (e.g. January 2016)
- vulnerable to receiver firmware "bugs"
- constitute a single-point-of-failure for many

Consequences to US economy of a 30-day outage:
> $1B / day loss (50% in telecom) [1]



[1] A. O'Connor et al., "Economic benefits of the global positioning system (GPS)," RTI International, 306 p., June 2019
[2] https://www.flightradar24.com/data/gps-jamming

Executive order 13905 directed NIST:

"…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

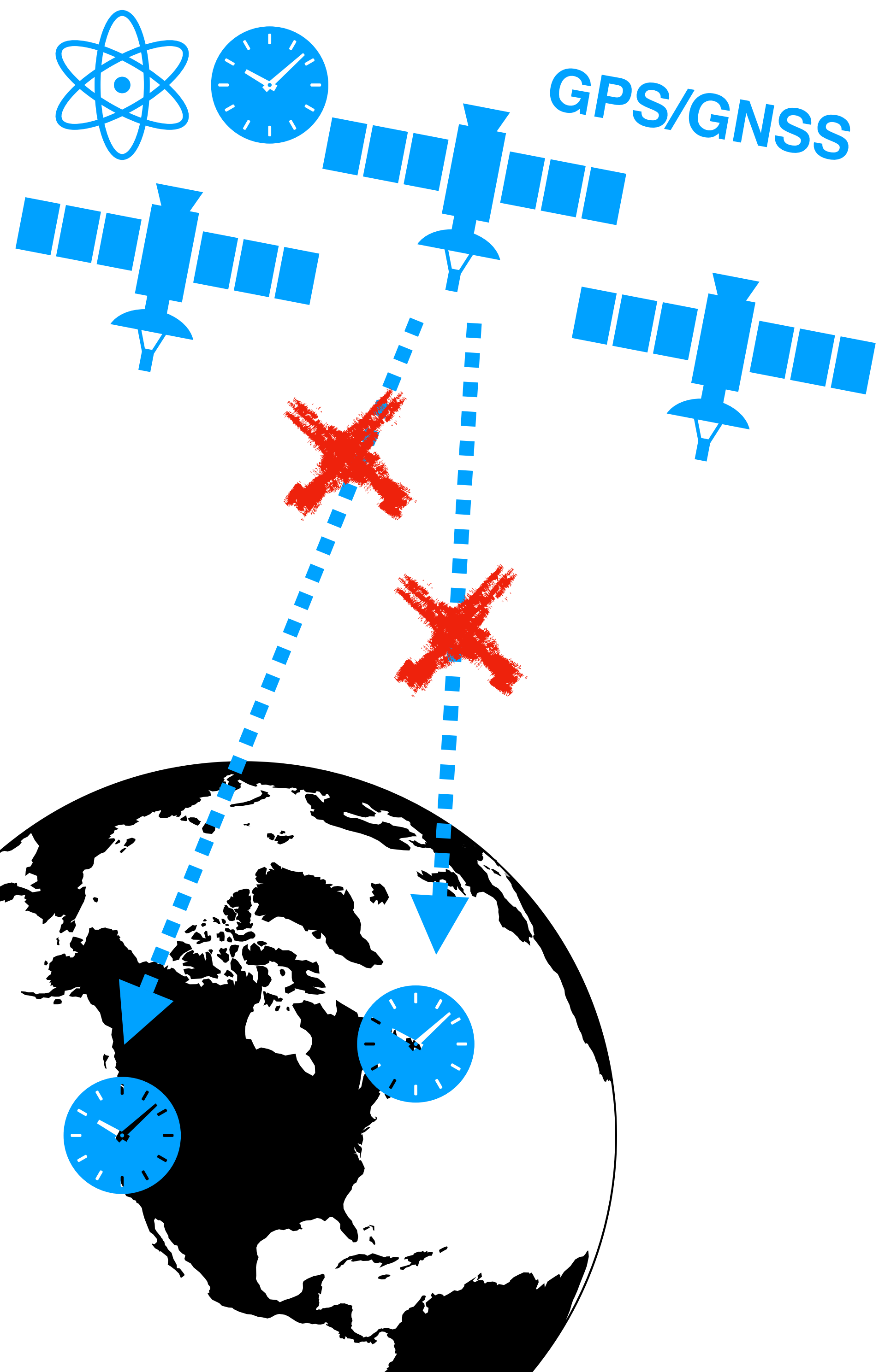
FEDERAL REGISTER

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



Among NIST’s responses to EO 13905

Several publications

Two new fee-based remote calibration services

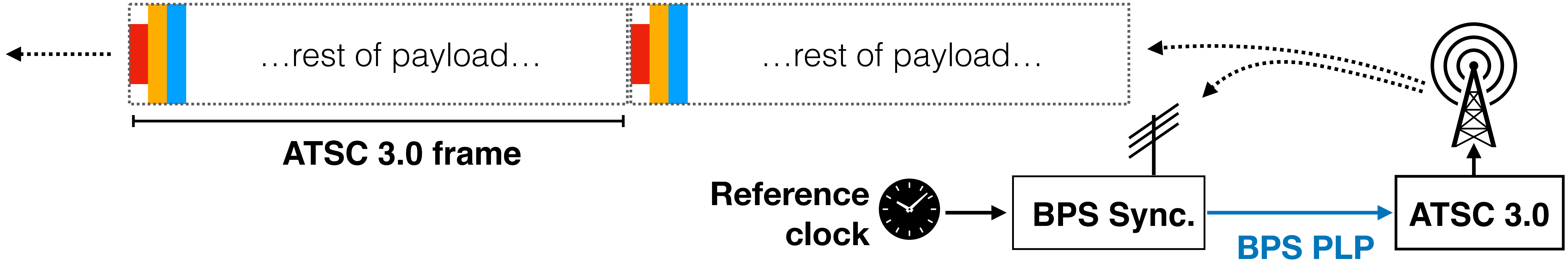
- “Time over Fiber”
- “Time over Satellite”

Cooperate Research & Development Agreements (CRADAs)

- LEO constellation operators
- GEO timing signal/GNSS-augmentation operator
- Terrestrial beacons, advanced WWVB receiver concepts
- ATSC 3.0 (“NextGen TV”) for time transfer

Basis for ATSC 3.0 / Broadcaster Positioning System (BPS) precise time transfer

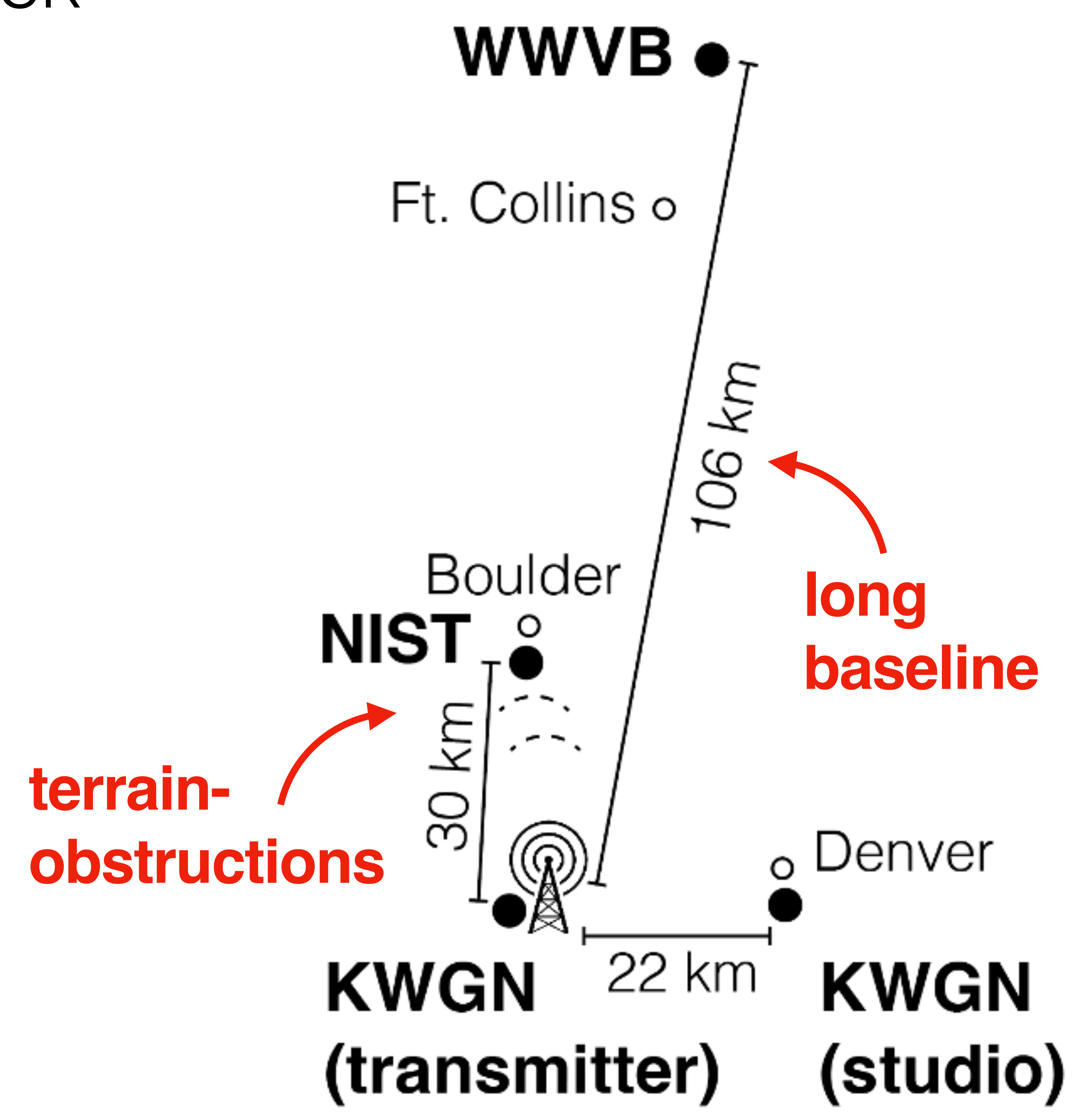
- Time-of-transmission of ATSC 3.0 **bootstrap symbol** encoded in **preamble**; additional data (e.g. transmitter location) in a small **physical layer pipe (PLP)**



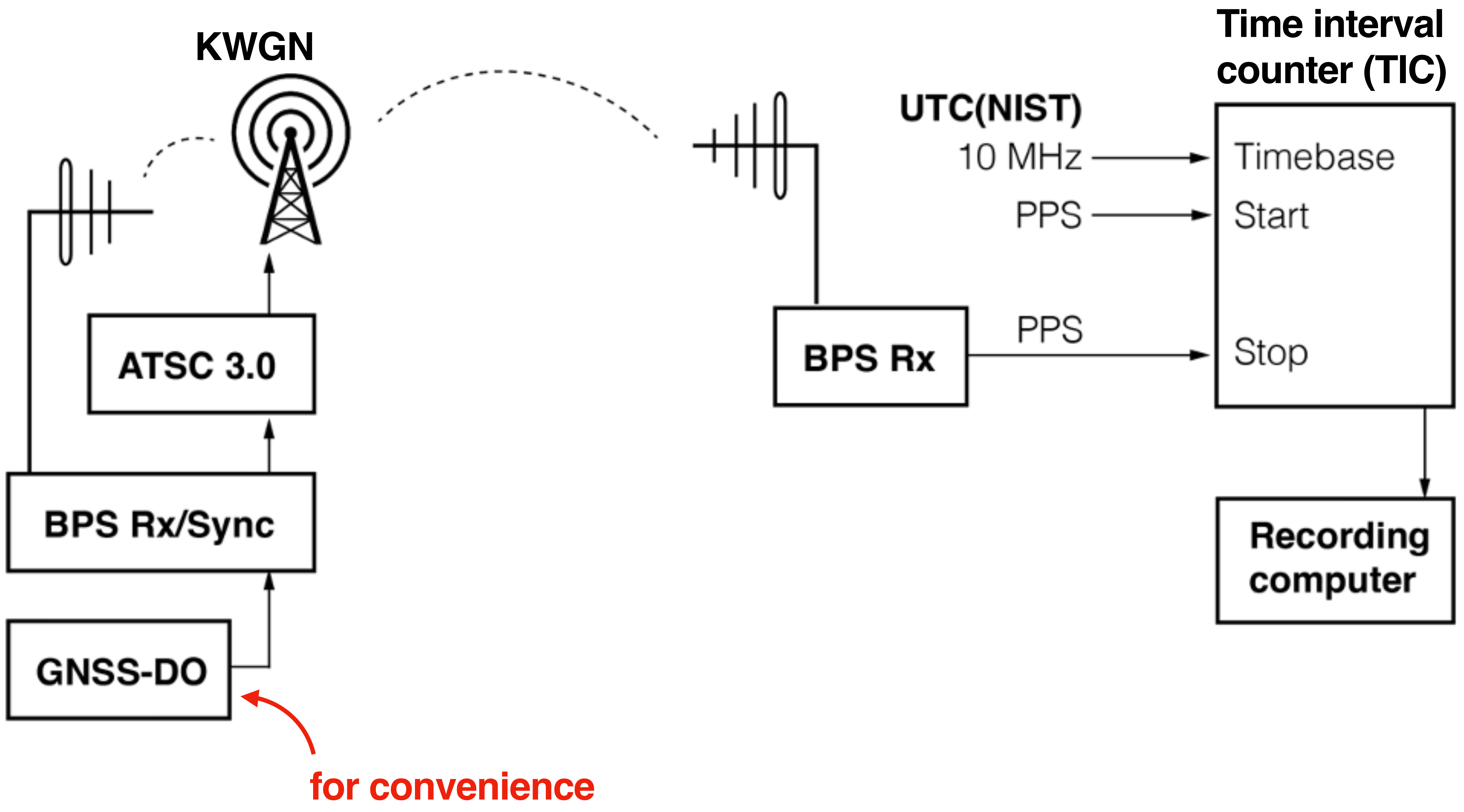
- By "wrapping the air-chain", BPS aims for wide compatibility; synchronizer device observes on-air transmission to compute correction data in the **BPS PLP**
- Very high (~1 MW) EIRP; jamming/spoofing difficult
- Transmitter infrastructure & spectrum in place; nearly 100% coverage of U.S.
- VHF/UHF largely line-of-sight, non-dispersive refraction
- ATSC 3.0 channel estimation features (multipath, co-channel interference)

