Timing Subcommittee Report

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

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CGSIC, 2020✦

★ brp1@nist.gov / / ✦ ~~the year of the toilet paper shortage~~ the joke from yesterday has been retracted to mourn the loss of more than 200000 American lives due to COVID-19

Civil GPS Service Interface Committee

Timing Subcommittee

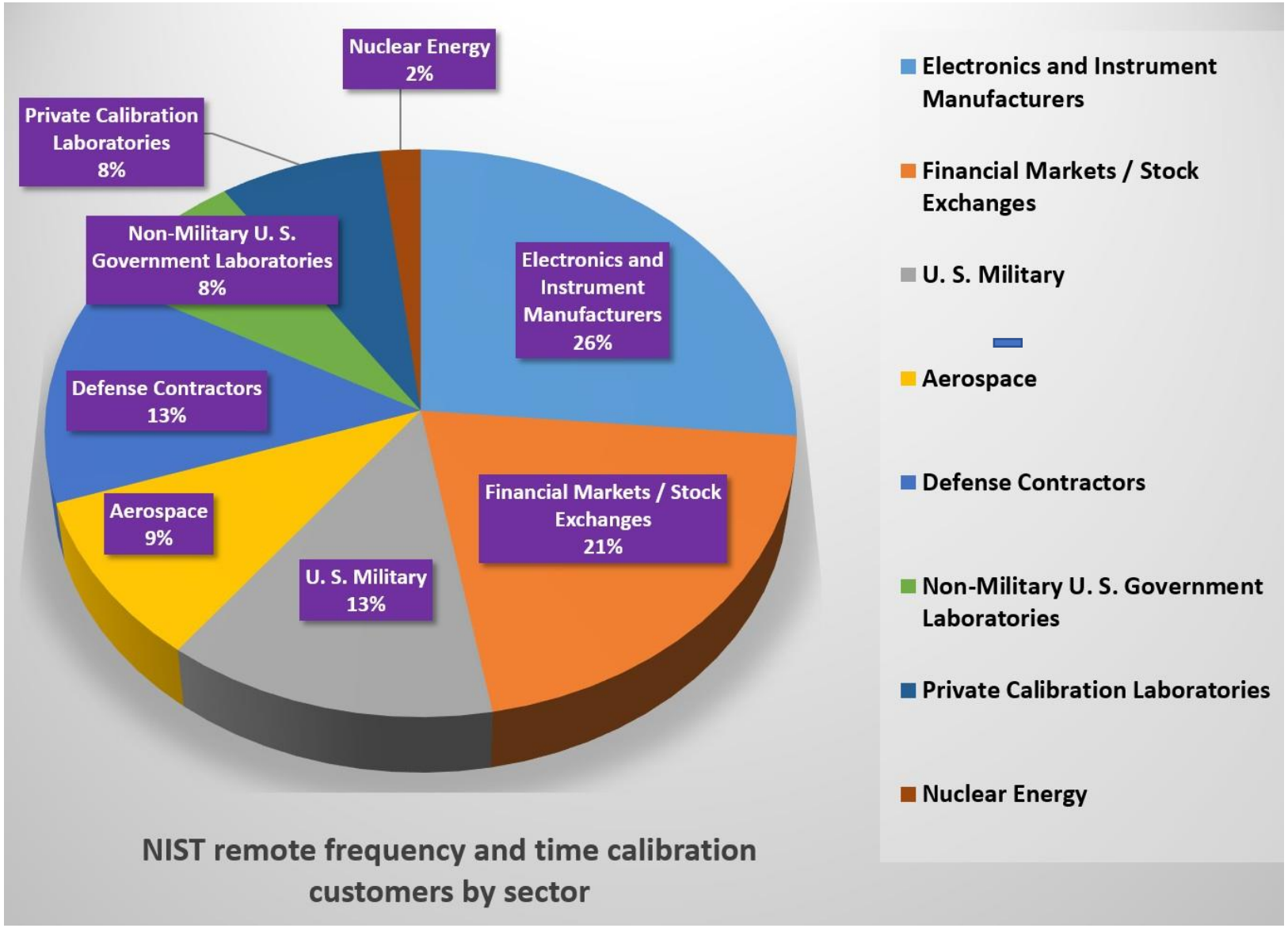
Chair: Dr. Bijunath Patla, National Institute of Standards and Technology (NIST)
Co-Chair: Dr. Lin Yi, NASA Jet Propulsion Laboratory (JPL)

