Real World Testing: Two-Way Satellite Time Transfer Enables Simplified Traceable Timing

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May 2024

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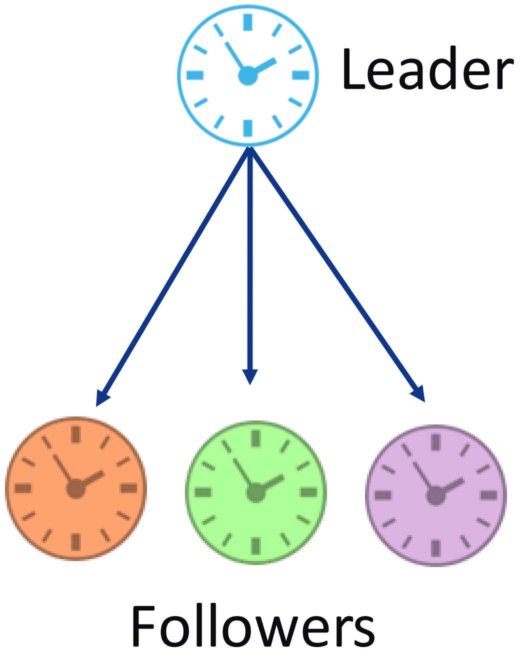
Agenda

- Two Way Time Satellite Transfer (TWSTT) using Geostationary satellites
- Deployment of TWSTT
- Results from recent TWSTT multi-site deployment
- Closing remarks and dispelling myths

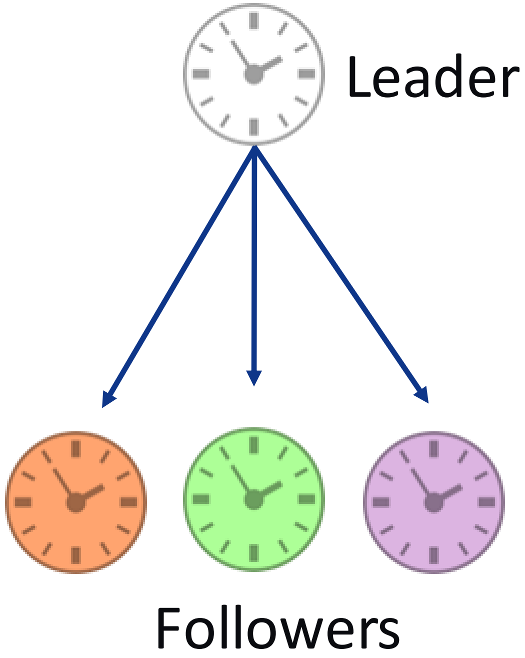
Leader -> Follower vs. Peer-to-Peer

GNSS



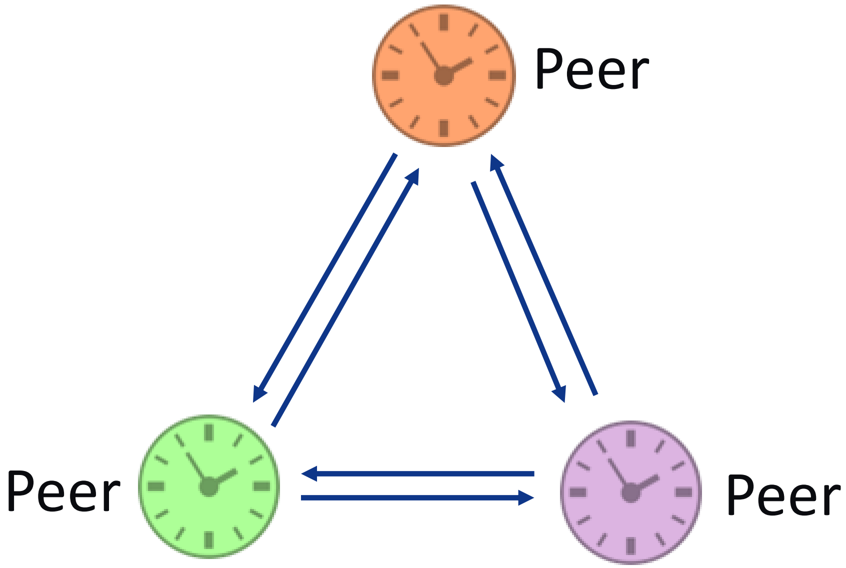
Concern of single point of failure

C-PNT



Concern of single point of failure

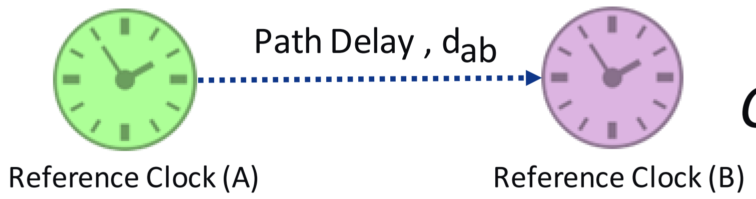
TWTT



Two-Way Time Transfer (TWTT) enables decentralized architecture which creates more resilience

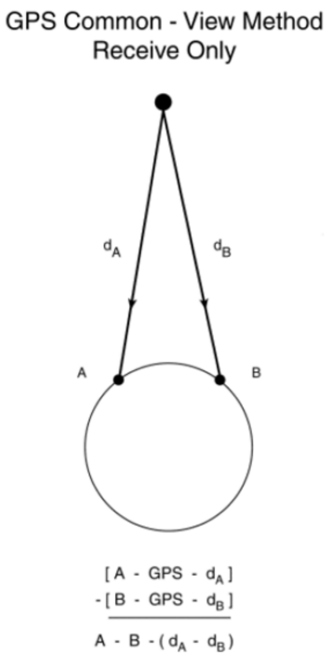
Time Transfer Techniques Compared

- **In general, most time transfer methods involve measuring two clocks using a timing signal sent between them (for example PPS, BPSK, etc)**
  - Delay of the medium must either be measured, modeled or otherwise accounted for

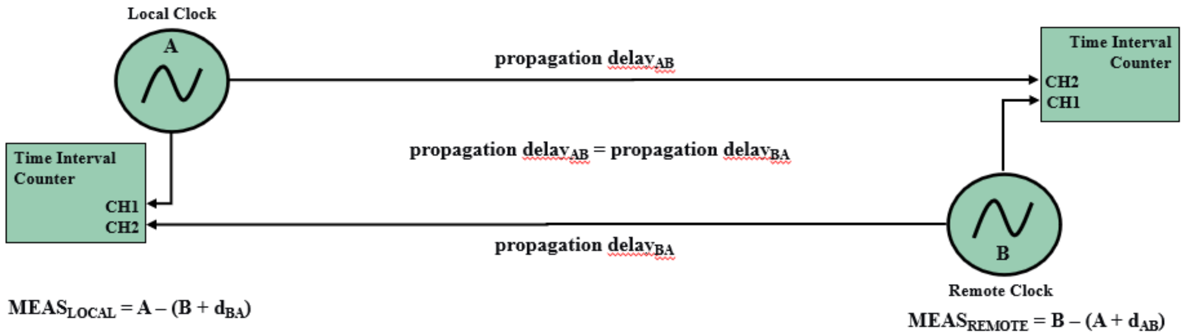


$$Meas_b = Clk_a + d_{ab} - Clk_b$$

- **Common view time transfer involves measuring a site's clock against a GPS satellite's clock**
  - Propagation delay (d_{ab}) of the GPS signal must be calculated and removed from the result
  - Involves taking the distance between the satellite and site (using satellite ephemeris) and calculating the propagation delay



- **Two-way time transfer involves trading timing measurements between two clocks over a common medium**
  - Since the propagation delay is equal in both directions, differencing the two measurements and dividing by 2 yields the clock offset between the clocks
  - In the case of two-way time transfer over satellite, the paths to and from the satellite at both stations are assumed to be equal