NIST / NAB / Nexstar (KWGN, Denver) collaboration

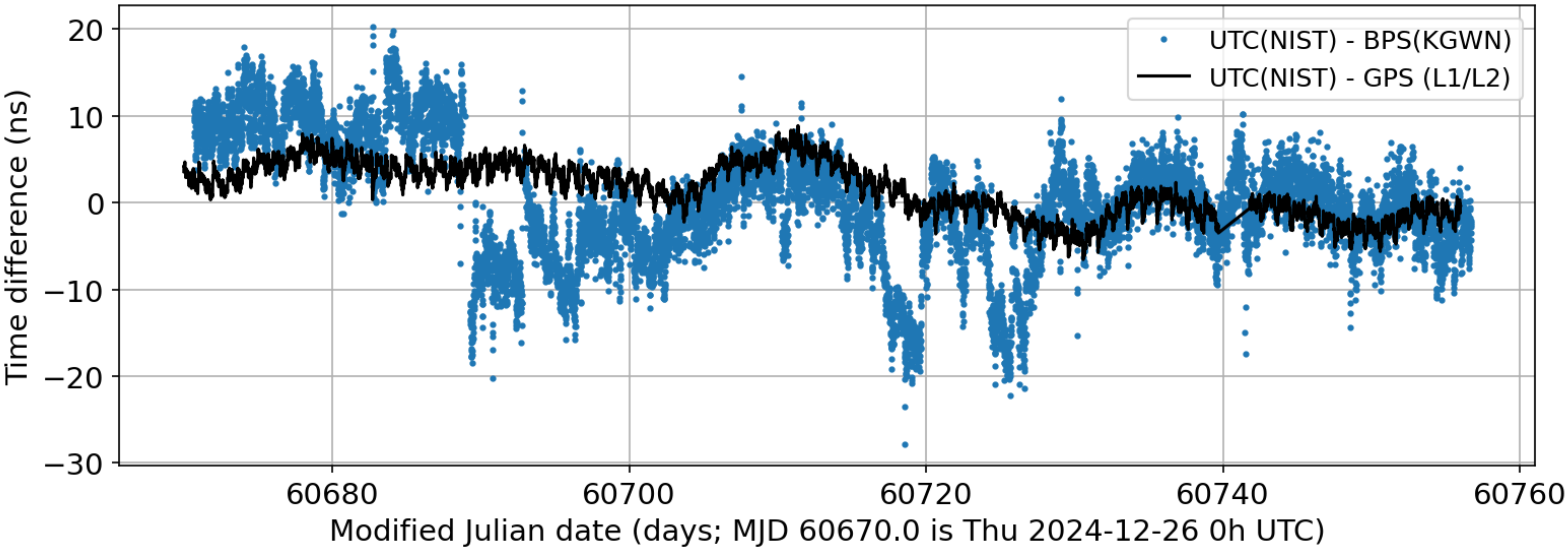
- Cooperative research & development agreement (CRADA)
- KWGN (UHF ch 34, 593 MHz, near Golden, CO) transmits ATSC 3.0/BPS
  - Time reference: a GNSS-disciplined Rb-clock (Microchip TP 4500)
  - Other NAB work: BPS from an independent atomic clock
- NAB installed BPS receivers (Avateq 1050)
  - NIST campus in Boulder, CO
  - NIST WWVB radio station near Ft. Collins, CO
  - KWGN studio, downtown Denver, CO
  - …all with COTS directional TV antennas
- NIST measures received BPS against:
  - UTC(NIST) at NIST-Boulder
  - A five-atomic clock ensemble UTC(NIST@WWVB)
  - … since September 3, 2024



Test arrangement



Example: 86 days, UTC(NIST) - BPS(KWGN)

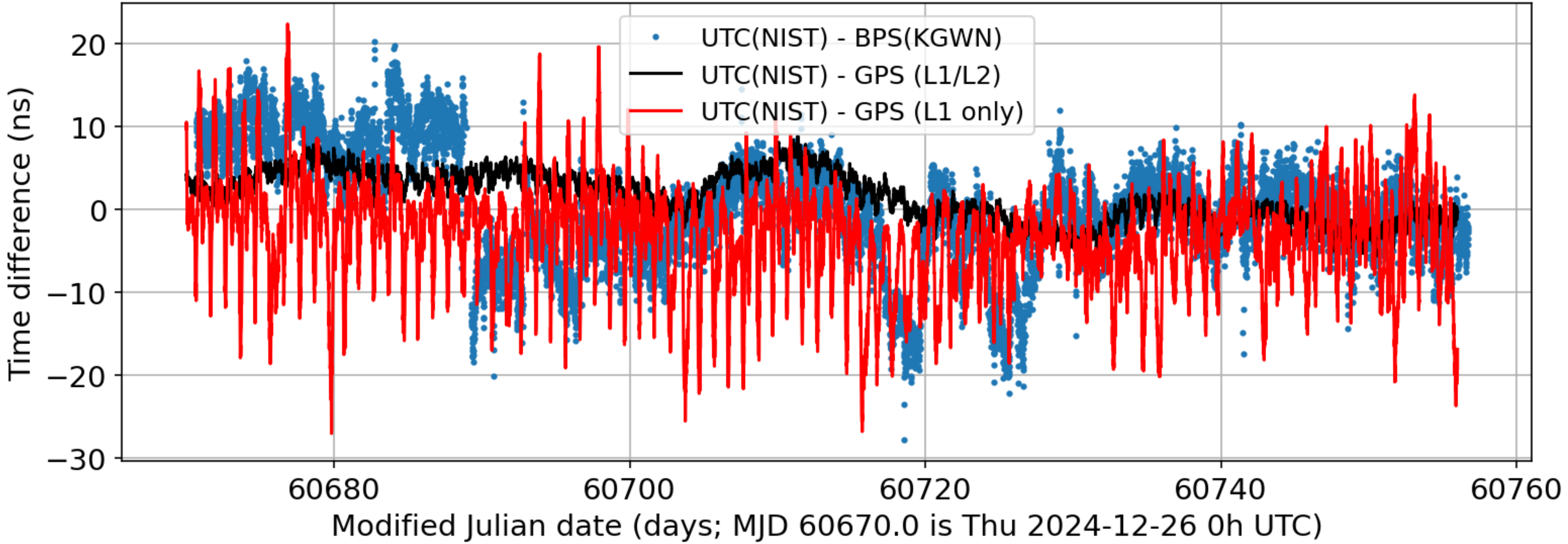


Displayed data are 10-minute averages.

Very little outlier removal (< 0.1%) pre-averaging: simple ±300 ns deviation-from-median threshold

Initial- or median offsets subtracted; goal is to study stability.

Received BPS peak variation comparable to single-frequency GNSS



Strong diurnal modulation in L1-only GPS: ionospheric variation, inadequate modeling in the GPS broadcast

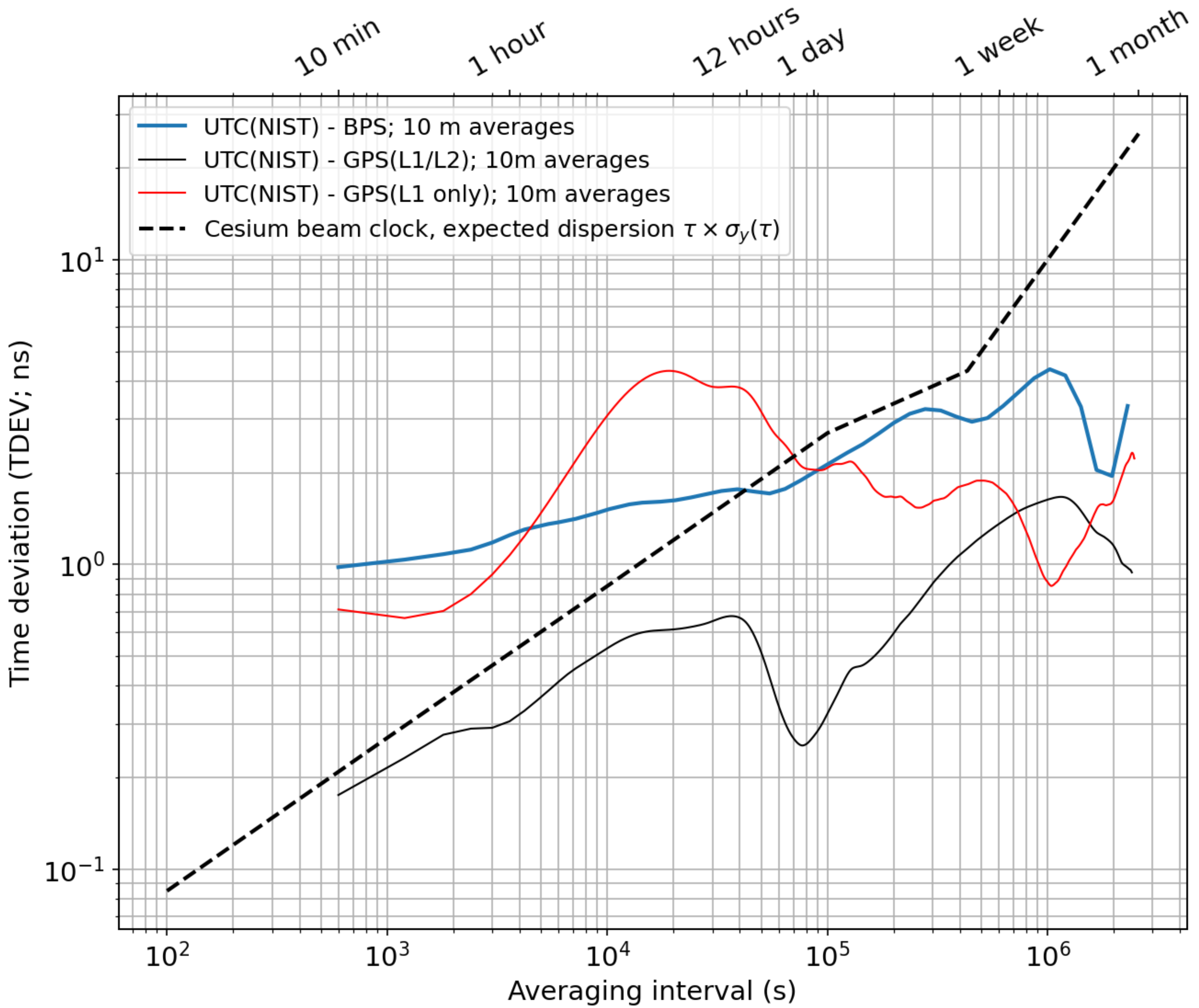
Stability of BPS vs. GPS vs. Cs atomic clock

BPS peak variations ~comparable to single-band GNSS

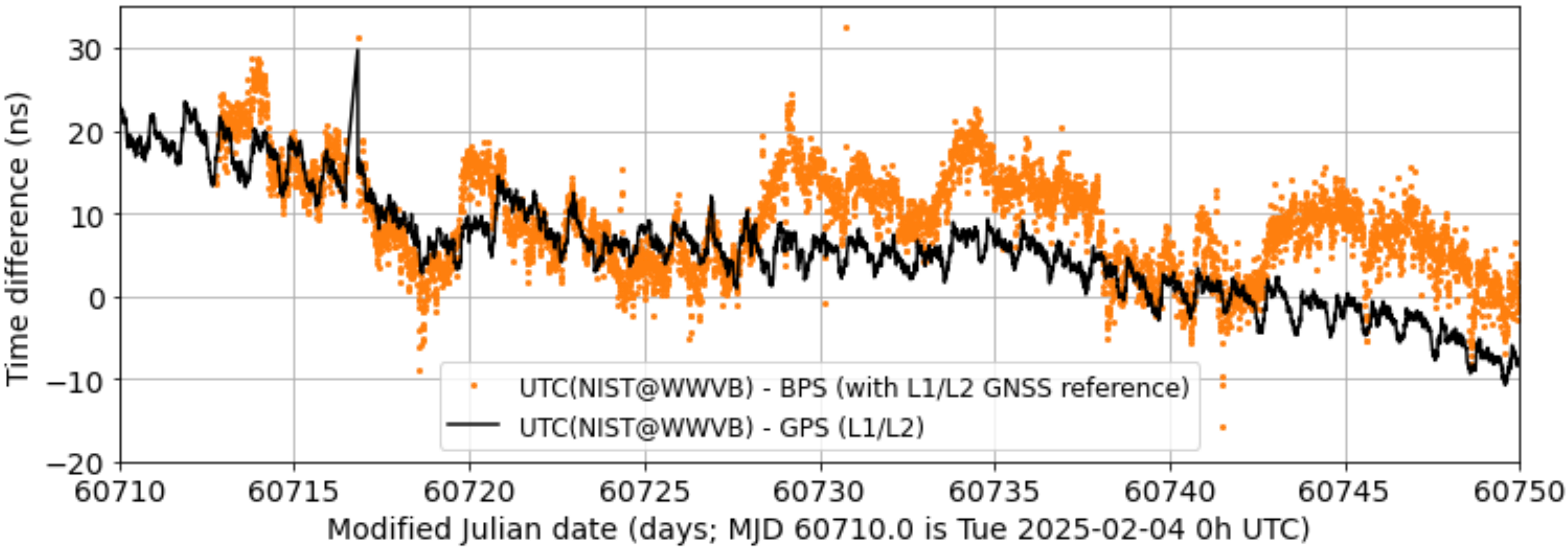
BPS: negligible diurnal

BPS can usefully calibrate a commercial Cs atomic clock in ~12 hours averaging

Noise is *overestimated* here: includes UTC(NIST), GNSS-DO, non-LOS path variation