21 September 2020

Theme and scope of this year's program

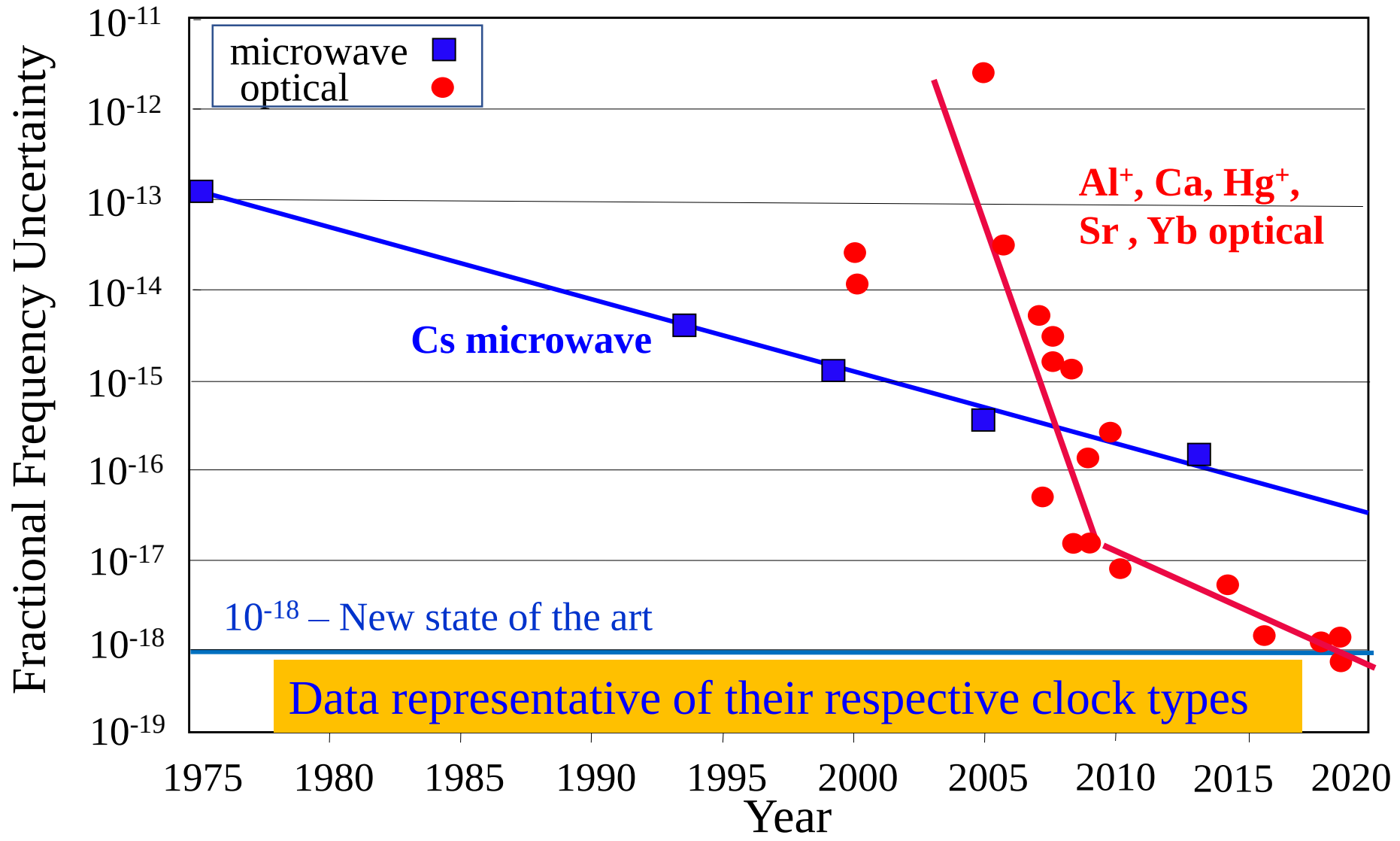
- Timing in a challenging and expansive landscape
- Atomic clocks and fundamental science