$(MEAS_{REMOTE} - MEAS_{LOCAL}) / 2 = B - A =$ Remote Clock Delay

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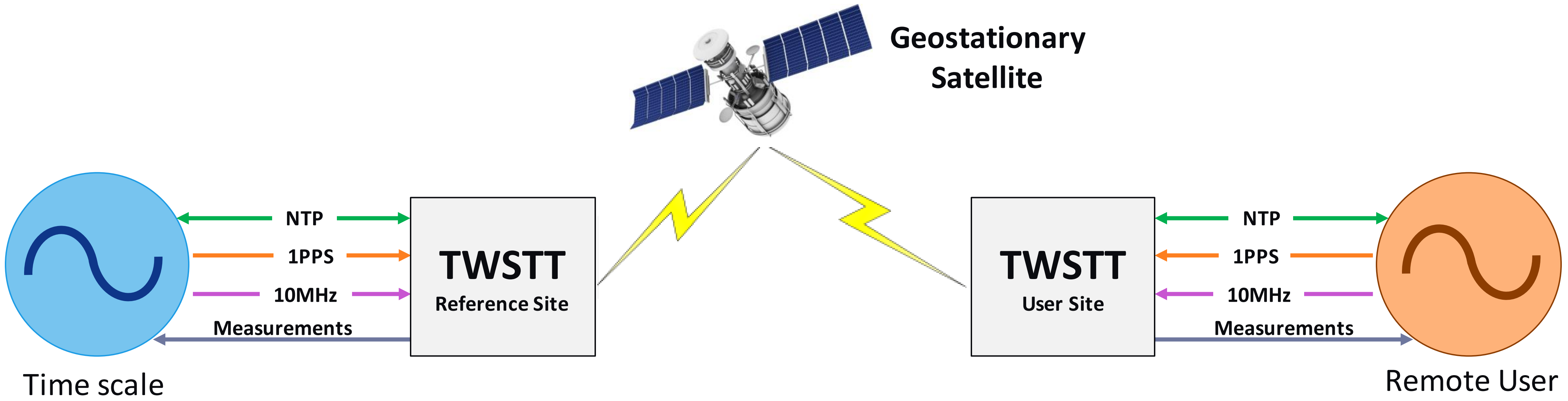
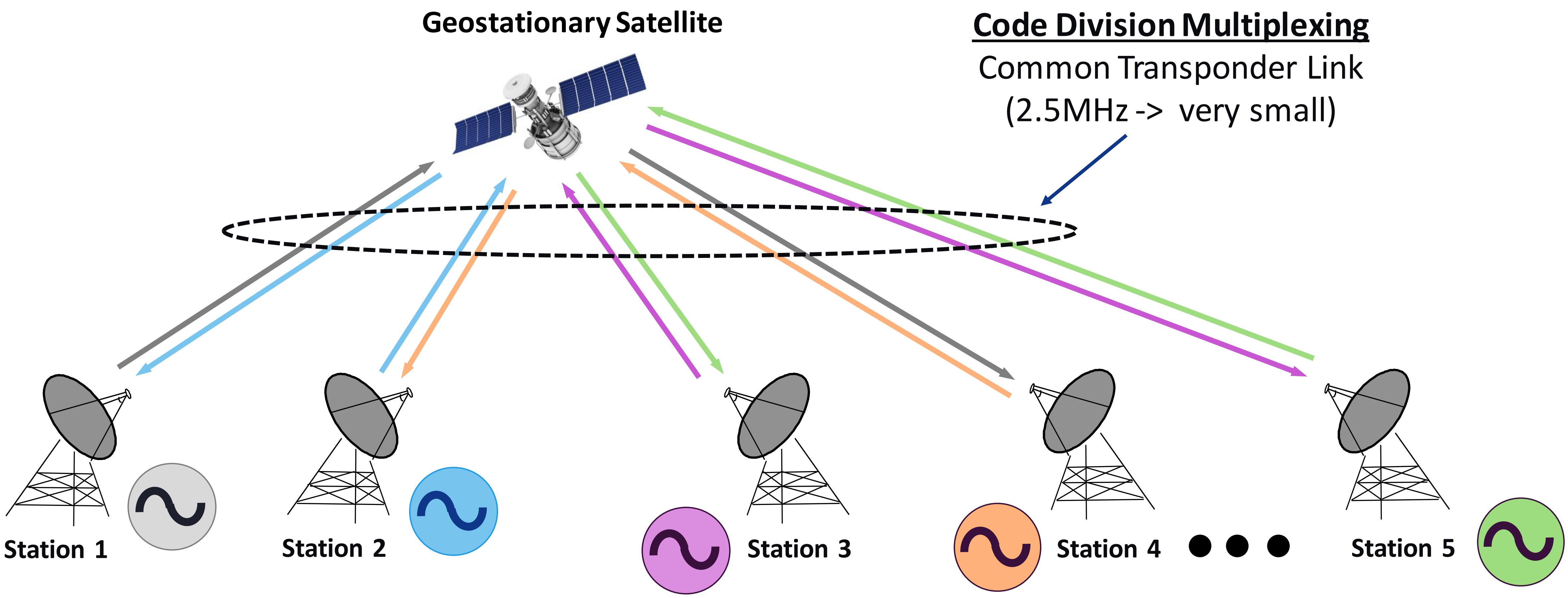
Two-Way Satellite Time/Frequency Transfer (TWSTT)

- **Key Benefits**
  - GNSS independent time transfer, typically within +/- 2 ns
  - Supports two-way (peer-to-peer) time comparison between multiple nodes
- **Use Cases**
  - Use measurements for quality control by comparing clocks on both ends of the link
  - Use measurements to steer the remote clock to the local clock (GNSS independent)



TWSTT Network – Working As A Group

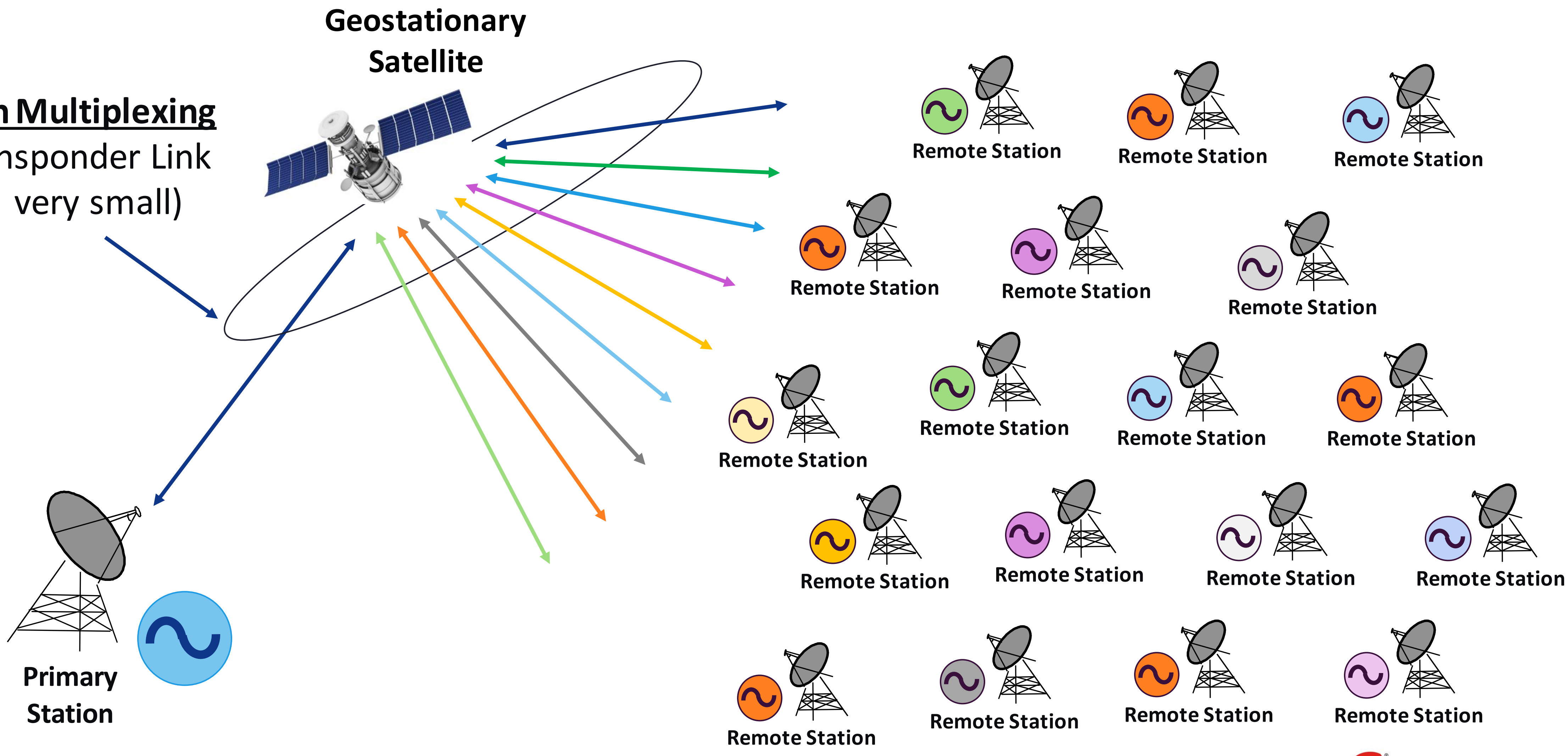
Multiple sites can perform clock comparisons sharing common link