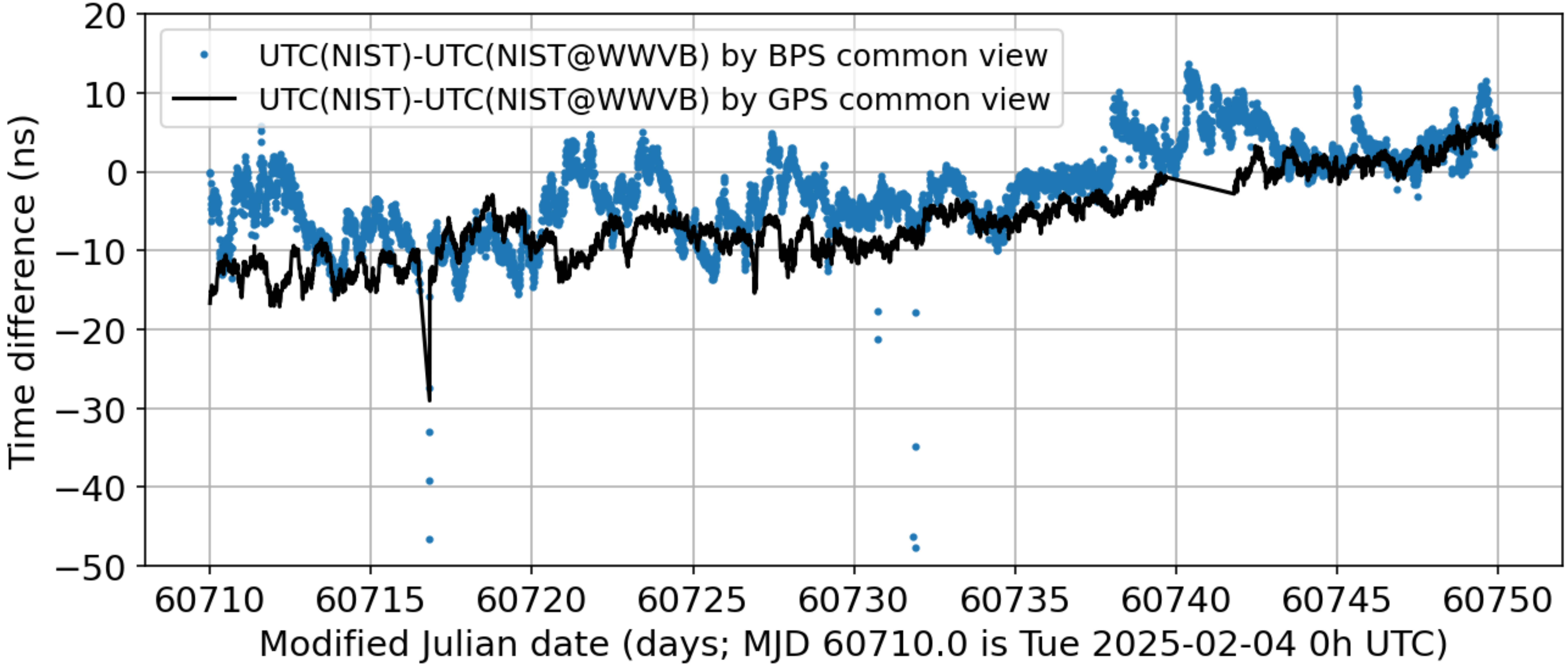


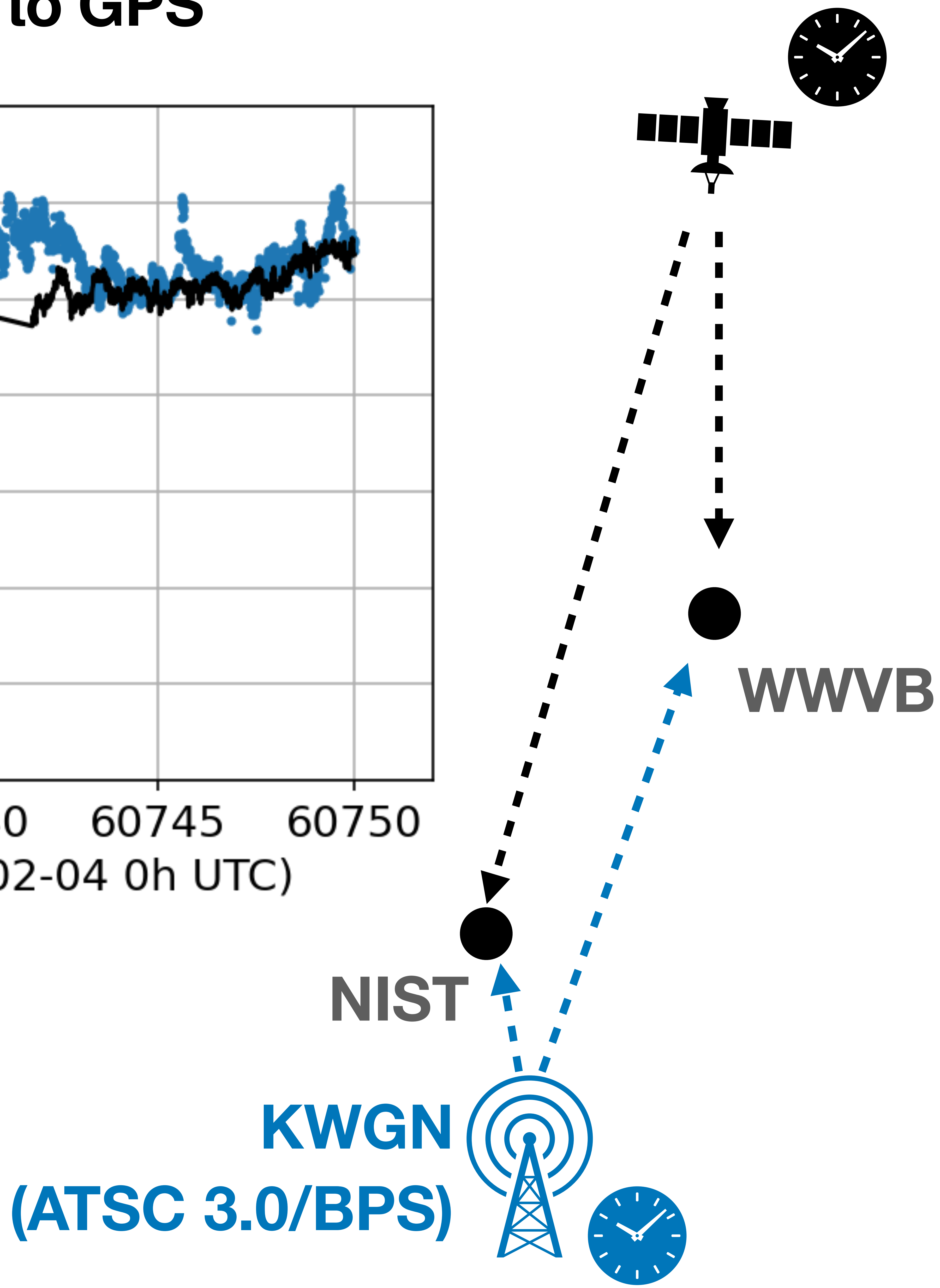
Example: 40 days, UTC(NIST@WWVB) - BPS(KWGN)



WWVB atomic clock ensemble is loosely-steered to UTC(NIST)

Example: BPS as a "transfer standard" comparable to GPS



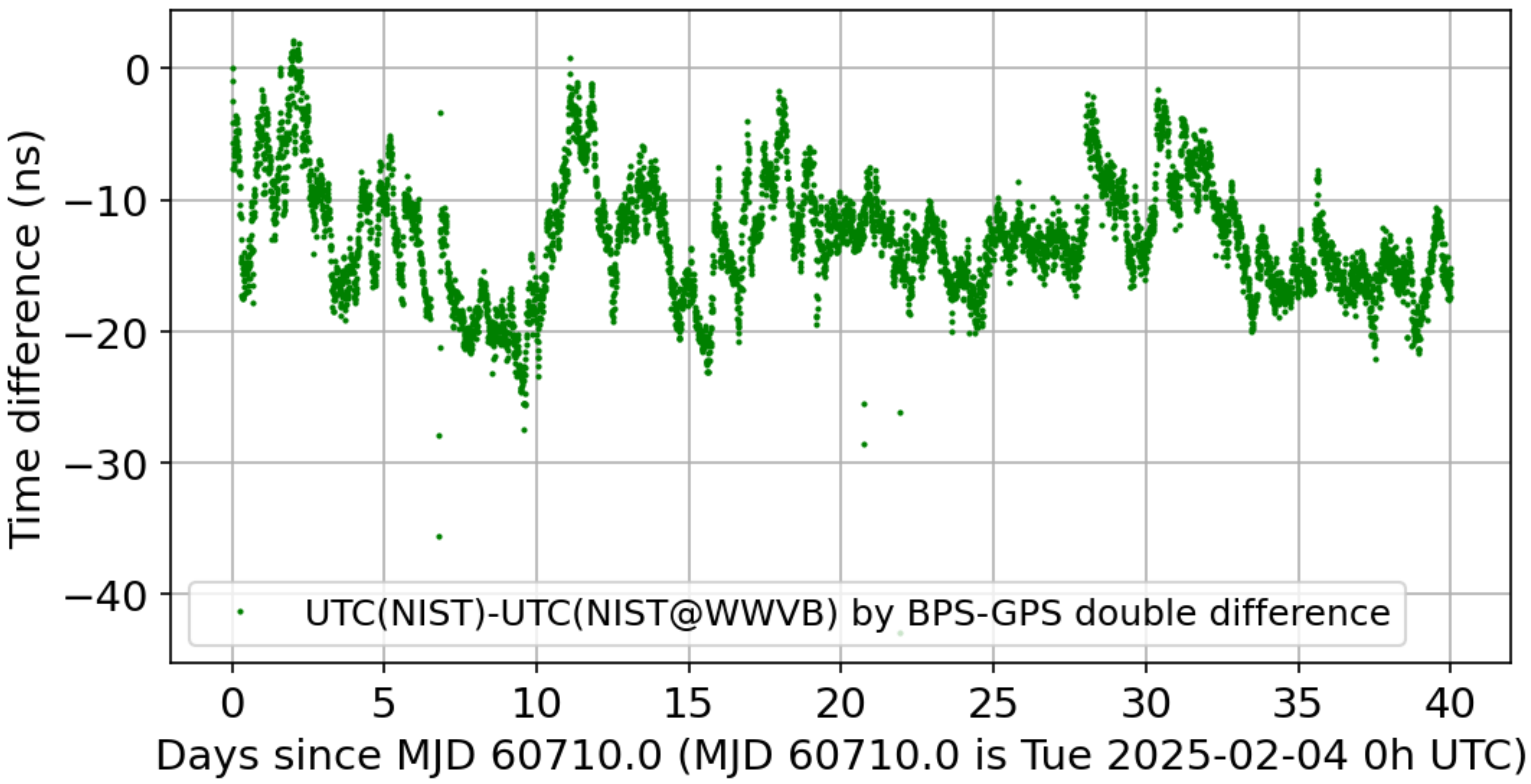


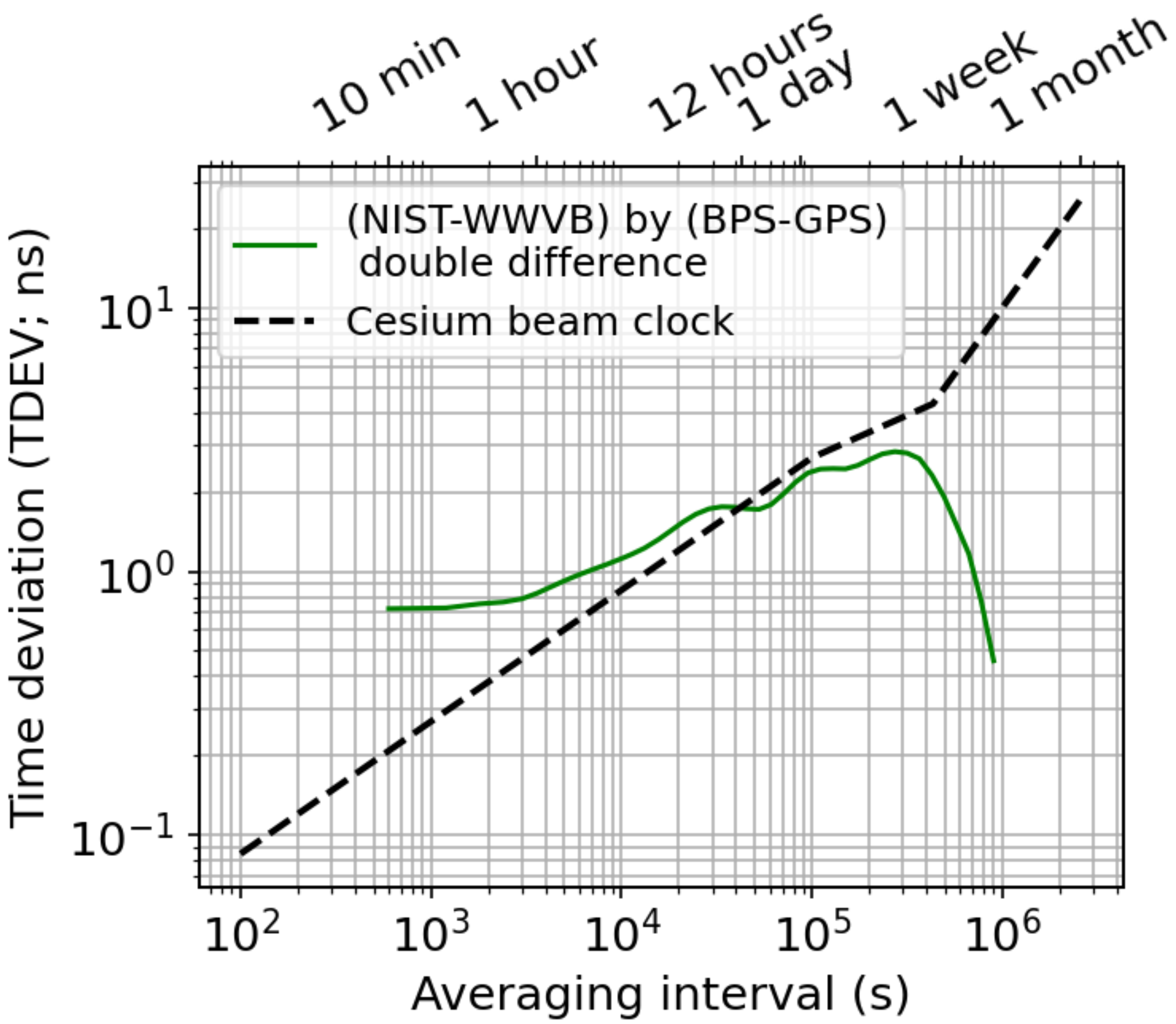
40 day data set: “Double difference” (NIST - WWVB) - (GPS - BPS)

Removes variation due to time scales, BPS reference clock, transmitter

Remaining sources of variation:

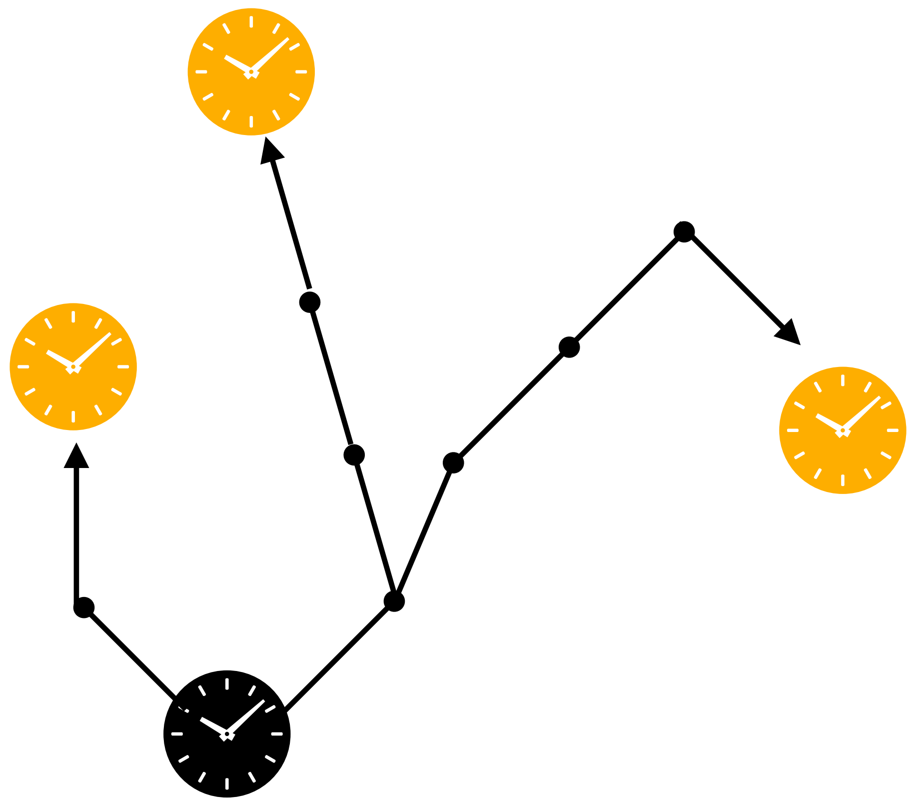
- The ~70 km non-common propagation between NIST and WWVB
- Two independent BPS receivers
- Noise in time interval counters, facility cabling, GPS-common-view technique