Theme and scope of this year's program

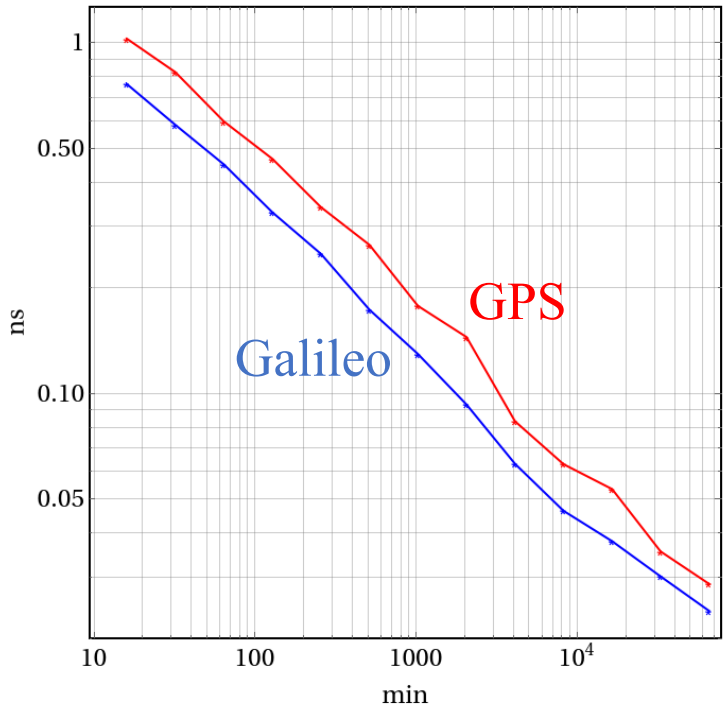


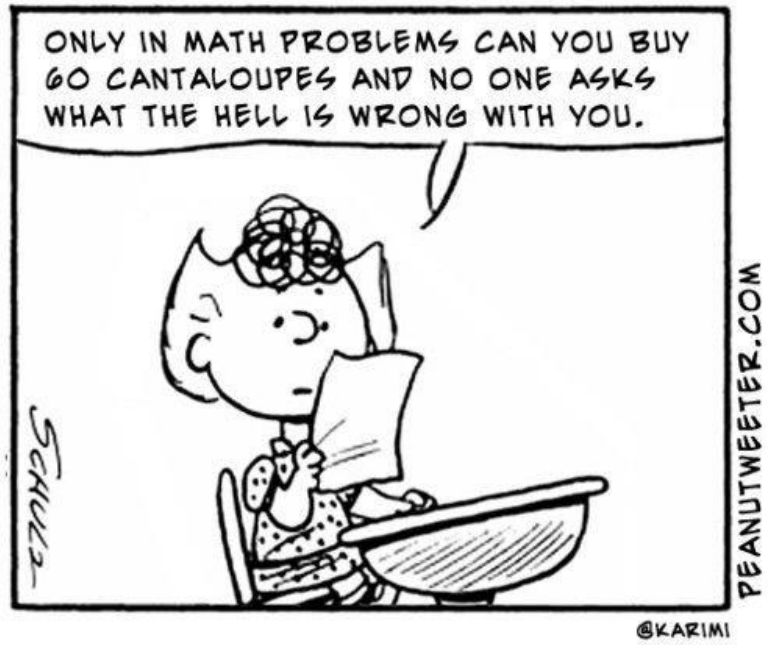
An example from NIST

Theme and scope of this year's program



Report from NIST / Bijunath Patla





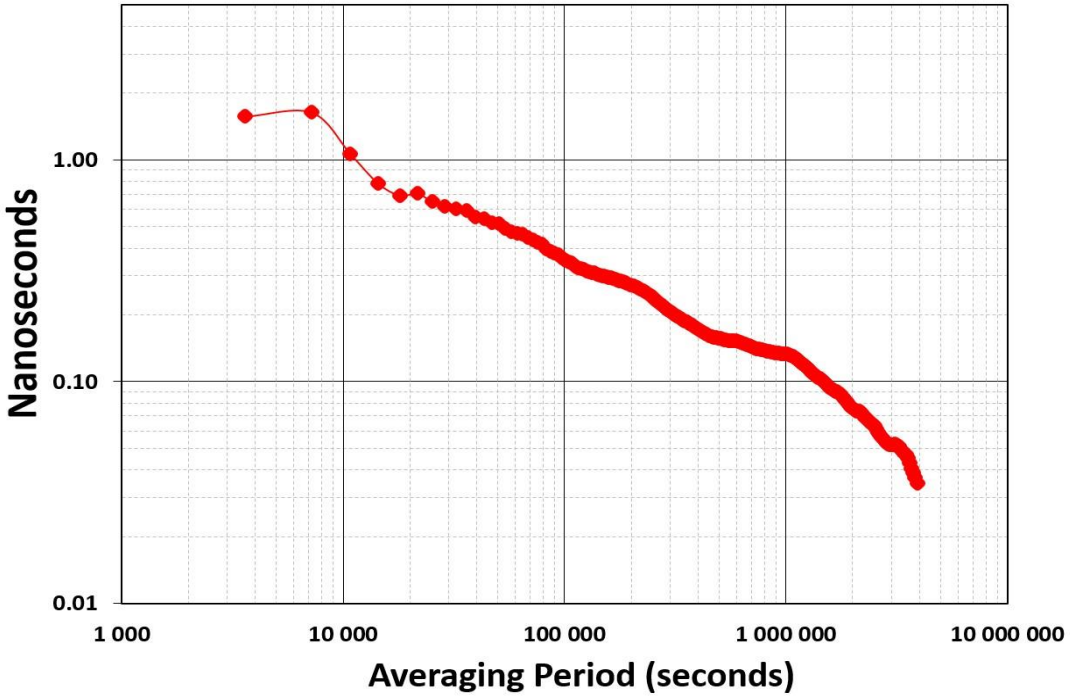
Because mathematicians care less about cantaloupes and more about averaging.

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

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

Report from NIST / Bijunath Patla

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.

Report from USNO / Stephen Mitchell

To ensure interoperability of all different GNSS

- Need to measure and report timing offset between systems
  - GPS-to-GNSS Time Offset (GGTO)
- Requires stable, repeatable GNSS receiver calibration for all GNSS signals

USNO will provide GGTOs for broadcast by GPS

- USNO is presently providing both GLONASS and Galileo time differences in support of special CNAV testing (not presently being broadcast)
- CNAV Message Type 35 contains the GPS-to-GNSS Offset (GGTO) for various systems
- Current schedule for broadcast is 2022 with the GPS Next Generation Operational Control System (OCX)

Report from USNO / Stephen Mitchell

- USNO will act to coordinate GGTO determination methods with other Global Navigation Satellite Systems and provide GGTO information to GPS
- Ensure consistent messaging from GNSS providers on using provided GGTO values
- Also supporting OCX, USNO will work with USAF for the determination of the GPS satellite and reference stations inter-signal and inter-frequency biases
  - This is needed to ensure that average constellation biases are removed in a consistent way to ensure accuracy for timing user community
  - Many different signal pairs to be available with differing biases per pair (e.g.: L1 C/A + L2C, L1C + L5Q, etc.)
  - Absolute calibrations to be used by USNO
- GNSS simulator calibration procedures are being validated and tested to ensure consistency and accuracy

Highlights of report from NRL / Mike Coleman

- U.S. Naval Research Laboratory, with a long background in GPS and timing applications, is designing the New GPS System Timescale.
- New timescale is being developed within GPS's Ground Control Segment upgrade, OCX.
- Timescale will combine satellite Rb and Cs clocks as well as monitor station commercial cesium clocks.

Goal: Generate an ensemble reference time that:

- estimates phase, frequency and drift of each member clock,
- is not solely dependent on any one clock as the master, and
- is capable to steering to any identified source, UTC(USNO) in particular.