TWSTT Network – Working At Scale

Time Division Multiplexing of transponder across large number of nodes

Time Division Multiplexing
Common Transponder Link
(2.5MHz -> very small)



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Deployment of TWSTT

NIST Two-Way Satellite Time/Frequency Transfer

NIST is offering UTC(NIST) via **two-way satellite time/frequency transfer (TWSTFT)**

Link stability ~ 1 ns
Inaccuracy ≤ 15 ns, depending on method of initial calibration

“Special test” profile:

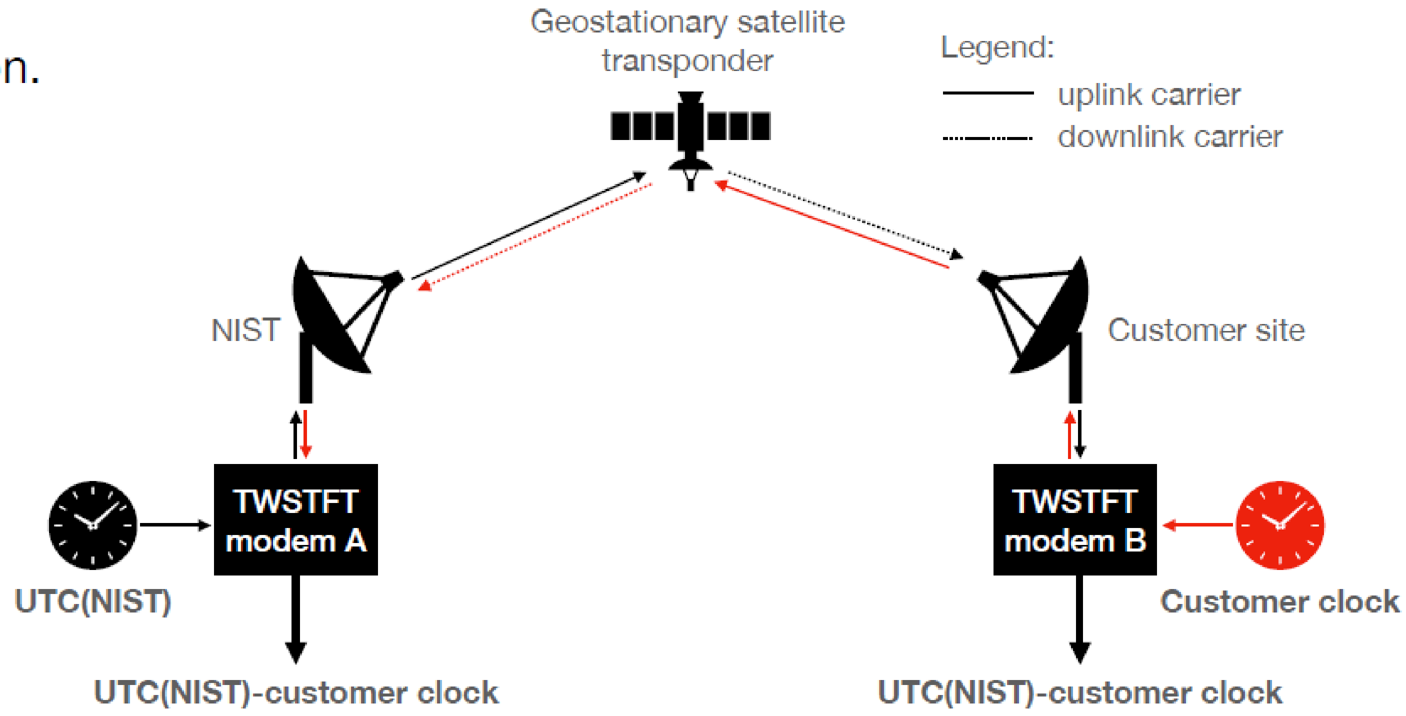
Started late CY 2023 with existing Earth station.
Subject to availability limitations.

“Service” profile:

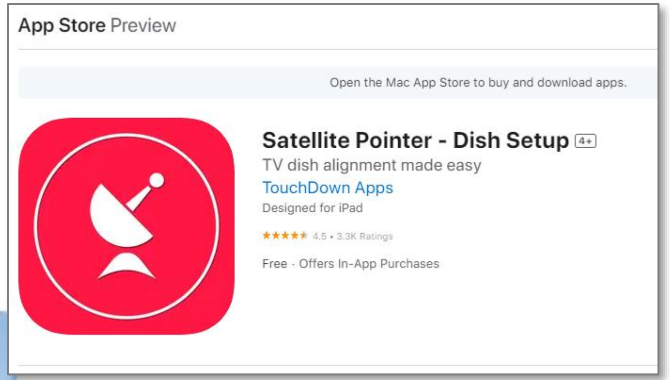
Available late CY24, demand-dependent.
Dedicated Earth station, satellite bandwidth.

Fees:

NIST services must recover all costs.



Satellite Finder From Your iPhone



(jeff.sherman@nist.gov prepared for: Dept. of Transportation Extended PNT Working Group, 16 Nov. 2021)

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Satellite Dish Deployments

Many Dish selection choices depending on location requirements

NIST Boulder

Beverly

Tuscaloosa

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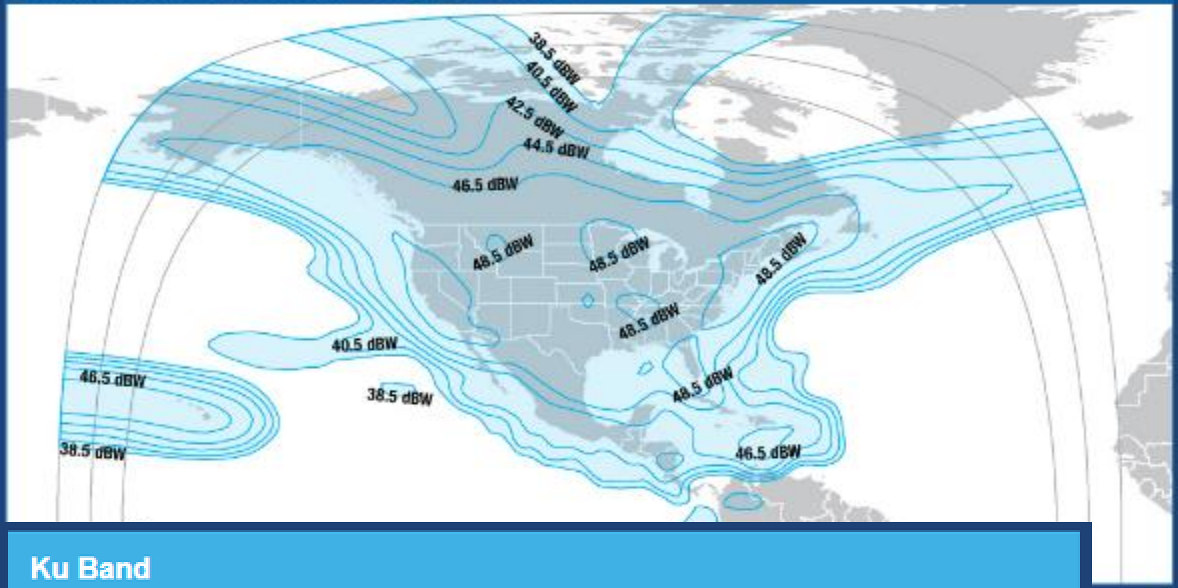
Easy to Find Satellite Coverage Online