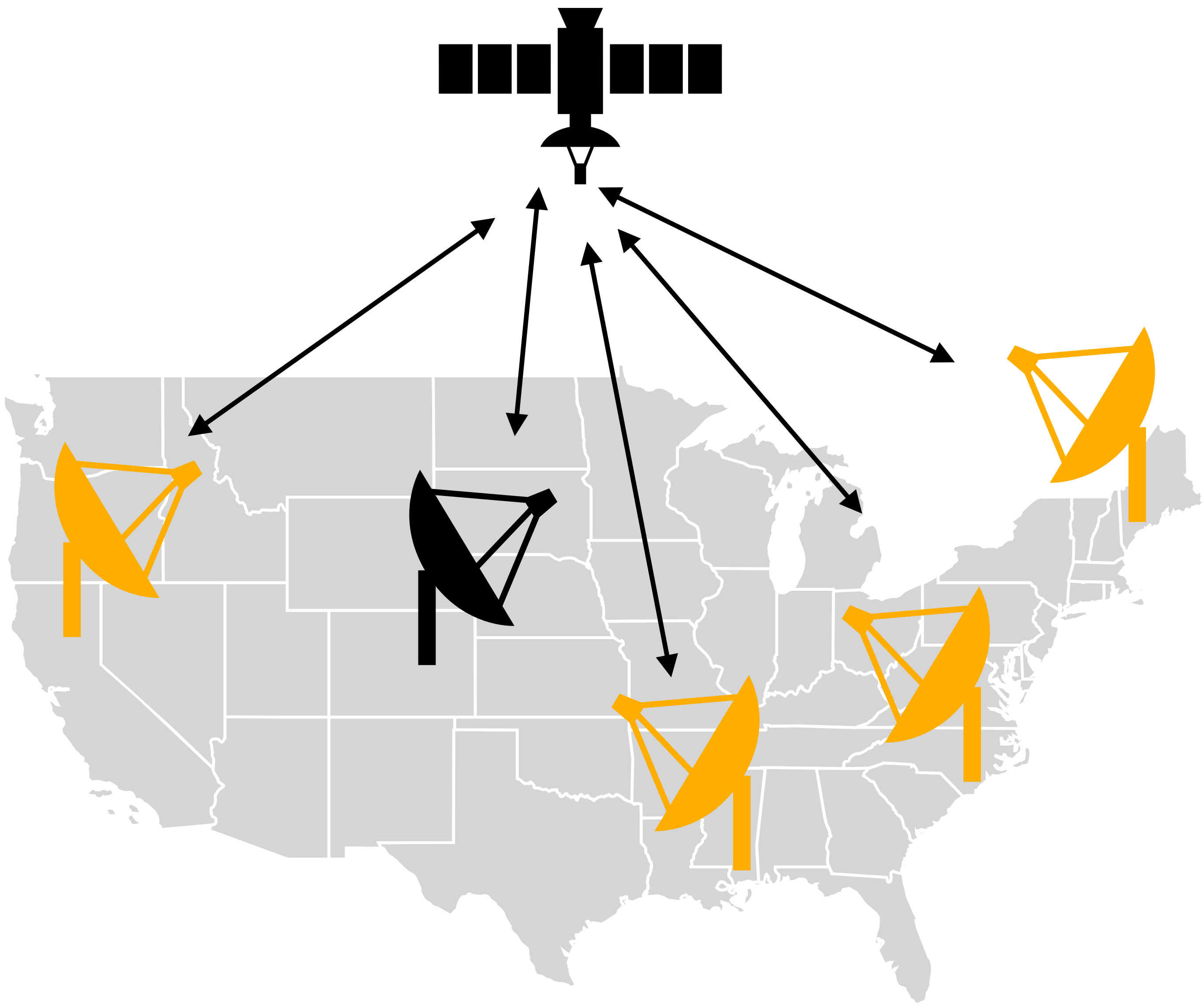
ns-level, traceable, GNSS-independent techniques:

“Time over Fiber”



- Setup/subscription fees in shop.nist.gov catalog
- Contact: Prof. Judah Levine (judah.levine@nist.gov)
- Stability depends *critically* on physical layer; ns-level achievable
- Point-to-point network model
- No space vulnerabilities
- Recurring costs can be expensive

“Time over Satellite” (two-way satellite time/frequency transfer)

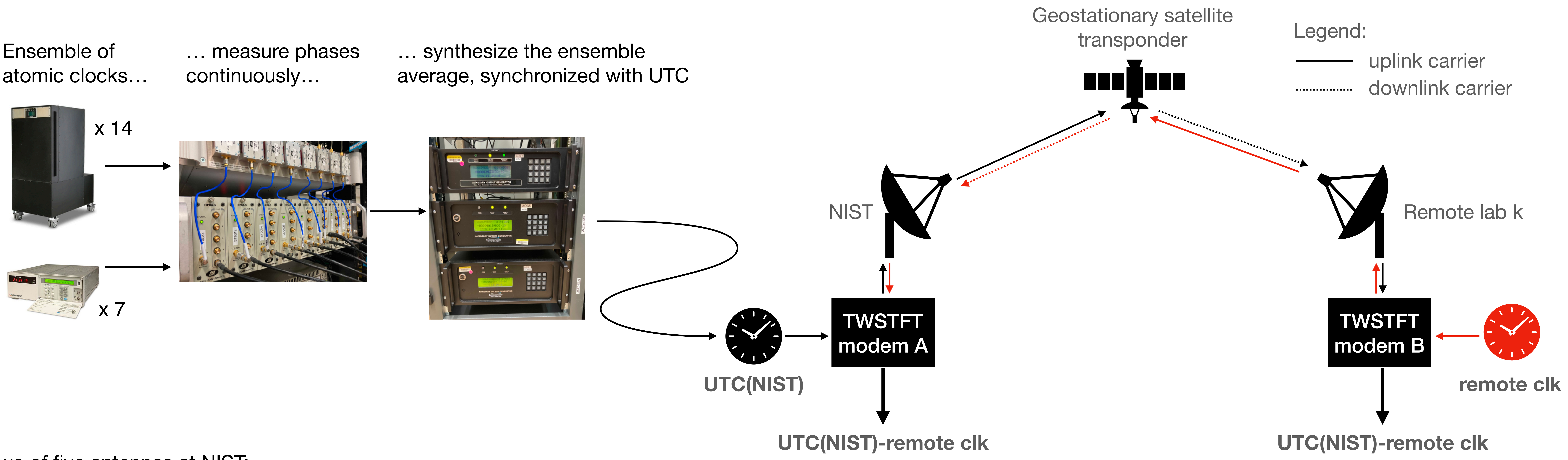


- Special Test service 78500S in shop.nist.gov catalog
- Contact: Jeff Sherman (jeff.sherman@nist.gov)
- ns-level stability from any implementation
- Mesh network model: all nodes can exchange time with each other
- Initial setup can be expensive
- Many nodes served by same leased bandwidth service

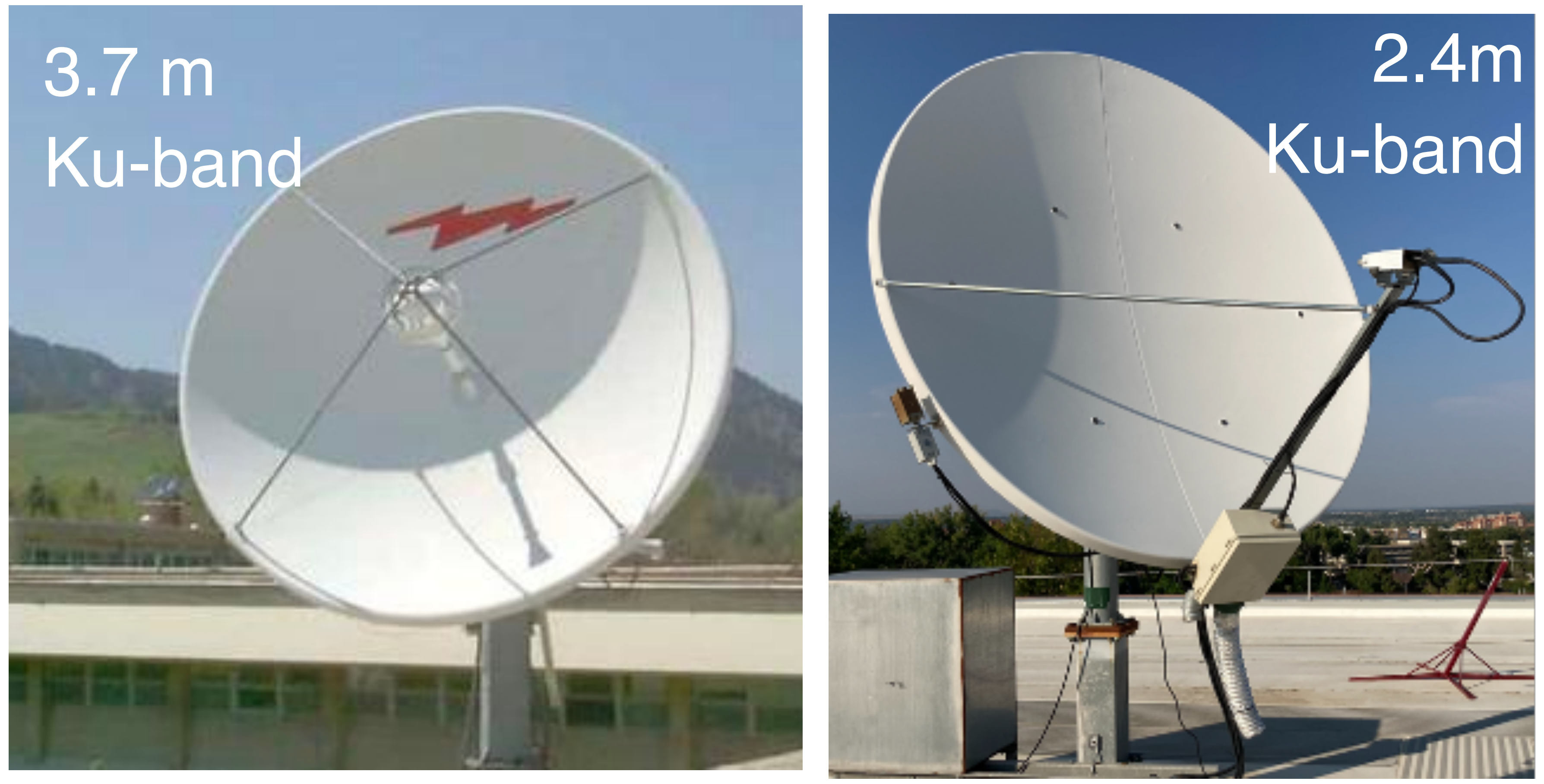
Some other possibilities (w/ external collaborators):

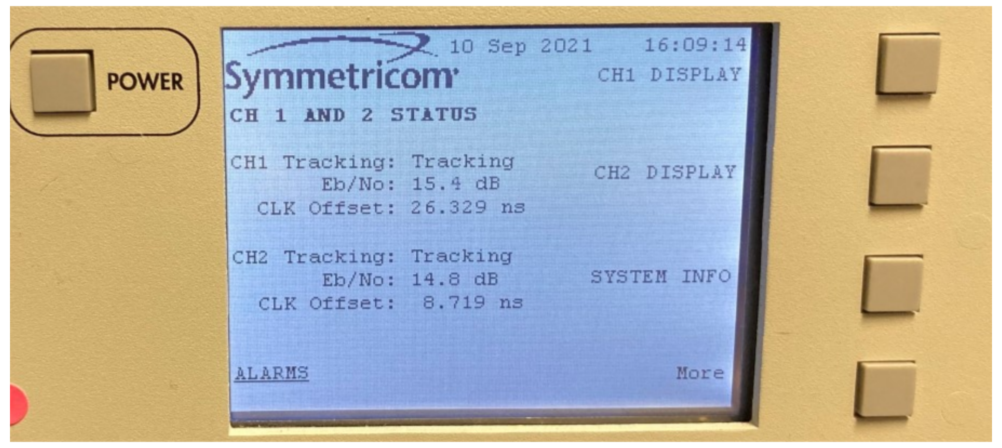
- LEO or GEO constellations
- Terrestrial beacons

Two-way satellite transfer (TWSTFT) of UTC(NIST)



Two of five antennas at NIST:





ATS-6502 modem
(Microsemi/Microchip; USA)

SATRE modem
(TimeTech; Germany)

A “Time over Satellite” network test

Five participating stations:

NIST (Boulder, CO)

Oak Ridge National Laboratory (ORNL)

Microchip (ATS-6502 modem manufacturer):

Boulder, CO
Beverly, MA
Tuscaloosa, AL

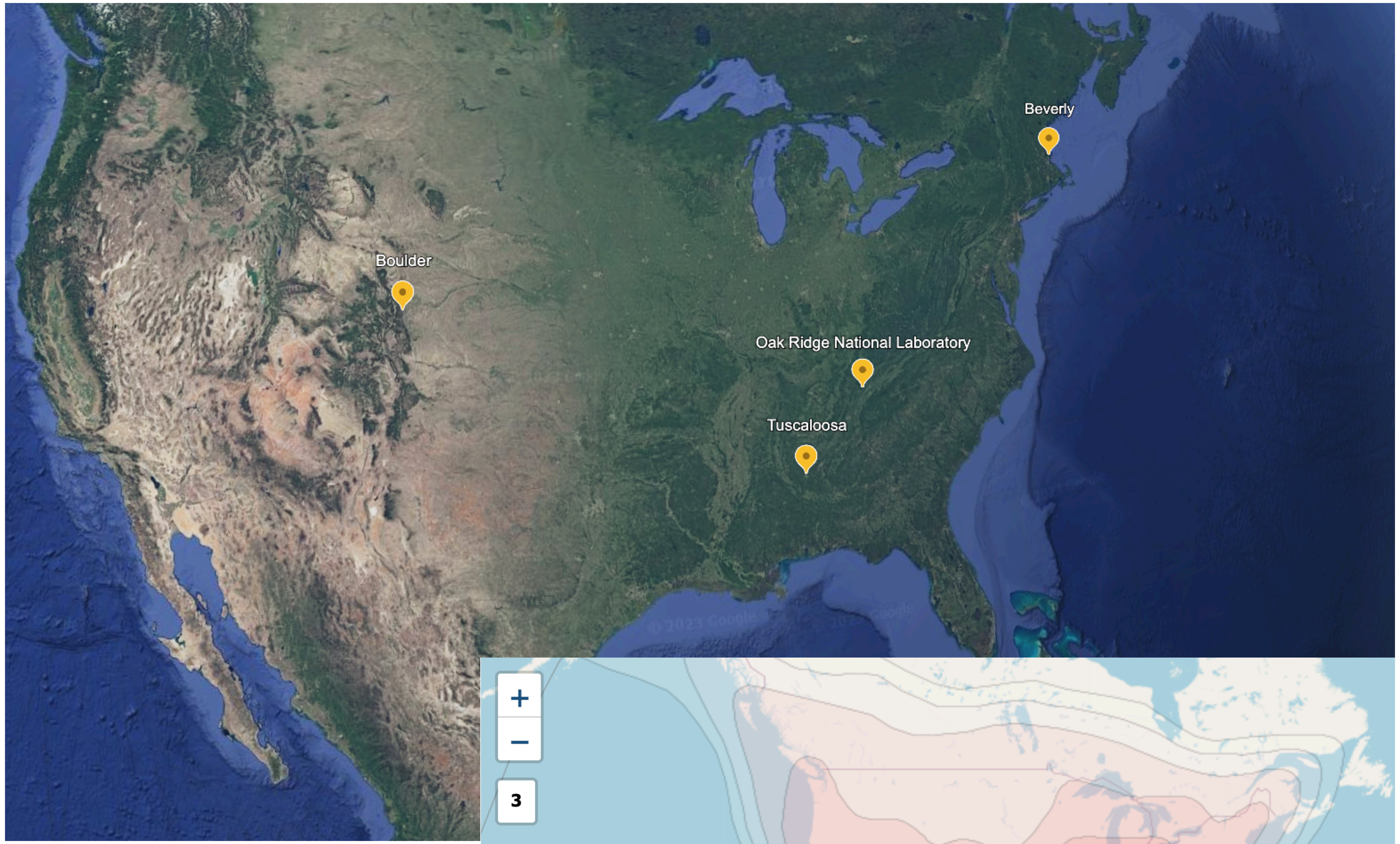
Parameters:

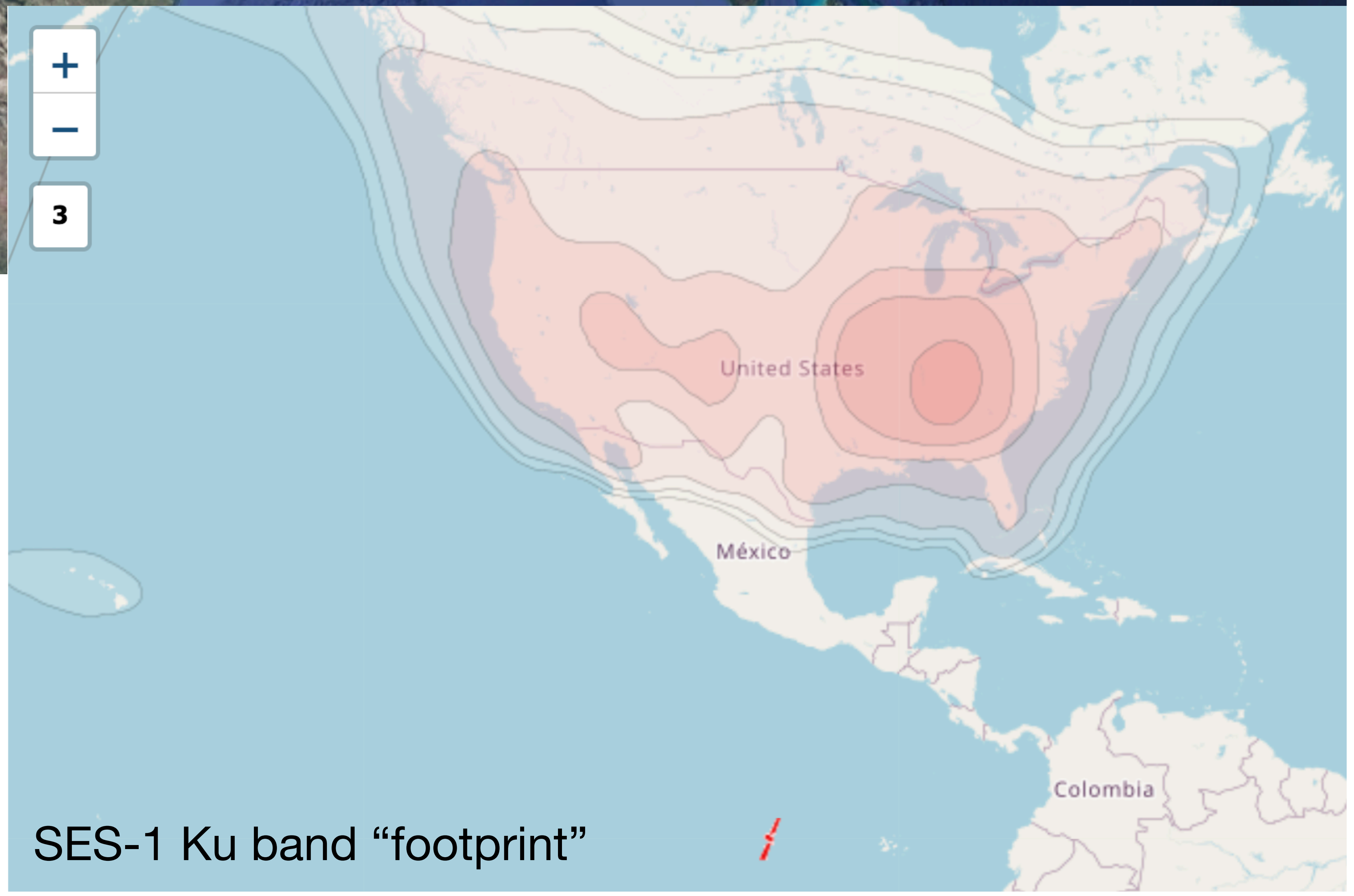
November 2023 - June 2024

ORNL purchased transponder bandwidth (Ku; 3 MHz) on SES-1 (101°W)

All stations (other than NIST) use a single atomic clock (or small ensemble) steered to GPS

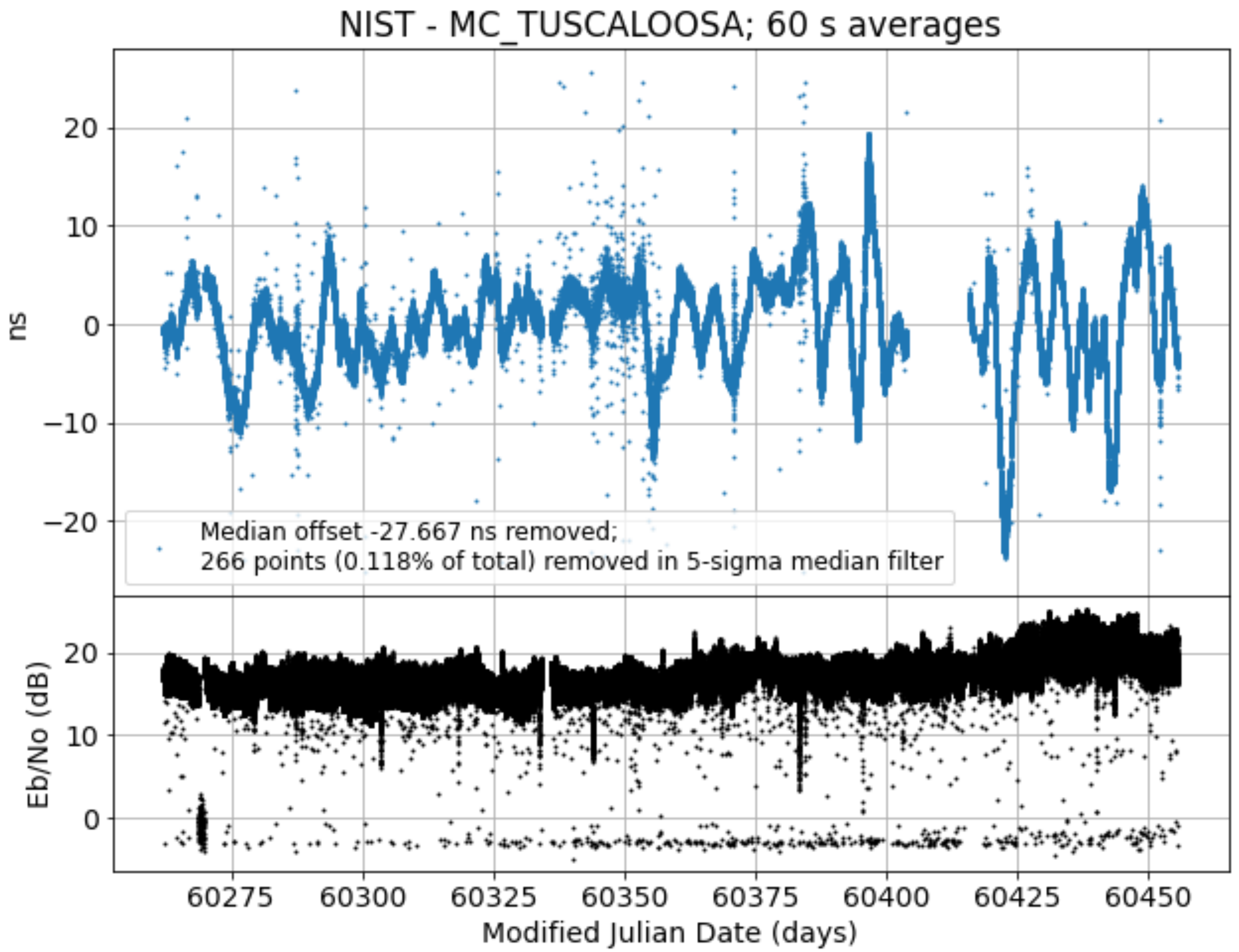
All stations used a Microchip ATS-6502 time transfer modem, commercially-available satcom parts.

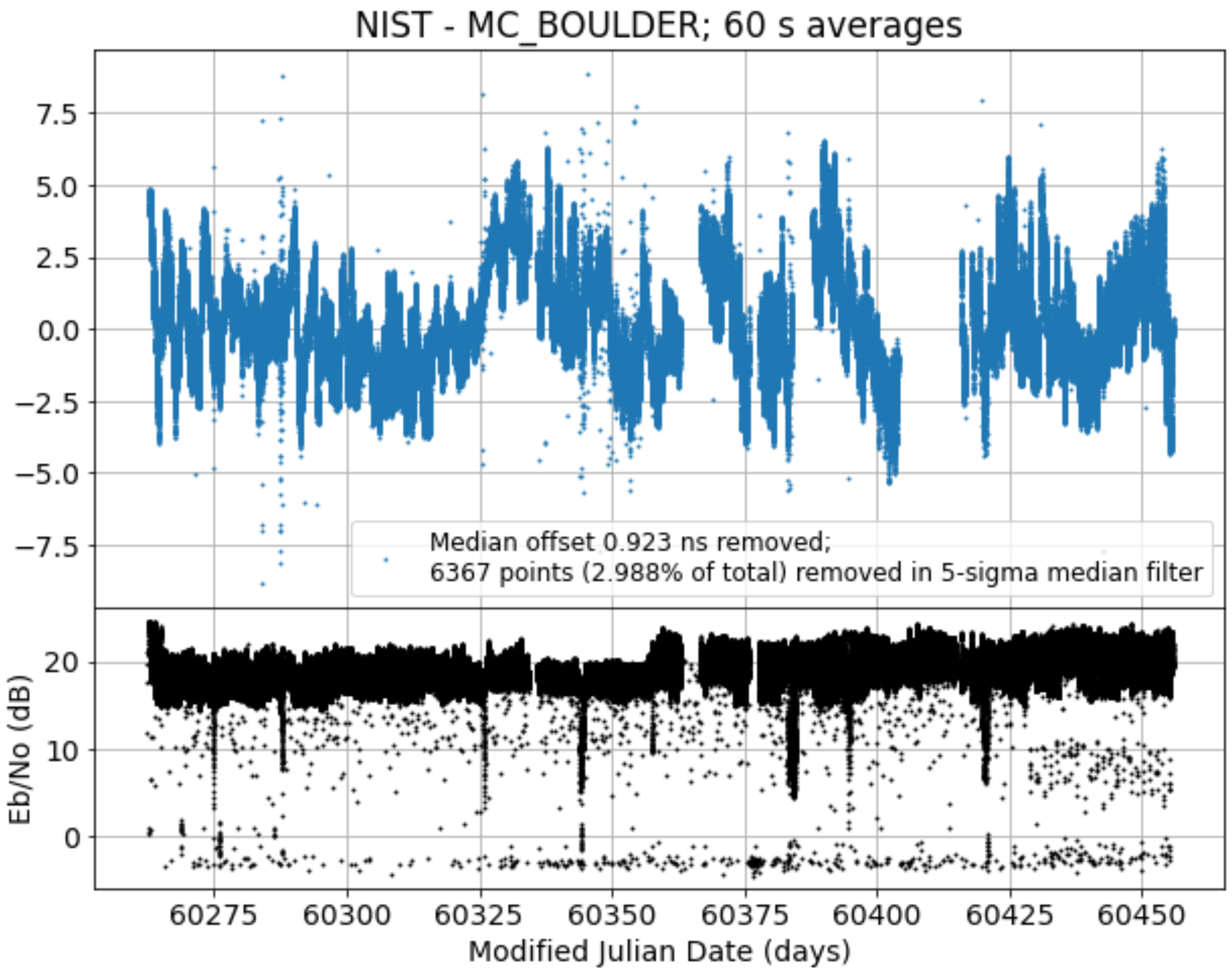




SES-1 Ku band “footprint”

Commercial TWSTFT link test: 194 days





NIST study of (post-processed) GPS carrier-phase (PPP) vs. TWSTFT

… roughly comparable performance ≤ **200 ps** flicker phase (over months)

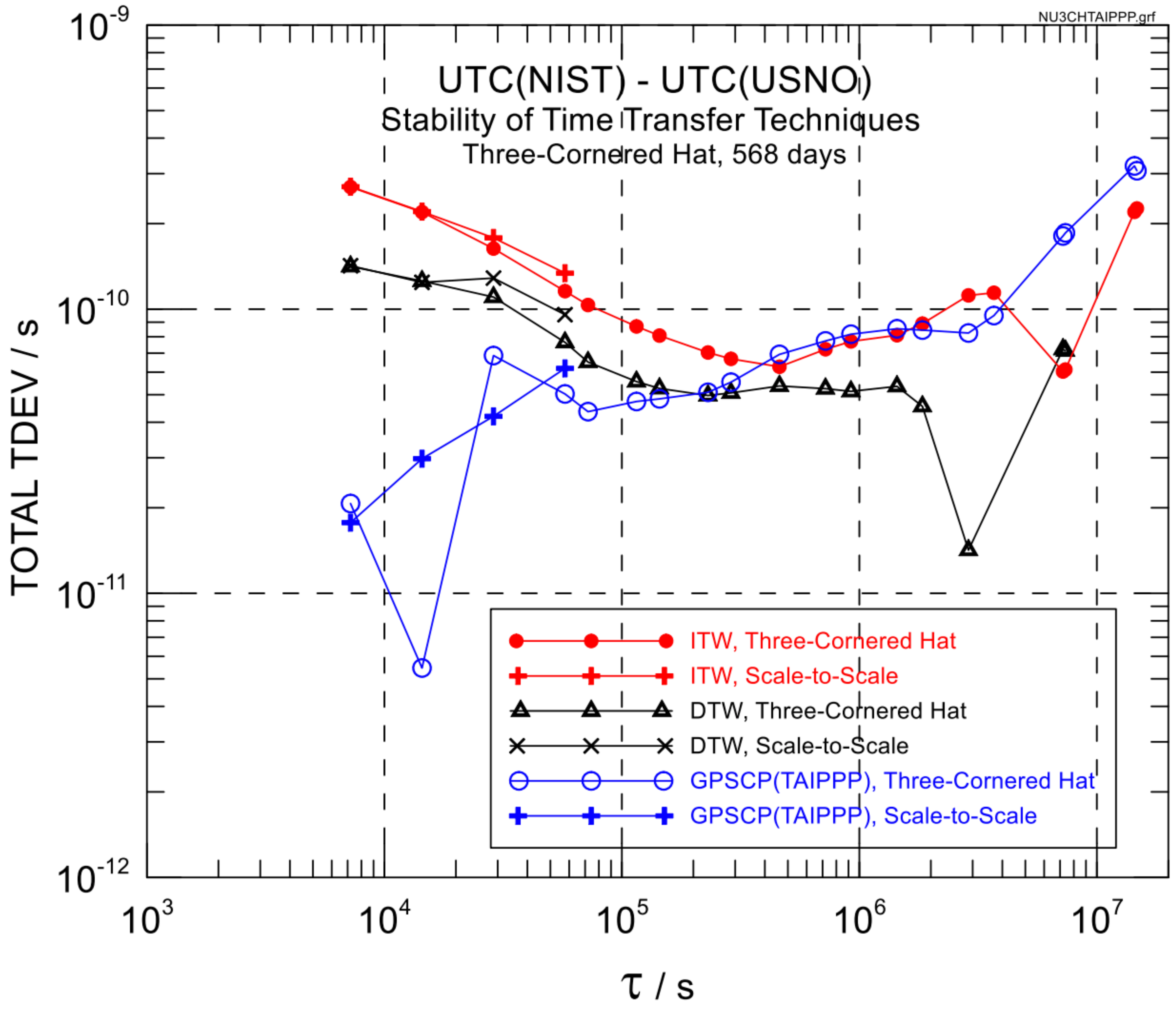


Figure 6. Three-cornered hat results for the indirect two-way (ITW), direct two way (DTW) and GPS carrier phase using TAIPPP (GPSCP(TAIPPP)).