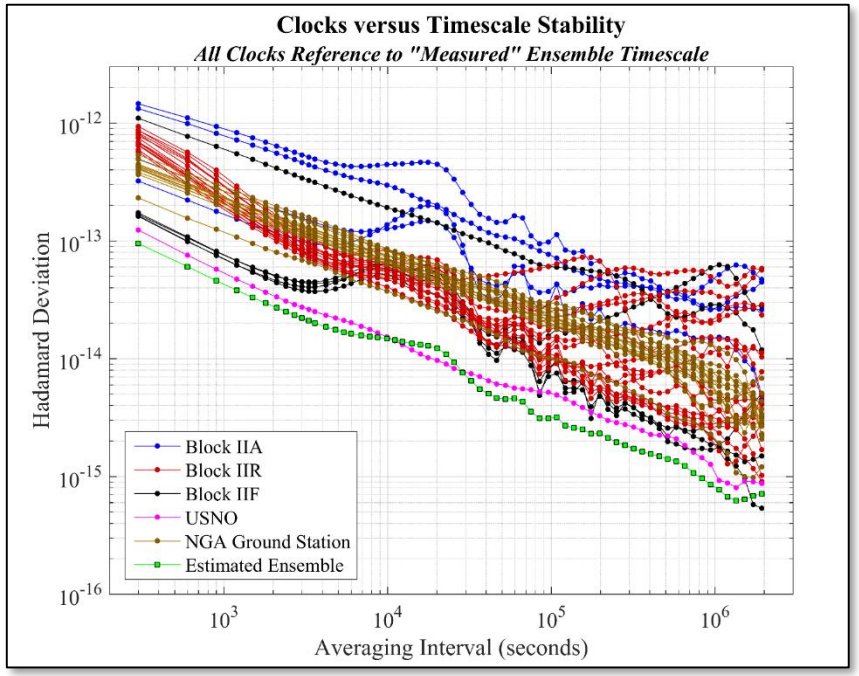
Timescale's Capabilities

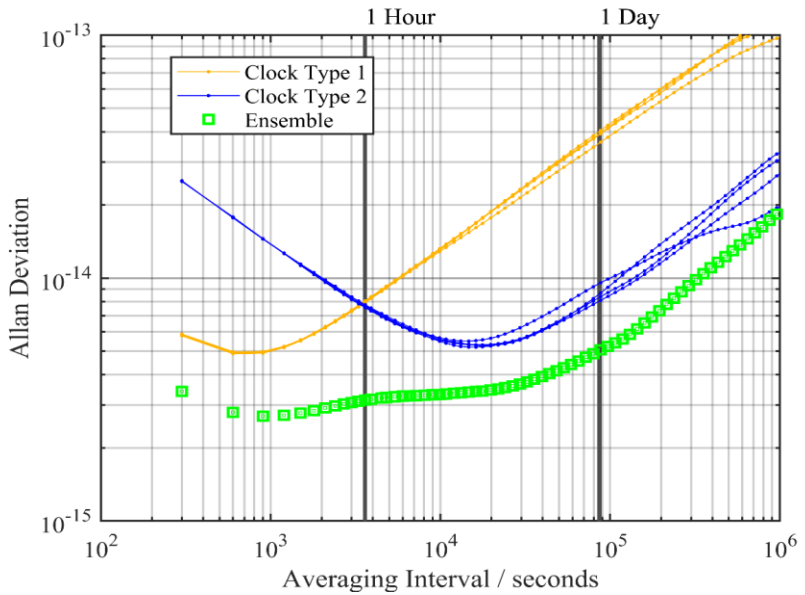
- NRL's timescale refined and completely re-coded in C++ with extensive testing.
- Standard Kalman Filter used to facilitate real-time implementation.
- Covariance factorized by $\mathbf{P} = \mathbf{U}\mathbf{D}\mathbf{U}^T$ to increase dynamic range and improve numerical stability of the recursion.