Galaxy 19 at 97° W

Station Kept

FOOTPRINTS | KEY PARAMETERS

Ku-band North America Beam Peak up to 49.5 dBW



Ku Band

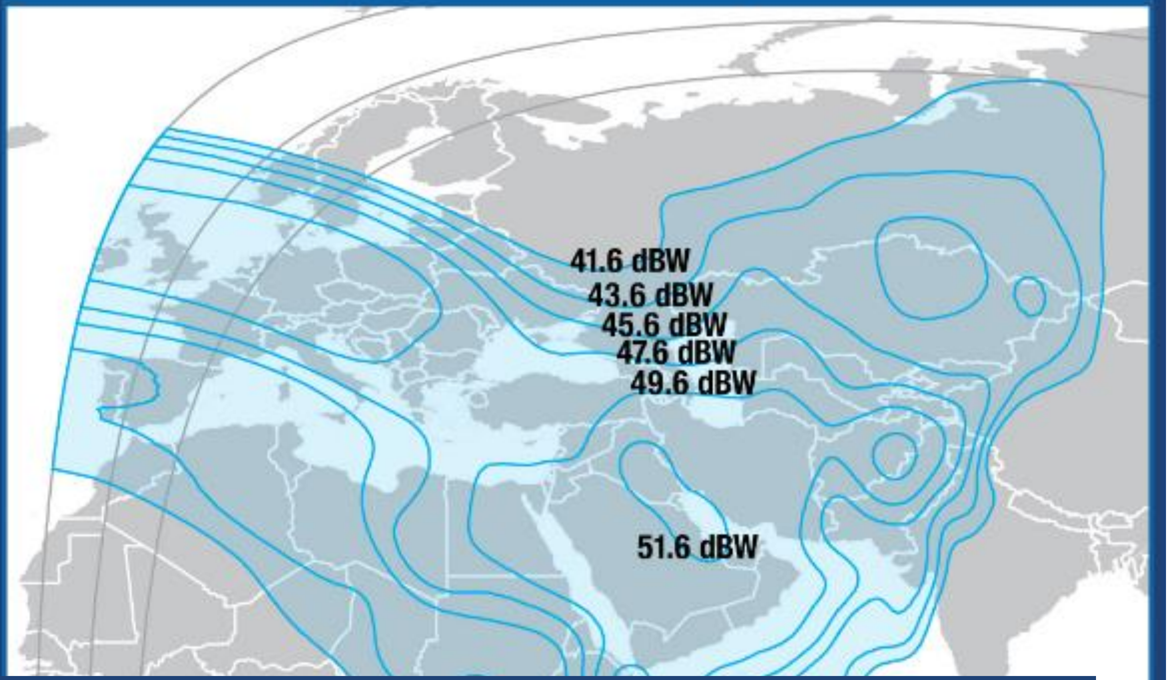
Ku-band North America Beam

Intelsat 17 at 66° E

Station Kept

FOOTPRINTS | KEY PARAMETERS

Ku-band Europe/ME Beam Peak up to 52.6 dBW



Ku Band

Ku-band Europe/ME Beam

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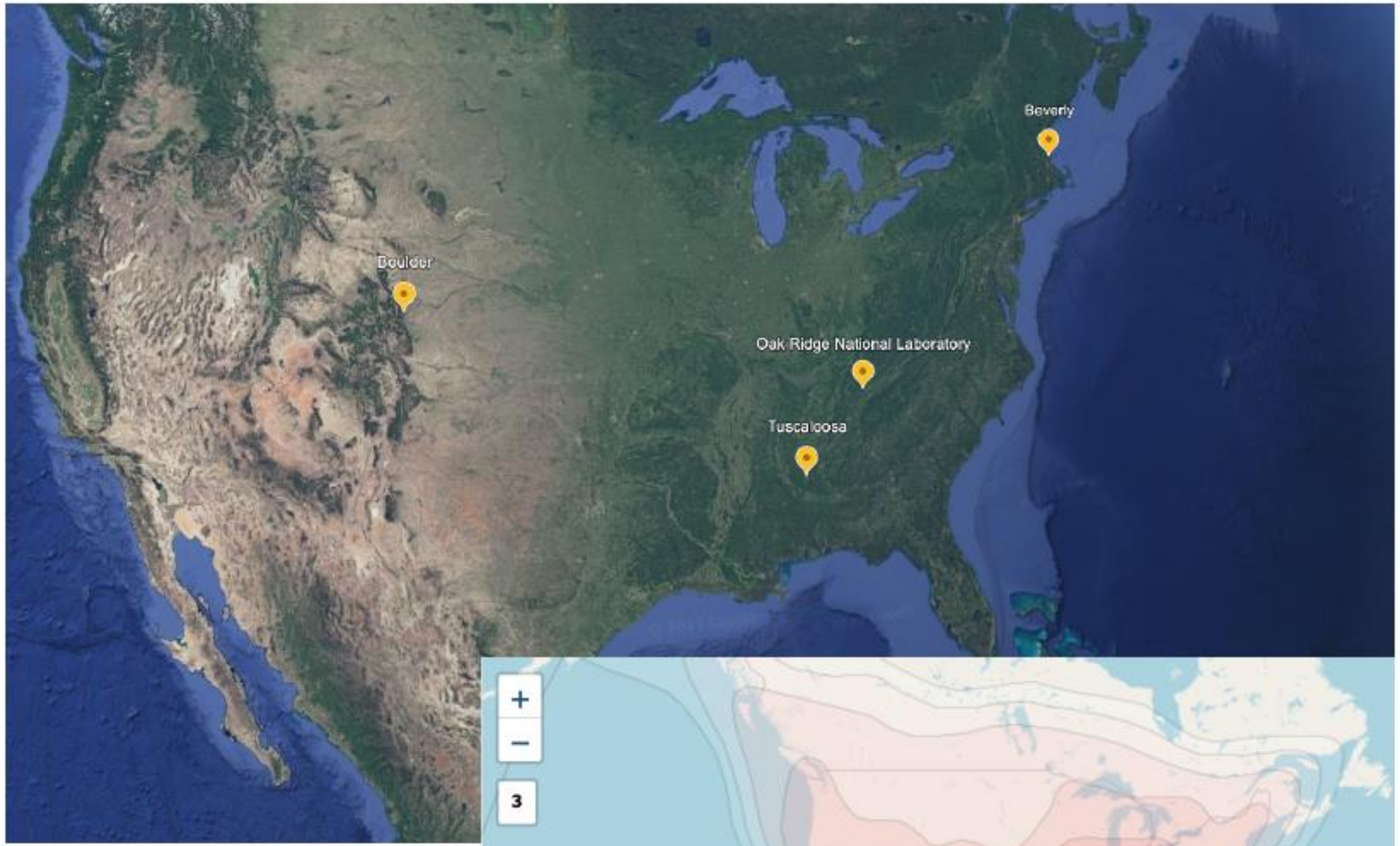
Results From Recent Multi-Site TWSTT deployment

Preliminary results: a "Time over Satellite" network

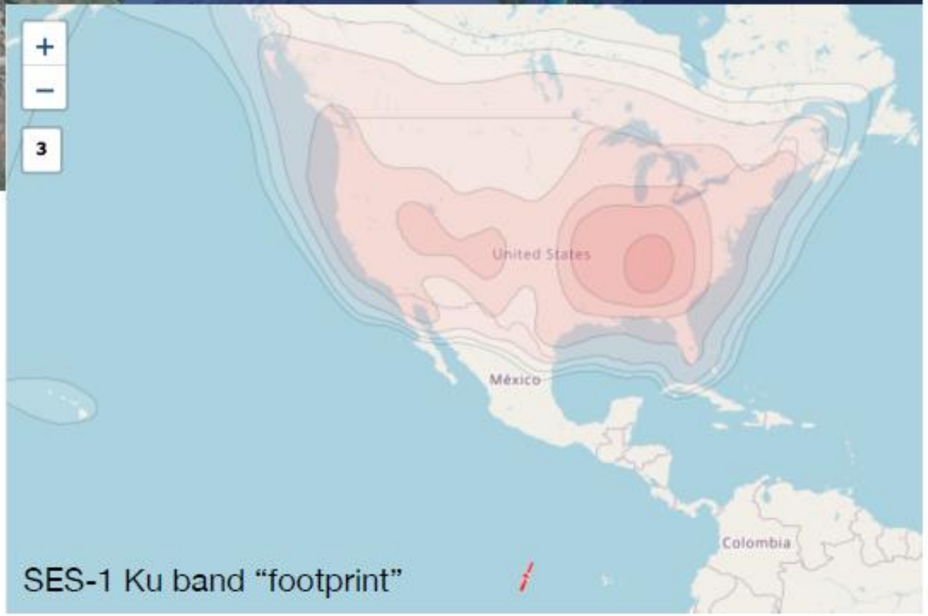
Five participating stations:

- NIST (Boulder, CO)
- ORNL
- Microchip:
  - Boulder, CO
  - Beverly, MA
  - Tuscaloosa, AL