"Indirect two-way": NIST - PTB - USNO (transatlantic)

"Direct two-way": NIST - USNO (CONUS)

GPS carrier phase (IPPP)

TE Parker, V Zhang, G Petit, J Yao, RC Brown, JL Hanssen, Metrologia **59** 035007 (2022)

NIST Time Realization and Distribution group

Remote calibrations
Andrew Novick
Ben Pera

WWV/WWVB, Ft. Collins
Matthew Deutch
Kyle Kniegge
Jim Spicer
William Yates

WWVH, Kauai, Hawaii
Steven Johnston
Chris Fujita
Adela Mae Ochinang

Recent visiting scientists
Terrence Jones (Jamaica)
Anectus Ndunguru (Tanzania)
Prof. Thejesh Bandi Nagabhushan (U. Alabama)

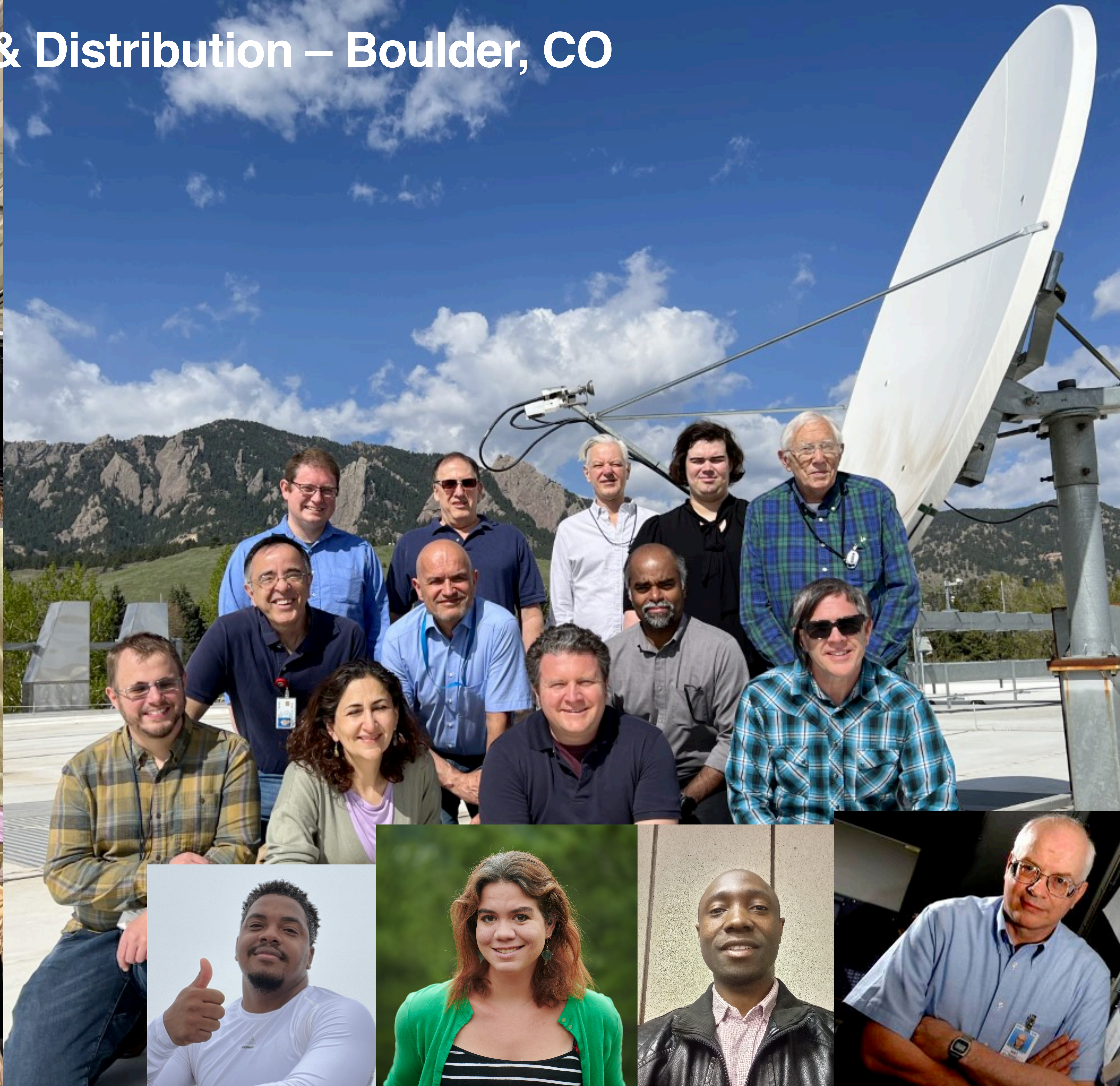
Division chief
Dr. Elizabeth Donley

Network time services / time scale
Prof. Judah Levine

Time scale operations/coordination
Dr. Jeff Sherman
Dr. Guilherme de Andrade Garcia
Dr. Tom Parker
Dr. Biju Patla

Frequency standards
Dr. Vladi Gerginov
Dr. Travis Briles
Dr. Alejandra Collopy
Dr. Greg Hoth

NIST Time Realization & Distribution – Boulder, CO



Director’s cut

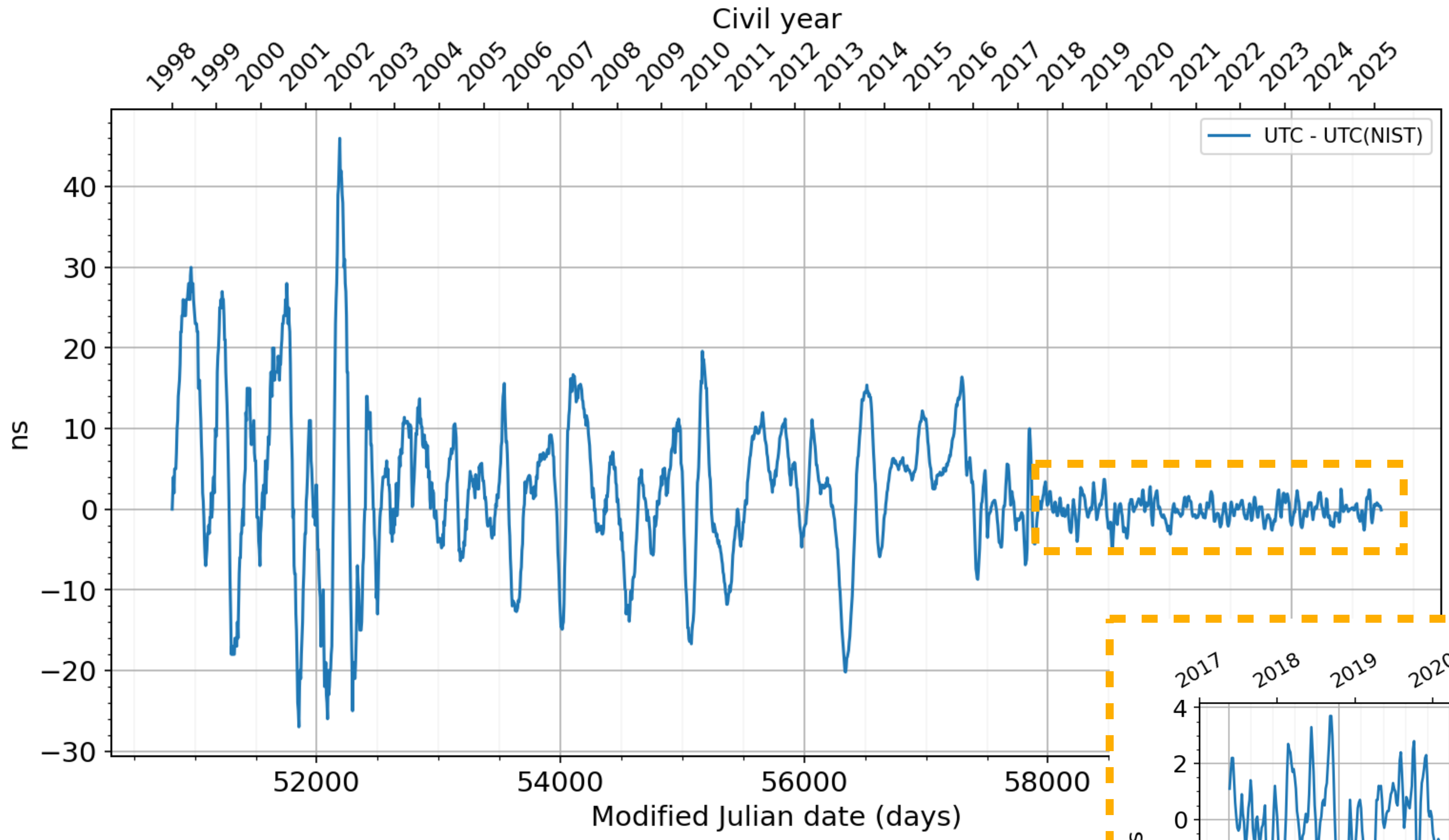
What’s NIST?

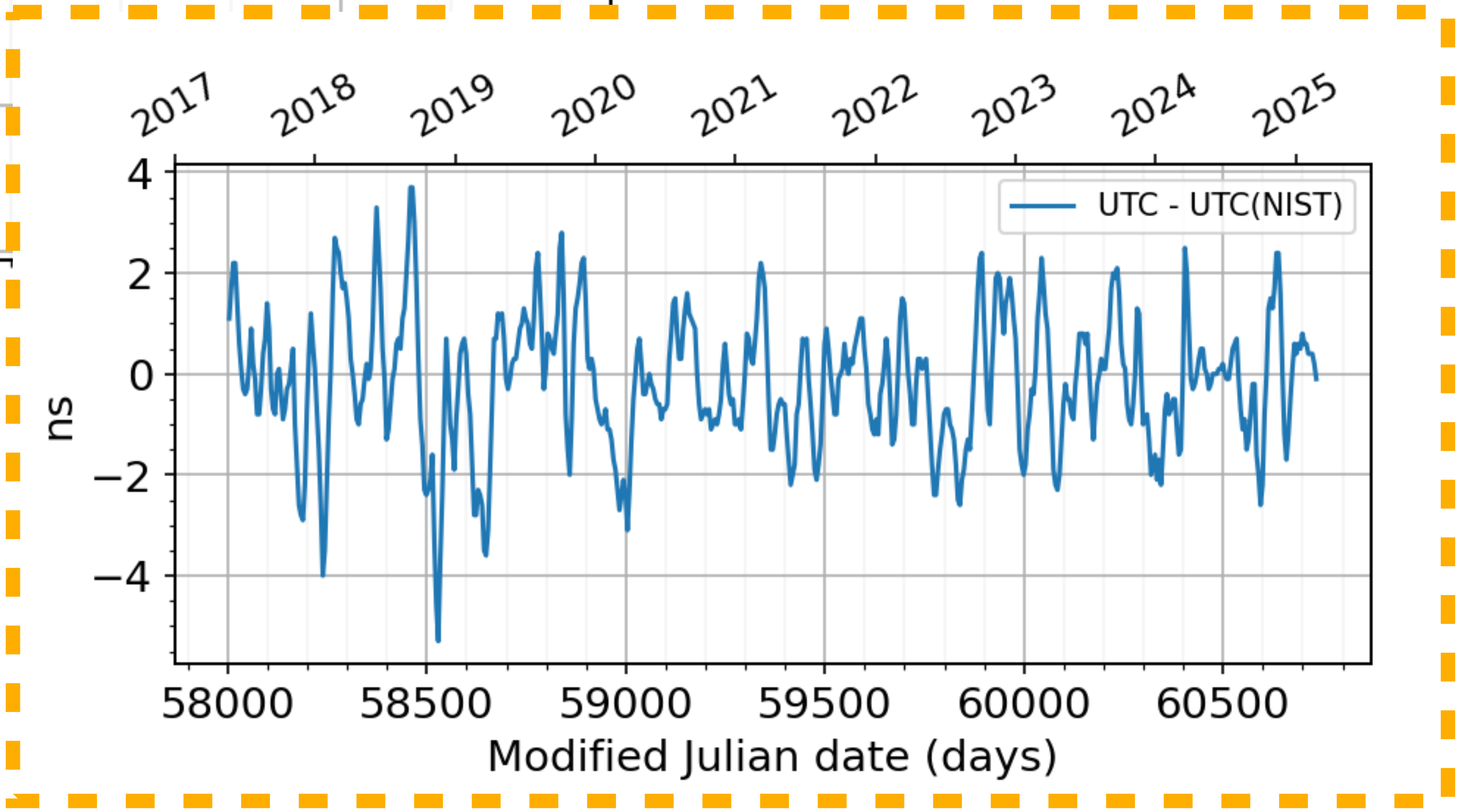
- Non-regulatory agency within Dept. of Commerce (1901-1988: NBS)
- The U.S.’s national metrological institute (*metrology*: science of measurement)
- ~ 3400 employees (about 30% students & postdocs)
- Article I, section 8: “…fix the standard of weights and measures”

x 5

UTC(NIST) - UTC typical performance

- Time offset < 2 ns
- Rate offset < 10^{-15}



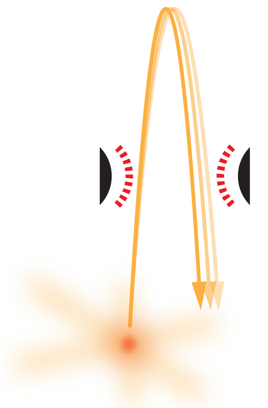


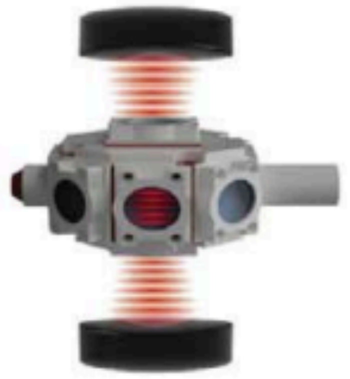
NIST Time and Frequency division (overview)

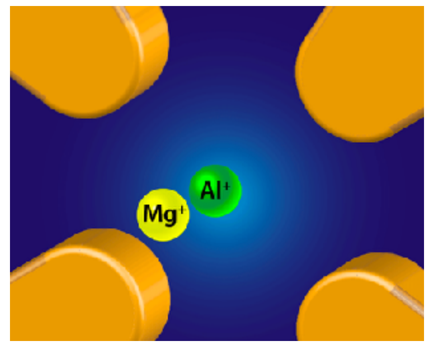
Continuously running atomic clock ensemble

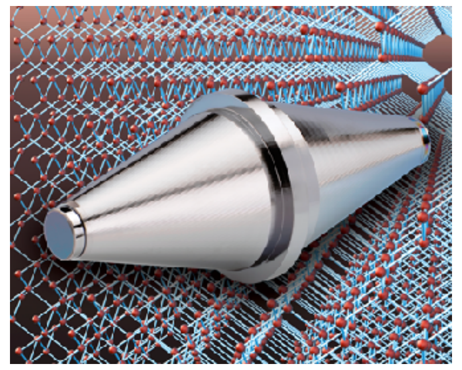
UTC(NIST)

High-accuracy atomic frequency references









Novel techniques:
ultra-stable oscillators,
fs-laser frequency combs,
laser cooling,
atomic state manipulation