Highlights of report from NRL / Mike Coleman

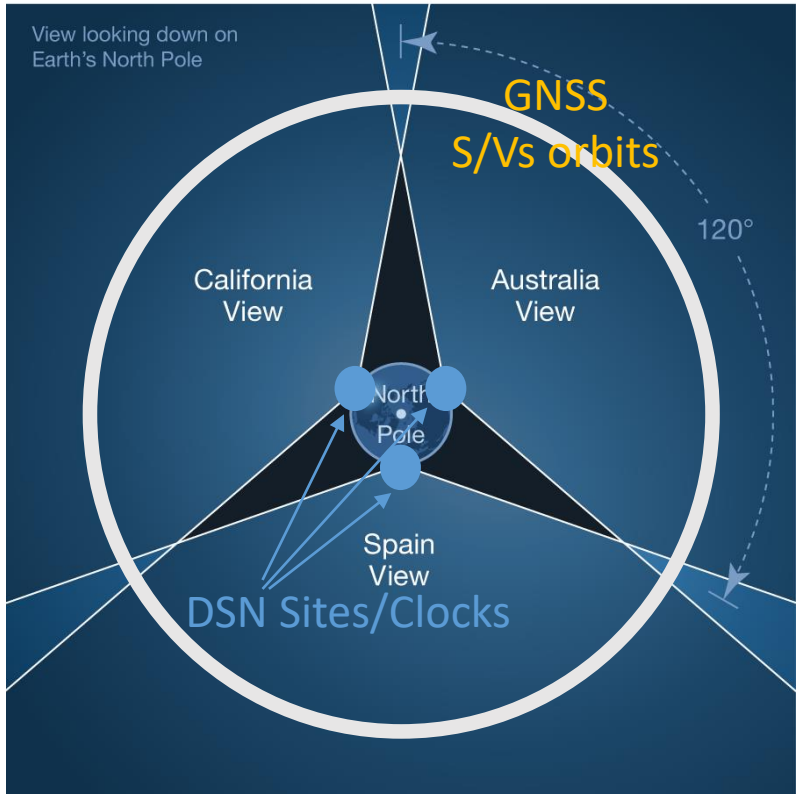
Features and Capabilities

- Algorithm models standard clock states and environmental 1/rev and 2/rev periodics.
- Responds to clock anomalies by repairing phase estimates and re-estimating frequency offsets.
- Reduces weight of outlier measurements to prevent unstable estimates and protect ensemble stability.





- (Left) Clock multi-weighting exploits the most stable clocks for each noise type yielding a more stable ensemble stability at most averaging intervals.
- (Above) Timescale stability is better than all member clocks at most intervals and no clock has more than 6.5% of the ensemble weight.



GNSS and Deep space Network

GNSS All-in-View Time transfer for clocks synchronization between JPL, Goldstone, Madrid and Canberra

Short baseline time transfer

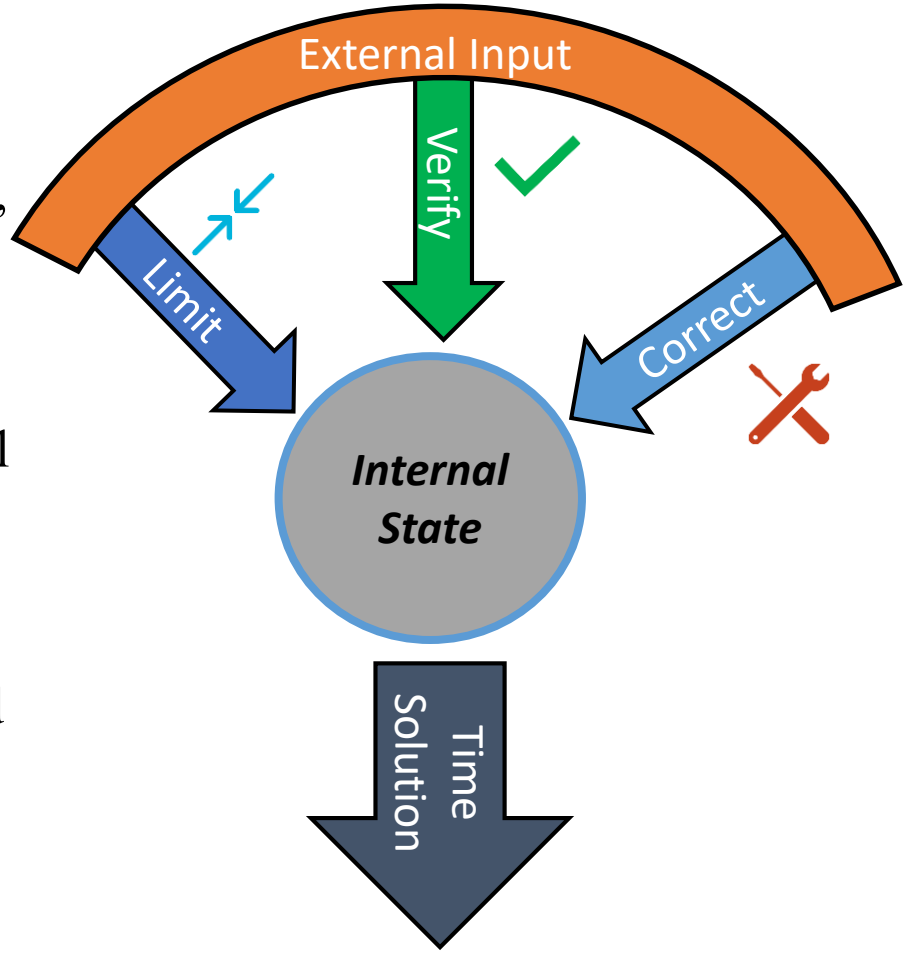
- JPL-Goldstone ~100miles

Long baseline time transfer

- Goldstone-Madrid ~ 5800 miles
- Madrid-Canberra ~11000 miles
- Goldstone-Canberra ~ 7700 miles