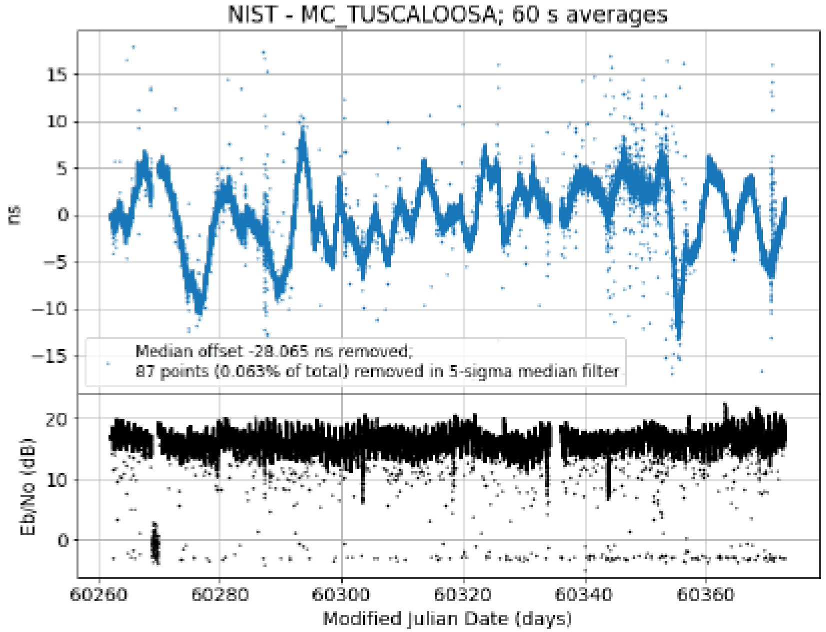


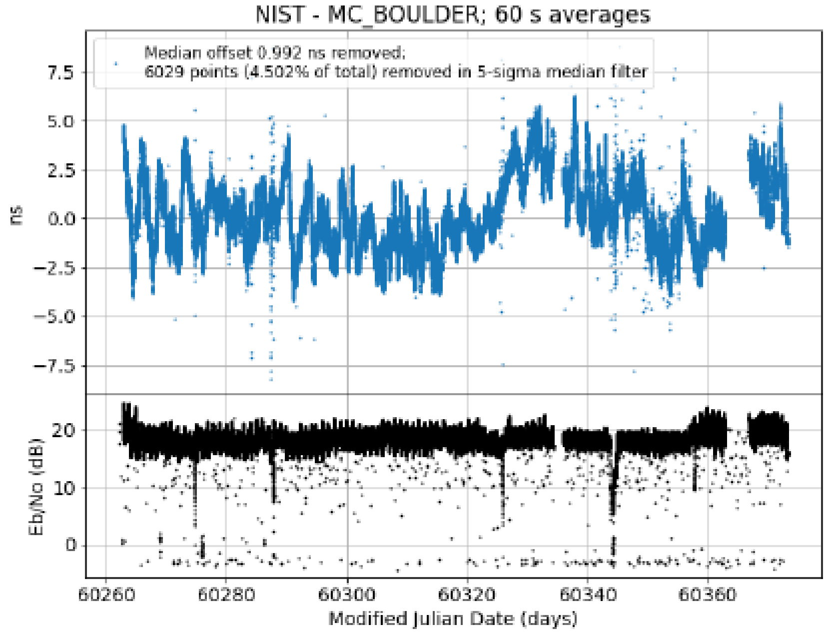
Test parameters:

- November 2023 - present
- 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"





110 days

Notes:

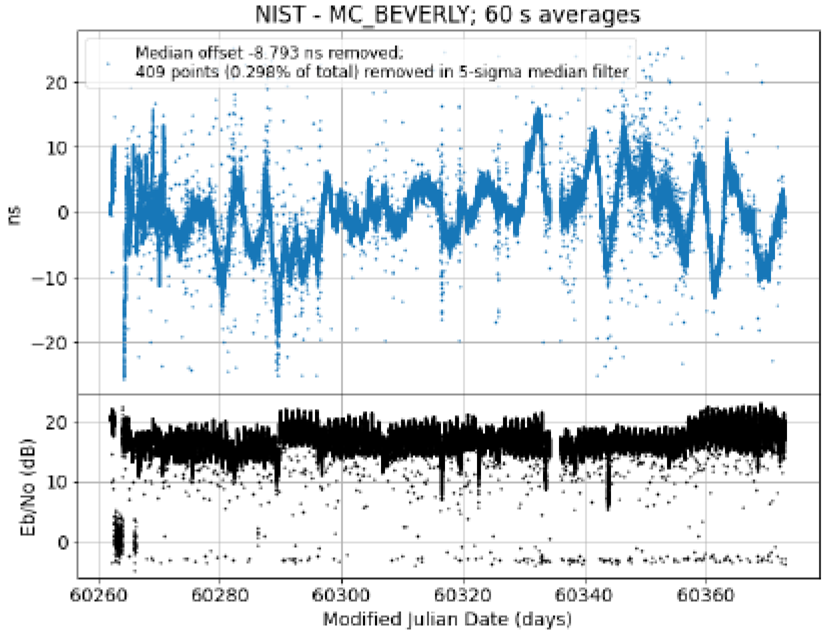
With no special calibrations, all stations report an offset with NIST < 30 ns.

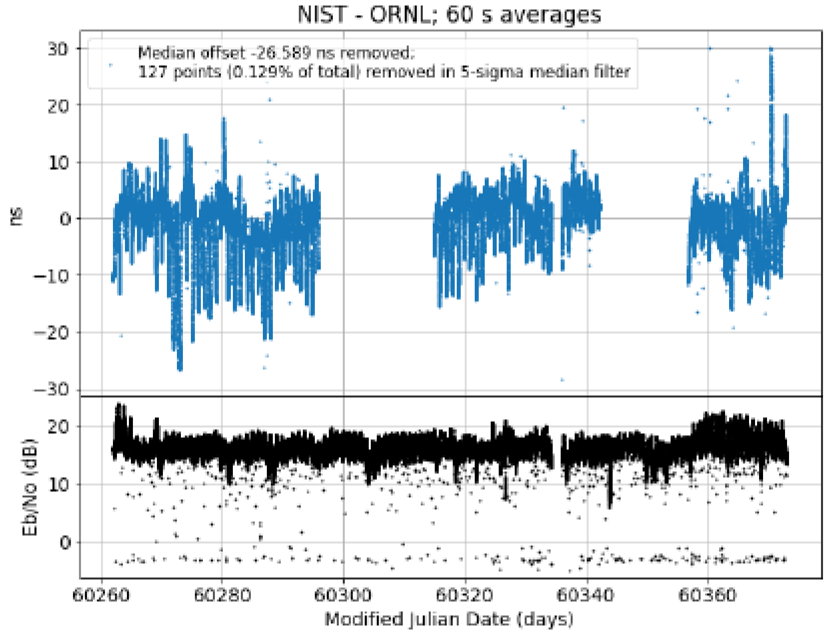
All stations measured their own "cable delay" to modem.

Excursions beyond 10 ns rare in all links.

Eb/No (energy-per-bit/noise ratio) is a Rx signal quality monitor.

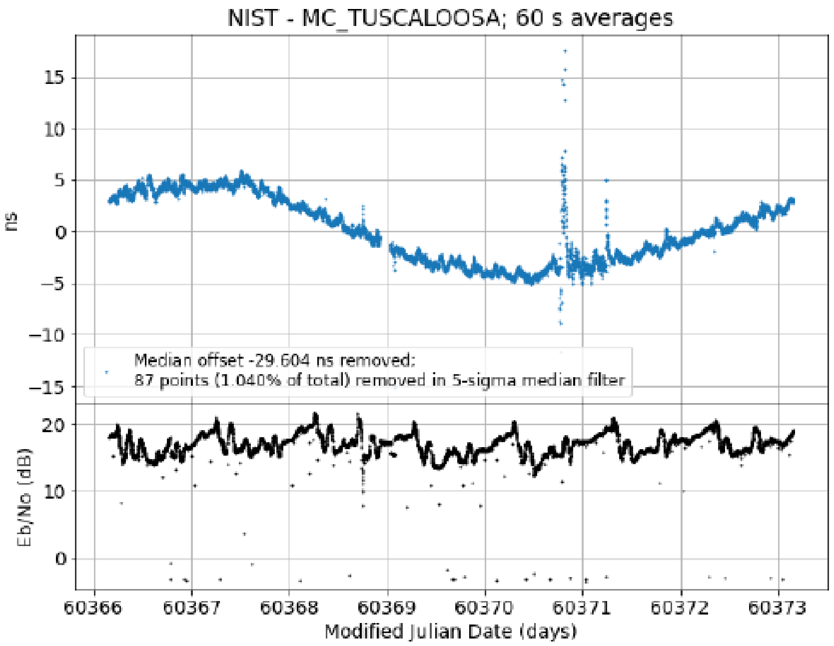
NIST interrupts link every hour (every 2 hours in first two months)