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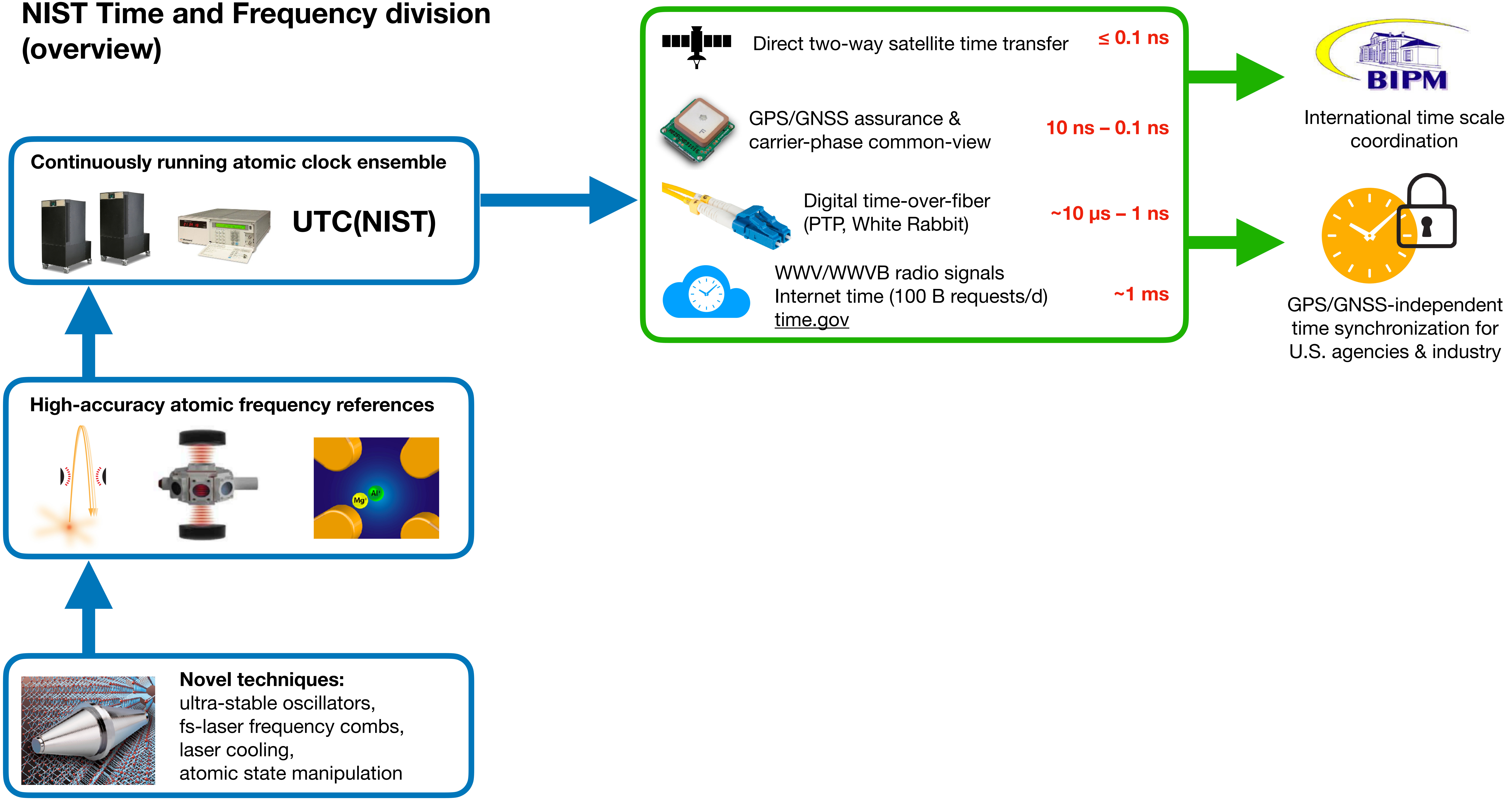

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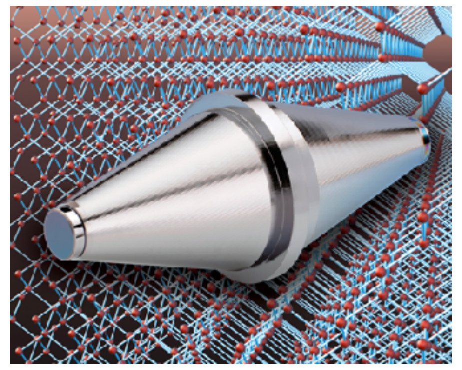

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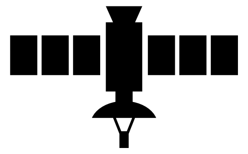
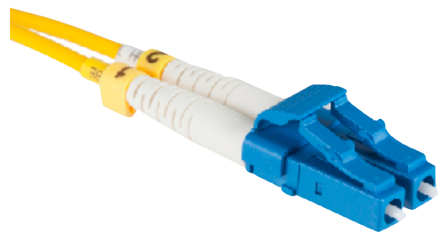
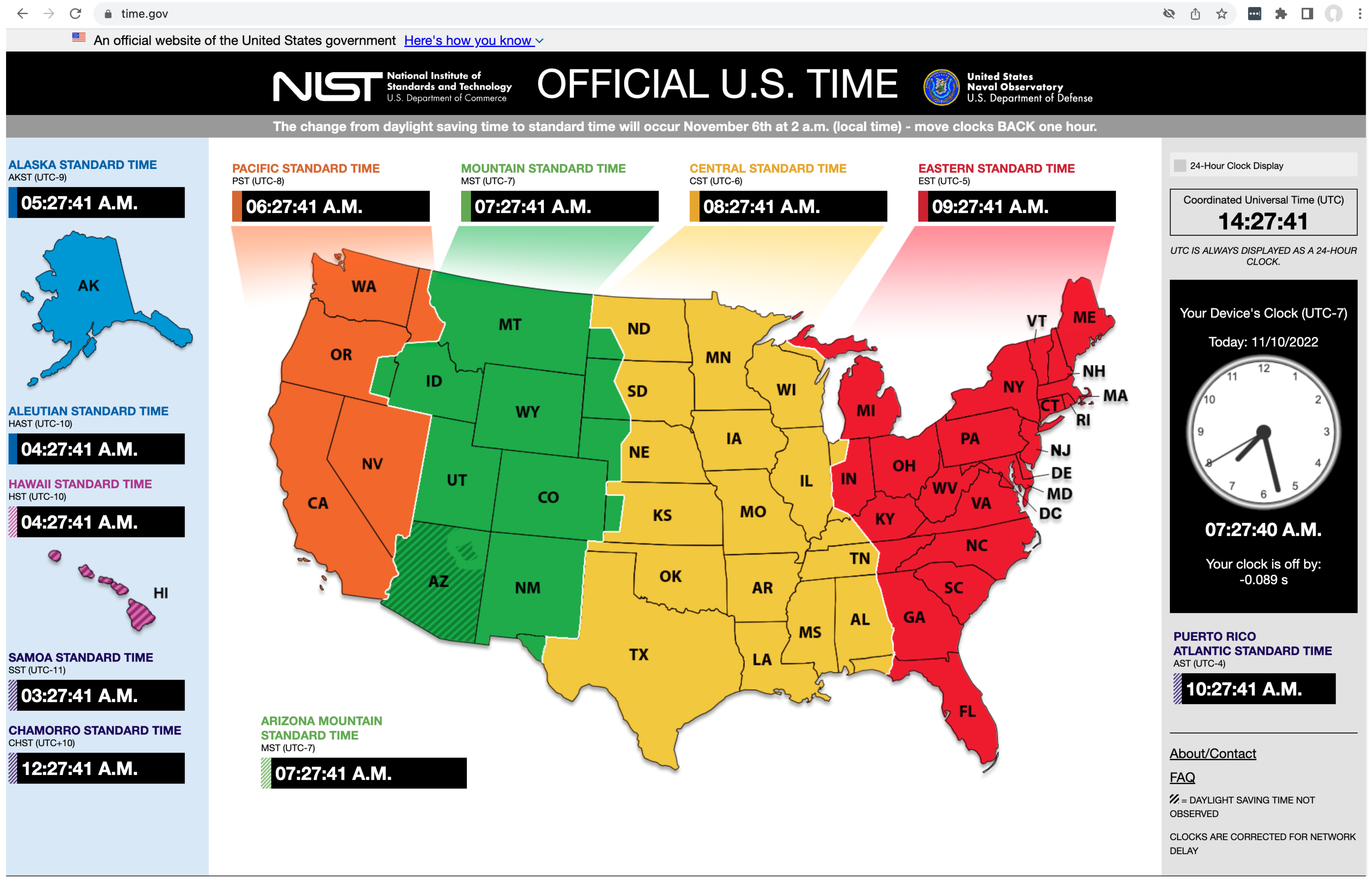


	Direct two-way satellite time transfer	≤ 0.1 ns
	GPS/GNSS assurance & carrier-phase common-view	10 ns – 0.1 ns
	Digital time-over-fiber (PTP, White Rabbit)	~10 µs – 1 ns
	WWV/WWVB radio signals Internet time (100 B requests/d) time.gov	~1 ms



International time scale coordination

GPS/GNSS-independent time synchronization for U.S. agencies & industry




NIST Time and Frequency division (overview)
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Mg+
Al+
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Direct two-way satellite time transfer
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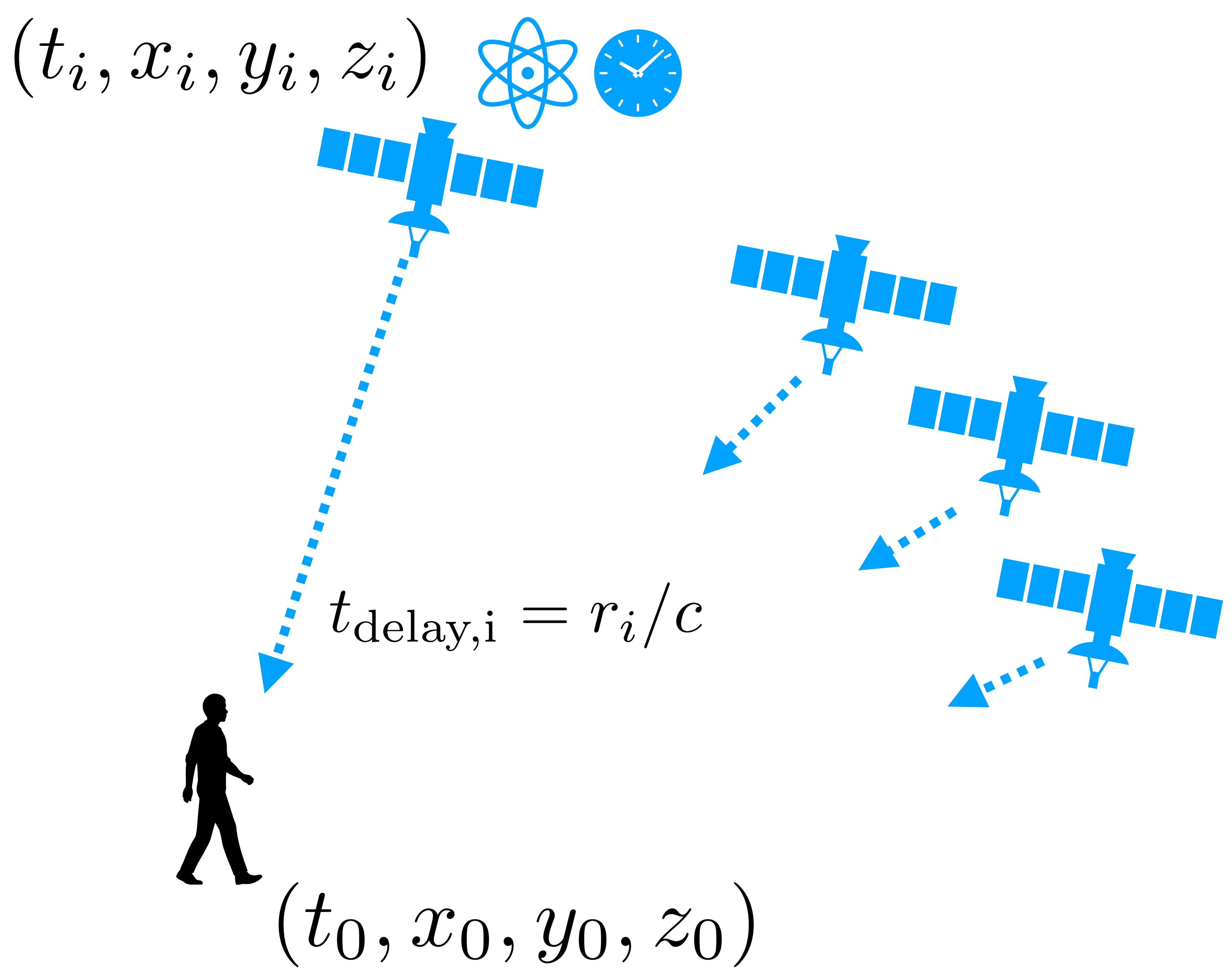
GPS/GNSS assurance &
carrier-phase common-view
10 ns – 0.1 ns
Digital time-over-fiber
(PTP, White Rabbit)
~10 µs – 1 ns
WWV/WWVB radio signals
Internet time (100 B requests/d)
time.gov
~1 ms
Novel sensing, relativistic geodesy,
fundamental science
Dimensional metrology (e.g. voltage)
Coherent optical phase
transfer (fiber, free-space)
≤ 1 fs
Low phase-noise microwave
synthesis & measurement
Quantum information processing
BIPM
International time scale
coordination
GPS/GNSS-independent
time synchronization for
U.S. agencies & industry
Technology transfer
Quantum networks
Advanced communication

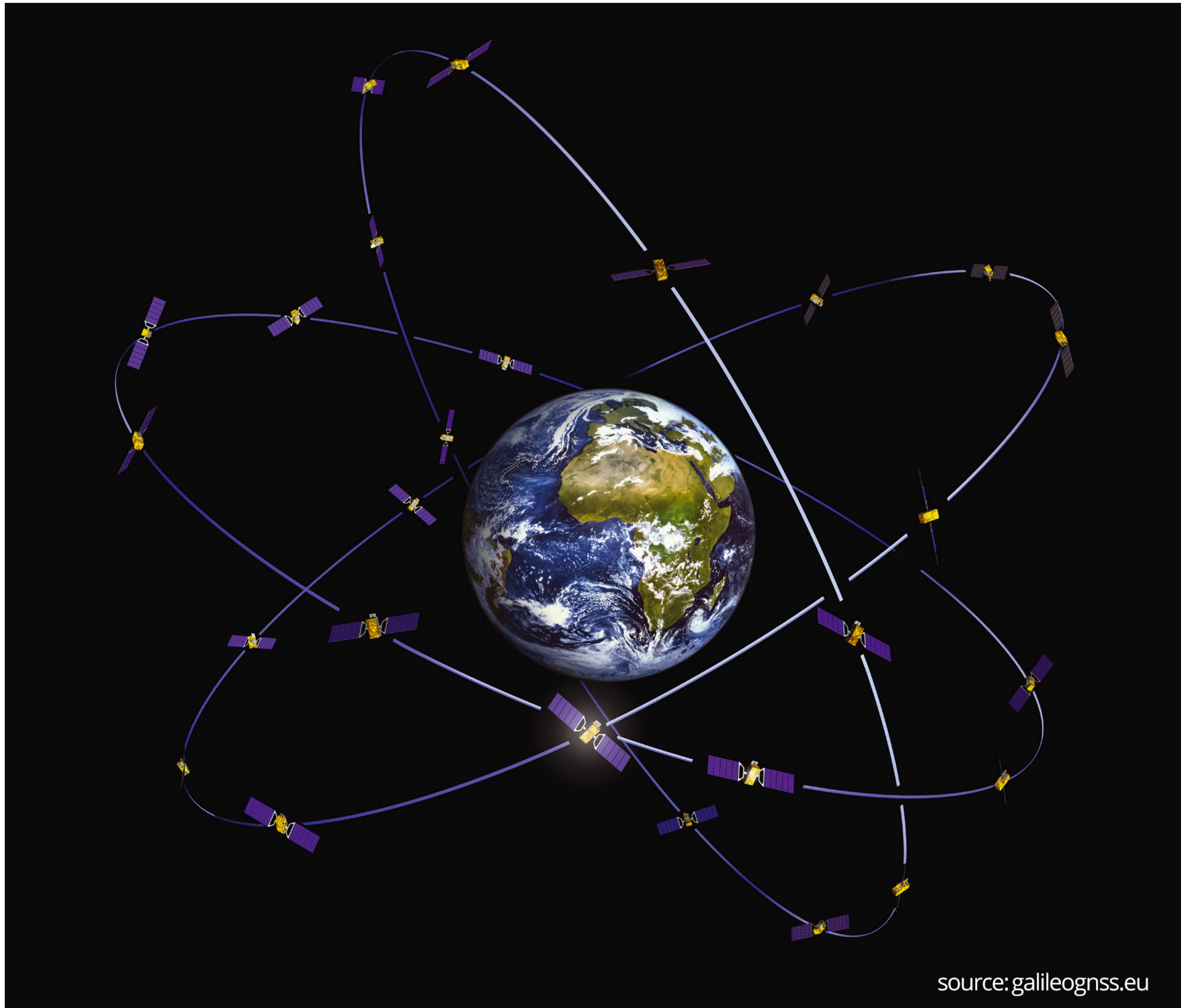
Global positioning / navigation satellite systems (GNSS), like GPS…