Control algorithms for resilient timing / Ilya Udovydchenkov

- Use known Resilient PNT techniques to withstand threats by *maintaining a protected internal state*
  - Ex: a local clock/oscillator
- The more isolated the internal state is from the rest of the system, the more protected it is from corrupted external input
  - If external input can influence the internal state, protection may include:
    - **Limit external input** when possible (isolate the internal state as much as possible)
    - **Verify external input** before it influences the internal state
    - Implement algorithms to **apply corrections** if corrupted external input infiltrates (recovery)



Control algorithms for resilient timing / Ilya Udovydchenkov

- Resilience is an important consideration in a PNT system design.
- Protect the internal state to achieve resilience.
  - Limit the time when external input (GPS) can influence a protected internal state (local clock)
- There are trade-offs in the design parameters of a resilient PNT system.
  - Balance between the convergence rate of a steering algorithm and the amount of system and external reference noise should be considered.

Resilient Techniques	Example Metric
Verify quality and accuracy	The fraction of the threats detected in a standardized list. May be weighted by threat importance or difficulty.
Limit the influence of external input	The fraction of time the internal state (clock) is protected from external information (GPS)
Correct PNT Solutions	The fraction of the threats corrected in a standardized list. May be weighted by threat importance or difficulty.
Predict future solutions	Covariance matrix
Recover performance	Mean time to recover

NIST network Time Services…/ Judah Levine

Standard NTP Service

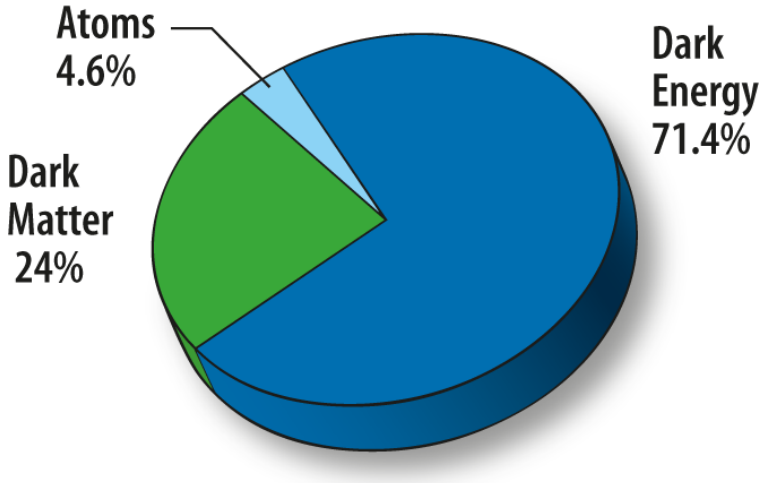
- 25 NTP servers at 4 locations
- Synchronized to local cesium clock ensemble at each site
  - Ensemble realizes UTC(NIST)
- Sites compared with each other
- Approximately 10^6 requests/second
- Accuracy at server about 5 μs
- Accuracy for user depends on network
  - Best 150 μs
  - Typical 5 ms – 10 ms

Authenticated NTP Service

- NTP messages authenticated with symmetric key algorithm
- 4 servers at different locations
- 800 registered users, each one has unique symmetric key
- Key linked to IP address(es) of client systems
- Authentication prevents spoofing and altering of messages
  - Does not improve accuracy

Atomic clocks for fundamental physics../Marianna Safronova

- Search for physics beyond the standard model by looking for variations in fundamental constants
- Search for dark matter
- Search for the violation of Lorentz invariance
- Tests of equivalence principle
- Perhaps even possible to detect gravitational waves



GPS/Galileo time transfer with absolutely calibrated Receivers / Roberto Prieto-Cerdeira

- A simple and accurate procedure for calibration of HW delays in GNSS receiver chains has been developed, executed and validated
- Delays with simulated signals:
  - Sub- to ns internal consistency
  - 1-2ns consistency with independent method (CNES)
- Comparison with real signals:
  - Sub- to ns consistency
- Comparison with existing GPS standard:
  - Few ns consistency

✓ On the basis of these results (and others), the BIPM CCTF Working Group on GNSS Time Transfer has decided to use the absolute calibration of the BP21 chain as standard for Galileo

✓ Standard already transferred to G1 laboratories in EURAMET and SIM, on-going for the other areas

✓ Future G1/G2 trips will include GPS + Galileo

Thank you all for participating.