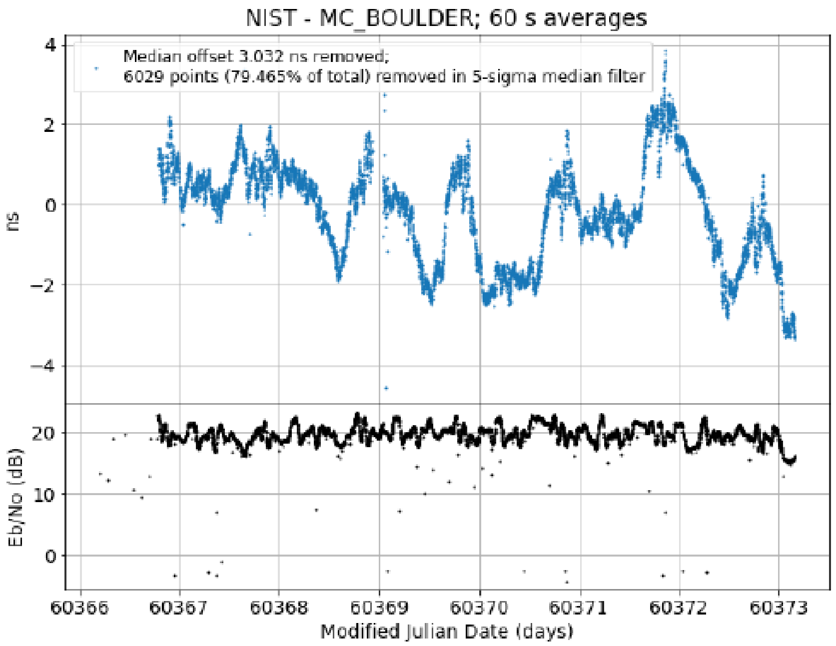




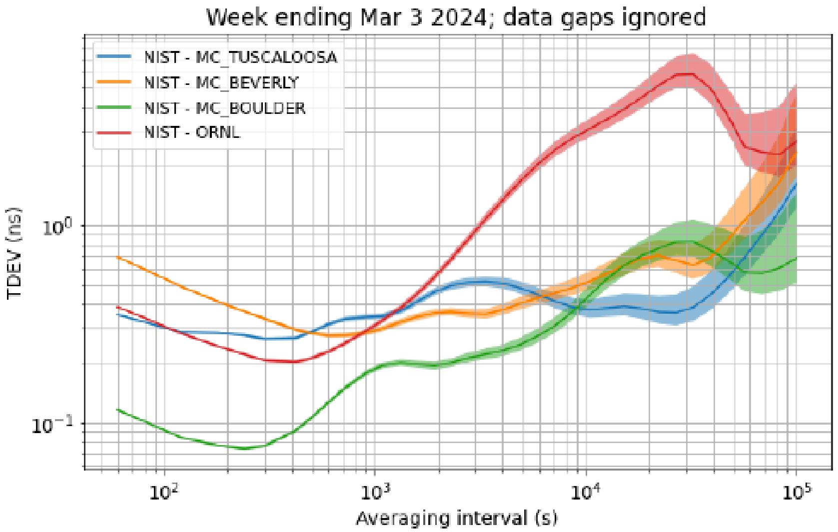
ORNL didn't save the correct default configuration into their modem; they had to take manual action to restart their link with NIST after reboots.

However, NIST measured ORNL's signal continuously.

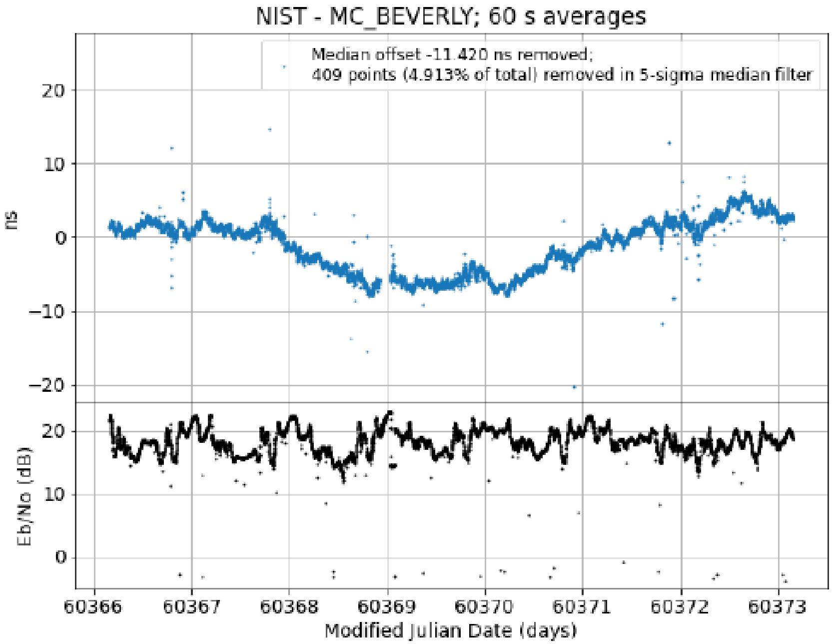


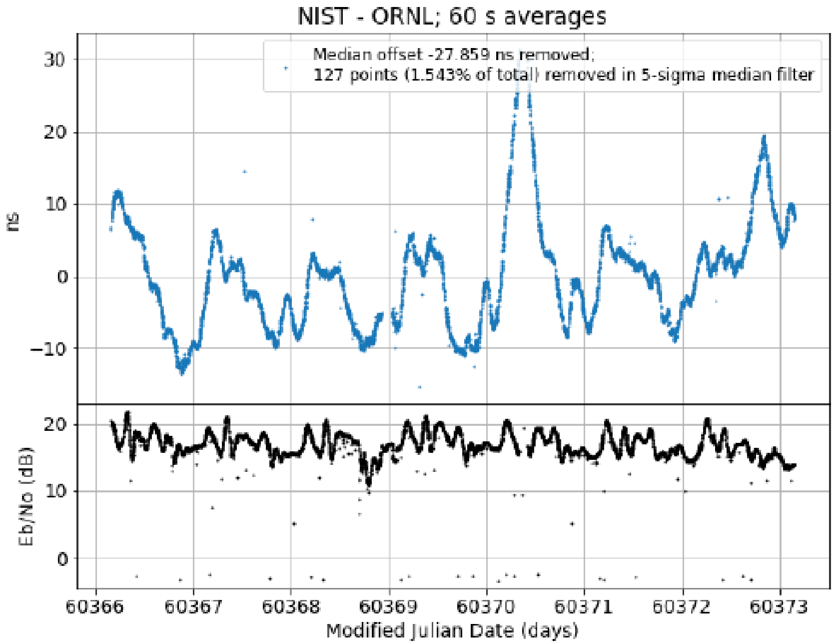


Recent 7 days



TDEV floor sets the limit of stability in any "steered remote clock" mode and gives an appropriate averaging interval.