Transmit an approximation to UTC with nanosecond-level stability and, potentially, traceability

~ $1.4T economic impact over 10 years

~ 2% of US economic activity depends on GPS/GNSS





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For some context

Speed of light	c = 299,792,458 m/s (exact)

For some context

Speed of light — c = 299,792,458 m/s (exact)

so in 1 nanosecond (ns)

(1 billionth of one second) … light travels ~ 0.984 feet

For some context

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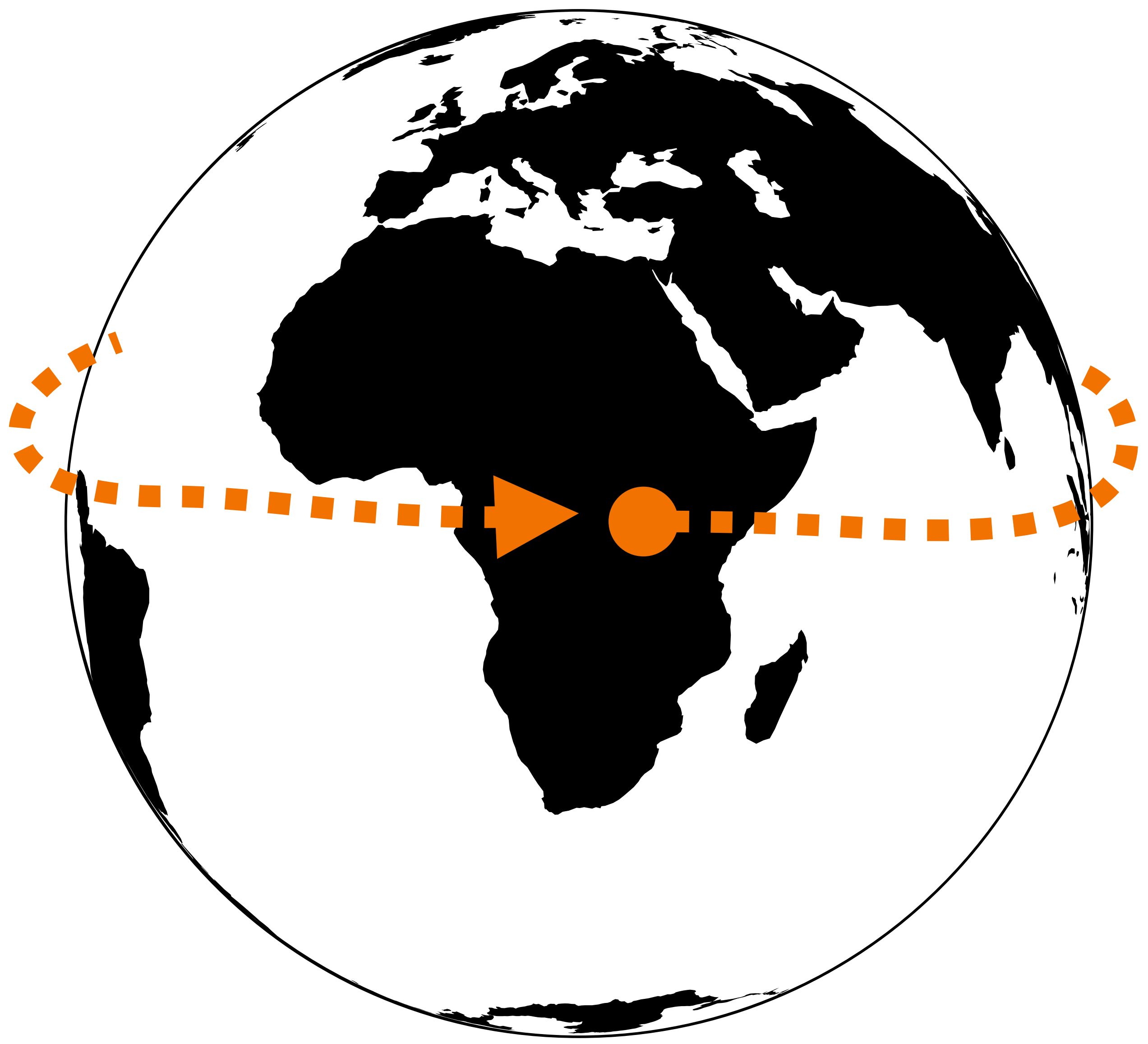
so in 1 nanosecond (ns) (1 billionth of one second) … light travels ~ 0.984 feet

or



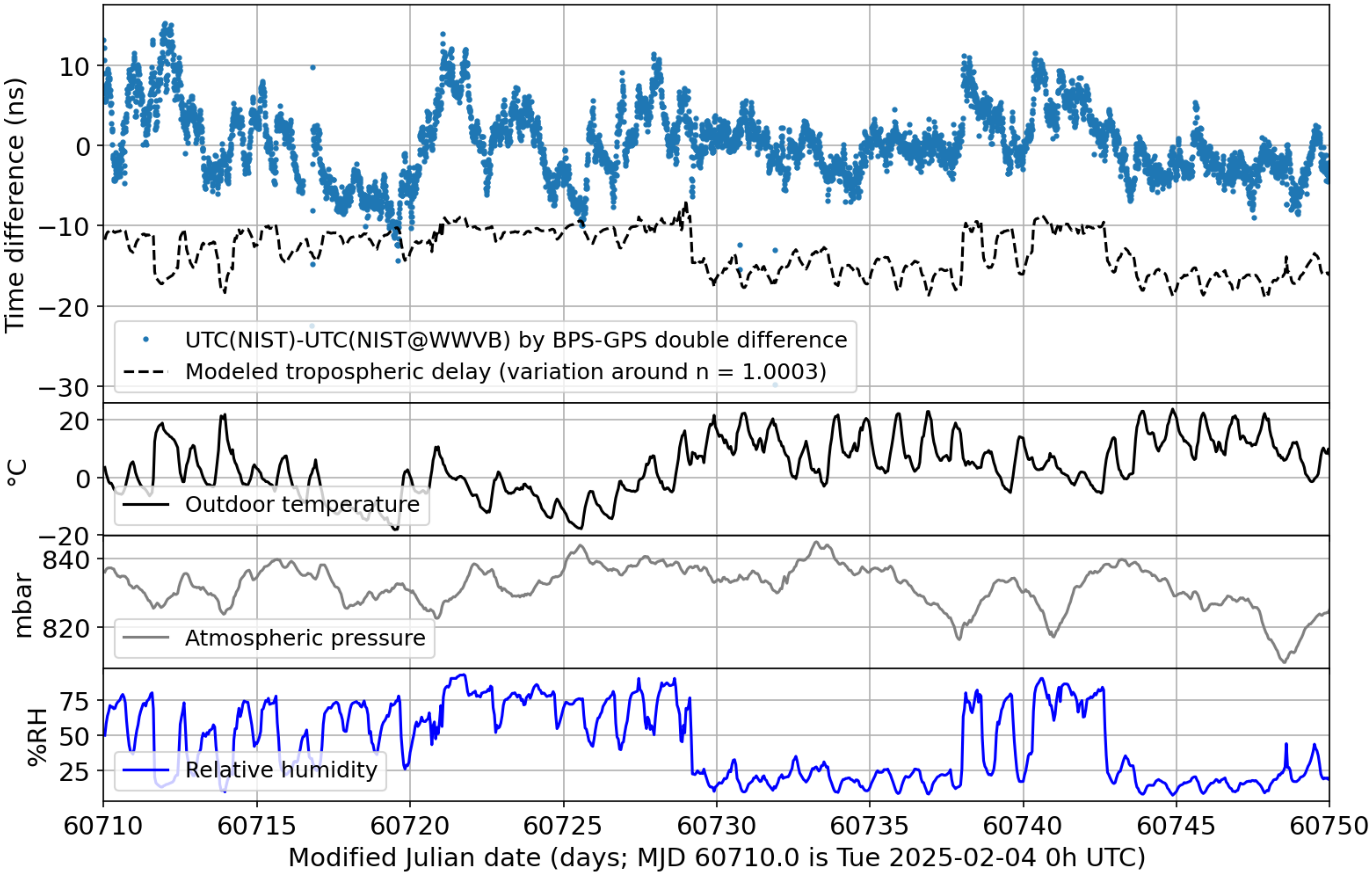
~200 ms (in fiber)

Unsuccessful: modeling variation as simple index-of-refraction *n(T, RH%, P)*

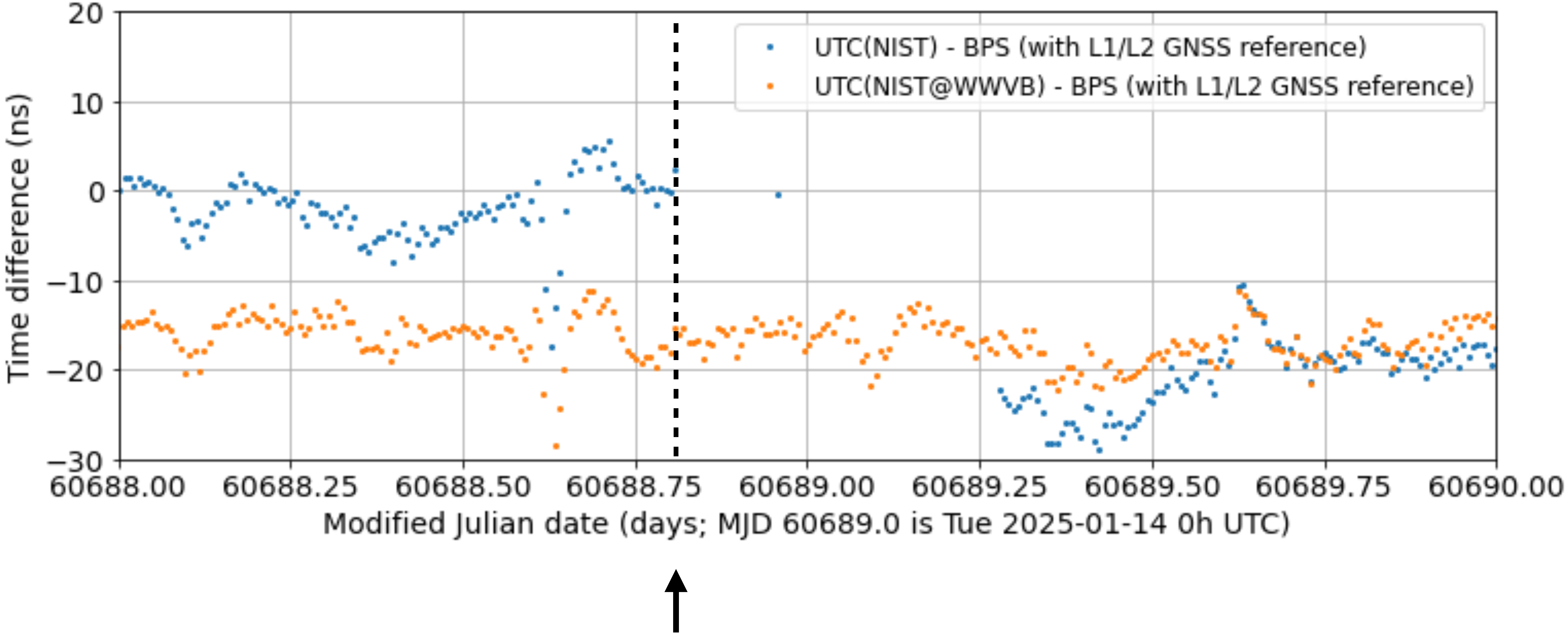
Single-point environmental data insufficient

NLOS variation (Boulder) may be dominant

Refractive effects on LOS path may be dominant



Anecdote about multi-path/co-channel interference variation

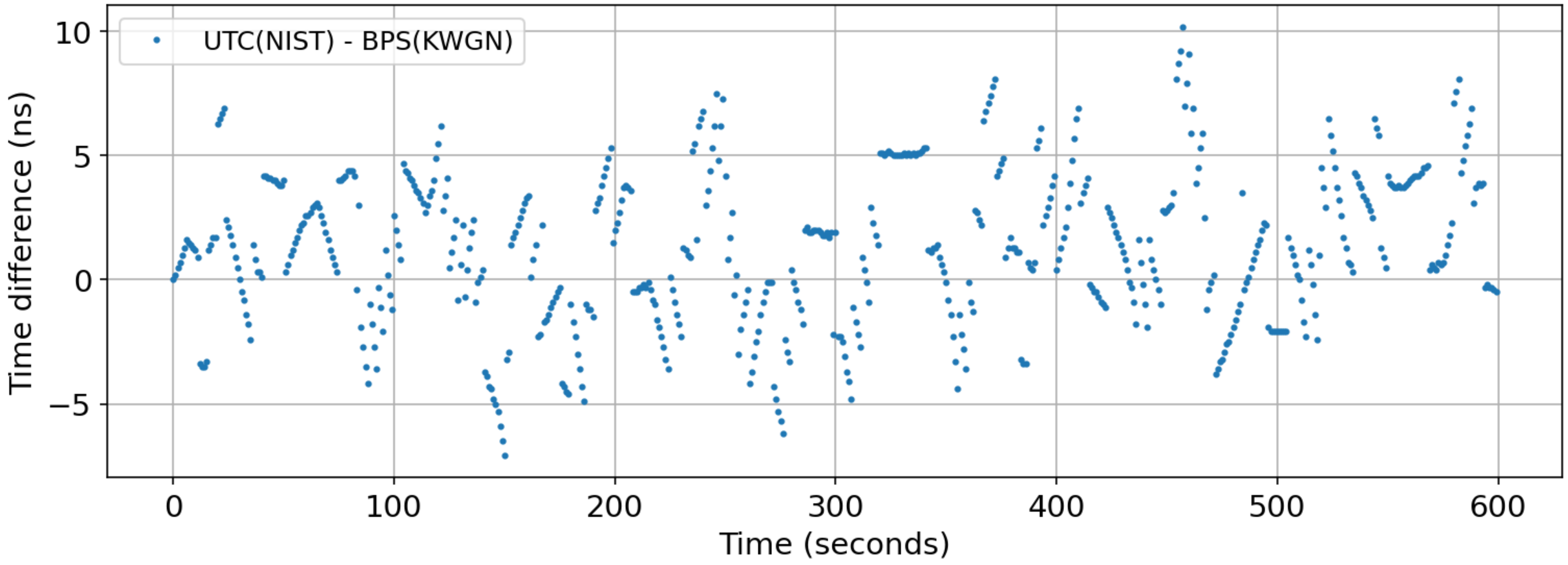


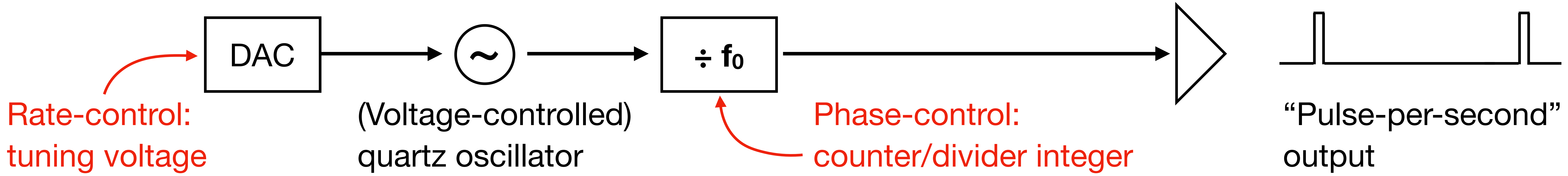
KWGN lowered transmitter power for maintenance operation

- Receiver in Boulder lost lock, reacquired with ~25 ns step
- No loss of lock or step seen at WWVB

Short term stability of BPS receiver output

Consistent with “quantization/sawtooth” servo design pattern; *not a fundamental limit*





Example mitigation in some GNSS timing receivers