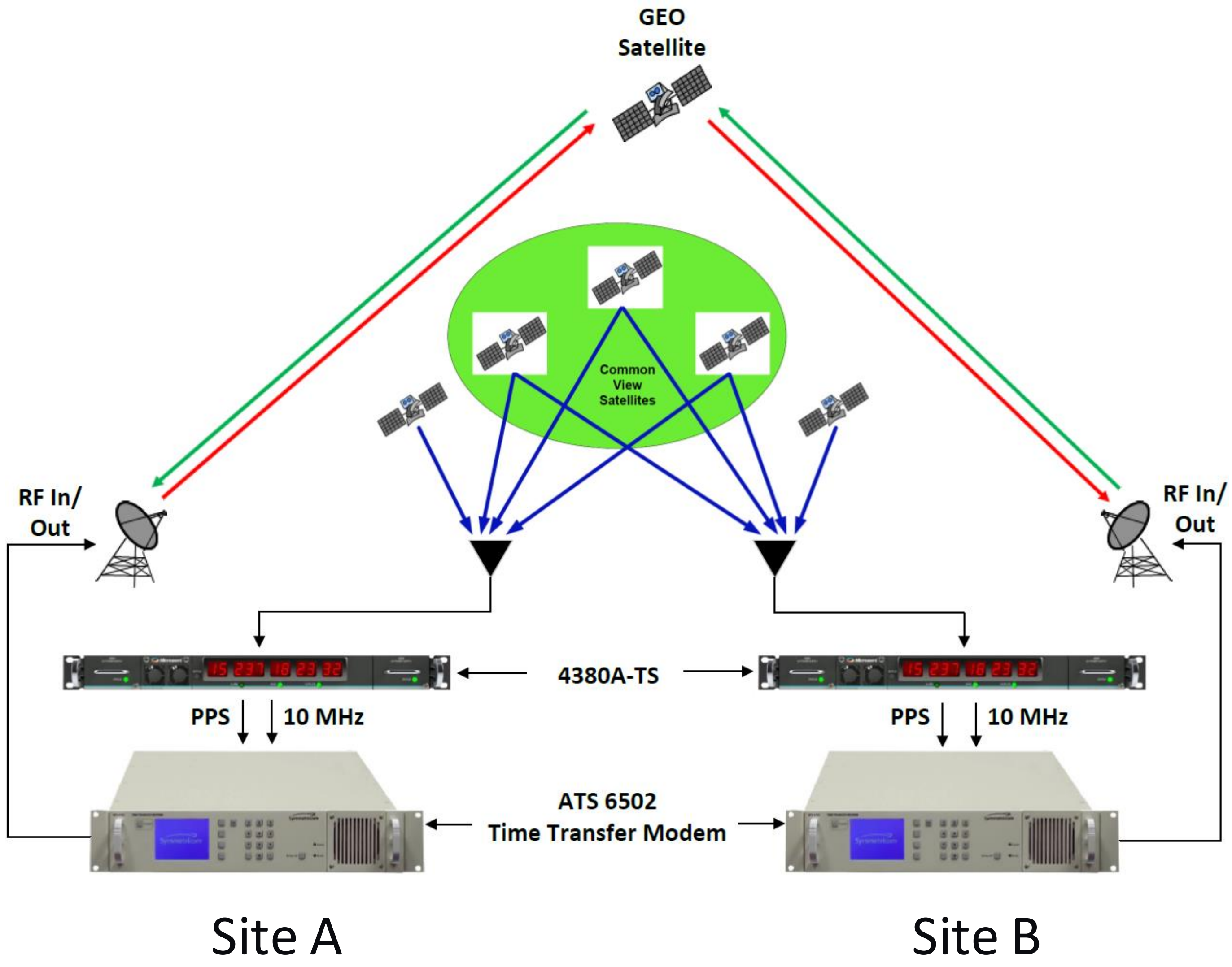




preliminary NIST results, shared by NIST and intended for public viewing

Methodology and Test Description at Microchip Sites

- **Timing system at each test site acts as GPS disciplined timing reference**
  - Includes L1/L2 GPS receiver to perform all GPS measurements
- **TWSTT modem measures the timing signals from the reference via TWSTT**
  - Accuracy: ~ 1 – 2 ns
- **Provides 2 independent measurement methods**
  - Common View: Measure two clocks via a third common clock (GPS satellite)
  - TWSTT: Measure the clock offsets directly over a GEO satellite



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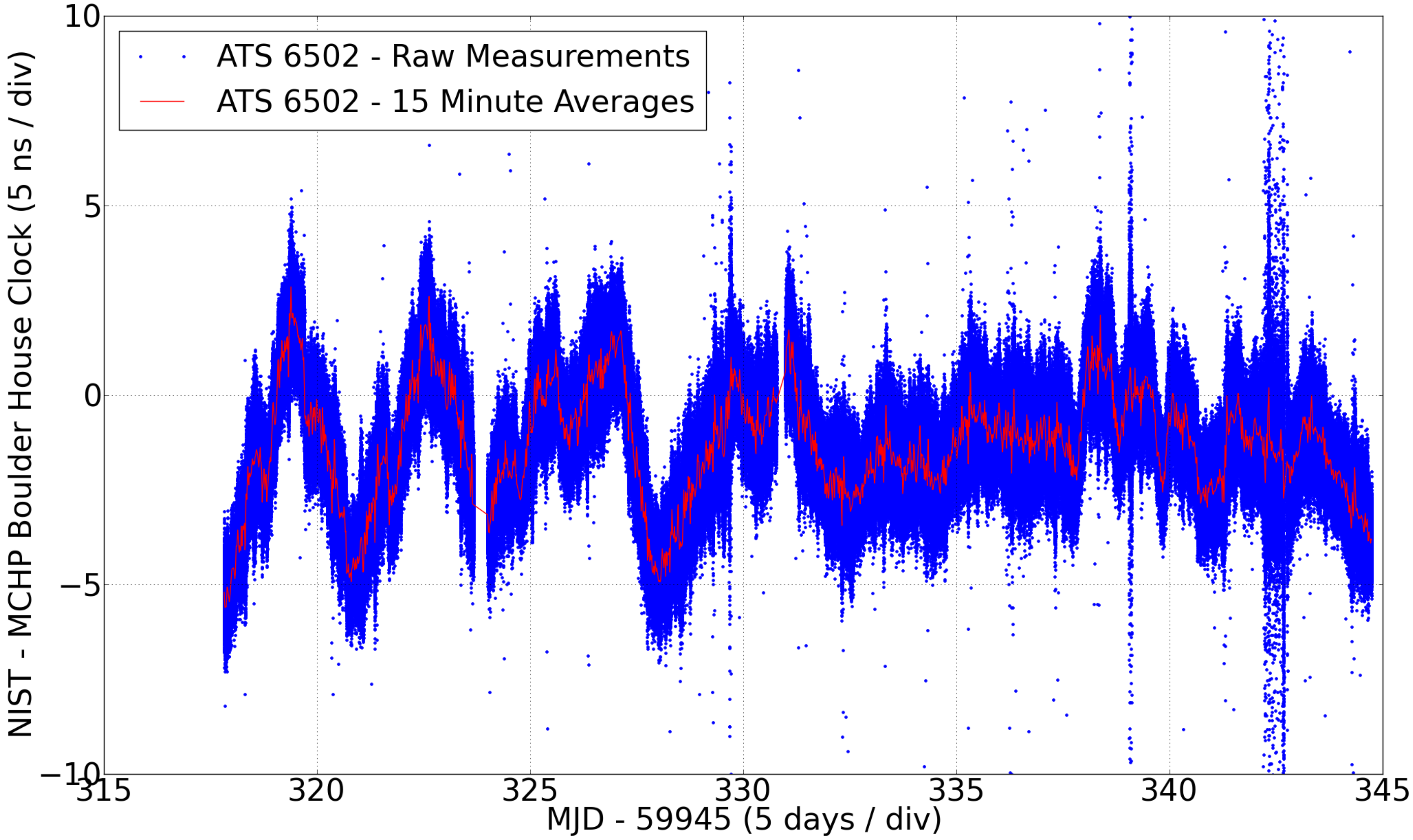
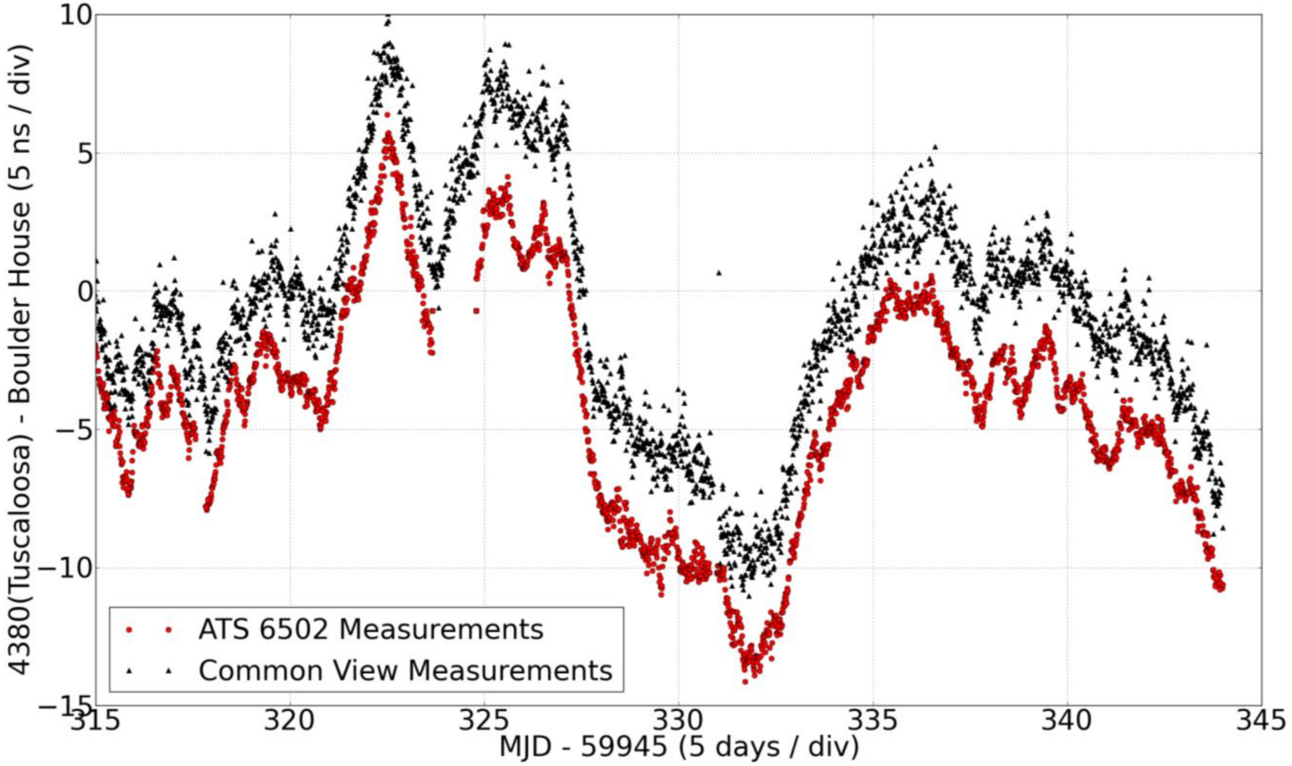
Test Results: TWSTT With NIST

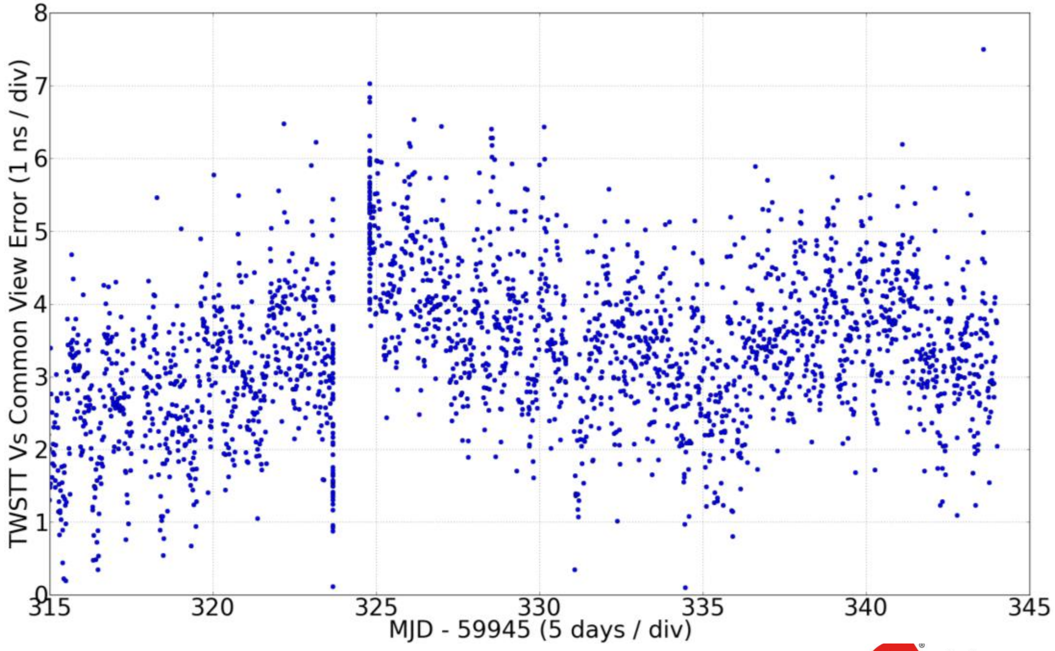
- **To analyze data, the raw measurements are averaged over 15-minute windows**



Test Results: Tuscaloosa Versus Boulder



- **Comparing the TWSTT modem results with the common view measurements shows qualitative agreement, but a slight offset this time**
  - Average Error: +3.3 ns
  - Error Standard Deviation: 1.2 ns



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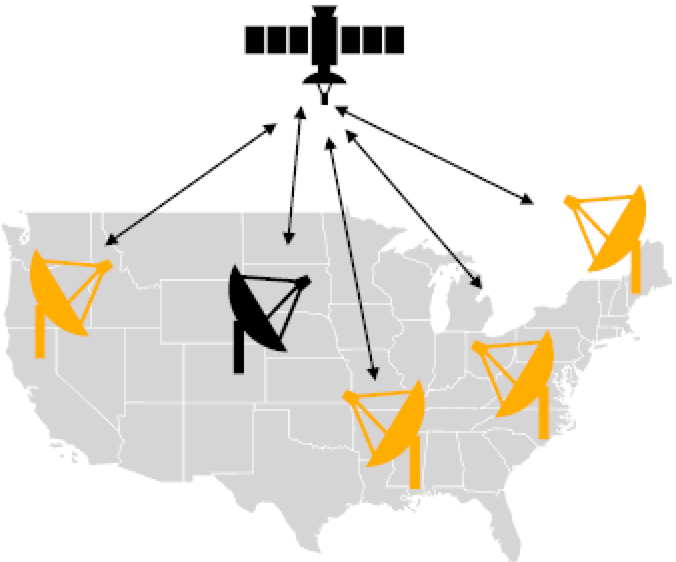
Closing Remarks and Myths Dispelled

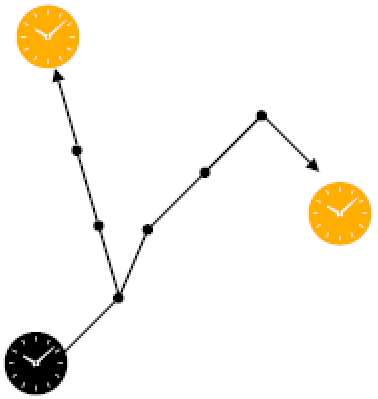
Comparison of < 1 μs techniques:

Time over Satellite



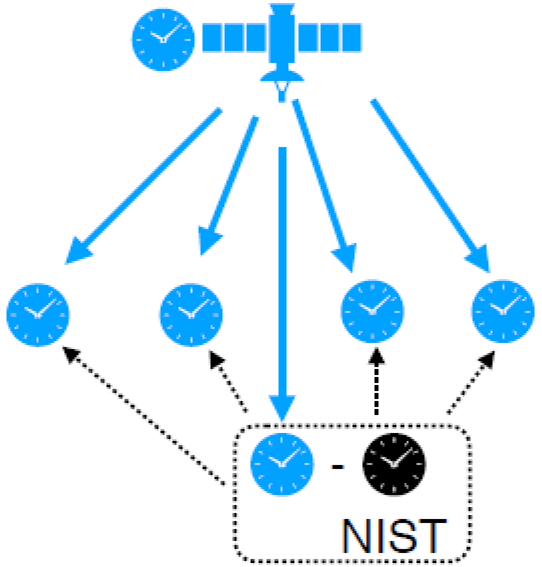
- Arbitrary mesh network
- Smaller recurring costs per node
- Traceable to UTC(NIST)
- Instability: < 0.2 ns (5 minutes avg.)
- Uncertainty:
  12 ns calibrated with GPS-CV
  ~1 ns calibrated with mobile TW

Time over Fiber



- Point-to-point
- High recurring costs per link
- Maybe traceable only for direct links to NIST
- Dark/un-routed < 1 ns
  Routed (e.g. OTN) ~ tens of μs
- Depends critically on physical layer
  < 200 ns, standalone (some configs.)
  12 ns calibrated with GPS-CV

GPS common-view (NIST TMAS)



- Hub-and-spoke
- Global range
- Traceable to UTC(NIST)
- ~ 2 ns (1 day avg.)
- 12 ns (95% c.i.)

Myths Dispelled about Geostationary TWSTT

- **“It’s expensive” -> Incorrect**
  - Pricing from geostationary satellite operators has come down
  - Sharing across multiple sites of common transponder lowers price
  - Time multiplexing of transponder enables scale and lowers price further

- **“It’s difficult to deploy” -> Incorrect**
  - UTC(NIST) traceable service available today
  - Small dish size using KU-band (typically 1.2 meters) simplifies installation

- **“It’s difficult to operate” -> Incorrect**
  - Equipment is COTS with commercial support resources available

Key Benefits of TWSTT Using Geostationary Satellites

- **Enables clocks in diverse geographical locations to be compared with high accuracy and to operate autonomously**

- **Enables global synchronization without a single point of failure**
  - Ideal for cloud service companies with dispersed data centers

- **Augments terrestrial (optical or RF) time distribution**
  - Provides greater redundancy and resilience

- **Provides traceability to UTC authorities (BIPM, NIST, PTB, other)**